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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS
OF SURFACE EFFECT SOLAR CELLS

by

Charles Edward Norman B.A.Sc., M.Eng.

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

This thesis describes the design, fabrication, testing and modelling of four types of surface effect solar cells: the inversion layer (IL) cell with either diffused or MIS contacts, the accumulation layer cell and the TiO_x -MIS cell. The work has concentrated on IL cells, but the theory, techniques and results can be applied to all photovoltaic devices.

After a review of basic photovoltaic theory, several surface effect cell structures are introduced. The MOS theory governing the operation of IL cells is derived and applied to designing an experimental contact grid pattern. The fabrication of surface effect cells is discussed and the electrical and optical tests developed to characterize them are described.

The modelling of surface effect cells is considered and several computer programs which simulate their operation are described. In particular, the program ILSCEL models all the important one and two-dimensional effects occurring in IL cells. The measured and modelled results for several IL cells are compared and found to be in excellent agreement. The model is thereby proven to be accurate and the cells are shown to operate as predicted by theory.

The IL cells fabricated to date have had AM1 efficiencies of 10-12%, close to that of conventional solar cells. The computer models are used to identify the factors presently limiting this efficiency and to explore the future potential of surface effect cells. With minor

process modifications, efficiencies above 15% are shown to be possible.. Since some surface effect cells can be made using low temperature and low cost processing, they have definite advantages over conventional diffused cells. Their development should therefore be continued.

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LIST OF PRINCIPAL SYMBOLS

$a(\lambda)$	optical absorption efficiency	
A	diode ideality factor (A_1 or A_2)	
c	speed of light in vacuum 3.00×10^{10}	cm/s
$c(\lambda)$	collection efficiency in a solar cell	
C	metal-oxide-semiconductor capacitance	F/cm ²
C_{ox}	oxide capacitance	F/cm ²
C_s	silicon capacitance	F/cm ²
D_n	diffusion constant for electrons	cm ² /s
D_p	diffusion constant for holes	cm ² /s
$E(x)$	electric field strength	V/cm
E_c	conduction band energy level	eV
E_f	Fermi level in the energy bandgap	eV
E_g	bandgap energy of a semiconductor	eV
E_i	intrinsic energy level	eV
E_s	surface electric field strength	V/cm
E_v	valence band energy level	eV
FF	fill factor of I-V curve	
$g(x)$	optical generation rate within solar cell	cm ⁻³ s ⁻¹
$g(\lambda)$	generation efficiency	
h	Planck's constant 6.626×10^{-34}	J·s
I	output current density	A/cm ²
I_o	reverse saturation diode current density	A/cm ²
I_L	photogenerated current density	A/cm ²

I_{sc}	short circuit, current density	A/cm^2
J_d	depletion collection current density	A/cm^2
$J_n(x)$	electron current density	A/cm^2
$J_p(x)$	hole current density	A/cm^2
k	Boltzmann's constant 1.38×10^{-23}	J/K
$k_{Si}(\lambda)$	extinction coefficient of silicon	
L_D	intrinsic Debye length in silicon	cm
L_n	diffusion length for electrons	cm
L_p	diffusion length for holes	cm
m_{air}	air mass	
$n(x)$	electron concentration	cm^{-3}
n_i	intrinsic electron concentration	cm^{-3}
n_{ox}	refractive index of oxide/AR coating	
n_{Si}	real part of the refractive index of silicon	
N_a	acceptor doping, density (p-type)	cm^{-3}
N_d	donor doping density (n-type)	cm^{-3}
N_f	grid finger density	cm^{-1}
$N_m(\lambda)$	air mass m solar spectrum	$cm^{-2} s^{-1} nm^{-1}$
N_{ss}	interface state density	$cm^{-2} eV^{-1}$
$p(x)$	hole concentration	cm^{-3}
P_{in}	incident solar power density (irradiance)	W/cm^2

$P_{\max}$	maximum output power density	W/cm^2
q	electronic charge 1.602×10^{-19}	C
$Q_e(\lambda)$	external current efficiency	
$Q_i(\lambda)$	internal current efficiency	
Q_{fb}	effective flatband charge density	cm^{-2}
Q_{ox}	effective oxide charge density	C/cm^2
Q_{ss}	surface state charge density (thermal SiO_2)	C/cm^2
r_s	sheet resistance of inversion layer	$\Omega/\square$
$R(\lambda)$	reflection coefficient	
$R_e(x)$	recombination rate	$cm^{-3}s^{-1}$
R_{IL}	inversion layer series resistance	$\Omega \cdot cm^2$
R_s	effective series resistance of solar cell	$\Omega \cdot cm^2$
S_b	back surface recombination velocity	cm/s
S_f	front surface recombination velocity	cm/s
SR	spectral response of solar cell	A/W
t_{air}	transmission of one standard air mass	
t_{ox}	thickness of oxide/AR coating	cm
T	absolute temperature	K
$u(x)$	normalized potential	
u_{fp}	normalized bulk Fermi potential	
u_s	normalized surface potential	
v	normalized junction voltage	
V	output voltage of solar cell	V

V_{fb}	flatband voltage in an MOS capacitor	V
V_g	MOS gate bias voltage	V
V_{oc}	open circuit voltage	V
w_c	bus bar width at wide end	cm
w_d	grid finger contact width	cm
w_f	grid finger metal width	cm
w_o	substrate thickness	cm
x	distance into silicon from front surface	cm
x_b	BSF region thickness	cm
x_d	depletion depth	cm
x_j	junction depth	cm
y	distance from grid finger on front surface	cm
z	distance along grid finger from bus bar	cm
$\alpha(\lambda)$	optical absorption coefficient of silicon	cm ⁻¹
ϵ_{ox}	permittivity of oxide	F/cm
ϵ_s	permittivity of silicon 1.04×10^{-12}	F/cm
η	overall power conversion efficiency of solar cell	%
λ	wavelength	cm
λ_c	centre wavelength of interference filter	cm
μ_n	electron mobility	cm ² /V/s
μ_{nl}	lateral mobility of electrons in inversion layer	cm ² /V/s

μ_p	hole mobility	$\text{cm}^2/\text{V/s}$
$\rho(x)$	charge density	C/cm^3
ρ_b	bulk resistivity of substrate	$\Omega \cdot \text{cm}$
ρ_c	metal-semiconductor contact resistivity	$\Omega \cdot \text{cm}^2$
ρ_m	grid metal sheet resistance	$\Omega/\square$
τ_n	electron lifetime	s
τ_p	hole lifetime	s
$\phi(x)$	electric potential	V
ϕ_{ms}	metal-semiconductor work function	eV

CHAPTER 1

INTRODUCTION

1.1 Background

The direct conversion of sunlight into electricity via the photovoltaic effect first became practical in the early 1950's with the birth of modern semiconductor technology and the demonstration of the first solar cells [1, 2]. These were essentially large area photodiodes formed by the diffusion of a p-n junction into a silicon substrate. The original 6% conversion efficiency was soon raised to the 10-12% level and the new devices found their first major application as power sources on spacecraft; a niche they occupied, relatively unchanged, for more than a decade. In space, the advantages of low weight and simple, reliable operation overcame the disadvantages of low power density and high cost which prevented the cells' acceptance in most terrestrial applications where much cheaper power was readily available.

However, in recent years, the growing demand for energy, coupled with the increasing environmental and national security risks involved in the extraction, transportation, utilization and disposal of conventional fuels and the rapid depletion of non-renewable reserves have escalated the cost of energy and forced society to look for alternate, renewable sources. The potential for abundant, safe, clean and cheap power from the sun has led to renewed interest in solar energy. Thus, photovoltaics has become more attractive and since 1970,

there has been growing support for solar cell research and development, especially for terrestrial applications [3].

The research is proceeding into many areas of materials and processing technology. As well as the traditional single-crystal silicon wafers, alternate materials such as GaAs, CdS-Cu₂S, polycrystalline and even amorphous silicon are being actively investigated [4, 5, 6, 7]. Also, various fabrication techniques like thin-film deposition, screen printing of contacts and ion implantation are being considered as alternatives to conventional processing [7, 8, 9]. The ultimate goal of this work is to raise the conversion efficiency or reduce the cost to a level where solar cells can compete economically with conventional energy sources. The long term goal of the U.S. Department of Energy is to produce cells at a cost of \$.50 per peak Watt output by the year 1986 [10].

Single crystal silicon solar cells with diffused n⁺-on-p junctions are still the mainstay of the photovoltaic industry, recently achieving up to 15-17% efficiency in normal sunlight [7] at an array cost of \$10-\$15 per installed peak Watt [10]. While this cost can doubtless be reduced by economies of scale and mass production techniques [11], the need for expensive single crystal substrates and high temperature processing will ultimately limit the minimum cost. A completely low temperature process which can utilize cheaper substrates (polycrystalline silicon for instance) is more desirable and has stimulated the study of non-diffused structures.

Many of these alternate structures are surface effect solar cells in the sense that their operation relies on energy band bending at the semiconductor surface. Schottky barrier and MIS solar cells are the most familiar examples of this class [12, 13, 14]. A more recent addition is the inversion layer (IL) or induced junction solar cell [15]. Such devices offer the potential of achieving the high efficiency of diffused cells with low temperature, low cost processing.

The concept of inversion layer photovoltaic devices dates back several years [16, 17], but has only recently received much attention. The investigation of IL cells at Carleton University began in 1973 with the development of a fabrication process [18]. The initial devices exhibited poor efficiency, but the process has been improved to yield 10-12% efficiency for IL cells with diffused contacts [19, 20]. Comparable results have been obtained here and elsewhere for IL cells with MIS contacts [21, 22].

1.2 Objectives of the Thesis

When the research for this thesis was initiated, only IL cells with low efficiency had been made. Their operation was disappointing and not fully understood [19]. A theoretical and experimental study of these and other surface effect cell structures was undertaken to elucidate their means of operation, to find ways of improving them and to determine their long range potential and limitations with respect to the photovoltaic industry's goals.

Investigation proceeded in four different but closely related areas. Hence, the research had four main objectives:

- i) To validate the inversion layer cell concept by designing and fabricating efficient IL solar cells using standard semiconductor processing techniques.
- ii) To test the devices to determine if they operate as expected and for comparison with other cells. This involved the development of standard and reliable electrical and optical test methods.
- iii) To advance the theory of inversion layer and other surface effect solar cells using semiconductor theory and computer modelling so that their operation could be fully understood and accurately predicted.
- iv) To theoretically explore the potential of surface effect cells using the computer models developed and thereby determine how these devices can be improved.

The purpose of this thesis is to present the methods used and the results obtained in fulfilling these objectives. Such a presentation should provide a sound basis for future development in this field.

1.3 Thesis Outline

The thesis is divided into nine chapters. The first is a general introduction to the purpose and nature of the dissertation and gives an overview of the subject's background. Chapter 2 reviews the basics of solar cells, their operation and characterization and serves to introduce the concepts and terminology used in the remaining chapters. In the third chapter, surface effect cell structures are

described and the theory behind their operation explained. Mathematical emphasis is placed on inversion layers and the MOS system. In Chapter 4, the tradeoffs and alternatives involved in the design and fabrication of inversion layer cells are discussed. The fifth chapter outlines the development and use of the electrical and optical test methods. Chapter 6 discusses the modelling of one and two dimensional effects in surface effect solar cells and outlines the operation of the computer models.

Chapters 4, 5 and 6 lay the groundwork for Chapter 7 where the theoretical and experimental results of the research are presented and discussed. The eighth chapter probes the potential of surface effect solar cells and identifies the factors presently limiting their performance. The ninth chapter summarizes the work and makes recommendations for future studies. Finally, several appendices serve to expand or clarify concepts introduced in the body of the thesis.

CHAPTER 2

SOLAR CELL FUNDAMENTALS

The study of solar cells involves concepts and terminology unique to the field. All solar cells operate on the same principles and can be characterized by the same methods. Before discussing surface effect solar cells, it is necessary to understand the basics of cell operation and the terms used for describing and comparing different cell types.

This chapter introduces the photovoltaic effect and other concepts common to all photovoltaic devices. The conventional, diffused-junction solar cell will be used to illustrate the ideas and will act as a standard against which other cell structures may be compared.

2.1 Solar Energy and Semiconductors

The most crucial element in any solar energy system is, of course, the sun itself. Designing solar cells for optimal usage of the available sunlight is an important part of photovoltaic work. This requires an understanding of the nature of incident sunlight.

Depending on the time of year, the solar irradiance on a plane facing the sun is 133-140 mW/cm² above the atmosphere. This power is distributed across the optical spectrum as shown in Figure 2.1. The air mass zero (AM0) photon flux is plotted for the range of wavelengths of interest in photovoltaics [23]. Not all this energy reaches

Fig. 2.1 The air mass zero solar spectrum and the optical transmissivity of one standard air mass.

the earth's surface, however. Atmospheric gases and suspended particulates absorb and scatter much of it, leaving less available for terrestrial solar energy conversion [24]. The fraction of photons at a given wavelength which penetrates vertically through a standard atmosphere to sea level is called the air transmission, t_{air} and is also plotted (dashed line) in Figure 2.1.

As the sun's angle in the sky changes, the light must pass through a varying thickness of air to reach the ground. This effect is characterized by the air mass as illustrated in Figure 2.2 a). Ideally, the air mass is the secant of the sun's angle relative to the zenith, measured at sea level on a clear day. Alternately, it is the number of standard air masses traversed by the light to reach the observer. Thus, air mass one (AM1) would occur at sea level, with the sun directly overhead on a clear day. In this situation, the irradiance would be $\sim 100 \text{ mW/cm}^2$ as shown in Figure 2.2 b) which illustrates the effect of air mass number on the total incident power [24]. If the air mass, m_{air} is known, the spectral distribution $N_m(\lambda)$ can be calculated:

$$N_m(\lambda) = N_o(\lambda) [t_{\text{air}}(\lambda)]^{m_{\text{air}}} \text{ cm}^{-2} \text{ s}^{-1} \text{ nm}^{-1} \quad (2.1)$$

using $N_o(\lambda)$ and $t_{\text{air}}(\lambda)$ from Figure 2.1. In reality, $t_{\text{air}}(\lambda)$ varies with the local atmospheric conditions and can never be known accurately. This accounts for the differences between the calculated and measured values of t_{air} in Figure 2.1 and is the cause of the uncertainty in P_{in} , the incident solar power in Figure 2.2 b). Since many solar cell characteristics vary with light intensity, the intensity or spectrum should be quoted when measurements are reported or compared.

Fig. 2.2 a) Definition of air mass.

b) Effect of air mass on solar power reaching the earth's surface.

In principle, solar cells can be made from any semiconducting material. However, for various reasons, some are more suitable than others. If the bandgap energy is too high ($E_g > \sim 2\text{eV}$), too few of the solar photons will be energetic enough to overcome it and produce current carriers. If, however, the bandgap is too low ($E_g < \sim 1\text{eV}$), the output voltage will be low. In both cases, cell efficiency will suffer. The optimum bandgap energy which will (all other parameters being equal) result in the highest output power is $E_g \sim 1.5\text{ eV}$ [26]. Another consideration is whether the bandgap is direct or indirect. An indirect bandgap requires phonon assistance in the absorption of light quanta. Therefore, the absorption coefficient will be lower than for a direct bandgap material and the substrate will have to be thicker to absorb the incoming light.

When silicon is examined with respect to these two criteria, it appears unsuitable. With an indirect bandgap of 1.109 eV (at room temperature), it is far from ideal. However, its many advantages over alternate materials have so far outweighed these problems. Silicon is inexpensive, abundant and easy to work with compared to more "ideal" materials such as InP or GaAs. For these reasons, it has been superior and is likely to continue as the most widely used material for solar cells. Therefore, this thesis will consider only silicon solar cells although much of the theory can be readily adapted to other materials.

When monochromatic light of wavelength λ enters a material, the number of photons remaining at a depth x is governed by Lambert's law of absorption:

$$N(\lambda, x) = N(\lambda, 0) \exp[-\alpha(\lambda)x] \quad , \quad \text{cm}^{-2} \text{s}^{-1} \text{nm}^{-1} \quad (2.2)$$

where $N(\lambda, 0)$ is the photon flux at the surface and $\alpha(\lambda)$ is the absorption coefficient for the material at that wavelength.

The absorptivity of silicon has been measured [27, 28] and is shown in Figure 2.3. High values for $\alpha(\lambda)$ at ultraviolet wavelengths ($\lambda < 400$ nm) indicate that UV light is absorbed close to the surface, while lower values at longer wavelengths imply deeper penetration. Classically, no absorption should occur at wavelengths longer than ~ 1100 nm as depicted by the solid line in Figure 2.3. Photons of longer wavelengths are not energetic enough to surmount the bandgap. However, all silicon cells exhibit some response even at $\lambda = 1200$ nm. This implies that some useful absorption occurs above the expected cutoff wavelength, λ_{co} . This effect has been explained as phonon-assisted absorption [29] and will be discussed further in Chapter 7. For the purpose of calculating the spectral response, this effect was modelled by extending $\alpha(\lambda)$ out to 1200 nm as shown. This has been done independently with good results by other investigators [30].

The dashed curve in Figure 2.3 illustrates the effect of a temperature change on $\alpha(\lambda)$. Also shown (dotted curve) is the real part of the refractive index for silicon, n_{Si} [28]. This is used in determining the reflection properties at the surface of the solar cell and will be discussed in subsequent chapters.

Fig. 2.3 Optical parameters for single crystal silicon.

2.2 The Photovoltaic Effect and Conventional Solar Cells

A photon of light is absorbed in silicon through the raising of an electron from the valence band to the conduction band, creating an electron-hole-pair (EHP). The rate of EHP generation is therefore, the rate of absorption which is the negative derivative of equation (2.2):

$$G(\lambda, x) = -\frac{d}{dx} N(\lambda, x) = \alpha(\lambda) N(\lambda, 0) \exp[-\alpha(\lambda)x] \quad \text{cm}^{-3} \text{s}^{-1} \text{nm}^{-1} \quad (2.3)$$

If the EHP's are not disturbed, they will move randomly within the crystal and eventually recombine producing no useful output. Thus, a solar cell is designed to separate the electrons from the holes in such a way that power can be delivered to an external load.

A schematic diagram of the structure of a conventional solar cell is given in Figure 2.4 a). Normally, a 2-10 $\Omega \cdot \text{cm}$, p-type substrate has a shallow (<1 μm) n^+ region diffused into its front surface. Ohmic contacts are applied at the front and back to conduct the current and usually an anti-reflective coating is deposited on the front surface. The front contact is in the form of a grid, designed to achieve a low resistance conduction path with a small contact area. (The metal grid shades the cell, rendering the area beneath it useless.)

The energy band diagram for the device at zero bias is depicted in Figure 2.4 b). In order to maintain a flat Fermi level and quasi-equilibrium conditions throughout the device, the bands must bend as shown, giving rise to a built-in potential and the electrostatic field in the depletion region as indicated in Figure 2.4 c).

Fig. 2.4 a) Conventional, diffused cell structure.

b) Energy band diagram, generation and collection.

c) Electric field and minority carrier distributions.

It is this field, $E(x)$ which is responsible for separating and collecting the light-generated EHP's. Electrons generated in the bulk enter the depletion region and are swept across to the n^+ side. Similarly, holes from the diffused region are collected by the field into the p-type bulk. The result is a steady current, I_L flowing in the reverse direction across the diode barrier. Outside the depletion region, the minority carriers flow toward the junction by diffusion. Under steady-state, short-circuit conditions, a distribution of excess holes in the n-region and electrons in the p-region will arise as shown in Figure 2.4 c) to support the diffusion.

Based on the above, a solar cell can be viewed as a current source in parallel with a p-n diode as illustrated in Figure 2.5 a). Usually, a series resistance, R_s is included in the model to represent the resistive losses within the device. When the cell is open circuited, the photocurrent, I_L will continue to flow across the junction, but a voltage will build up. This forward biases the junction causing an injection current to flow. At steady state, the forward current will equal I_L and no net current will result. By adjusting the load, R_L the cell can be operated at any point between the two extremes of open and short circuit. The resulting locus of current-voltage points is the output I-V curve shown in Figure 2.5 b). This curve is basically the normal diode curve shifted down the current axis by I_L and adjusted for series resistance. Thus, for typical values of R_s , the short circuit current, I_{sc} will equal I_L . I-V curves are normally plotted with the current axis inverted to yield a positive output power. At the "knee" of the I-V curve, is a point where the output

Fig. 2.5 a) Simple solar cell model.

b) Output current-voltage curve.

power (I-V product) is maximized and solar cells are usually operated at or near this point to deliver as much power to the load as possible.

The model in Figure 2.5 a) can be combined with simple semiconductor theory for a one sided step junction [31] to yield an ideal ($R_s=0$) approximation to the I-V curve:

$$I(V) = I_L - I_o [\exp(\frac{qV}{kT}) - 1] \quad \text{A cm}^{-2} \quad (2.4)$$

where kT/q is the thermal voltage (.026 V at 300K) and I_o is the reverse saturation diode current, given by:

$$I_o = \frac{q n_i^2}{N_a} \sqrt{\frac{D_n}{\tau_n}} \quad \text{A cm}^{-2} \quad (2.5)$$

where q is the electronic charge, n_i the intrinsic electron density, N_a the bulk doping density, D_n the diffusion constant for electrons in the bulk and τ_n the bulk lifetime.

2.3 Loss Mechanisms and Efficiency

The terminology used to quantitatively describe the various aspects of photovoltaic conversion can be introduced by considering the ways that energy is lost between its initial incidence on the cell and its final delivery to the load. Several losses occur before the light enters the silicon. The front contact grid necessarily covers a small part of the cell (usually 5-10%), which is then lost to photovoltaic action.

Reflection at the interface between air and bare silicon is about 35%, depending on the wavelength as shown in Figure 2.6. This loss can be substantially reduced by the application of one or more dielectric anti-reflection (AR) coatings as indicated in the figure. Typical materials used for AR coatings are SiO_2 , TiO_2 and Ta_2O_5 . Even the best materials are not ideal dielectrics however. All absorb some of the incoming light [32]. These effects are worst at ultraviolet wavelengths and it is difficult to conduct more than 30-40% of this light into the silicon. Fortunately, there are relatively few UV photons at ground level so that the loss is insignificant.

Once the light has entered the semiconductor, it must be absorbed. This poses no problem for wavelengths below 900 nm, but for less energetic photons, α is low and much of the radiation passes through the cell to be lost at the back contact. Photons with energies less than the bandgap cannot generate EHP's. Thus, essentially all the light at wavelengths greater than $1.12 \mu\text{m}$ (in silicon) cannot be used in photovoltaic conversion.* Furthermore, since each EHP has $\sim 1.1 \text{ eV}$ of energy, photons possessing more than this amount have the excess wasted as heat. These two effects result in the loss of more than half the energy in the AM0 spectrum.

Each step in conversion from light quanta into current flow can be characterized by an efficiency [33]. The absorption efficiency, $a(\lambda)$ is the fraction of photons entering the silicon which is absorbed.

* This is not entirely true as some phonon assisted absorption does occur at longer wavelengths (see sections 2.1 and 7.2) but it is a good approximation.

Fig. 2.6 Reflection coefficient for the air-silicon system showing the effectiveness of various antireflection coatings.

For a cell of thickness w_0 and a wavelength λ ,

$$a(\lambda) = 1 - \exp[-\alpha(\lambda)w_0] \quad (2.6)$$

that is, the fraction of photons entering the silicon which does not reach the back surface. Clearly, $a(\lambda)$ will be very close to unity for all short wavelengths and will drop at longer wavelengths to become almost zero above the cutoff wavelength. The quantum efficiency is the number of EHP's produced per photon at a given wavelength. It is generally assumed to be 100% over the entire spectrum. The product of the absorption and quantum efficiencies is called the generation efficiency, $g(\lambda)$ and is essentially equal to $a(\lambda)$.

Not all the generated holes and electrons cross the depletion region to be collected. Some recombine when they encounter the front or back surface. Others recombine in the bulk material, the n^+ diffused region or even in the depletion region during collection. Such collection losses are determined by the minority carrier lifetimes throughout the cell, the cell structure and the conditions at the front and back surfaces and are thus, design dependent. The fraction of generated carriers which successfully crosses the depletion region to contribute to the photocurrent is termed the collection efficiency, $c(\lambda)$. The derivation of $c(\lambda)$ is complex [7, 33] and will be dealt with in Chapter 6. The fraction of the incident photons at a wavelength λ resulting in a collected current flow at short circuit is called the external current efficiency, $Q_e(\lambda)$ and is given by:

$$Q_e(\lambda) = t(\lambda) g(\lambda) c(\lambda) \quad (2.7)$$

where $t(\lambda)$ represents the transmission of light into the solar cell. Over most of the spectrum, it will be $1-R(\lambda)$; where $R(\lambda)$ is the reflectance.

Figure 2.7 illustrates the above concepts for a typical diffused solar cell. (The curves are a composite of calculations and published results for typical cells and therefore do not portray any real cell.) The heavy solid line, $Q_e(\lambda)$ represents what would be measured by an experimenter (Chapter 5 describes techniques for measuring Q_e). The light, dashed lines under it indicate how much of the collection is contributed by each part of the cell. The dashed and dotted curves above $Q_e(\lambda)$ show where each of the various losses is important. The cell is designed to obtain maximum response at the peak of the solar spectrum. The data are corrected for grid shading and therefore apply only to the active area of the cell.

Often $Q_e(\lambda)$ is referred to as the overall collection efficiency. ~~As~~ the internal current efficiency, $Q_i(\lambda)$ is used to describe cell operation corrected for the reflectance. Another related characteristic is the spectral response which is the short circuit current output per watt of incident light at a given wavelength. It is simply $Q_e(\lambda)$ divided by the photon energy in electron volts. Once $Q_e(\lambda)$ is known, the cell photocurrent at each wavelength can be calculated as follows:

$$I_L(\lambda) = q N_m(\lambda) Q_e(\lambda) \quad \text{A cm}^{-2} \text{ nm}^{-1} \quad (2.8)$$

where the incident photon flux, $N_m(\lambda)$ is given by equation (2.1).

Fig. 2.7 Loss mechanisms in a typical diffused solar cell.

To obtain power from the cell, it must be operated at a non-zero voltage. The maximum voltage available is the open circuit voltage, V_{oc} . The ratio of V_{oc} to the bandgap is called the voltage factor, VF (typically VF ~ 0.5). By definition, no current flows at V_{oc} so that no power is available at this point either. The position on the I-V curve where maximum power is delivered occurs at a voltage less than V_{oc} and a current less than I_{sc} . This effect is characterized by the fill factor which is defined as follows:

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} \quad (2.9)$$

where I_{sc} is the current flowing at zero cell voltage. If I_{sc} is replaced by I_L (which is the current flowing at zero junction voltage), the equation gives the curve factor, CF which in most practical cells is equal to FF. The fill factor quantifies all the effects acting on the shape of the I-V curve, such as power lost through forward biasing the diode, series and shunt resistance losses.

The total cell output power can be calculated by integrating equation (2.8) across the spectrum:

$$P_{max} = q E_g VF FF \int_0^{\infty} N_m(\lambda) Q_e(\lambda) d\lambda \quad W \text{ cm}^{-2} \quad (2.10)$$

For practical purposes, the limits of integration are from 300 nm (below which there is negligible sunlight) to 1200 nm (above which Q_e drops to zero). The overall conversion efficiency, η can be

found as the ratio of output power, $P_{\max}$ to input power, P_{in} . This result will be the active area efficiency since grid shading has not been included. The input power can be determined by either integrating the entire spectrum $N_m(\lambda)$, direct measurement using a thermopile (or similar instrument), or using Figure 2.2 b) to obtain an estimate.

The maximum possible conversion efficiency of a silicon cell can be readily estimated. The inherent quantum mechanical losses due to insufficient energy above the cutoff wavelength and excess energy below cutoff reduce the energy available for photovoltaic conversion to 44% of the original power in the AM0 spectrum [34]. With zero reflection, complete absorption and no recombination losses, $Q_e(\lambda)$ would be unity. The maximum conceivable open circuit voltage for the structure shown in Figure 2.4 a) is about 0.7 Volts. The best possible fill factor for this device (assuming an ideal diode and no resistive losses) is approximately 0.82. These limits result in an efficiency of ~23%. This would be somewhat higher (~25%) for terrestrial applications due to the different spectral composition of sunlight at the earth's surface. More realistic assumptions about attainable values for V_{oc} and $Q_e(\lambda)$ yield more practical limits of 18-22% [34]. The following section describes how closely real cells have approached these limits.

2.4 Present Status and Limitations of Diffused Cells

In recent years, much effort has been spent trying to improve silicon solar cells [7, 32, 35, 36]. All the design dependent losses described above have been addressed in attempts to further increase the conversion efficiency. With an optimised two-layer AR coating,

the reflection and parasitic absorption losses can be kept at or below ~3%. Another technique is to roughen or "texturize" the front surface by using an anisotropic silicon etch. This produces a surface covered with microscopic pyramids or wedges which trap the incoming light. Such a surface with a single layer AR coating can almost eliminate the reflection loss [36]. Thus, no further major improvements are possible here.

A texturized surface can also significantly reduce the loss due to transmission of light through the cell. Since the incoming light strikes the pyramid faces obliquely, it will refract into the silicon at an acute angle. It therefore has farther to travel to reach the back surface; increasing its chances of absorption. If, in addition, an optically reflective back contact is used, any light reaching it will return into the bulk for a second chance at absorption. With these two methods, absorption losses can be minimized, even for thin cells [35, 36].

Typical diffused cells exhibit poor response in the blue and UV parts of the spectrum as indicated in Figure 2.7. One reason is that during the n^+ phosphorous diffusion, crystal damage and the high dopant level reduce the minority carrier lifetime at the surface to ~10 ns. Also, the silicon surface is poorly passivated by most AR coatings so that the surface recombination velocity is high. The result is that few of the holes generated in this region survive to be collected. Therefore, the highly doped surface region is often referred to as the "dead layer". Unfortunately, the absorption is highest at the surface, especially for short wavelengths, accounting

for the low response. By reducing the junction depth and the phosphorous concentration, these effects can be largely overcome. Cells made in this way have improved UV response and higher output currents [32].

Bulk recombination is a primary reason for poor response at near infra-red wavelengths (800-1000 nm). Electrons generated deep in the bulk by this light must diffuse a long way to reach the junction. During this time, they are liable to recombine if their lifetime is low. In a normal cell, the high temperature processing limits the lifetime to $< 10 \mu\text{s}$. Not only does this reduce the collection current, but it also lowers the open circuit voltage.

Back surface recombination is also a major problem. An ohmic contact acts as a sink for minority carriers and thus causes a very high surface recombination velocity ($S_b > 10^6 \text{ cm/s}$). Therefore, an electron generated halfway through the cell has an equal chance of being collected or being lost at the back. Fortunately, a method has been developed to reduce this loss [37]. If a p^+ diffusion is made into the back surface, a high-low junction results. This has a built-in field which repels electrons back into the bulk, preventing surface recombination. Such a structure is called a back surface field (BSF) and is incorporated into most high efficiency solar cells. As well as increasing the collection efficiency, the BSF region can raise the open circuit voltage [7, 37]. BSF operation and performance are discussed further in Chapters 6 and 8.

Several factors affect the shape of the I-V curve. The diode ideality factor, A is a number (usually between 1 and 2) which divides the voltage, V in equation (2.4) to obtain a better fit with

measured data. Crystal defects introduced during diffusion and other high temperature processes are thought to be responsible for A being greater than unity (the ideal value). These defects produce anomalous recombination effects in the space charge (depletion) region. Values of A greater than unity tend to reduce the fill factor slightly.

Series resistance further reduces the fill factor of a solar cell. It is composed of bulk silicon resistance, lateral sheet resistance in the n^+ region and front metal resistance in the contact grid pattern. Resistive losses can be substantially reduced with a good grid design. A typical 2 cm square solar cell has six grid fingers connected by an edge contact bar yielding a series resistance of $\sim .25 \Omega$. A finer grid pattern (50 fingers or more) can occupy the same cell area, but lower the resistance to $\sim .10 \Omega$ or less [32]. A shunt resistance (diode leakage) can also adversely affect the fill factor. However, this is generally not a problem in properly fabricated cells.

A typical, commercially available, diffused solar cell has a junction depth of $\sim 1/2 \mu\text{m}$ on a thick, $10 \Omega\text{-cm}$ substrate, with no BSF region and a single layer TiO_x AR coating. Such a cell, operating under AM0 sunlight achieves $I_{sc} \sim 38 \text{ mA/cm}^2$, $V_{oc} \sim .55 \text{ V}$, and $FF \sim .75$ for an efficiency of $\sim 11 1/2\%$. Incorporation of the changes described above can greatly improve these results. The "violet cell" [32] utilizes a Ta_2O_5 AR coating, a higher substrate doping level and a very shallow ($\sim .2 \mu\text{m}$) junction to achieve $\sim 14\%$ AM0 efficiency (corrected for grid shading). The "Comsat Non-reflective Cell" [36] added surface texturizing to reach $\eta > 15\%$ AM0.

Recently, thin cells with good BSF-regions have been made with 15.5% AMO efficiency [38]. These efficiency figures translate into 16-17% for AMI operation. By combining and optimizing these cell structures, 17-19% AMO efficiency (19-21% AMI) should be achievable, [35].

Unfortunately, these results can only be achieved at a cost far too high for large scale terrestrial applications. To maintain high efficiency, a high purity, single crystal substrate is required. When cheaper, lower grade material like polycrystalline silicon is used, the diffusion is non-uniform and difficult to control, and the efficiency is substantially lower. Also, the diffusion process requires high temperatures (800-1100°C) and therefore, must be performed under ultrapure conditions to prevent contamination. It is for these reasons that all diffused cells, even the 10-12% efficient ones are expensive and likely to remain so.

This chapter has served to introduce the photovoltaic effect and the devices which operate by it. Although solar cells are basically simple, many factors influence their conversion efficiency. Diffused cells can achieve high efficiencies, but have several disadvantages associated with the high-temperature processing. These include low bulk lifetime, high front surface losses and high cost. In the next chapter, solar cell structures which avoid these problems are introduced.

CHAPTER 3

SURFACE EFFECT SOLAR CELLS

In view of the high cost of diffused solar cells, other photovoltaic structures are being investigated. Several of these can be described as "surface effect cells" since they have in common a high electric field at the front surface of the substrate. The field arises in response to the deposition of a layer on top of the silicon and is fundamental to the cells' operation.

All such devices share several advantages over diffused cells. In the absence of diffusion-produced lattice defects and the presence of a high surface electric field, there can be no "dead layer". The current efficiency should therefore remain high at ultra-violet wavelengths. Also, diode ideality factors close to unity should result. The potential for completely low temperature processing implies that higher minority carrier lifetimes should be possible [7, 39]. This would improve collection from the bulk and raise the open circuit voltage. Low temperature processing also allows potentially cheaper substrates such as polycrystalline silicon to be used. Hence, surface effect cells have the potential for achieving high efficiency at low cost. This makes them viable contenders to meet the U.S. Dept. of Energy 1986 goals [10].

This chapter examines surface effect solar cells based on five different structures: Schottky barriers, MIS diodes, inversion layers, accumulation layers and a $\text{TiO}_x\text{-Si}$ heterojunction. The first two are discussed extensively in the literature [7, 12, 13, 14] and will only be introduced here. The remaining three structures are described in more depth. Most of the chapter is devoted to developing the MOS theory for the inversion layer cell.

3.1 Alternate Solar Cell Structures

The first four cells to be discussed are depicted in cross section on the left side of Figure 3.1. The corresponding energy band diagrams appear on the right. The diagrams are not to scale but are drawn to best illustrate the device structure and operation.

The Schottky barrier diode (Figure 3.1 a) was an early alternate cell structure. When a metal with a suitable vacuum work function such as gold or platinum is deposited on an n-type silicon substrate, the energy bands in the semiconductor bend to make the Fermi levels match. This causes the depletion of the silicon surface and the formation of a potential barrier which can act as a rectifier or photovoltaic collector. The structure is realized in practice by evaporating a thin (~6 nm) metal layer onto the cleaned substrate. Usually an antireflective coating is applied and a grid pattern of thicker metal is used to conduct the current collected at the Schottky contact [7, 12].

The I-V output curves for such cells are qualitatively similar to that in Figure 2.5. In fact, most solar cells exhibit this behaviour and can be adequately modelled with an equation of the following form:

Fig. 3.1 Various surface effect solar cell structures (left) with the corresponding equilibrium energy band diagrams (right).
 a) Schottky barrier cell, b) p-type MIS cell, c) diffused contact inversion layer cell, d) accumulation layer (grating) cell.

$$I(V) = I_{sc} - I_0 \exp \left[\frac{q(V + I R_s)}{A kT} \right] \quad A \text{ cm}^{-2} \quad (3.1)$$

where I_0 is the dark current, R_s the series resistance and A the diode ideality factor introduced earlier. Schottky cells have values of A close to unity and operate well at short wavelengths as expected [7].

Unfortunately, they have serious drawbacks. The barrier height is limited by the difference in vacuum work functions of the metal and the silicon. The highest barriers (on n-type silicon) are achieved only with the expensive noble metals. Also, the injection current is primarily a majority carrier flow so that the dark current, I_0 , is high and the open circuit voltage is low (typically, $V_{oc} < 0.4 \text{ V}$). Finally, even with a good AR coating, absorption in and reflection by the thin metal layer are considerable, causing some loss of short circuit current. In spite of these problems, 10% efficiency has been achieved with Schottky cells [7].

The introduction of a thin ($< 3 \text{ nm}$) insulating layer (usually SiO_2 ; $x \leq 2$) between the metal and the silicon has been found to increase the barrier height and suppress majority carrier conduction [7, 13, 14, 40]. The result is higher values for V_{oc} . The photocurrent can still flow by minority carrier tunnelling through the thin oxide. Such an MIS (metal insulator semiconductor) structure is portrayed in Figure 3.1 b). In this example, the substrate is p-type silicon. The largest barrier height for this type is obtained with a low work function metal such as aluminum or titanium. The presence of interface states in the insulator can modify the device operation slightly [14, 41]. MIS diodes with excellent dark I-V characteristics have been

made [13, 42]. Their operation closely fits the ideal theory of equations (2.4) and (2.5) when a series resistance term is included [42, 43]. In addition, >10% AM1 efficient MIS solar cells have been reported [14].

The inversion layer structure shown in Figure 3.1 c) eliminates the thin metal layer and operates on a different principle. The device is made by forming a thick oxide layer on a p-type silicon substrate. The positive charges present in the oxide near the SiO_2 -Si interface [44] strongly invert the silicon surface to induce a junction there. This junction acts as a shallow n^+p diode to separate and collect the photogenerated EHP's. The current is extracted by means of an external contact to the inversion layer. A diffused contact grid is shown in the figure, but MIS contacts have been used with similar success [21, 22, 42].

Such a structure has certain advantages: a high surface electric field, low surface recombination velocity due to oxide passivation and the absence of a diffusion over most of the surface. In addition, there is no light-absorbing metal layer. Unfortunately, two other problems arise. The surface state charge, Q_{ss} is not strong enough to invert a heavily doped substrate ($N_a > \sim 10^{17} \text{ cm}^{-3}$). This prevents high values of V_{oc} from being achieved through the use of low resistivity substrates. Also, due to the high sheet resistivity of even the strongest inversion layer, a very fine grid pattern is required to maintain an acceptably low series resistance. Even with these difficulties, 11% AM1 efficiency has been achieved and higher values should be possible [20]. Inversion layer theory is discussed in depth

later in this chapter. Fabrication of IL cells will be treated in Chapter 4.

The structures described so far are one dimensional in the sense that the minority carriers flow perpendicularly up to and across the junction (vertical collection) and the junction covers the entire area of the device. Thus, under forward bias, injection occurs everywhere across the surface. The injection area is actually slightly larger than the active area (in which photogeneration occurs) since no generation occurs under the metal grid. If the injection area could be reduced to a small fraction of the active area, a proportionately smaller injection current would flow at a given bias voltage. A higher open circuit voltage would then be required for the injection current to cancel the photocurrent.

An alternate, but equivalent explanation is that the current I_o in equation (3.1) is proportional to the diode area. If the diode area is reduced relative to the cell area then I_o is reduced while I_{sc} remains the same (in principle). The open circuit voltage is found by setting $I(V_{oc}) = 0$ in equation (3.1) to obtain:

$$V_{oc} = \frac{A kT}{q} \ln \left(\frac{I_{sc}}{I_o} \right) \quad \text{volts} \quad (3.2)$$

Clearly, a decrease in I_o will raise V_{oc} . In such a device, the carriers must travel laterally as well as vertically to be collected at one of the junction areas and the operation is two dimensional. Cells operating in this manner are referred to as lateral collection or grating solar cells [7].

One form of grating cell, the accumulation cell, is depicted in Figure 3.1 d). It can be made by reversing the elements of the IL cell (a p^+ contact diffusion on an n-type substrate). The oxide charge now drives the surface into accumulation and repels the minority carriers (holes) which must travel to one of the diffused regions to be collected. If the junction area is reduced to 2% of the total area, a 100 mV increase in V_{oc} should (in principle) result. However, since each carrier must diffuse farther to be collected than in a vertical collection cell, the bulk recombination losses will be higher and the photocurrent lower. A complex tradeoff exists between the potential enhancement of V_{oc} and the inevitable reduction of I_{sc} . It is not obvious whether the gains can compensate for the losses in any realizable structure. A simplistic method for modelling lateral collection is developed in Chapter 6 and this tradeoff is considered in Chapter 8.

3.2 TiO_x -MIS Solar Cells

The fifth surface effect structure to be considered is the TiO_x -MIS solar cell shown in Figure 3.2 a) [45]. It was thought that an inversion layer cell with MIS contacts could be enhanced by replacing the thick oxide with a commercially available TiO_2 - SiO_2 compound*. There was evidence that such a film held a higher effective oxide charge for a stronger inversion layer [21]. With a refractive index $n \sim 1.96$, a better antireflective match to silicon would also be obtained (see

* TITANIUMSILICAFILM "C" available from Emulsitone Company, Whippany, New Jersey 07981 U.S.A.

Fig. 3.2 a) TiO_x -MIS solar cell cross sectional structure.

b) Possible TiO_x - SiO_x -Si (SIS) equilibrium energy band diagram.

Figure 2.6). Finally, in spin-on form, use of the film vastly simplifies the processing.

When TiO_x -MIS devices were fabricated, they exhibited slightly higher open circuit voltages and substantially lower short circuit currents than comparable SiO_2 -MIS IL cells [45]. Since these are the characteristics expected for a grating solar cell, it was conjectured that lateral collection dominates and the operation is similar to that of the accumulation layer cell. Further evidence supported this hypothesis [45]. The short circuit photocurrent varied with grid finger spacing as expected for lateral collection. I_{sc} was also more dependent on the substrate resistivity than would be expected for a one dimensional structure. In a lateral collection cell, a larger portion of the carriers must diffuse long distances to reach the junction. The short circuit current will therefore be more sensitive to the small changes in minority carrier diffusion length associated with doping changes. Unfortunately, it was not clear how the TiO_x -MIS structure could operate as a grating cell.

TiO_x material is known to be semiconducting and generally, heavily n-type [46]. Thus, some form of SIS (semiconductor-insulator-silicon) heterojunction is likely. A possible band diagram for this structure is shown in Figure 3.2 b). Clearly, the device is not well understood. The presence of SiO_2 in the TiO_x and the fact that the layer is most probably amorphous further complicate the problem.

Some experiments with TiO_x were performed in an attempt to elucidate the role of the spin-on layer in the device operation. Structures made with contact fingers on top of the TiO_x film exhibited

no photovoltaic output and acted like very leaky capacitors with some rectification. Furthermore, measurement of the film resistivity yielded values on the order of $10^6 \Omega\text{-cm}$, indicating that the material is more like a glass insulator than a semiconductor. However, the layer plays a crucial role since devices made without it fail to produce any appreciable output.

To account for these results the following principle of operation is suggested. The SIS heterojunction is indeed present and collects carriers. However, these carriers have nowhere to go since the TiO_x side of the junction is effectively isolated from the contact by its high resistivity. Therefore, the SIS junction is open circuited and becomes forward biased to some value of V_{oc} . Every electron collected is reinjected back into the silicon bulk where it is free to be collected by the MIS contact. This mode of operation is utilized in a recently invented cell with two junctions, one of which is kept open circuited to "passivate" the front surface [47].

In the absence of further supporting evidence, this explanation must remain speculative. However, it does account for the results obtained to date and provides a model for TiO_x -MIS cell operation. If the TiO_x resistivity is sufficiently high and the SIS junction suitably one sided and lossless, the effective surface passivation will be as good as in the accumulation cell. The operation will then be entirely via lateral collection. It is unlikely, however, that a spin-on film could produce so ideal a junction. Some resistive and recombination losses are inevitable and these may ultimately limit the TiO_x -MIS cell performance. 10% efficient, large area devices have been fabricated however, and the simple processing is attractive.

3.3 Inversion Layer Theory

The diffused grid, inversion layer solar cell structure is repeated in more detail in Figure 3.3 a). The operation of the cell is as follows. Light enters from the front and generates electron-hole-pairs under the active area. The electrons are collected vertically across the junction and then flow as majority carriers through the inversion layer to the contact diffusion and out of the cell via the metal grid. In the figure, a p^+ BSF region has been added to enhance collection.

The principal parts of the device are lumped into electrical elements and shown schematically in Figure 3.3 b) as a simple model of the cell. Derivation of the photocurrent, I_L will be discussed in Chapter 6. After I_L , the most important part is the induced junction, modelled by the diode I_d . This junction can be described by:

$$I_d(V) = I_0 \left[\exp\left(\frac{qV}{A_1 kT}\right) - 1 \right] + I_1 \left[\exp\left(\frac{qV}{A_2 kT}\right) - 1 \right] \quad \text{A cm}^{-2} \quad (3.3)$$

where V is the internal bias voltage. For a lightly doped substrate with a heavily inverted surface, the junction approximates an n^+ on p step junction. I_0 therefore, is ideally given by equation (2.5)

and A_1 should be unity. The second term in equation (3.3) represents the space charge recombination current. Shockley-Read-Hall recombination theory yields values for I_1 an order of magnitude higher than I_0 and predicts $A_2=2$ [31]. Empirical values of I_1 are usually higher and values for A_2 between 1.6 and 4 have been observed. Because A_2 is greater than A_1 , the first term in equation (3.3) dominates at normal current levels.

Fig. 3.3 Diffused contact inversion layer solar cell:

- a) structural cross section showing operation,
- b) simple model for theoretical development.

Equation (3.3), with ideal values for I_0 and A_1 , has been found to adequately describe the behaviour of simple induced junctions [18, 19]. If the bulk doping level were increased or if the inversion layer became weak, injection into the inversion layer would need to be considered. The back surface boundary condition will also modify the value of I_0 in a thin cell. In such cases, more advanced theory is required. Equation (3.3) applies to the contact diode current, I_c as well. However, since this junction is diffused, the values of I_0 , I_1 , A_1 and A_2 will be even further from the ideal ones.

Electrons collected by the induced junction must all flow through the inversion layer sheet resistance to reach the contact. This loss can be lumped into a resistance R_{IL} . To design the optimum grid geometry, the value of this resistance is required. The sheet resistance of the inversion layer is given by:

$$r_s = \frac{1}{\mu_{nl} |Q_n|} \quad \Omega/\square \quad (3.4)$$

where Q_n is the inversion layer charge in coulombs per square centimeter and μ_{nl} is the lateral mobility for electrons in the inversion layer. Measured values of μ_{nl} are available [48] and can be adequately described by the following expression:

$$\mu_{nl} = 0.45 \mu_n \left(\frac{6 \times 10^4}{E_s} \right)^{.333} \quad \text{cm}^2 \text{V}^{-1} \text{s}^{-1} \quad (3.5)$$

where μ_n is the bulk electron mobility [49]. E_s is the electric field strength at the surface of the silicon:

$$E_s = \frac{-Q_s}{\epsilon_s} \quad \text{V cm}^{-1} \quad (3.6)$$

where $\epsilon_s = 1.04 \times 10^{-12} \text{ F cm}^{-1}$ is the permittivity of silicon and Q_s is the total charge (C cm^{-2}) in the silicon. To maintain charge neutrality, Q_s must equal $-Q_{ox}$, the effective charge in the oxide at the SiO_2 -Si interface. Q_s is composed of the inversion layer charge, Q_n plus the depletion charge, Q_d . The inversion charge is therefore given by:

$$Q_n = Q_{ox} - Q_d \quad \text{C cm}^{-2} \quad (3.7)$$

The value of Q_{ox} can be estimated from the fabrication process [44] or measured using C-V analysis (section 3.5). Simple theory can be used to obtain a good approximation for the depletion charge [31]:

$$Q_d = \sqrt{kT \epsilon_s N_a u_s} \quad \text{C cm}^{-2} \quad (3.8)$$

where N_a is the bulk doping level and u_s is the normalized surface potential (derived in section 3.4).

Equations (3.4) through (3.8) can be used to calculate the inversion layer sheet resistivity, r_s . The results are presented in Figure 3.4 for a wide range of Q_{ox} and N_a values. For each value of N_a , there is a Q_{ox} below which the surface is no longer strongly inverted and r_s becomes effectively infinite. Typical values of Q_{ox}/q vary from $1 - 10 \times 10^{11}$ charges/ cm^2 for thermal oxides [44] to 5×10^{12} for deposited SiO_2 [42] and perhaps $> 10^{13}$ charges/ cm^2 for other oxides [17]. The corresponding values of r_s are in the 5 - 50 $\text{k}\Omega/\square$ range. This is two orders of magnitude above comparable sheet

Fig. 3.4 Effect of oxide charge, Q_{ox} on the inversion layer sheet resistivity for different levels of substrate doping concentration, N_a .

resistivities for diffused cells and Schottky barrier cells, indicating the need for a much finer grid pattern on IL cells.

Once r_s is known, the lumped inversion layer series resistance, R_{IL} is determined by the contact grid geometry. The IL resistance for a cell with m narrow grid fingers per centimeter is derived in Appendix A:

$$R_{IL} = \frac{r_s}{12 m^2} \quad \Omega\text{-cm}^2 \quad (3.9)$$

The remaining element in Figure 3.3 b) is R_M . This is primarily the resistance of the grid metal, but also includes the bulk silicon resistance, the front and back metal-to-silicon contact resistances and any interconnect resistance. These terms are calculated from the cell geometry and known characteristics of the contact metal. The overall series resistance for the cell, R_s is the sum of R_{IL} and R_M . Typically, R_{IL} is the larger of the two.

3.4 Review of MOS Theory

The preceding section provides a good qualitative description of induced junctions and IL cell operation. If the device is to be fully understood and correctly modelled, however, a more quantitative analysis is required.

The heart of the cell is the inversion layer and the SiO_2 -Si system. Therefore, standard MOS theory can be applied [31]. Figure 3.5 shows the band diagram for an inverted p-type surface along with the resultant distribution of potential $u(x)$, electric field $E(x)$, and

Fig. 3:5. Potential, electric field and charge distributions near the surface of an inverted, p-type substrate. Inset: energy band diagram for inverted substrate.

the charge density, $\rho(x)$. Once these three are known, the IL system is characterized. The curves shown were calculated using the following theory.

The derivation of u , E and ρ involves the solution of Poisson's equation in one dimension:

$$\frac{d^2}{dx^2} \phi(x) = \frac{-\rho(x)}{\epsilon_s} \quad (3.10)$$

where $\phi(x)$ is the potential. The charge density, $\rho(x)$ is given by:

$$\rho(x) = q [p(x) - n(x) + N(x)] \quad \text{C cm}^{-3} \quad (3.11)$$

where p and n are the concentrations of holes and electrons, respectively and $N(x)$ is the net ionized impurity density. In the absence of an n-type diffusion and any substrate doping variations, $N(x)$ is equal to N_a^- , the ionized bulk doping level. If $n_i \ll N_a \ll 10^{19} \text{ cm}^{-3}$ then $N(x)$ is accurately given by:

$$N(x) = -2 n_i \sinh(u_{fp}) ; u_{fp} = \ln \left(\frac{N_a}{n_i} \right) \quad (3.12)$$

where u_{fp} is the bulk Fermi potential and n_i the intrinsic electron density. The hole and electron densities are given by:

$$p(x) = n_i \exp \left\{ \frac{q}{kT} [\phi_{fp} - \phi(x)] \right\} \quad \text{cm}^{-3} \quad (3.13a)$$

$$n(x) = n_i \exp \left\{ \frac{q}{kT} [\phi(x) - \phi_{fn}] \right\} \quad \text{cm}^{-3} \quad (3.13b)$$

where $\phi_{fp} = E_i - E_{fp}$ and $\phi_{fn} = E_i - E_{fn}$ from the band diagram.

$E_{fn} - E_{fp} = V$, the applied voltage. (In Figure 3.5, $V=0$) The potentials are usually normalized by setting $\phi = \frac{kT}{q} u$ and $V = \frac{kT}{q} v$.

When equations (3.12) and (3.13) are substituted into (3.11), the charge density as a function of $u(x)$ is found. This can then replace $\rho(x)$ in equation (3.10) and Poisson's equation becomes:

$$\frac{d^2 u}{dx^2} = \frac{1}{2L_D^2} [\exp(u - u_{fp} + v) - \exp(u_{fp} - u) + 2 \sinh(u_{fp})] \quad (3.14)$$

where $L_D = \sqrt{\frac{kT\epsilon_s}{2q n_i}}$ is the intrinsic Debye length ($L_D = 23.7 \mu m$ at

$T = 300 K$) and $u = u(x)$ is implied.

Equation (3.14) can be simplified by applying the rule for derivatives; $\frac{d^2 a}{dx^2} \cdot \frac{da}{dx} = \frac{1}{2} \frac{d}{dx} \left[\left(\frac{da}{dx} \right)^2 \right]$; where a is any function of x .

Application of this transformation yields:

$$\frac{d}{dx} \left[\left(\frac{du}{dx} \right)^2 \right] = \frac{1}{L_D^2} [e^{u-u_{fp}+v} - e^{u_{fp}-u} + 2 \sinh(u_{fp})] \frac{du}{dx}$$

where e^a has replaced $\exp(a)$. Integrating both sides of this equation and taking the square root produces the final form:

$$\frac{du}{dx} = -\frac{1}{L_D} [e^{u-u_{fp}+v} - e^{u_{fp}-u} + e^{u_{fp}-u} - e^{u_{fp}+2u} + 2u \sinh(u_{fp})]^{1/2} \quad (3.15)$$

Equation (3.15) can be integrated to find the potential:

$$x(u) = -L_D \int_{u_s}^u \{G(u)\}^{-1} du \quad \text{cm} \quad (3.16)$$

where $G(u)$ is the square root of the expression within the square brackets in equation (3.15) and u_s is the normalized surface potential.

Once $x(u)$ is found, $u(x)$ is known implicitly. The electric field, $E(x)$ is related to $u(x)$ by $E(x) = -\frac{d}{dx} \phi(x) = -\frac{kT}{q} \frac{du}{dx}$ and thus, comes directly out of equation (3.15):

$$E(x) = \frac{kT}{qL_D} \{G[u(x)]\} \quad \text{V cm}^{-1} \quad (3.17)$$

Equation (3.16) can be evaluated only if the surface potential is known. To find u_s , charge neutrality is invoked to give $Q_{ox} = -Q_s$; where Q_{ox} is the effective oxide charge and Q_s is the charge in the silicon. Q_s can be found by integrating Poisson's equation (3.10) as follows:

$$Q_s = -\int_0^\infty \rho(x) dx = -\epsilon_s \int_{\phi_s}^0 \frac{d^2}{dx^2} \phi(x) d\phi = -\frac{kT}{q} \epsilon_s \frac{du}{dx}$$

adding charge neutrality and equation (3.15) yields:

$$Q_{ox} = -Q_s = \frac{kT}{q} \frac{\epsilon_s}{L_D} \{G(u_s)\} \quad \text{C cm}^{-2} \quad (3.18)$$

Thus, u_s can be found for any Q_{ox} by implicit solution of (3.18).

In practice, this is done by iteration to find a u_s which satisfies the equality.

The charge density, $\rho(x)$ is found by placing equation (3.14) into (3.10) as follows:

$$\rho(x) = -\frac{\epsilon_s kT}{2qL_D^2} \left[e^{\frac{u-u_{fp}+v}{kT}} - e^{\frac{u_{fp}-u}{kT}} + 2 \sinh\left(\frac{u_{fp}}{kT}\right) \right] \quad (3.19)$$

Finally, it is useful to note that $\rho(x) = -\epsilon_s \frac{d^2}{dx^2} \phi(x) = \epsilon_s \frac{d}{dx} E(x)$.

Thus, the derivative of the electric field can also be found. This will be used later in modelling the solar cell operation.

3.5 MOS Capacitance

Although the foregoing analysis is sufficient for understanding IL cell operation, it is incomplete from the viewpoint of MOS theory.

If a metal gate is placed on top of the oxide as depicted in Figure 3.6 a), an MOS capacitor results. The behaviour of this device as characterized by a plot of gate capacitance versus gate voltage (the C-V curve) can yield useful information on the state of the SiO_2 -Si interface [50]. For this reason, the theory of C-V curve analysis will be developed.

The capacitance between the gate and back contact can be modelled as in Figure 3.6 b) by two capacitors in series:

$$C = \frac{C_{ox} C_s}{C_{ox} + C_s} \quad F \cdot cm^{-2} \quad (3.20)$$

where C_{ox} is the oxide capacitance, determined by the oxide permittivity,

Fig. 3.6 a) MOS capacitor structure, b) simple theoretical model, c) charge distribution, d) potential distribution, e) theoretical C-V curve.

ϵ_{ox} and thickness, t_{ox} :

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} F \text{ cm}^{-2} \quad (3.21)$$

The capacitance of the silicon, C_s can be found using equation (3.18), with $V=0$ and $N(x)=N_a$ as follows:

$$C_s = \frac{dQ_s}{d\phi_s} = \pm \frac{q \epsilon}{Q_s(u_s)} [2n_i \sinh(u_{fp} - u_s) - N_a] F \text{ cm}^{-2} \quad (3.22)$$

where $Q_s(u_s)$ is the total charge in the silicon and $\phi_s = \frac{kT}{q} u_s$ is the surface potential. When the square root was taken to obtain equation (3.15), the correct sign was chosen to yield the proper polarities for u_s , Q_s , etc. However, in the MOS capacitor, u_s may have both positive and negative values as the silicon surface becomes depleted or accumulated. Hence, the sign ambiguity must be retained in equation (3.22) and interpreted to keep C_s positive for all values of u_s . Using the above equations, the gate capacitance can be found for any value of u_s (except $u_s=0$).

To determine the gate voltage for each value of surface potential, the charge distribution across the capacitor (Figure 3.6 c) must be considered. For each u_s , the charge $Q_s = Q_n + Q_d$ can be found with equation (3.18). The charge Q_{ox} is the effective charge in the oxide at that value of u_s . If, in reality, the oxide charge is distributed throughout the oxide as $Q(x)$, its effect on the MOS system will be the same as that of a sheet charge, Q_{ox} at the interface. Q_{ox} is therefore the "effective oxide charge".

The first component of Q_{ox} is Q_{fb} , the "effective flatband charge". Q_{fb} has a fixed value. In an ideal oxide with no impurities, Q_{fb} will be equal to Q_{ss} which is essentially a sheet charge itself [44]. The other component of Q_{ox} is a charge which varies with u_s . This can be characterized as interface states which become charged or uncharged depending on the position of the Fermi level [51]. In reality, the interface state density, N_{ss} varies across the bandgap, but since N_{ss} is typically much smaller than Q_{fb} , it will be assumed constant in this analysis. Hence, the oxide charge will be modelled as follows:

$$Q_{ox} = q \left(Q_{fb} - \frac{kT}{q} u_s N_{ss} \right) \text{ C cm}^{-2} \quad (3.23)$$

The units for Q_{fb} are charges per cm^2 ; for N_{ss} , states per cm^2 of surface area per eV of bandgap. Q_{ox} is a true surface charge density as indicated.

The remaining charge in Figure 3.6 c) is Q_g , the gate charge. To maintain overall charge neutrality, Q_g must be the difference between Q_{ox} and Q_s . With the charges in the MOS system determined, the gate voltage can be obtained by integrating Poisson's equation (3.10) twice, using ϵ_{ox} in place of ϵ_s in the oxide. The result is in the form of a sum of voltages as depicted in Figure 3.6 d):

$$V_g = \phi_s + V_{ox} + \phi_{ms} \text{ volts} \quad (3.24)$$

where ϕ_s is the surface potential, V_{ox} the voltage drop across the oxide and ϕ_{ms} is the metal-semiconductor work function. This last term accounts for the difference between the vacuum work functions of the gate metal and the underlying silicon. Its value depends on the type of

metal and the silicon doping [49]. (For an aluminum gate and a 10 Ω -cm p-type substrate, $\phi_{ms} = -0.85$ volt.)

When the double integration is performed, the result is:

$$V_g = \frac{kT}{q} u_s - t_{ox} \frac{\epsilon_s}{\epsilon_{ox}} E_s - q \frac{Q_{ox}}{C_{ox}} + \phi_{ms} \quad \text{volts} \quad (3.25)$$

where t_{ox} is the oxide thickness and Q_{ox} is given by equation (3.23). The surface electric field, E_s is found using $u=u_s$ in equation (3.17). Again, the $\pm$ polarity ambiguity must be retained and properly interpreted (E_s is positive for $u_s > 0$). Hence, the gate voltage is found using equation (3.25) for any value of u_s .

Once C and V_g are known as functions of u_s , the C-V curve follows implicitly. To perform the repetitive calculations, a program (CEEVEE) was written in FORTRAN for use on the Xerox/Honeywell Sigma-9 computer at Carleton University. To generate the C-V curve for any MOS system, the user specifies N_a , t_{ox} , Q_{fb} , N_{ss} , ϵ_{ox} and the vacuum work function of the metal. The computer prints out C and V_g for a wide range of u_s values. Plotting the points yields a curve similar to the one in Figure 3.6 e).

In the preceding analysis, it is assumed that steady state conditions apply at all values of u_s . The resulting C-V curve will therefore be the low frequency limit (solid line in Figure 3.6 e). In practice, C-V measurements are made using an AC signal superimposed on the DC gate bias. The inversion charge, Q_n is not able to follow the high frequency signal and charge neutrality is maintained by varying the depletion charge. Thus, the capacitance seen by the signal is across the depletion region as well as the oxide and the C-V curve

remains low in inversion. CEEVEE also calculates the high frequency limit curve (dashed line in Figure 3.6 e). At frequencies normally used in C-V measurements (~1 MHz), the curve approaches this lower extreme.

By fitting the theoretical curve to the measured one, the important parameters of the MOS capacitor can be obtained. At large negative biases, the capacitance asymptotically approaches C_{ox} , allowing t_{ox} to be estimated from equation (3.21). For a fixed oxide thickness, the minimum capacitance depends only on N_a , the substrate doping. Usually however, N_a and t_{ox} can be obtained with better accuracy by other methods. The C_{ox} and C_{min} calculations could then be done to check that the capacitor is operating properly.

The primary use of C-V analysis is for measuring Q_{fb} , the flatband charge. Since Q_{fb} , as the main part of Q_{ox} , is fundamental to IL cell operation, its value must be known if a cell is to be accurately modelled. The flatband voltage ($V_g = V_{fb}$ at $u_s = 0$) is used to find Q_{fb} by setting $V_g = V_{fb}$ and $u_s = E_s = 0$ in equation (3.25). The flatband point cannot be calculated using CEEVEE (equation (3.22) becomes undefined for $u_s = 0$) but can be readily interpolated from the calculated $V_g(u_s)$ data.

The interface state density, N_{ss} determines the slope of the depletion portion of the C-V curve. A steep curve indicates a low density of states. By adjusting N_{ss} in CEEVEE to match the theoretical curve to the measured one, this density can be estimated. Unfortunately, real curves rarely match the calculated ones exactly. N_{ss} varies with u_s . Also, effects such as inversion layer fringing outside the gate area and oxide leakage will alter the measurements.

Fortunately, the flatband point can usually be reliably determined so that measured values of Q_{fb} will be accurate (typical uncertainty $\sim \pm 5\%$).

In this chapter, five types of surface effect solar cells were introduced as promising alternatives to conventional cells. The inversion layer cell was further discussed and the theory necessary for understanding its structure was developed. This theory will be used in Chapter 6 to develop a model for IL cells. The next chapter describes how the structures introduced here can be realized in practice.

CHAPTER 4

DESIGN AND FABRICATION OF SURFACE EFFECT SOLAR CELLS

Solar cell design involves the selection of a front contact grid pattern and the development of a fabrication process. Since all solar cells operate on the same principles, they will have the same basic structure: substrate, junction and front and back contacts. Therefore, many aspects of the design for one type of cell will apply to other cells. Similarly, many of the processing steps will be common to different structures.

In this chapter, the factors involved in the design of surface effect cells and the process steps used to construct them are considered. The design of an experimental grid pattern is described. The evolution of inversion layer cell processing is outlined. Finally, the fabrication of accumulation layer (grating) and TiO_x -MIS cells is discussed.

4.1 Contact Grid Design

Solar cells require front and back metal contacts to conduct the current to an external circuit. While the back contact may be a uniform metal layer, the front one must cover only a small fraction of the cell area in order to maximize the area exposed to the light (active area). However, the contact must also be close to every point on the front surface to reduce the lateral series resistance in the diffused region, inversion layer, or semitransparent metal layer (depending on the type of cell being designed). These conflicting requirements are satisfied through the use of a grid of narrow conductors spread across

the surface and connected together at a bonding pad for external connection.

In a typical 2 cm square diffused cell, the grid consists of six evenly spaced "fingers" connected by a wide busbar along one edge. The exact geometry is not important since the sheet resistance of the surface diffusion is low. As discovered in Chapter 3, however, the resistance of an inversion layer is typically much higher and grid design becomes critical to efficient cell operation.

In principle, the grid shading and series resistance could both be reduced to zero by using an infinite number of infinitely narrow grid fingers. In practice, the minimum finger width is limited by the process used to define the pattern. While advanced photoengraving techniques can achieve linewidths as low as 1-5 μm [52], the available photolithographic process was limited to a 10-12 μm minimum metal linewidth. For the design of experimental IL cells, a nominal linewidth of 16 μm was chosen to allow for misalignment errors and to provide reliable metal continuity.

To optimize the tradeoff between shading and series resistance, the grid finger spacing must be chosen carefully. A simple computer program was written to model the resistive losses in the inversion layer for a variable grid geometry [53]. This model later evolved into the two-dimensional model described in Chapter 6. The results obtained with this program are summarized in Figure 4.1. Figure 4.1 a) shows that the short circuit current, I_{sc} increases with grid spacing up to a point where the ohmic loss in R_{IL} causes it to drop. For line spacings less than 16 μm , the entire surface is covered in metal and no current is generated. As the oxide charge, Q_{ox} increases, R_{IL} is reduced and the drop in I_{sc} occurs at wider finger spacings.

Fig. 4.1. The effect of contact grid finger spacing on
 a) the short circuit current and b) the maximum
 output power of an inversion layer cell.

Figure 4.1 b) provides the basis for choosing the best grid finger spacing. For a given value of Q_{ox} , the cell output power, P_{max} passes through a maximum at one value of finger spacing. This optimum value depends on Q_{ox} and becomes less critical as Q_{ox} increases. Since the maximum output power increases with Q_{ox} , the highest oxide charge possible should be used. In the diffused IL cell process (see section 4.3), Q_{ox} is limited to the fixed charge Q_{ss} with a maximum value of -1×10^{12} charges cm^{-2} [44]. The grid therefore, was designed for this value. Figure 4.1 b) indicates that the optimum spacing (for AM1) with $\frac{Q_{ox}}{q} = 10^{12} cm^{-2}$ is in the 200-300 μm range. Thus, 254 μm was chosen somewhat arbitrarily (mask layout was simplified).

The grid pattern in its final form is shown in Figure 4.2. The 2 cm x 2 cm (a standard size) main cell is sectioned diagonally into quarters to provide a working device even if part of the wafer is damaged during fabrication. The contact windows in the oxide beneath the grid fingers are nominally 8 μm wide (the minimum photolithographically reproducible linewidth). In each quarter, a single bus bar (dark stripe), widening toward the edge, connects the fingers together and extends to a wide contact pad outside the active area. The pads are large to allow for various experimental bonding techniques. As designed, the grid shades 7.7% of the cell area (1.00 cm^2 for each quarter). The grid geometry is such that between the contact window and the bonding pad, the effective metal resistance is the same as that of ten squares of metal. Only the grid lines and bus bar make contact to the silicon. The remaining metal is above the thick oxide. The wide band surrounding

Fig. 4.2 Experimental IL cell front contact grid pattern with surrounding test devices.

Scale: 5 times real size.

the cell acts only to define the active area, preventing generation in the cell periphery.

In this experimental design, several test devices are positioned around the main cell. There are four small cells, each 1% the area of the large one. A 2000 square metal resistor, a 250 square diffusion resistor and a 1/10 square inversion layer resistor are included to measure the sheet resistance (ohms per square) of the various parts of the structure. The test cell without grid lines was designed to determine if useful collection can occur away from the contact regions. The square diode is used to measure the properties of the contact junction. Finally, several MOS capacitors are included for C-V analysis. The use of these test devices is outlined in Chapter 5. The mask was designed to fit a 1 1/2 inch wafer with an ample margin as shown in Figure 4.2.

Although designed for IL cells, the grid pattern can be used for other surface effect devices. In particular, the lateral collection devices (grating cell and TiO_x -MIS cell) require grid fingers that are less than ~ 2 diffusion lengths apart. Since $L_n \sim 150 \mu\text{m}$ in $10 \Omega\text{-cm}$, p-type silicon, the finger spacing of $254 \mu\text{m}$ is suitable for experimenting with these devices. The mask in Figure 4.2 is for experimental cells only. A production cell would have the entire wafer covered by a single grid pattern with a smaller contact pad.

4.2 Fabrication Processes

Each part of a solar cell structure can be realized in different ways. In this section, the processes which can be used for each step in the fabrication are described along with their advantages and disadvantages.

The choice of substrate material is primarily between single crystal and polycrystalline silicon. The latter is potentially the cheaper of the two and all surface effect cells can (in principle) be made using polycrystalline substrates. The main disadvantage is that polycrystalline silicon has a lower effective minority carrier lifetime than single crystal silicon. For this reason, the best results for all types of cells have been obtained using single crystal wafers. Since this thesis is device oriented rather than materials oriented, single crystal substrates were used exclusively in the fabrication.

For an IL cell, the substrate must be p-type. To ensure strong inversion using only Q_{ss} , the wafer should have the $\langle 111 \rangle$ orientation [44] and be lightly doped. A more heavily doped substrate will result in a higher open circuit voltage, but will be more difficult to invert and will reduce the photocurrent due to lower electron lifetime. Usually, doping levels in the range $10^{15} < N_a < 10^{16} \text{ cm}^{-3}$ produce the best results.

Wafer thickness is also important. A cell with a BSF region operates best if its thickness is less than one diffusion length. However, a thicker cell will absorb more light and in the absence of a BSF region will produce a higher output. The relationships between bulk doping, electron lifetime and substrate thickness are discussed in Chapter 8. Single crystal silicon cells are normally 50 - 500 μm thick.

The choice of whether or not to use a p^+ back surface field region depends on several factors. If the cell is more than a diffusion length thick, the BSF benefits will be small. In a properly designed cell, however, inclusion of a p^+ region can substantially increase the efficiency [35]. The choice is between high efficiency and process

simplicity. If an entirely low temperature process is desired, a BSF region would be difficult to incorporate. However, no masking step is required and a p^+ diffusion could readily be added to most processes.

The most straightforward method of producing a BSF region is by gaseous diffusion. This involves heating the wafer to a high temperature ($> 1000^\circ\text{C}$) for about 30 minutes in a boron-containing gas. Aside from the disadvantage of the high temperature, this also requires that the front surface be masked with SiO_2 to prevent a p^+ diffusion occurring there too. These problems can be partly avoided by combining the BSF diffusion with the back metallization. If a thick ($\sim 8 \mu\text{m}$) layer of aluminum is deposited on the back of the substrate and heated to $800\text{--}900^\circ\text{C}$ for a few minutes in a non-reactive gas, it will alloy with the silicon for an excellent contact and diffuse into the crystal to make a p^+ BSF region [37]. The p^+ concentration and diffusion profile are not critical [54]. Typically, the Al surface concentration is $\sim 10^{19} \text{ cm}^{-3}$ and the effective BSF depth is $\sim 1 \mu\text{m}$.

The basic II structure requires a thick oxide layer on the front surface. One way to form this layer is to grow SiO_2 thermally by oxidizing the surface of the wafer. This is a reliable process, producing good SiO_2 -Si interfaces with acceptable levels of Q_{ox} . However, the basic dry oxygen process requires several hours at a high temperature. It can be shortened by using a steam oxidation cycle, but still requires high temperatures [49].

Chemical vapour deposition (CVD) of SiO_2 is a promising alternative [22]. It is a fast, low temperature (as low as 250°C) process producing uniform, reproducible oxide layers. As an added

benefit, CVD oxides have higher values of effective oxide charge ($Q_{fb} = 1 \text{ to } 5 \times 10^{12} \text{ charges cm}^{-2}$) than possible with thermal oxides. Unfortunately, CVD oxides tend to be leaky and do not passivate the silicon surface as well as thermal oxides. Also, there has been some difficulty in depositing SiO_2 uniformly around aluminum grid lines.

Oxide layers can also be formed using spin on techniques or vacuum deposition. Solutions of SiO_2 and $\text{Ta}_2\text{O}_5\text{-SiO}_2$ are available in spin-on form.* As with the TiO_x compound, they should be inexpensive and easy to use. Layers of Ta_2O_5 , SiO_2 or SiO can be deposited by electron beam vacuum evaporation. Efficient IL cell structures using evaporated SiO layers have been reported [55]. While these techniques appear promising, there has been insufficient research done with them to evaluate their suitability for surface effect cells.

The choice of oxide thickness is dictated primarily by the reflection properties of the air-oxide-Si system. Figure 4.3 illustrates how the average reflectance of an SiO_2 layer varies with oxide thickness (t_{ox}) for different solar spectra. The calculated curves are weighted for an IL cell internal current efficiency. An unfortunate choice of t_{ox} could result in more than 25% reflectance loss. The optimum thickness is 100-120 nm for SiO_2 . The optimum thickness and average reflectance would be lower for a material such as TiO_x with a higher refractive index (see Figure 2.6). The optimum value of t_{ox} corresponds to quarter-wave matching at a wavelength of ~600 nm and imparts a dark blue colour to the solar cell.

* SILICAFILM and TANTALUMSILICAFILM are also available from Emulsitone Company, New Jersey, U.S.A.

Fig. 4.3 Average reflectance of a SiO_2 anti-reflection layer, weighted for a typical IL cell internal current efficiency.

The main function of the oxide in an IL cell is to invert the surface of the substrate. This is achieved through the action of positive charges trapped in the oxide during fabrication. The principal charge in thermal oxides is Q_{ss} , the surface state charge, thought to be associated with excess Si atoms close to the SiO_2 -Si interface [44, 56]. The value of Q_{ss} is highest on (111) oriented substrates and can be varied over a wide range by heat treatment in dry oxygen. Values of Q_{ss} as a function of heat-treat temperature are shown in Figure 4.4. The dashed line represents published results [44] and measured values for IL structures are indicated by x's. The circles and vertical bar represent values obtained with no heat treatment after the n^+ contact diffusion (done in a nitrogen ambient). While the measured values are widely scattered and not reproducible, they do show the advantage of a final heat treatment for increasing Q_{fb} .

Other types of oxide can be used to obtain higher oxide charge densities. CVD oxides appear to have high Q_{fb} values [22, 42] but again, the results are not reproducible. The SiO_2 spin-on process yields low Q_{fb} values ($< \sim 4 \times 10^{11} \text{ cm}^{-2}$), but it may be possible to raise this with a suitable heat treatment. Spin-on TiO_x layers which have not been bias-stressed during C-V analysis have insufficient charge to invert a $10 \text{ } \Omega\text{-cm}$ substrate. (This is further evidence that the TiO_x -MIS cell is not an IL structure.) Evaporated SiO layers have been produced with large values of Q_{fb} ($\sim 1 \times 10^{12} \text{ cm}^{-2}$) [55].

Once the internal structure is complete, contact to the inversion layer must be made. One way is to open a window in the oxide and make an n^+ diffusion. This works well, providing a low resistance contact to the inversion layer. Unfortunately, it requires a return to high temperature diffusion with all the associated disadvantages.

Fig. 4.4 Effect of oxide heat treatment temperature and ambient gas on effective flatband charge, Q_{fb} .

The most promising alternative is the MIS contact outlined in section 3.1 [21, 42]. The interfacial SiO_2 layer can be grown in the contact windows by a variety of low temperature processes [14, 21]. Simple dry oxidation at 450°C for a few minutes produces reliable thin oxide layers. To complete the MIS contact a metal is deposited over the thin oxide. The best results on p-type silicon have been achieved with aluminum due to its low vacuum work function.

The final process step is the application of metal conductors to the front and back contacts. A good solar cell metallization process satisfies several requirements. It must be able to produce the fine linewidths in the grid pattern. The front contact metal must be thick enough to provide a low resistance conduction path. Good ohmic contact to silicon is necessary. In the case of MIS and Schottky contacts, the metal must produce a high potential barrier. The metal should be suitable for bonding external interconnect leads. Finally, the process should be cheap, fast and adaptable to large scale production. Four metallization processes will be considered.

Evaporation and photolithography is the process most often used. A suitable metal (Al, Au or a double layer such as Ti-Ag) is deposited over the entire wafer surface by electron beam evaporation in a vacuum. The grid pattern is defined in photoresist using an optical mask and the excess metal is etched off, leaving the desired pattern. This method can produce the fine grid lines needed for IL cells and is reliable, yielding good low resistance contacts. However, it is also a complex process involving several steps and much handling of individual wafers. Thus, it is expensive, time consuming, and not practical for low cost production.

Much of the complexity and cost can be avoided by evaporating the metal through a foil shadow mask, thereby defining the pattern directly. The process is reduced to one step and wafer handling is minimized. This process is frequently used in diffused cell production, but one problem prevents its use for fine line patterns. Due to the thickness of the foil mask and the shadow method used, line widths less than $\sim 100 \mu\text{m}$ cannot be reliably defined. For minimal grid shading, the grid finger spacing must be several millimeters. Such grid geometries are incompatible with the IL and lateral collection solar cell structures reported to date.

Chemical plating is a potentially good candidate. Typically, a wafer with contact windows opened in the oxide is dipped into an electroless nickel solution [57]. A thin layer of Ni precipitates on the exposed silicon. This layer can be built up by electroplating copper to any desired thickness. A gold anticorrosion film is then electrolessly deposited on top [18]. This process has the advantage of requiring no second mask and the line width is limited only by the definition of contact windows in the oxide. Both front and back contacts are applied together. Also, the process is simple and can be applied to many wafers simultaneously. However, experience to date has failed to produce good plated IL cells [18, 19]. Typically, the nickel does not adhere well to the silicon. More work would be required to make plated contacts viable.

The fourth method is screen printing. In this process, a metallic paste is printed through a screen mask onto the substrate in the desired pattern. The wafer is then baked to harden the paste and drive off the organic solvent. The contact is fired at a high temperature

(600 - 1000°C) to bind the metal together and to the substrate.

Finally, a quick hydrofluoric acid dip is used to reduce the contact resistivity. Thick, low resistance, solderable contacts result.

Lower temperature materials such as solder or conductive epoxy can also be printed in this way. Unfortunately, the problem is again one of line definition. Due to the size of the screen mesh, only lines wider than $\sim 100 \mu\text{m}$ can be reliably printed. Also, the flux used in the pastes dissolves oxides, making screen printed MIS contacts impossible at present. However, the process is being experimented with for use in diffused-solar cells [58].

Most metals used on silicon must be sintered at 350 - 550°C after deposition to obtain good ohmic contacts. During this process, any layers between the metal and silicon are broken through or absorbed to bring the two into intimate contact. For this reason, sintering (or any other process above $\sim 300^\circ\text{C}$) after MIS contact formation should be avoided. Sintering normally requires only a few minutes and is done in a non-reactive gas ambient to prevent metal oxidation.

Once the cell is made, external leads or interconnect wires can be bonded to it by welding, soldering or conductive epoxy. Production cells would be connected together in arrays and encapsulated in panels for protection from environmental degradation. Since this thesis involves only experimental cells, array design will not be considered.

In developing an overall solar cell process, the above steps are chosen and arranged to yield the desired structure. The steps must be compatible with each other and subject to the requirements for temperature and cleanliness. For instance, polycrystalline substrates are not suitable for diffusion, the oxide heat treatment must be the

last high temperature process and MIS contacts should be made only after the back ohmic contact has been sintered. The following sections outline the development of processes for making several types of surface effect solar cells.

4.3 Development of Diffused IL Cells

The first inversion layer cells to achieve more than 10% AM1 efficiency were fabricated using the process outlined in Figure 4.5. At this time, MIS contacts were just beginning to be investigated for solar cells. Thus, for the experimental IL structure, it was decided to use the better understood diffused contacts.

The substrates chosen were 10 Ω -cm, p (111) type wafers 200 - 350 μ m thick. No attempt was made to reduce the thickness by etching though this is certainly possible [38]. Substrates with higher and lower resistivity (0.4 to 30 Ω -cm) were used for some cells, but failed to produce good results. Problems in fabrication, unrelated to the substrate doping, caused leaky junctions or high contact resistance and thus, low efficiencies. The superiority of (111) oriented silicon over (100) substrates was demonstrated, however. The latter exhibited higher series resistance due to lower oxide charge as expected with thermal oxides.

The p^+ back surface diffusion was initially used to obtain a good ohmic contact. Earlier contacts had rectifying characteristics which were prevented with the heavily doped surface [19]. Later, a better contact was developed and the p^+ region was retained for its BSF properties. However, after it was determined that the supposed benefits were negligible for thick cells (see section 8.1), the p^+ diffusion was dropped.

1. boron pre-deposition on back surface.
30 min at 1000°C in N_2 gas.
2. oxide growth and boron drive-in. 8 hr. at 1150°C in O_2 gas with HCl getter. $t_{\text{ox}} \approx \frac{1}{2} \mu\text{m}$, BSF depth $\approx 8 \mu\text{m}$.
3. photolithography and oxide etch to open front contact windows.
4. phosphorous pre-deposition on front surface.
15 min at 900°C in N_2 gas for a junction depth of $.6 - .7 \mu\text{m}$.
5. oxide heat treatment to raise Q_{ss} . 30 min at 700°C in O_2 gas.
6. aluminum deposition on front surface using electron beam evaporation.
 $1 \mu\text{m}$ of Al over $\approx 100 \text{ \AA}$ of Si .
7. photolithography and metal etch to produce metal grid pattern (40 lines per cm).
8. aluminum sinter to provide ohmic contacts.
15 min at 430°C in N_2 gas.
9. deposit gold on back surface and sinter 10 min at 350°C in N_2 gas.

Fig. 4.5 Initial process for fabricating efficient diffused contact inversion layer solar cells.

Early IL cells had thick ($\sim 0.5 \mu\text{m}$) oxides, requiring very long oxidations. It was thought that a thinner oxide would reduce the effectiveness of Q_{ss} to invert the silicon [18, 19]. However, later evidence [56] and experience proved this concern to be unfounded. Also, the antireflective benefits of a thinner layer as shown in Figure 4.3 were realized. Thus, later cells were made with oxides $\sim 110 \text{ nm}$ thick. This substantially reduced the oxidation time. Further reduction was possible using a pyrolytic oxidation ($2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$). With this process, 180-190 nm thick oxides could be grown in 20 minutes. The extra thickness (above 110 nm) was required to mask the silicon during the phosphorous grid diffusion and was etched off later.

The original inversion layer cells used no oxide heat treatment after the n^+ diffusion. The oxide charge was understandably low, partially accounting for the poor efficiencies obtained [18, 19]. Later, a 30 minute treatment in oxygen at 700°C was incorporated and higher Q_{ox} values were achieved [18, 19, 20]. Subsequent cells were treated at various temperatures ($550\text{--}800^\circ\text{C}$) in an attempt to further raise Q_{ox} . The values of Q_{fb} measured are shown in Figure 4.4. Generally, they were not predictable, non uniform and lower than expected. This may be due to impurities introduced into the oxide during high temperature processing or a reduction in Q_{ss} during contact sintering.

Plated metal contacts, described in section 4.2 were used initially to avoid the second photolithographic step listed in Figure 4.5. However, problems with poor adhesion to the wafer and parasitic Schottky barriers on the $10 \Omega\text{-cm}$, p-type substrates were encountered with the electroless nickel [18, 19]. Evaporated metal contacts with photolithographic

pattern definition have been used since. Initially, the electron beam evaporation facilities at the Communications Research Centre were used to deposit aluminum on the front.* Gold was deposited on the back surface by molybdenum filament evaporation at Carleton University. The acquisition of an E-beam system by Carleton later allowed both contacts to be deposited here.

At present, aluminum is used for both the front and back metallizations. The grid metal thickness has been increased to 3 μm for lower resistance. A thin layer of silver is evaporated over the back contact to make bonding with solder or conductive epoxy possible. This was also tried for the front contacts but it proved difficult to etch the silver without lifting the photoresist.

Many problems were encountered with the sintering of aluminum contacts. The standard 15 minutes at 450°C usually resulted in shorted or leaky junctions. The use of a deeper phosphorous diffusion and a 5 minute, 350°C sinter failed to rectify the problem. Most batches still had poor yields of operating cells. Only the inclusion of a thin ($\sim 100 \text{ \AA}$) evaporated layer of silicon between the substrate and the aluminum prevented junction shorting. The problem was eventually attributed to wax fumes interfering with oxide etching.** Wax is used to cover the oxide on the back of the wafer during contact window etching. If fumes from the hot wax condense on the front surface, the etching will be incomplete in places. After phosphorous diffusion, these

* I am indebted to Bob Kuley and Jocelyn Legault at C.R.C. for doing this processing.

** Another possibility is that when an aluminum contact over a shallow junction is sintered, some silicon is removed from the lattice near the junction, leaving defects which cause leakage.

residual patches of oxide are etched off, exposing weakly doped regions which short out upon sintering. Careful waxing in one batch avoided the fumes and resulted in 100% yield with good uniformity.

Completed solar cells were mounted on small circuit boards for ease of handling. Conductive epoxy was used to bond the back of the wafer. However, it was impossible to contact the aluminum front contact by this method. Instead, pointed wire probes were soldered to the circuit board and pressed down on the cell contact pads. This worked well, but of course could not be used in production.

The diffused IL cell process, as it has evolved to date is outlined in Figure 4.6. The complete detailed process is given in Appendix "B". The steps for forming the BSF region are optional and may be omitted with no change to the remaining process. Comparison of Figures 4.5 and 4.6 reveals that the process has been somewhat simplified. However, better results have been obtained with AMI efficiencies close to 12%.

4.4 Fabrication of MIS-IL Cells

While the diffused contact IL cell is capable of attaining good efficiencies, it is not suitable for volume production. The need for a mask alignment and repeated high temperature processes limit its potential for low cost manufacturing. The use of MIS contacts avoids the critical diffusion step and opens the way for a completely low temperature process. Since other researchers were working on MIS-IL cell structures [21, 22, 42, 45, 55], it was decided not to study them in depth for this thesis. However, some MIS-IL cell fabrication was undertaken.

1. oxide growth. 21 min at 1200°C dry-wet-dry cycle. $t_{\text{ox}} \approx 180 \text{ nm}$.
2. photolithography and oxide etch to open contact windows.
3. phosphorous pre-deposition on front surface. 10-20 min at 900°C in N_2 gas.
4. oxide heat treatment to raise Q_{ss} . 30 min at $\approx 600^{\circ}\text{C}$ in O_2 gas.
5. front metallization. $3 \mu\text{m}$ of aluminum over $\sim 100 \text{ \AA}$ of polycrystalline Si (E-beam evaporation).
6. photolithography and metal/silicon etch to define grid pattern.
7. aluminum sinter for good ohmic contacts. 5 min at 400°C in N_2 gas.

Fig. 4.6 Final process for fabricating diffused contact inversion layer solar cells.

2

Three different approaches, characterized by the type of oxide, were tried. These are illustrated schematically in Figure 4.7. The first, shown in Figure 4.7 a) is simply a modification of the diffused contact IL cell structure. Instead of a phosphorous diffusion, an MIS contact is made. A cell of this type was fabricated using a low temperature chemical oxidation to grow the thin oxide layer [21]. The completed device exhibited low open circuit voltage, low short circuit current and a poor fill factor for an overall active area efficiency of ~3.6% AM1. Better success with the same structure has been obtained by others (up to ~10% efficiency) [21, 22]. However, with two masks and a thermal oxidation there is little advantage over diffused IL cells. Therefore, this process was not pursued further.

Other methods for growing the MIS oxide were examined. The simplest was to leave the bare wafers exposed to air at room temperature for ~24 hours [22, 42]. However, MIS diodes fabricated by this method were leaky and produced low open circuit voltages when illuminated. The most reliable process tried was a dry oxidation at 450°C for 10 minutes, which yielded good, non leaky-oxides of the desired thickness (12-15 Å). This process was used to make MIS diodes with excellent dark characteristics.

The MIS-IL structure in Figure 4.7 b) was also constructed. In this process, the MIS oxide is grown and the metal grid is defined on the bare surface. A thick CVD oxide is then deposited at 250°C [22]. C-V analysis revealed a high oxide charge density ($Q_{fb} > 10^{12} \text{ cm}^{-2}$), but the cells operated poorly. The open circuit voltage was reasonable and the fill factor was excellent, but the short circuit current was an order of magnitude too low. Visual inspection at 500x magnification revealed the problem. The CVD oxide appeared to thin out in the vicinity

Fig. 4.7 Three MIS-IL solar cell structures:

- a) two mask, thermal oxide; b) one mask CVD oxide;
c) one mask spin-on oxide.

of the grid fingers as indicated in Figure 4.7 b). At the edge of the aluminum, the oxide was too thin to strongly invert the surface. Thus, the inversion layer in the active areas was isolated from the MIS contacts. Only a small amount of lateral collection occurred, resulting in the low value for I_{sc} . Since it was not clear how to obtain uniform deposition in the proximity of aluminum, this approach was also discontinued.

The structure in Figure 4.7 b) has the advantage of requiring only one photolithographic step. No mask alignment is required. Also, use of a CVD oxide renders a low temperature process possible [22]. These advantages are maintained in the structure shown in Figure 4.7 c) where a spin-on oxide has replaced the CVD layer, resulting in an even simpler process. Cells fabricated in this way had the same problem as described above. In this case, however, the oxide was too thick around the grid fingers. During spinning, the oxide solution wetted the aluminum to a depth of $\sim 2 \mu m$. When baked to densify the layer, these thick regions shrank away from the aluminum or cracked and lifted off the silicon. Again, the inversion layer was isolated from the contacts and I_{sc} was low.

Subsequently, the process was repeated, with care taken to reduce cracking and separation. The results, though better, were still poor (efficiencies less than 4%). In this case, C-V analysis indicated that the silicon was not strongly inverted due to a low oxide charge. More research will be required to determine if the charge can be increased or if other spin-on layers have more suitable properties.

The potential of MIS-IL cells is demonstrated by the recent report of 15% efficiency being achieved for a one mask, MIS-IL structure utilizing an evaporated SiO layer [55]. Further research into these low

temperature processes should produce similar results. Figure 4.8 outlines the process used to make the structures shown in Figure 4.7 b) and c).

It could be readily adapted to other spin-on or evaporated layers.

Aside from the advantages of low temperature and no mask alignment, there are fewer steps. Further simplification could be achieved by combining the sinter and MIS oxide growth in a single furnace process.

4.5 Fabrication of Other Surface Effect Cells

Of the remaining surface effect solar cells introduced in Chapter 3, attempts were made to fabricate only the accumulation layer/grading cell and the TiO_x -MIS cell. The processes used are outlined in Figure 4.9. The experimental grid pattern shown in Figure 4.2 was used for both devices.

The accumulation layer cell process (Figure 4.9 a) is similar in form and complexity to that of the initial diffused IL cell (Figure 4.5). An n-type substrate is used and an n^+ BSF region is incorporated. A long phosphorous diffusion has been found to "getter" impurities in the bulk silicon to produce very high lifetimes ($\tau_p - 400 \mu s$) in n-type substrates [59]. High minority carrier lifetimes are essential in lateral collection devices. A p^+ diffused front contact was used due to the lack of experience with MIS contacts on n-type silicon. The oxide heat treatment could be omitted since the strength of the accumulation layer should be relatively unimportant.

Three attempts were made to produce this type of cell. All three succumbed to processing problems unrelated to the structure, such as boron glaze on the wafers, or oxide etching difficulties. Two wafers which were completed had no rectifying properties at all, indicating the

1. deposit 1 μm of aluminum and 0.2 μm of silver on the back surface by E-beam evaporation.
2. sinter aluminum for 15 min at 450°C in N_2 gas.
3. grow thin oxide (~14 Å) on front surface. 450°C for 10 min in dry O_2 .
4. deposit 2 μm of aluminum on the front surface by E-beam evaporation.
5. photolithography and metal etch to define grid pattern.
6. a) deposit CVD oxide on front surface at 250°C for ~15 min.

OR

6. b) spin on SiO_2 layer on front and bake at up to 250°C for 15-30 min in air.

Fig. 4.8 Low temperature process used to fabricate inversion layer cells with MIS contacts.

a) Grating Solar Cell

1. phosphorous pre-dep on back surface 30 min @ 1000°C.
2. grow ≈ 180 nm SiO_2 with dry-wet-dry cycle at 1200°C.
3. photolithography to open contact windows.
4. boron pre-dep on front surface 30 min at 950°C.
5. oxide heat treatment 1 hr. at 550°C in dry O_2 .
6. evaporate 2 μm of Al on front using E-beam.
7. photolithography and metal etch to define grid pattern.
8. deposit 1 μm of Al and 0.2 μm of Ag on back.
9. sinter 5 min at 350°C.

b) TiO_x -MIS Cell

1. deposit 1 μm of Al and 0.2 μm of Ag on back surface.
2. sinter Al 15 min at 450°C in N_2 gas.
3. grow MIS oxide at 450°C in O_2 gas for 10 min.
4. deposit 2 μm of Al on front surface with E-beam.
5. photolithography and metal etch to define grid pattern.
6. spin-on TiO_x compound and bake at 100-200°C.

Fig. 4.9 Fabrication processes for a) accumulation layer/grating solar cells and b) TiO_x -MIS, low temperature solar cells.

absence of any p-n junction. At this time, the modelling results presented in section 8.3 were obtained. These indicated that a grating cell would be no better than a vertical collection, diffused junction device unless the bulk lifetime could be raised above $\tau_p \sim 30 \mu s$. Since such lifetimes had not yet been achieved, it was decided to discontinue fabrication of grating cells in favour of more promising structures.

The TiO_x -MIS process shown in Figure 4.9 b) is essentially the same as the low temperature MIS-IL cell process outlined in Figure 4.8. It therefore shares the same advantages. Initial TiO_x -MIS cells worked poorly due to leaky MIS contacts and cracked spin-on layers; the same problems that plagued the MIS-IL processing. However, a successful batch was later made with an active area AMI efficiency close to 9%. Better performance, in agreement with results obtained elsewhere [21, 45] could doubtless be achieved through process optimization.

4.6 Summary of Fabrication

Table 4.1 summarizes the experiments in fabricating surface effect cells for this thesis. Most of the processing was part of the diffused IL cell development, but significant work was done on the three other types of surface effect cells. The table shows the best conversion efficiencies (active area, AMI) achieved and summarizes the major problems encountered for each type. The best results achieved by other researchers or reasonably expected from theoretical considerations are included for comparison. The advantages and disadvantages of each structure are also listed. Finally, conclusions about the present status and future potential are briefly made.

type of cell	diffused IL	MIS-IL	accumulation layer	TiO _x -MIS
# batches (total wafers)	10 (65)	4 (12)	3 (8)	4 (8)
highest efficiency achieved (AM1)	11.75%	3.7% spin-on -6% thermal SiO ₂	non-operating ($<1\%$)	8.9%
problems encountered with processing	<ul style="list-style-type: none"> - shunted p-n junctions - low and unpredictable oxide charge 	<ul style="list-style-type: none"> - leaky MIS contacts - low Q_{ox} for spin-on SiO₂ - IL not connected to MIS contact 	<ul style="list-style-type: none"> - boron diffusion difficulties - oxide etching problem 	<ul style="list-style-type: none"> - cracking of TiO_x spin-on layer - non-optimum TiO_x thickness
potential efficiency [reference]	14-15% [section 8.2]	>10% [22] ~15% [55]	>12% [section 8.3]	$\geq 12\%$ [45]
advantages and/or disadvantages	<ul style="list-style-type: none"> - complex, high temperature processing - mask alignment required 	<ul style="list-style-type: none"> - simple, low temperature processing - one mask only - fast 	<ul style="list-style-type: none"> - potential for high efficiency - high lifetime required - complex, high temperature 	<ul style="list-style-type: none"> - simple, fast, low temperature processing - not fully understood
conclusions and comments	<ul style="list-style-type: none"> - high efficiency possible - not suitable for production at present 	<ul style="list-style-type: none"> - needs development - promising, low cost techniques 	<ul style="list-style-type: none"> - further work required - probably not suitable for production 	<ul style="list-style-type: none"> - needs further development and research - promising low cost device

TABLE 4.1 Summary of surface effect solar cell fabrication

The potential of surface effect solar cells is discussed more fully in Chapter 8. The following chapter describes the measurement techniques developed to test the cells' photovoltaic response and the diagnostic methods used to characterize the cell structure once it has been fabricated.

CHAPTER 5

ELECTRICAL AND OPTICAL TEST METHODS

To determine how well a solar cell operates, it must be subjected to a series of standard tests. Since photovoltaic research is a recent development at Carleton University and is still expanding, many of the test methods had to be developed as part of this work. A substantial amount of time was spent designing the tests, procuring and calibrating the equipment and refining the data collection and reduction techniques. This chapter describes the test procedures and apparatus used and discusses the data analysis and expected accuracy of the results.

5.1 Characterization of the Cell Structure

The inversion layer cell structure is composed of various parts, each of which must be characterized if the device is to be fully understood. The simplest of these are the components involved in the transport of current to the bonding pad: the metal grid, the n^+ diffusion and the inversion layer (as a conductor). Each of these has an associated test resistor on the metallization pattern shown in Figure 4.2.

The resistors were tested on an electroglas model 910 wafer prober coupled to a Tektronix type 576 curve tracer in the AC mode. The completed cell was placed on the vacuum chuck of the prober and a probe was lowered onto the metal pad at each end of the resistor being tested.

The resistance was calculated as the slope of the I-V plot displayed on the curve tracer. Measurements were corrected for probe resistance (about one ohm) which was determined by placing both probes on the same pad. For the diffusion and inversion resistors it was necessary to shut off the room lighting to avoid error due to photoinjection. The sheet resistivities were found from the known geometry of the test pattern. For the metal and diffusion resistors, the line widths differed from their nominal values and had to be measured under a microscope. Metal lines were 18-22 μm wide (16 μm nominal) and the contact diffusion windows were 10-15 μm wide (8 μm nominal).

Measured values of grid metal sheet resistance for several batches of cells are listed in Table 5.1. The theoretical values, included for comparison, were calculated for each thickness using the bulk resistivity of pure aluminum. With one exception, the measured values are in good agreement with theory and uniform from batch to batch. The long sinter at 430°C appears to increase the resistivity. This may be due to oxidation of grain boundaries in the aluminum caused by residual oxygen in the sinter gas. Presumably, the effect did not occur with the 450°C sintering because of the silver cover layer or the extra aluminum thickness.

Table 5.2 shows the values measured for diffusion sheet resistance in the contact windows. The theoretical values were calculated for the indicated diffusion parameters using published empirical results [31]. Again, the agreement between theory and experiment is quite close, with one exception. The last cells listed (79-B, 10-12) have anomalously high diffusion sheet resistivities. The wafers used for these devices

batch and cell numbers	aluminum thickness (μm)	sinter		sheet resistance ($\Omega/\square$)	
		time (min)-	temp ($^{\circ}\text{C}$)	measured	theory
76 1,5,6	1.00	15	430	.143 - .161	.027
76 3,4,7,8	1.00	10	350	.027 - .030	.027
78-A 2,6	2.00 plus 0.20 silver	10	450	.018 - .021	.012
78-F 3,4,9	2.00	5-15	350	.017 - .023	.014
79-A 1-6	2.00	none	T max = 250	.020 - .022	.014
79-B 1,3,7	3.00	5	450	.012 - .015	.009
79-B 2,4,5,6 8-12	3.00	5	400	.010 - .014	.009

Table 5.1 Grid metal sheet resistivity

batch and cell numbers	bulk doping Na (cm^{-3})	diffusion		sheet resistance ($\Omega/\square$)	
		time (min)	temp ($^{\circ}\text{C}$)	measured	theory
76 1,2,5,6	1.4×10^{15}	15	900	26 - 39	33
78-A 3,4	2.2×10^{15}	15	975	8 - 12	11.5
78-A 5,6	1.4×10^{15}	15	975	11 - 12	11.7
78-A 7,8	7×10^{14}	15	975	12 - 13	11.9
78-F 3,4,9	1.7×10^{15}	22	950	9 - 10	14
79-B 1-9	1.6×10^{15}	10	900	54 - 73	41
79-B 10-12	4.2×10^{15}	10	900	180 - 200	41.5

Table 5.2 Contact diffusion sheet resistivity

were (100) oriented and more heavily doped than the usual (111) substrates. Why the crystal orientation should affect the results to such an extent is uncertain.

Of the inversion layer resistors tested, several had anomalous values due to poor contacts or leaky junctions. The values for the remaining devices appear in Table 5.3. The calculated values were obtained from Figure 3.4. The flatband oxide charges were determined by C-V analysis. The differences between the measured and calculated results are typical of the uncertainty exhibited by lateral mobility measurements [48].

The last three entries in Table 5.3 are for cells with non-thermal oxides. The high inversion resistance for the CVD oxides indicates that the inversion layer is isolated from the MIS contact as mentioned in section 4.5. The oxide charge for the spin-on TiO_x cells could not be determined since all the MOS capacitors were leaky. The very high sheet resistance, however, indicates that the surface is not strongly inverted. This is final proof that the TiO_x -MIS structure is not an IL cell since the two devices performed quite well as solar cells. The low oxide charge in the spin-on SiO_2 devices is responsible for the high inversion layer resistance and the poor cell performance noted in section 4.5.

The test diode included in the metallization pattern in Figure 4.2 can be used to measure the characteristics of the contact junctions. However, the current-voltage curve for this diode will not conform to equation (3.3) for any choice of A_1 and A_2 . The reason is that the diffusion (or MIS region) makes electrical contact to the

batch and cell number	N_a (cm^{-3})	Q_{fb} (cm^{-2})	heat treatment		sheet resistance ($\text{k}\Omega/\square$)	
			time (min)	temp ($^{\circ}\text{C}$)	measured	calculated
76 5	1.4×10^{15}	6.2×10^{11}	30	700	37.5	24.5
76 6	1.4×10^{15}	5.7×10^{11}	30	700	32.8	27
76 1	1.4×10^{15}	1.8×10^{11}	sinter only		600	130
78-A 4	2.2×10^{15}	8.2×10^{11}	30	700	20.4	20
78-A 5	1.4×10^{15}	7.7×10^{11}	30	700	27.7	20.5
78-A 7	7×10^{14}	7.3×10^{11}	30	700	38.6	19.5
78-F 3	1.7×10^{15}	3.0×10^{11}	80	550	60	46
78-F 4	1.7×10^{15}	2.8×10^{11}	80	550	55	62
79-A 1,2	1.5×10^{15}	$9 - 19 \times 10^{11}$	CVD oxide 250 $^{\circ}\text{C}$		>100,000	11-20
79-A 3,4	1.5×10^{15}	?	spin-on TiO_x		>12,000	?
79-A 5,6	1.5×10^{15}	$0 - 3.4 \times 10^{11}$	spin-on SiO_2		variable >300	>40

? means that Q_{fb} could not be measured.

Table 5.3 Inversion layer sheet resistivity

inversion layer beneath the surrounding oxide and injection from the inversion layer into the bulk occurs. At high current levels, this "fringing" effect is minimal as the inversion layer sheet resistance acts to isolate the contact area. However, at lower bias levels, only a small potential is dropped across the IL sheet resistance and the injection occurs over a larger area. In the limit, for very low currents, the entire wafer becomes involved. Thus, the effective junction area varies with bias, causing the $\log(I)$ vs V curve to be distorted [22,60]. The problem can be avoided by etching off the oxide around the diode.

The test diode may also be used to measure the minority carrier lifetime in the substrate: Figure 5.1 a) shows a circuit schematic used to measure electron lifetime, τ_n . It is based on the reverse transient storage time method [61]. A negative pulse applied to the diode while a steady forward current I_F is flowing will cause the current to reverse. The reverse current, I_R is sustained for a time t_s by minority carriers stored in the bulk. Theory shows that the effective carrier lifetime can be approximated by:

$$\tau = \frac{t_s}{\ln \left(1 + \frac{I_F}{I_R} \right)} \quad (5.1)$$

For high current levels ($I_F > 2 \text{ A/cm}^2$) and long storage times, the lifetime appears to approach the bulk value, τ_n as shown for a typical diode in Figure 5.1 b). The high current level ensures that the diode is operating one dimensionally while the long storage time allows bulk recombination to dominate the minority carrier loss. For several test

Fig. 5.1 Bulk lifetime measurement a) test circuit and device measurements, b) graphical interpretation.

diodes on 8-10 Ω -cm substrates, lifetime values of 7-8 μ s were measured, in good agreement with values expected for that material [49].

C-V measurements were made using the arrangement depicted in Figure 5.2. A Boonton 71 A capacitance meter was employed. The bias was applied with a manually swept DC power supply. The high MOS capacitance level (~ 300 pF) rendered any stray capacitance negligible. Here again, the room lighting had to be turned off to obtain correct results. An alternate method for measuring the C-V characteristic was with a Boonton 75 D capacitance bridge and discrete bias voltages. This was slower but provided more accurate curves with less hysteresis and noise. Many of the MOS capacitors tested were leaky or faulty in other ways. However, at least one suitable device could usually be found on each wafer.

5.2 Solar Cell Electrical Tests

The most important characteristic for a completed solar cell is its illuminated I-V output curve. Two possible methods for measuring this are illustrated in Figure 5.3. Although neither was used exactly as shown, all the methods employed were hybrids of the ideas described here.

There are four main parts to the apparatus: the source, the cell holder, the test circuit and the data recording. Sources are discussed in more detail in the next section. All I-V curves were made using either the sun or an incandescent lamp. While the sun is best for determining how cells work under real conditions, a lamp can be set up in the laboratory at any time and provides a wide range of intensity levels.

Fig. 5.2 Capacitance vs voltage curve measurement apparatus.

Fig. 5.3 Two possible I-V test setups showing cell mounting and measurement circuitry.

The cell holder serves several functions. When illuminated by the sun, the cell must be positioned facing it. For a cell not mounted on a circuit board, a vacuum chuck to hold the cell in place and a probe to contact the bonding pad are required. Usually, a thermometer is included to measure the ambient temperature. Some attempt may also be made to monitor or even control the cell temperature. Finally, an opaque mask with an aperture can be utilized to limit the active area of the cell.

The measurement circuit is composed of a voltmeter, an ammeter and some provision for varying the operating point of the cell. In Figure 5.3 a), this is accomplished with a variable load resistance. In Figure 5.3 b) the current is varied by adjusting the potentiometer. The latter method allows all three quadrants of the I-V curve to be measured while the former is limited to only the positive output power quadrant. In both circuits, the operating point is controlled manually.

The I-V data were usually recorded as discrete values for analysis and plotting at a later time. A technique for semi-automatic plotting on an x-y recorder is shown in Figure 5.3 b). This simplifies the data recording, but does not allow for analysis prior to plotting. Such analysis might include normalization of the current to a unit area or correction for probe and interconnect resistance losses. Also, during the few seconds required to trace the curve, the cell temperature may rise enough to distort the plot. For these reasons, the most accurate results were obtained by discrete measurement.

The current and voltage readings are as accurate as the meters used (Fluke 8000A digital multimeters) but several factors can alter the results. With the circuit in Figure 5.3 a), the short circuit current cannot be measured because all ammeters have a non-zero internal

resistance. This is not a problem in a good cell where $I(V)$ remains relatively constant near the short circuit point. However, for cells with low shunt resistance or poor fill factors, it is difficult to extrapolate the curve to zero volts. For such cells, the arrangement in Figure 5.3 b) is more suitable. Another problem is that the light intensity may vary between measurements on a single cell or from one cell to the next.

The temperature of the cell, while illuminated, is unknown, but generally higher than the ambient. Since both cell voltage and current vary with temperature, it is difficult to compare cells tested under different conditions. Even a single cell may heat up between measurements. This problem is especially severe when a high intensity, incandescent lamp is used. Temperature effects were minimized in practice by quickly taking the readings when the light source was briefly flashed on. The cell was allowed to cool to ambient between readings, aided by a small fan. This procedure was time consuming and subject to other possible errors, but produced the most reliable results.

Many of these problems could be avoided with a more sophisticated test system such as the one described briefly in Appendix "C". A system similar to this is currently being developed at Carleton. When complete, it will include a solar simulator light source, a cell temperature controller and computer controlled I-V test circuitry. The system should allow solar cells of all types to be tested with unprecedented ease and flexibility.

Although the metal pattern shown in Figure 4.2 has an edge band to reduce peripheral collection, some collection from outside the cell, via the inversion layer under this band, does occur. Calculation shows that in a cell with $Q_{fb} = 6 \times 10^{11} \text{ cm}^{-2}$, this fringing current or peripheral collection accounts for ~2% of the total short circuit current under AM1 illumination. At the maximum power point, the contribution is much less (estimated to be <1%) but still represents an "error" in measuring the cell output. This effect also causes the fill factor to be somewhat lower than expected in the absence of peripheral collection. The problem is worse for the small test cells on the wafer since their perimeter-to-area ratio is an order of magnitude higher. For this reason, the small cells were not often tested.

At low light intensities (< .01 suns), the fringing problem becomes critical, with any contact on the pattern collecting current from the entire wafer area. To obtain meaningful, low intensity measurements, it was necessary to define the active area of the cell with a mask as indicated in Figure 5.3 a). Generation and thus, collection occur only in the illuminated regions. Limiting the active area in this way worked well for short circuit current measurements if the mask was close to the cell surface. At higher voltages, however, especially near the open circuit voltage, the opposite problem occurs. The peripheral regions are forward biased via the inversion layer and dark current injection takes place. Since there is no generation in this area (because of the mask), the injection area is larger than the active area and a slight drop in V_{oc} occurs. For this reason, masks were not used for normal intensity measurements and the I-V results therefore include ~2% extra current at $V=0$.

Once the I-V curve is obtained, the fill factor and maximum power can be calculated. The effective series resistance of the cell, R_s , can be estimated from a family of such curves made at different intensities [62]. If the light intensity is known, the efficiency can also be calculated. Intensity is measured with a pyrometer or standard cell or can be estimated from Figure 2.2 for sunlight. The measured efficiency will be meaningful only if the source is the sun or a properly designed solar simulator. Other sources (e.g. incandescent lamp) have different spectral compositions and would cause anomalous (low) efficiencies to be measured.

The solar cell as a diode can be characterized by dark I-V measurements. If the cell is shielded from all light and the data are taken over a wide current range (10^{-7} to 10^{-1} A/cm²), they should fit equation (3.3). Usually, the data are plotted on semilogarithmic paper as $\log(I)$ vs V to produce the dark I-V curve. In practice, the curve does not fit the expected straight line at high current levels due to the voltage dropped across the cell series resistance. Also, injection at the contact occurs in parallel with that of the induced junction (for an IL cell) so that the resultant curve is characteristic of neither junction alone. For these reasons, dark I-V curves have limited usefulness.

A better approach is to measure the short circuit current and open circuit voltage for a wide range of light intensities. Theory shows that the resultant illuminated I_{sc} vs V_{oc} curve also fits equation (3.3), but is unencumbered by series resistance. The data are also more representative of the cell's active area. Care must be taken, however, to ensure that the active area remains constant for all intensities.

This may be done using a mask as described above. Also, cell heating at high intensities artificially reduces V_{oc} unless precautions are taken to maintain a constant temperature.

5.3 Optical Test Equipment

Spectral response measurements for a solar cell can yield useful information about its internal operation. Estimates of bulk lifetime, surface reflectance and "dead layer" losses can be obtained by careful interpretation of such results. These effects are illustrated in Figure 2.7. The measurement of external current efficiency, $Q_e(\lambda)$ over the entire spectrum requires three things: a wide spectrum source, a means of selecting narrow bands of wavelengths and a calibrated reference detector.

The sun itself should be the ideal source for photovoltaic measurements. It has the necessary wide bandwidth and high intensity, provides parallel light rays and causes minimal cell heating. However, many problems are associated with using sunlight. Firstly, it is available only on very clear days outside the laboratory. Also, not all the sunlight incident on a surface comes directly from the sun. Even on a clear day, diffuse skylight of unknown spectral composition, orientation and intensity is present. Changing atmospheric conditions make even the direct rays vary in intensity. Thermal disturbances in the air likewise cause small intensity fluctuations. Finally, there is very little solar radiation at ground level for wavelengths below 300 nm. Therefore, for accurate, full spectrum, repeatable laboratory measurements, another source is needed.

An incandescent lamp can provide the needed stability, intensity and availability, but its 2800 K colour temperature is too low to produce appreciable UV light and causes excessive heating with its high infrared output. A tungsten halogen lamp was found to be more suitable.* With a 3400 K effective filament temperature, measurements at wavelengths as low as 300 nm could be made. The intensity was high enough and with a regulated power supply, the stability was excellent. For ultraviolet measurements down to 250 nm, a low pressure mercury arc lamp was used.** Although the lamp caused some noxious ozone formation and tended to have an unstable or drifting output, accurate measurements could be obtained without great difficulty.

To measure the spectral response using a wide-band source, discrete wavelengths must be selected. This was accomplished with a set of narrow-band, optical interference filters. The 28 filters span the spectrum from 250 to 1150 nm.*** Each filter came supplied with a measured transmission curve similar to the bell-shaped curve in Figure 5.4 a). For computational simplicity, the curves were approximated as shown by a rectangular passband $\Delta\lambda$ wide with 100% transmission, centred on λ_c (the centre wavelength of the filter). $\Delta\lambda$ was calculated by equating the areas under the two curves. The filter characteristics, including the leakage bandwidths are summarized in Table

* Spectro type DWY 120 volts - 650 watts or equivalent

** PEK type 107 (or equivalent) 100 watt mercury short arc lamp with a Micro Mechanics P-210-DMM power supply.

*** A set of ten filters ($\lambda_c = 708, 657, 592, 581, 550, 523, 485, 438, 425, 407$ nm) from Optics Technology Inc. Palo Alto Calif. (Some of these had been previously damaged by abuse.) The remaining 18 were purchased from Corion Corp. Holliston, Mass.

Fig. 5.4 a) Characterization of narrow band interference filters.
 b) effect of filter leakage on test cell response for $Q_e(\lambda)$ measurement at $\lambda_c = 407$ nm, showing need for correction.

λ_c (nm)	t_{peak} (%)	$\Delta 1/2$ (nm)	$\Delta 1\%$ (nm)	$\Delta 10^{-3}$ (nm)	$\Delta 10^{-4}$ (nm)	$\Delta\lambda$ (nm)	$\pm \%$
1135	22.2	12.7	25.7	39	>60	2.99	4
1056	41.7	4.8	11.5	19	~103	2.14	4 1/2
1011	42.1	10.2	16.7	24	~150	4.12	3
972	48.5	9.4	20.3	28	~ 50	4.54	3
927	44.9	10.9	17.5	24	~ 76	4.74	3
881	52.6	10.6	19.0	27	~ 70	5.41	2 1/2
794	50.5	15.9	30.4	43	~ 65	8.30	3
739	35.5	10.7	28.8	46	~170	4.49	3
708	35.3	18.4	108	248	~520	9.6	4
695	49.9	13.3	26.5	43	110	6.86	2 1/2
657	42.2	19.7	33.3	225	~530	12.2	4
620	42.1	11.8	33.3	55	~ 98	5.63	3
592	34.4	15.9	80	164	360	7.6	4
581	43.1	18.0	85	186	~490	10.1	6
550	41.9	18.5	73	204	440	10.0	3
523	35.7	16.7	79	174	390	8.1	3
497	34.6	10.2	26.2	55	~ 90	3.88	5
485	36.0	16.9	101	186	~400	9.1	4
461	49.7	5.7	15.2	30	~ 45	3.18	6
438	27.7	14.5	67	139	~330	5.74	2
425	30.9	17.9	69	149	~360	7.05	2
407	30.3	19.4	69	152	~340	6.90	2
377	23.8	9.4	18.9	32	~ 85	2.34	3 1/2
353	19.5	13.8	38.3	61	86	3.20	3 1/2
335	29.8	13.7	39.7	77	125	4.75	2 1/2
310	27.1	12.6	33.9	52	112	3.91	2 1/2
279	21.2	13.1	29.4	45	110	3.11	3
252	21.8	12.4	29.6	42	155	3.07	2 1/2

Table 5.4 Optical interference filter characteristics.
 λ_c =centre wavelength, t_{peak} =peak transmission,
 $\Delta 1/2$ =half power bandwidth, $\Delta 1\%$ =1% transmission
bandwidth, $\Delta 10^{-3}$ =1/10% bandwidth, $\Delta 10^{-4}$ =1/100%
bandwidth, $\Delta\lambda$ =idealized bandwidth and uncertainty.

Initially, the supplied transmission curves were used directly and any leakage outside the passband was assumed to be negligible. However, it was observed that a bright source could be clearly seen through the UV filters. Also, different $Q_e(\lambda)$ results were obtained using different sources. These facts indicated that significant out-of-band leakage did occur. Subsequent measurement of the long wavelength "tails" of the filters confirmed this suspicion. The 1%, 1/10% and 1/100% bandwidth data in Table 5.4 are based on these measurements.

The actual transmission curve (a composite of the supplied curve and measured data) for one of the filters is shown (dotted line) in Figure 5.4 b). Even with a logarithmic transmission scale, it can be seen that appreciable leakage occurs far from the peak. Although this leakage is orders of magnitude below the peak transmittance, three factors combine to make it important. The response of a test cell at any wavelength is proportional to the product of the source intensity, the filter transmission and the cell's own current efficient, $Q_e(\lambda)$ at that wavelength. For the example shown in the figure, the source and $Q_e(\lambda)$ both drop off quickly at short wavelengths so that the resultant response is heavily weighted toward longer wavelengths. Finally, the response "tail" is much wider than the peak. Thus, the integrated cell response may contain more out-of-band current than in-band current. The example shown is the worst case encountered, but it clearly indicates that correction is required for $Q_e(\lambda)$ measurements made with these filters. Such a correction is outlined in section 5.4.

To provide a calibrated reference detector, a standard cell was purchased from OCLI.* The absolute spectral response shown in Figure 5.5 (dashed line) was supplied. However, the accuracy was guaranteed to no better than $\pm 5\%$ of the peak value, rendering the cell useless for measurements below a wavelength of 450 nm. Recalibration was therefore undertaken. Various methods were attempted, producing similar results, shown as data points in the figure. The methods involved comparing the OCLI cell with another device or assuming a known spectrum for the source. The solid line in Figure 5.5 represents the most likely values. The best estimate of spectral response (SR in mA/mW) for the OCLI cell at each of the filter centre wavelengths is given in Table 5.5. The estimated uncertainty is less than the OCLI quoted value for all wavelengths.

The second detector purchased was the thermopile referred to in Figure 5.5.** It operates by detecting the temperature rise caused by the light incident on a black surface. It should thus have a flat response throughout the entire passband of the quartz window ($\lambda = 200$ nm to 4.5 μ m). Unfortunately, the responsivity quoted by the manufacturer (10.9 volts per watt $\pm 5\%$) was inappropriate. It had been calibrated using a blackbody source having a substantial spectral component beyond 4.5 μ m in the far infrared. Hence, this detector also had to be recalibrated. It was tested in AM1.27 sunlight on a very clear day. Care was taken to include all the diffuse skylight and exclude any

* Optical Coating Laboratories Inc. standard cell CSC-12 serial number 00127.

** Barnes Engineering Company type 21-330 calibrated thermopile.

Fig. 5.5 Spectral response curve for OCLI standard cell CSC-12 #127 showing results of various calibration methods.

λ_c (nm)	SR mA/mW	$\pm$ %	λ_c (nm)	SR mA/mW	$\pm$ %
252	.0016	-50	581	.284	3
279	.0009	-50	592	.297	2
310	.0023	-25	620	.329	2
336	.0056	-20	657	.380	3
353	.0070	12	695	.415	2
377	.011	10	708	.428	2
407	.038	9	739	.452	2
425	.060	8	794	.490	2
438	.066	7	881	.521	2
461	.098	5	927	.510	2
485	.138	3	972	.458	2
497	.157	3	1011	.333	2
523	.198	5	1056	.151	4
550	.242	4	1135	.028	10

Table 5.5 Calibrated values of spectral response for OCLI standard cell #127 and estimated uncertainty. (July 1978)

sources of reflected light. The resultant responsivity of 14.5 V/W ($\pm 3\%$ estimated uncertainty) gives good agreement in Figure 5.5 and should be accurate for optical measurements.

In using the thermopile, especially at low intensities, the small signal level caused several problems. The active area of the device is assumed to be 1 mm square. Thus, even at AM1, the signal was only ~ 14 mV and with the interference filters, signals as low as 10 μ V had to be measured. A FLUKE model 8300A digital micro-voltmeter was used for this purpose. The meter had a zero voltage offset of a few microvolts which biased the measurements. Also, there was a continual jitter or noise of about ± 1 μ V (the least significant digit on the meter) which limited the accuracy at low signal levels. This is the reason for most of the high uncertainty for the UV measurements listed in Table 5.5.

Correction also had to be made for thermal offset. When the lamp was on, the filter and other optical equipment heated up above the temperature of the thermopile case. A signal developed due to the non-equilibrium blackbody radiation. This offset was 5-40 μ V depending on how long the lamp had been on. To obtain a correct measurement, the thermopile signal was first recorded with the lamp on. The light was then blocked with an opaque object (rather than switching the lamp on and off) and the offset signal recorded. The difference between the readings yielded the desired signal. Since any meter offset was common to both signals, only the one correction was necessary. However, because two signals were measured, the uncertainty due to noise was doubled to ± 2 μ V. This could be reduced somewhat by averaging multiple readings.

5.4 Optical Test Methods

A "black box" was constructed to hold the test and standard cells, the interference filters and any necessary apertures. It was designed to keep the entire assembly pointed at the sun and to prevent extraneous light from reaching the cells. The box was intended for use in measuring spectral response and cell reflectance and had optical biasing capability.

Some solar cells exhibit a non-linear relationship between light intensity and short circuit current, especially at the very low intensities encountered in spectral response measurements. Such measurements are therefore often done with white light superimposed on the monochromatic test beam to bias the cell to a higher current level. The test beam is chopped and the AC component of the cell output is taken as the measurement. Fortunately, comparison with the OCLI standard cell (known to be linear from .5 μ A to 200 mA) revealed no appreciable non-linearities for the IL cells tested. Optical biasing was therefore unnecessary and the spectral tests done at microampere levels should be valid at normal light intensities.

With the sun as the source, the equation used to determine the external current efficiency from black box measurements was:

$$Q_e(\lambda_c) = \frac{I_{sc}(\lambda_c)}{q \text{ Area } \Delta\lambda N_o(\lambda_c)(t_{air}^m)^{air}} \quad (5.2)$$

where $I_{sc}(\lambda_c)$ is the short circuit current measured using the filter with centre wavelength λ_c , Area is the active area of the test cell, $\Delta\lambda$ is the idealized filter bandwidth and N_o , t_{air} , m_{air} define the solar spectrum as in equation (2.1).

Equation (5.2) was used to obtain the triangular data points in Figure 5.5. Due to the accumulated uncertainties in Area, $\Delta\lambda$ and t_{air} , the resultant $Q_e(\lambda)$ values could not be expected to be very accurate. For this reason and due to the inherent shortcomings of the sun, the "black box" saw only limited use for this type of spectral measurement. The main problem was having to wait for a clear day and then setting up all the equipment outdoors. Also, reliable measurements at ultraviolet wavelengths could not be obtained due to insufficient UV sunlight.*

To avoid these problems, an optical bench was set up in a dark room for use with artificial light sources. This proved to be easier to use, more adaptable to changes in apparatus and suitable for UV measurements. Also, testing could be done at any time with better accuracy. The test assembly is shown schematically in Figure 5.6. The lamp supply was a Sorensen Nobatron, model DCR300-5A. A FLUKE 8000A multimeter was used for the measurements. The cell was well baffled and shielded to ensure that only the monochromatic light passing through the filter reached it. With the optical bench arrangement, cells could be readily interchanged and other sources could be used.

* With minor modifications, the "black box" has recently been adapted for measuring $Q_e(\lambda)$ and reflectance in the laboratory, using either of the two sources described in section 5.3. With a calibrated IL cell as the reference standard, accurate measurements can now be obtained quickly and easily for all types of solar cells.

To measure short circuit current at low intensities, a current amplifier was built. By switching the feedback resistor over four ranges, currents from 1 μ A to 10 mA could be measured accurately. For the lowest currents, the amplifier zero offset had to be carefully adjusted to obtain good results. Also, a calibration factor, different for each of the current ranges, was used to correct for the resistors being slightly different from their nominal values. Apart from these considerations, the amplifier was easy to use.

Measurement of external current efficiency with the apparatus illustrated in Figure 5.6 was straightforward. After zeroing the amplifier offset, the lamp was turned on and the desired filter inserted. Short circuit current readings were then taken for the test and standard cells, making certain that the cells were in the same position. The test cell current efficiency was calculated as follows:

$$Q_e(\lambda_c) = \frac{hc}{\lambda_c} SR_S(\lambda_c) \left\{ \frac{I_{sc T}}{I_{sc S}} \cdot \frac{Area_S}{Area_T} \right\} \quad (5.3)$$

where SR_S is the spectral response given in Table 5.5, hc/λ_c is the photon energy in eV, I_{sc} is the measured short circuit current and Area is the illuminated active cell area. The subscripts S and T refer to the standard and test cells respectively. The OCLI cell active area was measured to be 0.896 cm². The active area of the test cell depended on the aperture used and the grid shading.

Fig. 5.6 Optical-bench solar cell test setup showing source, filter, device under test and short circuit current measurement technique.

The accuracy of $Q_e(\lambda)$ measured by this method is limited by the uncertainties in the response of the standard cell (Table 5.5), the calculated area and the measured currents. Thus, accurate values could be obtained for long wavelengths. However, the inaccuracy of the OCLI standard cell at blue and UV wavelengths reduced the usefulness of this technique.

The method which proved to be the most accurate and the one used for most of the $Q_e(\lambda)$ results presented in Chapter 7 was to replace the standard cell with the thermopile detector. Although the measurements became more difficult to perform, the results were more reliable. Having measured the illuminated thermopile signal V_{th} and the thermal offset V_{os} as described in section 5.3, the measured current efficiency could be determined:

$$Q_m(\lambda_c) = \frac{hc}{q\lambda_c} \cdot \frac{I_{scT}}{Area_T} \cdot \frac{0.145}{(V_{th} - V_{os})} \quad (5.4)$$

where I_{scT} and $Area_T$ are defined above and $0.145 \text{ Vcm}^2/\text{W}$ is the product of the thermopile area and responsivity.

As mentioned in the previous section, the measured current efficiencies must be corrected for filter leakage. The correction is simplest when the thermopile is used since its responsivity is flat across the spectrum. A computer program, QFIX was written to accept the $Q_m(\lambda_c)$ measurements from equation (5.3) and determine the corrected $Q_e(\lambda_c)$ values. The program operates by simulating the experiment. Starting with the longest wavelength filter ($\lambda_c = 1135 \text{ nm}$), the short circuit current of the test cell is calculated:

$$J_{sc}(\lambda_c) = q \int_0^{\infty} N_s(\lambda) t_{\lambda_c}(\lambda) Q_c(\lambda) d\lambda \quad A \text{ cm}^{-2} \quad (5.5)$$

where the integrand is the response function shown in Figure 5.4 b).

$N_s(\lambda)$ is the source spectrum (photons $\text{cm}^{-2}\text{s}^{-1}\text{nm}^{-1}$) and $t_{\lambda_c}(\lambda)$ is the filter transmission. In the program, the tungsten halogen lamp is modelled as a 3400K blackbody and the filter transmission curves are approximated by a summation of exponential functions. $Q_c(\lambda)$ is the assumed current efficiency of the test cell. Initially, $Q_c(\lambda)$ is set equal to $Q_m(\lambda_c)$ with exponential interpolation used for wavelengths between the discrete values of λ_c .

The integration in equation (5.5) is done numerically with $d\lambda = \delta\lambda = 2 \text{ nm}$. The upper limit of integration is 1200 nm (above which $Q_c = 0$) and the lower limit is the point where t_{λ_c} drops toward zero as shown in Figure 5.4 b). A similar integral is used to calculate the power incident on the cell (or thermopile):

$$P(\lambda_c) = q \int_0^{\infty} \frac{hc}{\lambda} N_s(\lambda) t_{\lambda_c}(\lambda) d\lambda \quad W \text{ cm}^{-2} \quad (5.6)$$

where hc/λ is the photon energy. The limits of integration are the same as above. The ratio of current to power yields the simulated measured current efficiency:

$$Q'_m(\lambda_c) = \frac{hc}{q\lambda_c} \cdot \frac{J_{sc}(\lambda_c)}{P(\lambda_c)} \quad (5.7)$$

Initially, with $Q_c = Q_m$, Q'_m will not equal Q_m due to the filter leakage. However, by comparing Q'_m and Q_m , $Q_c(\lambda_c)$ can be adjusted and the integration in equation (5.5) recalculated to obtain a Q'_m closer to Q_m . By iterating this process, Q'_m can be made to approach Q_m . When the two are sufficiently close, the $Q_c(\lambda_c)$ value is the corrected external current efficiency for that wavelength. The entire algorithm is repeated for each filter in order of decreasing λ_c .

As indicated in the previous section, the correction can be substantial. For the example in Figure 5.4 b), the correction ratio is $Q_c(\lambda_c)/Q_m(\lambda_c) = .517$; $\lambda_c = 407$ nm. The largest corrections occur with the filters $\lambda_c = 406, 425, 438$ and 485 nm and usually amount to a ~10% decrease in $Q_m(\lambda_c)$. At longer wavelengths, the filter leakage becomes insignificant. For $\lambda_c < 400$ nm, the tungsten halogen lamp is not bright enough to produce sufficient response in the thermopile. Thus, the mercury arc lamp was used for UV measurements. Since its spectrum is not heavily weighted toward long wavelengths, the corrections for filter leakage should be small (less than ~2%). However, they cannot be determined since the spectrum is not accurately known.

It is possible that errors due to filter haziness, multiple reflections and detector misalignment remain unaccounted for, but these are expected to be small (less than 1%). In general, $Q_e(\lambda)$ measurements made by the different techniques were in fair agreement and with care, repeatable results could be obtained. The accuracy should be about $\pm 5\%$ over most of the spectrum.

Using the tests described in this chapter, every part of the IL solar cell structure can be characterized and the important aspects of completed solar cells can be measured. The experimental results for completed cells will be presented in later chapters. To know if the cells are working properly and to determine where improvements can be made, the results must be compared with theory. The next chapter discusses how the operation of surface effect cells can be modelled to predict their spectral and I-V behaviour.

CHAPTER 6

SOLAR CELL MODELLING6.1 Introduction

Although a solar cell is an inherently simple device, being merely a pn diode, its operation can be very complicated and difficult to understand. This is because the requirements for efficient photovoltaic conversion are different from and more involved than those for a simple rectifier. Simple diode theory, summarized in equations (2.4) and (2.5) is inadequate to accurately describe the operation of most cells and does not provide a basis for improving their design.

Thus, there is a need for more complex theoretical analysis of solar cells. Much work has been done on the modelling of conventional cell structures for the purpose of exploring their operation under all conditions and in an attempt to yield ever higher efficiencies through process modifications [7,18,35,63]. Partly analytical solutions are possible [7], but the most accurate models, incorporating all the effects which occur in solar cells, use numerical methods and computer simulation of the cell structure and operation [35, 63].

Since the inversion layer cell structure differs fundamentally from that of the diffused cell, the details of its operation and optimization will necessarily be different as well. Until recently, only one limited model of the IL cell had been developed [18]. Hence, extensive work on the detailed modelling of the entire device was undertaken. The purposes were to elicit a better understanding of the

photovoltaic action of an induced junction, to explore the potential and limitations of the IL cell concept and, ultimately, to provide a tool for the design of more efficient cells.

The philosophy adopted in developing the model was to start from basic semiconductor theory, with as few empirical additions as possible and at the same time to include all the important factors affecting photovoltaic performance. This is in keeping with recent indications that accurate solar cell modelling can be expected only when all such factors are accounted for [30]. It was felt that such an approach would, in the end, be the most versatile and provide the most insight into cell operation although it necessarily entailed complex and detailed analysis.

Any such undertaking requires that certain assumptions be made to provide a basis for addressing the problem. Therefore, in the development, it is assumed that low level injection and quasi-equilibrium conditions apply and that in all conditions, non-degeneracy holds so that Boltzmann statistics and the usual semiconductor theory based on it apply. Other reasonable assumptions which simplify the analysis are that the silicon bandgap remains constant throughout the cell and that minority carrier recombination in the bulk is characterized by a constant lifetime. Further assumptions will be introduced as needed.

Most of the discussion in this chapter deals with the modelling of inversion layer cells. However, the concepts and theory can be readily applied to other surface effect structures. Optical effects within the cell and the modelling of external current efficiency are described. The central sections of the chapter cover the analysis of

one and two-dimensional current flow in the IL cell and the computer model developed to simulate its operation. Finally, the modelling of lateral collection in the grating solar cell is considered.

6.2 Modelling Optical Effects

As indicated in Chapter 2, optical effects are fundamental in calculating the photocurrent, I_L and therefore, the output power of the cell. For modelling purposes, the solar spectrum $N_m(\lambda)$, given by equation (2.1) was assumed. The values for $N_o(\lambda)$ and $t_{air}(\lambda)$ were taken from Figure 2.1 and the air mass, m_{air} was left as a parameter. Though significant, the effects of atmospheric conditions on the spectrum could not be accurately characterized and therefore were not included.

Several factors must be considered in finding the light intensity within the cell itself. In the inversion layer cell, these are controlled by the optical properties of the air-oxide-silicon system, shown schematically in Figure 6.1 a). The first loss suffered by the incident light is reflection, $R(\lambda)$. The reflectance of a thin, uniform dielectric layer on a semi-infinite silicon substrate can be calculated by considering the impedance mismatch resulting from the changes in refractive index of the propagating media [7,64]. The resulting power reflection coefficient for normally incident light is given by:

$$R(\lambda) = \left| \frac{R_{ox} + R_{Si} \exp(-j2\theta)}{1 + R_{ox} R_{Si} \exp(-j2\theta)} \right|^2 \quad (6.1)$$

Fig. 6.1 a) Optical characteristics of the air-oxide-silicon system.

b) Optical carrier generation rate in the silicon substrate for an optimum SiO_2 AR coating.

$$\text{with } \theta = \frac{2\pi n_{\text{ox}} t_{\text{ox}}}{\lambda} ; R_{\text{ox}} = \frac{1-n_{\text{ox}}}{1+n_{\text{ox}}} ; R_{\text{Si}} = \frac{n_{\text{ox}}-n_{\text{s}}}{n_{\text{ox}}+n_{\text{s}}}$$

where most of the parameters are defined in Figure 6.1 a). n_{s} is the complex refractive index of silicon, given by:

$$n_{\text{s}} = n_{\text{Si}}(\lambda) - j k_{\text{Si}}(\lambda) ; k_{\text{Si}}(\lambda) = \frac{\lambda \alpha(\lambda)}{4\pi} \quad (6.2)$$

where k_{Si} is the extinction coefficient for silicon. For most wavelengths, n_{s} is essentially real and equation (6.1) can be simplified [7]. However, at ultraviolet wavelengths, $\alpha(\lambda)$ is large and k_{Si} must be included for accurate results. Silicon dioxide behaves like an ideal dielectric over the entire spectrum of interest for photovoltaics. Therefore, n_{ox} is real and essentially constant. For other oxides (notably SiO and TiO_x) however, there is some absorption at UV wavelengths and n_{ox} also would become a complex variable in λ .

With the presence of surface states, excess silicon atoms, traps and impurities at or near the Si-SiO_2 boundary [44, 51, 56], the possibility of some attenuation of light at the interface must be considered. Early IL cell current efficiency measurements seemed to support this "parasitic absorption" hypothesis [20, 42]. More recent calculations and measurements however, demonstrate this effect to be of much less importance than initially thought and recent IL cells exhibit no parasitic absorption at all. When properly interpreted, the $Q_{\text{e}}(\lambda)$ data can be accurately modelled using only complex reflectance. (See section 7.2 for further discussion of this question.)

The photon flux entering the active part of the cell is therefore given by $[1 - R(\lambda)]N_m(\lambda)$.^{*} These photons are absorbed and generate electron-hole-pairs as described in Chapter 2. If the generation rate given by equation (2.3) is integrated across the AM1 spectrum, the result is $g(x)$ as shown in Figure 6.1b). Most of the generation takes place close to the surface, with very little occurring deeper than 100 μm into the bulk.

In developing the IL cell model, it was assumed that the photons enter perpendicularly and that any which penetrate to the back surface are lost. These assumptions are accurate for most cells and the foregoing derivation of generation rate, $g(x)$ can be used. However, for cells with texturized front surfaces or optically reflective back contacts (not to be confused with BSF regions), the theory would have to be modified [35, 36].

6.3 Calculating Current Efficiency

Under short circuit (zero bias) conditions, the operation of a vertical collection cell is simplified and an analytic solution can be found for the current flow. The current efficiency can therefore be calculated without resorting to full numerical simulation. The assumption of vertical collection renders the cell operation one-dimensional so that the structure shown in Figure 6.2 a) can be used. The energy band diagram in Figure 6.2 b) demonstrates the basis for

* For oxides other than SiO_2 which have some optical absorption, the transmission coefficient would have to be calculated separately since reflection plus transmission would no longer equal unity.

Fig. 6.2 a) One-dimensional structure of an IL solar cell (not to scale).

b) Equilibrium energy band diagram showing depletion and BSF regions.

c) Electric field, $E(x)$ and excess electron distribution, $n'(x)$ at short circuit (not to scale).

division of the cell into the three regions as indicated.

The depth of the depletion region, x_d can be derived using simple MOS theory [31]:

$$x_d = \sqrt{\frac{\epsilon_s \phi_s}{q N_a}} \quad \text{cm} \quad (6.3)$$

where ϕ_s is the surface potential derived in section 3.3 and the other terms have their usual meanings. The effective back surface field depth, x_b depends on the p^+ diffusion profile and can be estimated from a knowledge of the process used. Both x_d and x_b are usually on the order of 1 μm ; much less than the thickness of the cell, w_o .

The external current efficiency at a wavelength λ is given by:

$$Q_e(\lambda) = \frac{J_d(\lambda) + J_n(\lambda)}{qN_m(\lambda)} \quad (6.4)$$

where the numerator represents the current density in the cell at short circuit due to the incoming photons at that wavelength. J_d is the current collected in the depletion region and J_n is that coming from the neutral bulk. Because the BSF region is narrow and at the back of the cell where little generation occurs, its direct contribution to the collected current is negligible and therefore, not included in the calculation. (The beneficial aspects of the BSF region arise indirectly, through the enhancement of bulk current.)

Numerical analysis, using the methods developed later in this chapter, has shown that essentially all the carriers generated in the depletion region at short circuit are successfully collected. The

high electric field in this narrow region, the passivated front surface and the high lifetime (near the bulk value) combine to ensure negligible recombination. This is one of the main advantages of surface effect cells over conventional diffused cells where the surface "dead layer" [32] causes high recombination losses. The IL cell depletion collection current is thus given by:

$$J_d(\lambda) = q N_m(\lambda) [1-R(\lambda)] [1-\exp(-\alpha(\lambda)x_d)] \quad \text{A cm}^{-2} \quad (6.5)$$

This is simply the number of photons entering the cell minus those penetrating to x_d .

Calculation of the electron collection current, J_n requires solving the one-dimensional steady-state continuity equation for electrons in the bulk:

$$\alpha(\lambda) [1-R(\lambda)] N_m(\lambda) \exp[-\alpha(\lambda)x] + \frac{1}{q} \frac{d}{dx} J_n(x) - \frac{n'(x)}{\tau_n} = 0 \quad (6.6)$$

The first term represents the generation rate of free electrons; the second, the change in their rate of flow; the third, their rate of recombination, τ_n being the electron lifetime in the bulk. Since there is no electric field in the neutral bulk, the current is diffusion controlled.

$$J_n(x) = q D_n \frac{d}{dx} n'(x) \quad \text{A cm}^{-2} \quad (6.7)$$

where D_n is the electron diffusion constant. $n'(x)$ is the concentration of excess (non-equilibrium) electrons and is shown schematically in Figure 6.2 c). $J_n = J_n(x_d)$ is found by substituting equation (6.7) into equation (6.6), solving for $n'(x)$ and then evaluating equation (6.7) at $x=x_d$.

The solution of the continuity equation requires two boundary conditions, one at the front and one at the back of the neutral bulk region. At the edge of the depletion region, it is assumed that $n'(x_d) = 0$. While this is not exactly true, numerical calculation indicates that it is a good approximation. $n'(x_d)$ is typically of the same order as n_i , the intrinsic electron concentration, while $n'(x)$ may be two orders of magnitude higher throughout most of the bulk. (The zero bias curves in Figures 7.14 and 7.15 illustrate this point quite well.) Since $n'(x_d) \ll n'(x)$ for most values of x , the $n'(x_d) \sim 0$ assumption is reasonable.

In the absence of a back surface field, the bulk extends to an ohmic contact which approximates an ideal sink for minority carriers so that $n'(w_0) = 0$ is the boundary condition. Alternately, an ideal BSF region would act as a perfect electron "mirror" and $\frac{d}{dx} n'(w_0 - x_b) = 0$ would apply. Real boundaries are not so ideal. In principle, it is possible to include the BSF region in the solution of the continuity equation by considering the p^+ diffusion profile and its effect on the electric field, the electron lifetime and the diffusion constant. However, in most cases, these effects are not accurately known and the resultant solution would no longer be analytic in nature.

Fortunately, the action of a back surface field can be modelled by an effective surface recombination velocity given by [65]:

$$S_b = \frac{N_a}{N_a +} \frac{D_n +}{L_n +} \left\{ \frac{S_b + \left(\frac{L_n +}{D_n +} \right) \cosh \left[\frac{x_b}{L_n +} \right] + \sinh \left[\frac{x_b}{L_n +} \right]}{\cosh \left[\frac{x_b}{L_n +} \right] + S_b + \left(\frac{L_n +}{D_n +} \right) \sinh \left[\frac{x_b}{L_n +} \right]} \right\} \text{ cm s}^{-1} \quad (6.8)$$

where N_a is the bulk doping level and the + superscript refers to conditions in the p^+ region. Thus, N_a^+ is the average doping level in the BSF region, D_n^+ is the diffusion constant and $L_n^+ = \sqrt{D_n^+ \tau_n^+}$ is the diffusion length. S_b^+ is the surface recombination velocity at w_0 , the back contact. Therefore, the boundary condition at the back surface has the following representation:

$$J_n(w_0 - x_b) = qD_n \frac{d}{dx} n'(w_0 - x_b) = -qS_b^+ n'(w_0 - x_b) \quad (6.9)$$

In this form, $n'(x)$ and its first derivative at $x = w_0 - x_b$ are related through S_b and D_n . A good BSF solar cell will have $S_b < 10$ cm/s whereas an ohmic contact may have $S_b \sim 10^7$.

With the boundary conditions known, equation (6.6) can be solved and $J_n(x_d)$ found. This solution has been developed by others [7,18] and need not be repeated here. The final form, adapted to the structure in Figure 6.2 a) is as follows:

$$J_n = qN_m(1-R) \left\{ \frac{\alpha L_n e^{-\alpha x_d}}{\alpha^2 L_n^2 - 1} \right\} \cdot \left\{ \frac{S_b \left(\frac{L_n}{D_n} \right) \cosh \left[\frac{w_b}{L_n} \right] - e^{-\alpha w_b} + \sinh \left[\frac{w_b}{L_n} \right] + \alpha L_n e^{-\alpha w_b}}{S_b \left(\frac{L_n}{D_n} \right) \sinh \left[\frac{w_b}{L_n} \right] + \cosh \left[\frac{w_b}{L_n} \right]} \right\} \quad (6.10)$$

(A/cm²)

where $w_b = w_o - x_d - x_b$ is the width of the bulk region, $L_n = \sqrt{D_n \tau_n}$ is the bulk diffusion length and J_n , N_m , R and α are understood to be functions of λ .

The results of equations (6.5) and (6.10) for a set of wavelengths across the spectrum can be used in equation (6.4) to yield the theoretical external current efficiency, $Q_e(\lambda)$. A computer program (QEFF) was written to perform these calculations for any specified IL cell structure. The program generates $Q_e(\lambda)$ values at 20 nm intervals across the spectrum from 200 to 1200 nm. Reflection is calculated as in equation (6.1) and the optical parameters N_o , t_{air} , n_{Si} and α are taken from Figures 2.1 and 2.3. The external current efficiency is independent of the spectrum used (N_m cancels out in the equation for Q_e) but if the total current in equation (6.4) is integrated across the spectrum $N_m(\lambda)$, the short circuit current for the cell at that air mass will result.

The calculated $Q_e(\lambda)$ results for modelled cells are presented and compared with measured values for real cells in Chapter 7. With the results obtained in this section, the operation of IL cells under short circuit conditions can be adequately modelled. However, at non-zero voltages, some of the above assumptions no longer hold (for example, $n'(x_d)$ increases exponentially with applied voltage) and a more complex numerical solution becomes necessary.

6.4 Full One-Dimensional Modelling

When the voltage across the junction of a cell is allowed to take on non-zero values, the conditions within the depletion region begin to be important and more fundamental boundary conditions are

required. The true boundaries are the front and back of the silicon itself and the variation of electric field with the voltage becomes the controlling factor. Thus, full modelling of the hole concentration as well as that of electrons throughout the entire cell is necessary. As before, the continuity equation must be solved, but the solution is now considerably more involved.

The steady state continuity equation for holes is:

$$g(x) - \frac{1}{q} \frac{d}{dx} J_p(x) - R_e(x) = 0 \quad \text{cm}^{-3} \text{s}^{-1} \quad (6.11)$$

where $g(x)$ and $R_e(x)$ are, respectively, the generation and recombination rates at x and $J_p(x)$ is the hole current. In general, the current includes both drift and diffusion terms:

$$J_p(x) = -qD_p \dot{p}(x) + q\mu_p E(x)p(x) \quad \text{A cm}^{-2} \quad (6.12)$$

where $p(x)$ is the total hole concentration and $\dot{p}(x)$ is its first derivative in x . $E(x)$ is the electric field strength and D_p and μ_p are, respectively, the diffusion constant and mobility of holes in silicon. Both D_p and μ_p are assumed to be constant in x and equal to their bulk values which are dependent only on the impurity density, N_a . D_p and μ_p are related by Einstein's relation: $\mu_p = \beta D_p$; where $\beta = q/kT = 38.46 \text{ V}^{-1}$ at $T = 300\text{K}$. The generation rate in equation (6.11) is found by integrating equation (2.3) as follows:

$$g(x) = \int_0^{\infty} [1-R(\lambda)] \alpha(\lambda) N_m(\lambda) \exp [-\alpha(\lambda)x] d\lambda \quad \text{cm}^{-3} \text{s}^{-1} \quad (6.13)$$

using the air mass m spectrum and the reflectance, $R(\lambda)$. The recombination rate in equation (6.11) is given by Shockley-Read-Hall recombination theory [31]:

$$Re(x) = \frac{p(x) n(x) - n_i^2}{[n(x) + n_i] \tau_p(x) + [p(x) + n_i] \tau_n(x)} \quad \text{cm}^{-3} \text{s}^{-1} \quad (6.14)$$

where $n(x)$ is the total electron concentration, n_i is the intrinsic carrier density and $\tau_p(x)$ and $\tau_n(x)$ are the position dependent minority carrier lifetimes of holes and electrons respectively. In the bulk, under low level injection, $p(x) \gg n(x)$ and equation (6.14) simplifies to $Re(x) = n(x)/\tau_{nBULK}$. If equation (6.12) is inserted into equation (6.11), the result can be rearranged to yield:

$$p(x) = \beta E(x) \ddot{p}(x) + \beta \dot{E}(x) \dot{p}(x) + \frac{Re(x)}{D_p} - \frac{g(x)}{D_p} \quad \text{cm}^{-5} \quad (6.15)$$

where $\ddot{p}(x)$ is the second derivative of p and $\dot{E}(x) = \frac{d}{dx} E(x)$.

The equations for electrons are similar. The one-dimensional, steady state, electron continuity equation requires that:

$$g(x) + \frac{1}{q} \frac{d}{dx} J_n(x) - Re(x) = 0 \quad \text{cm}^{-3} \text{s}^{-1} \quad (6.16)$$

where the electron current is given by:

$$J_n(x) = q D_n \dot{n}(x) + q \mu_n E(x) n(x) \quad \text{A cm}^{-2} \quad (6.17)$$

Combining these two equations and rearranging yields:

$$n(x) = -\beta E(x) \dot{n}(x) - \beta \dot{E}(x) n(x) + \frac{Re(x)}{D_n} - \frac{g(x)}{D_n} \quad \text{cm}^{-5} \quad (6.18)$$

where $Re(x)$, $g(x)$ and $E(x)$ are the same as above and D_n is the diffusion constant for electrons.

The differential equations (6.15) and (6.18) must be solved to find $n(x)$ and $p(x)$ and hence, the current. Since an analytical solution is not possible due to the nature of $E(x)$, $g(x)$ and $Re(x)$, a numerical solution must be sought. The development of such a solution, using a finite differences technique is described in Appendix "D". Because two such equations are being solved, four boundary conditions are required: two for holes and two for electrons.

The electron boundary condition at the back surface is the one used in the preceding section, that is, an effective recombination velocity, S_b . While this is not a truly fundamental condition, it vastly simplifies the analysis. Also, the operation of the cell is relatively insensitive to conditions at the back surface and no sacrifice in accuracy is likely to arise through the use of S_b . The hole boundary condition at the front of the cell is even simpler. It is assumed that no surface recombination occurs so that $J_p(0) = 0$ since no holes cross the $x=0$ boundary. This assumption is supported by three arguments. Firstly, SiO_2 provides excellent passivation of silicon surfaces. and very low recombination velocities are typical ($S_f < 10$ cm/s) [31]. Second, the value of S_f is known to vary with the surface potential in such a way that, with a heavily inverted surface, S_f will be orders of magnitude below its midgap value [66]. Finally, with the high electric field in an IL cell, even moderately high ($\sim 10^4$ cm/s) recombination velocities have little effect on the hole concentration [18]. A non-zero value of S_f could be readily incorporated if it proved necessary.

The above two boundary conditions apply to electrons and holes as minority carriers. The remaining two conditions are for the majority carriers. Under the low level injection assumption, the majority carrier concentrations will be relatively unaffected by photogeneration and minority carrier collection. Thus, the unilluminated values provide the boundary conditions: $p(x) = N_a$ in the bulk (i.e. $p(x_d) = N_a$) and $n(0) = n_i \exp(u_s - u_{fp} + v)$ as in section 3.3 where N_a is the acceptor doping level and u_s , u_{fp} and v are the normalized surface, Fermi and bias potentials respectively.

The application of these boundary conditions to the solution of the continuity equations is explained in Appendix "D". The operation of the algorithm for finding the one-dimensional current flow for the structure in Figure 6.2 a) will be briefly outlined. First of all, the generation rate throughout the cell is determined, using equation (6.13), the $\alpha(\lambda)$ and $N_m(\lambda)$ data from Chapter 2 and the reflection coefficient, equation (6.1). For each bias voltage, the surface potential, electric field and its derivative are evaluated using the methods developed in section 3.3. Because the recombination rate in the depletion region depends on both $p(x)$ and $n(x)$, equations (6.15) and (6.18) must be solved iteratively. The finite differences algorithm described in Appendix "D" is used for each iteration. Fortunately, recombination within the depletion region is a relatively minor effect and two iterations usually suffice to obtain self consistent $p(x)$ and $n(x)$ distributions.

Once these are known, the current flowing in the cell could in principle be found directly with equations (6.12) and (6.17). However, this method is very sensitive to numerical errors. Typically, the drift and diffusion components of the current oppose each other so that any error in p or n is magnified in taking the difference. Also, the diffusion current requires that $\dot{p}(x)$ and $\dot{n}(x)$ be found and numerical differentiation further accentuates any errors. Thus, an error in p or n of 0.1% could readily become $\pm 10\%$ for a current calculated in this manner.

A less direct method, but one yielding more accurate results is to integrate the recombination rate throughout the cell and subtract the result from the known total generation rate. At steady state, the difference must of course equal the current flowing out of the cell. This technique integrates or averages any random numerical errors. Furthermore, in a normal cell at low voltages, the recombination rate is much smaller than the generation rate so that the error in the resultant current is further reduced. Hence, even localized errors of $\pm 10\%$ in p or n can be tolerated and excellent accuracy results. At higher voltages, the recombination rate approaches the generation rate and the current error increases. For negative currents (biases above the open circuit voltage), recombination exceeds the generation and the previous current calculation method may yield more accurate results.

The one-dimensional current need be determined at only a few voltages. Current-voltage points in between can be accurately found using exponential interpolation. Thus, the I-V curve for the structure in Figure 6.2 a) is found. To obtain the I-V curve which would be measured at the cell terminals, the grid geometry and other two-dimensional effects must be considered.

6.5 Modelling Two-Dimensional Effects

An inversion layer solar cell is not the simple one-dimensional device shown in Figure 6.2. Since the grid metal does not cover the entire cell, collected electrons from the bulk must flow along the inversion layer to a grid finger and then through the metal to the contact pad. This horizontal current path introduces an appreciable series resistance which must be taken into account if the cell is to be accurately simulated.

Fortunately, in any well designed IL cell, vertical collection dominates since all points in the inversion layer will have approximately the same bias. Lateral current flow is restricted to majority electrons within the inversion layer. Hence, the results of the one-dimensional model can be used as a starting point for a two-dimensional model. The model chosen consists of three parts as shown in Figure 6.3 a): current flow through the inversion layer to the grid finger, flow along the grid finger and flow along the bus bar to the contact pad.

The first step involves the area in the figure enclosed by the dashed rectangle. In this region, it is assumed that the current $I(y)$ flows perpendicularly to the grid finger and is independent of the distance z along the finger. This is clearly not true near the bus bar where the current may flow directly to the bus bar in the z direction. However, since the grid fingers are typically much longer than the separation between them, negligible error arises in making this assumption. Hence, the area shown can be modelled by a series of identical one-dimensional slices connected via the inversion layer to the grid finger. This arrangement is depicted schematically in Figure 6.3 b).

Fig. 6.3 a) Modelled current paths in an inversion layer cell.

b) Lumped element, two-dimensional model of current flow through the inversion layer toward grid finger.

Each of the vertical slices through the cell can be thought of as a current source in parallel with a diode as shown in Figure 2.5 a). Except for the factor γ , each slice is characterized by the $I(V)$ relationship determined from the one-dimensional model described in the preceding section. In the one-dimensional solution, there is a distribution of excess electrons in the bulk. The same model would predict no excess electrons under the grid finger where the generation rate is zero. Clearly, some of the excess electrons will diffuse laterally under the grid finger to fill the void and will not be available for vertical collection. Since this effect is relatively small and would be difficult to model accurately, it was decided to approximate it with the redistribution factor γ .

Carriers generated close to the junction and far from the grid finger have a negligible chance of lateral collection. Those generated at the edge of the grid finger, however, have an even chance of being collected under it. The probability of lateral collection from a point (x, y) (y is the distance from the grid finger) was therefore assumed to be $0.5 \exp(-y/x)$. By integrating the AML generation rate, weighted by this probability, across x for a representative cell geometry, an estimate of $\gamma(y)$ was determined.

The results were found to fit the following simple expression:

$$\gamma(y) = 1 - .35 \left[\exp\left(-\frac{\sqrt{y}}{L}\right) - \exp\left(-\frac{\sqrt{y + w_f}}{L}\right) \right]; L \approx 9.2 \left(1 - \frac{23}{w_o}\right) \quad (6.19)$$

where all distances are in micrometers. The term with the grid finger width, w_f enters the expression because some excess electrons will diffuse under the grid finger from the other side ($y < 0$).

Examination of equation (6.19) indicates that γ deviates appreciably from unity only when y is within about 50 μm of the grid finger.

The laterally diffusing electrons are not all lost, but may be collected at the contact junction under the grid finger, giving rise to the lateral collection current I_{lc} shown in Figure 6.3 b). Some electrons will be lost to recombination during lateral diffusion, and a simple diffusion length model is assumed to represent this effect. I_{lc} will therefore be the sum of the missing currents, weighted by recombination:

$$I_{lc} = \sum_{n=1}^N (1-\gamma_n) I(V_n) \exp\left[-\frac{y_n}{L_n}\right] \quad (6.20)$$

where y_n is the lateral distance from the n 'th slice to the grid finger and L_n is the electron diffusion length (in μm). Again, it should be stressed that this redistribution phenomenon is a second order effect so that any errors arising from the simplistic treatment of it should be insignificant.

In Figure 6.3 b), the resistors R_k ; $k=1$ to N represent the inversion layer sheet resistance given by equation (3.4) and are thus, dependent on the voltages V_k . The algorithm for solving the circuit in Figure 6.3 b) proceeds as follows. A value of V_N , slightly below the open circuit voltage of the one-dimensional model, is chosen. The current I_N is found by exponential interpolation of the one-dimensional $I(V)$ data. R_N is evaluated as a function of V_N and $V_{N-1} = V_N - I_N R_N$ is calculated. The algorithm continues along the string, adding I_k at each node V_k until the current from the active cell area, I_1 is found.

Several effects are modelled at the contact, under the grid finger. The redistributed lateral collection current, I_{lc} is added. The contact diode itself is forward biased by V_o and a parasitic injection current, I_{inj} flows. Theoretically, I_{inj} is given by:

$$I_{inj}(V_o) = \text{Area} \left[I_o \exp\left(\frac{qV_o}{A_o kT}\right) + I_1 \exp\left(\frac{qV_o}{A_1 kT}\right) \right] \text{ Amperes} \quad (6.21)$$

$$\text{where } I_o = \frac{qn_i^2}{N_a} \sqrt{\frac{D_n}{\tau_n}}, \quad I_1 = \frac{qx_d n_i}{\tau_p + \tau_n} \text{ A cm}^{-2} \text{ and } A_o = 1, A_1 = 2.$$

Area is one half the grid finger contact area, x_d is the depletion width and τ_p is the hole lifetime in the depletion region. The expression for I_1 is a simplification of the result of the Sah-Noyce-Shockley space charge recombination theory [67]. This simplification produces no appreciable error since the second term in equation (6.21) is relatively small at normal light intensities.

The theoretical equation for I_{inj} is accurate for good MIS contacts [14,42]. Most diffused contacts also exhibit a double exponential I-V relationship, but with different values for I_o , I_1 , A_o , A_1 . This non-ideality is usually attributed to lattice damage created during diffusion and as such cannot be accurately predicted by theory. Thus, empirical values for I_o , I_1 , A_o and A_1 must be used if the simple theory is not adequate. The IL cell model has provision for either type of junction. When I_o , I_1 , A_o , A_1 are known, they can be employed. Otherwise, the theoretical values are used by default. Experience has shown that there is very little difference in the I-V curves calculated using the two contact models.

For the electrons to enter the grid metal, they must pass through the contact resistance R_c . This is simply the contact resistivity, ρ_c ($\Omega\text{-cm}^2$) divided by the same Area as used in equation (6.21). For a diffused contact, ρ_c is usually small; typically less than $.030 \Omega\text{-cm}^2$ depending on the metal and the sintering process used [57,58]. In a cell with MIS contacts however, ρ_c may be higher due to the intervening thin oxide [42,43]. This is the only difference (from a modelling point of view) between the two types of contact. Thus, one model can be used for both diffused and MIS-IL cells.

Once the grid finger is reached and a single I-V pair has been calculated, V_N is decremented and the process repeated for the next I(V) point. In this way, the entire I(V) curve can be generated. If the points are closely spaced, linear interpolation will suffice for finding I(V) between the calculated values.

The resistive loss through the grid finger can be modelled by a single lumped resistance. The derivation of the value of this resistance is the same as that used in Appendix "A" to derive equation (3.9). Thus, the effective resistance is that of one third the grid finger length, l_f . Since the model in Figure 6.3 considers only half the area serviced by the finger, only half the finger width, w_f should be used in the calculation. The effective grid finger resistance is therefore:

$$R_f = \rho_m \frac{2 l_f}{3 w_f} \quad \Omega \quad (6.22)$$

where ρ_m is the metal sheet resistance (typically .005 to .04 $\Omega/\square$) which depends on the metallization process.

Another resistance which may be considered at this time is that of the p-type substrate. For the dashed Area indicated in Figure 6.3 a) and the bulk thickness w_b , the substrate resistance is given by:

$$R_{\text{sub}} = \frac{w_b}{\text{Area}} \rho_b \quad \Omega ; \quad \rho_b = \frac{1}{q\mu_p N_a} \quad \Omega\text{-cm} \quad (6.23)$$

where ρ_b is the substrate resistivity and μ_p is the mobility of holes in the bulk. To correct for these losses, $I(V) (R_f + R_{\text{sub}})$ is subtracted from each of the voltage values calculated above. For convenience, the current values are normalized to one square centimeter by dividing by the same Area used in equation (6.22).

The losses associated with the bus bar and current flow to the contact pad are modelled next. The grid pattern assumed for this purpose is shown in Figure 6.4 a). Although the geometry is considerably different from that shown in Figure 4.2, it is easier to describe mathematically and its use should cause no serious errors. M pairs of grid fingers are attached to the bus bar which widens linearly to a width w_c at the bonding pad. Each grid finger pair services an area as shown inside the dashed line in Figure 6.4 a). The I-V curve for each finger pair is the one developed in the last paragraph, adjusted for this area.

The schematic for the bus bar model appears in Figure 6.4 b). Each of the M grid areas is represented by an $I(V_m)$ section in parallel with a bus bar segment. Each segment is comprised of a contact resistance, a parasitic contact diode and a substrate resistance. The

Fig. 6.4 a) Modelled grid geometry.

b) Schematic of model for bus bar losses.

characteristics of these three elements are the same as described above for the grid finger except that the area is different for each segment of the bus bar. The principal loss along the bus bar is due to the voltage dropped through the metal sheet resistance. This is modelled by the resistors R_{bm} which are determined by the bus bar geometry.

At the contact pad, a peripheral fringing current is added. The purpose is to model the leakage of photocurrent from outside the edge band of the cell. Because there is no grid pattern in the peripheral region, the induced junction here will be biased at the open circuit voltage. Leakage to the main cell occurs via R_p , the inversion layer resistance encountered under the edge band. Because R_p will be large (on the order of 1500Ω for each centimeter of cell perimeter), this model should be sufficient to predict the increase in short circuit current due to peripheral collection. In a production cell, there would be no area outside the cell and fringing currents would not be a problem. This situation is modelled by setting the width of the edge band, w_e very large so that R_p becomes effectively infinite.

The final $I_{out} - V_{out}$ curve for the entire modelled cell is found in exactly the same fashion as for the model in Figure 6.3. V_M is set slightly below V_{oc} and I_M found by subtracting I_{inj} from $I(V_M)$. I_{inj} must be solved iteratively as the voltage across the parasitic diode depends on the voltage dropped across the two resistors R_c and R_{sub} . Once I_M is known, V_{M-1} can be found and another current added. At V_{out} , the peripheral current, I_p is added, giving one $I_{out}(V_{out})$ point. V_M is then decremented and the process repeated. With suitable choices of V_N , twenty or thirty $I_{out} - V_{out}$ pairs can be generated, spanning the entire curve from V_{oc} to I_{sc} . In this manner, the measured cell output curve is simulated.

6.6 Use and Limitations of the Model

In its present form, the inversion layer solar cell model is a computer program, named ILSCEL, written in simple FORTRAN. The model incorporates most of the theory developed in this chapter. A complete listing of the program, along with its data file and a sample run are given in Appendix "E". Comment lines within the program are provided to help decipher its operation and interpret the data values. The algorithm will be described briefly.

Initially, the one-dimensional cell is defined by its structural and semiconductor parameters which occupy the first two lines of the data file. The operating conditions (air mass, concentration factor and cell temperature) are then specified and the electronic constants evaluated (n_i , β , intrinsic Debye length, etc.). Next, the optical data (refractive index, absorption coefficient, air mass zero spectrum and air transmissivity) are read in for wavelengths spaced every 20 nm from 1200 to 200 nm. From these, the reflection coefficient is found, allowing the generation rate throughout the cell to be determined.

For each bias voltage, Poisson's equation is solved to find the potential, the electric field and its derivative in the depletion region. At the same time, the x-axis (distance into the cell) is quantized into discrete x_i points extending through the bulk. After setting the initial approximations for p and n at each x_i in the depletion region, the finite difference algorithm developed in Appendix "D" is applied and iterated to solve for p(x) and n(x) throughout the entire one dimensional cell. Once these distributions are known, the recombination rate is integrated across the cell thickness. This rate is subtracted from the total generation rate to obtain the current flowing at that voltage.

When the current has been found at several bias points and the exponential interpolation parameters have been determined, the one-dimensional I-V curve is complete. The last section of the program models the two dimensional parasitic effects in the inversion layer, contact regions and grid metal. The final output of the program is a set of current voltage pairs which define the I-V output curve of the modelled cell. The output power at each point is also determined.

A printout of the results at any stage in the program can be obtained by setting output flags in the data file. If all the flags are set, a wealth of information is produced: optical generation rate, electric field strengths, $p(x)$ and $n(x)$ distributions and the one dimensional I-V curve. If none of the flags is set "true", only the final $I_{out} - V_{out}$ curve is printed.

An important consideration in any numerical model is the number of discrete slices into which the structure must be divided. If the division is too coarse, the results will be inaccurate. If the structure is divided too finely, the program execution will be slow and the accumulated numerical errors will become significant. Ideally, the division is such that the results are insensitive to small changes in the size of the slices. In ILSCEL, the spatial quantization of the x axis into an x_1 array is controlled by the model parameter, N_s .

The distance from the front surface to the junction, x_j is divided into N_s slices. The remaining depletion region ($x_j < x < x_d$) is partitioned into roughly half this number. The remainder of the cell (the bulk) is divided into about N_s slices. The exact number of slices in each section depends on the cell structure and bias voltage. For $N_s = 100$, the thickness of the slices varies from ~3 nm at the front surface to ~10 μm

at the back. This basis for partitioning the structure was chosen by trial and error.

When $N_s \leq 20$, the program either will not run due to an execution error or produces meaningless results. At $N_s \geq 50$, the results are more reasonable but still sensitive to small changes in N_s . For $N_s = 100$ to 200, accurate and essentially constant results are obtained. At $N_s \sim 250$, the execution becomes too slow and numerical precision problems start appearing at higher values. Thus, the program is usually run with $N_s = 100$ or 150.

Quantization of the cell surface (y-z plane in Figure 6.3 a) can be much coarser. This is because the two-dimensional effects act only to modify the one-dimensional results. Thus, only ten slices are used to model the inversion layer (N in Figure 6.3 b), while five segments suffice for the bus bar (M in Figure 6.4 b). No significant change results from the use of finer divisions. Also, breaking up the spectrum into 20 nm slices appears to be adequate for calculating the reflectance and generation rate. Only in a structure with a very thick ($\geq 1 \mu\text{m}$) oxide would a finer partitioning be necessary.

The choice of voltage points for calculating the one-dimensional current is left to the user. Bias voltages are read from the data file (after the optical parameters) as fractions of an internally-estimated open circuit voltage. As there is little change in current up to about 75% of V_{oc} , the voltage points are not equally spaced. A final voltage above V_{oc} is selected to allow the algorithm to stop when a negative current is calculated. When the structural parameters or operating conditions of the cell approach the limits imposed by the underlying assumptions (for instance, low level injection), the voltage fractions must be chosen carefully to obtain reasonable results.

To make the model as theoretically accurate as possible, most of the semiconductor parameters are calculated within the program as functions of the operating temperature. These include the carrier mobilities, lifetimes in the depletion region, the intrinsic carrier density and the thermal voltage. Models for these and other parameters are presented in Appendix "D". The models are based on accepted theory or empirical fitting of published data [27,28,31,49].

Considering the complexity of the algorithm, the program runs relatively quickly and cheaply. A complete $I_{out} - V_{out}$ simulation, based on five one-dimensional bias voltages, can usually be obtained for less than \$1.00 in computer "resource units" on the Honeywell Sigma 9 computer at Carleton.* The execution time is always less than the standard 30 seconds allotted for time-share users. This is a considerable improvement over one previously published model for diffused solar cells [63], indicating that the techniques used here may have broader applications. The program ILSCEL is also easy to use. The operator chooses which printout flags to set and selects 19 parameters which define the cell structure and operating conditions. The program can then be run without knowing how it works. Finally, much of the program can be readily modified if special structures or operating conditions are to be modelled.

* \$1.00 in computer resource units is equivalent to 30 seconds of CPU time, 40 minutes of terminal connect time, or about 40 pages of printout.

As with any complex numerical algorithm, ILSCEL has limitations. Some error or uncertainty will always be present and the program will not work for all conceivable combinations of structural parameters. Some of the error arises from the theory since it is a mathematical model of reality. Also, with the finite difference algorithm, some approximation and numerical error is inevitable. For a typical IL cell structure, this minimum uncertainty seems to be about $\pm \frac{1}{2}\%$ in the $I_{out} - V_{out}$ data.*

This uncertainty increases when the structural parameters approach their limits. The program is most sensitive to low values of bulk lifetime, τ_n . This is because the back surface boundary condition is used to find the electron concentration at the junction. As the lifetime is reduced, the relationship between the two positions becomes increasingly tenuous. Closely linked to this sensitivity are the bulk doping level, N_a which affects τ_n and the cell thickness, w_o . In general, the uncertainty seems to increase from a minimum of $\pm \frac{1}{2}\%$ inversely with τ_n^2 and directly with w_o . Thus, a typical simulation with $w_o = 300 \mu m$ and $\tau_n = 10 \mu s$ will be well behaved, while another with $w_o = 1000 \mu m$ and $\tau_n = 1 \mu s$ may not run at all. As a rule, if w_o is less than three or four diffusion lengths, $L_n = \sqrt{D_n \tau_n}$, the model works well.

Other limitations are imposed by the breakdown of the assumptions stated in section 6.1. For example, at AM1, as N_a is reduced below

* In the sense used here, "uncertainty" is a measure of the variation in results caused by infinitesimal changes in one or more of the input parameters (notably N_a). This should represent the error between the numerical solution and a hypothetical "exact" solution. It should not be confused with the difference between the real and the modelled I-V curves.

$\sim 10^{14} \text{ cm}^{-3}$, the low level injection assumption no longer applies.

Similarly, as the oxide charge is reduced for a given N_a , the surface becomes less heavily inverted. The program cannot handle weak inversion ($u_s \leq 2 u_{fp}$) and will not run under such conditions. Finally, since the algorithm computes total hole and electron concentrations, these must differ significantly under illumination from their equilibrium levels. Thus, the model is unreliable for light levels below about 5% of AM1.

Fortunately, the program works well for most practical IL cell structures. Values of N_a from 10^{14} to 10^{17} cm^{-3} , τ_n from 0.4 to 400 μs and w_o from 20 to 1000 μm have been successfully modelled, though not all combinations within these bounds will work. Providing they have reasonable values, the remaining device parameters have little effect on the accuracy of the results.

6.7 Modelling Lateral Collection

The methods developed above work well for modelling the inversion layer solar cell and, with some modification, could be applied to any device in which vertical collection dominates. For any type of grating solar cell, however, the one-dimensional solution is clearly inadequate and some form of two-dimensional model is required to manage the lateral collection. Since the accumulation layer solar cell (described in Chapter 3) is the best understood of the surface effect devices which operate by lateral collection, it will be used to illustrate the modelling concepts.

The two-dimensional structure of an accumulation layer cell is depicted in cross section in Figure 6.5 a). The region to be modelled occupies the space from the centre-line of one grid finger to the point halfway to the next finger ($0 \leq y \leq y_N$). The solution will clearly be symmetric about these two boundaries. This means there is no net carrier flow across them and the "effective recombination velocity" is $S = 0$ at $y = 0, y_N$. The back surface, x_M can also be characterized by an effective recombination velocity, S_b as in equation (6.8), substituting parameters for n-type silicon. If the front surface is heavily accumulated, there will be a strong electric field to prevent the surface recombination of holes. Furthermore, this field will extend only to a very shallow depth (typically $\sim 0.1 \mu\text{m}$). Thus, the electric field can be ignored, and the front surface approximated simply by $S_f = 0$ for collection purposes.

In principle, the current flow at the junction could be found by solving the two-dimensional steady-state continuity equation. In the absence of an electric field, the flow of excess holes, $p'(x,y)$ is diffusion controlled and the continuity equation is given by:

$$D_p \nabla^2 p'(x,y) + g(x,y) - \frac{p'(x,y)}{\tau_p} = 0 \quad \text{cm}^{-3} \text{s}^{-1} \quad (6.24)$$

where D_p and τ_p are the diffusion constant and lifetime for holes in the n-type bulk and $\nabla^2 = \frac{d}{dx^2} + \frac{d}{dy^2}$ is the two-dimensional Laplacian. The generation rate, $g(x,y)$ is independent of y except that it is zero under the grid finger. Equation (6.24) cannot be solved analytically with the appropriate boundary conditions. Similarly, a numerical solution like that developed in Appendix "D" for the one-dimensional structure

Fig. 6.5 a) Two-dimensional cell structure showing section to be considered in modelling lateral collection.

b) Simple two-dimensional diffusion problem in circular coordinates.

would be far too cumbersome in two dimensions even if simplifications were made. Therefore, another approach must be sought.

One way to find the current collected at zero bias is to find the collection from a point source at (x,y) and then apply the superposition principle to integrate the contributions from all (x,y) points where generation occurs. However, even with a point source, the solution of equation (6.24) is difficult. The simplest problem of this nature is to find $p'(x,y)$ for a point source at the centre of an infinite plane. This problem becomes one-dimensional if it is transformed into circular coordinates, (r,θ) as depicted in Figure 6.5 b). The continuity equation for this problem is given by [68]:

$$\frac{\partial^2 p'(r)}{\partial r^2} + \frac{1}{r} \frac{\partial p'(r)}{\partial r} = \frac{p'(r)}{L_p^2} \quad \text{cm} \quad (6.25)$$

where r is the distance from the source and $L_p^2 = D_p \tau_p$. Even this equation appears to have no analytical solution. The solution, $p'(r)$ must, of course, exist and would be similar to that shown in Figure 6.5 b), but it is in the form of an infinite series in r . Since this simple problem has no straightforward solution, it was decided not to pursue this approach for the more difficult solar cell geometry.

The second method considered was a matrix relaxation model.

In this technique, the diffusion of holes to satisfy the continuity equation is directly simulated. As illustrated in Figure 6.6 a), the modelled region is broken up into a two-dimensional matrix of small blocks or elements. Each element has an excess hole concentration $p'_{i,j}$. The cell operation is simulated by considering the change in each element

Fig. 6.6 a) Two-dimensional matrix-relaxation model.

b) Transient response showing slow approach to steady state short circuit current flow.

during a time interval δt . The diffusion of holes into or out of an element depends on the values of p' in the four neighbouring elements and the distances between their centres. In addition, there is a known generation rate and a recombination loss of $\delta t \cdot p'_{i,j} / \tau_p$. The boundary conditions are readily incorporated into this relaxation procedure. If the matrix of discrete points is made fine enough, it should accurately mimic the $p'(x,y)$ distribution and the collection of holes at the junction. Starting with $p'(x,y) = 0$ at $t = 0$ as an initial condition and using a constant generation rate, repeated relaxation of the $p_{i,j}$ matrix should produce the transient response of the cell as shown in Figure 6.6 b). After several τ_p periods, the solution should approach steady state, allowing the short circuit current to be evaluated.

Such a model was realized in the form of a computer program. The relaxation algorithm was easily implemented and the generation rate was determined by the methods described in section 6.2. The junction was initially modelled as an ideal minority carrier sink ($p'(0,y) = 0$; $y_1 \leq y \leq y_2$). Although the model worked, it soon became apparent that it was far too slow. To avoid oscillating solutions, the time interval,

δt had to be very small; $\delta t < \tau_p \left[\frac{\delta x, y}{L_p} \right]^2$; where $\delta x, y$ is the smallest

element dimension and L_p is the diffusion length for holes. Thus, even for a coarse array (10 x 15 elements), several hundred relaxations were required to reach one lifetime τ_p . The execution time limit imposed by the Sigma 9 system was reached long before steady state was achieved. Since an accurate model would require a much finer grid (about 30 x 50 elements) and would be evaluated for several voltage biases, an excessive

amount of execution time (several hours) would be required to model one structure. Hence, this method was also abandoned. This approach could best be implemented using an array processor. Alternately, a more sophisticated relaxation algorithm could, perhaps, allow larger δt intervals to be used for faster execution.

Since finding a true two-dimensional solution proved to be such a formidable task, it was decided to approximate the solution using one-dimensional theory and superposition. In this method, illustrated in Figure 6.7 a), carriers generated at a point x,y are assumed to flow only toward or away from the junction, along the w axis. The "depth", $W(x,y)$ of this one-dimensional slice can be readily determined from its geometry. The distribution of excess holes, $p'(w)$ will resemble that shown in Figure 6.7 b). The current collected from the generation at (x,y) is determined from the slope of $p'(w)$ at the junction as indicated in the figure. The total current is obtained by integrating across all values of x,y as follows:

$$J_p = \int_0^{w_b} \int_{\frac{w_f}{2}}^{\frac{1}{2N_f}} J_p(x,y) dy dx \quad \text{A cm}^{-2} \quad (6.26)$$

where w_f is the grid finger width and w_b is the thickness of the bulk silicon. N_f is the number of grid fingers per centimeter.

The current collected from the point x,y can be found using the same theory which provided equation (6.10). For a point source, however, the solution is simpler. The steady state hole distribution $p'(w)$ around a point source $g(0)$ on an infinite line is given by [31]:

Fig. 6.7 a) Use of one-dimensional slices to approximate the two-dimensional structure.

b) One-dimensional model for collection from point (x,y).

$$p'(w) = \frac{g(0) \tau_p}{2L_p} \exp \left[-\frac{|w|}{L_p} \right] \text{ cm}^{-3} \quad (6.27)$$

A novel way of applying the boundary conditions at the junction and $W(x,y)$ is to treat these two ends as electronic "mirrors" which "reflect" the excess hole distribution back upon itself. For this purpose, a hole reflection coefficient is defined in the following manner:

$$R = \frac{\frac{D_p}{L_p} - S}{\frac{D_p}{L_p} + S} \quad (6.28)$$

where S is the relevant surface recombination velocity. Thus, at the junction, S_J approaches infinity (all holes reaching the junction are collected) and $R_J = -1$. This indicates that $p'(0) = 0$ which is the usual form for the junction boundary condition. An ideal back surface field will have S_b close to zero so that $R_b = +1$ and $\frac{dp'(w)}{dw}$ at $W(x,y)$ will be zero as expected for a BSF cell. When the "optics" of this two mirror system are considered, the $p'(w)$ distribution shown in Figure 6.7b) results. The same distribution would be found using conventional means for solving the continuity equation.

Once $p'(w)$ is known, the collected current can be found as the diffusion of holes across $w=0$. For the geometry depicted in Figure 6.7 b), the analysis produces the following expression:

$$J_p(x,y) = q \frac{g(x)}{2} (1-R_J) \left\{ e^{-w'/L_p} + \left[R_J e^{-w'/L_p} + e^{w'/L_p} \right] \sum_{n=1}^{\infty} R_b^n R_J^{n-1} e^{\frac{-2nW(x,y)}{L_p}} \right\} \quad (6.29)$$

where $w' = \sqrt{x^2 + y^2}$. For numerical purposes, the infinite series summation converges rapidly.

A simple algorithm based on these concepts was written to model lateral collection solar cells. The integration in equation (6.26) was done numerically. For each discrete x, y point, $W(x, y)$ and w' were found and equation (6.29) evaluated using the same generation rate as in the previous models. For non-zero bias voltages, the simple model shown in Figure 2.5 a) was employed. The contact diffusion was modelled by equations (2.4) and (2.5), with allowance made for the reduced junction area. A single, lumped series resistance was assumed and its value estimated from the grid geometry.

Clearly, this is an overly simplistic model since it is not two-dimensional in nature. The assumption of no diffusion perpendicular to the w axis is highly questionable. Current crowding near the contact will distort $p'(w)$ and reduce the collection. Similarly, injection from the narrow junction will be two-dimensional. Finally, no allowance is made for the high level injection effects which are likely to occur near the contact even at normal light intensities due to the decreased junction area. Taken together, these effects are likely to cause the model to predict optimistic results: higher short circuit currents and open circuit voltages than could be expected for a real device. The amount of error would depend on the width of the junction in relation to the grid finger spacing.

Despite these deficiencies, the model was used to compare lateral and vertical collection devices. The results are presented in Chapter 8 with the understanding that they are somewhat biased in favour of the lateral collection cell. For comparison purposes, the vertical

collection cell was modelled using the same simple methods reduced to one dimension, x . This should improve the validity of the comparison since some of the simplifications will be common to both devices.

6.8 Conclusions

With the techniques described in this chapter, most of the characteristics of inversion layer cells can be theoretically predicted. The theory is not simple however, and complex analysis, requiring numerical solutions and computer programs, was necessary to obtain an accurate model. The program ILSCEL accounts for most of the effects occurring in solar cells and thus, should be successful in simulating their behaviour. Although this model is specific to the IL solar cell, many of the concepts and results can be applied to other vertical collection devices.

The formidable difficulties involved in attempting to develop a true, two-dimensional model have been demonstrated. A simple quasi-two-dimensional model of lateral collection has been achieved, but only with a loss of confidence in the results. The model is based on a novel approach to solving the continuity equation.

The accuracy of the IL cell models is tested in the following chapter, where their predictions are compared with measured results for real solar cells. The true power of computer modelling is demonstrated in Chapter 8 where the models are used to explore the potential of surface effect cells.

CHAPTER 7

EXPERIMENTAL AND THEORETICAL RESULTS

The only valid method of evaluating a new solar cell concept is to make a device, see how well it works and compare it with other cells. In this chapter, the experimental and theoretical results for inversion layer cells are presented and compared to determine how well the cells operate, how closely the models developed in Chapter 6 can predict the cells' response and how the IL cell compares with conventional, diffused cells.

Most of the results are presented in the form of graphs which either display the measured and modelled characteristics together or compare measured values for different types of cells. A discussion accompanies each of the figures, giving added information, analysis and reasons for apparent discrepancies. The first section considers the operation of real IL cells. The following two sections deal with the optical characteristics and current-voltage relationships respectively, for both modelled and real cells. The model ILSCEL is used in the last section to investigate the internal operation of inversion layer cells.

7.1 Measured IL Cell Characteristics

The most important characteristic of a solar cell is its illuminated current-voltage output curve. Figure 7.1 shows a family of I-V curves for an IL cell measured at several light intensities. This device was fabricated using the process outlined in Figure 4.5. The I-V test circuit in Figure 5.3 a) was used to obtain the curves.

Fig. 7.1 I-V output curves for an inversion layer solar cell under different light intensities, showing inadequacy of simple theory, and method for measuring series resistance.

The cell was mounted on a small circuit board with its entire surface exposed to the light. The light intensity was set at arbitrary (unmeasured) levels, hence the uncertainty in labelling the top curve "AM1". The cell exhibits a respectable short circuit current and open circuit voltage. The curves have a good shape and fair values of fill factor. From measurements made in AM 1.46 sunlight, the active area efficiency of this cell was estimated to be $\eta = 10.5\%$.

The ideal solar cell I-V curve, given by equation (2.4) with the same short circuit current, is included in Figure 7.1 for comparison. The difference between the two indicates why a more sophisticated model is required. Most of this difference can be attributed to the cell's series resistance, R_s , which can be estimated from the measured curves as illustrated in the figure. It can be readily demonstrated that the slope of the line joining the points $I = I_{sc} - \Delta I$ for any reasonable value of ΔI will be the negative reciprocal of R_s [62]. The value obtained in this manner from Figure 7.1 is $3.9 \pm .1 \Omega$. This represents the resistance of one quadrant of the cell since the current axis has been normalized to a cell area of 1 cm^2 .

The series resistance can also be estimated theoretically. Using the grid geometry from Figure 4.2 and equations (3.4) to (3.9), the inversion layer resistance is found to be $R_{IL} = 1.8 \Omega\text{-cm}^2$. The oxide charge density in the calculation was determined by C-V analysis. The geometry and measured sheet resistance of the front contact grid yield a value of $1.6 \Omega\text{-cm}^2$ for the metal resistance. The bulk resistance of the $10 \Omega\text{-cm}$ substrate, $270 \mu\text{m}$ thick is $0.27 \Omega\text{-cm}^2$. Adding these values gives a total series resistance of $3.7 \Omega\text{-cm}^2$, in very good agreement with the measured value. The slight difference may be due to the

aluminum-silicon contact resistance which is difficult to estimate or measure.

As described in section 5.2, the diode properties of a solar cell can be investigated by plotting the short circuit current versus the open circuit voltage for a wide range of illumination levels. Such an $I_{sc} - V_{oc}$ curve for the same cell as above is plotted in Figure 7.2. The active area was kept constant during the measurements by means of an aperture. The measured curve fits the ideal, one-sided diode theory quite well at normal intensity levels. The diode factors A_1 and A_2 are close to their ideal values, indicating that the induced junction operates as expected. Much of the departure from ideality at low current levels can be accounted for by the presence of the diffused contacts in parallel with the induced junction. At high current levels, cell heating reduced V_{oc} slightly. At the highest intensities, the series resistance begins to affect I_{sc} , causing it to drop below the photocurrent, I_L .

According to the Sah-Noyce-Shockley model, the space-charge-recombination dominated portion of the curve should occur at much lower current levels than exhibited in Figure 7.2 [67]. Thus, it is apparent that a more complex recombination process is occurring at low voltages. Such behaviour is characteristic of diffused junctions, implying that the contact regions dominate the injection at low values of forward bias.

Further evidence of this is presented in Figure 7.3 where the dark I-V curve of a diffused diode is plotted (dotted line). The device is the test diode shown in Figure 4.2. Since a different cell was used, quantitative comparison with Figure 7.2 is impossible. The oxide around the diode was etched off prior to testing to isolate the

Fig. 7.2 Illuminated $I_{sc} - V_{oc}$ curve for an inversion layer solar cell.

Fig. 7.3 Dark I - V curves for diffused, MIS and theoretical contact diodes.

diffusion from the surrounding inversion layer, thus ensuring a constant injection area at all current levels. As can be seen, the curve is far from ideal. The high values of A_1 and A_2 are usually attributed to crystal defects and impurities introduced during the high temperature diffusion.

For comparison, the curve for an MIS contact is included in the figure (solid line) [42]. It is much closer to ideal. In the absence of defects and impurities, the junction operates according to simple theory. However, some differences still remain, especially at low current levels where the recombination theory fails to predict the behaviour. Even though the measured curves are quite different in this region, the effect on solar cell output will be minimal since a poor diode factor causes only a slight reduction in fill factor. At the normal operating point, all three curves are fairly close together.

The distortion due to series resistance is much more evident in the dark I-V curves shown in Figure 7.3 than in the $I_{sc} - V_{oc}$ curve in Figure 7.2, notwithstanding the higher resistance of the complete cell. This demonstrates the superiority of the illuminated $I_{sc} - V_{oc}$ technique for characterizing solar cells. Also, the series resistance effect is more pronounced in the MIS contact than in the diffused one. This indicates that MIS diodes may have a higher contact resistance than diffused ones.

One final way of directly examining the induced junction is through C-V analysis. Using the circuit shown in Figure 5.2, the capacitance-voltage characteristics for the MOS test capacitors on several of the IL cell wafers were measured. The C-V curve for one such capacitor

is shown in Figure 7.4. The oxide around this particular device was etched off prior to testing. If the capacitor had not been isolated from the surrounding inversion layer in this way, the strong inversion portion of the curve ($u_s > 2 u_{fp}$) would be slightly distorted due to fringing effects. For the rest of the curve the peripheral inversion layer has no effect so that the results of C-V analysis of non-isolated capacitors should be valid.

Using the program CEEVEE, developed from the theory in Chapter 3, and the measured oxide thickness and substrate doping, the theoretical C-V curve for this capacitor was calculated (dashed curve in Figure 7.4). By adjusting the flatband charge, Q_{fb} and the interface state density, N_{ss} , a good fit was obtained to the measured curve. Not all the measured curves could be fitted this closely, but accurate Q_{fb} values could almost always be determined.

In the absence of a metal gate, the oxide-silicon system will be biased at zero volts and therefore, will be in strong inversion. Thus, Figure 7.4 directly shows the presence of an induced junction. The good agreement between the theoretical and measured C-V curves is further evidence that the junction is operating correctly. The small differences between the two can be ascribed to uncertainties in the device parameters and the fact that N_{ss} is not constant (as assumed in the theory), but varies with the surface potential, u_s [51]. With the exception of the TiO_x coated wafers, all the devices tested by this technique were strongly inverted. However, there was great variation in Q_{fb} and N_{ss} as indicated in Figure 4.4. The Q_{fb} values measured were typically lower than expected, different from wafer to wafer and, in general, not reproducible. Fortunately, cells with low oxide charge densities still function, but with lower fill factors.

Fig. 7.4 Measured capacitance-voltage curve for an MOS test capacitor and the best-fit theoretical curve used to determine Q_{fb} and N_{ss} .

The above figures explicitly demonstrate how ideal the induced junction is when operated in isolation. This is one of the advantages of the inversion layer approach: the structure is simple and can be accurately described by theory.

7.2 Spectral Characteristics

The most revealing test of how well a solar cell structure operates as a photovoltaic collector is the measurement of its spectral response or external current efficiency, $Q_e(\lambda)$ over the entire spectrum. Although, as indicated in Chapter 5, measurement of $Q_e(\lambda)$ can be difficult and time consuming, it yields a wealth of information on the one-dimensional operation of the solar cell. It is thus, an excellent diagnostic tool when coupled with an accurate method for theoretically predicting the spectral response.

The calculated $Q_e(\lambda)$ curve and measured values for an inversion layer solar cell are given in Figure 7.5. The agreement between the two is quite good, with most of the measured points close to the predicted curve. The indicated uncertainty is primarily due to the small signal level of the thermopile detector. The measured values were obtained using the optical bench technique described in section 5.4. The program QFIX was used to correct for filter leakage. The program QEFF, incorporating the theory in sections 6.1 and 6.2 was employed to calculate the theoretical curve.

The dip in $Q_e(\lambda)$ at ultraviolet wavelengths is caused by the high reflectance of the air-SiO₂-Si system, indicated by the dotted curve, $R(\lambda)$ in the figure. For $\lambda < 500$ nm, $Q_e(\lambda)$ is essentially equal to $1-R(\lambda)$ as expected for a vertical collection surface effect cell. The high UV

Fig. 7.5 Measured and calculated external current efficiency, $Q_e(\lambda)$ and calculated reflection coefficient, $R(\lambda)$ for an inversion layer solar cell.

reflectance is due to poor impedance matching to the complex refractive index of silicon. Figure 2.6 shows that even the best AR coatings work poorly at these wavelengths.

At the centre of the curve, near the peak of the solar spectrum, $Q_e(\lambda)$ approaches 90%, indicating a combination of low reflectance and high collection efficiency, both of which are necessary for a good solar cell. At longer wavelengths, the curve fits very well to the theory for a bulk lifetime of 2 μ s. This was unexpected since the measurement technique shown in Figure 5.1 yielded a value of τ_n close to 7 μ s for this cell. However, the 7 μ s curve (dashed line) clearly does not fit the data. The difference in injection levels during the two tests may be responsible for this apparent anomaly. In Figure 5.1, the current density through the diode is about 3 A/cm², while the current level during a $Q_e(\lambda)$ measurement is typically a few μ A/cm². It is possible that the effective minority carrier lifetime is varying with injection level. An increase in lifetime by a factor of five from low level to higher level injection has been previously reported [39]. Thus, the apparent change in τ_n for this cell is reasonable.

At longer wavelengths, the $Q_e(\lambda)$ curve in Figure 7.5 drops quickly and approaches zero for $\lambda > 1200$ nm. This drop can be partially attributed to an increase in $R(\lambda)$ and higher recombination losses. (The free electrons, generated deeper in the bulk at long wavelengths, have farther to go before being collected.) However, the main effect is a loss of absorption efficiency as the photons of lower energy pass through the cell.

As discussed in Chapter 2, there should be a cutoff wavelength $\lambda_{co} = 1120$ nm, above which no absorption occurs. Clearly, there is some collection at $\lambda_c = 1135$ nm however, and most silicon cells still generate a small current at $\lambda = 1200$ nm. This has been explained by phonon-assisted absorption [29]. Since most optical absorption in silicon is indirect, thermal phonons are required to change the momentum of the valence electrons as they are excited to the conduction band. For photons with energies slightly less than the bandgap, the thermal energy of the phonon may be sufficient to aid in the electron's excitation. This phonon-photon absorption would presumably be a low probability event, accounting for the low $Q_e(\lambda)$ values shown. In calculating the theoretical curve, this complex effect was modelled by artificially extending the absorption coefficient, $\alpha(\lambda)$ past λ_{co} as shown in Figure 2.3.

From Figure 7.5, it is apparent that the IL cell continues to operate well into the ultraviolet portion of the spectrum. There appears to be no "parasitic absorption" as previously thought [53] which would reduce $Q_e(\lambda)$ at short wavelengths. For $\lambda < 300$ nm, there may be a small additional loss but this is not definite and, if present, it would have little practical importance.

Current efficiency measurements were also made on an older IL cell and the results are presented in Figure 7.6. Here again, the data fit the theoretical curve well over most of the spectrum. The dips in $Q_e(\lambda)$ are mostly caused by the reflectance of the thick oxide ($t_{ox} = 455$ nm) as shown by the $R(\lambda)$ curve. It was these measured results which first suggested the need to optimize the oxide thickness for better anti-reflection properties. This cell also exhibits a lower lifetime than

Fig. 7.6 Measured and calculated external current efficiency for an early inversion layer solar cell showing the poor antireflection properties of a thick oxide layer.

expected, but the discrepancy is larger than in Figure 7.5. The presence of a p^+ diffused BSF region which could reduce the bulk lifetime toward the back may be partly responsible for the increased difference. Also, the cell had a sintered gold back contact and gold is known to reduce carrier lifetimes [49]. Both these effects would be strongest at long wavelengths as shown since the generation is closer to the back of the cell.

At ultraviolet wavelengths, the measured points in Figure 7.6 are consistently below the theoretical curve, indicating the presence of some parasitic absorption. During the fabrication of this cell, a thin (~10 nm) layer of silicon was deposited prior to the aluminum evaporation to achieve better front contacts (see section 4.3). Although a silicon etch was used to remove this layer from the active area of the cell, the etch rate was subsequently found to be much slower than expected. Thus, it is possible that some silicon remained on the oxide surface. This would be difficult to detect, but of course, would act as a parasitic absorption layer. Also, these measurements were made two years after the cell was fabricated. During this time, dust and other contaminants which could affect the short wavelength response accumulated on the surface of the cell. Whatever the explanation, there is no need to invoke a built-in parasitic layer as originally hypothesized.

Figure 7.7 is included to show how inversion layer cells compare with conventional, diffused ones. Here, measured $Q_e(\lambda)$ curves are plotted for the two types. The "poor diffused cell" is the OCLI standard cell which is designed for linearity and stability rather than efficiency. The "good diffused cell" has higher response over most of the spectrum, probably due to a superior AR coating and a shallower junction. All three

3

Fig. 7.7 Comparison of the spectral response of an inversion layer solar cell with conventional devices showing the superiority of the IL cell at ultraviolet wavelengths.

devices have similar responses near $\lambda = 1100$ nm, demonstrating that conventional cells exhibit low lifetimes at low intensities as well. The greatest difference occurs at ultraviolet wavelengths. The OCLI cell has very little response below $\lambda = 400$ nm while even the good diffused cell drops off sharply at that wavelength. The inversion layer cell, however, maintains a relatively high response out to the shortest wavelengths. This demonstrates one of its advantages over diffused cells.

7.3 Current-Voltage Results

While the $Q_e(\lambda)$ curves are revealing and instructive, the I-V output curve is the most important solar cell characteristic and the most difficult to model accurately. Figure 7.8 compares the theoretical I-V curve from the program ILSCEL with the measured one for an inversion layer cell.

The top curve (dashed line) is the ideal solar cell curve given by equation (2.4). Equation (2.5) was used to find the saturation current, I_{00} . The short circuit photocurrent for this curve was determined by integrating the theoretical $Q_e(\lambda)$ response (Figure 7.6) across the AM 1.46 spectrum. The next lower curve is the one-dimensional I-V curve predicted for this cell by the program ILSCEL. Although there are subtle differences, the two curves are in good agreement. In particular, the two different methods for calculating I_{sc} agree very closely. The good fit between the curves verifies the assumptions used to derive the ideal theory summarized by equations (2.4) and (2.5), if only for this particular cell structure.

Fig. 7.8 Development of the modelled I-V curve for a complete inversion layer solar cell and comparison with the measured curve.

The second dotted curve represents the I-V output from the model shown in Figure 6.3 b). The short circuit current has been reduced by grid finger shading and the reduction in fill factor due to the inversion layer resistance is evident. The third dotted curve in Figure 7.8 is the final $I_{out} - V_{out}$ curve of the model which includes the effects of bus bar shading, metal resistance and peripheral collection as illustrated in Figure 6.4. The solid line is the measured curve for the real cell under the same conditions. As can be seen, the two curves are in excellent agreement! This validates the model and gives final proof that the IL cell operates as expected. The small ($\sim 1\frac{1}{2}\%$) difference between the measured and modelled short circuit currents can be accounted for by uncertainty in the AM 1.46 spectrum.

The good fit in Figure 7.8 was achieved by assuming a bulk lifetime of 10 μs , slightly above the 7 μs value which was measured for this device. This may be because the τ measurement was made using the diffused diode. The lifetime may be higher in the active area where no diffusion is present. Alternately, the effective lifetime may be different depending on whether an injection or collection current is flowing. Fortunately, the discrepancy is not large.

In Figure 7.9, the measured and modelled I-V curves are compared for two other IL cells. The top graph is for a more recent diffused IL cell while the bottom results are for an MIS-IL device [22]. For both of these, the fit is again quite good, although not as close as in Figure 7.8. The more recent diffused IL cell (#78-F₃) incorporates some improvements over earlier devices (#76-5 in Figure 7.8). The oxide thickness is at the optimum value for minimal reflection and the metal resistivity

Fig. 7.9 Comparison of measured I-V curves with those predicted by numerical modelling for two inversion layer solar cells.

is considerably lower. As a result, the active area efficiency is somewhat higher, ~11% at AM1. Unfortunately, the oxide charge has a low value ($Q_{fb} = 3 \times 10^{11} \text{ cm}^{-2}$).

Figure 7.9 b) demonstrates the importance of knowing all the relevant parameters if a meaningful comparison is to be made between theory and experiment. Several of the important parameters, including temperature, light intensity and bulk lifetime were not measured for this cell. The values given in the figure were estimated from previous experience. It would be quite simple to adjust the unmeasured parameters to obtain a much better fit than shown, but such a comparison would be meaningless. From this it is clear that all the parameters and operating conditions must be determined before a real cell can be modelled.

The largest difference between the curves compared in Figures 7.8 and 7.9 is not in the current or voltage, but rather in their shape. The measured curves are all somewhat more rounded than the theoretical ones, with the latter having a sharper "knee" near the maximum power point. This difference is probably due to variations in the structural parameters across the surface of the cell. As mentioned before, Q_{fb} variations of as much as $\pm 30\%$ across a wafer are not uncommon. There are also small flaws in the grid geometry and oxide of any real cell as well as random crystal faults within the silicon itself. Even the qualitative effects of these imperfections on the solar cell would be difficult to predict. The simplifications made in modelling the two-dimensional effects (section 6.5), especially the bus bar shape and the peripheral collection current, could also subtly alter the shape of the resultant I-V curves.

These effects, combined with uncertainties in all the device parameters, make it unreasonable to expect the theoretical curves to agree with the measured data more closely than $\sim \pm 2\%$. Since the observed agreement is, for the most part, within $\pm 3\%$, it can be concluded that the model is accurate and the cells work properly.

Some of the versatility of the model is illustrated in the following two figures. Figure 7.10 shows the effect of changing the operating temperature of a modelled IL cell. The indicated temperature coefficients for open circuit voltage, short circuit current and maximum output power are similar to those found for conventional cells under the same conditions [7]. These curves show the importance of accurately modelling the effect of temperature on all the semiconductor parameters. The importance of quoting the cell temperature with all reported results is also clearly demonstrated.

Figure 7.11 illustrates the effect of operating the same modelled cell at various concentrations of AM1.5 sunlight. The severe degradation of the curve at high intensities due to the large series resistance is apparent. At a concentration of four, the short circuit current has dropped below the photocurrent ($I_L = 99 \text{ mA/cm}^2$). These results show that the IL cell in its present form is not suitable for concentration applications. No measured data are available for comparison with these theoretical results because of the difficulty in maintaining a known cell temperature and obtaining a uniform concentration of sunlight.

Fig. 7.10 Modelling the effect of temperature on IL cell current-voltage output curves.

Fig. 7.11 Modelling the effect of sunlight concentration on the output of an inversion layer solar cell.

7.4 Inversion Layer Cell Operation

The computer program ILSCEL can be used to provide information on the internal operation of the device being modelled. Such data are useful in clarifying how each part of the structure functions. Fundamental to the inversion layer cell is the behaviour of the induced junction itself. Figure 7.12 shows how the normalized potential $u(x)$ and the electric field strength $E(x)$ vary throughout the depletion region of a modelled cell for different bias voltages. These results were calculated by ILSCEL using the MOS theory developed in Chapter 3. Implicit in the calculations is the assumption that, under low level injection conditions, $u(x)$ and $E(x)$ are unaffected by the photogeneration and collection in the cell. From Figure 7.12, the thickness of the inversion layer can be estimated (30-50 nm, depending on the voltage). The reduction in depletion depth and band bending with increasing forward bias are also apparent.

The front surface of the silicon ($x=0$) is an important part of the cell. The electron concentration at this point is one of the boundary conditions for solving the continuity equations. Figure 7.13 demonstrates how several of the surface parameters in a typical structure vary with increasing forward bias. The surface potential, u_s decreases as the band bending is lessened. The junction depth, x_j and depletion depth (not shown) are also reduced. To maintain overall charge neutrality when the depletion charge decreases, the charge density in the inversion layer must increase. Thus, both the surface electron density, $n(0)$ and surface electric field, E_s rise with increasing forward bias. These variations are all governed by Poisson's equation as it applies to the SiO_2 -Si system. Accurately determining their dependence on junction voltage is the basis of a successful solar cell model [30].

Fig. 7.12 Potential and electric field distributions within an inversion layer cell at various values of forward bias voltage.

Fig. 7.13 Effect of junction forward bias voltage on the surface parameters of an IL solar cell.

Perhaps the most interesting results provided by ILSCEL are the variations of the electron and hole concentrations throughout the cell under illumination. Figure 7.14 shows $p(x)$ and $n(x)$ in the depletion region of a modelled IL cell for different voltage levels. Here again, the contraction of the depletion region and reduction of the junction depth with increasing forward bias are evident. In this figure, however, the junction is the metallurgical junction (the point where $p=n$). This differs slightly from the depth, x_j shown in Figure 7.13 which is based solely on the potential distribution. The two definitions are the same only under zero illumination.

At zero bias, the minority carrier concentrations are much different from their equilibrium values, while the majority levels are only marginally higher. As the voltage increases, injection occurs, causing both $p(x)$ and $n(x)$ to rise. This results in more recombination and thus, less overall current flow. Even above the open circuit voltage, however, the minority electron concentration remains below the bulk dopant level, N_a . Thus, the low-level injection assumption is validated for this structure. If the intensity were increased by a concentration factor of ten or if N_a were reduced to $\sim 10^{14} \text{ cm}^{-3}$ or less, the assumption would no longer hold. Under such conditions, the model calculates a negative potential at the junction which of course causes an execution error.

In the neutral bulk, the hole concentration is essentially equal to the doping level. However, the minority electron distribution in this region is quite revealing as shown in Figure 7.15. Here, $n(x)$ is plotted for a cell structure modelled with and without a BSF region.

Fig. 7.14 Electron and hole distributions in the depletion region of an inversion layer cell for various values of forward bias voltage.

Fig. 7.15 Minority electron distributions in the bulk of a modelled IL cell for several bias levels, with and without a back surface field.

The entire depletion region occupies less than one micrometer, along the left edge of the figure. Two effects are immediately apparent. First, biases up to 0.3 volts have very little effect on the electron density throughout most of the bulk. Only above 0.4 volts does $n(x)$ begin to increase noticeably above its short-circuit level. This is the reason for the square shape of the I-V curve for a solar cell without resistive losses. Coupled with this effect is a shift in the type of current flowing and its direction. Below V_{oc} , the slope of $n(x)$ at the edge of the depletion region is negative, indicating that collection dominates. Above V_{oc} (e.g. $V = 0.55$ volts), the slope is reversed as the injection current becomes the larger component.

The second important effect demonstrated in Figure 7.15 is the action of the back surface field. In the absence of a p^+ diffusion, recombination at the back surface reduces the electron level throughout the bulk. Even at zero bias, there is useful collection from only the upper 70 μm of the substrate (at $x = 70 \mu m$, $n(x)$ passes through a maximum). Deeper than this, the net flow of electrons (via diffusion) is toward the back where they are lost. When a BSF region is present however, the slope of $n(x)$ at zero bias remains negative all the way to the p^+ diffusion. As a result, the short circuit current is higher. Also, as the voltage increases and electrons are injected into the bulk, they are shielded from the lossy back surface by the BSF region. Thus, a higher electron concentration is required to produce the same overall recombination rate. The result is a higher open circuit voltage for the BSF cell as indicated in the figure.

These results apply equally well to all solar cells. The benefits of a BSF region are even more pronounced in cells with thinner

substrates ($w_0 < 100\mu\text{m}$). For cells greater than two diffusion lengths thick, the beneficial effects become negligible. This dependence on cell thickness is discussed further in the following chapter.

7.5 Conclusions

The results presented in this chapter are very encouraging. Inversion layer solar cells exhibiting respectable efficiencies (10-12 % active area, AM1) have been made and shown to perform as expected. The ability of the numerical models, QEFF and ILSCEL to accurately predict the response of real cells and simulate their operation has been demonstrated. Finally, the measurement techniques have been shown to yield meaningful and useful results.

Inversion layer cell efficiencies of 10-12 % are not the highest that can be achieved, however. The theoretical and experimental results have revealed certain deficiencies in present and past structures and pointed to areas in which improvement is possible. The next chapter utilizes the models developed in Chapter 6 to investigate the limitations of the IL cell and other surface effect solar cells and how their structures can be optimized to yield higher efficiencies.

CHAPTER 8

THE FUTURE OF SURFACE EFFECT SOLAR CELLS8.1 Introduction

At present, several types of surface effect solar cells have been shown to be feasible, but none is yet truly competitive with conventional, diffused devices. The best efficiency reported to date is ~15% for an MIS-IL structure with an evaporated SiO layer [55]. However, this result required the use of an extremely fine grid geometry (up to 200 grid lines per centimeter). The best results for most other surface effect cells are substantially lower. MIS cells [14], diffused junction IL cells and TiO_x-MIS cells [45] have all achieved active area, AM1 efficiencies of only ~12%, below the value for typical, diffused cells. Furthermore, most of the surface effect cell fabrication processes are not suitable for large scale, low cost production. The diffused IL cell, for example, requires a mask alignment and is therefore, too complex. Other devices require critical processing which limits the yield of efficient cells and is difficult to control. Finally, some structures are not fully understood or have not even been demonstrated yet. If surface effect cells are to become a real alternative, their efficiency must be raised and maintained at a high level while their processing is simplified and made economically attractive.

The purpose of this chapter is to employ the computer models developed in Chapter 6 and validated in Chapter 7 to investigate how surface effect cells can be improved to achieve these goals and whether

further development is warranted. As in previous chapters, the discussion is centred around, but not limited to the inversion layer cell. Section 8.2 considers the interrelations among the IL cell structural parameters and the tradeoffs involved in optimizing a process. The third section explores the limitations of the IL structure and predicts its future potential. Suggestions for raising the efficiency and simplifying the fabrication are outlined. The final section discusses the optimization and potential of lateral collection devices.

8.2 Optimizing Inversion Layer Cells

To obtain the highest possible efficiency from a given type of solar cell, its structure must be optimized. Once this has been done, the process can be adjusted to yield the desired result. Optimizing a cell structure is not straightforward, however. Many of the device parameters are interdependent and produce conflicting effects on the cell. For example, increasing the substrate doping will increase the open circuit voltage, but will also reduce the short circuit current. To elucidate the complex relationships between structural parameters and cell operation and to evaluate the tradeoffs involved in cell design, a computer model can be used. Numerical simulation of solar cells allows differing structures to be easily compared. The inversion layer results in this section were calculated using the programs QEFF and ILSCEL. Obtaining the same results by fabricating and testing real cells would be time consuming and prone to error, if possible at all.

Some of the IL cell parameters can be easily chosen, independently of the others. A few have been dealt with in previous chapters. The oxide thickness has a unique optimum value as shown in Figure 4.3. The bulk lifetime and oxide charge should be maximized for best results. Even for these, however, it is interesting to determine what effect a change will have on cell performance.

Figure 8.1 illustrates what happens to the current efficiency of an IL cell when the bulk lifetime, τ_n varies. To eliminate the effect of reflection, the internal current efficiency, $Q_i(\lambda)$ is plotted. The vertical axis has a logarithmic scale to accentuate the differences at long wavelengths and only the infra-red portion of the response is plotted since $Q_i(\lambda)$ approaches unity at shorter wavelengths. As well as the obvious advantage of a high lifetime, two other effects are shown. Firstly, the increase in $Q_i(\lambda)$ is not linear in τ_n . An order of magnitude increase in τ_n produces an increase in photocurrent of only 5-10%. Such a logarithmic dependence could be expected from the absorption and collection mechanisms. Second, the increase in $Q_i(\lambda)$ with τ_n saturates at about 100 μ s. Above this value, the diffusion length is longer than the cell thickness and almost all the photoelectrons are collected. $Q_i(\lambda)$ is then limited only by the absorption efficiency of the substrate. In this situation, the bulk is said to be "transparent" to minority carriers since they pass through it without loss.

Figure 8.2 gives a better indication of how the cell performance is affected by τ_n . Here, the short circuit current, open circuit voltage and maximum output power are shown as functions of bulk lifetime for IL cells with and without BSF regions. A scale showing the

Fig. 8.1 Effect of bulk lifetime on the internal current efficiency of an IL cell at infra-red wavelengths.

Fig. 8.2 Variation of the short circuit current, open circuit voltage and maximum output power with bulk lifetime for inversion layer solar cell structures with and without a back surface field region.

electron diffusion length is included for convenience. In this figure, the saturation of I_{sc} at high lifetimes implied by Figure 8.1 is clearly shown. However, V_{oc} (and hence, P_{max}) continues to increase with τ_n . For this structure without a BSF region, there is little to be gained by increasing τ_n beyond 30 μs . It is interesting to note that the "break point" where V_{oc} begins to saturate for non BSF cells occurs where the diffusion length equals the cell thickness. This supports the empirical observation that a BSF region is most useful when the diffusion length is longer than the cell thickness [37]. For BSF cells, V_{oc} begins to increase faster with τ_n at this point!

Since the cell thickness (w_o) and BSF region appear to be intimately involved in the cell performance, their effects should also be considered. Figure 8.3 shows what happens to the internal current efficiency of a modelled cell when w_o is varied. As expected, a thicker cell absorbs more long wavelength photons and a BSF region improves the collection efficiency. Also, the BSF advantage is less for thicker substrates. For very thin cells, even visible wavelength ($\lambda \leq 700$ nm) collection suffers when no BSF region is present. These results should apply equally well for all vertical collection solar cells, including conventional, diffused cells.

An interesting effect demonstrated in this figure is that for BSF cells, the 100 μm thick substrate produces a higher response over much of the spectrum than the thicker, 300 μm one. This is due to the electron reflecting property of the BSF region. An electron "mirror" at $x = 100$ μm produces more collection at the junction than a "transparent" surface at the same position (as in the thicker substrate). At longer wavelengths, the increased absorption in the thicker cell becomes more

Fig. 8.3 Effect of substrate thickness (w_0) and back surface field (or lack of same) on the internal current efficiency of a modelled IL cell.

important and the effect is lost. This "mirror" effect actually causes a reduction in the short circuit current of a BSF cell as w_0 is increased past the electron diffusion length.

The drop in I_{sc} for thick BSF cells is evident in Figure 8.4. Here, P_{max} , I_{sc} and V_{oc} are plotted as functions of w_0 for modelled IL cells with and without BSF regions. The results in this figure provide a good example of computer aided cell optimization. The plot of P_{max} versus w_0 for BSF cells shows a clearly optimal cell thickness near $w_0 = 85 \mu m$. This is surprisingly narrow and would have been difficult to ascertain without a sophisticated cell model. Only recently has the advantage of using thin substrates for diffused cells been recognized [35,38]. Figure 8.4 illustrates another important effect. As the cell is made narrower, the open circuit voltage increases for BSF cells, but decreases for non-BSF cells. This follows from the way a BSF region functions as discussed in Chapter 7.

In this figure, it can again be seen that a BSF region has its greatest benefit in thin cells. The high efficiency can be maintained even for very thin BSF cells ($w_0 < 30 \mu m$) in spite of the loss of short circuit current. This means that efficient thin film silicon solar cells should be feasible. However, a p^+ BSF region must be incorporated to achieve these results. As w_0 increases, the p^+ region has less effect, becoming insignificant for very thick cells. The decision to omit the BSF region in the most recent IL cells ($w_0 \approx 330 \mu m$) was based on results similar to these. The small gain in output power under these conditions simply did not warrant the extra processing. If the bulk lifetime in these substrates could be raised to $\tau_n > 30 \mu s$, however, a p^+ diffusion would be beneficial since the diffusion length would then be greater than w_0 .

Fig. 8.4 Effect of cell thickness and back surface field on IL cell output. $N_A = 1 \times 10^{15} \text{ cm}^{-3}$, $\tau_n = 10 \mu\text{s}$, $Q_{\text{fb}} = 9 \times 10^{11} \text{ cm}^{-2}$, Air Mass 1.0, $t_{\text{ox}} = 115 \text{ nm}$, 40 grid lines per cm, ~7% grid metal shading.

The non-BSF short circuit current results shown in Figure 8.4 for $w_o > 400 \mu m$ are misleading. One would expect the curve to approach but not exceed the value for thick BSF cells. It seems likely that with $w_o > 2 L_n$ and an ohmic back surface (no BSF), the model is developing numerical difficulties, resulting in an increased error ($\sim 1 1/2\%$ instead of $\pm 1/2\%$). This small discrepancy is also reflected in the P_{max} curves. The output power for very thick cells should be the same with or without a BSF region.

The qualitative effects shown in Figure 8.4 apply to most vertical collection solar cell structures. The quantitative results however, will vary if any of the cell parameters are changed. Thus, if τ_n were increased for instance, the optimum w_o would increase as well and the curves shown would be shifted up and toward the right in the figure.

Much work has been done to find the optimum substrate resistivity for diffused solar cells [35,69]. The bulk doping level, N_a is of primary importance since most of the cell parameters are dependent on it to some degree. Since an IL cell has the added complex relationship between N_a , Q_{fb} and the inversion layer resistance, it is unlikely that the optimum doping level will be the same. Figure 8.5 predicts the effect of varying N_a on the IL cell performance. Calculated values of P_{max} , I_{sc} , V_{oc} and fill factor are plotted for two levels of flatband oxide charge, Q_{fb} . A substrate resistivity scale (p-type silicon) is included for convenience. Since it is unreasonable to expect the bulk lifetime to remain constant when N_a is changed, τ_n was made to vary with N_a according to equation (F.5) in Appendix "F" [49].

Fig. 8.5 Effect of bulk doping level on IL cell output.

Cell thickness = 250 μm , t_{ox} = 115 nm, AM1,

$T = 298 \text{ K}$, BSF region used, bulk lifetime coupled to N_a . Values are calculated.

The effect of N_a on I_{sc} and V_{oc} is as expected and the P_{max} curves clearly show an optimum value for bulk doping ($N_a = 3 \times 10^{15} \text{ cm}^{-3}$ for $Q_{fb} = 9 \times 10^{11} \text{ cm}^{-2}$). While lower values of N_a yield higher short circuit currents, the voltage and fill factor suffer. At higher doping levels, the lifetime drops, reducing I_{sc} . Also, the inversion layer resistance increases as a larger portion of Q_{fb} is required to deplete the surface. Eventually, for very high N_a levels, the substrate cannot be strongly inverted, the inversion layer resistance becomes effectively infinite and the cell no longer operates in the inversion layer mode (the program ILSCEL will not run either). Under these conditions, the cell becomes a lateral collection device similar to that modelled in section 6.7 with one important difference. Instead of a passivated front surface with a recombination velocity close to zero, the cell has a depleted surface characterized by a high recombination velocity [31]. Thus, most of the photogenerated electrons are lost at the front surface. Only those which diffuse to the contact junction are beneficially collected, resulting in a very low short circuit current. This has been confirmed experimentally. IL cells made on 0.4 $\Omega\text{-cm}$ substrates ($N_a \sim 7 \times 10^{16} \text{ cm}^{-3}$) produced very little photovoltaic output, even though they exhibited diode characteristics.

The fact that the optimum substrate doping level depends on Q_{fb} demonstrates that computer aided optimization is highly process dependent. For a given structure, the process should be adjusted to maximize Q_{fb} and τ_n and to yield the correct oxide thickness. Then the computer program can be employed to determine the best values for N_a , w_o , BSF region and grid geometry. The optimum values would have to be recalculated if Q_{fb} or τ_n changed significantly.

Part of the design optimization involves determining the best grid geometry and, primarily, the optimum grid finger density, N_f . In Chapter 4, it was found that, in general, a cell should use the narrowest grid finger width that can be reliably defined. Since the minimum linewidth is very process dependent, and is important in limiting the efficiency of IL cells, its effect on grid geometry and cell output will be discussed in the following section:

8.3 The Potential and Limitations of IL Cells

Through experience and by reading the available literature, it is usually possible to estimate the maximum values of bulk lifetime and oxide charge which can be expected from any given IL cell fabrication process. The program ILSCEL can then be used to optimize the structure and predict the highest possible efficiency for it. In this way, a candidate process can be evaluated without having to fabricate a large number of devices. Also, the parameters which limit the cell output can be quickly identified and investigated before cells are made.

The fundamental limitations for IL cells are the same as those for all silicon photovoltaic devices. If a cell 1000 μm thick with no reflectance, no grid shading and negligible recombination could be made, it would produce a short circuit current of 44.1 mA/cm^2 at AM1. If the bulk doping level were also high, the open circuit voltage could conceivably approach 0.7 volts. Under these conditions, the fill factor could be no higher than 0.84, giving an overall efficiency of ~26%. This value is, of course, unrealistic. However, it provides an absolute upper bound for efficiency.

Without making any major changes in the present diffused-IL cell process (outlined in Figure 4.6), some improvement in performance can be achieved. With proper control of the oxide heat treatment, reproducible values of Q_{fb} in excess of 10^{12} cm^{-2} should be possible [44]. Figure 8.5 indicates that near this value the optimum substrate doping is $N_a \sim 5 \times 10^{15} \text{ cm}^{-3}$. By annealing the wafers at -500°C or by pulling them out of the high temperature furnaces more slowly to reduce thermal stresses, it should be possible to maintain the present lifetime in these substrates or even raise it to $\tau_n \sim 15 \text{ } \mu\text{s}$. Finally, the resistance loss in the grid metal can be reduced simply by making the grid thicker. With these few changes made, ILSCEL predicts an AM1 efficiency over 14%. The I-V curve for this optimized cell is the one labelled "practical goal" in Figure 8.6. Such a result for IL cells would make them comparable in efficiency with good diffused ones as indicated in the figure. Further increases could be achieved by incorporating a BSF region and optimizing the cell thickness.

As concluded in Chapter 4, the present diffused-IL cell process is not suitable for low cost production. However, simulations of MIS-IL cells predict that the one mask, low temperature process outlined in section 4.4 should be capable of achieving the same efficiencies. In fact, without the high temperature thermal stresses, even higher values of bulk lifetime should be possible in MIS-IL cells [39]. Hence, the continued development of these devices appears to be worthwhile.

Fig. 8.6 I-V output curves showing improvements which could be realized in IL solar cells, the maximum possible, and the level for diffused cells.

The conversion efficiency can be substantially raised by changing the process to further push back the limitations. The recent report of a 15% efficient MIS-IL structure [55] demonstrates the potential of the inversion layer cell concept. A very fine grid geometry (5 μm linewidths) and an evaporated SiO₂ oxide layer were employed to achieve these results. There are possibilities for further improvement. An oxide of chromium has been shown to develop a very high oxide charge (on the order of 10^{13} cm^{-2}) when deposited on silicon [17]. This seems to be the limiting value for Q_{fb} . In addition, both silicon monoxide and chromium oxide provide good antireflection properties.

The remaining factors which limit the efficiency of IL cells are bulk lifetime and grid geometry. As mentioned before, annealing of silicon wafers can yield very high bulk lifetimes, (τ_n up to 300 μs) even in low resistivity substrates [39]. With this value, a BSF region would be very beneficial, even for a thick cell. In the future, it may be possible to define grid lines as narrow as 1 μm , while retaining low metal resistivity. A very fine, low loss grid geometry would then be possible. When all these parameters are included in an ILSCEL simulation, the result is an "ultimate potential" efficiency above 20% as shown in Figure 8.6. While the development of such a cell is not being seriously proposed, these results indicate that there is ample opportunity for innovation and improvement.

The calculated external current efficiency curves for the hypothetical IL cells described above are plotted in Figure 8.7. The benefits of increased bulk lifetime and an optimized single-layer AR coating are evident. The low response in the ultraviolet region is a

Fig. 8.7 Calculated external current efficiencies for various "improved" inversion layer solar cells.

result of the antireflective match to the longer wavelengths at the peak of the solar spectrum. By changing the thickness and refractive index of the AR coating, the response can be made to peak at any wavelength. An example of this is the "UV enhanced IL cell" shown in the figure. The cost of extending the UV response in this way is, of course, a loss in response elsewhere and a lower overall efficiency.

The results in Figure 8.7 are calculated on the assumption that the AR layers act as perfect dielectrics. In most materials other than SiO_2 , this is not true and some absorption occurs, especially at UV wavelengths. This effect could readily be taken into account if the absorption were known, but such information is usually unavailable or ambiguous.

In the foregoing discussion, it has been shown that the cell efficiency is limited by the material and structural parameters. These in turn are limited by the process used to make the device. While it may be conceivable to fabricate a 20% efficient IL cell, the requisite process would likely be unsuitable for economic production. Practical, low cost processing imposes constraints on which structures can be realized. Thus, it is not the efficiency which should be maximized, nor is it necessarily the cost per cell which should be minimized; rather, the cost per unit efficiency or the cost per peak watt of output power should be minimized.

A good illustration of the effect of a process variable on solar cell performance is in the design of the front contact grid. This is especially important in IL cells where a fine grid is necessary. With the photolithography used for the present IL cells, the minimum linewidth is about 10 μm . For any given linewidth, there will be an

optimum choice of grid finger spacing which yields the maximum cell output power. This effect is shown in Figure 8.8 where $P_{\max}$ is plotted as a function of N_f , the number of grid fingers per centimeter for several grid finger widths, w_f . The results are for a hypothetical IL cell and were obtained using the program ILSCEL, modified to produce all the results in one run.

The curve for each value of w_f exhibits a peak at the optimum grid finger density. To the left of the peak, the fingers become farther apart and the inversion layer series resistance is too large. To the right, the resistance is low, but the grid covers too much of the cell area. For $w_f = 10 \mu\text{m}$, the value $N_f = 60 \text{ cm}^{-1}$ provides the best tradeoff between these two losses. The $w_f = 20 \mu\text{m}$ curve is more representative of the IL cells made to date. The value of 40 lines/cm chosen for the geometry in Figure 4.2 is evidently close to the optimum value.

Although the MIS-IL process may be suitable for production in its present form, it still requires vacuum metallization and photolithography; both expensive, low throughput processes. The economics could be made more attractive if the contact grid could be screen printed onto the wafer. At present, screen printing and MIS contacts appear to be incompatible, but this may change with advances in metal pastes or conductive epoxy. Alternately, vacuum evaporation could be retained and screen printing used only to apply the etch resist. Conventional screen masks have a minimum linewidth of ~5 mils (125 μm). As shown in Figure 8.8, this would produce an unacceptably low cell output. Special foil masks are available, however, through which 2 mil

Fig. 8.8 The effect of grid finger density on the output power of an inversion layer solar cell for various grid finger widths.

(-50 μm) lines can be printed. With such linewidths, a total area efficiency in excess of 10% would be possible. This would be acceptable for a low cost process. Such a process would be compatible with polycrystalline substrates and spin-on oxides, giving even more potential for cost reduction.

From the results presented here and in Chapter 7, it is possible to identify the major constraints which are presently limiting IL cell performance and must be overcome to obtain higher efficiency. Foremost among these is the high inversion layer sheet resistance. Part of the problem is that the Q_{fb} values obtained recently have been lower than expected. However, even with a high oxide charge density, the sheet resistance would remain much higher than in a diffused cell. This fact will prevent the use of IL cells in high concentration applications (greater than 5 times AML) where low series resistance is crucial. The effects of high sheet resistance can be reduced by resorting to a very fine grid pattern, but this can be undesirable from a processing viewpoint and does not entirely eliminate the problem.

Another concern is that SiO_2 is a relatively poor AR coating and therefore limits the value of I_{sc} which can be obtained. Materials like SiO and chromium oxide make better AR coatings while maintaining high positive charge densities [17, 55]. However, much work is still required to fully develop and characterize them. A final problem which has yet to be addressed is the possibly high contact resistance of MIS contacts. This is more important in MIS-IL cells than in normal MIS cells due to the smaller contact area of the former. Again, more work must be done to determine the extent of this problem.

Arrayed against these disadvantages are the incontestable advantages and future potential of the IL cell. To start with, the ultraviolet response has been shown to be much better than for diffused cells. The main advantages however are in processing. The possibility for low temperature fabrication has been demonstrated [22] and the potential exists to reduce the cost with cheaper substrates and simpler processing. Therefore, the IL cell remains a viable alternative to diffused cells and further development is warranted.

How do the other surface effect solar cells compare with inversion layer cells? The only real competitor among vertical collection devices is the MIS cell which has similar advantages and potential. However, by its very structure the MIS cell has two drawbacks. As mentioned in Chapter 3, the thin metal layer over the entire surface will invariably absorb ~10% of the incoming light. Also, this layer must be deposited by vacuum evaporation whereas the IL cell has the potential (albeit undemonstrated) of not requiring vacuum deposition. The remaining surface effect cells introduced in Chapter 3 operate by lateral collection and are discussed in the next section.

8.4 Investigating Lateral Collection Solar Cells

According to the descriptions given in Chapter 3, the accumulation layer cell and the TiO_x -MIS cell operate on the same principle, the lateral collection of minority carriers at small area junctions. Apart from their structures, the two cells differ only in the mechanisms controlling the front surface boundary condition. Thus, the simple model for lateral collection cells developed in Chapter 6 should apply equally well (or equally poorly) to both. The specific

structure which will be considered is the accumulation layer, grating solar cell depicted in Figure 3.1 d). This has a diffused junction on an n-type substrate so that the minority carriers are holes. Because of the simplicity of the model, it is difficult to make meaningful comparisons with other devices, especially inversion layer cells. However, by reducing the same simple theory to one dimension, a comparison with diffused p^+ on n cells is possible.

The outputs of a hypothetical accumulation layer (grating) cell and a p^+-n-n^+ one-dimensional cell are compared in Figure 8.9. P_{max} , I_{sc} and V_{oc} are plotted as functions of the grid finger density, N_f . The bulk lifetime, τ_p was chosen as representative of the doping level $N_d = 10^{15} \text{ cm}^{-3}$. While the open circuit voltage of the grating cell is much higher than for the conventional device as expected, the short circuit current is much lower for values of N_f less than 100 lines/cm. The reason is that for coarser grids, the line spacing is larger than the diffusion length. Recombination between grid fingers is therefore high and the collected current low. For $N_f > 100 \text{ cm}^{-1}$, grid shading becomes important and the current for both types of cell drops.

The grating cell output power follows the current and peaks at $N_f = 100$. While the maximum power possible is quite high, it is clearly below that of the conventional cell (upper dashed curve). Also, the conventional cell peaks at a value of N_f more suitable for screen printing (10 lines/cm). Thus, there seems to be no reason to develop this cell unless improvements can be made. After these results were obtained, no further processing of accumulation layer cells was undertaken.

Fig. 8.9 Theoretical comparison of a grating solar cell (lateral collection) and a conventional solar cell (vertical collection), both with diffused junctions and BSF regions.

However, it may be possible to raise the lifetime above $8 \mu\text{s}$ by phosphorous gettering during the n^+ BSF diffusion [59]. The resulting longer diffusion lengths would allow high collection efficiency to be maintained for coarser grid geometries. This effect is illustrated in Figure 8.10 where the grating cell and conventional cell are again compared, but for several values of bulk lifetime. For clarity, only P_{max} for the two cells is plotted in this figure. The output power from both cells increases with τ_p , but the grating cell improves more rapidly and has a substantial advantage for the highest τ_p values. The breakeven point, where the two cells perform equally well, occurs around $\tau_p = 30 \mu\text{s}$. As an added benefit, as the lifetime increases, the peak output for the grating cell shifts to lower values of N_f , allowing coarser grid geometries to be used.

The results in Figure 8.10 give a new reason for developing grating cells. The structure modelled was by no means optimum. By changing the contact area, the bulk doping level and cell thickness, improvements could doubtless be obtained and very high efficiencies made possible. However, since a high τ_p is required, it is unlikely that such devices could ever be made cheaply. The only method of obtaining permanently high lifetimes in n-type silicon is with a long, high temperature diffusion [59]. Also, the substrate must be defect free, ruling out the use of polycrystalline silicon.

From the above discussion, the accumulation layer cell can be seen to have certain advantages over the TiO_x -MIS cell. The latter uses a p-type substrate so that it is not possible to use an n^+ phosphorous getter to achieve high electron lifetimes. Moreover, the front surface

Fig. 8.10 Theoretical comparison of a grating solar cell and a conventional cell (both with diffused junctions) for various values of bulk lifetime.

"passivation" in the TiO_x device is more complex and probably less effective. Finally, the higher contact resistance of the MIS diodes could become a problem when the contact area is reduced to a small fraction of the total area. However, the TiO_x -MIS structure has other advantages. As previously mentioned, it can be fabricated quickly and cheaply using low temperature processes. Also, since the mobility of electrons is higher than that of holes, the diffusion length for a given minority carrier lifetime will be longer in the TiO_x -MIS cell. For these reasons, development of this novel device should be continued. Perhaps the ideas and results presented here can be applied to improving its performance.

The results given in this chapter demonstrate the high potential of inversion layer and other surface effect solar cells to become contenders with conventional; diffused cells. These devices are even more promising in view of the possibilities which exist for low temperature and low cost fabrication of them. However, the promise has yet to be fulfilled and much research is required to realize their full potential and to develop a process suitable for economical, large scale production.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS9.1 Summary and Conclusions

A good summary of the results achieved during the research for this thesis is contained in Figure 9.1. It depicts the past advances in inversion layer cells, their current status as photovoltaic converters and their promising potential for the future. The I-V curves shown in the figure reflect all the major areas of investigation undertaken in this work: the design and fabrication of surface effect solar cells, the test methods developed to measure the curves and other cell properties, the theoretical analysis and computer modelling used to simulate real cells and identify future goals.

During the course of this work, the objectives put forth in Chapter 1 have been fulfilled. Several types of surface effect solar cell have been introduced, described and compared. Of these, four were selected for further investigation: the diffused contact inversion layer cell, the MIS-IL cell, the accumulation layer cell and the TiO_x -MIS cell. Fabrication processes for these four were developed and the diffused-IL process has been implemented to make cells with 11-12% active area, AM1 efficiencies. Thus, the IL cell concept has been validated as an alternative to diffused cells.

Electrical and optical test methods and the corresponding data analysis techniques have been developed for characterizing the structure and performance of IL cells. Many of the methods can be applied

Fig. 9.1 Past improvements and future potential for inversion layer solar cells.

to any type of photovoltaic device. The results of these tests have been shown to be accurate and useful for comparing how different cells function.

Several computer programs have been written (CEEVEE, QEFF and ILSCEL among them) combining semiconductor theory and numerical methods to model the surface effect cells. In particular, the sophisticated and versatile program ILSCEL has been shown to accurately simulate the operation of inversion layer cells and predict their performance. The excellent agreement which has been obtained between the predicted and measured characteristics indicates that IL cells are now fully understood and operate as expected. Finally, the computer models have been used to investigate the potential and limitations of the four types of surface effect cells.

From the theoretical and experimental results presented in this thesis, several conclusions may be drawn:

- i) The maximum theoretical conversion efficiency of surface effect solar cells is ~21% (AM1), the same as for conventional, diffused cells. Since both types of cell operate on the same photovoltaic principles, neither has any fundamental advantage over the other.
- ii) Inversion layer cells do have some practical advantages over diffused cells, however. They have superior ultraviolet spectral response and their near-ideal operation renders them easier to understand and model accurately. The most important advantage, however, is their potential for low-temperature, low-cost fabrication.

- iii) The main disadvantage of the IL cell is the high inversion layer sheet resistance. This necessitates the use of a very fine grid geometry and will prevent the use of IL cells in high concentration applications.
- iv) Through process optimization, the present diffused-IL cell structure should be capable of achieving conversion efficiencies of 14-15% (active area, AM1). Low oxide charge density appears to be the factor currently limiting the efficiency to less than 12%.
- v) Unfortunately, the present diffused-IL cell structure is not suitable for low cost production since it requires complex processing (i.e. two masks). However, large scale, economical production of the MIS-IL cell should be possible since it can be made quickly, using low temperature processing. Moreover, even higher efficiencies should be possible with this structure since oxides with better antireflection properties and higher charge densities can be employed. The recent report of a 15% efficient, low temperature MIS-IL cell demonstrates the high potential of these devices [55].
- vi) Lateral collection, surface effect cells are capable of achieving high efficiencies, but only when substrates with high minority carrier lifetimes are used. This requirement may limit their acceptance for large scale production since most inexpensive substrates exhibit low lifetimes. The complex processing presently required to fabricate accumulation layer cells makes them even less acceptable for production at present.

- vii) The TiO_x -MIS cell has been proven not to be an inversion layer device. All of its observed characteristics can be explained in terms of lateral collection. Therefore, it is subject to the same limitations as the accumulation layer cell. However, since the processing is much simpler and cheaper for the TiO_x -MIS cell, it remains a viable contender for low cost production.

9.2 Recommendations

Although much work has been done, it cannot be considered complete. A great deal of research is still required in many of the above areas before surface effect cells in whatever form can become competitive in the photovoltaic industry. Thus, it is highly recommended that work be continued in the following areas:

- i) Fabrication of optimized diffused-IL cells to realize cells with 14% efficiency, thereby proving the potential of this device.
- ii) Investigation of the low temperature MIS-IL structure, using CVD, spin-on and evaporated oxides to determine the best process. After this, the research should concentrate on scaling up the fabrication for large scale production.
- iii) Operating accumulation layer cells should be made to prove the feasibility of the concept and to test the accuracy of the simple lateral collection model.
- iv) Further investigation of the TiO_x -MIS cell to determine if the theory describing its operation is true and how the efficiency can be improved.

- v) In many of these areas, the modelling techniques presented here could be applied to speed up process optimization and cell improvement.
- vi) Research at Carleton University on all types of solar cells would be greatly enhanced by the acquisition of a dedicated test system similar to that described in Appendix "C".

It is gratifying to see much of the theory, test methods and fabrication experience presented in this thesis being applied to the photovoltaic research program at Carleton. Many of the above recommendations are being implemented under the current NRC contract and much progress can be expected. Perhaps under the impetus of this work, surface effect cells in general and inversion layer cells in particular will emerge as important advances in the photovoltaic art and gain the recognition they rightly deserve.

REFERENCES

- [1] D.M. Chapin, C.S. Fuller and G.L. Pearson, "A new silicon p-n junction photocell for converting solar radiation into electrical power", J. Appl. Phys., 25, 676-677, May 1954.
- [2] M.B. Prince, "Silicon solar energy converters", J. Appl. Phys., 26, 534-540, May 1955.
- [3] Energy Research and Development Administration, "Photovoltaic conversion program: summary report ERDA 76-161", Washington, D.C., Nov. 1976.
- [4] See, for instance, various papers from Sessions 2, 7 and 13, Conf. Record, 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976.
- [5] Various papers, especially those starting on pp. 381, 449, 473, 483 and 487, IEEE Trans. on Electron Devices, "Special issue on photovoltaic devices", Vol. ED-24, No. 4, April 1977.
- [6] Various papers from sessions III-B, IV-B, V-B, VI-B and XI-B, Conf. Rec. 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978.
- [7] H.J. Hovel, "Semiconductors and Semimetals Vol. 11 Solar Cells", Academic Press, New York, 1975.
- [8] See, for instance, papers starting on pp. 429, 438, 442 and 446 in IEEE Trans. on Electron Devices, Vol. ED-24, No. 4, April 1977.
- [9] Various papers from Sessions III-A, V-A, VI-A, VII-A and VIII-A, Conf. Rec. 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978.
- [10] P.D. Maycock, "The development of photovoltaics as a power source of large scale terrestrial application", 13th IEEE Photovoltaic Specialists Conference, Conf. Rec. pp. 5-8, June 1978.
- [11] Session IV-A, "Low cost research and development for large scale production", 13th IEEE Photovoltaic Specialists Conference, Conf. Rec. pp. 238-280, June 1978.
- [12] R.J. Stirn and Y.C.M. Yeh, "Solar and laser energy conversion with Schottky barrier solar cells", Conf. Rec. 10th IEEE Photovoltaic Specialists Conference, pp. 15-24, Palo Alto, California, Nov. 13-15, 1973.

- [13] See, for instance, various papers in Session 12, "MIS and Schottky barrier cells", 12th IEEE Photovoltaic Specialists Conference, Conf. Rec. pp. 847-927, Nov. 1976.
- [14] D.L. Pulfrey, "MIS solar cells: a review", IEEE Trans. on Electron Devices, Vol. ED-25, No. 11, pp. 1308-1316, Nov. 1978.
- [15] G.C. Salter and R.E. Thomas, "Silicon solar cells using natural inversion layers found in thermally-oxidized p-silicon", Solid State Electronics, Vol. 20, pp. 95-104, 1977.
- [16] R.L. Call, "Inversion layer solar cell fabrication and evaluation", Final Report, JPL Contract No. 953461, Sept. 1973.
- [17] J. Lindmayer, "Surface inversion solar cell and method of forming same", U.S. Patent No. 3,769,558, Oct. 30, 1973.
- [18] G.C. Salter, "Investigation of silicon solar cells with field induced junctions", Technical report, Faculty of Engineering, Carleton University, Ottawa, Canada, Jan. 1975.
- [19] C.E. Norman, "Electrical and radiation characterization of an induced junction solar cell", Technical Report, Faculty of Engineering, Carleton University, Ottawa, Canada, Nov. 1975.
- [20] C.E. Norman and R.E. Thomas, "Inversion layer solar cells with 10-12% AM1 efficiencies", 12th IEEE Photovoltaic Specialists Conference, Conf. Rec. pp. 993-996, Nov. 1976.
- [21] P. Van Halen, R.E. Thomas, R. Mertens and R. Van Overstraeten, "Inversion layer silicon solar cells with MIS contact grids", 12th IEEE Photovoltaic Specialists Conf. Rec., pp. 907-912, Nov. 1976.
- [22] R.E. Theriault, "A low temperature fabrication process for the inversion layer silicon solar cell", M.Eng. thesis and technical report, Faculty of Engineering, Carleton University, Ottawa, Canada, Sept. 1978.
- [23] M.P. Thekaekara, "Solar energy outside the earth's atmosphere", Solar Energy, 14, pp. 109-127, 1973.
- [24] S.I. Sivkov, "Computation of solar radiation characteristics", Israel Program for Scientific Translations, Jerusalem, 1971. (translated from Russian)

- [25] P. Moon, Journal of the Franklin Institute, Vol. 230, p. 583, 1940. Also, see ref. [7], p. 37.
- [26] J.J. Loferski, "Theoretical considerations governing the choice of the optimum semiconductor for photovoltaic solar energy conversion", Journal of Applied Physics, Vol. 27, No. 7, pp. 777-784, July 1956.
- [27] W.C. Dash and R. Newman, "Intrinsic absorption in single-crystal germanium and silicon at 77°K and 300°K", Phys. Rev. Vol. 99, No. 4, pp. 1151-1155, Aug. 1955.
- [28] H.R. Philipp and E.A. Taft, "Optical constants of silicon in the region 1 to 10 eV", Phys. Rev. Vol. 120, No. 1, pp. 37-38, Oct. 1960.
- [29] H.P.D. Lanyon, A.K. McCurdy and R.A. Tuft, "Infrared photoresponse of silicon devices at 1.15 microns", 13th Photovoltaic Specialists Conf. Rec. pp. 60-65, June 1978.
- [30] C.R. Fang and J.R. Hauser, "Comparison of theoretical and experimental solar cell performance", 13th Photovoltaic Specialists Conf. Rec. pp. 1318-1326, June 1978.
- [31] A.S. Grove, "Physics and technology of semiconductor devices", Wiley, New York, 1967.
- [32] J. Lindmayer and J.F. Allison, "The violet cell: an improved silicon solar cell", Comsat Technical Review, Vol. 3, No. 1, pp. 1-21, Spring 1973.
- [33] A. DeVos and H.J. Pauwels, "Collection efficiency of heterojunction solar cells", IEEE Trans. on Elect. Devices, Vol. ED-24, No. 4, pp. 388-391, April 1977.
- [34] M. Wolf, "A new look at silicon solar cell performance", IEEE 8th Photovoltaic Specialists Conf. Rec. pp. 360-371, Seattle, Wash. Aug. 1970.
- [35] J.R. Hauser and P.M. Dunbar, "Performance limitations of silicon solar cells", IEEE Trans. on Electron Devices, Vol. ED-24, No. 4, pp. 305-321, April 1977.
- [36] R.A. Arndt, J.F. Allison, J.G. Haynos and A. Meulenbergh, Jr., "Optical properties of the comsat non-reflective cell", IEEE 11th Photovoltaic Specialists Conf. Rec., pp. 40-43, Scottsdale, Ariz., May 1975.

- [37] J. Mandelkorn and J.H. Lamneck, Jr., "Simplified fabrication of back surface field silicon cells and novel characteristics of such cells", 9th IEEE Photovoltaic Specialists Conf. Rec., p. 60, Silver Spring, Md, May 1972.
- [38] See, for instance, several papers on thin silicon cells in Session V-C of the 13th Photovoltaic Specialists Conf. Rec., pp. 438-458, June 1978.
- [39] K. Graff, H. Pieper and G. Goldback, "Carrier lifetime doping of p-type silicon by annealing processes", Semiconductor Silicon 1973, Electrochemical Society.
- [40] W.A. Anderson, J.K. Kim and A.E. Delahoy, "Barrier height modification in silicon Schottky (MIS) solar cells", IEEE Trans. on Elect. Dev., Vol. ED-24, No. 4, pp. 453-457, April 1977.
- [41] S.J. Fonash, "The role of the interfacial layer in metal-semiconductor solar cells", Journal of Applied Physics, Vol. 46, No. 3, pp. 1286-1289, March 1975.
- [42] R.E. Thomas, G.C. Salter, C.E. Norman and R.E. Theriault, "Conversion of solar energy to electricity by photovoltaic methods - development of inversion layer silicon solar cells", Final Report, DSS Contract No. OSQ77-00091, Carleton University, July 1978.
- [43] M.A. Green, F.D. King and J. Shewchun, "Minority carrier MIS tunnel diodes and their application to electron and photovoltaic energy conversion - I. theory", Solid State Electronics, Vol. 17, pp. 551-561, 1974.
- [44] B.E. Deal, M. Sklar, A.S. Grove and E.H. Snow, "Characteristics of the surface-state charge (Q_{ss}) of thermally oxidized silicon", J. Electrochem. Soc., Vol. 114, No. 3, pp. 266-274, March 1967.
- [45] P. Van Halen, R.P. Mertens, R.J. Van Overstraeten, R.E. Thomas and J. Van Meerbergen, "New TiO_x -MIS and SiO_2 -MIS silicon solar cells", IEEE Trans. on Elect. Dev., Vol. ED-25, No. 5, pp. 507-511, May, 1978.
- [46] F.A. Grant, "Properties of rutile (titanium dioxide)", Review of Modern Physics, Vol. 31, No. 3, pp. 646-674, July 1959.
- [47] S.Y. Chiang, B.G. Carbajal and G.F. Wakefield, "Thin tandem junction solar cell", 13th Photovoltaic Specialists Conf. Rec., pp. 1290-1293, June 1978.

- [48] O. Leistiko, A.S. Grove and C.T. Sah, "Electron and hole mobilities in inversion layers on thermally oxidized silicon surfaces", IEEE Trans. on Electron Devices, Vol. ED-12, pp. 248-254, May 1965.
- [49] H.E. Wolf, "Silicon semiconductor data", Pergamon Press, Oxford, 1969.
- [50] K.H. Zaininger and F.P. Heiman, "The C-V technique as an analytical tool: Parts I and II", Solid State Technology, Vol. 13, pp. 49-56, May 1970 and pp. 46-55, June 1970.
- [51] L.M. Terman, "An investigation of surface states at a silicon/silicon oxide interface employing metal-oxide-silicon diodes", Solid State Electronics, Vol. 5, pp. 285-299, 1962.
- [52] See, for example, several papers in IEEE Transactions on Electron Devices, Vol. ED-25, No. 4, "Special issue on fine line device fabrication", pp. 401-434, April 1978.
- [53] C.E. Norman and R.E. Thomas, "Computer modelling of inversion layer solar cells", Proc. Photovoltaic Solar Energy Conf. Luxembourg, pp. 910-919, Sept. 27-30, 1977.
- [54] J.G. Fossum, "Physical operation of back-surface-field silicon solar cells", IEEE Trans. on Elect. Dev., Vol. ED-24, No. 4, pp. 322-324, April 1977.
- [55] R.B. Godfrey and M.A. Green, "A 15% efficient MIS solar cell", Applied Physics Letters, Vol. 33, No. 7, pp. 637-639, Oct. 1978.
- [56] J.S. Johannessen, W.E. Spicer and Y.E. Strausser, "An auger analysis of the SiO₂-Si interface", Journal of Applied Physics, Vol. 47, No. 7, pp. 3028-3037, July 1976.
- [57] M.V. Sullivan and J.H. Eigler, "Electroless nickel plating for making ohmic contacts to silicon", J. Electrochem. Soc., Vol. 104, pp. 226-230, April 1957.
- [58] H.C. Lin, D.P. Spittlehouse and Y.W. Hsueh, "Contact resistance of silver ink on solar cell", 13th Photovoltaic Spec. Conf. Record, pp. 593-596, June 1978.
- [59] J.G. Fossum, R.D. Nasby and E.L. Burgess, "Development of high-efficiency p⁺-n-n⁺ back-surface-field silicon solar cells", 13th Photovoltaic Spec. Conf. Record, pp. 1294-1299, June 1978.

- [60] C.R. Fang and J.R. Hauser, "A two dimensional analysis of sheet resistance and contact resistance effects in solar cells", 13th Photovoltaic Spec. Conf. Record, pp. 1306-1311, June 1978.
- [61] P.E. Gray, D. DeWitt, A.R. Boothroyd and J.F. Gibbons, "Physical electronics and circuit models of transistors", SEEC Vol. 2, Wiley, New York, 1964, p. 85.
- [62] R.J. Handy, "Theoretical analysis of the series resistance of a solar cell", Solid State Electronics, Vol. 10, pp. 765-775, Aug. 1967.
- [63] J.G. Fossum, "Computer-aided numerical analysis of silicon solar cells", Solid State Elect., Vol. 19, pp. 269-277, 1976.
- [64] D.T. Paris and F.K. Hurd, "Basic electromagnetic theory", McGraw-Hill, Toronto, 1969.
- [65] M.P. Godlewski, C.R. Baraona and H.W. Brandhorst, Jr., "Low-high junction theory applied to solar cells", 10th Photovoltaic Spec. Conf. Rec., pp. 40-49, Nov. 13-15, 1973.
- [66] D.J. Fitzgerald and A.S. Grove, "Surface recombination in semiconductors", Surface Science, Vol. 9, pp. 347-367, 1968.
- [67] H.J. Hovel, "The effect of depletion region recombination currents on the efficiency of Si and GaAs solar cells", 10th Photovoltaic Spec. Conf. Record, pp. 34-39, 1973.
- [68] C. Lanza and H.J. Hovel, "Efficiency calculations for thin-film polycrystalline semiconductor Schottky barrier solar cells", IEEE Trans. Elect. Dev., Vol. ED-24, No. 4, pp. 392-396, April 1977.
- [69] P.A. Iles, and S.I. Soclof, "Effect of impurity doping concentration on solar cell output", 11th Photovoltaic Spec. Conf. Record, pp. 19-24, May 6-8, 1975.
- [70] B. Ross and J.R. Madigan, "Thermal generation of recombination centres in silicon", Phys. Rev., Vol. 108, No. 6, pp. 1428-1433, Dec. 1957.

APPENDIX "A"

DERIVATION OF INVERSION LAYER RESISTANCE

The contact grid geometry under consideration is depicted in Figure A.1 a). The grid lines are one centimeter long and are spaced $1/m$ centimeters apart (i.e. m lines per cm). The sheet resistance is $r_s \Omega/\square$. Because of the inherent symmetry on either side of each grid line, only the interval $0 \leq x \leq 1/2m$ need be considered. In order to simplify the analysis, two reasonable assumptions will be made: the finger width is much less than the finger spacing and the voltage across the induced junction is everywhere less than $V_{oc}/2$ so that the short circuit current flows. Under these assumptions, the lateral current density in the inversion layer is as shown in Figure A.1 b).

The power being dissipated in the sheet resistance in a segment dx long and 1 cm wide is given by:

$$p(x, x+dx) = [I(x)]^2 dR \quad ; \text{ where } dR = r_s dx \quad (A.1)$$

The total power being dissipated from $x=0$ to the centre line is the integral of equation (A.1) with $I(x)$ from Figure A.1 b) included:

$$P_T = \int_0^{1/2m} I_{sc}^2 \left(\frac{1}{2m} - x \right)^2 r_s dx = \frac{I_{sc}^2 r_s}{24 m^3} \quad (A.2)$$

Fig. A.1 Derivation of inversion layer resistance:

a) geometry between grid fingers, b) lateral current distribution within the inversion layer at short circuit.

Multiplying this by $2m$ yields the total power being dissipated per square centimeter of cell area at short circuit:

$$P_T = \frac{I_{sc}^2 r_s}{12 m^2} \quad (A.3)$$

However, the total power can also be expressed as $P_T = I_{sc}^2 R_{IL}$ where R_{IL} is the effective lumped inversion layer series resistance in $\Omega\text{-cm}^2$. Rearranging this and comparing with equation (A.3) produces the final result:

$$R_{IL} = \frac{r_s}{12 m^2} \quad (A.4)$$

This result is different by a factor of $2/3$ from the usual, simpler analysis [32] but is analytically more correct. Equation (A.4) should apply to all practical solar cells since the assumptions hold for any well designed geometry (one with low grid shading and low series resistance).

By way of an example, a typical diffused cell has six grid fingers in 2 cm for $m=3$ and an n^+ diffusion sheet resistivity of $50 \Omega/\square$, giving an " R_{IL} " = $.46 \Omega\text{-cm}^2$ or " R_{IL} " = $.116 \Omega$ for the 4 cm^2 cell. An inversion layer cell with $r_s = 20,000 \Omega/\square$ (a typical value) would require $m \geq 60$ lines/cm to match this resistance.

APPENDIX "B"

DETAILED DIFFUSED-IL CELL FABRICATION SCHEDULE

- A. Select and Measure Wafers (to characterize substrates)
- material: 1 1/2" dia., p-type, <111> silicon wafers
 - scribe identification numbers on front, near edge of wafer
 - measure wafer thickness with micrometer
 - measure wafer resistivity with 4 point probe
- B. Prefurnace Clean (to prepare wafers for high temp. furnace)
- 5 min boil in trichloroethylene (tric)
 - 15 min etch in hot Caro's acid
 - 10 min rinse in flowing deionized (DI) water
 - 5 min etch in concentrated nitric acid (HNO_3) at 75-80°C
 - 10 min DI water rinse
 - 2 min etch in 10% hydrofluoric acid (HF)
 - 10 min DI water rinse
 - blow wafers dry with clean nitrogen gas (N_2)
- C. First Oxidation (to mask the front surface during p+ diffusion)
- oxidation tube should be gettered with HCl for one hour prior to use
 - furnace temperature = 1200°C -- gas flow = 1.5 l/min O_2
 - load wafers onto boat - 5 min warm up in boat carrier
 - 30 sec push to centre of tube - 5 min dry O_2

- 4 min pyrolytic H_2O (900 ml/min H_2 plus > 600 ml/min O_2)

- 5 min dry O_2 - 30 sec pull - unload wafers

Result: ~180 nm of SiO_2 on both sides of wafers

D. Oxide Etch (to expose the backs of the wafers for diffusion)

- wax fronts of wafers (hot wax applied with glass slide)

- 2 min etch in 25% HF - 10 min DI water rinse

- blow dry with N_2 - 5 min boil in tric to remove wax

- 5 min boil in fresh tric

E. Prefurnace Clean (to prepare wafers for diffusion furnace)

- 15 min etch in hot Caro's acid - 10 min DI water rinse

- 5 min in concentrated HNO_3 at 75-80°C - 10 min DI rinse

- ~15 sec etch in 10% HF - 10 min DI water rinse

- blow dry with N_2 - load wafers onto boron predep boat

F. Boron Predeposition (p+ diffusion on back surface for BSF region)

- boron predep tube should be doped for 1 hour prior to use

- tube temperature = 1000°C (dopant source is BBr_3 liquid)

- gas flow = 1.7 l/min N_2 plus 36 ml/min O_2

- 5 min warm up in boat carrier - 30 sec push into furnace

- 5 min temperature stabilization in tube

- 30 min dope (add 26 ml/min N_2 passed over dopant to N_2 and O_2)

- 3 min flush (dopant turned off) - 30 sec pull

- 5 min cool at end of tube - unload

G. Oxide Strip (to remove boron surface deposits)

- 2 min etch in 50% HF - 10 min DI water rinse
- blow dry with N_2 - load wafers onto oxidation boat

H. Second Oxidation (to form IL structure)

- oxidation tube should be gettered for 1 hour prior to use
- tube temperature = $1200^{\circ}C$ - gas flows same as in C
- 5 min warm up in boat carrier - 30 sec push to centre
- 5 min dry O_2 - 4 min pyrolytic H_2O - 5 min dry O_2
- 5 min getter (1.2 l/min O_2 plus 30 ml/min HCl)
- 3 min flush (HCl turned off)-30 sec pull
- 2 min cool in boat carrier - unload wafers

Result: ~190 nm of SiO_2 on both sides of wafers

I. First Photolithography (to define contact grid pattern)

- prebake wafers 30 min in dry air at $200^{\circ}C$
- spin diluted, filtered Waycoat photoresist on the front of the wafers, 30 sec at 5,000 RPM.
- bake wafers 20 min at $85^{\circ}C$
- mask wafers (contact window mask) - expose to UV light for 1.5 sec
- develop photoresist (90 sec in Waycoat developer, 20 sec in clean developer, 20 sec in Waycoat thinner, 20 sec in methanol)
- blow dry with N_2 - inspect under microscope
- post bake 30 min at $145^{\circ}C$ in air prior to etching

J. Oxide Etch (to open contact windows in the oxide)

- wax backs of wafers - etch in buffered HF until through to bare silicon (-2 min depending on oxide, etch temperature, etc.)
- 10 min DI water rinse - blow dry with N_2
- inspect under microscope for complete etching
- 5 min wax removal in boiling tric - 5 min boil in fresh tric

K. Prefurnace Clean (to prepare wafers for phosphorous furnace)

- 15 min etch in hot Caro's acid - 10 min DI water rinse
- 5 min etch in HNO_3 at $75-80^\circ C$ - 10 min DI water rinse
- 10 sec etch in 10% HF - 10 min DI water rinse
- blow dry with N_2 - load wafers into phosphorous predep. boat

L. Phosphorous Predeposition (to form n^+ contact diffusions)

- phosphorous predep. tube should be doped for 1 hr prior to use
- tube temperature = $950^\circ C$ (dopant source is $POCl_3$ liquid)
- gas flows same as in F - 5 min warm up in boat carrier
- 30 sec push into centre - 5 min temperature stabilization
- 20 min dope - 3 min flush - 30 sec pull
- 2 min cool in boat carrier - unload wafers

Result: phosphorous n^+ junction depth $\sim 0.6 \mu m$

M. Oxide Heat Treatment (to raise the value of Q_{ss})

- tube temperature = $500^\circ C$ (or other temperature)
- gas flow = 2 l/min dry O_2 - load wafers onto boat
- 1 min warm up at tube mouth - 15 sec push to centre
- 80 min heat treat (less time at higher temperature)
- 15 sec pull - 1 min cool at mouth - unload wafers

N. Pre-Metal Etch (to remove phosphorosilicate glass)

- 10 sec etch in 10% HF - 10 min DI water rinse
- blow dry with N_2 - inspect oxide colour
- continue etching in 10% HF until the correct colour (dark blue) is obtained - rinse in DI water - blow dry with N_2

Result: ~110 nm of SiO_2 and open contact windows

O. Front Metallization (to contact the front of the cell)

- place wafers front surface up on evaporation plate and load into bell jar - draw a vacuum
- deposit 20 kÅ of aluminum at a rate of ~15 Å/sec
- release vacuum - unload and inspect wafers

Result: 2 µm of Al over front surface of wafers

P. Second Photolithography (to define the metal grid pattern)

- 30 min prebake at 200°C - spin photoresist on front
- 20 min bake at 85°C - align second mask over first pattern
- expose - develop - blow dry with N_2 - inspect
- 30 min post bake at 145°C just prior to etching

Q. Metal Etch (to remove unwanted aluminum)

- etch wafers in concentrated phosphoric acid (H_3PO_4) at 55-60°C, agitating constantly - etch until through plus -30 sec - 10 min DI water rinse
- blow dry with N_2 - inspect under microscope

Result: Metal grid pattern on front of cell

R. Wafer Clean (to prepare the back surface for contacting)

- remove photoresist, 10 min in J-100 microstrip at 100-110°C
- 30 min DI water rinse - blow dry with N₂
- etch SiO₂ off backs of wafers with one or more drops of concentrated HF applied in the centre and allowed to spread to edge before rinsing
- 10 min DI water rinse - blow dry with N₂

S. Back Metallization (to make contact to the backs of the cells)

- place wafers back surface up on evaporator plate and load into bell jar - draw a vacuum
- deposit 10 kÅ of aluminum at -15 Å/sec - release vacuum
- replace aluminum boule with silver crucible insert
- draw vacuum - deposit 2 kÅ of silver on top of Al
- release vacuum - unload and inspect wafers

T. Sintering (to obtain good ohmic contacts)

- test cells before sintering to determine if it is required
- furnace temperature = 350°C - gas flow = 2 l/min N₂
- 1 min warm up - 15 sec push - 5 min sinter
- 15 sec pull - 1 min cool - unload

Result: completed diffused-IL solar cells

NOTES:

- 1) Most of the chemicals used are toxic or corrosive. Appropriate safety precautions should be followed (use of rubber gloves, fume hood, wash hands, etc.)
- 2) Prefurnace cleaning must be done just prior to loading wafers into the quartz boat.
- 3) Hot Caro's acid is made by adding one part H_2O_2 to ~8 parts concentrated sulfuric acid (H_2SO_4) which has been heated to $110^\circ C$. The resulting acid should be used within 15 min.
- 4) Steps C. through G. are for BSF cells and may be omitted.
- 5) The oxidation and diffusion temperatures are arbitrary. If different temperatures are used, the times should be adjusted accordingly.
- 6) Each photolithography with its subsequent etch should be completed in one day for best results.
- 7) The high temperature steps following the boron predeposition serve to drive in the boron to an effective p+ diffusion depth of ~.6 to ~.7 μm .

APPENDIX "C"

PLANNED SOLAR CELL TEST SYSTEM

The facility currently being developed at Carleton for the testing of solar cell I-V characteristics is illustrated in Figure C.1. The system consists of three main parts, each of which will be briefly described: the test apparatus, the interface circuitry and the control computer.

An Oriel 6732 solar simulator (with a 6741 output beam assembly) is used as the light source to provide accurate simulation of the spectrum and intensity of sunlight. The test cell is held in place by a vacuum chuck. Contact to the cell is made with separate current and voltage probes to avoid errors caused by probe contact resistance. The light intensity is monitored by a photodiode mounted off to the side of the vacuum chuck.

An integrated circuit temperature sensor (Analog Devices AD590JF) is held against the back surface of the solar cell to monitor its temperature. The cell itself is held in good thermal contact with the vacuum chuck. Four thermoelectric heat pumps (Borg-Warner TM930-35 DL) allow the chuck to be cooled (or heated). Waste heat is rejected to a fan-cooled heatsink.

The interface circuitry consists of several modules for digital-to-analog (and vice versa) conversion and measurement control. The current-voltage data are obtained by biasing the cell to a known current level and measuring the resultant cell voltage. Several current ranges (20 μ A to 10 A) can be selected. A complete I-V

Fig. C.1 Schematic of computer-controlled solar cell I-V test facility.

curve is obtained by sweeping the current through its range.

The temperature control circuit adjusts the current to the thermoelectric heat pumps to maintain the sensed temperature within $\pm 0.1^\circ\text{C}$ of the set point temperature. Although not included in the present design, computer control of cell temperature and the light intensity are possible future additions (indicated in the figure by dashed control lines). All three interface modules are connected to the microcomputer data/control bus as shown in the figure.

The Radio Shack TRS-80 microcomputer provides versatile control and adaptable data analysis. The measurement software is designed to allow ease of use by an inexperienced operator. Using flexible test circuitry and a microcomputer allows many solar cell tests and analyses to be performed. These include the following: illuminated I-V curves; calculation of I_{sc} , V_{oc} , P_{max} , fill factor and possibly, efficiency; dark log (I) vs V measurements and calculation of diode parameters; measurement of light intensity and cell temperature. These data are displayed in suitable format on the CRT screen. Curves may be traced on an x-y recorder for more accurate hard copies.

The addition of computer control of light intensity and cell temperature would allow parametric measurements to be made (e.g., V_{oc} vs temperature, log (I_{sc}) vs V_{oc} , etc.). Also, the software could be expanded to do statistical analysis on a batch of cells. The entire facility as planned should be operational by July 1979.

APPENDIX "D"

FINITE DIFFERENCES SOLUTION TO THE CONTINUITY EQUATIONThe Finite Difference Approach

The problem posed in section 6.4 was to solve the one-dimensional continuity equations for holes and electrons throughout the entire thickness of the inversion layer cell. The problem is solved when $p(x)$ and $n(x)$ as shown in Figure D.1 a) are known. Since the differential equations (6.15) and (6.18) cannot be solved analytically, the finite differences numerical method was chosen. In this approach, the continuous structure of the cell is approximated by a set of discrete points in x as shown in Figure D.1 b). Thus, the thickness x becomes a set of x_i values and any variable in x , $h(x)$ becomes a set of discrete points $h(x_i) = h_i$. Thus, the continuity equations (6.15) and (6.18) are written as follows:

$$p_i = \beta E_i p_{i-1} + \beta E_i p_i + \frac{Re_i}{D_p} - \frac{G_i}{D_p} \quad (D.1)$$

$$n_i = -\beta E_i n_{i-1} - \beta E_i n_i + \frac{Re_i}{D_n} - \frac{G_i}{D_n} \quad (D.2)$$

for holes and electrons respectively. G_i indicates the average of the generation rate, $g(x)$ between two points in x .

The solution could be simplified if the x_i points were uniformly spaced. However, since the depletion depth, x_d is much narrower than the cell thickness, a great many ($>10^4$) points would be required through the bulk to accommodate the fine spacing needed

Fig. D.1 a) Hole and electron densities in an operating solar cell.
 b) Finite differences representation for the inversion layer ($0 < x < x_J$) and the p-type region ($x_J < x < w_0 - x_b$).

in the depletion region where p and n vary rapidly in x . Thus, it was decided to use a non-uniform spacing which allows the same accuracy to be achieved with fewer points (<500) even though the algebra is more tedious.

The simplest technique for solving equations (D.1) and (D.2) would be to start at one boundary, where the majority carrier density is known (e.g. $p(x) = N_a$ at $x = x_d$), and work toward the other boundary, where the minority carrier density is unknown, but where a known boundary condition can be applied. This method works well in principle, however, since p and n vary by typically six orders of magnitude from the front to the back of the cell, it would tax the numerical precision of most computers. For this reason, another approach was adopted which, again, is more complex, but (again) requires substantially less computation time. A reference point somewhere inside the cell is chosen and the computation proceeds from this point toward both boundaries where the boundary conditions are applied simultaneously.

The reference point is arbitrary, but the junction, x_j is a convenient choice since it is where the majority and minority carriers are reversed. It is also a good conceptual choice for understanding the operation of the algorithm. Hence, the carrier concentrations are referenced to the junction in the following manner:

$$p_i = a_{pi} + b_{pi}p_j + c_{pi}p_j \quad \text{and} \quad p_i = d_{pi} + e_{pi}p_j + f_{pi}p_j \quad (D.3)$$

$$n_i = a_{ni} + b_{ni}n_j + c_{ni}n_j \quad \text{and} \quad n_i = d_{ni} + e_{ni}n_j + f_{ni}n_j \quad (D.4)$$

where the terms a through f are the finite difference coefficients and the subscripts p,n refer to holes and electrons respectively. The junction reference values are p_J , n_J and their derivatives. Since x_J is chosen to be the reference point on the basis of the electric potential calculation (as described in section 3.4), it is unlikely that p_J and n_J will be equal. (In this sense, x_J is not strictly speaking the junction, but it will be very close and for convenience will be referred to as the junction.)

Solutions for $0 \leq x < x_J$

Since the approach chosen proceeds from the junction toward the front and back, the solution will be slightly different on either side of x_J . On the inversion layer side of the junction, the first derivatives of the discrete n_i and p_i distributions can be seen from Figure D.1 b) to be given by:

$$p_i = \left. \frac{dp}{dx} \right|_{x_i} = \frac{\Delta p_i}{\Delta x_i} = \frac{p_{i+1} - p_i}{x_{i+1} - x_i} \quad \text{for holes} \quad (D.5)$$

$$n_i = \left. \frac{dn}{dx} \right|_{x_i} = \frac{\Delta n_i}{\Delta x_i} = \frac{n_{i+1} - n_i}{x_{i+1} - x_i} \quad \text{for electrons} \quad (D.6)$$

By reapplying this numerical differentiation procedure, it can be shown that the second derivatives are given by:

$$\dot{p}_i = \frac{2(\dot{p}_i - \dot{p}_{i-1})}{x_{i+1} - x_{i-1}} \quad (D.7)$$

cm⁻⁵

$$\dot{n}_i = \frac{2(\dot{n}_i - \dot{n}_{i-1})}{x_{i+1} - x_{i-1}} \quad (D.8)$$

The approximation signs indicate that this approach is not exact.

However, when the number of x_i points becomes sufficiently large, the error involved will become insignificant.

The generation term in equations (D.1) and (D.2) is given by:

$$\hat{G}_i = \frac{N_{i-1} - N_i}{x_i - x_{i-1}} \quad ; \quad N_i = \int_0^\infty N_m(\lambda) [1 - R(\lambda)] e^{-\alpha(\lambda)x_i} d\lambda \quad (D.9)$$

where N_i is the number of photons penetrating to x_i . The recombination rate in equations (D.1) and (D.2) can be represented by:

$$Re_i = \frac{p_i}{\tau_i} \quad ; \quad \tau_i = \left[\frac{n_i + n_o}{n_i - \frac{n_o^2}{p_i}} \right] \tau_{pi} + \left[\frac{p_i + n_o}{n_i - \frac{n_o^2}{p_i}} \right] \tau_{ni} \quad (D.10)$$

where τ_i is the effective lifetime at x_i and is derived from the Shockley-Read-Hall recombination theory expressed in equation (6.14). The intrinsic carrier concentration is denoted here by n_o to avoid confusion with $n_i = n(x_i)$. In this way, the recombination rate is controlled by the minority carrier concentration. Since τ_i depends in a non-linear way on both n_i and p_i , it cannot be known at the outset. Thus, the algorithm requires an iterative solution, with τ_i being

calculated using the p_i , n_i values from the previous approximation (or initial estimate). Fortunately, the variation of τ_i with p_i and n_i is small and confined to positions near the junction. Hence, the iteration quickly converges (only two iterations are usually required) to a self-consistent set of p_i and n_i .

Equation (D.1) can be solved by equating it with (D.7). When equation (D.10) is added and the like terms in p_i are collected together, the result is:

$$\dot{p}_{i-1} = (1 - \delta_i \beta E_i) \dot{p}_i - \delta_i (\beta \dot{E}_i + \frac{1}{\tau_i D_p}) p_i + \delta_i \frac{\hat{G}_i}{D_p} \quad (D.11)$$

where $\delta_i = \frac{1}{2} (x_{i+1} - x_{i-1})$.

Finally, if equations (D.3) are substituted (with appropriate changes in index i) and the terms in p_j and $\dot{p}_j$ collected together, the result has the form:

$$\dot{p}_{i-1} = a_{pi-1} \dot{p}_i + b_{pi-1} p_j + c_{pi-1} \dot{p}_j$$

where:

$$\begin{aligned} a_{pi-1} &= (1 - \delta_i \beta E_i) a_{pi} - \delta_i (\beta \dot{E}_i + \frac{1}{\tau_i D_p}) d_{pi} + \delta_i \frac{\hat{G}_i}{D_p} \\ b_{pi-1} &= (1 - \delta_i \beta E_i) b_{pi} - \delta_i (\beta \dot{E}_i + \frac{1}{\tau_i D_p}) e_{pi} \\ c_{pi-1} &= (1 - \delta_i \beta E_i) c_{pi} - \delta_i (\beta \dot{E}_i + \frac{1}{\tau_i D_p}) f_{pi} \end{aligned} \quad (D.12)$$

Similarly, changing i to $i-1$ in equation (D.5), adding equations (D.3) and rearranging results in an equation of the form:

$$p_{i-1} = d_{pi-1} + e_{pi} p_J + f_{pi} \dot{p}_J$$

where:

$$d_{pi-1} = d_{pi} - (x_i - x_{i-1}) a_{pi-1}$$

$$e_{pi-1} = e_{pi} - (x_i - x_{i-1}) b_{pi-1} \quad (D.13)$$

$$f_{pi-1} = f_{pi} - (x_i - x_{i-1}) c_{pi-1}$$

Thus, equations (D.12) and (D.13) are used recursively to find the finite difference coefficients for $1 \leq i < J$ and hence, reference all the p_i in $0 \leq x < x_J$ to the junction.

The analysis for electrons proceeds in the same manner.

Adding (D.10) to (D.2) and equating with (D.8) results in:

$$\dot{n}_{i-1} = (1 + \delta_i 8E_i) \dot{n}_i + \delta_i 8\dot{E}_i n_i + \delta_i \frac{(\hat{G}_i - Re_i)}{D_n} \quad (D.14)$$

Substitution of equations (D.4) and rearrangement of the results yields the recursive formulae for the coefficients of $\dot{n}_{i-1}$:

$$a_{ni-1} = (1 + \delta_i \beta E_i) a_{ni} + \delta_i \beta E_i d_{ni} + \delta_i \left[\frac{\hat{G}_i - R e_i}{D_n} \right]$$

$$b_{ni-1} = (1 + \delta_i \beta E_i) b_{ni} + \delta_i \beta E_i e_{ni} \quad (D.15)$$

$$c_{ni-1} = (1 + \delta_i \beta E_i) c_{ni} + \delta_i \beta E_i f_{ni}$$

Placing equations (D.4) into (D.6) and rearranging produces the remaining coefficient recursion formulae:

$$d_{ni-1} = d_{ni} - (x_i - x_{i-1}) a_{ni-1}$$

$$e_{ni-1} = e_{ni} - (x_i - x_{i-1}) b_{ni-1} \quad (D.16)$$

$$f_{ni-1} = f_{ni} - (x_i - x_{i-1}) c_{ni-1}$$

These sets of equations are used to recursively reference all the values of n_i to n_j and $\dot{n}_j$ as in equations (D.4). Since the recombination R_1 is controlled by p_1 , it appears as a known term (with $\hat{G}_1$) in equations (D.15). Values of p_1 from the previous iteration are used to evaluate it in equation (D.10).

Solutions for $x_j < x \leq w_o - x_b$

On the p side of the junction, the solution procedure is the same, with electrons becoming the minority carriers and the recursions advancing the index i . Thus, the finite difference relations for holes in this region are:

$$\dot{p}_i = \frac{p_i - p_{i-1}}{x_i - x_{i-1}} \quad (D.17)$$

and

$$\ddot{p}_i = \frac{2(\dot{p}_{i+1} - \dot{p}_i)}{x_{i+1} - x_{i-1}} \quad (D.18)$$

and for electrons:

$$\dot{n}_i = \frac{n_i - n_{i-1}}{x_i - x_{i-1}} \quad (D.19)$$

and

$$\ddot{n}_i = \frac{2(\dot{n}_{i+1} - \dot{n}_i)}{x_{i+1} - x_{i-1}} \quad (D.20)$$

The recombination rate is now electron controlled:

$$Re_i = \frac{n_i}{\tau_i} \quad ; \quad \tau_i = \left[\frac{n_i + n_o}{p_i - \frac{n_o}{n_i}} \right] \tau_{pi} + \left[\frac{p_i + n_o}{p_i - \frac{n_o}{n_i}} \right] \tau_{ni} \quad (D.21)$$

Since the derivations are the same as above, only the resulting recursion formulae need be given. For the majority holes these are:

$$a_{pi+1} = (1 + \delta_i \beta E_i) a_{pi} + \delta_i \beta \dot{E}_i d_{pi} + \delta_i \left[\frac{Re_i - \hat{G}_i}{D_p} \right]$$

$$b_{pi+1} = (1 + \delta_i \beta E_i) b_{pi} + \delta_i \beta \dot{E}_i e_{pi} \quad (D.22)$$

$$c_{pi+1} = (1 + \delta_i \beta E_i) c_{pi} + \delta_i \beta \dot{E}_i f_{pi}$$

where $\delta_i = \frac{1}{2} (x_{i+1} - x_{i-1})$ as before, and:

$$d_{pi+1} = d_{pi} + (x_{i+1} - x_i) a_{pi+1}$$

$$e_{pi+1} = e_{pi} + (x_{i+1} - x_i) b_{pi+1} \quad (D.23)$$

$$f_{pi+1} = f_{pi} + (x_{i+1} - x_i) c_{pi+1}$$

Finally, for the minority electrons in the p-region:

$$a_{ni+1} = (1 - \delta_i \beta E_i) a_{ni} + \delta_i \left(\frac{1}{\tau_i D_n} - \beta \dot{E}_i \right) d_{ni} - \delta_i \frac{\hat{G}_i}{D_n}$$

$$b_{ni+1} = (1 - \delta_i \beta E_i) b_{ni} + \delta_i \left(\frac{1}{\tau_i D_n} - \beta \dot{E}_i \right) e_{ni} \quad (D.24)$$

$$c_{ni+1} = (1 - \delta_i \beta E_i) c_{ni} + \delta_i \left(\frac{1}{\tau_i D_n} - \beta \dot{E}_i \right) f_{ni}$$

and

$$d_{ni+1} = d_{ni} + (x_{i+1} - x_i) a_{ni+1}$$

$$e_{ni+1} = e_{ni} + (x_{i+1} - x_i) b_{ni+1} \quad (D.25)$$

$$f_{ni+1} = f_{ni} + (x_{i+1} - x_i) c_{ni+1}$$

Equations (D.22) to (D.25) apply to the depletion region on the bulk side of the junction. For values of x_i in the neutral bulk region (most of the cell), these equations can be greatly simplified since $E_i = \dot{E}_i = 0$ and τ_i becomes τ_n , the bulk lifetime. Furthermore, only electrons need to be considered since $p_i = N_a$ in the bulk. The result of applying the four sets of recursion formulae is that all carrier concentrations are referenced to the junction. All that remains is to find the values of p_J , n_J , $\dot{p}_J$ and $\dot{n}_J$.

Operation of the Algorithm

Since the solution is iterative, an initial approximation to $p(x)$ and $n(x)$ is required to base the recombination rate $Re(x)$ and lifetime τ_i on. For the zero bias condition, $V = 0$, the equilibrium distributions can be used, calculated from $u(x)$, the normalized potential which is derived in Chapter 3. ($u(x)$ is available in the algorithm (as $u(x_i) = u_i$) because it is needed in finding E_i and $\dot{E}_i$.) For $V \neq 0$, the p and n distributions for the previous bias voltage can be used as the initial approximation.

To solve for $p(x)$ and $n(x)$, the algorithm starts at the junction where:

$$a_J = b_J = 0, c_J = 1 \text{ and } d_J = f_J = 0, e_J = 1 \quad (D.26)$$

for both holes and electrons (that is; $\dot{p}_J = \dot{p}_J$, $p_J = p_J$ and $\dot{n}_J = \dot{n}_J$, $n_J = n_J$ in equations (D.3) and (D.4)). Then, stepping toward the front for each i , τ_i and R_i are evaluated using equation (D.10) and the previous estimates of p_i and n_i . The finite difference

coefficients at x_{i-1} are determined by applying equations (D.12), (D.13), (D.15) and (D.16). By recursive use of these equations, the algorithm steps from $i = J$, the junction to $i = 2$, yielding the coefficients a_1, b_1, c_1, d_1, e_1 and f_1 for both holes and electrons at the front surface of the cell.

Returning to the junction where equations (D.26) still apply, the algorithm next steps toward the back using equations (D.21) for the recombination and (D.22) through (D.25) for the coefficients. For holes, the algorithm stops at x_d , the edge of the depletion region and a_{pd} through f_{pd} are found. For electrons, the algorithm continues past x_d , using $\tau_i = \tau_n$ and the simplified version of equations (D.24), through the bulk, to the effective back surface $x = w_o - x_b$ where a_{nb} through f_{nb} are found.

The only remaining task is to solve for p_J, n_J and their derivatives by means of the boundary conditions. For holes, low level injection requires that $p_d = N_a$. Adding the form of p_d from equation (D.3) and rearranging yields:

$$p_J = \frac{N_a - d_{pd} - f_{pd} p_J}{e_{pd}} \quad (D.27)$$

As discussed in section 6.4, the front boundary condition for holes is $J_p(0) = 0$. When this is compared with equation (6.12), the result is: $\dot{p}_1 = \beta E_1 p_1$, where E_1 is the electric field strength at the front surface. When equations (D.3) with $i = 1$ are inserted into this result, the following is obtained:

$$a_{p1} + b_{p1} p_J + c_{p1} \dot{p}_J = \beta E_1 (d_{p1} + e_{p1} p_J + f_{p1} \dot{p}_J) \quad (D.28)$$

Substituting equation (D.27) into (D.28) yields a single equation in one unknown, p_J which has the following solution:

$$p_J = \frac{e_{pd}(\beta E_1 d_{pl} - a_{pl}) + (N_a - d_{pd})(\beta E_1 e_{pl} - b_{pl})}{e_{pd}(c_{pl} - \beta E_1 f_{pl}) + f_{pd}(\beta E_1 e_{pl} - b_{pl})} \quad (D.29)$$

Placing this result into equation (D.27) yields the value of p_J .

The boundary condition for electrons at the front ($x_1 = 0$) also follows from the low level injection assumption. As given in section 6.4, $n_1 = n_0 \exp(u_s - u_{fp} + v) = K$; where K is merely a notation to avoid confusion. When n_1 is replaced by equation (D.4) with $i = 1$, the result can be rearranged to yield:

$$n_J = \frac{K - d_{n1} - f_{n1} n_J}{e_{n1}} \quad (D.30)$$

The boundary condition at $x = w_0 - x_b$ is given by equation (6.9):

$\dot{n}(w_0 - x_b) = -q S_b n_b$. Equating this to equation (6.17) with $E(w_0 - x_b) = 0$ yields $D_n \dot{n}_b = -S_b n_b$. Substitution of equations (D.4) with $i = b$ produces the following:

$$D_n (a_{nb} + b_{nb} n_J + c_{nb} \dot{n}_J) = -S_b (d_{nb} + e_{nb} n_J + f_{nb} \dot{n}_J) \quad (D.31)$$

Equations (D.30) and (D.31) have only two unknowns. Thus, if (D.30) is substituted into (D.31), the result can be solved for $\dot{n}_J$ to yield:

$$\dot{n}_J = \frac{e_{n1}(S_b d_{nb} + D_n a_{nb}) + (K - d_{n1})(D_n b_{nb} + S_b e_{nb})}{-e_{n1}(S_b f_{nb} + D_n c_{nb}) + f_{n1}(D_n b_{nb} + S_b e_{nb})} \quad (D.32)$$

Finally, n_j is found by placing this result into equation (D.30).

With the junction conditions known, p_1 and n_1 can be found throughout the cell using the finite difference coefficients d , e and f in equations (D.3) and (D.4). As indicated above, because the recombination is calculated from an initial estimate of $p(x)$ and $n(x)$, this solution will not be exact. The entire algorithm must be iterated, using successive estimates of p_1 and n_1 , until the results converge. Usually, however, acceptable accuracy is obtained after only two iterations.

APPENDIX "E"

ILSCEL PROGRAM LISTING, DATA FILE AND SAMPLE RUN

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1.000 C                               ILSCEL
2.000 C
3.000 C   THIS PROGRAM MODELS THE OPERATION OF AN INVERSION LAYER
4.000 C   SOLAR CELL BY CALCULATING THE CURRENT-VOLTAGE CURVE UNDER
5.000 C   SPECIFIED OPERATING CONDITIONS.
6.000 C   THE FIRST PART CONCERNS A ONE DIMENSIONAL SLICE THROUGH
7.000 C   THE CELL. FROM IT'S SURFACE PROPERTIES AND THE SOLAR LIGHT
8.000 C   INTENSITY, THE PHOTON FLUX THROUGHOUT THE CELL IS DETER-
9.000 C   MINED. FOR EACH VOLTAGE VALUE, THE STEADY STATE POTENTIAL
10.000 C   AND ELECTRIC FIELD DISTRIBUTION ARE SOLVED USING POISSON'S
11.000 C   EQUATION, THESE ARE THEN USED TO CALCULATE THE MINORITY
12.000 C   CARRIER CONCENTRATION THROUGHOUT THE CELL AND HENCE, THE
13.000 C   CURRENT FLOW ACROSS THE JUNCTION USING A FINITE DIFFER-
14.000 C   ENCES SOLUTION TO THE CONTINUITY EQUATION.
15.000 C
16.000 C   START BY DECLARING THE VARIABLES AND ARRAYS
17.000 C   IMPLICIT REAL(A-Z); COMPLEX NC, PC, RC
18.000 C   INTEGER I, IJ, ID, IB, IL, IC, K, L, M, M1, NUMBER, NO, N3
19.000 C   LOGICAL GOP, GOL, GOF, GOMC, GOIV, GOIV2, GO2, DIFUSE
20.000 C   REAL X(600), XL(300), NL(300), TN(201), TP(201), G(600),
21.000 C   * DX2(600), HF(350), HDF(350), DP(350), EP(350), FP(350),
22.000 C   * DN(600), EN(350), FN(350), J1(20), V1(20), J0(20), A0(20),
23.000 C   * V2(50), J2(50), FY(40)
24.000 C   DOUBLE PRECISION NJ2, NDJ2, EN2(600), FN2(600)
25.000 C   WHERE NL = PHOTON FLUX AT XL (CM-2 S-1)
26.000 C   X, XL = DISTANCE INTO SILICON (CM)
27.000 C   TN, TP = LIFETIME OF ELECTRONS & HOLES AT X (SECONDS)
28.000 C   DP-FN = FINITE DIFFERENCE COEFFICIENTS
29.000 C   JT = OUTPUT CURRENT DENSITY (A CM-2)
30.000 C   VT = OUTPUT VOLTAGE (VOLTS)
31.000 C   THE OTHER ARRAYS HOLD FUNCTIONS OF X USED IN THE FINITE
32.000 C   DIFFERENCE ALGORITHM. MOST OF THE INTEGERS ARE STEP OR LOOP
33.000 C   COUNTERS OR POSITION MARKERS.
34.000 C   AS A PRELIMINARY, SET UP THE DEVICE STRUCTURE, OPERATING
35.000 C   CONDITIONS, MODEL PARAMETERS AND PHYSICAL CONSTANTS.
36.000 C   READ IN THE ONE DIMENSIONAL STRUCTURAL PARAMETERS.
37.000 C   READ, W0, NA, QFB, NSS, TOX, NOX, WPP, NAB
38.000 C   WHERE W0 = THICKNESS OF SOLAR CELL (CM)
39.000 C   NA = BULK DOPING LEVEL (P-TYPE) (CM-3)
40.000 C   QFB = MEASURED EFFECTIVE FLATBAND OXIDE CHARGE (CM-2)
41.000 C   NSS = MEASURED INTERFACE STATE DENSITY (CM-2 EV-1)
42.000 C   TOX = OXIDE THICKNESS (NANOMETERS)
43.000 C   NOX = REFRACTIVE INDEX OF OXIDE
44.000 C   WPP = THICKNESS OF BSF REGION (CM)
45.000 C   NAB = DOPANT DENSITY IN THE BSF REGION (CM-3)

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46.000 C READ IN THE MINORITY CARRIER LIFETIME COEFFICIENTS
47.000     READ,TP0,TPP,TPE,TN0,TNP,TNE,TBULK
48.000 C READ IN THE OPERATING CONDITIONS (AIR MASS, ETC.)
49.000     READ,TEMP,MAIR,KSUN
50.000 C READ IN THE MODEL PARAMETER AND PRINTOUT FLAGS
51.000     READ,NUMBER,GOP,GOL,GOF,GOMC,GOIV,GOIV2,GO2
52.000 C SET OR CALCULATE THE PHYSICAL CONSTANTS
53.000     Q=1.6E-19;ESI=1.04E-12;BETA=11538./TEMP
54.000     NI=3.73E16*TEMP**1.5*EXP(-7014./TEMP)
55.000     LDI=16.746*SQRT(TEMP/NI)
56.000 C
57.000 C     MOVE ON TO FIND THE LIGHT FLUX THROUGHOUT THE CELL.
58.000 C FIRST FILL THE LIGHT POSITION VECTOR. MAKE THE POINTS CLOSE
59.000 C TOGETHER AT THE FRONT AND FURTHER APART AT THE BACK.
60.000     I=0;XT=0.0;WB=W0-WPP
61.000     DELX=2E-7;DX=2.0*W0/NUMBER
62.000     10 I=I+1;NL(I)=0.0
63.000     XL(I)=XT;XT=XT+DELX
64.000     IF (DELX.LT.DX) DELX=1.25*DELX
65.000     IF(XT.LT.WB) GO TO 10
66.000     IL=I;XL(IL)=WB
67.000 C     CALCULATE THE NUMBER OF PHOTONS ENTERING THE CELL AT EACH
68.000 C WAVELENGTH, USING THE SOLAR SPECTRUM AND OXIDE REFLECTANCE
69.000     ROX=(1.0-NOX)/(1.0+NOX);AOX=12.56637*NOX*TOX
70.000     20 READ,LAMBDA,NSI,ALPHA,NL0,TAIR
71.000 C WHERE NSI = REAL PART OF THE SILICON REFRACTIVE INDEX
72.000 C     LAMBDA = WAVELENGTH OF LIGHT (NM)
73.000 C     ALPHA = ABSORPTION COEFFICIENT OF SILICON (CM-1)
74.000 C     NL0 = AIR MASS ZERO SPECTRUM (CM-2 S-1 NM-1)
75.000 C     TAIR = TRANSMISSION COEFFICIENT OF ONE AIR MASS
76.000     IF(LAMBDA.EQ.0.0) GO TO 40
77.000     NL0=NL0*KSUN*TAIR**MAIR
78.000     ALPHA=ALPHA*(1.0+(.43E-3+3.17E-6*LAMBDA)*(TEMP-300.))
79.000     NSI=NSI*(1.0+4.25E-5*(TEMP-300.))
80.000     NC=CMPLX(NSI,-ALPHA*LAMBDA/12.566E7)
81.000     PHASE=CMPLX(0.0,AOX/LAMBDA)
82.000     RC=(NOX-NC)/(NOX+NC)*CEXP(-PHASE)
83.000     RC=(ROX+RC)/(1.0+ROX*RC)
84.000     RL=CABS(RC)**2.0
85.000     NL0=20.0*NL0*(1.-RL)
86.000 C NOW FILL IN THE PHOTON FLUX ARRAY USING ALPHA TO FIND HOW
87.000 C MANY OF NL0 ARE LEFT AT EACH XL(I) INTO THE SILICON.
88.000     I=0
89.000     30 I=I+1;DELTA=NL0*EXP(-ALPHA*XL(I))
90.000     NL(I)=NL(I)+DELTA
91.000     IF(DELTA/NL(I).LT.1E-7) GO TO 20
92.000     IF(I.LT.IL) GO TO 30
93.000     GO TO 20
94.000 C PRINTOUT THE NL(X) DISTRIBUTION AND THE GENERATION RATE
95.000 C FOR EVERY M'TH VALUE OF XL IF GOL IS 'TRUE'.
96.000     40 M=NUMBER/15+1
97.000     IF(.NOT.GOL) GO TO 60
98.000     OUTPUT ' I XL(I) NL(XL) GL(XL)'
99.000     I=3-M
100.000     50 I=I+M-1;GL=(NL(I-1)-NL(I+1))/(XL(I+1)-XL(I-1))

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101.000      PRINT,I,XL(I),NL(I),GL
102.000      IF(I.LE.IL-M) GO TO 50
103.000 C    BEFORE WE CAN GO ON TO MODELLING THE CELL, WE MUST
104.000 C FIRST CALCULATE MANY OTHER PARAMETERS AND CONSTANTS:
105.000 C BULK MOBILITY AND LIFETIME TEMPERATURE COEFFICIENTS;
106.000      60 MUP=(3E2/TEMP)**2.7*(43.+1./(1.47E-13*NA**.614+2.22E-3))
107.000      MUN=(3E2/TEMP)**2.5*(60.+1./(4.75E-13*NA**.549+7.58E-4))
108.000      PTP=TPP*EXP(-1154./TEMP);PTN=TPN*EXP(-1615./TEMP)
109.000      TBULK=TP0+(TBULK-TP0)*EXP(1154.*(3.33E-3-1./TEMP))
110.000 C EFFECTIVE BSF SURFACE RECOMBINATION VELOCITY (AT WB), SB;
111.000      MUB=(3E2/TEMP)**2.5*(60.+1./(4.75E-13*NAB**.549+7.58E-4))
112.000      TNB=TN0+PTN*NAB**TNE;LN=SQRT(MUN*TBULK/BETA)
113.000      LNB=SQRT(MUB*TNB/BETA);P1=EXP(WPP/LNB)
114.000      IF(WPP.EQ.0.0) SB=1E7;GO TO 65
115.000      SB=NA*MUN/(NAB*BETA*LN)*(P1+1./P1)/(P1-1./P1)
116.000 C BULK FERMI LEVEL AND OTHER PHYSICAL CONSTANTS;
117.000      65 P2=NA/NI;UFP=ALOG(P2)
118.000      NISQ=NI*NI;BLDI=BETA*LDI
119.000      DDP=MUP/BETA;DDN=MUN/BETA;TBLDSQ=2.0*BLDI*LDI
120.000 C AND AN ESTIMATE OF THE OPEN CIRCUIT VOLTAGE.
121.000      VOC1=ALOG(KSUN*.045*(1.-.33*SQRT(MAIR)))/(Q*NISQ/NA*
122.000      * SQRT(DDN/TBULK))/BETA
123.000 C PRINTOUT SOME OF THESE PARAMETERS IF GOP IS 'TRUE'.
124.000      IF(GOP) OUTPUT NI,MUP,MUN,SB,TBULK
125.000 C SET UP VARIOUS BOUNDARY AND INITIAL CONDITIONS:
126.000      IJ=NUMBER+1
127.000      DEEX=W0/NUMBER;X(1)=0.0;USF=25.0
128.000      VINT=0.0;K=0
129.000 C
130.000 C    THE FIRST TASK FOR THE MODEL IS TO SOLVE POISSON'S
131.000 C EQUATION AT THIS VOLTAGE TO OBTAIN THE POTENTIAL, ELECTRIC
132.000 C FIELD AND ITS DERIVATIVE AT EACH POINT UP TO THE BULK.
133.000 C THESE ARE THEN USED ALONG WITH THE LIFETIME AND THE KNOWN
134.000 C LIGHT FLUX TO FILL THE FINITE DIFFERENCE VECTORS, HF(X),
135.000 C HDF(X),G(X) & DX2(X) THROUGHOUT THE CELL. THE CELL IS
136.000 C DIVIDED INTO THREE AREAS FOR THIS PURPOSE: FRONT TO JUNCTION,
137.000 C JUNCTION TO EDGE OF DEPLETION, AND THE BULK.
138.000 C
139.000 C FIRST, ITERATIVELY CALCULATE THE SURFACE POTENTIAL, USF.
140.000      70 K=K+1;VEE=BETA*VINT;P3=EXP(VEE)
141.000      IF(GOF.OR.GOMC) OUTPUT ' ',VINT,' '
142.000      80 QS=ESI/(GEE(USF,P2,P3)*BLDI)
143.000      QOX=Q*(QFB-USF*NSS/BETA)
144.000      USF=USF+2.0*ALOG(QOX/QS)
145.000      IF(ABS((QOX-QS)/QOX).GT..001) GO TO 80
146.000 C SETUP THE SURFACE CONDITIONS AND POTENTIAL STEP SIZES.
147.000      G1=GEE(USF,P2,P3);EFS=1.0/(G1*BLDI)
148.000      U1=USF;P1=EXP(U1);N2=NL(1)
149.000      IF(GOF) OUTPUT ' I      X(I)      U(X)      EF(X) '
150.000      DELU=(USF-UFP+VEE/2.0)/NUMBER;DU=DELU/3.0
151.000      I=1;L=1
152.000 C FIND THE ELECTRIC FIELD, ITS DERIVATIVE & LIFETIMES AT X.
153.000      90 EF=1.0/(G1*BLDI)
154.000      DEF=(P2/P1-P1*P3/P2-P2+1./P2)/TBLDSQ
155.000      IF(GOF.AND.(I-1)/M.EQ.1.0*(I-1)/M) PRINT,I,X(I),U1,EF,DEF

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156.000      N1=NA+P1*NI/P2
157.000      TP(I)=TP0+PTP*N1**TPE
158.000      TN(I)=TNO+PTN*N1**TNE
159.000 C DECREMENT THE POTENTIAL, U1 AND DO A TEN SLICE NUMERICAL
160.000 C INTEGRATION OF 'GEE' TO FIND THE NEXT POSITION, X(I+1).
161.000      U1=U1-DELU;P1=EXP(U1)
162.000      DG=0.0;G2=GEE(U1,P2,P3)
163.000      DO 100 IC=1,2,1;DG=DG+GEE(U1+IC*DU,P2,P3)
164.000      100 CONTINUE
165.000      X(I+1)=X(I)+LDI*DU*(.5*(G1+G2)+DG)
166.000      G1=G2
167.000 C FILL UP THE FINITE DIFF. VECTORS FOR ALL BUT THE FIRST SPOT.
168.000      IF(I.EQ.1) GO TO 110
169.000      DX=(X(I+1)-X(I-1))/2.;DX2(I)=DX
170.000      N1=NL(L-1);X1=XL(L-1)
171.000      N1=N1-(X(I)-X1)*(N1-NL(L))/(XL(L)-X1)
172.000      G(I)=DX*(N2-N1)/(X(I)-X(I-1));N2=N1
173.000      HF(I)=BETA*EF*DX
174.000      HDF(I)=BETA*DEF*DX
175.000 C STEP INTO THE SILICON BY INCREMENTING I (AND PERHAPS L) AND
176.000 C REPEAT THE ABOVE UNTIL WE REACH THE JUNCTION (IJ).
177.000      110 I=I+1
178.000      120 IF(X(I).LE.XL(L)) GO TO 130
179.000      L=L+1;GO TO 120
180.000      130 IF (I.LE.IJ) GO TO 90
181.000 C HAVING REACHED THE JUNCTION, PRINTOUT THE FIELD VALUES
182.000 C THERE AND RESET (OR LABEL) THE INITIAL CONDITIONS.
183.000      U1=UFP-VEE/2.0
184.000      IF(GOF) PRINT,IJ,X(IJ),U1,EF,DEF
185.000      NJUNK=N1;TPP=TP(IJ)
186.000      DELU=2.0*U1/NUMBER;DU=DELU/3.0
187.000      U1=U1-DELU;G1=GEE(U1,P2,P3)
188.000 C PROCEED INTO THE DEPLETION REGION AS ABOVE. NOTE THAT THE
189.000 C GENERATION, G(I) IS SHIFTED +1 IN I TO ACCOMMODATE TWO VALUES
190.000 C AT THE JUNCTION (ONE FOR EACH SIDE). ELECTRON MOBILITY IS
191.000 C USED AND THE LIFETIMES ARE CONSTANT (TPP & TBULK)..
192.000      140 N1=NL(L-1);X1=XL(L-1)
193.000      N1=N1-(X(I)-X1)*(N1-NL(L))/(XL(L)-X1)
194.000      G(I)=DX*(N2-N1)/(X(I)-X(I-1));N2=N1
195.000      HF(I-1)=BETA*EF*DX
196.000      HDF(I-1)=BETA*DEF*DX
197.000      P1=EXP(U1)
198.000      EF=1./(G1*BLDI)
199.000      DEF=(P2/P1-P1*P3/P2-P2+1./P2)/TBULDSQ
200.000      IF(GOF.AND.I/M.EQ.1.0*I/M) PRINT,I,X(I),U1,EF,DEF
201.000 C DECREMENT THE POTENTIAL AND SEE IF WE'VE REACHED THE BULK.
202.000      U1=U1-DELU;IF(U1.LE..01) GO TO 170
203.000      DG=0.0;G2=GEE(U1,P2,P3)
204.000      DO 150 IC=1,2,1;DG=DG+GEE(U1+IC*DU,P2,P3)
205.000      150 CONTINUE
206.000      X(I+1)=X(I)+LDI*DU*(.5*(G1+G2)+DG);G1=G2
207.000      DX=(X(I+1)-X(I-1))/2.0
208.000      DX2(I)=DX;I=I+1
209.000      160 IF(X(I).LE.XL(L)) GO TO 140
210.000      L=L+1;GO TO 160

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211.000 C LABEL THE END OF THE DEPLETION REGION.
212.000 170 ID=I+1;U1=U1+DELU
213.000 IF(GOF) PRINT,I,X(I),U1,EF,DEF
214.000 DDX=X(I)-X(I-1);DX=1.05*DDX
215.000 HF(I)=BETA*EF*DX
216.000 HDF(I)=BETA*DX*DEF
217.000 DX2(I)=DX;I=I+1
218.000 C FIND THE X, DX2 AND G VECTORS THROUGHOUT THE BULK.
219.000 DDX=1.1*DDX;X(I)=X(ID-1)+DDX
220.000 180 IF(X(I).LE.XL(L)) GO TO 190
221.000 L=L+1;GO TO 180
222.000 190 N1=NL(L-1);X1=XL(L-1)
223.000 N1=N1-(X(I)-X1)*(N1-NL(L))/(XL(L)-X1)
224.000 G(I)=DX2(I-1)*(N2-N1)/(X(I)-X(I-1))
225.000 N2=N1
226.000 IF(DDX.LT.DEEX) DDX=1.1*DDX
227.000 X(I+1)=X(I)+DDX
228.000 IF(X(I+1).GE.WB) GO TO 200
229.000 DX2(I)=(X(I+1)-X(I-1))/2.0
230.000 I=I+1;GO TO 180
231.000 C WE HAVE REACHED THE BACK SURFACE SO LABEL IT.
232.000 200 IB=I
233.000 C
234.000 C WE CAN NOW GO ON TO FIND THE TOTAL CURRENT FLOW; THE SUM
235.000 C OF THE MINORITY CURRENTS, JP AND JN AT THE JUNCTION. FROM
236.000 C AN INITIAL APPROXIMATION OF P(X) AND N(X), THE ALGORITHM
237.000 C WORKS TOWARD THE FRONT AND BACK TO FIND P & N AND THEIR
238.000 C DERIVATIVES AT THE JUNCTION (PJ,NJ,PDJ,NDJ). THESE THEN FORM
239.000 C THE BASIS OF A NEW APPROXIMATION OF P(X) AND N(X). THE
240.000 C ALGORITHM IS ITERATED UNTIL SUFFICIENT SELF CONSISTENCY IS
241.000 C ACHIEVED.
242.000 C
243.000 C FIRST, FIND THE INITIAL APPROXIMATION OF P(X) AND N(X) AT
244.000 C ZERO VOLTS. FOR NON-ZERO VOLTAGES, THE PREVIOUS DISTRIBUTIONS
245.000 C ARE USED.
246.000 IF(K.GT.1) GO TO 230
247.000 PJ=0.;PDJ=0.;NJ=0.;NDJ=0.
248.000 I=1;U1=USF
249.000 210 P1=EXP(U1-UFP)
250.000 DP(I)=NI*(1./P1+KSUN)
251.000 DN(I)=NI*(P1+KSUN)
252.000 I=I+1;U1=U1-DELU
253.000 IF(U1.GT.0.0) GO TO 210
254.000 NX=20.0*KSUN*NI
255.000 220 DN(I)=NX
256.000 I=I+1;IF(I.LE.IB) GO TO 220
257.000 230 NLP=NL(1)-NJUNK;NLN=NJUNK-NL(IL)
258.000 C SET ITERATION COUNTER, M1.
259.000 M1=0
260.000 240 M1=M1+1;NLAST=NX
261.000 C SETUP THE JUNCTION BOUNDARY CONDITIONS.
262.000 I=IJ
263.000 NXJ=DN(I)+EN(I)*NJ+FN(I)*NDJ
264.000 XJ=DP(I)+EP(I)*PJ+FP(I)*PDJ
265.000 P1=NXJ-NISQ/PXJ

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266.000      TAU=((NXJ+NI)*TP(I)+(PXJ+NI)*TN(I))/P1
267.000      R1=PXJ/TAU
268.000      AP1=0.;AN1=0.;BP1=0.;BN1=0.;CP1=1.;CN1=1.0
269.000      DP(I)=0.;DN(I)=0.;EP(I)=1.;EN(I)=1.;FP(I)=0.;FN(I)=0.
270.000 C STEP TOWARD THE FRONT USING THE FINITE DIFF. ALGORITHM.
271.000      250 I=I-1
272.000      NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
273.000      PX=DP(I)+EP(I)*PJ+FP(I)*PDJ
274.000      I=I+1;H1=1.0+HF(I);H2=HDF(I)
275.000      AN1=H1*AN1+H2*DN(I)+(G(I)-DX2(I)*R1)/DDN
276.000      BN1=H1*BN1+H2*EN(I)
277.000      CN1=H1*CN1+H2*FN(I)
278.000      H1=2.0-H1;H2=H2+DX2(I)/(TAU*DDP)
279.000      AP1=H1*AP1-H2*DP(I)+G(I)/DDP
280.000      BP1=H1*BP1-H2*EP(I)
281.000      CP1=H1*CP1-H2*FP(I)
282.000      XX=X(I)-X(I-1)
283.000      DN(I-1)=DN(I)-XX*AN1;DP(I-1)=DP(I)-XX*AP1
284.000      EN(I-1)=EN(I)-XX*BN1;EP(I-1)=EP(I)-XX*BP1
285.000      FN(I-1)=FN(I)-XX*CN1;FP(I-1)=FP(I)-XX*CP1
286.000      I=I-1;P1=NX-NISQ/PX
287.000      TAU=((NX+NI)*TP(I)+(PX+NI)*TN(I))/P1
288.000      R1=PX/TAU;IF(I.GT.1) GO TO 250
289.000 C WE'VE REACHED THE FRONT. RETURN TO THE JUNCTION AND RESET
290.000 C THE INITIAL CONDITIONS THERE.
291.000      I=IJ;P1=PXJ-NISQ/NXJ
292.000      TAU=((NXJ+NI)*TPP+(PXJ+NI)*TBULK)/P1
293.000      R1=NXJ/TAU
294.000      APB=0.;ANB=0.;BPB=0.;BNB=0.;CPB=1.;CNB=1.0
295.000 C STEP TOWARD THE BACK USING THE FINITE DIFF. ALGORITHM.
296.000      260 I=I+1
297.000      NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
298.000      PX=DP(I)+EP(I)*PJ+FP(I)*PDJ
299.000      I=I-1;H1=1+HF(I);H2=HDF(I)
300.000      APB=H1*APB+H2*DP(I)+(DX2(I)*R1-G(I+1))/DDP
301.000      BPB=H1*BPB+H2*EP(I)
302.000      CPB=H1*CPB+H2*FP(I)
303.000      H1=2.0-H1;H2=DX2(I)/(TAU*DDN)-H2
304.000      ANB=H1*ANB+H2*DN(I)-G(I+1)/DDN
305.000      BNB=H1*BNB+H2*EN(I)
306.000      CNB=H1*CNB+H2*FN(I)
307.000      XX=X(I+1)-X(I)
308.000      DP(I+1)=DP(I)+XX*APB;DN(I+1)=DN(I)+XX*ANB
309.000      EP(I+1)=EP(I)+XX*BPB;EN(I+1)=EN(I)+XX*BNB
310.000      FP(I+1)=FP(I)+XX*CPB;FN(I+1)=FN(I)+XX*CNB
311.000      I=I+1;P1=PX-NISQ/NX
312.000      TAU=((NX+NI)*TPP+(PX+NI)*TBULK)/P1
313.000      R1=NX/TAU;IF(I.LT.ID) GO TO 260
314.000      EN2(I)=EN(I);FN2(I)=FN(I)
315.000 C CONTINUE TOWARD THE BACK THROUGH THE BULK SILICON.
316.000      270 H2=DX2(I)/(TAU*DDN)
317.000      ANB=ANB+H2*DN(I)-G(I+1)/DDN
318.000      BNB=BNB+H2*EN2(I)
319.000      CNB=CNB+H2*FN2(I)
320.000      XX=X(I+1)-X(I)

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321.000      DN(I+1)=DN(I)+XX*ANB
322.000      EN2(I+1)=EN2(I)+XX*BNB
323.000      FN2(I+1)=FN2(I)+XX*CNB
324.000      I=I+1
325.000      IF(I.LT.IB) GO TO 270
326.000 C WE HAVE REACHED THE BACK. NOW USE THE FRONT AND BACK BOUND-
327.000 C ARY CONDITIONS TO FIND NEW ESTIMATES OF PJ,PDJ & NJ,NDJ.
328.000      PDJ=(EP(ID)*AP1+(NA-DP(ID))*(BP1-BETA*EFS*EP(1))-BETA*
329.000      * EFS*EP(ID)*DP(1))/(BP1*FP(ID)-CP1*EP(ID)+BETA*EFS*
330.000      * (FP(1)*EP(ID)-EP(1)*FP(ID)))
331.000      PJ=(NA-DP(ID)-FP(ID)*PDJ)/EP(ID)
332.000      P1=NI*EXP(USF-UFP+VEE)
333.000      NDJ2=(EN(1)*(SB*DN(IB)+DDN*ANB)+(P1-DN(1))*(DDN*BNB+SB*
334.000      * EN2(IB)))/(FN(1)*(DDN*BNB+SB*EN2(IB))-EN(1)*(SB*FN2(IB)+
335.000      * DDN*CNB))
336.000      NJ2=(P1-DN(1)-FN(1)*NDJ2)/EN(1)
337.000      NJ=NJ2;NDJ=NDJ2
338.000      NX=DN(IB)+EN2(IB)*NJ2+FN2(IB)*NDJ2
339.000      IF(ABS((NX-NLAST)/NX).GT..02.AND.M1.LT.5) GO TO 240
340.000 C WE HAVE FOUND THE CORRECT VALUES OF PJ,NJ,ETC. SO WE CAN
341.000 C FIND THE HOLE AND ELECTRON CURRENTS CROSSING THE JUNCTION
342.000 C THIS IS DONE BY INTEGRATING THE RECOMBINATION THROUGHOUT
343.000 C THE CELL AND SUBTRACTING IT FROM THE GENERATION
344.000      I=IJ;RTOTL=0.0
345.000      P1=NJ-NISQ/PJ
346.000      TAU=((NJ+NI)*TP(I)+(PJ+NI)*TN(I))/P1
347.000      R1=PJ/TAU;RJ=R1
348.000 275 I=I-1
349.000      NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
350.000      PX=DP(I)+EP(I)*PJ+FP(I)*PDJ
351.000      P1=NX-NISQ/PX
352.000      TAU=((NX+NI)*TP(I)+(PX+NI)*TN(I))/P1
353.000      R2=PX/TAU
354.000      RTOTL=RTOTL+0.5*(R1+R2)*(X(I+1)-X(I))
355.000      R1=R2;IF(I.GT.1) GO TO 275
356.000      JP=Q*(NLP-RTOTL);QP=JP/(Q*NLP)
357.000      I=IJ;RTOTL=0.0;R1=RJ
358.000 276 I=I+1
359.000      NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
360.000      PX=DP(I)+EP(I)*PJ+FP(I)*PDJ
361.000      P1=PX-NISQ/NX
362.000      TAU=((NX+NI)*TP(I)+(PX+NI)*TBULK)/P1
363.000      R2=NX/TAU
364.000      RTOTL=RTOTL+0.5*(R1+R2)*(X(I)-X(I-1))
365.000      R1=R2;IF(I.LT.ID) GO TO 276
366.000 277 I=I+1
367.000      NX=DN(I)+EN2(I)*NJ2+FN2(I)*NDJ2
368.000      R2=NX/TBULK
369.000      RTOTL=RTOTL+0.5*(R1+R2)*(X(I)-X(I-1))
370.000      R1=R2;IF(I.LT.IB) GO TO 277
371.000      RTOTL=RTOTL+NX*(WB-X(IB))/TBULK
372.000      JN=Q*(NLN-RTOTL-SB*NX);QN=JN/(Q*NLN)
373.000 C PRINTOUT P(X) & N(X) AND THE CURRENTS IF 'GOMC' IS-'TRUE'
374.000      IF(.NOT.GOMC) GO TO 290
375.000      OUTPUT ' ', I, X(I), N(X), P(X)

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376.000      I=1
377.000 280 PX=DP(I)+EP(I)*PJ+FP(I)*PDJ
378.000      NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
379.000      PRINT,I,X(I),NX,PX
380.000      I=I+M;IF(I.LT.ID) GO TO 280
381.000      I=ID;NX=DN(I)+EN(I)*NJ+FN(I)*NDJ
382.000      PRINT,I,X(I),NX,NA
383.000 281 I=I+M
384.000      NX=DN(I)+EN2(I)*NJ2+FN2(I)*NDJ2
385.000      PRINT,I,X(I),NX
386.000      IF(I.LE.IB-M) GO TO 281
387.000      OUTPUT ' '
388.000      PRINT,PJ,PDJ,JP,QP
389.000      PRINT,NJ,NDJ,JN,QN
390.000 C CALCULATE THE TOTAL CURRENT AND FILL THE J1 & V1 ARRAYS.
391.000      290 J1(K)=JP+JN;V1(K)=VINT
392.000 C GO ON TO THE NEXT VOLTAGE IF THE CURRENT IS POSITIVE.
393.000      READ,FV;VINT=FV*VOC1
394.000      IF(J1(K).GT.0.0.OR.K.LT.3) GO TO 70
395.000 C FINALLY, PRINT OUT THE I-V POINTS IF GOIV IS 'TRUE'.
396.000      M1=K-1;IF(.NOT.GOIV) GO TO 310
397.000      OUTPUT ' ','ONE DIMENSIONAL I-V CURVE',' '
398.000      OUTPUT ' ' K ' ' V ' ' I(V) ' ',' '
399.000      300 PRINT,K,V1(K),J1(K)
400.000      K=K-1;IF(K.GE.1) GO TO 300
401.000      310 IF(.NOT.GO2) STOP
402.000 C
403.000 C
404.000 C THE SECOND PART OF THE PROGRAM MODELS THE RESISTIVE
405.000 C LOSSES INVOLVED IN CURRENT FLOW THROUGH THE INVERSION LAYER
406.000 C AND SUBSTATE TO THE CONTACT REGIONS AND THE THROUGH THE
407.000 C METAL GRID GEOMETRY TO THE EXTERNAL CONTACT PAD. OTHER
408.000 C EFFECTS INCLUDED IN THIS "QUASI 3-DIMENSIONAL" MODEL ARE:
409.000 C INJECTION LOSSES AT THE CONTACTS; MINORITY CARRIER DIFF-
410.000 C USION AND COLLECTION UNDER THE CONTACTS; AND ADDITIVE FRINGE
411.000 C CURRENTS AROUND THE CELL'S PERIPHERY. ALL THE CURRENTS
412.000 C PRINTED OUT ARE PER SQ CM OF CELL AREA.
413.000 C
414.000 C FIRST, FIND THE EXPONENTIAL INTERPOLATION PARAMETERS, J0 & A0
415.000      A0(1)=1.0;K=1;JSC=J1(1)
416.000      J0(1)=(JSC-J1(2))*EXP(-BETA*V1(2))
417.000      320 K=K+1
418.000      A0(K)=BETA*(V1(K+1)-V1(K))/ALOG((JSC-J1(K+1))/(JSC-J1(K)))
419.000      J0(K)=(JSC-J1(K+1))*EXP(-BETA*V1(K+1)/A0(K))
420.000      IF(K.LT.M1) GO TO 320
421.000 C FIND THE OPEN CIRCUIT VOLTAGE
422.000      VOC1=A0(K)*ALOG(JSC/J0(K))/BETA
423.000 C FIND AND READ IN THE CELL'S GRID GEOMETRY DATA.
424.000      330 READ,FV
425.000      IF(FV.NE.0.0) GO TO 330
426.000      READ,NF,WF,WD,WC,WE,RHOMET,RHOCON,ACELL,DIFUSE
427.000 C WHERE NF = NUMBER OF CONTACT GRID FINGERS PER CM.
428.000 C WF = WIDTH OF METAL GRID FINGER (CM)
429.000 C WD = WIDTH OF CONTACT DIFFUSION (CM)
430.000 C WC = WIDTH OF MAIN CONTACT BAR NEAR BOND PAD (CM)

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431.000 C      WE = WIDTH OF PERIPHERY EDGE BAND      (CM)
432.000 C      RHOMET = TOP METAL SHEET RESISTIVITY (OHMS PER SQUARE)
433.000 C      RHOCON = CONTACT RESISTIVITY      (OHMS-CM2)
434.000 C      ACELL = AREA OF THE SOLAR CELL      (CM2)
435.000 C      DIFUSE = 'TRUE' IF DIFFUSED CONTACTS ARE USED
436.000 C SET THE THREE DIMENSIONAL MODEL PARAMETERS.
437.000      NO=10;N3=5
438.000 C CALCULATE OR SET THE CONTACT DIODE DARK CURRENT PARAMETERS.
439.000      IF(DIFUSE) GO TO 332
440.000      P1=WB/LN;P2=EXP(P1);P3=1./P2
441.000      P1=P2+P3;P2=P2-P3;P3=SB*LN/DDN
442.000      J01=Q*NISQ*DDN/LN/NA*((P3*P1+P2)/(P3*P2+P1))
443.000      J02=Q*NI*X(ID)/(SQRT(TPP*TBULK)*UFP)*1.57
444.000      A1=1.0;A2=2.0;GO TO 335
445.000 332 READ,J01,A1,J02,A2
446.000      J01=J01*EXP(.0022*BETA/A1)**(TEMP-300.)
447.000      J02=J02*NI/1.15E10
448.000 C CALCULATE AND PRINTOUT THE INVERSION LAYER LATERAL MOBILITY.
449.000 335 MUL=.45*MUN*(6E4/EFS)**.333
450.000      MUL=AMIN1(MUL,.45*MUN)
451.000      IF(GOP) OUTPUT MUL
452.000 C CALCULATE THE CURRENT REDISTRIBUTION FACTORS, FY.
453.000      LY=9.2E-4*(1.0-23E-4/WB)
454.000      DY=(1./NF-WF)/(2.*NO);I=1
455.000 340 XX=DY*(1-.5)
456.000      FY(I)=1-.35*EXP(-SQRT(XX/LY))+.35*EXP(-SQRT((XX+WF)/LY))
457.000      I=I+1;IF(I.LE.NO) GO TO 340
458.000 C CALCULATE SOME DERIVED VALUES.
459.000      WZ=.5*(1.-WC/2.);R0=DY/(MUL*WZ)
460.000      VSF=(USF+VEE)/BETA;QD0=SQRT(2.*Q*ESI*NA)
461.000      ALD=DY*WZ;AREA=N0*ALD+WZ*WF/2.
462.000      RCON=RHOCON*2./(WZ*WD)
463.000      RSUB=WB/(Q*MUP*NA*AREA)
464.000 C SETUP THE VOLTAGE STEP SIZE AND INITIAL VALUES.
465.000      DV=.001/KSUN;VOUT=VOC1
466.000      VN=VOC1+DV/2.;L=1
467.000 C SET THE BOUNDARY CONDITIONS AT THE END OF THE INVERSION
468.000 C LAYER (HALFWAY BETWEEN GRID FINGERS)
469.000 350 LASTV=VOUT;VN=VN-DV;VOUT=VN
470.000      IT=0.0;ICON=0.0;I=N0;K=M1
471.000 C FIND THE CURRENT FLOWING OUT OF THIS ONE DIMENSIONAL SLICE BY
472.000 C EXPONENTIAL INTERPOLATION OF THE J1 AND V1 DATA POINTS.
473.000 360 IF(VOUT.GT..3*VOC1) GO TO 370
474.000      II=JSC;GO TO 390
475.000 370 IF(VOUT.GT.V1(K)) GO TO 380
476.000      K=K-1;GO TO 370
477.000 380 II=JSC-J0(K)*EXP(BETA*VOUT/A0(K))
478.000 C ADD UP THE COLLECTED AND REDISTRIBUTED CURRENTS.
479.000 390 JI=ALD*II;IT=IT+FY(I)*JI
480.000      ICON=ICON+(1.-FY(I))*JI*EXP(-I*DY/LN)
481.000 C SUBTRACT THE I L SHEET RESISTANCE VOLTAGE DROP FROM VOUT.
482.000      VOUT=VOUT-IT*R0/(QOX-QD0*SQRT(VSF-VOUT))
483.000 C GO ON TOWARDS THE CONTACT TO THE NEXT SLICE.
484.000      I=I-1;IF(I.GT.0) GO TO 360

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485.000 C WE'VE REACHED THE CONTACT, SO ADD ON THE REDISTRIBUTED
486.000 C CURRENT AND SUBTRACT THE CONTACT INJECTION CURRENT.
487.000      IT=IT+ICON-WZ*WD/2.*(J01*EXP(BETA*VOUT/A1)+J02*EXP(BETA*
488.000      * VOUT/A2))-5*WZ*(WF-WD)*(JSC-II)
489.000 C CORRECT FOR SUBSTRATE AND CONTACT RESISTANCE AND SET V2 & J2.
490.000      VOUT=VOUT-IT*RSUB-IT*RCON
491.000      V2(L)=VOUT;J2(L)=IT
492.000 C ADJUST THE VOLTAGE STEP SIZE AND GO ON TO THE NEXT VALUE.
493.000      IF(VOUT.LT.0.0) GO TO 400
494.000      IF(VOUT.LT..25) DV=.04
495.000      L=L+1;IF(LASTV-VOUT.GT..015) GO TO 350
496.000      DV=2.0*DV;GO TO 350
497.000 C NORMALIZE THE AREA, PRINT OUT THE V2-I2 VALUES AND THEN
498.000 C CORRECT FOR GRID FINGER SERIES RESISTANCE.
499.000      400 RFING=RHOMET*(1.-WC/2.)/(3.*WF)
500.000      IF(GOIV2) OUTPUT ' ','QUASI 2 DIMENSIONAL J-V CURVE'
501.000      IF(GOIV2) OUTPUT ' ','      V2      J(V2) ',' '
502.000      410 VOUT=V2(L)-RFING*J2(L);J2(L)=J2(L)/AREA
503.000      IF(GOIV2) PRINT,V2(L),J2(L);V2(L)=VOUT
504.000      L=L-1;IF(L.GT.0) GO TO 410
505.000 C
506.000 C      NOW WE CAN MODEL THE GRID GEOMETRY RESISTIVE LOSSES TO
507.000 C OBTAIN THE QUASI 3-DIMENSIONAL RESULTS. THIS MODELS THE
508.000 C LOSSES IN THE MAIN CONNECTING BUSBAR OF THE GRID. FIRST,
509.000 C SET THE NEW INITIAL CONDITIONS.
510.000      DV=.01;VN=V2(1)
511.000      R0=(WE+(1.+1./KSUN)*.5/NF)/(MUL*4./SQRT(ACELL))
512.000      OUTPUT ' ','SOLAR CELL OUTPUT I-V CURVE',' '
513.000      OUTPUT '      VOUT      IOUT      POWER',' '
514.000 C SET THE BOUNDARY CONDITIONS AT THE END OF THE CONTACT BAR.
515.000      420 VOUT=VN;IT=0.0;I=1;K=2
516.000 C FIND THE CURRENT FROM THIS SEGMENT BY LINEAR INTERPOLATION.
517.000      430 IF(VOUT.GE.V2(K)) GO TO 440
518.000      K=K+1;GO TO 430
519.000      440 DI=(1.-I*WC/N3)/N3*(J2(K)-(J2(K)-J2(K-1))*(VOUT-
520.000      * V2(K))/(V2(K-1)-V2(K)))
521.000 C FIND THE CURRENT LOST TO INJECTION UNDER THE BUS BAR.
522.000      ACON=I*WC/(N3*N3);RCON=RHOCN/ACON
523.000      II=0.0
524.000      450 ILAST=II;VT=VOUT-II*RCON
525.000      II=ACON*(J01*EXP(BETA*VT/A1)+J02*EXP(BETA*VT/A2))
526.000      IF (ABS((II-ILAST)/II).GT..005) GO TO 450
527.000 C FIND THE CURRENT FLOWING THROUGH THIS SEGMENT
528.000      IT=IT+DI-II
529.000 C CORRECT FOR METAL RESISTANCE AND GO ON TO THE NEXT SEGMENT.
530.000      VOUT=VOUT-IT*RHOMET/(I*WC)
531.000      I=I+1;IF(I.LE.N3) GO TO 430
532.000 C FINALLY, ADD ON THE FRINGING CURRENT, CALCULATE THE OUTPUT
533.000 C POWER, PRINT OUT THE VALUES AND GO ON TO THE NEXT POINT.
534.000      IT=IT+(VOC1-VN)*(QOX-QD0*SQRT(VSF-VN))/R0
535.000      POWER=IT*VOUT
536.000      PRINT,VOUT,IT,POWER
537.000      IF(VOUT.LT..35) DV=.05
538.000      VN=VN-DV;IF(VOUT.GT.0.0) GO TO 420
539.000      STOP
540.000      END

```

```

541.000 C
542.000 C THE FOLLOWING FUNCTION IS USED TO FIND X AND EF AS FUNCTIONS
543.000 C OF U IN THE DEPLETION REGION ( $0 < X < X(ID)$ ).
544.000     REAL FUNCTION GEE(U,P2,P3)
545.000     REAL U,P1,P2,P3;P1=EXP(U)
546.000     GEE=1./SQRT(P3*(P1-1.)/P2+P2*(1./P1-1.)+U*(P2-1./P2))
547.000     RETURN
548.000     END

```

DATA FILE : ILDAT

```

1.000 250E-4 6E15 1E12 5E11 115 1.46 8E-5 2E19
2.000 3.6E-7 1.164E5 -.567 1.12E-6 3.79E5 -.555 10E-6
3.000 300 1.0 1.0
4.000 100 T F F F T F T
5.000 1200 3.53 2.3 2.92E14 .884
6.000 1180 3.54 3.7 2.98E14 .821
7.000 1160 3.55 5.4 3.05E14 .710
8.000 1140 3.56 8.3 3.13E14 .547
9.000 1120 3.58 13.5 3.20E14 .409
10.000 1100 3.59 19 3.28E14 .681
11.000 1080 3.60 29 3.38E14 .910
12.000 1060 3.61 43 3.49E14 .904
13.000 1040 3.62 60 3.58E14 .932
14.000 1020 3.63 80 3.67E14 .922
15.000 1000 3.64 108 3.76E14 .920
16.000 980 3.65 143 3.85E14 .913
17.000 960 3.66 187 3.94E14 .851
18.000 940 3.67 2.5E2 4.01E14 .76
19.000 920 3.68 3.1E2 4.02E14 .750
20.000 900 3.69 4.0E2 4.04E14 .77
21.000 880 3.70 5.0E2 4.08E14 .910
22.000 860 3.70 6.1E2 4.17E14 .923
23.000 840 3.71 7.4E2 4.27E14 .923
24.000 820 3.72 9.0E2 4.37E14 .852
25.000 800 3.73 1.07E3 4.46E14 .880
26.000 780 3.74 1.26E3 4.55E14 .91
27.000 760 3.75 1.5E3 4.62E14 .80
28.000 740 3.77 1.8E3 4.69E14 .920
29.000 720 3.78 2.0E3 4.76E14 .85
30.000 700 3.79 2.4E3 4.82E14 .873
31.000 680 3.81 2.8E3 4.87E14 .869
32.000 660 3.83 3.3E3 4.92E14 .893
33.000 640 3.86 3.9E3 4.97E14 .879
34.000 620 3.89 4.3E3 5.00E14 .863
35.000 600 3.92 4.9E3 5.03E14 .844
36.000 580 3.97 5.6E3 5.01E14 .831
37.000 560 4.02 6.5E3 4.8E14 .900
38.000 540 4.09 7.7E3 4.83E14 .890
39.000 520 4.15 9.2E3 4.83E14 .840

```

40.000	500	4.22	1.15E4	4.85E14	.796
41.000	480	4.32	1.6E4	4.92E14	.768
42.000	460	4.47	2.2E4	4.77E14	.738
43.000	440	4.68	3.0E4	3.97E14	.717
44.000	420	4.99	4.2E4	3.65E14	.720
45.000	400	5.48	7.5E4	3.03E14	.700
46.000	380	6.56	2.6E5	2.16E14	.557
47.000	360	6.24	1.08E6	2.04E14	.464
48.000	340	5.17	1.13E6	1.87E14	.365
49.000	320	5.04	1.28E6	1.42E14	.20
50.000	300	4.85	2.0E6	.77E14	.08
51.000	280	2.97	2.2E6	.37E14	.01
52.000	260	1.77	1.8E6	.19E14	.001
53.000	240	1.80	1.6E6	.08E14	1E-4
54.000	220	1.44	1.74E6	.06E14	1E-4
55.000	200	1.00	1.6E6	.01E14	1E-4
56.000	0	0	0	0	0
57.000		.80			
58.000		.92			
59.000		.96			
60.000		.99			
61.000		1.02			
62.000		1.10			
63.000		1.30			
64.000		1.50			
65.000		0.0			
66.000	40	16E-4	10E-4	.07	.05 .012 .015 4.0 F
67.000	2E-8	1.4	2E-6	2.5	

SAMPLE RUN (using above data)

!SET F:1/ILDAT;IN;SAVE

!FLAG ILSCEL
 FLAG VERSION D04
 WITH>F:1=105

NI = 1.360159E+10
 MUP = 383.564
 MUN = 1084.36
 SB = 11.5330
 TBULK = 9.962989E-06

ONE DIMENSIONAL I-V CURVE

K	V	I(V)
6	.583816	-.291473E-01
5	.566645	.450441E-02
4	.549474	.172327E-01
3	.526579	.258055E-01
2	.457895	.324627E-01
1	.000000	.328106E-01

MUL = 372.539

SOLAR CELL OUTPUT I-V CURVE

VOUT	IOUT	POWER
.569752	-.187507E-02	-.106832E-02
.559005	.260394E-02	.145562E-02
.548331	.661659E-02	.362809E-02
.537761	.997951E-02	.536659E-02
.527213	.132068E-01	.696278E-02
.516743	.159385E-01	.823611E-02
.506315	.184394E-01	.933613E-02
.495959	.204986E-01	.101665E-01
.485651	.222577E-01	.108095E-01
.475398	.237350E-01	.112836E-01
.465147	.251802E-01	.117125E-01
.454983	.261108E-01	.118800E-01
.444830	.270013E-01	.120110E-01
.434733	.275377E-01	.119715E-01
.424652	.280018E-01	.118910E-01
.414607	.282648E-01	.117188E-01
.404568	.284825E-01	.115231E-01
.394548	.286135E-01	.112894E-01
.384532	.287078E-01	.110391E-01
.374522	.287761E-01	.107773E-01
.364515	.288207E-01	.105056E-01
.354510	.288583E-01	.102306E-01
.344507	.288856E-01	.995131E-02
.294501	.289686E-01	.853127E-02
.244500	.290222E-01	.709594E-02
.194500	.290704E-01	.565420E-02
.144500	.291169E-01	.420739E-02
.945001E-01	.291621E-01	.275582E-02
.445003E-01	.292062E-01	.129968E-02
-.549974E-02	.292492E-01	-.160863E-03

STOP

APPENDIX "F"

MODELLING SEMICONDUCTOR PARAMETERS

In developing the inversion layer cell model, every attempt was made to maintain accuracy. Thus, it was essential that the variations of the silicon semiconductor parameters with doping level and temperature be correctly modelled. The following is a list of the mathematical models used to represent these variations.

The accepted model for the intrinsic carrier density in silicon is given by reference [49]:

$$n_i = 3.73 \times 10^{16} \cdot T^{3/2} \exp\left(\frac{-7014}{T}\right) \text{ cm}^{-3} \quad (\text{F.1})$$

where T is the absolute temperature in degrees Kelvin. From equation (F.1), the intrinsic Debye length can be obtained as follows:

$$L_D = \sqrt{\frac{kT\epsilon_s}{2q^2 n_i}} = 16.746 \sqrt{T/n_i} \text{ cm} \quad (\text{F.2})$$

where k , ϵ_s and q have their usual meanings.

More difficult to model were the carrier mobilities and lifetimes. The following approximations were obtained by curve fitting to published experimental data [49]. The error involved in curve fitting is typically less than the variations in the measured data. The carrier mobilities for electrons and holes in the bulk are modelled as follows:

44

OF / DE

OF / DE

$$\mu_n = \left(\frac{300}{T}\right)^{2.5} \left[\frac{1}{4.75 \times 10^{-13} N^{.5486} + 7.58 \times 10^{-4}} + 60 \right] \text{ cm}^2 \text{ v}^{-1} \text{ s}^{-1} \quad (\text{F.3})$$

$$\mu_p = \left(\frac{300}{T}\right)^{2.7} \left[\frac{1}{1.47 \times 10^{-13} N^{.614} + 2.22 \times 10^{-3}} + 43 \right] \text{ cm}^2 \text{ v}^{-1} \text{ s}^{-1} \quad (\text{F.4})$$

where N is the total dopant density (donors plus acceptors) in cm^{-3} .

The carrier lifetimes for electrons and holes within the depletion region are modelled as follows:

$$\tau_n = 1.12 \times 10^{-6} + 3.79 \times 10^5 C_B^{-.555} \exp \left[\frac{-1615}{T} \right] \text{ seconds} \quad (\text{F.5})$$

$$\tau_p = 3.6 \times 10^{-7} + 1.164 \times 10^5 C_B^{-.567} \exp \left[\frac{-1154}{T} \right] \text{ seconds} \quad (\text{F.6})$$

where C_B is the total density of charges (donor and acceptor centres plus holes and electrons). The data used were for "as grown" Czochralski crystals [49]. Since the lifetime measured in silicon has been found to be highly dependent on processing [34] as well as doping, the bulk lifetime in the program was left as a parameter to be chosen by the modeller. The program adjusts the value for changes in temperature away from $T = 300\text{K}$ using the temperature dependence in equation (F.5). The temperature dependencies included in equations (F.5) and (F.6) were obtained from other published results [70].

The optical parameters of silicon also vary with temperature to a small extent. The real part of the refractive index for silicon varies as follows [49]:

$$n_{\text{Si}}(T) = n_{\text{Si}}(300) [1 + 4.2 \times 10^{-5} (T - 300)]. \quad (\text{F.7})$$

where $n_{Si}(300)$ is the real part of the refractive index measured at room temperature [28]. This relationship is independent of the wavelength, λ . Since the bandgap of silicon varies with temperature and since the absorption of light is assisted by thermal phonons, the absorption coefficient will also vary with temperature. This variation can be approximated as follows:

$$\alpha(\lambda, T) = \alpha(\lambda, 300) [1 + (4.3 \times 10^{-4} + 3.17 \times 10^{-7}) (T - 300)] \text{ cm}^{-1} \quad (\text{F.8})$$

where $\alpha(\lambda, 300)$ is the absorption coefficient at room temperature [27] and λ is in nanometers. The variation with temperature given in equation (F.8) is a first order approximation only. It may not apply for $\lambda < 400 \text{ nm}$ where the measured data were supplied for only one temperature. However, since the correction produced by equation (F.8) is small, little error should result because of this uncertainty.

END

1 8 1 2 8 1

FIN