**Polysilicon Metal-Semiconductor-Metal Photodetectors
for 1550 nm Light**

by

Yumei (Jennifer) Liu, M. Sc.

A thesis submitted to the

Faculty of Graduate Studies and Research

in partial fulfillment of the requirements for the degree of

Master of Applied Science

Ottawa-Carleton Institute for Electrical Engineering

Department of Electronics

Faculty of Engineering

Carleton University

© Yumei (Jennifer) Liu, 2004

National Library
of Canada

Bibliothèque nationale
du Canada

Acquisitions and
Bibliographic Services

Acquisitions et
services bibliographiques

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

ISBN: 0-612-89852-0

Our file Notre référence

ISBN: 0-612-89852-0

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this dissertation.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de ce manuscrit.

While these forms may be included in the document page count, their removal does not represent any loss of content from the dissertation.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

Metal-semiconductor-metal (MSM) photodiodes are attractive in optoelectronic integrated circuits, as a result of their ease of integration into silicon CMOS technologies. 1550 nm is the wavelength of choice in long-haul telecommunications due to the low absorption and low dispersion of optical fiber at this wavelength. Demonstration of CMOS-compatible MSM devices operating at 1550 nm is the goal of this thesis.

MSM photodiodes were fabricated on polysilicon deposited by a variety of techniques. The highest responsivity obtained at 1550 nm was 0.34 mA/W. Dark currents were relatively high perhaps due to poor passivation of grain boundary states or surface roughness. It was found that polysilicon with grain sizes between 6 nm and 13 nm provides the best photoresponse at 1550 nm.

Attempts were also made to fabricate Germanium MSM photodetectors. Unfortunately, all of these devices had very high dark currents, so that no measurable photoresponse was obtained at 1550 nm.

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor, Dr. Garry Tarr, for his guidance and support throughout this project.

Thanks should go to those people who helped me perform electrical and photonic measurements. They are: Dr Martine Simard-Normandin and Dr. Brian Oliver at MuAnalysis, Dr. Andy Knights and Dr. Doug Bruce from McMaster University, Dr. Sebastien Jouan from ST Microelectronics and graduate students of Department of Electronics at Carleton University----Steven McGarry, Xiaoming Guo and Xuefei Pan.

I am also grateful to Lyall Berndt, Carol Adams and Rob Vandusen, who helped all the experimental work in the Microfabrication Lab at Carleton University.

Many of the semiconductor films used in this project were provided by ST Microelectronics. I would like to thank Brian Tait of STM for arranging for growth of this material.

Thanks are also due to Dr. Tom Smy from Department of Electronics at Carleton University for his support at the beginning of this project.

Final thanks goes to my husband, Rongfeng, for all his encouragement and support.

TABLE OF CONTENTS

Chapter 1 INTRODUCTION.....	1
1.1 Background	1
1.1.1 Optoelectronic Integrated Circuits	1
1.1.2. Optical Communications.....	2
1.1.3 MSM Photodiode Approaches to 1550 nm Detection.....	3
1.2 Thesis Contributions.....	7
1.2.1 Silicon MSM photodiodes.....	7
1.2.2 Germanium MSM photodiodes.....	8
1.3 Thesis Outline.....	8
Chapter 2 PROPERTIES OF POLYCRYSTALLINE SILICON AND GERMANIUM	
2.1 Polycrystalline Silicon.....	10
2.1.1 Electrical Properties of Polycrystalline Silicon.....	10
2.1.2 Optical Properties of Polycrystalline Silicon.....	17
2.1.3 Grain Boundary Passivation.....	17
2.2. Amorphous Silicon.....	18
Chapter 3 OPERATION THEORY OF MSM PHOTODIODES	22
3.1 Metal - Semiconductor Junction.....	22
3.1.1 Schottky Contact.....	22
3.1.2 Ohmic Contact.....	28
3.2 MSM Theory	29
3.2.1 Dark Current.....	31
3.2.2 Quantum Efficiency.....	38
3.2.3 Capacitance.....	42
3.2.4 Bandwidth.....	43
3.3 Device Design.....	44

Chapter 4	SILICON MSM PHOTODIODES FABRICATION AND EVALUATION	
4.1	Silicon MSM Photodiode Fabrication.....	46
4.1.1	Absorption Layer Preparation.....	46
4.1.2	Interdigitated Electrodes Fabrication.....	50
4.2	Performance Evaluation of Silicon MSM Photodiodes.....	53
4.2.1	PECVD Silicon MSM Photodiodes.....	55
4.2.2	Sputtered Silicon MSM Photodiodes.....	56
4.2.3	LPCVD and RTCVD MSM Photodiodes.....	58
4.2.4	Implanted SOI MSM Photodiodes.....	64
Chapter 5	METAL-GERMANIUM-METAL PHOTODIODES	68
5.1	Device Fabrication.....	68
5.2	Experimental Results and Discussions.....	69
5.2.1	Material Analysis.....	69
5.2.2	Dark Current and DC Photoresponse Measurements.....	72
Chapter 6	CONCLUSIONS AND RECOMMENDATIONS	75
References		78

LIST OF FIGURES

Fig.1-1 (a) Signal attenuation and (b) chromatic dispersion in optical fibers	3
Fig.1-2 Absorption coefficients of some semiconductors used in optoelectronics	4
Fig.1-3 Bandgaps for unstrained and pseudomorphic $\text{Si}_{1-x}\text{Ge}_x$ alloys.....	5
Fig.2-1 Grain boundary in polysilicon.....	12
Fig.2-2 The barrier height as a function of the dopant concentration for polysilicon.....	13
Fig.2-3 Grain boundary barrier and parabolic potential barrier in polysilicon	15
Fig.2-4 Two-photo detection in polysilicon.....	17
Fig.2-5 Energy-band diagram of amorphous silicon.....	19
Fig.3-1 Band diagrams of metal and n-type semiconductor ($\Phi_m > \Phi_s$).	23
Fig.3-2 Energy-band diagram of a Schottky barrier.....	25
Fig.3-3 Possible conduction processes in a forward-biased M-S contact with a degenerately doped n-type semiconductor.....	27
Fig.3-4 Evolution of I-V plots of a diode from rectifying to ohmic contact.....	29
Fig.3-5. Schematic illustration of an interdigitated MSM photodiode.....	30
Fig.3-6 (a) Schematic diagram of one-dimensional MSM structure. (b) The energy band diagram of MSM at thermal equilibrium.....	31
Fig.3-7 The corresponding energy band diagram of an MSM with a cathode contact on contact No.1.....	32
Fig.3-8 Electric field and energy band diagram at different biases.....	35
Fig.3-9 The electric field lines of equal potential below the electrodes of an MSM photodiode under a 10 V bias.....	40
Fig.3-10 Current-voltage (I - V) characteristics of a silicon MSM photodiode for light with different incident powers.....	41
Fig.3-11 Capacitance versus edge length for an MSM photodiode and pin photodiode.....	43
Fig.4-1 Photographs of MSM photodetector fabricated in this project.	50
Fig.4-2 Basic steps for fabrication of an MSM photodiode	51

Fig.4-3. Plot of the peak Raman frequency as a function of the grain size in the polycrystalline silicon films	54
Fig.4-4 Surface photograph of the annealed PECVD MSM photodetector	56
Fig.4-5 Raman spectra for as sputtered and annealed sputtered silicon	56
Fig.4-6 Photocurrent and dark current of sputtered Si MSMs versus applied biases	57
Fig.4-7 SEM micrographs of polysilicon films	59
Fig.4-8 Raman spectra of silicon films prepared by LPCVD and RTCVD.....	60
Fig.4-9 Dark current and photo current versus applied bias for polysilicon MSMs.....	62
Fig.4-10 Raman spectra of SOI MSMs.	65
Fig.5-1 TEM images: (a) and (b) PG6, (c) and (d) PG30, (e) and (f) PG39.....	71
Fig.5-2 SEM images of germanium films.....	72
Fig.5-3. Dark current of RTCVD and sputtered germanium MSM detectors.....	73

LIST OF TABLES

Table 4.1 Implantation energy and dose of SOI.....	47
Table 4.2 Silicon active layer list for MSM Photodiodes	49
Table 4-3 Photocurrents and Raman shifts of MSMs.....	63
Table 4.4 Raman shift and photoresponse of implanted SOI MSMs	66
Table5.1 Metal-germanium-metal detector sample list.....	69

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

λ	wavelength of light
E_{ph}	photon energy
ν	frequency of electromagnetic radiation
c	speed of light in a vacuum
h	Planck's constant
q	electronic charge
N_D	dopant density
ϵ_s	permittivity of silicon
x_d	width of the depletion region
E_g	bandgap of semiconductors
J_F and J_R	current densities for forward and reverse biases
n	free carrier density
μ_{eff}	effective mobility
σ	conductivity
v	thermal velocity
Φ_m and Φ_s	work functions of the metal and the semiconductor
Φ_b	Schottky barrier height
Φ_n and Φ_p	Schottky barriers for electrons and holes
χ_s	electron affinity
V_{bi}	built-in potential
V_n	potential difference between the Fermi level and conduction band
Φ_T	thermal potential
A^*	effective Richardson constant
m^*	effective mass
V_{RT}	reach-through voltage

V_{FB}	flat-band voltage
$\mathfrak{R}$	responsivity
α	absorption coefficient
η_i	internal quantum efficiency
η_e	external quantum efficiency
I_d	dark current
I_p	current with light incidence
I_{ph}	photocurrent

Abbreviations

M-S.....	metal-semiconductor
MSM	metal-semiconductor-metal
FETs	field effect transistors
OEICs.....	optoelectronic integrated circuits
LPCVD	low pressure chemical vapor deposition
PECVD.....	plasma enhanced chemical vapor deposition
RTCVD	rapid thermal chemical vapor deposition
UHV-CVD	ultra high vacuum chemical vapor deposition
MBE	molecular beam epitaxy
SOI.....	silicon-on-insulator
FA	furnace anneal
RTA.....	rapid thermal anneal
CMOS	complementary metal-oxide semiconductor
LOR	lift-off resist
SEM.....	scanning electron microscopy
TEM.....	transmission electron microscopy

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Optoelectronic Integrated Circuits

Optoelectronic integrated circuits (OEICs) integrate optical and electronic devices on the same substrate. Silicon based OEICs are good candidates to overcome the interconnect bottleneck problem in high-density optical telecommunication systems. The photoreceiver can be a good example of an OEIC, in which a photodetector is monolithically integrated with a preamplifier. Electronic components such as field effect transistors (FETs) are often planar, while most optical devices are vertical structures, therefore a planar photodetector is preferred for integration of a photoreceiver. The photodetector with the minimum number of processing steps is also desired to reduce the complexity of the photoreceiver. A p-i-n photodiode can be a candidate for the receiver OEIC, however, planar integration of the p-i-n diode and FET is complex and costly [1.1]. An interdigitated metal-semiconductor-metal (MSM) photodiode is a device that is very suitable for the receiver OEIC. The MSM photodiode was first proposed by Sugeta *et al.* in 1979 [1.2] and then reported by Figueroa [1.3] and by Wei *et al.* in 1981 [1.4]. Interdigitated MSM photodiodes are extremely easy to fabricate and their electrode deposition step could be processed at the same time with the metallization of other parts of integrated photoreceivers, such as planar FETs. In addition, planar MSM detectors exhibit very low capacitance per unit area. The low capacitance per

unit area permits relatively large interdigitated area on an MSM device, which makes it easy to couple the optical fiber to the photodetector. The large area also helps make a highly sensitive photoreceiver possible. The drawbacks for an MSM are high dark current and low quantum efficiency, which will be discussed in Chapter 3.

1.1.2. Optical Communications

Attenuation and chromatic dispersion are the two important parameters of optical fibers and they are plotted as a function of wavelength in Fig.1-1[1.5]. Attenuation in optical fibers is caused by absorption and scattering. As shown in Fig.1-1 (a), the minimum attenuation happens at wavelength of 1550 nm. The corresponding attenuation is 0.35 dB/km, which represents an amplitude reduction of 4%/km. The chromatic dispersion describes phenomenon where different wavelengths of light travel through the fiber at slightly different velocities. At around 1300 nm, the optical signal can be assumed to be reproduced exactly due to its almost zero chromatic dispersion (see Fig.1-1(b)). The minimum attenuation and chromatic dispersion are always required for the design of the optical telecommunication systems. So photodetectors operating in the two low absorption windows of silica fibers around 1300 nm or 1550 nm wavelength are therefore highly desirable for long-haul fiber communication. The aim of this project is to produce an MSM photodiode, which allows the fabrication of long-wavelength (1550 nm) OEICs on silicon.

Fig.1-1 (a) Signal attenuation and (b) chromatic dispersion in optical fibers [1.5].

1.1.3 MSM Photodiode Approaches to 1550 nm Detection

The wavelength of light (λ) is related to the photon energy (E_{ph}) (in eV) by

$$\lambda = \frac{c}{\nu} = \frac{hc}{E_{ph}} = \frac{1240}{E_{ph}} \text{ nm} \quad (1.1)$$

where ν is the frequency of electromagnetic radiation, $c = 3 \times 10^8$ m/s is the speed of light in a vacuum, and $h = 6.62 \times 10^{-34}$ J-s is Planck's constant.

From Eq.1.1, it can be seen that the required semiconductor energy bandgap to absorb 1550 nm light is around 0.8 eV. For the semiconductor with bandgap higher than 0.8 eV, the response of 1550 nm light cuts off abruptly because the incident photon does not have enough energy to move an electron from the valence band to the conduction band, that is $h\nu < E_g$. Those wavelengths that the semiconductor is sensitive to are called the spectral range of the photodetector. Fig.1-2 shows the absorption spectral range for several semiconductor materials.

Fig.1-2 Absorption coefficients of some semiconductors used in optoelectronics [1.5].

III-IV semiconductors, such as indium gallium arsenide (InGaAs) with direct bandgap of 0.8 eV, are the classic absorbing materials for the 1550 nm wavelength optical fiber telecommunication applications. InGaAs MSM photodiode exhibited excellent characteristics on bandwidth and quantum efficiency [1.6]. Epitaxial growth of good-quality InGaAs on a silicon substrate would be an extremely difficult undertaking. Even if the problem of heteroepitaxy could be overcome, the instability of III-V compounds at high temperatures limits their integration to the back-end of the silicon process technology. In general, integration of InGaAs MSM with silicon CMOS is likely to be extremely complicated and expensive [1.7].

$\text{Si}_{1-x}\text{Ge}_x$ alloy is an alternative candidate for 1550 nm photodetection because its bandgap energy changes with the fraction of germanium from 0.6 eV to 1.2 eV [1.8]. Fig.1-3 shows the energy gap values of $\text{Si}_{1-x}\text{Ge}_x$ alloy as a function of germanium content.

However, the high lattice mismatch between silicon and germanium, which is greater than 4%, leads to a critical thickness of the SiGe layer beyond which dislocations will be formed. For the photodetector with $\text{Si}_{1-x}\text{Ge}_x$ active layer thickness greater than the critical value, the high density of misfit dislocations increases the dark current. Strained $\text{Si}_{0.5}\text{Ge}_{0.5}$ could be an approach to detect light at 1550 nm, since its energy gap is around 0.8 eV, as shown in Fig.1-3. However the critical thickness of $\text{Si}_{0.5}\text{Ge}_{0.5}$ is around 10 nm [1.9], [1.10], which is too thin to get good photoresponse at 1550 nm wavelength. Recently Janz *et al.* [1.9] report a strained superlattice $\text{Si}_{1-x}\text{Ge}_x$ photodetector with photoresponse of 0.16A/W at 1550 nm wavelength. The SiGe alloy was deposited by the combination of ultra high vacuum chemical vapor deposition (UHV-CVD) and molecular beam epitaxy (MBE), which are costly and difficult.

Fig.1-3 Bandgaps for unstrained and strained pseudomorphic $\text{Si}_{1-x}\text{Ge}_x$ alloys [1.8].

For the relaxed $\text{Si}_{1-x}\text{Ge}_x$, a large fraction of germanium, almost 100%, is needed to detect light at 1550 nm. The relaxed germanium film could be thick enough to offer good

photoresponse. Recently, Colace *et al.* have made many contributions on pure germanium photodetectors [1.10-1.14]. In 1998, they reported a metal-germanium-metal photodetector with a maximum responsivity of 0.24 A/W at 1300 nm under a 1V bias and response time of about 2 ns [1.11]. The thick relaxed germanium layers (well over the critical thickness) were epitaxially grown on silicon after insertion of a low-temperature-grown germanium buffer layer. In 2002, they reported a germanium-on-silicon pin photodetector with responsivity as high as 0.75 A/W at 1550 nm, time response < 200 ps and dark current as low as 1.2 μ A [1.12]. Germanium in this device was epitaxially grown on silicon by chemical vapor deposition, employing a low temperature germanium buffer layer and cyclic thermal annealing to reduce the threading-dislocation density. Recently this group deposited polycrystalline germanium on a silicon substrate using thermal evaporation to make a heterojunction photodetector [1.13]. This polycrystalline device exhibits responsivity of 5 mA/W at 1550 nm, dark current density of 1 mA/cm², and a pulse response faster than 200 ps. However, the drawbacks of this device are the reduced carrier mobility and lifetimes due to the lower evaporated material quality.

In 2002 Buca *et al.* reported an ultrafast germanium MSM photodiode with 12.5 ps full width at half maximum and the overall external quantum efficiency of 7.5% at wavelength of 1500 nm [1.14]. The active layers are 270 nm thick germanium films, grown on silicon (111) by MBE, which is a relatively sophisticated and expensive deposition technique.

Today's standard CMOS (complementary metal-oxide semiconductor) technology for integrated circuits is based on silicon substrates. Therefore, silicon MSM photodiodes are

fully compatible with CMOS processing. However, most of the previous work on silicon MSMs has emphasized short-wavelength [1.15-1.22], since silicon has very weak absorption over the 1550 nm wavelength range due to its indirect band structure and bandgap energy of 1.12 eV. A very thick absorption depth would be necessary for a silicon MSM in order to get any photoresponse at 1550 nm, which results in low response speed. The poor quantum efficiency, approaching zero for monocrystalline silicon, and the restricted speed have limited the applications of silicon MSM photodetectors in telecommunications.

Some attempts have been reported to increase the quantum efficiency and response speed of the silicon MSM photodiode. The Laih and Lin group [1.16-1.21] have been working on amorphous silicon MSM detectors with U-shaped trench electrodes. These devices exhibited high response speed attributed to the trench electrodes resulting in a stronger lateral electric field in the light absorption region of photodetectors. This group reported an intrinsic hydrogenated amorphous silicon MSM detector [1.21] with a full width at half maximum (FWHM) of 68.18ps under a bias of 10 V. Under a bias of 4V, this MSM detector had a responsivity of 0.24 W/A as measured with an 830 nm incident laser. Sharma *et al.* [1.22] reported a silicon MSM detector integrating a 1000-nm-deep subwavelength grating on the top of the active region. The grating structure could act as an effective anti-reflection coating and increase the light absorption near the surface. Therefore, external quantum efficiency as high as 81% at 700 nm wavelength and response speed of 600 ps at 900 nm wavelength were achieved from this structure.

1.2 Thesis Contributions

1.2.1 Silicon MSM Photodiodes

Silicon MSM photodiodes demonstrating good performance at 800-860 nm wavelengths for short-haul communications have been made at Carleton University in previous research projects [1.23],[1.24]. The present project explores the possibility of extending the spectral range of silicon MSM photodiodes to the 1550 nm wavelength appropriate for long-haul telecommunications applications. To the author's knowledge, this is the first time silicon MSM devices have been fabricated and characterized for 1550 nm operation. Polycrystalline and amorphous silicon active layers have been prepared by various deposition techniques and with different thickness. Some of the polysilicon MSM photodetectors showed some surprisingly high photoresponse at 1550 nm, but leakage currents were high. In order to compare the photoresponses for MSM photodiodes with different grains sizes, the active materials were analyzed using microprobe Raman spectroscopy.

1.2.2 Germanium MSM Photodiodes

An attempt to fabricate a SiGe-based photodiode operating at 1550 nm was made at Carleton University's Microfabrication Laboratory in a previous project [1.24]. Due to the temperature limitation of the RTCVD system in this laboratory, the resultant germanium film was too rough to produce a rectifying Schottky contact. The present project took advantage of the commercial RTCVD system at Lawrence Laboratories (Phoenix, Arizona) to prepare the relaxed germanium active layers. The germanium layers were analyzed with several techniques and discussions on the characteristics of germanium MSM photodiodes are

provided.

1.3 Thesis Outline

Chapter 1 is a thesis introduction and reviews previous research on silicon and germanium based MSM photodiodes for 1550 nm. Chapter 2 details the relevant material properties of the semiconductors used here. Chapter 3 discusses the operation theory of the MSM photodiode and its characteristics including dark current, quantum efficiency, capacitance and bandwidth. Chapter 4 concentrates on the fabrication and electronic and optical testing of silicon MSM photodiodes, then discusses the relationship between the photoresponse and grain size. Chapter 5 describes the unsuccessful attempts to produce a useful germanium MSM photodiode. Finally, conclusions of this project and suggestions for future work are presented in Chapter 6.

CHAPTER 2

PROPERTIES OF POLYCRYSTALLINE SILICON AND GERMANIUM

2.1 Polycrystalline Silicon

Polycrystalline silicon consists of small crystallites joined together by grain boundaries. Each crystallite can be considered as a small single crystal, while the atoms in the grain boundary are disordered. Therefore the grain boundary acts as a transitional region between two single crystals.

Polycrystalline silicon is usually deposited by chemical vapor deposition at temperatures of approximately 625°C, giving an average grain size of about 70 nm [2.1]. Normally the grain structure of polysilicon is columnar with column diameters in the range of 20-100 nm. The grains in the silicon are enlarged with the increase of the depositing temperature and their sizes can reach around 300 nm with deposition temperature at around 1100°C [2.2]. The grain size also increases as the polysilicon film becomes thicker.

2.1.1 Electrical Properties of Polycrystalline Silicon

The presence of grain boundaries in polycrystalline silicon causes the electrical conduction process in it to differ from that of monocrystalline silicon.

Due to the disordered atoms in the grain boundary, there may be a lot of defects in polysilicon, which may result in dangling bonds. These dangling bonds lead to allowed states within the bandgap of the polysilicon. Therefore, many free carriers can be trapped at these midgap states, which are called trapping states. The traps may be electrically charged.

It is assumed that the grain boundary in Fig.2-1(a) [2.3] is normally a few angstroms wide, which is much narrower than the grain. The charge trapped at the grain boundaries is compensated by oppositely charged depletion regions surrounding the grain boundaries, shown in Fig.2-1(b) [2.3]. The electrical charge in the depletion regions forms a curved energy band, resulting in the potential barrier qV_B , shown in Fig.2-1(c). Carriers moving from one crystal to another have to overcome this barrier. The barrier height V_B depends on the dopant concentration and parameters of traps, such as trap density and energy level, and is given by [1.5]

$$V_B = \frac{qN_D}{2\epsilon_s} x_d^2 \quad (2.1)$$

where q is the electronic charge, N_D is the dopant density (in this instance n-type polysilicon), ϵ_s is the permittivity of silicon and x_d is the width of the depletion region.

When polysilicon is lightly doped, nearly all the free carriers in the grain, contributed by the dopant atoms, can be trapped at the grain boundary if the energy levels of the traps are deep enough. Therefore the grains of polysilicon with low dopant concentration can be completely depleted and the width of the depletion region on each side of the grain boundary will reach half of the grain size L . Then the barrier height can be expressed as

$$V_B = \frac{qN_D}{2\epsilon_s} \left(\frac{L}{2}\right)^2 = \frac{qN_D L^2}{8\epsilon_s} \quad (2.2)$$

From Eq.2.2, it can be seen that the barriers to conduction for lightly doped silicon are small and carriers can move easily from one grain to another.

Fig.2-1 Grain boundary in polysilicon. (a) Schematic of polysilicon with grain boundary in one dimension. (b) Charged traps and depletion regions. (c) Potential barriers[2.3].

As the doping increases, more carriers are trapped at the grain boundary and the barrier heights also increase, while the width of the depletion region decreases with the increasing dopant concentration. After the dopant concentration reaches a critical value N^* ($N^* = N_T/L$), the number of trapped carriers per unit area of grain boundary remains at a constant value of N_T . The carriers that are not trapped by the grain boundary lead to a neutral region in the grain, thus the depletion region is shrunk. The width of the depletion region can be expressed in the term of N_T

$$x_d = \frac{N_T}{2N_D} \quad (2.3)$$

The corresponding barrier height can be expressed

$$V_B = \frac{qN_D}{2\epsilon_s} \left(\frac{N_T}{2N_D} \right)^2 = \frac{qN_T^2}{8\epsilon_s \cdot N_D} \quad (2.4)$$

Based on Eq.2.2 and Eq.2.4, the dependence of barrier height on the dopant concentration is plotted in Fig.2-2. When the dopant concentration in polysilicon is increased, the barrier height first increases linearly with the increase of concentration until a maximum barrier height is reached, and then decreases.

Fig.2-2 The barrier height as a function of the dopant concentration for polysilicon [2.4].

When a bias is applied on polysilicon, the potential barrier in one side of the grain boundary increases (reverse biased), while the barrier on the other side decreases (forward biased). The applied bias is not divided uniformly by the two barriers. However, when the applied bias is small, we can assume that approximately half of the voltage is applied on each barrier. Another commonly-used assumption is that the applied biases on every grain boundary are equal, denoted as V_G , thus the applied voltage appearing on one barrier V can be expressed as $V = \frac{V_G}{2}$. Therefore the thermionic current densities for both forward and

reverse biases are

$$J_F = qnv_c \exp\left[-\frac{q}{kT}\left(V_B - \frac{1}{2}V_G\right)\right] \quad (2.5)$$

$$J_R = qnv_c \exp\left[-\frac{q}{kT}\left(V_B + \frac{1}{2}V_G\right)\right] \quad (2.6)$$

where n is the free carrier density, v_c is the collection velocity ($v_c = \sqrt{kT/2\pi \cdot m^*}$), and V_B is the barrier height with no applied bias. The net current density is

$$\begin{aligned} J = J_F - J_R &= qnv_c \exp\left(-\frac{qV_B}{kT}\right) \left[\exp\left(\frac{qV_G}{2kT}\right) - \exp\left(-\frac{qV_G}{2kT}\right) \right] \\ &= 2qnv_c \exp\left(-\frac{qV_B}{kT}\right) \sinh\left(\frac{qV_G}{2kT}\right) \quad (2.7) \end{aligned}$$

When the applied voltage is small compared to the thermal voltage kT/q , $\sinh\left(\frac{qV_G}{2kT}\right)$ is approximately equal to $\left(\frac{qV_G}{2kT}\right)$, therefore Eq.2.7 can be rewritten as

$$J = \frac{q^2 nv_c V_G}{kT} \exp\left(-\frac{qV_B}{kT}\right) \quad (2.8)$$

From current density J , the average conductivity σ of polysilicon can be expressed as

$$\sigma = \frac{JL}{V_G} = \frac{q^2 nv_c L}{kT} \exp\left(-\frac{qV_B}{kT}\right) \quad (2.9)$$

In polysilicon, the effective mobility μ_{eff} describes the ability of carriers to move over the grain boundary. Using Ohm's law ($\sigma = qn\mu$), μ_{eff} is related to the potential barrier height V_B as follows:

$$\mu_{eff} = \frac{qv_c L}{kT} \exp\left(-\frac{qV_B}{kT}\right) \quad (2.10)$$

From Eq.2.10, it can be seen that effective mobility of polysilicon depends strongly on the barrier height. Over a certain dopant concentration, the effective mobility first decreases with the increase of the dopant concentration, until dopant reaches its critical concentration N^* . After this critical value, the effective mobility begins to increase due to a reduction in the barrier height. The minimum effective mobility is reached at the critical dopant concentration.

Therefore, the critical concentration N^* is an important parameter for polysilicon. From the definition $N^* = N_T/L$, it can be seen that for a certain trap density N_T in the grain boundary, the critical concentration N^* changes inversely with grain size L .

The parabolic depletion-region potential barriers, shown in Fig.2-2, explain the carrier trapping in the grain boundaries. However, the grain boundaries themselves can also impede the movement of carriers due to their disordered structures. This additional impedance can be modeled as a high and narrow potential barrier at the grain boundary, see Fig. 2-3. This additional barrier, called the grain boundary barrier, has a width of around 1 nm and bandgap higher than that of polysilicon. When the polysilicon is lightly doped, the parabolic potential barrier is the main factor that blocks the current flow, while at the moderate and high dopant concentration, the high grain boundary barrier becomes the dominant factor.

Fig.2-3 Grain boundary barrier and parabolic potential barrier in polysilicon [2.4].

The above discussions focus on the conduction only by thermionic emission of carriers over the top of the potential barrier. However, when the temperature is so low that only a few carriers have enough energy to overcome the potential barrier, some carriers could tunnel through the top narrow part of the potential barrier. The combination of thermionic emission and tunneling is called thermionic-field emission.

The potential barriers, formed by trapping the dopants, impede the majority carriers

moving from one grain to another. However, the potential barriers are attractive to minority carriers, thus the lifetime of minority carriers could be reduced due to the presence of potential barriers on each side of the grain boundaries [2.5, 2.6]. The effective minority-carrier lifetime τ_{eff} can be expressed as [2.6]

$$\tau_{eff} = \frac{1}{\sigma \cdot v N_{sr}} \quad (2.11)$$

where σ is the capture cross section, v is the thermal velocity of the carriers, and N_{sr} is the effective density of recombination centers (cm^{-3}). From Eq.2.11, we can also find that higher density of recombination centers N_{sr} leads to a shorter minority-carrier lifetime.

If the grains are assumed to be cubic, the density of recombination centers N_{sr} could be given by

$$N_{sr} = \frac{6N_{ss}}{L} \quad (2.12)$$

where L is the grain size and N_{ss} is the concentration of recombination centers per unit area at the grain boundary. Then Eq.2.11 now becomes

$$\tau_{eff} = \frac{L}{6\sigma \cdot v N_{ss}} \quad (2.13)$$

When the three parameters (capture cross section σ , thermal velocity v and concentration of recombination centers per unit area N_{ss}) in Eq.2.13 are given, the minority-carrier lifetime increases linearly with the size of the grain.

Based on the above discussions, we can see that grain boundary states between the columnar grains in polysilicon result in high trap density, which decreases both the carrier mobility and the lifetime by acting as traps and recombination centers [2.7-2.11].

2.1.2 Optical Properties of Polycrystalline Silicon

The optical absorption in polysilicon depends strongly on the deposition conditions as it is sensitive to the crystal structure. The optical properties of polysilicon differ somewhat from those of monocrystalline silicon, due to the presence of grain boundaries. The defects in the grain boundary can lead to states within the bandgap that act as generation-recombination centers. Incident light with energy less than the bandgap energy of polysilicon could be absorbed by these states within the bandgap. Fig.2-4 illustrates the two-photon detection process. After the first photon absorption, an electron can be excited to the midgap states, releasing a hole; the absorption of the second photon may result in the emission of the trapped electron to the conduction band. The electron and hole contribute to the photocurrent. Therefore the grain boundaries in the polysilicon result in it having a higher optical absorption than monocrystalline silicon. An absorption depth of 2 μm at 780 nm wavelength was reported [2.12] for polysilicon films deposited by low-pressure chemical vapor deposition at 625°C, which is much less than the 10 μm absorption depth for monocrystalline silicon.

Fig. 2-4 Two-photo detection process in polysilicon.

2.1.3 Grain Boundary Passivation

As discussed above, traps located at the grain boundaries adversely affect the electrical properties of polycrystalline silicon by decreasing the mobility and lifetime of carriers. Therefore, it is necessary to reduce the active trap density associated with the grain boundary. This can be done by either reducing the effectiveness of trapping sites in grain boundaries, called grain boundary passivation, or removing the grain boundaries themselves. However, the presence of the grain boundary increases the optical absorption, and removing it may have a negative impact on polysilicon as the active layer of the photodetector. Grain boundary passivation is normally used to improve the electrical properties of polysilicon.

Traps are related to the dangling bonds at the grain boundaries and trap efficiency of polysilicon can be suppressed by terminating the dangling bonds. Atomic hydrogen is often used to passivate the dangling bonds and other defects at grain boundaries and reduce the number of active traps there. Annealing the polysilicon at the temperature of 400 °C in hydrogen atmosphere can allow hydrogen to diffuse into the grain boundary, reduce the efficiency of the trap state, and increase the mobility and lifetime of carriers of the polysilicon. Therefore, polysilicon films used as the active layers of photodetectors are often annealed in hydrogen atmosphere at low temperature, since the annealing could improve their electrical properties. However, there is a risk that hydrogen annealing might decrease optical absorption for photon energies greater than bandgap E_g .

2.2 Amorphous Silicon

Compared to crystalline silicon, amorphous silicon has suppressed carrier mobility and lifetime and better optical absorption as a result of the greater structural disorder within it. Amorphous silicon also has a wider direct band gap.

There are well-defined conduction and valence bands in single crystalline silicon and within the grains of polysilicon. In these materials electrons and holes move freely in the conduction and valence bands, respectively. These energy states are considered to be non-localized, and are called extended states. In amorphous silicon, the sharp valence and conduction band edges, which normally exist in crystalline silicon, are replaced by band tails extending into the energy gap (called shallow states) and a large number of midgap states exist in the energy band gap (called deep states), as shown in Fig.2-5. These states within the band gap are called localized states, where carriers are confined as if they were attached to the host atom. The energy levels E_c and E_v , shown with two dotted energy lines in Fig.2-5, are called energy boundaries, which separate the localized states and non-localized states (here non-localized states refer to the energy states above E_c and below E_v). The transport of carriers in the disordered amorphous silicon involves frequent trapping and detrapping in localized states, and transport in extended states [2.13]. The balance between trapping and detrapping determines the free-carrier density. Only free carriers- the carriers in extended states- can drift in the electrical field, with carrier mobility between 1 and 10 cm^2/Vs . Trapping and detrapping are both slow, with a typical mobility between 10^{-6} and $10^{-3} \text{ cm}^2/\text{Vs}$ [1.5]. Owing to the low carrier mobility, conduction through the localized states is insignificant.

Fig.2-5 Energy-band diagram of amorphous silicon [1.5].

As mentioned above, a large density of band-tail states and midgap states exists in amorphous silicon. These localized states could trap carriers and make them non-mobile. Therefore, the carrier lifetime in amorphous silicon is shorter than that in crystalline silicon [2.13].

Also due to the absence of crystalline periodicity, the electron states of amorphous silicon cannot be described by Bloch's theorem, which is normally used to explain the broad semi-continuous energy bands in crystalline silicon. The momentum difference between the valence band peak and the conduction band minimum is not well-defined and electrons can transfer easily from the valence band to the conduction band without changing momentum. Optical transition in amorphous silicon is equally allowed between any states in the valence and conduction bands, which results in a relatively higher optical absorption than polysilicon. Furthermore, the effective band gap of amorphous silicon is higher than that for polycrystalline silicon. Hydrogenated amorphous silicon typically has a direct bandgap of 1.6

eV, while polysilicon has an indirect bandgap of 1.1 eV. The bandgap of amorphous silicon depends strongly on the deposition conditions and the amount of hydrogen incorporated.

The low carrier mobility and short carrier lifetime of amorphous silicon causes a poor photogenerated-carrier collection efficiency and small responsivity. Therefore, much current research, including this project, focuses on increasing the quantum efficiency of amorphous silicon. The grain size for recrystallized amorphous silicon can be greater than that of polysilicon. Larger grains in crystallized amorphous silicon lead to lower trap density, so carrier mobility and carrier lifetime can be greatly increased. However, it is found that the absorption coefficient of re-crystallized amorphous silicon becomes less than that of films, which are initially polycrystalline, and can approach to that of monocrystalline silicon [2.4]. The low absorption coefficient in crystallized amorphous silicon is consistent with the large grain size seen in the film after annealing. Therefore, for polysilicon used in thin-film transistors, larger grains are always desirable. However, silicon with grain size close to that of monocrystalline is not suitable for the active layer of a photodetector, since its optical absorption is very low. In selecting material for a photodetector, one must strike a compromise between the high mobility provided by large grain sizes, and the high optical absorption obtained with small grain sizes.

CHAPTER 3

OPERATION THEORY OF MSM PHOTODIODE

3.1 Metal-Semiconductor Junction

Metal-semiconductor (M-S) contacts are generally divided into two classes: rectifying (ohmic) and non rectifying (Schottky-barrier) contacts.

3.1.1. Schottky Contact

The energy-band diagrams for a metal and semiconductor (n-type) before making contact are shown in Fig.3-1(a), where Φ_m and Φ_s represent the work functions of the metal and the semiconductor, respectively [1.5]. Here we assume that Φ_m is greater than Φ_s . χ_s is the electron affinity. From Fig.3-1 (a), it can be seen that $q\Phi_m$ (or $q\Phi_s$) represents the energy required to release an electron from the Fermi level of metal (or semiconductor) to the vacuum level and $q\chi_s$ specifies the energy required to bring an electron from the bottom of the conduction band to the vacuum level.

When the metal and semiconductor are brought together, electrons in the semiconductor, having higher energy than those in the metal, cross over to the metal until the Fermi levels for the metal and semiconductor are aligned, called thermal equilibrium. The aligning results in the lowering of the Fermi level of the semiconductor by $q(\Phi_m - \Phi_s)$. The migration of the electrons from the semiconductor to the metal leaves behind ionized donors as fixed positive charges creating a depletion layer with a width of X_d . The depletion of electrons in the vicinity of the interface produces an upward band-bending near the surface. The built-in

potential V_{bi} describes this band-bending, which is defined as the difference of the two work functions

$$V_{bi} = \phi_m - \phi_s \quad (3.1)$$

(a)

(b)

Fig. 3-1 Band diagrams of metal and n-type semiconductor ($\Phi_m > \Phi_s$). (a) Before contact. (b) After contact and at thermal equilibrium [1.5].

When the thermal equilibrium is reached, electrons in the semiconductor have to get the energy of qV_{bi} in order to move to the metal, as depicted in Fig.3-1 (b), and electrons in the metal also see a barrier, which is given by

$$q\phi_b = q(\phi_m - \chi_s) \quad (3.2)$$

where Φ_b is Schottky barrier height and q is the electronic charge (1.602×10^{-19} J).

When a bias voltage is applied to the metal-semiconductor junction, the extra potential difference appears across the depletion layer because the depleted region has the highest resistance. When a negative voltage V is applied to the semiconductor with respect to the metal, the conduction band edge E_c in the semiconductor rises relative to the top of the barrier and the depletion region becomes thinner, as seen in Fig. 3-2 (a). Therefore the barrier height V_{bi} seen by electrons in the conduction band of the bulk semiconductor is reduced to $(V_{bi} - V)$. The barrier height Φ_b seen from the view of an electron at the Fermi level in the metal remains unchanged. The reduced band-bending on the semiconductor side makes it easier for electrons in the semiconductor to move to the metal. This is the forward-bias condition, which enables a large current to flow from metal to semiconductor. On the other hand, when a positive voltage V is applied to the semiconductor, the M-S contact is under the reverse bias, as seen in Fig.3-2(b). From Fig.3-2(b) it can be seen that the energy band of the semiconductor is bent even further and the width of depletion region is increased. Therefore the potential barrier for electrons in the semiconductor is increased from V_{bi} to $(V_{bi} + V)$ and electron flow from semiconductor to metal is almost negligible. The nearly constant small reverse current is due to the flow of electrons from metal to semiconductor over an unchanged barrier Φ_b .

Fig.3-2 Energy-band diagram of a Schottky barrier. (a) With forward bias, (b) With reverse bias, where $X_{d1} < X_{d2}$ [1.5].

When the semiconductor is uniformly doped, the space-charge-layer width X_d of the Schottky barrier under the reverse bias V_R is given by [1.5]

$$x_d = \left[\frac{2\epsilon_s (V_{bi} + V_R)}{qN_D} \right]^{1/2} \quad (3.3)$$

where V_R is the applied voltage, N_D is the doping level in the semiconductor, ϵ_s is permittivity of the semiconductor. Therefore, the capacitance of the junction is given by

$$C = \frac{\epsilon_s}{x_d} = \left[\frac{q\epsilon_s N_D}{2(V_{bi} + V_R)} \right]^{1/2} \quad (3.4)$$

Eq. (3.4) can be rewritten as

$$\frac{1}{C^2} = \frac{2(V_{bi} + V_R)}{q\epsilon_s N_D} \quad (3.5)$$

The plot $1/C^2$ vs. V_R is a straight-line. The semiconductor doping N_D and the built-in potential V_{bi} can be calculated from the slope and intercept of such a $1/C^2$ -V plot. Once built-in voltage V_{bi} is determined, the barrier height Φ_b can be calculated using

$$\phi_b = V_{bi} + V_n \quad (3.6)$$

where V_n is the potential difference between the Fermi level and conduction band and its value can be given by

$$V_n = \phi_T \ln \frac{N_c}{N_D} \quad (3.7)$$

with $\phi_T = kT/q$

where ϕ_T is called thermal potential, k is Boltzmann constant (1.38×10^{-23} J/K), T is temperature in Kelvin, N_c is effective density-of-states in conduction band ($2.8 \times 10^{19} \text{ cm}^{-3}$ at 300K for silicon).

For a M-S contact, the current transport can occur by three different mechanisms: thermionic emission, thermionic-field emission, and field emission. These processes are shown in Fig. 3-3[3.1]. Current flow in a rectifying contact is normally described by thermionic emission theory. For a rectifying M-S contact under forward bias, current flow results from the thermionic emission of electrons in the semiconductor over the potential barrier. The other two current modes will be discussed in section 3.1.2.

Fig. 3-3 Possible conduction processes in a forward-biased M-S contact with a degenerately doped n-type semiconductor [3.1].

The thermionic current density J_F under the forward-bias voltage V_F is given by

$$J_F = A^* T^2 \exp\left(\frac{-q(\phi_b - V_F)}{kT}\right) = J_0 e^{V_F / \phi_T} \quad (3.8)$$

$$\text{with } J_0 = A^* T^2 \exp\left(\frac{-q\phi_b}{kT}\right) \quad (3.9)$$

where $A^* = 4\pi \cdot qm^* k^2 / h^3$ is the effective Richardson constant, m^* is effective mass, and h is Planck's constant (6.625×10^{-34} Js).

The current due to the reverse-bias voltage results from electron transport from the metal to the semiconductor. The magnitude of the reverse current is obtained by setting a zero voltage in Eq. (3.8), and zero voltage corresponds to the reverse saturation current density J_0 . Thus, the current density for both forward and reverse bias is given by

$$J = J_0 (\exp(V / n\phi_T) - 1) \quad (3.10)$$

where n is the ideality factor, and equals 1 for an ideal Schottky diode.

Ideally, the reverse current density, according to Eq. (3.9), should be a constant J_0 .

However, when the M-S contact is biased by a voltage V , there is an external field applied to

the contact. Although this field is not constant with distance, the value at the surface E_{ext} can be used as a good approximation, which is given by [2.1]

$$E_{ext} = \sqrt{\frac{2qN_D}{\epsilon_s} (V_{bi} + V)} \quad (3.11)$$

The external field lowers the work function $q\Phi_m$ of a metal by $q\Delta\Phi$, which is called image-force lowering. $\Delta\Phi$ is given by

$$\Delta\phi = \sqrt{\frac{qE_{ext}}{4\pi\epsilon_s}} \quad (3.12)$$

The reduction of the surface work function of metal makes it easy for an electron in the metal to overcome the barrier and move to the semiconductor side, and thus gives rise to a higher thermionic-emission current. Therefore, the reverse saturation current density J_0 is modified to be

$$J_0 = A^* T^2 \exp\left(\frac{-q(\phi_b - \Delta\phi)}{kT}\right) \quad (3.13)$$

Eq. (3.13) is more accurate to describe the I-V characteristics of a Schottky diode, especially under the reverse-bias.

3.1.2 Ohmic Contact

Among the three current modes shown in Fig.3-3, field emission involves quantum mechanical tunneling through the barrier at energies below the top of the barrier. The combination of thermionic emission and tunneling is called thermionic field emission. Field emission and thermionic field emission normally happen in semiconductors heavily doped and with large bias voltages. The M-S contact changes from a rectifying (Schottky barrier) to non-rectifying (ohmic) one as these two modes of current transport dominate.

As the doping in the semiconductor is increased, for example if it is doped with an impurity density of 10^{19} cm^{-3} or higher, the depletion region of the junction becomes very narrow, which can be seen from

$$x_d = \left[\frac{2\epsilon_s (V_{bi} + V_R)}{qN_D} \right]^{1/2} \quad (3.3).$$

Now carriers can tunnel through instead of going over the potential barrier, as shown in Fig. 3-3. Electrons on either side of the barrier may tunnel across to the other side and this can result in a rapid increase of current even with reverse bias. Thus, an essentially symmetrical I-V curve for both forward and reverse bias is realized, as shown in Fig.3-4. The barrier is non-rectifying, and a low contact resistance is achieved. The evolution of the I-V characteristics in going from a Schottky to an ohmic contact is shown in Fig. 3-4 [3.1].

Fig. 3-4 Evolution of I-V plots of a diode from rectifying to ohmic contact [3.1].

3.2 MSM Theory

Normally in a planar MSM configuration the metal electrodes are interdigitated, as shown in Fig.3-5, where the two contact metals are exactly same and light absorption occurs

near the semiconductor surface between the electrodes. A planar MSM is a two-dimensional device with nonparallel electric field lines in the absorption layer, which is different from one-dimensional back-to-back MSM (see Fig.3-6).

A photodetector's performance is characterized by its dark current, quantum efficiency, and bandwidth (or speed).

Fig.3-5. Schematic illustration of an interdigitated MSM photodiode [1.6].

3.2.1 Dark Current

The dark current of a photodetector is the current measured under normal operating bias when there is no light incident on the device. A model that provides an accurate description of the dark current of an interdigitated MSM photodiode has yet to be developed, since the complete understanding of the dark current of the planar device requires an accurate

description of the two-dimensional electrode electric field in the active layer and a full consideration of both thermionic and tunneling current. However for an interdigitated MSM, the region of interest is that directly below the interelectrode gap and around $1\mu\text{m}$ from the surface. Therefore, the two-dimensional MSM can be approximated by the theory of one-dimensional MSM, which has been fully treated by Sze [3.2].

Fig.3-6 (a) Schematic diagram of one-dimensional MSM structure. (b) The energy band diagram of MSM at thermal equilibrium [3.2].

For an MSM photodiode, the dark current mainly results from thermionic emission, which means some carriers can overcome the Schottky barrier at the contacts when a bias is applied. The dark current of a single Schottky M-S junction can be explained by considering only the electron current if the semiconductor is n-type. For an MSM, both electron and hole current components may have to be considered in order to determine the dark current. Φ_n

and Φ_p ($q\Phi_p = E_g - q\Phi_n$), shown in Fig. 3-6(b), are the Schottky barriers for electrons and holes, respectively. Under a certain bias, carriers overcoming these two Schottky barriers contribute to the total dark current. In Fig.3-6, V_{bi} is the built-in potential and L is the electrode spacing.

Since the MSM photodetector has two Schottky barriers connected back to back, bias of any polarity will put one Schottky barrier in the reverse condition and the other in the forward condition. As shown in Fig. 3-7, when a negative voltage V is applied to contact No.1 with respect to contact No.2, the contact No.1 is reverse biased and the contact No.2 is forward biased. The applied voltage V is shared between the two contacts

$$V = V_1 + V_2 \quad (3.14)$$

where V_1 and V_2 represent the voltage dropped across contact 1 and 2, respectively. Since contact No.1 is reverse-biased, its depletion is wider than that of contact No.2 and most of the voltage drop will occur across the depletion region of contact No.1. That is, $V_2 < V_1$.

Fig. 3-7 The corresponding energy band diagram of an MSM with a cathode contact on contact No.1 [3.2].

As the applied voltage increases, the sum of the two depletion widths also increases. Eventually at a certain bias, the two depletion regions touch each other and the sum of the two depletion widths equals exactly to the electrode spacing L . This phenomenon is called reach-through and the voltage is named reach-through voltage V_{RT} . This situation is illustrated in Fig. 3-8(a) [3.2]. As the voltage increased further, a point is reached at which the electric field at $x = L$ becomes zero and the energy band there becomes flat. This is the flat-band condition with the corresponding flat-band voltage V_{FB} , shown in Fig. 3-8(b). The value of V_{FB} can be estimated by a one-dimensional depletion equation

$$V_{FB} = \frac{qN_D}{2\epsilon_s} L^2 \quad (3.15)$$

where N_D is the effective carrier concentration and L is the electrode spacing. Because the absorption region of an MSM may be fully depleted under the flat-band condition, the device can be very fast, as both carriers move at their saturation velocities. When the applied voltage is less than V_{FB} , a potential well is formed, as shown in Fig.3-8(a), which could trap electrons. So in order to get a good photoresponse, the MSM photodiode should be biased at a voltage which is greater than the flat-band voltage V_{FB} .

For a voltage higher than V_{FB} , the energy band is bent further downward as illustrated in Fig. 3-8(c) and at a certain voltage the avalanche breakdown happens on the reverse-biased contact. With the development of semiconductor process technology, especially lithography, the electrode spacing L can be made smaller than the required depletion width at breakdown voltage. So an MSM can be completely depleted before avalanche breakdown occurs.

Under typical bias conditions shown in Fig.3-5, the electron current results from the

thermionic emission of electrons from contact No.1 and the hole current is due to the thermionic emission of holes from the contact No.2. For small bias, the effective barrier for electrons at contact No. 1 is Φ_n and at contact No.2 the barrier for holes is given by $(\Phi_p + V_{bi} - V_2)$. At low biases (before the reach-through condition), electron injection at the reverse-biased contact is the dominant current component, and the injected hole current from forward-biased contact is generally much smaller than the electron current.

When the applied voltage reaches V_{RT} , the MSM structure is entirely depleted. With further increase in applied voltage, the electron current remains small but the injected hole current from the forward-bias contact begins to increase rapidly. The reason for the increasing of hole current is because that the hole barrier $(\Phi_p + V_{bi} - V_2)$ is lowered. In some cases the hole current can be many orders of magnitude larger than the electron current.

At flat-band voltage V_{FB} , the hole current reaches a critical value as the hole barrier approaches a limiting magnitude Φ_p , which can be seen in Fig.3-8(b). For bias larger than V_{FB} , the barrier lowering effect at reverse-biased contact must be considered. Therefore, with voltages in excess of V_{FB} the current increases very slowly due to the Schottky barrier height lowering with the external field.

Fig. 3-8 Electric field and energy band diagram at different biases: (a) reach through voltage, (b) flat band voltage, and (c) higher than flat band voltage [3.2].

If the simplest thermionic emission analysis is used and the tunneling current is ignored, the total current density of thermionic emission can be expressed [3.2]

$$J = A_n^* T^2 \exp\left[\frac{-q(\phi_n - \Delta\phi_n)}{kT}\right] + A_p^* T^2 \exp\left[\frac{-q(\phi_p - \Delta\phi_p)}{kT}\right] \quad (3.16)$$

where, $A_{n,p}^*$ are Richardson constants for the electron and hole, respectively, and $\Delta\Phi_{n,p}$ are the respective Schottky barrier height lowerings for the electron and hole due to the image force effect, which can be determined by Eq.3.12.

To decrease the dark current, there is a trade-off between the electron injection at the reverse-biased contact and the hole injection at the forward-biased contact. At low bias voltage, the main source of dark current is electron injection and the increased hole injection becomes significant with the increase of the bias. Therefore both hole and electron injection should be reduced in order to get lower dark current. The lowest dark current is achieved when the electron and hole barrier heights are approximately equal, that is $q\Phi_p = q\Phi_n = E_g/2$. This is normally the basic rule to choose the appropriate electrode metal for an MSM photodiode.

Compared to other photodiodes, the dark current for the interdigitated MSM photodiode is relatively higher. The current flows laterally in the planar MSM device. Lateral current can involve strong interactions with the surface. The high density of surface states may cause trap assisted tunneling, which leads to large leakage current.

MSM photodiodes with the low dark current are desirable for a higher performance lightwave communication system since a high device dark current would cause difficulty in light signal detection and, hence, result in a higher bit-error rate. Improvements in device

design have resulted in MSM photodiodes with low dark current. It is reported [1.14, 3.3] that a significant reduction in dark current without sacrificing the responsivity or the bandwidth was realized by placing the electrode tips and the contact pads on top of an insulating layer of silicon nitride or silicon oxide. The reduction in dark current is due to the elimination of leakage current between the contact pads and a reduction in tunneling and thermionic emission current in the high electronic field regions near the tips of the electrodes and contact pads. Recently Chui *et al.* [3.4] demonstrated that the dark current of a silicon based asymmetric MSM photodiode could drop by five orders of magnitude without sacrificing the photocurrent compared to that of the symmetric MSM device. In this technique, two kinds of metals with different work functions were used as electrode contacts so that the barrier heights for both electrons and holes can be increased at the same time. Lin *et al.* [1.21] have reported a new MSM structure with very high photocurrent-to-dark current ratio ($\sim 10^3$) under a very weak 830 nm incident light power ($0.5 \mu\text{W}$) by employing very thin amorphous silicon-alloy on the top of crystalline silicon substrate. The amorphous layer could act as barrier layer due to its higher bandgap than crystalline silicon.

3.2.2 Quantum Efficiency

Light absorption in the photodetector will generate electron-hole pairs when the photo energy of incident light is higher than the energy gap of the semiconductor. Ideally, each incident photon would result in the charge of one electron flowing in the external circuit. In practice, several physical factors can reduce the responsivity, such as contact shadowing, reflection on the semiconductor surface, electron-hole recombination and incomplete

absorption due to relatively thin active layer. Once the photons have entered the semiconductor, the photodetection process consists of (1) absorption and (2) collection of the photogenerated electron-hole pairs. The internal quantum efficiency η_i compares the collected photocurrent to the number of photons in the active layer, which depends on the absorption coefficient α and the length of the absorbing region d by

$$\eta_i = 1 - e^{-\alpha d} \quad (3.17)$$

The external quantum efficiency η_e is proportional to the internal efficiency, but also takes reflection on the interface and contact shadowing into account. Typically, the refractive index for silicon is 3.42. Owing to the difference of refractive indexes of silicon and air, silicon reflects approximately 30% of the incident light. Application of antireflection (AR) coating dielectric material, such as Si_3N_4 , Al_2O_3 , ZnS , or MgF_2 , can routinely reduce this optical power loss to less than 5% [1.1]. Contact shadowing occurs when an electrical contact blocks a portion of the active absorbing region. The MSM is illuminated through the top electrode structure, which is opaque to a fraction of the incident signal. The blocking effect can be accounted for by

$$\frac{S}{A} = \frac{L}{L+W} \quad (3.18)$$

where S is the semiconductor area exposed to incident light, A is the total photodetector area, W is the width of the contact fingers and L is the interdigitated spacing. Therefore, the external quantum efficiency of MSM can be written as

$$\eta_e = \eta_i (1 - R) (S/A) = (1 - e^{-\alpha d}) (1 - R) \frac{L}{L+W} \quad (3.19)$$

Because the external quantum efficiency η_e compares the incident photon flux to the

collected photocurrent, it can be defined as

$$\eta_e = \frac{I_{ph}/q}{P_0/h\nu} \quad (3.20)$$

where I_{ph} is the photocurrent, P_0 is the power of incident photon and ν is the frequency of the incident light.

In Eq.3.20, the ratio (I_{ph}/P_0) is called the responsivity $\mathfrak{R}$, with units of A/W. So the Eq.3.20 can be re-written as

$$\eta_e = \frac{\mathfrak{R}h\nu}{q} = \frac{\mathfrak{R}hc}{q\lambda} \quad (3.21)$$

Because the photocurrent and power of the incident light are easy to measure, it is convenient to use responsivity to evaluate the performance of a photodetector instead of quantum efficiency.

Complete depletion for a one-dimensional MSM occurs at the punch-through bias and the capacitance remains constant thereafter. In a two dimensional device, the interdigitated MSM continues to deplete regions further from the surface, under the electrodes, and beneath the absorption layer. The potential distribution in a typical interdigitated MSM diode with 1 μm finger and 2 μm spacing for a 10 V bias is given in Fig.3-9 [1.6], [3.5]. The electric field lines were calculated using a finite element computer program by Soole *et al.* [1.6]. The magnitude of the electric field is proportional to the density of equipotential lines. Therefore, within the active layer of MSM diode, the electric field is highest near the surface and becomes weaker as depth increases. When the absorption occurs in the high field region, the electric field can quickly separate the electron-hole pairs before they can recombine.

Fig.3-9 The electric field lines of equal potential below the electrodes of an MSM photodiode under a 10 V bias [1.6].

The measured dc current-voltage characteristics for an interdigitated silicon MSM photodetector [1.15] are shown in Fig.3-10. The finger spacing and width of the interdigitated electrodes were both 100 nm and the silicon active layer was 100 nm. The photocurrent density is shown first to rise with voltage and then becomes saturated. The low voltage knee occurs because the low electric field is insufficient to separate the photogenerated carriers until the flat-band condition is achieved at the anode. Above the knee, there is a slight rise in signal with bias as the depletion width increases. This knee bias is close to flat-band voltage V_{FB} of the one-dimensional MSM model, which is given by

$$V_{FB} = \frac{qN_D}{2\epsilon_s} L^2 \quad (3.15)$$

The current flow in the interdigitated MSM at low bias would occur predominantly in a thin subsurface layer, so Eq.3.15 might be a good approximation for the knee bias in the

interdigitated MSM device. The MSM is normally biased at a voltage higher than flat-band voltage in order to get good responsivity.

Fig.3-10 Current-voltage (I - V) characteristics of a silicon MSM photodiode for light with different incident powers. The curve with the smallest current density shows the dark current-voltage characteristics [1.15].

Although contact shadowing for MSM photodiode cannot be completely eliminated, it can be seen from Eq.3.19 that it is desirable to reduce the contact width W to the greatest extent possible. The finger width could be reduced to submicron values by electron beam lithography, which is very expensive. It is reported that transparent indium-tin-oxide (ITO) or semi-transparent thin Au metal layers have been used to reduce the effect of contact shadowing [3.6]. However, when the wavelength of the incident light is >1550 nm, ITO electrodes become non-transparent. Furthermore, ITO or thin metal electrodes having a relatively higher resistance would result in a larger RC time constant and hence reduce the device response speed [3.6]. Recently bottom ridged electrodes have been reported to increase the quantum efficiency [3.7]. The ridged electrodes offer a relatively smaller electrode area on the surface and a stronger lateral electric field in the absorption layer, which could

effectively increase the responsivity of the device.

3.2.3 Capacitance

The capacitance of an MSM photodiode depends on the total device area and the width and separation of the electrode fingers. For an undoped and infinitely thick semiconductor, an approximate value for the capacitance can be calculated by a theoretical model based on conformal mappings [3.8]

$$C = \frac{K(k)}{K(k')} \times \frac{\epsilon_0 (1 + \epsilon_r) A}{L + W} \quad (3.22)$$

where A is the interdigitated area (the total photodetector area) in the MSM structure, W and L are the finger width and finger spacing, ϵ_0 is the dielectric constant of free space, ϵ_r is the relative dielectric constant of the semiconductor, and K(k) is the complete elliptic integral of the first kind

$$K(k) = \int_0^{\pi/2} \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}} \quad (3.23)$$

$$\text{with } k = \tan^2 \left(\frac{\pi \cdot W}{4(W + L)} \right) \quad (3.24)$$

$$\text{and } k' = \sqrt{1 - k^2} \quad (3.25)$$

The capacitance per unit area of typical interdigitated MSM photodiodes is much less than that of a conventional pin photodiode with equal photosensitive area. Fig.3-11 shows the comparison of calculated capacitance of an MSM structure and pin photodiode [1.6].

Devices are assumed to be square, with $\sqrt{A}$ being the length of one of its sides. The electrode spacings of the three MSMs are 1, 2, and 3 μm , separately. The solid and dashed lines are for electrode widths of 1 and 0.5 μm , respectively. Two InGaAs pin photodiodes

have the absorbing layers of 0.5 and 2 μm . It is seen that capacitance of the MSM is significantly lower than that of the pin, even when comparing the rather thick (2 μm) pin and the narrow spacing (1 μm) MSM.

The low capacitance means that an MSM with large interdigitated area might be used with ease with a multimode fiber, which significantly decreases the complexity of the integration process.

Fig.3-11 Capacitance versus edge length for an MSM photodiode and pin photodiode [1.6].

3.2.4 Bandwidth

Three physical effects determine the bandwidth of photodetectors: (1) diffusion of carriers generated outside the space-charge region, (2) the RC time constant, and (3) the transit time, which is the time it takes the photogenerated carriers to drift through the space-charge region. Since diffusion times are typically very large (on the order of a nanosecond per micrometer), consideration has to be given in the design of the photodetector to minimizing the amount of light absorbed outside the space-charge region.

As discussed previously, low capacitance per unit area is one of the attractive attributes of

the MSM photodiode. A capacitance of ~ 40 fF, which is the typical capacitance for an MSM with $1\mu\text{m}$ electrode width and $2\mu\text{m}$ spacing, gives an RC charging time of just 2 ps into a $50\ \Omega$ load, while the transit time of the photogenerated carriers is a few tens of ps. Therefore, the frequency response of the MSM detector is mainly determined by the transit time of the carrier.

Both the electrode spacing and the applied bias determine carrier transit time. The electrode spacing determines the distance carriers must travel, and the correct applied bias ensures complete depletion of the active region. Under sufficient bias, all carrier generation takes place within the high field region and the carriers travel at saturation velocity.

To produce high quantum efficiency for an MSM photodiode, a relatively thick absorption layer and wide spacing of the finger are required to absorb more optical signal. However, its operating speed can be limited by the slow response of carriers generated in the low electric field regions deep under the electrodes and the long transit time resulting from the wide spacing. So a tradeoff exists between bandwidth and quantum efficiency.

3.3 Device Design

In the present project, MSM devices with the interdigitated structure shown in Fig. 3-5 were fabricated. The width and spacing of the finger were both set to $2.5\ \mu\text{m}$, which is the minimum resolvable feature size for photomasks generated in Carleton's Microfabrication Facility. Since the target thickness of the absorbing film was in the range $1 - 2\ \mu\text{m}$, a finger spacing of $2.5\ \mu\text{m}$ is also appropriate to achieve high electric fields throughout the semiconductor film, which is required for efficient carrier extraction and to provide

maximum response speed. Ten 100 μm long pairs of fingers were used, giving a total optical absorption area of 100 μm by 100 μm . This total area should be enough to absorb effectively all the light emitted by a single-mode silica fiber placed in close proximity to the detector without adding excessive capacitance. Titanium was used as the Schottky barrier metal since it is known to provide a barrier height near midgap when deposited on silicon.

CHAPTER 4

SILICON MSM PHOTODIODE FABRICATION AND EVALUATION

4.1 Device Fabrication

4.1.1 Absorption Layer Preparation

Starting substrates were (100) oriented p-type silicon wafers with a resistivity of 1-5 Ωcm . SiO_2 layers with a thickness of 100 nm were grown thermally on top of the silicon substrates to electrically isolate photoactive layers from the substrates. Active layers of amorphous and polycrystalline silicon were prepared by low pressure chemical vapor deposition (LPCVD), plasma enhanced chemical vapor deposition (PECVD), and rapid thermal chemical vapor deposition (RTCVD). RTCVD samples were obtained from Lawrence Laboratories, Phoenix, Arizona, and PECVD and LPCVD samples from Strataglass, Mountain View, California. For comparison, LPCVD samples were also grown in Carleton's Microfabrication facility at a temperature of 627 °C and pressure of 10 Torr from a SiH_4 source.

Chemical vapor deposition of amorphous silicon is a costly procedure, since deposition rates are very low, forcing the use of large quantities of silane. Sputtering of silicon is a low-cost approach to amorphous silicon deposition. The drawbacks of sputtering technology are the low deposition rate and poor film quality. Nevertheless, polycrystalline silicon thin film transistors prepared by sputtering, with electrical properties comparable to their CVD counterpart, have been fabricated [4.1]. On the basis of this result, there was some hope for

producing sputtered silicon with high mobility suitable for the active layer of MSM photodetector. Therefore, several amorphous silicon samples were prepared in a Materials Research Corporation 8620 diffusion-pumped sputtering system at Carleton's Microfabrication Facility. The silicon films were sputtered in argon atmosphere, with the base pressure of 5×10^{-7} Torr and sputtering pressure of 8 mTorr and DC power at 100W.

Implanting of silicon-on-insulator (SOI) material is another approach for preparing amorphous silicon films over oxide. High quality SOI material is readily available from electronics industry wafer suppliers. Amorphization by silicon implantation can be easily integrated with conventional CMOS processing. Damage introduced by ion implantation has been reported [4.2] to increase both the long-wavelength quantum efficiency and speed at the wavelength of $1.06 \mu\text{m}$. In this project, SOI wafers obtained from SOITEC corporation with $1.5 \mu\text{m}$ silicon film thickness and $0.5 \mu\text{m}$ buried oxide thickness were implanted with Si^+ ions at 77K to produce an amorphous silicon layer. Table 4.1 lists the implantation energies and doses. Due to the high dose required, only a small region at the center of each sample was implanted.

Table 4.1 Implantation energy and dose of SOI

Energy	Dose
1.6 MeV	$1.2 \times 10^{15} \text{ cm}^{-2}$
1.15 MeV	$0.8 \times 10^{15} \text{ cm}^{-2}$
0.7 MeV	$0.6 \times 10^{15} \text{ cm}^{-2}$
0.3 MeV	$0.4 \times 10^{15} \text{ cm}^{-2}$

All amorphous silicon films wafers examined here were annealed in nitrogen atmosphere to be recrystallized in order to increase the photoresponse. The annealing time required for recrystallization has been found by other researchers to vary with annealing temperature and the deposition conditions, such as deposition rate and deposition temperature. Higher deposition rate results in decreased nucleation rate, thus it takes longer for such films to be crystallized. Shorter crystallization time is observed for higher deposition temperature [4. 3]. Girginoudi *et al.* [4. 4] reported a two-stage annealing, which involves furnace anneal (FA) for 6 hours at 600 °C, followed by rapid thermal anneal (RTA) at 850 °C in a five steps of 30 seconds each. The low temperature furnace treatment at 600 °C allowed the growth of large grains, which may contain defects inside them, and the RTA at 850 °C could eliminate those defects within grains. The two-stage anneal resulted in a 100 nm thick polysilicon film with large grains free of in-grain defects, low surface roughness, and higher carrier mobility [4. 4]. Therefore, the amorphous films (except implanted SOI) in this project were annealed using the above two-step procedure (furnace annealing for 6 hours at 600 °C, followed by rapid thermal annealed for five steps of 30 seconds at 850 °C in nitrogen atmosphere). In order to observe the effect of RTA, one amorphous sample (labeled ST513) was only furnace annealed. Table 4.2 summarizes the semiconductor films used to make MSM detectors here.

Table 4.2 Silicon active layer list for MSM Photodiodes

Deposition Process	Labeled Number	Thickness (nm)	Film Structure*	Deposition Process	Labeled Number	Thickness (nm)	Film Structure*
LPCVD	ST642	500	Amorphous	RTCVD	ST239	1000	Poly
	ST532	500	Recrystallized (FA+RTA)	RTCVD	ST254	2000	Poly
	ST513	500	Recrystallized (FA)	LPCVD	PT71	19000	Poly
LPCVD	ST11	500	Poly	Sputtered	SP111	2000	Amorphous
PECVD	ST191	1000	Amorphous		SP131	2000	Recrystallized
	ST193	1000	Recrystallized	Implantation	SOI11	1500	Amorphous
LPCVD	ST44	1000	Poly		SOI12	1500	Recrystallized

* Film structure refers to as-deposited film.

4.1.2 Interdigitated Electrodes Fabrication

Electron beam evaporated titanium-aluminum was used for the electrode metal, typically 30 nm Ti followed by 100 nm Al. Titanium was chosen as the layer contacting with the silicon because it leads to equal electron and hole Schottky barrier height (approximately 0.5 eV) close to one half the bandgap of silicon ($E_g = 1.12$ eV) [1.5]. In this way the dark current of the photodiode caused by thermionic emission of carriers over the Schottky barrier will be minimized. Also titanium has good adhesion to silicon. Aluminum was used as the top metal because of its ability to reduce the resistance and good adherence to gold bond wires.

The width and spacing of the interdigitated contacts are both $2.5\ \mu\text{m}$ and each electrode consists of ten parallel fingers joined together at one end, giving an absorbing interdigitated area of $100 \times 100\ \mu\text{m}^2$ attached to a $50\ \mu\text{m}$ by $50\ \mu\text{m}$ probe pad. The small pad size minimizes device capacitance. Fig.4-1 presents a photomicrograph.

Fig.4-1 Photographs of MSM photodetector fabricated in this project. (a) Detector array, (b) Enlarged picture of interdigitated electrodes.

The interdigitated electrodes were patterned by lift-off lithography. Before applying the lift-off resist (LOR) resist, silicon wafers should be baked at 200 °C for 30 minutes in a convection oven to dehydrate the surface. The basic steps of the electrode fabrication are illustrated in Fig.4-2.

Fig.4-2 Basic steps for fabrication of an MSM photodiode.

For clean lift off processing, the LOR film should be thicker than the metal layer. The spinning speed of resist LOR3A was 3000 rpm for duration of 45 seconds, which created a resist layer with thickness of around 340 nm. The LOR3A was then prebaked at 175 °C for 5 minutes. The next resist layer was image resist (S1811), which was coated at 4000 rpm for 30 seconds. The resist stack was prebaked at 100 °C for 1 minute. The basic functions of the

prebake of LOR are to dry the LOR film and to control undercut rate. The prebake temperature of LOR and exposure time of image resist are very critical in determining undercut rate of LOR, although prebake time, and develop time also have influence on the undercut. Once the development processes have been decided, careful design of the prebake temperature and exposure time enable good control of the undercut. After several trial experiments, 30 seconds of the exposure time and prebake temperature of 175 °C for 5 minutes were set for this project. The bi-layer resists are developed in MF321 developer for around 1.5 minutes. The LOR3A develops isotropically, thus a bi-layer reentrant sidewall was created, see Fig.4-2(d).

The wafers were transferred into a Technics Planar Etch II planar plasma etcher to clear away any remaining photoresist just before metal deposition, since the remaining photoresist will create gaps in the metal electrodes after lift-off. The plasma etch was performed for a total of 1.5 minutes in oxygen at a pressure of 0.3 Torr and a power of 100W. The Ti/Al metal layer was evaporated in a cryopumped Balzers BA510 e-beam evaporator with a base pressure of 2×10^{-7} Torr. The total thickness of metal was 130 nm, which is less than that of resist LOR3A (300nm). The reentrant profile of LOR3A enables a discontinuous metal deposition, see in Fig.4-2(e), thus the LOR remover (Microposit Remover 1165) could penetrate into the LOR3A through the discontinuous metal layer and dissolve the bi-layer resist stack. Therefore, only metal in contact with the silicon surface is left after lift-off. Microposit remover 1165 was put into two tanks, and wafers stayed in each tank for around 30 minutes respectively. Ultrasonic vibration was used to help to improve the lift-off

efficiency.

MSM samples were then annealed in a molecular hydrogen atmosphere for 10 minutes at 400 °C in an effort to maximize responsivity. As discussed previously, hydrogen can bind with dangling bonds at crystalline boundaries in polysilicon, thus both carrier mobility and lifetime could be increased by the hydrogen passivation.

4.2 Performance Evaluation of Silicon MSM Photodiodes

Raman Spectroscopy

Raman spectroscopy is a simple and non-destructive method of analyzing crystallinity in semiconductor surface regions. In this project, Raman Spectroscopy was used to estimate the relative grain sizes of silicon active layers prepared in various ways. The ISA MOLE 3000 Raman Microprobe with excitation wavelength of 488 nm (provided by an argon ion laser) was used to record Raman spectra of the silicon MSM samples at room temperature. In order to avoid local recrystallization during the Raman measurement, the incident laser power on the MSM photodiodes was controlled to the order of 10 mW, which was verified to be sufficiently low to avoid thermal crystallization by the laser beam. For the wavelength of 488 nm, the penetration depth is 1000 nm for monocrystalline silicon and about 100 nm for the amorphous silicon and varies between 100 and 1000 nm depending upon the state of the material [4.5]. The minimum thickness of the polycrystalline and amorphous silicon layers here is 500 nm and that of monocrystalline silicon is 1500 nm (see chapter 4.2.4), therefore the Raman scattering from the underlying silicon substrates could be negligible.

The Raman spectrum peak of amorphous silicon is located at around 480 cm^{-1} , the peak frequency and the linewidth of the polycrystalline silicon Raman band are about 517 cm^{-1} and 5 cm^{-1} , respectively, and the peak frequency of Raman spectrum of single crystalline silicon lies at 520 cm^{-1} with a narrow linewidth of around 3.5 cm^{-1} [4.5-4.11]. The Raman band narrows with the increase of the laser power, while the Raman peak frequency does not change.

Fig.4-3. Plot of the peak Raman frequency as a function of the grain size in the polycrystalline silicon films [4.9].

The approximate grain size can be determined from Raman shift by Fig.4-3 [4.9]. The curve in Fig.4-3 shows the peak Raman frequency observed in the polycrystalline silicon films as a function of the grain size, which was determined from (111) X-ray diffraction peak. There is some uncertainty in the grain sizes inferred from different diffraction lines. For example, the average grain size of the polysilicon deposited by LPCVD at $620\text{ }^{\circ}\text{C}$ was estimated to be 10 nm obtained from the (111) diffraction line, and was as high as 77 nm when the (220) diffraction line was used [2.1]. Nevertheless, X-ray diffraction line is a

suitable way to get an order of magnitude grain size and relative trends for the polysilicon layers. From dots on the solid line in Fig.4-3, it was seen that for a grain size less than ~ 15 nm, the Raman shift decreased from the single crystal value of 520 cm^{-1} to about 513.5 cm^{-1} for a grain size of ~ 4.7 nm. Therefore, the curve shown in Fig.4-3 allows using the Raman shift to be used to estimate the crystallite size.

Photoresponse

Photoresponse measurements were taken at Carleton University using a continuous wave Nortel LC155CA-20 laser light source operating at 1550 nm. The laser output power from the end of the single-mode optical fiber was around 25 mW. The bias on the MSM photodiode and DC current output from it were monitored with a Hewlett-Packard 4155A Semiconductor Parameter Analyzer. The core diameter of the single mode fiber is $9\text{ }\mu\text{m}$, which is less than the size of the active interdigitated area of MSM photodiode ($100\times 100\text{ }\mu\text{m}^2$). The optical fiber was put in a micro-positioner, which could be operated manually in three dimensions. The end of the fiber was positioned directly above the detector with the incident light as perpendicular as possible to the detector plane, which was accomplished by viewing the detector and fiber through a microscope. During the photocurrent test, the position of fiber was adjusted in three dimensions until the maximum output current was observed. Maximum output current corresponded to the optimum alignment of incident light on the detector.

4.2.1 PECVD Polysilicon MSM Photodiodes

No measurements were possible on crystallized amorphous silicon films prepared by

PEVCD, due to delamination of these films during annealing, which is shown in Fig.4-4.

Fig.4-4 Surface photograph of the annealed PECVD MSM photodetector.

4.2.2 Sputtered Silicon MSM Photodiodes

Raman spectra for as sputtered and annealed sputtered silicon are shown in Fig.4-5. The Raman shift ($\sim 505\text{cm}^{-1}$) of as-sputtered silicon (SP111) is much higher than that of amorphous silicon ($\sim 480\text{cm}^{-1}$), which means that some crystallization occurs during the deposition. For annealed sputtered silicon (SP131), the strong peak appearing at 507cm^{-1} and the shoulder at lower frequencies results from an amorphous-like component indicating incomplete crystallization during the crystallization anneal.

Fig.4-5 Raman spectra for as sputtered and annealed sputtered silicon.

The incorporation of oxygen during sputtering could influence the properties of the sputtered films, which may be one reason for the apparently high crystallinity of as sputtered films. Normally there are two steps in a crystallization process. The first step is the nucleation of crystallites in the amorphous layer, and the second one is the crystallization of adjacent amorphous material around these initial nuclei, until all of the amorphous material is crystallized. When the initially deposited layer contains some nuclei, the time required for the crystallites to include to all the amorphous material may be impractically long. Since the as-sputtered film (SP111) is not amorphous and it may contain some nuclei, the time to recrystallize this film could be much longer than usual. That may be the reason why the two-stage crystallization anneal, which could normally crystallize amorphous silicon, could not crystallize the sputtered film completely. The other explanation might be the present of impurities in the films.

Dark current (I_d) and photocurrent (I_p) of sputtered silicon MSM detectors are shown in Fig.4-6. Photocurrents for both as sputtered (SP111) and annealed sputtered (SP131) MSM detectors were very small, only a few nA.

Fig.4-6 Photocurrent and dark current of sputtered Si MSMs versus applied biases.

4.2.3 LPCVD and RTCVD MSM Photodiodes

Surfaces of the active polysilicon films prepared by LPCVD and RTCVD were inspected by Scanning Electron Microscopy (SEM) at Carleton, as shown in Fig.4-7. The magnification is 15,000 times and the length of the bar in the SEM images is 1 μm .

Comparing two polysilicon films with same thickness of 50 nm (ST11 and ST532) prepared by LPCVD, it is found that as deposited polysilicon film (ST11) has characteristically rough surface; while the surface of recrystallized amorphous film (ST532) is much smoother. The surface roughness is increased with the increase of the film thickness. Polysilicon films with thickness of 2 μm (ST254 and PT71) have the highest surface roughness. A columnar profile is visible clearly in the thick polysilicon films.

The grain size comparison of various silicon films is shown by their Raman spectra in Fig.4-8. The very broad and weak Raman peak at around 480 cm^{-1} for ST642 (see Fig.4-8(a)) shows the formation of amorphous silicon during LPCVD process. The Raman shift of recrystallized amorphous silicon film (ST532) is around 516 cm^{-1} , corresponding to a grain size of $\sim 6\text{ nm}$ (see Fig.4-3), which is much less than the reported grain size (50nm) of the recrystallized amorphous film annealed under the same condition [4.5]. Amorphous silicon films prepared by different deposition rate and deposition temperature require different annealing time. The grain size of recrystallized amorphous silicon film increases with annealing time. The small grains in ST532 may be due to the relatively short annealing time.

Fig.4-7 SEM micrographs of polysilicon films.

The Raman shifts of polysilicon films ST11 and PT71 are both 519 cm^{-1} , and the peaks of the Raman spectra of all the other polysilicon films are $\sim 516\text{ cm}^{-1}$. The difference of grain size among these polysilicon films may be because of various deposition conditions.

Higher deposition temperature could result in larger grains in polysilicon [4.12].

Fig.4-8 Raman spectra of silicon films prepared by LPCVD and RTCVD

Polysilicon MSM photodiodes were measured in the dark and then under the 1550nm laser. Plots of dark current (I_d) and photocurrent (I_p) for poly silicon MSM devices versus applied bias are shown in Fig.4-9. ST254 and PT71 had very high dark currents, which may be attributed to the rough surfaces. This roughness has been known to cause large leakage current in MSM photodetectors, since surface roughness may result in trap assisted tunneling [4.13, 4.14]. It is found that the relatively higher dark current decreased with time and normally became relatively stable within two minutes after measurement. For MSMs ST11 and ST532 with lower initial leakage, dark currents changed little with time. In order to avoid the transient effect, current measurements were taken two minutes after the bias was first applied across the detector.

Fig.4-9 Dark current and photo current versus applied bias for polysilicon MSMs at 1550nm.

For comparison, photocurrents and Raman shifts of silicon MSMs are listed in Table 4-3. Raman shifts of the two recrystallized amorphous silicon films, ST532 and ST513, are almost the same (see Fig.4-8(a)), which means that grains with almost same size exist in the two films. ST532 annealed by FA and RTA has higher photoresponse than ST513 with only furnace anneal (see Table 4-3), which demonstrated the ability of high temperature RTA to reduce the defects with grains, thus increasing photoresponse even if grain size remains constant. Comparing with the small photoresponse of sputtered silicon films, whose Raman shifts are 505 cm^{-1} and 507 cm^{-1} , it appears that polysilicon films with grain sizes corresponding to Raman shift between 516 cm^{-1} and 519 cm^{-1} are good candidates to absorb the light with wavelength of 1550nm. The polysilicon with Raman shift between 516 cm^{-1} and 519 cm^{-1} have grain size of about 6- 13 nm (see Fig.4-3). No large photoresponse difference was found from MSM detectors with Raman shifts of 516 cm^{-1} and 519 cm^{-1} and the reason may be because that several factors besides grain size, such as the defects within grains, could affect the photo response.

Table 4-3 Photocurrents and Raman shifts of MSMs.

MSM	Raman shift (cm^{-1})	Photocurrent (10 V bias)	MSM	Raman shift (cm^{-1})	Photocurrent (10 V bias)
ST642	480	0	ST239	516	1.8 μA
ST513	515.9	441 nA	PT71	519	8.1 μA
ST532	516.3	650nA	ST254	516	8.4 μA
ST11	519.3	273 nA	SP111	505	9.5 nA
ST44	515	950nA	SP131	507	14 nA

Responsivity measurements were attempted on the amorphous devices (ST643), but they appeared to have no detectable photoresponse. The reason might be the recombination of photogenerated carriers before they are collected by the electrodes, since there are many defects in amorphous silicon, which would capture the free carriers. The wider effective bandgap in amorphous silicon might be another reason. However, crystallized amorphous silicon MSMs (ST532) has much enhanced photoresponse compared to as deposited polysilicon MSMs (ST11). The relatively higher responsivity in ST532 is attributed to the defect-free grains formed during the crystallization anneal, which could increase the carrier mobility and lifetime.

The highest photoresponses in this project are from polysilicon MSMs (ST254 and PT71) with 2 μm thick active layers, which had a responsivity of 0.34 mA/W, and corresponding external quantum efficiency of 0.07% at 10 V bias. Accounting for light blocked by contact fingers (~ 50 % coverage) and reflected by the air-silicon interface (~

30% reflection) gives an internal quantum efficiency of 0.2%. This quantum efficiency estimate is based on the laser power output, while the light actually reaching the device may be less due to non-normal illumination and loss at the splice. The calculated efficiency would be higher if these losses were accounted for. Due to the very low absorption coefficient of silicon at the wavelength of 1550 nm, the penetration depth is much higher than 2 μm . Therefore only a very small portion of incident photons are absorbed by the active layer, which results in the poor responsivity in this project. To the author's knowledge, the highest photoresponse from the MSM detector at 1550 nm was reported by Buce *et al.* [1.14]. They fabricated a metal-germanium-metal photodiode with an overall external quantum efficiency of 7.5% and photoresponse of 90 mA/W at the wavelength of 1550nm. The 270 nm thick germanium film in the above MSM was grown by molecular beam epitaxy (MBE), which is complex and costly.

4.2.4 Implantation of SOI MSM Photodiodes

The Raman spectrum of an SOI sample amorphized by silicon ions implantation (labeled SOI11) is shown in Fig.4-10(a). The asymmetric Raman spectrum showed no sharp peaks for frequency shifts above 300 cm^{-1} and only a very weak and broad peak near 480 cm^{-1} , which indicates that implantation resulted in amorphization of the surface of SOI11 sample. The photoresponse for the implanted SOI11 MSM detector at 1550nm was almost zero. Its dark current was as high as 1.9 μA at 10V bias. The Raman spectrum for a non-implanted part of the sample, labeled SOI8, is given in Fig.4-10(b). A Raman shift (521 cm^{-1}) appropriate to

single crystal silicon was found for this device. The photoresponse at 1550 nm was effectively zero.

Fig.4-10 Raman spectra of SOI MSMs. (a) As implanted and annealed SOI. (b) Fully recrystallized SOI.

An implanted SOI sample (labeled SOI12) was then furnace annealed for 5 minutes in nitrogen atmosphere at 500 °C to observe optical and electrical changes with annealing. The Raman shift of SOI12 is $\sim 509 \text{ cm}^{-1}$ (see Fig.4-10(a)). The photoresponse of SOI12 is almost zero, which may be due to the relatively small Raman frequency (509 cm^{-1}). As discussed above, silicon films with grain sizes corresponding to Raman shift between 516 cm^{-1} and 519 cm^{-1} are good candidates to absorb the light at 1550nm and the Raman shift of SOI12 is not in this range.

In order to increase the grain size, the implanted SOI3 was then annealed in three steps

of 60 seconds at 850 °C in nitrogen atmosphere by RTA (labeled SOI3). Its Raman spectrum is shown in Fig.4-10(b). It can be seen that the implanted part was completely crystallized after anneal, due to the Raman shift of 521cm^{-1} . It was at first thought that the reason for this total crystallization may be because of too long an annealing time. Another implanted SOI sample (labeled SOI4) was therefore annealed for just 5 seconds at the same temperature. However, the same Raman shift as that of SOI3 was reached (see Fig.4-10(b)). No measurable photoresponse was from SOI3, SOI4 and SOI8. Attempted anneal conditions of implanted SOI and their corresponding Raman shifts are listed in Table 4-4.

Table 4.4 Raman shift and photoresponse of implanted SOI MSMs.

Process	Labeled Number	N ₂ Anneal	Photocurrent (10V bias)	Raman shift (cm^{-1})
Implanted SOI	SOI11	No	0	480
	SOI12	FA	0	509
	SOI3	RTA (3x60s)	0	521
	SOI4	RTA (5s)	0	521

By comparing the implanted SOI MSM devices reported by Sharma [4.2] and those examined in this project, it is considered that the failure reason here may be because of the improper implanted profile. Ion implantation of SOI reported by Sharma created a highly absorbing damaged silicocon layer around 1 μm below the surface, with a peak at 0.7 μm and near-surface damage of 25% of the peak damage. A dark current as low as 630 pA at 10V

bias and an internal quantum efficiency of 23% at the wavelength of 1060 nm were measured from that implanted SOI MSM detector[4.2]. The relatively undamaged surface material allowed the formation of high quality Schottky barrier, which resulted in the low dark current. In this project, the Raman band of SOI11 in Fig.4-10 shows that around 100 nm silicon film under the surface was amorphized, since the penetration depth of 488 nm light in amorphous silicon is about 100 nm [4.5]. The reason of high dark current for SOI11 may be because the too damaged surface prevents the formation of good Schottky barriers. The implanted films recrystallized too readily, which may be attributed to the incomplete amorphization of SOI because the implant was not done correctly for some reason. Therefore, optimization of implant condition and recrystallized anneal cycles could make it possible to obtain useful polysilicon films from implanted SOI.

CHAPTER 5

METAL-GERMANIUM-METAL PHOTODIODES

Poly germanium would seem to be an ideal material for 1550 nm detection, since its bandgap is below 0.8 eV. Amorphous and poly germanium MSM detectors were fabricated and characterized here in an attempt to test this contention.

5.1 Device Fabrication

Starting substrates are (100) oriented p-type silicon wafers with a resistivity of 1-10 Ωcm . In similar fashion to the polysilicon MSM detectors, 100 nm thick SiO_2 layers were grown thermally on these substrates. 50 nm thick amorphous silicon seed layers and 500 nm polycrystalline or amorphous germanium active films were deposited onto SiO_2/Si substrates using rapid thermal chemical vapor deposit (RTCVD) in ASM Epsilon at Lawrence Laboratories (Phoenix, Arizona). Exact details of the deposition process are proprietary to Lawrence Labs. The amorphous silicon seed layer facilitates the nucleation of germanium on SiO_2 layer [5.1]. Because of the lower bandgap and much higher intrinsic carrier concentration of germanium compared to silicon, germanium photodetectors typically have a much larger leakage current than silicon [1.12]. Therefore, a silicon capping layer with thickness of 40nm was deposited onto some samples in an attempt to provide a higher Schottky barrier at the detector electrodes.

For comparison, 200nm thick germanium and 20nm thick silicon cap layers (labelled SP1) were sputtered onto SiO_2/Si substrates using a Varian 200 sputtering system in Carleton's Microfabrication Facility. Both silicon and germanium films were sputtered in

argon atmosphere, with a base pressure of 3×10^{-7} Torr and Ar pressure during deposition of 4 mTorr. The germanium target has resistivity of 5-50 Ω -cm and it was sputtered by DC pulse with a power of 200W. Silicon films were sputtered with RF power of 200W. Kobayasi *et al.* [5.2] reported the amorphous-to-polysilicon transition temperature for germanium deposition is around 400°C. Sputtered films in this project were then annealed at 410°C for 1 minute by RTA in order to recrystallize the amorphous germanium, since detectors based on amorphous germanium on silicon exhibited no photoresponse for wavelengths greater than 1200 nm [1.10]. The structures of the above samples are given in Table 1.

Table5.1 Metal-germanium-metal detector sample list.

Wafer number	Process	Target thickness(nm)
PG6	Si cap / α -Ge/ α -Si/ SiO ₂	40/500/50/100
PG30	poly-Ge/ α -Si/ SiO ₂	500/50/100
PG39	Si cap /poly-Ge/ α -Si/ SiO ₂	40/500/50/100
SP1(annealed)	Si cap / α -Ge/ SiO ₂	20/200/100

The same fabrication process and same electrode metals as that of silicon MSMs were employed to make metal-germanium-metal photodiodes.

5.2 Experimental Results and Discussions

5.2.1 Material Analysis

Transmission Electron Microscopy (TEM) images for the above RTCVD samples were provided by ST Microelectronics (Ottawa), as shown Fig.5-2. It can be seen that the layer

thickness and crystallinity are not as expected, which demonstrates the difficulty and complexity of germanium deposition. Sample PG6 should have consisted of 500nm thick amorphous germanium, however around 900nm thick polygermanium with columnar grains was found, as can be seen in Fig.5-1(a). The amorphous seed layer was fully recrystallized and no cap was visible on top of the germanium layer. Voids were found in the bottom of both the germanium and silicon seed layer (see Fig.5-1(b)). The thickness of poly germanium PG30 with columnar grains is variable (500nm to 900nm). There was an unknown cap layer with thickness of 44nm and the silicon seed layer was still in an amorphous state as expected (see Fig.5-1(c) and (d)). As shown in Fig.5-1(e), the thickness of the poly germanium film PG39 was around 850nm. Here the amorphous silicon seed layer is re-crystallized. Voids could be found at the interface of silicon and germanium layers (see Fig.5-1(e) and (f)).

To observe the film surfaces, SEM images of RTCVD germanium samples were taken by ST Microelectronics, as shown in Fig.5-2 (a),(b) and (c). For comparison, SEM image of polysilicon sample (labeled ST11) with the thickness of 500 nm taken at Carleton is given in Fig.5-2 (d). The surfaces of germanium films are much rougher than that of polysilicon, which may pose problems in Schottky diode formation.

(a)

(b)

(c)

(d)

(e)

(f)

Fig.5-1 TEM images: (a) and (b) PG6, (c) and (d) PG30, (e) and (f) PG39

Fig. 5-2 SEM images of germanium films: (a) PG6, (b) PG30, (c) PG39 and (d) ST11. In picture (d), the magnification is 15K and the length of the bar in the SEM images is 1 μm .

5.2.2 Dark Current and DC Photoresponse Measurements

Dark currents of germanium MSM detectors were measured with a Hewlett-Packard 4155 Semiconductor Parameter Analyzer at Carleton University. It was found that the dark currents for PG6, PG30 and PG39 are almost the same. Plots of dark currents of RTCVD sample PG39 and sputtered sample SP1 versus applied biased are shown in Fig.5-3. From

Fig.5-3, it can be seen that the dark current of PG39 is extremely high and has already reached the current limit of 1 mA at the bias of ~ 0.5 V.

A 4-point probe was used to measure the resistivity of germanium layers. Resistivities of PG6, PG30 and PG39 were almost the same (around $0.05\Omega\text{cm}$), which is almost four orders of magnitude smaller than intrinsic monocrystalline germanium [1.13]. The very high large dark current for RTCVD MSM detector may be due to the high inherent conductivity and high surface roughness. The metal-germanium contact maybe transform from a Schottky diode to ohmic contact. Therefore, highly conductive RTCVD germanium layers prevented the build up of an efficient Schottky barrier at the metal-semiconductor interface and were not suitable for useful MSM photodetectors.

Fig.5-3 Dark current of RTCVD and sputtered germanium MSM detectors.

The sputtered germanium had a slightly higher film resistivity ($\sim 0.1\Omega\text{cm}$) and lower MSM photodiode dark current than RTCVD germanium samples (see Fig.5-3). However, no

detectable photoresponse at 1550nm was seen from this material.

Chromium (Cr) electrodes have been reported to form good Schottky barriers on germanium [1.14]. So instead of Ti, Cr was deposited on sample PG6 as the electrode metal in an attempt to decrease the dark current. The result is that there is no dark current difference between MSM with Cr electrodes and that with Ti electrodes.

CHAPTER6

CONCLUSIONS AND RECOMMENDATIONS

Employing polysilicon as the active layer, a responsivity of 0.34 mA/W at 1550 nm wavelength was measured for a polysilicon MSM photodetector with ~ 2 μm thick active layer and a 100 μm by 100 μm light absorbing area. The dark current was relatively high, around 40 μA at 10 V bias. The high dark current may result from surface roughness at the Schottky contacts, or from unpassivated recombination/generation centers at grain boundaries. In either case it may prove possible to reduce the dark current with improved processing.

By comparison of photocurrents of silicon MSM detectors with different active layers, it was found that polysilicon films with grain sizes between 6 nm and 13 nm are good candidates to absorb the light at 1550nm. No detectable photoresponse at 1550 nm was measured from amorphous silicon MSM detectors, as the effective bandgap is wider than that of polysilicon and the inherent defects in amorphous silicon may cause free carriers to recombine before they reach the electrodes. Single crystalline silicon is not suitable for absorption of 1550 nm light, since the photoenergy lies far below the bandgap, and there are no defect centers to contribute to absorption.

Crystallized amorphous silicon films seem a very good choice for light absorption at 1550 nm, since crystallized amorphous silicon MSM detectors (ST532) fabricated here gave more than three times larger photocurrent than as deposited polysilicon MSMs (ST11) at the

same film thickness. The relatively higher photoresponse in crystallized amorphous silicon MSM device is attributed to the defect-free grains formed during the crystallization anneal, which could increase the carrier mobility and lifetime.

Implanted SOI is a good alternative way to get thick amorphous silicon film. Some experimentation was done here with SOI films amorphized by high energy silicon implantation. This structure is attractive, since 1550 nm rib waveguide device in SOI are widely used [6.1-6.3]. Unfortunately, no measurable photoresponse was obtained from the detectors provided here. When the amorphized layer were recrystallized, the Raman shift approached that of monocrystalline silicon, indicating that very little of the damage produced by the implant remained. In the future it may prove possible to obtain useful polysilicon films using this technique if the complete thickness of the film is amorphized and anneal cycles are selected to provide explosive crystallization.

Attempts were also made on the fabrication of metal-germanium-metal photodetectors operating at 1550nm. However, too rough and highly conductive germanium layers resulted in the failure of the fabrication of efficient Schottky barriers at the metal-semiconductor interfaces. Several approaches have been reported suitable for decreasing the surface roughness of the germanium films. The use of chemical/mechanical polishing (CMP) on partially graded buffer layer resulted in a high quality germanium film on silicon, since threading dislocation density could be decreased by CMP [6.4]. The introduction of a pure-germanium buffer layer grown at low temperature could confine the dislocation at the heterointerface, which allowed the growth of a thick, fully relaxed epilayer [1.11]. The

heterointerface, which allowed the growth of a thick, fully relaxed epilayer [1.11]. The alloying of germanium with a small fraction of carbon atoms could lead to a lattice-matched material, since carbon could counter balance the strain caused by germanium [6.5].

As discussed earlier, coating quarter-wavelength thickness of silicon nitride anti-reflection layer on top of silicon active layer is a well-known way to increase photoresponse, and could easily be applied to the devices reported here. The relatively lower responsivity reported in this project is due to the poor absorption of polysilicon film at the wavelength of 1550 nm. Therefore, increasing the light penetration path so that most of the light can be absorbed is an efficient way to boost photoresponse. A waveguide MSM detector could provide a long optical path, which is not limited by the thickness of the absorbing layer [6.6], and thus lead to an excellent responsivity. High frequency response can also be reached in a waveguide MSM device, since the carrier transit distance is independent of the absorption length for light in the detector.

The relatively higher dark current for polysilicon MSM detector would lead to higher bit-error rate. Several ways have been reported to reduce dark current. Placing the electrode tips and the contact pads on top of an insulating layer of silicon nitride or silicon oxide could reduce the dark current significantly without sacrificing the responsivity, and would increase bandwidth by reducing parasitic capacitance. As mentioned earlier, employing a very thin amorphous silicon layer as the barrier layer and using two kinds of electrode metals in order to increase the barrier for both holes and electrons are also effective ways to reduce current leakage.

REFERENCES

- [1.1] Mario Dagenas *et al.*, Integrated Optoelectronics, Academic Press, 1995
- [1.1] T.Sugeta, T.Urisu, "High gain metal- semiconductor-metal photodetector for high-speed optoelectronic circuits," *IEEE Trans. Electron Dev.*, **ED-26**, 1855, 1979
- [1.2] C. W. Slayman *et al.*, "Frequency and pulse response of a novel high speed interdigital surface photoconductor (IDPC)," *IEEE Electron Dev. Lett.*, **EDL-2**, 112, 1981
- [1.3] L. Figueroa and C.W. Slayman, "A novel heterostructure interdigital photodetector (HIP) with picosecond optical response," *IEEE Electron Dev. Lett.*, **EDL-2**, 208, 1981
- [1.4] C.J. Wei, *et al.*, "Symmetrical Mott barrier as a fast photodetector," *Electron. Lett.*, **17**, 688, 1981
- [1.5] Edward S. Yang, Microelectronic Devices, McGraw-Hill, Toronto 1988
- [1.6] Julia B. D. Soole and Hermann Schumacher, "InGaAs metal-semiconductor-metal photodetectors for long wavelength optical communications," *IEEE J. of Quan. Electronics*, **27(3)**, 737, 1991
- [1.7] M. Herrscher *et al.*, "Epitaxial liftoff InGaAs/InP MSM photodetectors on Si," *Electron. Lett.*, **31**, 1383, 1995
- [1.8] S.S. Iyer *et al.*, "Heterojunction bipolar transistors using Si-Ge alloys," *IEEE Trans. Electron Dev.*, **36**, 2043, 1989
- [1.9] S. Janz *et al.*, "Si/Si_{1-x} Ge_x photodetectors using three-dimensional growth modes to enhance photoresponse at $\lambda = 1550$ nm," *J. Vac. Sci Technol.*, **18**, 588, 2000
- [1.10] L Colace *et al.*, "Ge-on-Si approaches to the detection of near-infrared light," *IEEE J. of Quan. Electronics*, **35(12)**, 1843 (1999)
- [1.11] L. Colace *et al.*, "Metal-semiconductor-metal near-infrared light detector based on epitaxial Ge/Si," *Appl. Phys. Lett.*, **72**, 3175, 1998
- [1.12] Silvia Fam *et al.*, "High performance germanium-on-silicon detectors for optical communications," *Appl. Phys. Lett.*, **81**, 586, 2002
- [1.13] Gianlorenzo Masini *et al.*, "2.5 Gbit/s polycrystalline germanium-on-silicon photodetector operating from 1.3 to 1.55 μ m," *Appl. Phys. Lett.*, **82**, 2524, 2003

-
- [1.14] D. Buca *et al.*, "Metal-germanium-metal ultrafast infrared detectors," *J. Appl. Phys.*, **92**, 7599, 2002
- [1.15] M. Y. Liu *et al.*, "140-GHz metal-semiconductor-metal photodetectors on silicon-on-insulator substrate with a scaled active layer," *Appl. Phys. Lett.* **65**(7), 887, 1994
- [1.16] L.H. Lai *et al.*, "High-performance metal-semiconductor-metal photodetector with a thin hydrogenated amorphous silicon layer on crystalline silicon," *Electron. Lett.*, **31**, 2123, 1995
- [1.17] L.H. Lai *et al.*, "Characteristics of Si-based MSM photodetectors with an amorphous-crystalline heterojunction," *Solid-state Electron.*, **41**, 1693, 1997
- [1.18] L.H. Lai *et al.*, "Characteristics MSM photodetectors with trench electrodes on P-type Si wafer," *IEEE Trans. Electron Devices*, **45**, 2018, 1998
- [1.19] L.H. Lai *et al.*, "A U-grooved metal-semiconductor-metal photodetector (UMSM-PD) with an i-a-Si:H overlayer on a [100] P-type Si wafer," *IEEE Photonics Tech. Lett.*, **10**, 579, 1998
- [1.20] C.S. Lin *et al.*, "Reducing Dark current in a high-speed Si-based interdigitated trench-electrode MSM photodetector," *IEEE Trans. Electron Devices*, **50**, 1306, 2003
- [1.21] C.S. Lin *et al.*, "High-sensitivity planar Si-based MSM photodetector with very thin amorphous silicon-alloy quantum-well-like barrier layers," *IEEE Photonics Tech. Lett.*, **15**, 966, 2003
- [1.22] A.K. Sharma *et al.*, "Optical and electrical properties of nanostructured metal-silicon-metal photodetectors," *IEEE J. Quan. Electron.*, **38**(12), 1651 (2002)
- [1.23] R. P. Macdonald, Components for a Low-Cost Integrated Silicon Optical Receiver, PhD Thesis, "Carleton University, 2001
- [1.24] Amanda DeVries, Silicon Based Metal-Semiconductor-Metal Photodetectors, Master Thesis, Carleton University, 2001
- [2.1] G Harbeke *et al.*, "Growth and physical properties of LPCVD polycrystalline silicon films," *J. Electrochem. Soc.*, **131**, 675, 1984
- [2.2] T.J. Kamins *et al.*, "Structure of chemically deposited polycrystalline-silicon films," *Thin*

Solid Films, **16**, 147, 1973

[2.3] G.Baccarani *et al.*, "Transport properties of polycrystalline silicon films," *J. Appl. Phys.* **49(11)**, 5565, 1978

[2.4] Ted Kamins, Polycrystalline silicon for integrated circuits and display, Kluwer academic publishers, Boston/Dordrecht/ London, 2nd edition, 1998

[2.5] Howard C. Card and Edward S. Yang, "Electronic processes at grain boundaries in polycrystalline semiconductors under optical illumination," *IEEE Trans. on Electron Dev.*, **ED-24**, 1977

[2.6] Amal K. Ghosh *et al.*, "Theory of the electrical and photovoltaic properties of polycrystalline silicon," *J. Appl. Phys.* **51**, 446, 1979.

[2.7] John. Y. W. Seto, "The electrical properties of polycrystalline silicon films," *J. Appl. Phys.* **46(12)**, 5247, 1975.

[2.8] Soumen Das and Samir K. Lahiri, "A large-bias conduction model of polycrystalline silicon films," *IEEE Trans. on Electron Dev.*, **41(4)**, 524, 1994

[2.9] N.C.C.Lu *et al.*, "A conduction model for semiconductor-grain boundary-semiconductor barriers in polycrystalline silicon films," *IEEE Trans. on Electron Dev.* **ED30**, 137, 1983

[2.10] E.S.Yang *et al.*, "Majority carrier current characteristics in large-grain polycrystalline-silicon-Schottky-barrier solar cells," *IEEE Trans. on Electron Dev.* **ED-28**, 1131, 1981

[2.11] George J. *et al.*, "Conduction properties of lightly doped polycrystalline silicon," *Solid-State Electronics*, **21**, 1045, 1978

[2.12] Warren B.Jackson *et al.*, "Density of gap states of silicon grain boundaries determined by optical absorption," *Appl. Phys. Lett.* **43(2)**, 195, 1983

[2.13] D.S.Shen *et al.*, "Carrier lifetime in amorphous semiconductor," *J. Appl. Phys.* **75**, 7349, 1994

[3.1] Pallab Bhataharya, Semiconductor Optoelectronic Devices, Upper Saddle River, NJ: Prentice hall, c1997

-
- [3.2] S. M. Sze *et al.*, "Current transport in metal-semiconductor-metal (MSM) structures," *Solid-State Electron.*, **14**, 1209 (1971)
- [3.3] Walter A. Wohlmuth *et al.*, "Dark current suppression in GaAs metal-semiconductor-metal photodetectors," *IEEE Photo. Tech. Lett.*, **8**, 1061, 1996
- [3.4] C. O. Chui *et al.*, "Effective dark current suppression with asymmetric MSM photodetectors in group IV semiconductors," *IEEE Photonics Tech. Lett.*, **15**, 1585, 2003
- [3.5] P. R. Berger, "MSM photodiodes," *IEEE Potentials*, **15(2)**, 25, 1996
- [3.6] Seo, J. W. *et al.*, "A comparative study of metal-semiconductor-metal photodetector on GaAs with indium-tin-oxide and Ti/Au electrodes," *IEEE Photonics Tech. Lett.*, **4**, 888, 1992
- [3.7] Li-Hong Lai *et al.*, "Amorphous metal-semiconductor-metal photodetector with bottom ridged Cr electrodes," *Electronics Letters*, **35**, 1021, 1999
- [3.8] Y. C. Lim *et al.*, "Properties of alternately charged coplanar parallel strips by conformal mappings," *IEEE Trans. Electron Dev.*, **ED-15**, 173, 1968
- [4.1] T. Serikawa *et al.*, "Low-temperature fabrication of high-mobility poly-Si TFT's for large-area LCD's," *IEEE Trans. Electron Dev.*, **36**, 1929, 1989
- [4.2] A. K. Sharma *et al.*, "Ion implantation enhanced metal-Si-metal photodetectors," *IEEE Photonics Tech. Lett.*, **6**, 635, 1994
- [4.3] Miltians K. Hatalis and David W. Greve, "Large grain polycrystalline silicon by low-temperature annealing of low-pressure chemical vapor deposited amorphous silicon films," *J. Appl. Phys.* **63**, 2260, 1988
- [4.4] G. Girginoudi *et al.*, "Electrical and structural properties of poly-Si films grown by furnace and rapid thermal annealing of amorphous Si," *J. Appl. Phys.*, **84**, 1968, 1998
- [4.5] J. F. Morhange *et al.*, "Raman study of laser annealed silicon," *Solid State Comm.*, **31**, 805, 1979
- [4.6] Z. Iqbal *et al.*, "Raman scattering from hydrogenated microcrystalline and amorphous silicon," *J. Phys. C: Solid State Phys.*, **15**, 377, 1982
- [4.7] Pham V. Huong *et al.*, "Infrared and resonance Raman spectroscopic studies of

- semiconductors doped amorphous silicon," *J. of Molecular Stru.*, **115**, 473, 1985
- [4.8] S. Nakashima *et al.*, "Raman Scattering study of ion implanted and C.W.-laser annealed polycrystalline Silicon," *Solid State Comm.*, **40**, 765, 1981
- [4.9] Z.Iqbal *et al.*, "Raman scattering from small particle size polycrystalline silicon," *Solid State Comm.*, **37**, 993, 1981
- [4.10] Kohji Mizoguchi *et al.*, "Characterization of thermally annealed thin silicon films on insulators by Raman image measurement," *J. Appl. Phys.*, **78(5)**, 3357, 1995
- [4.11] G.Kanellis *et al.*, "Effect of dimensions on the vibrational frequencies of thin slabs of silicon," *Phys.Rev. B*, **21**, 1543, 1980
- [4.12] T. I. Kamins and T.R.Cass "Structure of chemically deposited polycrystalline-silicon films," *Thin solid films*, **16**, 147, 1973
- [4.13] J. Klingenstein *et al.*, "Photocurrent gain mechanisms in metal-semiconductor-metal photodetectors," *Solid-state electron.*, **37**, 333, 1994
- [4.14] J. Burm *et al.*, "Low-frequency gain in MSM photodiodes due to charge accumulation and image force lowering," *IEEE Photonics Tech. Lett.*, **8**, 113, 1996
- [5.1] Y. Z-Q. Li *et al.*, "Structure and properties of rapid thermal chemical vapor deposited polycrystalline silicon-germanium films on SiO₂ using Si₂H₆, GeH₄ and B₂H₆ gases," *J. Appl. Phys.*, **83(10)**, 5469, 1998
- [5.2] Hiroaki Kobayashi *et al.*, "Electrical properties of evaporated polycrystalline Ge thin-films," *Thin Solid Films*, **300**, 138, 1997
- [6.1] P.D. Trinh *et al.*, "Silicon-on-insulator (SOI) phased-array wavelength multi/demultiplexer with extremely low-polarization sensitivity," *IEEE Photonics Tech. Lett.*, **9**, 940, 1997
- [6.2] S.L.Tsao *et al.*, "Simulation of a 2/spl times/2 MMI SOI WDM coupler," *Lasers and Electro-Optics*, **2**, 210, 2001
- [6.3] Eric Cassan , "Low-Loss Light Distribution in Silicon-on-Insulator Rib Waveguides," *IEEE J. of Selected Topics in Quan. Electron.*, **9**, 460, 2003
- [6.4] M.T.Currie *et al.*, "Controlling threading dislocation densities in Ge on Si using graded

SiGe layers and chemical-mechanical polishing,” *Appl. Phys. Lett.*, **72**, 1718, 1998

[6.5] S. Shao *et al.*, “1.3 micron photoresponsivity in Si-based GeC photodiodes,” *Appl. Phys. Lett.*, **72**, 1860, 1998

[6.6] M. H. Leary *et al.*, “MSM waveguide photodetectors optimized for monolithic integration with high electron mobility transistors,” *IEEE J. Lightwave Tech.*, **13**, 1514, 1995