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**LA THÈSE A ÉTÉ
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ELECTRON BEAM INTERACTIONS WITH GALLIUM
ARSENIDE FIELD EFFECT TRANSISTORS

by

C

Raymond F. Haythornthwaite, B.Sc., M.Eng.

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

Doctor of Philosophy

Department of Electronics
Faculty of Engineering
Carleton University
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18 April 1980

The undersigned recommend to the Faculty of Graduate Studies
the acceptance of the thesis;

Electron Beam Interactions With Gallium
Arsenide Field Effect Transistors

submitted by Raymond Frank Haythornthwaite in partial
fulfillment of the requirements for the degree of Doctor
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ABSTRACT

This thesis describes the interactions between 1-40KV electron beams and gallium arsenide field effect transistors. The influences of the beam on the Schottky barrier gate current and channel current are studied in detail under various gate drain and substrate biasing conditions because of their relevance to reliability analysis.

After describing essential device characteristics basic interaction processes, and experimental procedures, possible causes of the interactions are studied in terms of channel resistance parameters and either rejected or studied in more detail.

The gate current stimulation process is investigated experimentally and generated carrier diffusion lengths measured on actual FETs. A detailed model is developed to calculate the beam generated gate current in four device regions. Computer generated predictions are found to be similar to the experimental results.

The more complex channel current generation process is studied experimentally to measure the influence of both beam and device parameters at different sites on the device. Two distinct mechanisms are reported; a long range effect involving overall changes of substrate bias, and an effect with only a short range of influence in which the increase in channel current follows a normal distribution with

distance. Theoretical models have been proposed to explain some of the observed effects but await improved models of the substrate and better two-dimensional device models on unstimulated FETs before they can be further developed. A series of engineering relationships has been described to enable future workers to predict optimum beam stimulation conditions for device analysis. A series of recommendations for future work is made.

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My only regret is that my mother died before this work could be completed. It is dedicated to her.

Note in Explanation

The use of the 'TEXT' wordprocessor in writing this Thesis.

The Sigma 9 'TEXT' wordprocessor and editing system was used throughout the preparation of this thesis. Despite its many advantages, 'TEXT' has two major limitations in the production of scientific documents. It cannot write superscripts and subscripts if fully automatic printing is required, and the number of available characters for use in scientific equations is limited to ANSCII standard symbols.

Thus, as the use of scientific notation in the body of the thesis is not possible, the computer format has been used instead, (e.g. 1E-6 for one millionth), and the bracket notation has been used in place of subscripts, e.g. R(DS) in place of R subscript DS. It has often been more convenient to use the full name such as gate to source current rather than its symbolic equivalent.

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$I_{GS}(z)$	Gate current generated when the beam is at position z	A
JEOL	Japanese Electron Optical Ltd (SEM makers)	
k	Boltzmann's constant $1.38E-23$	J/K
k, k', k	Constants	
L	Gate length	cm
L	Diffusion length of carriers generated in GaAs	cm
L^*	Effective diffusion length of beam generated carriers in GaAs measured along surface	cm
L	Diffusion length	cm
$L(i)$	Diffusion length of beam generated carriers in region i of gate current model	cm
m	Mass of electron	g
m	Factor in denominator of exponential term of diode equation	
m	Constant in beam sensitivity relationships	
n	Electron concentration	cm^{-3}
n^*	Increase in electron concentration generated by the electron beam	cm^{-3}
N_D	Concentration of donors in epitaxial layer of GaAs FET	cm^{-3}
p^*	Increase in hole concentration generated by the electron beam	cm^{-3}
q	Charge on electron $1.602E-19$	C
Q	Total trapped positive charge created by the beam	C
r	Radius of hemisphere of electron beam generated carriers	cm
$r, r(i)$	Distance between depth element dy and collecting area dA in gate current model (total or in i th region)	cm
R	Radius of ball of trapped charge created by beam	cm

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LIST OF PRINCIPAL SYMBOLS

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a	Constant in electron range equation	
A	Area	cm ²
A	Ampere	A
A*	Effective Richardson Coefficient	A.cm ⁻² .K ⁻²
AEI	Absorbed Electron Image	
A(Y)	Attenuation factor	
b, b'	Constants	
B	Backscattering coefficient	
c, c'	Constants	
CRC	Communications Research Centre	
C-V	Capacitance - Voltage	
dA	Area element	cm ²
d(Al)	Thickness of Aluminum gate	cm
d _{EFF}	GaAs effective thickness of gate metal	cm
dE(i)	Fraction of beam energy absorbed in Region i	J
dE(y)	Fraction of beam energy absorbed at depth y	J
dI(z)	Element of current at position z on gatewidth axis	A
dV(z)	Change in voltage of back gate at position z on gatewidth axis	V
dW(L, z)	Change in back gate depletion layer width in the active region at position z caused by the long and short range effects	cm
d(zB)	Distance between position B and z on the gatewidth axis	cm
D	Diffusion coefficient	cm ² /s
D*	Ambipolar diffusion coefficient	cm ² /s
eV	Electron volt	eV
E	Electric field strength	V/cm

EBIC	Electron beam induced current	A
EBICC	Electron beam induced channel current	A
EBS	Electron beam stimulated (diode)	A
f	Correction factor for effects of contacts used in gate current model	
f( )	Function of term in brackets	
F	Abbreviation defined in equation (10.3) to shorten subsequent equations	
F	Farad	F
FET	Field effect transistor	
g_{pc}	Photoconductive gain	
$g(z)$	Transconductance of back gate at position z	
GaAs	Gallium arsenide	
GHz	Gigahertz	s ⁻¹
HP	Hewlett Packard	
I_{B_s}	Electron beam current at sample	A
I_{DIODE}	Electron beam generated current in EBS diode	A
I_d I_{DS}	Drain current or channel current	A
$I_{DS}(L)$	Channel current caused by long range beam stimulation effect	A
$I_{DS}(L, z)$	Channel current at position z caused by long range beam stimulation effect	A
$I_{DS}(S)$	Channel current caused by short range beam stimulation effect	A
$I_{DS}(S, z)$	Channel current at position z generated by short range beam stimulation effect	A
$I_{DS}(t)$	Time dependent channel current	A
I_{GS}	Gate to source current	A
$I_{GS}(i)$	Gate current induced by the beam depositing energy in region i	A

$I_{GS}(z)$	Gate current generated when the beam is at position z .	A
JEOL	Japanese Electron Optical Ltd (SEM makers)	
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Q	Total trapped positive charge created by the beam	C
r	Radius of hemisphere of electron beam generated carriers	cm
$r, r(i)$	Distance between depth element dy and collecting area dA in gate current model (total or in i th region)	cm
R	Radius of ball of trapped charge created by beam	cm

$R(I,J)$	Resistance between two generalized regions I and J within the substrate	ohm
R	Electron beam penetration range in GaAs	cm
ROI	Region of influence of the electron beam	
s	Distance of the beam from a point on the channel	cm
S	Source region of FET	
$S1, S2$	Labelled source regions	
SEI	Secondary electron image	
SEM	Scanning electron microscope	
SHIC	Proprietary name for integrated circuit sample holder	
SI	Semi-insulating	
(t)	Time dependent	
t_{av}	Average stopping time of beam electron in GaAs	s
$t(n)$	Lifetime of electrons	s
$t(SD)$	Electron transit time between source and drain	s
T	Kelvin temperature	K
v	Carrier velocity ; velocity of electron	cm/s
v_s	Saturated carrier velocity in active layer	cm/s
V	Volts	V
$V(A)$	Voltage at position A under channel	V
$V(B)$	Voltage of surface at position B	V
$V(BG)$	Voltage across back gate of GaAs FET	V
V_{BI}	Built in voltage of semiconductor junction	V
V_{DS}	Drain voltage	V
V_{GS}	Gate voltage	V
V_{SUB}	Substrate voltage	V

W	Active channel thickness	cm
W_{AL}	Active layer thickness	cm
W_{BG}	Thickness of portion of back gate depletion layer in epitaxial layer	cm
W_{EPI}	Epitaxial layer thickness	cm
W_{DEP}	Schottky gate depletion layer thickness	cm
x	Position on the axis parallel to gatelength	cm
$X_1 - X_2$	Coordinates of limits of integration in gatelength axis in gate current model	cm
y	Position on axis directed into GaAs	cm
Y	Coordinate on y axis	cm
$Y(i)$	Coordinate defining limits of region in gate current model	cm
z	Position on axis directed along gatewidth	cm
Z	Gatewidth	cm
Δ	Large scale change operator	
ϵ	Dielectric constant	
ϵ_0	Permittivity of space $8.86E-14$	F/cm
θ	Angle between direction of electron beam and area element dA in gate current model	
$\lambda(y)$	Fraction of beam energy deposited at depth y as defined by equation (3.2)	
μ, μ_n	Mobility of electrons in GaAs	$\text{cm}^2/\text{V/s}$
σ	Standard deviation of normal distribution	
$\rho(Al)$	Density of aluminium	g/cm^3
$\rho(GaAs)$	Density of GaAs	g/cm^3

CHAPTER 1

INTRODUCTION

1.1 Background

The Gallium Arsenide Field Effect Transistor (GaAs FET) is a microwave transistor with great potential for both low noise and high power applications. It is also employed increasingly as the active element in ultra high speed integrated circuits. Leichti has made a comprehensive review of GaAs FET literature[1] and indicated many possible developments and applications. He also reviewed fabrication processes and possible reliability problems.

An even channel current distribution within the device is necessary for predictable and reliable operation. It is especially important to avoid hot spots caused by local excessive current densities. Unfortunately, the small interelectrode dimensions necessary for microwave frequency operation often make small topographical defects very important, as these may cause uneven or unstable operation, yet make adequate conventional optical inspection procedures almost impossible. Scanning Electron Microscopy therefore assumes major importance in the search for highly reliable device structures. The potential of the Scanning Electron Microscope (SEM) is, however, only achieved when it is used in several of its complementary modes to study the FET, yet

the interactions between the SEM and the FET have not been adequately characterized.

It was quickly realized that the absorbed electron image (AEI) operating mode can provide useful information on current flow within a semiconductor device by displaying any changes in current at a device terminal as a function of electron beam position.[2]

During early experiments using the AEI mode to determine suitable SEM inspection methods for a GaAs FET application in the Hermes communications satellite at the Communications Research Centre (CRC), unexpected irregularities in source-drain current were discovered when the beam was scanned near the gate electrodes.[3,4] These irregularities were thought to be probable sites for failure mechanisms. Several important observations were made during these investigations.

- 1) Nanoampere changes in electron beam current provoked changes of several milliamperes in source-drain current.
- 2) For constant beam voltages, the induced source-drain current was only weakly dependent on beam current.
- 3) The effect of the very small diameter beam must spread over considerable distances, otherwise unacceptable local current densities must exist in the channel region.
- 4) A long range mechanism must exist to transmit the effects of the beam stimulation on isolated parts of the device to the active channel.

5) A slow trapping mechanism was discovered which was stimulated by the beam and lasted for several seconds after the beam was removed.

The field of interaction of electron beams with gallium arsenide FETs is essentially unexplored apart from the early CRC work. Present work has indicated that the drain-source or channel current is influenced by two or more distinct mechanisms described as short range and long range effects. The Electron Beam Induced Channel Current (EBICC) is also influenced by the following parameters; gate voltage, drain voltage, electron beam current, electron beam accelerating voltage, and by the presence of attenuating metal layers such as device electrodes. In addition, the induced current is very sensitive to beam position and unexpectedly large device current changes have been observed when the beam is far from the channel and shielded by biased electrodes.

As the concepts of the long and short range channel current stimulation mechanisms are central to this thesis it is worth describing them in more detail. The electron beam produces a local, or short range effect which is centred on the beam which produces a change in current in any part of the channel that lies within the Region of Influence (ROI) of the short range effect. This change is always an increase, which lessens, following approximately a normal or Gaussian distribution as distance from the beam increases. The beam also generates a smaller magnitude change in

channel current at a greater distance from the channel which is called the long range effect. This occurs as a result of changes in substrate bias and may cause either increases or decreases in channel current depending on the potential of the surface where the beam is focussed. The two mechanisms act essentially independently and additively.

Initial work at CRC established that the observed effects are characteristic of devices made by several manufacturers and cannot be attributed merely to process abnormalities but are inherent properties of the gallium arsenide transistor.

Since the initial work was undertaken, GaAs FETs have developed considerably in power capability and the market has expanded to the extent that the GaAs FET is now the accepted device for many applications above 1 GHz and is rapidly replacing the travelling wave tube in power amplifiers. It has therefore become increasingly important to detect possibly defective devices by a rapid and efficient process and the SEM is perhaps the best available method. However, before this work was started, little was known about the mechanisms of the interactions between the SEM and the GaAs FET.

1.2 Objectives of the thesis

The objectives of the thesis are to investigate further,

both experimentally and theoretically, the interactions between an electron beam and GaAs FETs, using a SEM.

The main thrust of the thesis is, in the absence of an adequate body of previously published work, largely experimental, to establish the significance of the individual electron beam and device parameters on device performance. It will provide a basis for future model development, and help optimize SEM operating conditions for practical studies during device development and reliability analysis.

A combination of careful experimentation and theoretical review is also necessary to establish the basic mechanisms for beam induced channel current changes. The results will provide a better understanding of how dc current is distributed within practical devices and thereby provide a basis to test the models of transistor behaviour being developed by other workers, especially in the areas of substrate properties and optical stimulation. The specific objectives of this thesis can be listed as:

- 1) Establish how the electron beam parameters (accelerating voltage, beam current, beam position) affect the electrical properties of the Schottky barrier gate electrode.
- 2) Model the above in terms of changes in gate current.
- 3) Establish experimentally the relationship between the beam parameters and the induced channel current at different positions of the electron beam.

- 4) Study the interaction between the beam and the channel current for different device biasing conditions.
- 5) Consider the possible mechanisms for the observed results and eliminate those which are not acceptable for theoretical or experimental reasons.
- 6) Develop empirical models or suggest mechanisms to explain the observed effects.

1.3 Thesis outline

The thesis is divided into eleven chapters of which the first has provided a general introduction and detailed the objectives of the thesis. Chapter 2 reviews basic GaAs FET theory and describes the devices used for the bulk of this thesis. The third chapter considers the different interactions between an electron beam and solid matter before concentrating on interactions with semiconductors. Chapter 4 reviews photon interactions with semiconductors and thereby eliminates some of the earlier proposed interaction mechanisms. The experimental equipment and methods used to record results are discussed in Chapter 5. The sixth chapter considers further possible interaction mechanisms between the electron beam and the FET in terms of how the beam could modify the characteristics of a simple resistive channel. Some possible mechanisms are then eliminated and the areas for more detailed experimental studies are more closely defined.

In Chapter 7 the results of studies of the beam on the Schottky barrier gate are presented and a detailed model of the mechanisms involved is developed. Chapters 8 and 9 consider the far more complicated interaction mechanisms between the beam and the channel. In Chapter 8 the results of experiments to study the effects of stationary beams on specifically selected areas are described, and engineering relationships between beam parameters and the stimulated channel current are established.

The results obtained provide a means of separating the effects of two distinct beam stimulation mechanisms. These results are applied to the more general results of Chapter 9 and 10 where the position and time dependant results are considered and developed into simple empirical models.

The final chapter summarizes the results and makes recommendations for future studies. Three appendices serve to provide supplementary information on areas important for understanding the work in this thesis. Appendix 1 is concerned with the properties of the semi-insulating substrate and Appendices 2 and 3 relate to the computer programs used in this work.

CHAPTER 2

REVIEW OF GaAs FET STRUCTURES AND THEORY

2.1 Introduction and history

This chapter reviews the important features of the GaAs FET structure and goes on to describe the particular devices used in this work in greater detail. A brief review is then made of gallium arsenide properties which distinguish these devices from silicon FETs. Finally, dc operating characteristics are outlined.

The GaAs FET has developed rapidly over the last few years into a commercially successful low noise solid state device for amplifiers and oscillators suitable for use at frequencies above 1GHz. The device is inherently simple and is being developed both as a power device and as an active element of an integrated circuit based on GaAs instead of silicon.[1]

2.2 Device Structure

Figure 2.1 shows a SEM micrograph of a GaAs FET of the type used in this work which is capable of passing a maximum drain to source current of about 80mA (or 1.6A per cm gate width). The designs of other manufacturers differ in detail but are similar in overall concept.

Figure 2.1 Overall SEM view of Hewlett Packard Experimental GaAs FET

Figure 2.2 Cross section of typical FET showing four regions 1) the gate depletion region, 2) the active channel, 3) the semi-insulating substrate and 4) the ohmic contact regions. The gate length is approximately 1 micrometer.

The structure of the device may be described by referring to the section shown schematically in Figure 2.2. The semiconducting portion consists of a semi-insulating gallium arsenide substrate upon which is grown an active n-type epitaxial GaAs layer (approximately 0.2 micrometers thick) doped with approximately $1E+17$ atoms of sulphur or selenium per cubic centimeter. The layer may be grown by either liquid or gas phase epitaxy. Sometimes a near intrinsic buffer layer is grown before the active layer to reduce unwanted substrate effects. The active area is defined by mesa etching to include only the channel region and the source and drain ohmic contacts. The active area is made as small as possible to reduce capacitance for good high frequency operation. In practice, its area is determined by the required areas for reliable wire bonding. The active gate is approximately 1 micrometer long and 500 micrometers wide. The gate contact is placed on the semi-insulating substrate to reduce capacitance. The narrow and thin gate stripe must therefore climb the relatively large mesa edge and this can be a severe reliability hazard because discontinuities caused by gate metal thinning or narrowing can occur during the photo resist definition and metal etching processes at the mesa step. The HP devices used in this work show no evidence of this problem and would be suitable for reliable operation.

The substrate material is made semi-insulating during the crystal growth process by adding sufficient chromium to compensate for residual n-type impurities when attempts are made to grow intrinsic gallium arsenide.[5] Chromium, in the lattice, forms mid band gap acceptor states, so that providing the concentration is greater than the n-type impurities, the material becomes highly resistive. The mechanism is essentially similar to the action of gold in silicon. Further details on the chromium compensation process are included in Appendix 1.

The ohmic contacts are typically made from deposited gold-germanium alloy overcoated with gold. This system gives satisfactory low resistance contacts but may create problems of poor wetting between the gold-germanium and the gold. Germanium precipitation may also occur. Other metals, such as nickel, are therefore added between the gold-germanium and the gold to improve wetting and act as barrier layers to reduce gallium migration into the gold. It is usual to plate the ohmic contacts with gold to reduce resistance still further.

The source and drain contacts are identical metallurgically and normally differ only in area and the number of bond wires required for adequate impedance at microwave frequencies. Typically two or more source bonds are required and the source contact area therefore may be significantly larger. The substrate is normally internally connected to the source.

The gate metal must form a good Schottky barrier with n-type gallium arsenide. The system must also be metallurgically stable, provide low leakage junctions and be capable of economic formation into fine dimensions. Aluminum closely meets these requirements and has become the most usual material although titanium, titanium-tungsten and nickel are also used. [1]

The separation between source and drain is about 3 micrometers as the gate is 1 micrometer long. These small dimensions are necessary because a fundamental limitation to high frequency operation in GaAs FETs is the transit time of carriers between source and drain. The active area is usually covered by a silicon oxide or nitride layer to protect against scratches during assembly and particles which might cause short circuits in packaged devices. The passivation provides some measure of corrosion resistance in humid environments. The higher band gap of GaAs (1.43 eV) makes surface band bending less significant than in silicon so that surface channels are not normally a serious problem.

As with all high frequency devices, parasitic capacitances and inductances resulting from the package design can limit device performance. Extensive work by the device designers [1] has led to the development of complex ceramic packages that reduce parasitics yet provide good thermal characteristics and permit repeatable measurements for device characterisation at microwave frequencies. High

power transistors are now packaged using matching networks tailored bond wire profiles for controlling inductance, and sometimes flip-chip assembly.[1] Unfortunately these techniques and the passivation layer make SEM examination difficult especially when stable electron beam currents are required because the insulators become electrically charged and laterally displace the beam.

2.3 Experimental devices used in this work

The devices used in the majority of this work were manufactured by Hewlett Packard (HP) in their research and development laboratories in 1975.

Although essentially similar to HP production devices, they are development samples and do not have guaranteed microwave performance. Fabrication details are also not precisely known. They were supplied in chip form and lack the final gold plating and scratch protection layers characteristic of production devices. From the experimental viewpoint this is advantageous as both features would hinder electron beam penetration. The devices were mounted at CRC for this work on four lead TO18 or 8 lead TO5 packages to avoid the complications introduced by ceramic microwave packages during SEM examination. Consequently microwave measurement capability has been sacrificed but this has been compensated for by the ability to make separate connections to both source electrodes and to the substrate bottom

contact. The latter is usually connected to the source within the package and so is unavailable for measurement purposes.

The substrate material is single crystal chromium compensated semi-insulating <100> gallium arsenide. The active layer is grown approximately 0.4 micrometers thick with a doping level of $1E+17$ atoms of sulphur per cubic centimeter. The mesa is then defined using photoresist and approximately one half micrometer of GaAs is etched. The contacts are formed using photoresist and are approximately 0.3 micrometers thick. The aluminum gate is formed first by defining its location using photoresist. A trough is then etched in the active layer to produce a channel of the required thickness based on measurements already obtained for the layer thickness and resistivity. The aluminum is then deposited over the device and excess is removed using standard photoresist lift-off techniques. The etched trough is approximately 0.2 micrometers deep on the experimental devices and the aluminum thickness is approximately 0.57 micrometers. Figure 2.3 shows a typical device before the aluminum gate has been etched off and Figure 2.4 depicts a different device after the gate metal has been removed. The etched trough, the mesa edge and the metal contacts can be clearly seen.

The overall semiconductor chip dimensions are approximately 660x285 micrometers per side and the substrate

Figure 2.3 View of HP GaAs PET from the side showing mesa edge and channel topography a) low magnification, b) high magnification

Figure 2.4 SEM view of HP FET after gate has been removed by etching

Figure 2.5 Curve tracer characteristics of FET HP6
Vertical : drain current. Horizontal : drain voltage. The maximum current corresponds to zero gate voltage. The steps are negative gate voltage

is about 120 micrometers thick. The bottom contacts of the dice were gold coated by the manufacturer and were attached to the headers using conductive epoxy. The source, drain and gate electrodes were connected to the header using gold wires and wedge or ball bonding.

Typical measured electrical parameters of the device are listed in Table 1. Figure 2.5 shows the drain to source current versus voltage characteristics as a function of negative gate voltage measured on a Tektronix 576 curve tracer. The maximum current corresponds to zero gate voltage. Pinch-off occurs at a gate voltage of about minus 1.8 volts.

2.4 Gallium arsenide material properties

Gallium arsenide is finding increasing use in the manufacture of microwave transistors. It is superior to silicon because of its higher electron mobility and drift velocity at electric fields below saturation. It forms good Schottky barriers with many metals, hence Schottky gates are readily fabricated so that the need for an insulated gate is avoided. The smaller area schottky junction results in reduced capacitance compared to an insulated gate.

The higher electron mobilities of n-GaAs permit larger geometries than for equivalent silicon devices but even so, microwave operation above 10 GHz requires lengths of one micrometer or less to keep channel transit time short. As

Table 1

Details of Experimental Devices used in this Thesis.

Manufacturer : Hewlett Packard R&D Laboratories.

Power	0.4W
Maximum channel current	80mA
Pinch off voltage	-1.8 to -2.0V
Transconductance	35mA/volt at $V_{DS}=1V$
Max. usable frequency	14GHz
Dimensions of semiconductor	
Channel length	1 micrometer
Channel width	500 micrometers
Drain-to-source separation	3 micrometers
Mesa thickness	0.4 micrometers
Aluminum thickness	0.58 micrometers
Channel etch depth	0.2 micrometers
Calculated active layer thickness	0.2 micrometers
Doping density	$1E17$ per cubic cm. Liquid phase epitaxy.
Package	T018(4 pin) or T05(8 pin)
Die thickness	120 micrometers
Approx. substrate resistivity	$1E8$ to $1E9$ ohm.cm.

can be seen from Table 2 [6], p-type gallium arsenide has low hole mobility and so is unsuitable for use in microwave FET applications. The inherent advantages of high electron mobility are not fully realized, because, with the small dimensions, even low biases create very high electric fields, causing drift velocity to saturate. Thus maximum drift velocity becomes the important parameter. The prediction of carrier transit times and current densities in GaAs FETs is further complicated because carrier velocity initially increases and then decreases (Figure 2.6). This is because the energy band structure of GaAs has two conduction band minima differing by approximately 0.36 eV. The higher minimum corresponds to a lower electron mobility and higher effective mass. Some electrons are stimulated to the higher energy minimum as the field increases, so that in the highest field regions of a GaAs FET the average mobility decreases and first a negative (accumulation) region and then a positive (depletion) region develops, forming a stable and stationary Gunn domain at the drain side of the gate. [8, 10-15] This is the principal reason why the traditional gradual channel model for FETs is inadequate for high frequency GaAs FETs. [7]

2.5 GaAs FET mode of operation

In a typical GaAs FET application, the source is held at ground potential and the drain voltage at about +5V. The

Table 2

Properties of Si and GaAs,

	Silicon	GaAs	
Atoms per cubic centimeter	5E22	2.2E22	
Molecular weight	28.8	144.63	
Lattice constant	.357	.357	nm
Crystal structure	Diamond	Zinc blende	
Specific gravity	2.33	5.32	
Dielectric constant	11.8	10.9	
Band gap at 300K	1.12	1.43	eV
Effective density of states-in-valence band	1.02E19	7E18	*
Conduction band	2.8E19	4.7E17	*
Drift mobility -electrons	1000	8500	cm.cm/(V.s)
-holes	500	400	
Minority carrier lifetime	2.5E3	1E-8 to 1E-11	s
Intrinsic carrier concentration	1.6E10	1.1E7	*
Work function	4.8	4.7	V
Electron affinity	4.05	4.07	V
Saturated drift velocity at 1E5V/cm 300K	8E6	1E7	cm/s
Effective mass -electrons	0.97	0.068	
-holes	0.16	0.12, 0.5	

* per cubic centimeter.

Figure 2.6 Electron velocities in GaAs and Silicon as a function of electric field [6]

source to drain current is modulated by the gate bias, which normally is kept at zero for power devices, or slightly negative for low noise applications.

Initially the drain current is proportional to the drain voltage as shown in Figure 2.5 because current flow is determined by the carrier velocity which is proportional to the applied electric field at low drain voltage. When the voltage is increased beyond about 0.5 volts, the drain current gradually saturates, mainly because the carrier velocity saturates. There is also some saturation because the depletion region under the Schottky barrier attempts to widen with the increasing drain to gate voltage. This in turn tends to reduce the cross section of the active channel. In order to preserve current continuity, the carrier density in the region between the centre of the gate and the edge of the gate on the drain side must increase. This produces two effects. First, it opposes the depletion layer widening and second, it produces a field between the gate and the drain. The voltage drop between source and drain largely occurs because of this field.[7]

A negative bias on the Schottky gate controls drain current because the depletion layer formed reduces the active channel cross section. However, pinch-off does not occur in the manner predicted in the long channel device models [6] because a small cross section of active channel is always present.[7] Because there is a transverse voltage

across the channel from source to drain due to the applied drain voltage, the shape of the depletion region appears as in Figure 2.2.

The shape of the family of drain to source current versus voltage curves of Figure 2.5 appears to be very similar to those predicted by simple gradual channel theory but the short channel models predict higher drain currents. Although true pinch-off does not occur, it is still convenient to refer to the voltage at which drain current is effectively reduced to zero as the pinch-off voltage.

Modelling of short channel devices made from GaAs is further complicated by the need to incorporate the stable Gunn domain caused by the decrease in mobility at high fields.[8, 10-15] Such domains account for a large part of the source drain voltage drop and lead to predictions of drain current maxima at intermediate drain voltages. These have been observed,[8] but when they are not, it has become usual to explain the anomaly in terms of an additional current flowing in the semi-insulating substrate.[11, 12]

Such currents are thought to be caused by injection of majority carriers into the substrate from the active layer.[13]

None of the models developed so far consider in detail the second (or back) gate which exists in the form of a junction between the heavily doped epitaxial layer and the semi-insulating substrate. This type of junction is

described as a high-low junction in this thesis. By biasing the substrate it is possible to modulate the drain current.[16] Normally the bias on the substrate contact is held constant by connecting it to the source which is maintained at ground potential so that the back gate is not important. The RC time constant of the back gate is very large because of the high substrate resistance and the high frequency performance of the device would seriously deteriorate if attempts were made to modulate the device using it.

The maximum voltages that can be applied to the device are limited by the onset of breakdown between the drain and the gate to about 10 volts. As pinch-off occurs typically at a gate voltage of -2V for 0.2 micrometers channel thickness devices, drain voltage rarely exceeds 8 volts. Because saturation occurs at drain voltages of approximately 2 volts, FETs are normally operated with drain voltage between 2 and 5 volts which is the region of optimum microwave performance.

This chapter has introduced the gallium arsenide FET and outlined some of its characteristic properties. The particular characteristics of the devices used in the experimental part of this thesis have been described. In the next chapter the basic interactions between an electron beam and semiconductors are described.

CHAPTER 3

ELECTRON BEAM INTERACTIONS WITH SEMICONDUCTORS

3.1 Introduction

Since its initial development as a high resolution microscope capable of magnifications and depths of focus far superior to those of an optical microscope, the SEM has increasingly been used as a tool for materials studies.[17]

The electron beam generated, for example, by a scanning electron microscope interacts with matter by depositing its energy locally within the sample. This chapter describes how the beam modifies the sample and outlines the physical extent and nature of the interactions in semiconducting samples.

3.2 Interaction products

When the electron beam of a Scanning Electron Microscope interacts with a solid sample, several different reactions take place which are essentially similar for insulator, semiconductor and conductor but the relative magnitude and types of secondary reactions can differ.

The incident electron energy is insufficient to displace atoms from a lattice so that all interactions in the SEM involve electron-electron, electron-photon or electron-phonon scattering. Each incident high energy

electron is capable of exciting many electrons from their orbitals into a free state with excess kinetic energy. The generated electrons may, in turn, excite further electrons into excited states. Thus the overall result is the generation of many free electrons with kinetic energies just below the bonding energy. These are known as secondary electrons and if generated near the surface may be emitted from the sample.

In addition, some electrons are emitted with precise energies characteristic of the atom from which they were released and are called Auger electrons. Both Auger and secondary electrons have low energies and are deflected by small electric fields. These electrons are collected by detectors for processing into images for SEM display in the Secondary Electron Image (SEI) mode.

Some higher energy electrons may be reversed in momentum and emerge from the sample as backscattered electrons. The amount of backscattering, which in the case of GaAs is about 30%, [17] is proportional to elemental composition and topography of the sample. It is not very sensitive to beam accelerating voltage.

Another effect is the formation of an electrical current from the sample. Electrons flowing from the sample must, according to Kirchhoff's law, balance the electrons emitted (backscattered, Auger and secondary) and the primary electron beam current. The sample current can be used as a

source of information for display on the SEM.[17] This mode is known as specimen current, Absorbed Electron Image current (AEI) or alternatively, Electron Beam Induced Current (EBIC). A development of this operating mode is used extensively in the work described.

Simple solution of Kirchhoff's law is not possible for insulating samples or for semiconductors. For an insulator, charge is frequently deposited on the surface or within the specimen so that the equation must also involve a charging current term. This charge seriously degrades SEM performance.

3.3 Semiconducting samples

In a semiconducting sample further complications to the simple current balance equation occur. The high energy primary electrons produce many electron-hole pairs when valence band electrons are raised to the conduction band. Thus local increases in carrier concentrations occur analogous to photo-conductive effects.

In a neutral semiconductor remote from p-n junctions, high field regions or external connections, the electrons eventually recombine with the holes with no measurable external disturbance. If, however, the electron-hole pairs are generated near a p-n junction, the field separates the electrons and holes and prevent them from recombining. Thus a beam induced effect occurs analogous to the photo voltaic

effect when light stimulates a p-n junction. A similar analog to the photoconductive effect also exists when the generated carriers contribute to current flow between two terminals when a bias is applied.

The benefits of the conductive mode of the SEM are immediately obvious for identification of defect sites in semiconductor devices and such analysis was first performed on silicon and on compound semiconductors by Sulway and Thornton.[2] It also provides a very useful method of identifying how devices actually operate by inducing small perturbations at otherwise inaccessible points within the device and measuring the effects at an output. Use of the conductive mode has been widespread for silicon and LED devices but the technique was not used for direct observation of electrical defects in GaAs FETs until the work by the author and his co-workers.[3,4] The conductive mode was used to try to locate regions of reduced channel current to verify if these correlated with damage observed during routine secondary electron SEM observations. However, the changes in drain current were far greater than expected from simple photoconductivity considerations. In this work the conductive mode and voltage contrast modes of the SEM have been used to study and understand the interactions of electron beams with the various regions of GaAs FETs.

3.4 Measurement of semiconductor parameters using the electron beam

As previously mentioned, the electron beam can produce considerable local increases in mobile carrier density. Monitoring of the changes in current as a function of beam position or time can provide data on important material properties.

When the electron beam can be rapidly switched on and off (beam blanking), or precisely located, it is possible to measure lifetimes or diffusion lengths of the beam stimulated carriers by measuring currents at nearby contacts.[18-21] The electron beam method has significant advantages because the carrier sources are small and therefore are easier to use if the diffusion length is short. Furthermore, using an electron beam, it is possible to measure lifetimes under metal regions which are opaque to light because the beam penetrates thin layers with predictable attenuation. However, allowance must be made for effects such as injection from the contact metal, absorption of the beam by the contact and the current flow through the semi-insulating substrate with its associated lifetime. In Chapter 7, measurements of the diffusion lengths in the active layers of GaAs FETs are reported for the first time insofar as the author is aware. The composite diffusion length of the carriers generated in and below the active channel was found to be 0.25 micrometers

while that of carriers generated in the semi-insulating layer alone was 1.4 micrometers.

Since the purpose of this work is to determine the nature and magnitude of the beam stimulation in practical devices rather than obtain precise diffusion lengths in semiconductor material, detailed corrections for surface recombination, attenuation, etc, are unnecessary. The diffusion lengths and lifetimes obtained are valid estimates of the rate of return to the unstimulated state at the relevant position on the device.

3.5 Beam penetration range

The depth of penetration of the beam into materials is clearly an important parameter in studies of electron beam stimulation of semiconductor devices yet the topic is not well understood and numerous definitions of range are in use. The topic has been comprehensively reviewed by Schumacher.[22] Martinelli and Wang [23] and Everhart and Hoff [24] have more recently developed equations for predicting the range of electrons in solid materials. Martinelli and Wang [23] experimentally determined the range ($R_{\text{subscript G}}$) for gallium arsenide by depositing known thicknesses of GaAs onto plates of fluorescent material and observing the first evidence of fluorescence. They arrived at the relationship

$$R_G = 2 V_B^{1.46} \quad (3.1)$$

where the accelerating voltage ($V_{\text{subscript B}}$) is measured in kilovolts. This expression has been used throughout this work. A considerable variation occurs in the calculated range for any particular accelerating voltage as can be seen from Figure 3.1 where the three relationships are compared. Knowledge of the range is necessary for the calculation of how beam energy is deposited in GaAs and in the calculation of the concentrations of generated electron-hole pairs. These concentrations are in turn needed for the development of adequate models to explain device behaviour under electron beam stimulation.

3.6 Energy deposition in GaAs

Detailed calculation of the rate at which energy is deposited in material as the electron beam is attenuated by scattering is a very complex process and Monte Carlo methods are normally used.[25] Gruen,[26] however, experimentally determined the energy deposition profile of electron beams in air, by normalizing for penetration range, initial energy of the beam and for attenuating material density. Gruen's data have been extended to all materials.[22,24] The universal curves are reproduced in Figure 3.2 where the horizontal axis is the fraction of the penetration range which has been normalized already to make it applicable to all materials by dividing the actual range by the material density. The vertical axis gives the fraction of the total

Figure 3.1 Electron range in GaAs versus accelerating voltage according to Schumacher (S) [22], Martinelli and Wang (MW) [23] and Everhart and Hoff (EH) [24]

energy deposited in any small element of the penetration range. (In the normalization system used, the total area under the curve is unity.)

Everhart and Hoff,[24] measured the energy deposited in the oxide of a silicon metal oxide capacitor as a function of accelerating voltage and used curve fitting techniques to develop a formula for calculating the fraction of the total energy deposited in any segment of the penetration range

$$\lambda(y) = 0.60 + 6.21y - 12.4y^2 + 5.69y^3 \quad (3.2)$$

The curves have been made universal by normalizing the depth to the penetration range and the energy to the total incident energy. This formula produces a curve which approximates Gruen's curves and is very suitable for use directly, or in integrated form in computer programs such as the one developed in this work to calculate the magnitude of the increase in gate current during beam stimulation.

3.7 Induced carrier concentrations

One possible explanation of the beam stimulated current increases is that the beam produces additional carriers in the channel or in the substrate which increase conductivity or change the active layer thickness by modifying the depletion layer boundaries.

Figure 3.2 Normalized depth-dose curves for electron beam energy deposition according to Everhart and Hoff [24] and Gruen [26]

Figure 3.3 Approximation of the volume containing electron beam generated carriers

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It is therefore necessary to determine the magnitude of the beam induced changes in carrier concentrations in order to determine if these effects are significant. As the shape of the actual region of increased carrier density is difficult to determine exactly, the hemispherical approximation shown in Figure 3.3 is used where r is its radius and L^* is the generated carrier diffusion length.

$$r = 0.5 R_G + L^* \quad (3.3)$$

According to Seikanowitz et al, [27] electron-hole pairs are generated in gallium arsenide by electron beams with almost 100 percent conversion efficiency and the average energy of the carrier pairs is 4.6eV. Thus the average concentration of carrier pairs produced per second is given by

$$p^* = n^* = \frac{I_B}{q} \cdot \frac{\eta_B}{4.6} \cdot \frac{2t(n)}{3\pi r^3} \quad (3.4)$$

where $t(n)$ is the lifetime of the electrons generated.

The lifetime can be calculated from experimentally determined diffusion lengths. Such lengths have been measured by other workers using various techniques [19,20] on specially prepared samples. However, in this work, as described in Chapter 7, diffusion length is measured directly on FET devices.

The value of the carrier lifetime in semi-insulating GaAs is given by

$$\tau(n) = \frac{L^2}{D^*} \quad (3.5)$$

where D^* is the ambipolar diffusion coefficient and L is the diffusion length.

Using appropriate values for D^* and the experimental results quoted in Chapter 7, for the diffusion length, the lifetime has been determined to be approximately one nanosecond for semi-insulating material and three to thirty picoseconds for the active region (depending on the value of mobility assumed). Thus the concentrations of generated carriers in the active and semi-insulating substrate can be obtained from equation (3.5) by substitution of the appropriate numerical values and are found to be between $1.7E13$ and $1.7E14$ per cubic centimeter in the active layer and $6.5E14$ in the semi-insulating substrate assuming 15KV accelerating voltage and 1nA beam current. Experimental results described in Chapter 7 indicate that the generated carrier concentrations vary directly with beam current.

The values calculated are for rather large SEM beam currents. It is common to use significantly smaller currents for routine device examination. However, even with nanoampere currents the increase in carrier concentration in the active layer is only about 0.3 percent of the normal

concentration. However, in the semi-insulating substrate the generated concentration approaches the usual concentration of the shallow donors and the chromium deep acceptor concentration. It is comparable to and almost certainly exceeds the difference between the chromium and shallow donor concentrations so that the semi-insulating properties will be disturbed and become locally conducting. It is clear, therefore, that the beam generated channel current increase cannot be explained in terms of increased carrier concentration in the active region but the possibility of the increase in substrate current being significant cannot be excluded.

This chapter has reviewed how electron beams of the type generated in a SEM interact with semiconductors and introduced relationships to calculate penetration range and the beam energy absorbed by the sample at different depths. The magnitude of the increased carrier concentration caused by the beam has also been estimated. Chapter 4 considers how photons generated during beam absorption may influence GaAs FETs.

CHAPTER 4

PHOTON INTERACTIONS WITH GaAs FETs

4.1 Introduction

This chapter considers the effects of photon stimulation of GaAs FETs for two reasons. First, the electron beam produces photons as it is absorbed in the material so that the possibility exists that the generated photons may travel through the gallium arsenide and be reabsorbed in the channel region, thereby accounting for the long range electron beam induced channel current.

The second reason is the close similarity in results between electron beam and photon stimulation of channel current in GaAs FETs. Comparative studies of the two mechanisms can provide valuable information on the basic mechanisms causing changes in channel current. In particular the significance of high energy carriers which are produced in the presence of the electron beam but not when light stimulated can be assessed.

The effects of different types of photon interaction on GaAs FETs are discussed in this chapter. All photons with energies above about 0.5eV are potentially able to interact with GaAs containing deep traps or impurity levels. Optical and infra-red stimulation are particularly significant because of the 1.43eV band-gap and the presence of deep traps near the band centre.

An inevitable side effect of electron beam irradiation is the generation of X-radiation when the beam interacts with inner electron orbitals. As semiconductors are only partly transparent to soft X-rays, reabsorption may occur in areas physically separate from the beam, causing long range interactions.

4.2 X-ray irradiation

High energy incident electrons are capable of stripping electrons from inner atomic orbitals. These orbitals refill with electrons from outer orbitals resulting in characteristic X-ray emission. The samples are, however, partly transparent to X-rays and further interaction is possible some distance from the original beam. It was originally thought that re-absorption of the X-radiation may result in carrier formation at distant locations in GaAs FETs.

The experimental results described in Chapter 9 indicate, however, that this mechanism cannot explain drain current increases at a distance from the beam, because very different effects are seen when the beam is adjacent to regions of different potential. (Figures 4.1 and 4.2) For example, if the beam is on a positively biased region, such as the drain, channel current increase is normally positive but if the beam is on negatively biased material such as the gate pad, a decrease in drain current occurs. As X-ray

Figure 4.1 a) Linescans across device showing induced channel current and SEI signal

Figure 4.1 b) Linescans across device showing how the measured substrate current and SEI signal change with beam position

Figure 4.2 SEI image and linescan of line traversed in Figure 4.1. The scale corresponds to 100 micrometers

propagation is unaffected by electric fields of the magnitude experienced in a FET, no difference would be expected in the current generated in the channel as a result of the beam being on material of different potentials but at an equal distance from the channel. Further, more current is produced when the beam is on the drain than when it is on the source, yet metallurgical conditions are identical. Reversing the functions of the source and drain produces more stimulation from the region that was the source, indicating that electrical rather than geometrical effects determine the increase in drain current and that the influence of X-ray radiation is insignificant. Figure 4.1 also shows the observed changes in substrate voltage and current resulting from beam stimulation. Their importance will be discussed in Chapter 6.

4.3 Cathodoluminescence

Radiation, of energy equal to the band-gap energy, is emitted by a semiconductor when direct recombination occurs with electrons dropping directly from the conduction band to the valence band. In the case of gallium arsenide, near infra-red energy is emitted which is known as cathodoluminescence when such emission results from recombination following electron beam stimulation. The process is efficient for GaAs as the band-gap structure permits direct transitions with no phonon interaction.

Propagation of infra-red radiation might, at first sight, be expected to play a significant role in the observed effects on a gallium arsenide FET when it is stimulated by an electron beam, because it provides a possible transport mechanism to explain how the electron beam affects areas of the device several diffusion lengths away from the incident beam. Such an effect has been reported [30] for anomalous currents in GaAs. As in the case of X-rays however, the same experimental results make it unlikely that this mechanism plays a significant part in explaining the electron beam induced currents in a GaAs FET.

4.4 Deep traps and optical stimulation of GaAs FETs

Problems associated with the semi-insulating substrate resulting from unpredicted changes in resistivity on heating (known as thermal conversion) have provoked many workers to study the chromium doping process using optical stimulation methods.[31-39] Appendix 1 reviews semi-insulating GaAs and the chromium doping process in particular. The results have indicated a very complex series of processes which result in increased conductivity or charge trapping depending on the incident photon energy.

A conventional GaAs FET, when stimulated by light, appears to be a possible replacement for an avalanche photodiode and work has been published [41-45] showing that drain current increases by a useful amount under practical

illumination conditions. These results closely parallel the electron beam stimulation results reported here. The explanations have, however, concentrated on the effects of the light on the Schottky barrier and have supposed that the light alters the gate bias photovoltaically, which in turn modulates the channel current.

Graffueil et al[43] and Tegude et al[44] have modelled the effects of an increase in carrier concentration on the Schottky barrier depletion layer thickness and related this to the change in drain current.

Edwards[45] has studied how a FET responds without a gate electrode and found that photoconductive changes in drain current still occur and are of similar magnitude to those of gated devices. He has also shown that laser stimulation can change the voltage induced at the substrate. The relationship between illumination and channel current is very nonlinear. The process is less efficient at higher light intensities. Further, he has concluded that the light does not have to strike the FET close to the channel and that both fast and slow response effects occur.

4.5 Similarities with electron beam stimulation

The optical stimulation effects studied by Edwards on FETs [45] from the same batch as the electron beam work presently being reported have revealed several close similarities in the stimulation effects.

Both methods inject energy into defined regions of the FET and produce excess electron-hole pairs. It soon became apparent that comparisons of the results of the two methods would provide important information concerning the stimulation mechanisms. For example, if identical results were obtained for optical stimulation and SEM beam stimulation, the effects of the high energy primary electrons in disturbing electric field stimulation need not be considered in explaining the results. The available evidence, although not conclusive, indicates that similar gate and drain current stimulation mechanisms exist for both optical and SEM stimulation.

A control experiment was necessary to provide direct evidence that similar processes were indeed occurring. In an experiment to see if the stimulation methods interact, a device was operated in the SEM and the beam used to stimulate additional channel current. The FET was then illuminated with flood beam tungsten light from the optical microscope lamp integrated into the SEM and used in microprobe analysis. Additional drain current stimulation occurred. The electron beam was then switched off and the amount of stimulation from the light alone was measured. The increase in drain current with both stimulants on together was less than the individual components alone, indicating that they interact. It is possible that both light generated electrons and free electrons created by the

electron beam attempt to fill the same deep chromium traps in the semi-insulating substrate. Both mechanisms exhibit a fast and slow time dependent effect. The results of this simple experiment are displayed in Table 3.

4.6 Comparison of electron and optical stimulation

Both methods have advantages and disadvantages. Optical stimulation is more convenient as it does not require high vacuum and attaching bias and measuring lines is much simpler. High frequency measurements can be made with relative ease.

However, without complex optics, obtaining fine spatial resolution is difficult and high magnification photographs cannot easily be obtained. By using laser illumination or passing the beam through a spectrometer grating, almost monoenergetic stimulation can be obtained. The electron beam however offers fine modulation, the ability to penetrate metal layers, accurate knowledge of penetration depth and more precise monitoring of input energy (beam current and voltage). However, the energy spectrum and distribution of the created carriers is not known, and the high energy electrons may disturb the internal electric field and add another variable. High frequency measurements are very difficult to perform because of the need for long electrical leads into the SEM, and the possible interaction between the rf and the magnetic fields in the SEM lenses may reduce resolution and beam stability.

Table 3

Results of Light + SEM Stimulation.

	Stimulation Method	Increase in Channel Current
1	Spot electron beam	1.4mA
2	Flood illumination	5.9mA
1+2	Spot electron beam and flood illumination.	6.3mA

4.7 Conclusions

This chapter has discussed the effects of photon generation and stimulation in the GaAs FET and has briefly discussed possible interactions with deep traps within the substrate. On the basis of experimental results, it has been concluded that photon transport mechanisms are unable to explain the long range channel current stimulation effect. The similarities between electron beam and photon beam stimulation have been briefly explored and lead to the belief that the mechanisms are basically similar. In the next chapter the experimental equipment and techniques used in this thesis are described.

CHAPTER 5

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

5.1. Introduction

The scanning electron microscope has found extensive use in the study of semiconductor devices. Not only is it an invaluable tool for reliability analysis, but it also is a convenient source of electron irradiation in the energy range 1-40 KeV. This range of energy contributes significantly towards ionizing radiation damage in numerous semiconductor devices.[17,46,47] A small directable beam of the SEM has been used by Norman et al to irradiate selected parts of devices.[46]

In this chapter, the essential operating characteristics of the SEM are briefly reviewed together with the important characteristics of the ancilliary equipment. The method of recording the results is outlined and the precautions necessary are discussed.

5.2. The Scanning Electron Microscope

The SEM used in this work is a Japanese Electron Optical Limited (JEOL) JSM 35 research instrument which is equipped for wavelength dispersive X-ray microanalysis. It has accessories which permit detection of backscattered electrons and allow image display (mapping) of both high and

low impedance electrical signals. The beam accelerating voltage is variable in kilovolt steps between 1KV and 39KV while the beam current can be infinitely varied by adjustment of the condenser lens within the approximate range 1 picoampere to 0.5 microamperes. The beam can be scanned in a conventional rectangular raster with constantly variable dimensions at any magnification as a linescan in the X direction with variable length and as a fixed or movable spot. The input can be displayed in any mode as an intensity or a Y-modulated signal.

Three valuable features provide extra experimental control of the beam and have been used extensively to isolate spatial and time sensitive artifacts. The beam may be electronically rotated to any angle. Thus, by rotating the beam through 180 degrees, the beam can be made to scan the device from opposite directions without moving the device physically. Additionally, the scan speed for a complete raster or for a linescan can be altered by a ten position switch from approximately one second per scan to approximately 480 seconds per scan in the recording mode. In the 'photo' mode, a single scan only is made which can be recorded. These two features make it possible to separate stimulation effects that are determined solely by the present position of the beam, from effects that were generated during an earlier part of the scan but persist due to their slower decay rates.

The third feature is the ability to cut off the beam to the sample using an additional beam blanking lens. The beam is rapidly defocussed by supplying current to the lens so that very few electrons maintain their original trajectory towards the sample. The remainder are scattered and do not pass through the beam defining spray apertures. The current reaching the sample is reduced to less than 0.1 percent of the original beam current. Experimental tests have indicated that the beam current changes to within 10 percent of its final value when switched on or off within 10 microseconds, but that the final 10 percent decays very much more slowly. The current supplies to the electron gun, high voltage supplies, lens excitation and scanning coil currents are not altered when the beam is blanked so that all the critical SEM parameters remain stable and the beam remains essentially unchanged from one stimulation period to another. This feature allows the experimenter to align and focus the beam onto the relevant part of the device, establish that all experimental variables are adjusted correctly and check required photographic exposures with the same beam conditions that will be used during the experiment. The beam can then be blanked to allow the beam stimulation effects to decay to zero before starting the experiment. Without beam blanking there is always a degree of uncertainty about how much stimulation results from the setting up or stabilization period.

Sensitive experiments indicated that the beam blanking was not as perfect as hoped for, with more channel current stimulation existing than was expected when the beam was blanked. The cause was traced to photon stimulation originating from the hot tungsten filament which is not turned off during blanking. The effect can be reduced by using the smallest final aperture. However, the channel current stimulation caused by the light from the filament is normally less than one percent of the electron beam stimulation and its effect is ignored or zeroed out.

Experience has shown that stable and valid results are only obtained with accurately positioned filaments and well aligned lens columns. New filaments are used for an hour or two and realigned before results requiring stable beam currents are attempted. Variations of less than 5 percent in beam current are routinely achieved over periods of several minutes when measured using a small Faraday cup. Each device holder contains a Faraday cup mounted as close to the device under test as possible. The cup is made from a T018 transistor lid in which a 0.002 mm diameter hole has been drilled. The lids are attached to the device holder with silver paste and connected via a picoammeter to ground.

The accelerating voltage is controlled by varying the feedback resistor from the triode gun. It has not been possible to calibrate the accelerating voltage absolutely but the values of feedback current were measured and found to be self consistent within 1% for all beam voltages.

5.3 Electrical connections

Electrical connections were made to the device using the JEOL-made SHIC accessory. The device under test, mounted on a low frequency T05 or T018 header was plugged into a modified sample holder used for integrated circuits (SHIC) which consists of a device socket attached to a 22 contact two sided printed circuit board which was electrically isolated from the remainder of the holder. The transistor on the holder could be passed through the SEM airlock and slid onto the stage. The edge connectors of the printed circuit board in the holder were plugged into an Amphenol socket mounted on the stage which was in turn wired to a multipin feedthrough socket through the vacuum chamber wall. The external connections were made via low frequency screened cable to the BNC sockets at the front of the SEM.

The device holder was decoupled at each pin using a 47 ohm resistor and a 30 pF capacitor in series to ground. Two of the feedthrough leads to the SHIC interface were assigned to each device pin to allow for Kelvin contact measurements.

The nature of the feedthrough connections and the need for flexible connections between the stage and the feedthrough precluded measurement of beam stimulation properties at gigahertz frequencies.

5.4 Ancilliary equipment

The original equipment for measuring changes in current

[3,4] was reassembled but the method of measuring changes in source current was found to be critical. The series resistor used to detect source current changes introduced grounding problems between the SEM and the remainder of the test apparatus. More seriously, however, it removed the source from true ground potential and so introduced biasing changes in the device which introduced complications when interpreting results. The problems were specially significant when comparisons were being made between currents flowing to the two sources in the Hewlett Packard devices. A new system was therefore built which used a common ground plane and could control and monitor drain voltage, drain current and changes in source current in addition to monitoring and controlling gate voltage and current. Figure 5.1 illustrates the circuit in block diagram form.

A dual system was built so that both sources could be maintained very close to ground potential with or without beam stimulation. The monitored source was connected to a variable negative power supply via a resistor. The point between the resistor and the source was connected (via Kelvin leads) to one input of an operational amplifier whose other input was connected to true ground. By adjusting the negative supply, the source could be brought to ground

Figure 5.1 Block diagram of circuit used to bias GaAs FET for electron beam stimulation tests

Figure 5.2 Gate biasing and measurement circuit. The substrate circuit is similar except the voltage is 45V and the series resistance 1Mohm

potential at any time by obtaining zero input offset and hence zero output of the operational amplifier. Any subsequent change in source current produced an offset voltage across the operational amplifier inputs and an output corresponding to 1V per mA. The drain current was monitored using remote sensing by connecting the inputs of an operational amplifier across a precision sensing resistor. This method eliminates drain current changes when meter ranges are altered. Using this system the previous ground loop problems were completely eliminated. It was also found that high quality power supplies and digital meters could be used without introducing voltage spikes into the system, improving measurement accuracy. No oscillation above 5 mV amplitude was observed at up to 10 MHz even with the long lead lengths to the device in the SEM. Changes in source current of approximately 1 microampere could readily be detected. Drain current changes of 10 microamperes can be measured.

Gate current is measured using a logarithmic amplifier, a HP 425A picoammeter or a Keithley 612 electrometer-picoammeter in the circuit of Figure 5.2. An external output from the picoammeter drove an XY recorder. Gate voltage was capable of being set to plus or minus 0.001V. There was always at least 10 kilohm resistance in the gate circuit for protection.

A similar measurement system was used for substrate current measurement with the differences that the battery voltage was 45V and the minimum series resistance was 1 megohm.

5.5 Method of recording results

May and Bellier, in earlier work, developed a very elegant technique for displaying the channel current or changes in channel current directly onto the SEM secondary electron image.[4]

In this work it was necessary to provide plots of gate current, substrate voltage and substrate current in addition so that a different display method was required. The specially built test apparatus previously described for controlling drain and gate bias, and monitoring changes in source current was provided with outputs capable of driving a Hewlett Packard 7001AR XY recorder. The picoammeters and high impedance voltmeters used for monitoring gate and substrate currents and voltages each had output terminals suitable for driving the XY recorder. This recorder has a built in linear voltage ramp so that the X-axis can be used as a time axis. The SEM was adapted so that the drive to the photographic shutter mechanism on the recording CRT was tapped to provide a drive to the recorder's ramp starting circuit and pen lowering circuit. The ramp time on the XY recorder was adjusted to be the same as the time the shutter

was open on the SEM. The shutter is internally designed to open and close automatically at the beginning and end of the linescan or picture frame.

The problem of identifying the exact physical position on a device corresponding to an electrical parameter change was solved by recording the secondary electron image Y modulated linescan signal simultaneously on the XY recorder and on Polaroid film on the SEM recording screen. The SEI two dimensional intensity modulated image and an unmodulated line indicating the exact position of the linescan were recorded on the same Polaroid emulsion. The SEI linescans provided a common reference between the graphs and the SEM photographs.

It was found that at magnifications greater than 1000 a slight shift in beam position could occur. Checks were made at frequent intervals to ensure that such shifts remained within acceptable experimental error.

The linescan time was usually set to 97 seconds per scan but for specific purposes, scans in the range 5 to 476 seconds were used. The scan rate of 97 seconds per scan corresponded to a recorder speed of 10 seconds per inch.

Whenever possible, voltage and currents were monitored using 5 digit voltmeters so that readings could be made with adequate accuracy and an estimate obtained of the stability of the set parameters such as drain and gate voltage during a scan. Currents were measured as voltages across an

operational amplifier input or resistor for source and drain currents respectively but were measured directly using an analog picoammeter for gate and substrate currents because sufficiently sensitive digital meters were not available.

5.6 Protection from excess radiation

Although unpublished results at CRC indicated that GaAs FETs did not appear to be sensitive to ionizing radiation, care was taken to reduce beam radiation on the active areas of the device to a minimum. Whenever practicable, the beam was blanked between observations and unnecessary scanning at high magnifications over the active regions was avoided for two reasons. Firstly, the radiation dosage can be reduced significantly, and secondly, the beam contamination resulting from diffusion pump oil cracking is reduced. Excessive surface contamination might alter the surface potential of the substrate.

Some devices were extensively studied taking many hours of beam time. It has not been feasible to measure the radiation dosage because of the frequent changes of beam voltage, current and position.

On the rare occasions a large unexpected change in drain current was noted, it was either attributable to an error in biasing or to serious damage resulting from overstress to the device. No consistent gradual changes were observed in any devices that could be attributed to radiation damage.

All experimental results used in this thesis were obtained using devices which were functioning correctly unless otherwise reported. An example of the latter case is the use of devices where the gate metal has been etched off.

5.7 Conclusions

This chapter has summarized the experimental equipment and techniques used in the detailed work which will be described in Chapter 7 to 10. The next chapter serves as an introduction for the experimental results and outlines the different regions of the device which are susceptible to electron beam stimulation.

CHAPTER 6

POSSIBLE ELECTRON BEAM STIMULATION MECHANISMS

6.1 Introduction

In this chapter, the possible mechanisms that may cause changes in electrical characteristics when a GaAs FET is stimulated by an electron beam are discussed. The device parameters which have been observed to change as a result of beam stimulation are gate current, drain-source (channel) current and induced substrate voltage and current. In this work the drain, gate, applied substrate and beam voltage and beam current have been treated as the experimentally controlled parameters.

Some of the possible mechanisms are eliminated and the more probable mechanisms are identified for study in greater detail in following chapters. The problems involved in the development of a comprehensive model to explain electron beam induced gate and channel current changes are discussed. The realization of such a model is beyond the scope of this work for several reasons. First, the most sophisticated two dimensional numerical models presently available are of unstimulated FETs and yet they still do not adequately account for the full influence of the substrate. The models ignore the fact that small changes in trap occupancy can have major effects on substrate conductivity or back gate

depletion layer width. When the substrate is considered [12,13], it is merely treated as a parasitic resistance between source and drain that accounts for any other discrepancies in the model.

Secondly, modelling is complicated because some of the beam induced effects seem to be unrelated to others and may best be described by separate models. For example, the experimental results suggest that changes in gate current are independent of changes in the channel current. This result is unexpected but provides important clues to the processes involved.

Finally, if the model is to apply to large beam currents, the electrical disturbances in the device caused by the beam become significant. At beam currents below one nanoampere, these effects are almost certainly not significant as outlined in section 6.4.

6.2 The influence on channel current

In its simplest form, the FET can be treated as a variable resistance, the channel, between the source and drain ohmic contacts.

This resistance can be modified by altering its dimensions or its resistivity. Its value is given by

$$R_{SD} = \frac{L}{qn\mu_n ZW} \quad (6.1)$$

where L , Z and W are the length, width and thickness of the channel. The resistance is a minimum since W is a maximum when no Schottky barrier or back gate depletion region is present. In normal operation, a negative bias on either of these electrodes causes the depletion region to widen, which in turn reduces W , increases R and decreases the channel current.

The behaviour of the FET under the influence of the electron beam can also be considered qualitatively in terms of this simple picture. The beam normally reduces the channel resistance (i.e. increases drain current) and so must change one or more of the parameters in equation (6.1). However, q is constant and L and Z are geometrically fixed parameters, so that the carrier concentration, the mobility and the channel thickness are the only alterable parameters.

In the next sections, the sensitivities of these parameters to an electron beam will be examined by considering the regions of the device described in Figure 2.2 in the light of the available device models and the experimentally variable parameters. This will eliminate some of the effects as possible explanations of the observed experimental results described in Chapters 9 and 10.

6.3 Carrier concentration increases

6.3.1 The active region

Equation 6.1 predicts a linear decrease in channel

resistance as the carrier concentration, n , in the channel is increased by the beam. This is the electron beam analog of photoconductivity. The theories developed to explain photoconductivity are applicable to electron beam stimulation. Photoconductive current gain occurs when the lifetime of the generated excess carriers exceeds the transit time of the carriers between the ohmic contacts. This gain is usually defined as the lifetime of the generated carriers, $t(n)$, divided by the carrier transit time between source and drain, $t(SD)$.

$$g_{pc} = \frac{t(n)}{t(SD)} \quad (6.2)$$

The former was found using equation (3.5) to be approximately 2.8 ps based on the diffusion length of 0.25 micrometers reported in section 7.6 while the transit time for the 3 micrometers separation between source and drain is approximately 15ps assuming maximum electron carrier velocity ($2E7$ centimeters per second) over the whole transit path. Thus the photoconductive gain in the active channel is less than unity in these devices. However, each 15KV primary electron produces approximately 3260 electron-hole pairs in GaAs.[27] It can be seen from equation 3.4 that the carrier concentration will be increased by approximately $4.7E14$ per cubic centimeter per nanoampere beam current at 15KV. The increase is generated

in a volume extending about one diffusion length beyond the volume in which the primary electron energy is dissipated. This can be approximated by the hemisphere of radius r whose thickness is the active layer thickness illustrated in Figure 3.3 and described by equation (3.3). The value of r is approximately 2.1 micrometers in the experimental devices at 15KV based on the range calculated from equation 3.1 and the experimentally determined diffusion length of carriers in semi-insulating GaAs (1.4 micrometers) described in section 7.6. The diffusion length of carriers in semi-insulating material applies because carriers generated in the substrate will diffuse into the active layer and contribute to current. The increase in channel current is given by

$$\Delta I_{DS} = \frac{\Delta n}{n} \cdot \frac{2r}{Z} \cdot I_{DS} \quad (6.3)$$

where Δn is the increase in carrier concentration.

This corresponds to approximately 3.1 microamperes for an 80mA device with 500 micrometers gate width and $1E17$ carrier concentration per cubic centimeter in the active channel.

In Chapter 9, more sophisticated treatment reveals that the effect extends to approximately 80 micrometers rather than the 4.2 in this simple analysis. Even with this increase the predicted increase in current is only approximately 60 microamperes. The contribution of hole current has been

ignored because of the much smaller hole mobility. The predicted increase in the electron beam induced channel current increase, (EBICC) is about three orders of magnitude less than the experimentally observed results reported in Chapter 8.

Any change in carrier concentration in the channel produces several second order effects. The higher carrier concentration restricts the extent of the Schottky barrier depletion region so that the available channel thickness is larger with beam stimulation than without. Assuming the single sided step junction approximation for the depletion layer width [6] is valid, then

$$W_{DEP} = \left[\frac{\epsilon \epsilon_0}{qn} (V_{BI} - V_{GS} - \frac{kT}{q}) \right]^{1/2} \quad (6.4)$$

The active channel thickness increases by a factor proportional to the reciprocal of the square root of the carrier concentration, so that under beam stimulation the channel resistance also changes by the same factor provided that the change is too small to affect other factors. The change in active channel thickness caused by changes in the Schottky gate depletion layer thickness is clearly of even smaller magnitude than that caused by the increase in carrier concentration and so is not a significant factor in channel current stimulation.

Any increase in carrier concentration will produce a further, second order effect which tends to reduce current flow. At high internal fields, corresponding to drain voltages above about 1V, the carrier mobility within the channel drops as the field increases. An increase in field can result when the beam is located between the gate and the drain because the increased carrier concentration produces greater current and hence greater voltage drop. This tends to limit the increase in channel current and compensate for the previous two effects. This is discussed further in Chapter 9. From this discussion it is clear that the increase in carrier concentration in the active layer is not a major factor in the increased channel current phenomenon.

6.3.2 The semi-insulating substrate

A far more significant effect may occur when the beam stimulates a region of the semi-insulating substrate under the active channel, if the beam is able to convert a small volume of the substrate to a highly conductive state by interfering with the chromium compensation mechanism, or the depletion layer width is altered by charge trapping in the substrate. This is described in section 6.5 2. The increase in conductivity is, however, thought to be dependent upon the specific material properties of the semi-insulating substrate.[5] In particular, it depends on the degree of compensation provided by the chromium and the

effects of oxygen deep donor states.[35-37] The increase in conduction may be accompanied by an increase in positive trapped charge resulting in changes in the back gate depletion region as described in section 6.5.2.

In its simplest form, compensation occurs when the chromium concentration in the material exceeds the shallow donor concentration so that the Fermi level is effectively pinned at approximately mid band.[5] This compensation capability is limited to about $1E16$ donor atoms per cubic centimeter,[36,37] which is the maximum chromium solid solubility in GaAs. Furthermore, during the high temperature epitaxial growth, chromium outdiffuses and shallow donors diffuse into the substrate so that the ability of the chromium to compensate near the interface between the active layer and the substrate is effectively reduced. It is possible that small increases in electron concentration fill the available chromium traps causing the substrate to conduct and creating a charged region under the active layer. Using this argument, it is apparent that a comparatively small increase in electron concentration, certainly below $1E15$, can make the substrate conduct appreciably.

The electron trapping process in chromium doped GaAs is known to have a slow component. Time constants extending to seconds have been measured [3,4,16,48]. Any trap occupied by an electron may therefore remain filled for a long time

compared with the electron generation rate. Each additional filled trap effectively reduces the capability to compensate and the material becomes progressively more conducting as the electron beam irradiation process continues until equilibrium is reached when the chromium traps are filled and the electron generation and recombination rates equalize.

The contribution to conductivity of holes is probably insignificant because the hole mobility is low compared to the electron mobility, and also because holes quickly recombine once they reach the active layer.

The calculation based on equation (3.4) indicates that approximately $4.9E14$ carrier pairs per cubic centimeter per nanoampere beam current will be generated in a hemispherical volume of radius r , based on the volume approximations shown in Figures 6.1 and 6.2 for a beam voltage of 15KV and current of 1nA. The additional channel current generated by the beam can be calculated, providing that the source to drain resistance of this volume can be estimated. In view of the imprecise assumptions made already, a sophisticated calculation of the resistance is not justified. Without serious error, the resistance of a box with a length equal to the source drain separation, 3 micrometers, and width 4.5 micrometers and depth 3.05 micrometers can be substituted for the hemisphere to aid calculations. The volumes of the two shapes are almost equal.

Figure 6.1 Section of device showing approximate extent of beam induced carrier concentration

Figure 6.2 Plan view of approximate extent of beam induced carrier concentration

Using the above box, the resistance calculated from equation (6.1) is 3.35 kilohms. A resistance of this magnitude would contribute an additional 0.3 milliamperes of channel current per volt in the absence of photoconductive gain. Although it was shown that photoconductive gain in the active layer is less than unity, it will now be shown that this is not the case in the semi-insulating layer.

The carrier velocity, v , from the definition of mobility, is given by

$$v = \mu_n E \quad (6.5)$$

where E (volts per centimeter) is the average field assumed to exist as a result of the drain bias. Combining (6.5) and Einstein's equation gives

$$v = \frac{EDq}{kT} = \frac{V_{DS} Dq}{L_{SD} kT} \quad (6.6)$$

Thus, assuming a value of 4.5 micrometers as the average value of the current path length between the source and drain electrodes through the substrate based on the box approximation, the transit time can be calculated

$$t_{SD} = \frac{L_{SD}}{v} \quad (6.7)$$

The lifetime is given by

$$t(n) = \frac{L^2}{D} \quad (6.8)$$

so that, from equations (6.2), (6.6), (6.7) and (6.8), the photoconductive gain is

$$g_{pc} = \frac{L^2}{L_{SD}^2} \cdot \frac{qV_{DS}}{kT} \quad (6.9)$$

Assuming the measured value of 1.4 micrometers for the diffusion length in the substrate the photoconductive gain in the substrate is 3.72 per volt applied to the drain. The overall EBICC is therefore

$$\Delta I_{DS} = g_{pc} \frac{V_{DS}}{R_{SD}} = \frac{q L^2 V_{DS}^2}{kT L_{SD}^2 R_{SD}} \quad (6.10)$$

Combining this with equation (3.4) which gives the increase in carrier density in terms of the beam parameters and equation (6.1) the final expression for the increased channel current is

$$\Delta I_{DS} = \frac{L^2}{L_{SD}^2} \cdot \frac{qV_{DS}^2}{kT} \cdot \frac{V_B I_B}{4.6 \cdot 2\pi r^2 L} \quad (6.11)$$

Using (6.11) the predicted EBICC is 1.1 milliamperes when the drain voltage is 1V.

This value, given by equation (6.11) has the correct magnitude so that it is likely that conduction effects in the substrate are significant but unfortunately the model is unrealistic in some respects. First it predicts a greater sensitivity to drain voltage compared with the experimental values which are reported in Chapter 9. Secondly, the model predicts an increase in drain current, proportional to the beam current whereas in practice a relationship of the form

$$I_{DS} = c' \cdot I_B^{3.8} \quad (6.12)$$

is reported experimentally in Chapter 8 for beam currents up to 3nA focussed on the gate metal. The constant, c' , depends upon experimental conditions.

6.4 The influence of carrier velocity

In addition to carrier concentration changes, changes in carrier velocity could also contribute to an increase in channel current by reducing the channel resistance (6.1). The carrier velocity is strongly influenced by the electric fields within the active layer. It is, however, difficult to see how the electron beam could influence carrier velocity sufficiently to explain drain current changes under all biasing conditions. For example, at high drain voltages, the channel current saturates and sometimes decreases as a result of the stationary Gunn domains which

result from the reduction in carrier velocity at high electric fields [6, 10-12] but this effect should not be significant at drain voltages below one volt, yet large drain current increases occur below one volt. The presence of the Gunn domains is believed to limit EBICC increases above 1 volt.

An increase in drain current could result from a reduction in the field between the gate and drain caused by the beam widening the channel because of increased substrate conduction. However, in this case the increase in channel width itself would account for much of the increase in drain current and the mobility changes themselves would be secondary. Interactions between carrier velocity and channel width are considered in more detail in Chapter 9.

It could also be argued that the high electric fields produced while the primary electrons are being stopped in the gallium arsenide could significantly alter the internal fields and hence the carrier velocity thereby increasing channel current. However, the primary electrons arrive at the surface at approximately 160 ps intervals when the beam current is one nanoampere. Although calculations of the average transit time of the primary electrons before coming to rest cannot be made with accuracy because these paths cannot be accurately determined, conservative estimates can be made. If it is assumed that the total path travelled by a typical primary electron is 1000 times the penetration

2

range of 1.7 micrometers and that the velocity decreases in a linear manner to zero from its initial velocity in vacuum v , then

$$qV_B = \frac{1}{2}mv^2 \quad (6.13)$$

and m is the non-relativistic mass of the electron and v is 7.25×10^8 centimeters per second. The average stopping time is found by inserting v into the equation (6.14)

$$t_{av} = 1000 R_G \cdot \frac{2}{v} \quad (6.14)$$

This gives an average stopping time of 47 ps. The previously obtained lifetimes of the generated carriers were about 2.8 ps in the active layer so that generation and recombination activity resulting from one primary electron will have become insignificant before the next primary electron arrives.

It can therefore be assumed that since electron dielectric relaxation times are of the order of 0.1 picosecond the active layer electric fields are undisturbed by the electron beam for most of the time. Further, the disturbance is only influential over about 6 Debye lengths (or about 0.06 micrometers in the active channel) so that the distance over which an electron is accelerated is small and its effect will be insignificant.

Also, in gallium-arsenide, increases in electric field beyond a critical field strength, which is already exceeded under normal device operation at drain biases above about 1V, tend to reduce carrier velocity.

It can therefore be concluded that the high accelerating voltages and great energies of the primary electrons compared with the carriers have little or no influence on the increase in drain current. This is experimentally supported by the results obtained by Edwards [45] who uses light to stimulate channel current, because, in his case, there are no accompanying high accelerating voltages or high energy particles, yet increases in channel current of the same order have been observed.

6.5 Influence of channel thickness

It can be seen in equation (6.1) that the channel resistance depends inversely on the thickness W , of the active layer. Current modulation in a FET is normally achieved by altering the channel thickness by the application of gate voltage to change the depletion layer thickness. In a GaAs FET only the top gate is intentionally modulated; the back gate between the substrate and the active layer is undesirable and its effect minimized by connecting it electrically to the source. Changes in channel current could result from beam induced changes in the properties of either gate. These possibilities have

been explored experimentally in detail because they suggest several possible mechanisms to explain beam current stimulation effects.

The effects of the beam on the Schottky barrier gate have been studied in terms of the changes in gate current and how these relate to the change in channel current. The changes in both gate and channel current have been correlated to the beam position and the changes in gate current have been modelled.

Numerous experimental data led to the conclusion that the Schottky barrier is not altered by the beam in a way that would change the channel current. This was demonstrated dramatically by the observation that the channel current changes were essentially unaltered when the gate electrode had been removed by etching.

The other ways that the channel thickness can be altered are by modulation of the back gate and by the decrease in the depletion layer widths caused by increased carrier concentration. The latter has been discussed briefly (Section 6.3), and shown to be insignificant in terms of active channel current. The former is almost certainly responsible for a significant part of both the long and short range effects and will be discussed in detail in Chapters 9 and 10.

Back gate changes are almost certainly responsible for the long time constant effects reported earlier [3,4,16,48]

and are attributed to slow-trapping states in the semi-insulating layer.

6.5.1 Influence of the Schottky Barrier

Both the gate current at constant gate bias and the channel current, measured as the source current, at constant drain bias vary as functions of the beam position when the beam is scanned along the major dimensions of the gate (width) or across the gate (length). However, the relationships are not simple. Figure 6.3 shows a beam scan along the gate and Figure 6.4 shows the corresponding micrograph with the SEI linescan superimposed. In Figure 6.3 the gate current and change in source current are shown together with a reference scan of the secondary electron image signal strength for comparison with Figure 6.4.

The gate current scan shows that gate current rises rapidly as the mesa edge is approached from the semi-insulating GaAs and falls within about 4 micrometers to a stimulated level greater than in the semi-insulating substrate when the beam is on the active layer.

The graph of increase in source current dips below the unstimulated value at either edge of the channel on the semi-insulating layer, rises gradually over about 40 micrometers to an equilibrium value of increased drain current as the beam is moved from the edge of the channel. Clearly no simple correlation exists between the two effects

Figure 6.3 Line scans of gate current and channel current increases as the beam is scanned along the gate

Figure 6.4 SEI image and linescan of line traversed in Figure 6.3. The scale corresponds to 100 micrometers

and this is an important result. The peaks and troughs in the two curves do not correspond spatially and the rates of change of the two currents with position do not in general correlate. No changes in gate voltage were observed in the circuit shown in Figure 5.2 when either drain or gate current change even though the 10 Megohm internal impedance digital voltmeter can be read to .01% of the gate voltage. This indicates that the internal impedance of the Schottky barrier remains essentially constant and hence that the barrier depletion width is not altered by the beam.

The changes in gate current have been studied in detail because an understanding of how the beam affects the Schottky barrier can provide the reliability engineer or device designer with information about abnormal current densities in the device. For example, sudden dips in the induced gate current are a more accurate and less ambiguous indicator of defects in the Schottky barrier than are sudden changes in drain current.

The study of changes in gate current also provides a simple method of determining diffusion lengths of generated carriers within transistors. The measurements made of the diffusion lengths of carriers generated in the semi-insulating material and in a section of the device containing the active layer on the semi-insulating substrate have been used in the drain current models already described briefly and will be used in the gate current model described in detail in Chapter 7.

The results of studies of changing beam parameters, gate voltage and beam position are presented in Chapter 7 and lead to the model of the gate current stimulation mechanism.

6.5.2 Influence of the back gate

The substrate back contact is normally connected to the source and it is usual to assume that the substrate has no influence on device properties. However the high resistivity of the substrate and the presence of a high-low junction between the heavily doped n-type active layer and the substrate permit appreciable potential differences to exist within the substrate even when there is an external electrical connection between the back contact and the source:

Barrera, [16] using a separate external substrate connection, has shown that appreciable changes in drain current can be caused by applying substrate bias. As Barrera used Hewlett Packard devices made about the same time as the devices used in this work, the author measured how the devices used here reacted to substrate bias changes without beam stimulation. Figure 6.5 shows typical results for a device with gate shorted to the source. An initial rapid increase in drain current was observed with positive substrate bias. The effect rapidly saturated to a maximum of about 1.8mA increase in drain current for all substrate voltages greater than +6V. Far greater decreases were

Figure 6.5 Influence of substrate bias on drain current with no beam stimulation

observed when the substrate bias was negative. It was possible to reduce the total drain current from about 64.5mA at zero gate and +2V drain bias to about 6mA with -30V applied to the substrate.

This result shows that a strong back gate effect exists which is capable of pinching off the active layer almost completely. It also shows that under normal conditions the back gate depletion layer only extends slightly into the active layer because of the limited drain current increase under positive substrate bias.

In comparison, the Schottky barrier gate depletion layer at zero bias occupies about 56% of the total epitaxial layer thickness according to simple single sided abrupt junction theory (equation (6.4)). Curve tracer experiments show that about +0.7v on the gate can increase drain current by 80 percent.

Although these results show that back gate bias has an important effect on channel current it is not easy to measure directly because of the large substrate series resistance which has approximately the same magnitude as the high-low junction impedance. An estimate can be made of the relative sensitivities of the two gates by comparing the voltages needed at the substrate contact and at the Schottky gate to produce similar changes in drain current.

Such a comparison was made by maintaining the substrate bias at zero and controlling the channel current by means of

the gate. The process was repeated but with the gate grounded and the substrate modulated.

A curve showing the comparison is given in Figure 6.6. For gate voltages between zero and -0.6V, the relationship between gate and substrate biases has the form

$$V_{SUB} = 10.3 V_{GS} \quad (6.15)$$

and between a gate voltage of between -1.0V and -1.5V, it has the form

$$V_{SUB} = .38 V_{GS} \quad (6.16)$$

Between these gate voltages there is a smooth transition. Figure 6.7 shows a similar relationship but with the active layer thickness as the equalizing parameter instead of drain current. The active channel thickness is calculated from equation (6.4) and the equation

$$W_{AL} = W_{EPI} - W_{DEP} \quad (6.17)$$

The close similarity between the shapes of Figures 6.6 and 6.7 and the similar numerical constants linking the gate and substrate voltages in each suggests that the channel current density must be similar in each vertical element of the active layer.

SCHOTTKY BARRIER VOLTAGE

Figure 6.6 The relationship between the gate and substrate voltages required to produce a given channel current

Figure 6.7 The relationship between the gate and substrate voltages required to produce a given channel thickness

This is confirmed by the results of Figure (6.8) which show the relationship between drain current experimentally measured as a function of gate voltage and the active layer thickness calculated as a function of gate voltage. The relationship breaks down when the gate voltage approaches pinch-off where the current density decreases.

The reduced current density near the substrate interface corresponding to the near pinch-off condition can be explained in terms of lower carrier concentration in this region. This is due to out diffusion of electrons from the highly doped epitaxial region into the substrate and a chromium concentration diffusion tail forming in the active layer during epitaxial growth and a corresponding increase in resistivity over this region. These results are in agreement with the results predicted by Zuleeg and Lehovic [50] who have used C-V plots to predict the characteristics of the interface between the active layer and various substrate materials.

The preceding results have shown that changes in applied substrate bias can cause channel current variations. It has also been experimentally established in this work that an electron beam scanned across the top surface of a GaAs FET can induce changes in the back contact potential. An example of this was shown in Figure 4.1. The induced bias measured at the substrate varied between approximately -0.92 volts maximum when the beam was on the gate pad to about +0.38 volts with the beam on the drain metal.

Figure 6.8 Relationship between drain current and active channel thickness.

A comparison of the plots of change in drain current and substrate voltage as a function of the beam position show that the drain current decreases when the induced substrate bias is negative and increases when the substrate bias is positive. The stimulated drain current was a maximum when the beam was in the vicinity of the channel even though the induced substrate voltage was virtually zero at this position. This can be explained by the drain current increase being caused by two mechanisms which are additive. These are the long and short range effect mechanisms. The change in active channel thickness is thought to be partly responsible for both long and short range effects. The long range effect is believed to be caused by beam induced changes in the substrate potential which changes the extent of the back gate depletion region over a large part of the channel. The EBICC only changes slowly with distance. The short range effect however is centred around the position of the beam and only extends a short distance with a rapid fall off in intensity. It is attributed to changes in substrate trapped charge density which acts as if it were a positive back gate bias and to increased substrate current as described earlier in section 6.3.2.

These effects will be considered in Chapter 9 and 10 in more detail.

6.6 The contact region

There is little experimental evidence to indicate that the ohmic contact regions play a significant role in determining the behaviour of the device under electron beam stimulation apart from attenuating the beam when it is directed onto them. This reduces the energy deposited into the gallium arsenide and causes less beam stimulation than would otherwise occur. Allowance can be made for the effects of the contacts by converting the thickness of the contacts into an 'effective' thickness of gallium arsenide by multiplying by the ratio of the density of the contact to the density of gallium arsenide or by assuming an attenuation factor $A(Y)$ as has been done in the empirical models.

The large and rapid variations in the induced drain current curves correlate directly with the uneven contact metal thickness in the experimental devices. The black spots in the SEI images of the contact regions (e.g. Figure 4.2) have been shown by microprobe analysis to correspond to areas where the gold is missing.

In the absence of evidence to the contrary it has been assumed throughout this work that the injection efficiency of the metal contacts into the active layer is unaltered by the beam. However, there is evidence that the injection efficiency into the semi-insulating substrate is enhanced by the beam and this is thought to be an important factor in

the long range effect. This is described in more detail in Chapter 10.

6.7 Conclusions

In this chapter the possible influences of the electron beam on the FET channel have been reviewed in terms of how the beam affects the various parameters of an elementary model of the channel.

It has been shown that some possible explanations can be eliminated in addition to the photon mechanisms already rejected in Chapter 4. The magnitude of the beam induced changes in active channel carrier concentration and change in Schottky barrier depletion layer width have been found inadequate to explain the observed effects. However, the magnitude of beam induced changes in the substrate caused by increased carrier concentration and photoconductive gain, make increased substrate conductivity a possibility although the simple model developed in this chapter predicts too great a dependence on drain voltage and beam current.

The results of experiments which indicated that the beam induced gate current and channel current mechanisms are essentially independent have been reviewed. The results have indicated that simple increased substrate conductivity cannot explain the observed changes in channel current with the beam at a distance from the channel so that there must be at least three beam stimulation mechanisms acting in a

FET; one causing gate current stimulation and the others resulting in channel current changes.

In the next chapter the experimental evidence to show how the gate current is stimulated will be presented and a detailed model developed to explain the more significant results..

The more complex EBICC processes are studied in Chapters 8 to 10. In Chapter 8 the increase in channel current as a function of beam parameters is investigated. Chapter 9 is concerned with the changes in channel current which occur when the beam is at a considerable distance from the channel. The experimental evidence for this effect will be presented in terms of its dependence on device parameters. Theoretical and empirical models will be developed in Chapter 10.

CHAPTER 7

ELECTRON BEAM INDUCED GATE CURRENT

7.1 Introduction

The results of studies of how the electron beam current influences the gate Schottky barrier leakage current are presented in this Chapter. A model is developed to explain how the gate current changes as a result of beam stimulation. It includes the effects of gate voltage, beam position, beam current and accelerating voltages. The knowledge of the generated carrier diffusion lengths in active and semi-insulating GaAs is essential to the model. The results of experiments to obtain the diffusion lengths are included. Following step by step development of the model, the experimental results are compared with the prediction of the model for specific conditions.

Finally, the value of the electron beam analysis technique to study defects in Schottky gates is discussed.

7.2 The Schottky gate characteristics

The gate electrode on a GaAs FET of the type used in this work consists of a 1 micrometer long and 500 micrometers wide aluminum Schottky barrier. There is no passivating layer and no diffused guard ring around the barrier. Furthermore the edges of the gate can extend

about five micrometers onto the substrate at each end of the channel. The contact pad is situated on the substrate and has an area approximately 25 times greater than the Schottky barrier and is connected by a narrow aluminum stripe to the active gate region. (Figure 2.1) It would therefore be expected that the gate diode characteristics would be poor. However, this is not the case.

Figures 7.1 and 7.2 show the forward and reverse leakage characteristics of a typical device. Measurements were made in the test circuit shown in the Figure 5.2 with the device in the SEM. Similar results were obtained using a Tektronix 576 curve tracer.

Forward characteristics are good with the parameter m in the diode equation (7.1) having a value of 1.74

$$I_{GS} = A^* T^2 \exp \left(\frac{q V_{GS}}{m k T} \right) \quad (7.1)$$

No signs of the abnormal values of m observed in earlier devices were observed.[3] A built-in potential of 0.87 volts has been calculated using the thermionic emission theory for Schottky barriers [6] and the appropriate physical values. This differs from the reported value of 0.82 for the built-in voltage on aluminum-n-type gallium arsenide.[6] The 0.87V value has been used in depletion layer calculations throughout this work.

Figure 7.1 Forward Schottky barrier gate characteristics of a HP GaAs FET with and without beam stimulation

Figure 7.2 Reverse leakage characteristics of the HP FET depicted in Figure 7.1 with and without beam stimulation

The reverse leakage characteristics show a smooth onset of breakdown with no discontinuities, indicating that the barrier has no regions of premature breakdown or surface channelling. Figure 7.2 also shows that the reverse leakage current, when the device is stimulated by a 0.1 nA electron beam, is not significantly different in shape from that expected for a photostimulated diode.

It is assumed, therefore, that changes in gate current are likely to be genuine changes in the Schottky barrier and not the result of changes in parasitic leakage paths.

7.3 The effect of beam position

The increase in gate current resulting from beam interactions with the Schottky barrier is very sensitive to the beam location.

Figure 7.3 shows how the gate current changes as the beam is scanned from edge to edge of the device (including the entire gate width) with the drain, source and substrate grounded, at several gate biases. At the far left of the scans the beam is a sufficient distance from the gate metal that the measured gate current is the same as that of the unstimulated device. The gate current rises rapidly to a peak as the beam moves over the mesa step and onto the active region.

Figure 7.3 The effect of different gate voltages on beam induced gate current as a function of beam position along the gate

Figure 7.4 The effect of the extra metallization at the mesa edge on electron beam induced gate current

On this particular device, the stimulated gate current falls to a minimum before rising to an almost constant value in the middle section of the device. At the center of the gate (at the junction with the metal leading from the gate contact) there is a small peak. The gate current follows essentially the same changes in reverse order as the beam moves towards the right edge of the device. This result is typical of several obtained although each device has characteristic fluctuations and differences in sensitivity to beam current which are attributed to local abnormalities and the magnitude of the unstimulated gate current. Several points are noted. First, the effect occurs at all gate voltages although the effects of the beam are most noticeable at zero or low gate voltages. At higher gate voltages the natural leakage currents equal or dominate the beam stimulated current. As the induced gate current occurs at zero gate voltage, the induced current is photovoltaic.

Secondly, the sharp peaks at the edge of the mesa are attributed to a geometric effect which widens the depletion layer and therefore provides more efficient current collection. This is illustrated in Figure 7.4. At the mesa edge the ratio of surface gate metal to volume of active semiconductor is greater than in the centre of the device. This region has more gate charge per unit volume than the remainder of the device, so that the depletion layer locally widens. This effect is the opposite of that in shallow

diffused planar junctions where the depletion region narrows when there is junction curvature.[21] The small peak at the midpoint of the gate occurs because of a similar sensitive site nearby where the metal track to the gate contact pad crosses the mesa edge. A large peak is observed when the electron beam is placed on or near this step. Edwards [45] has observed similar sensitive regions using a laser spot adjacent to the gate metal to stimulate the gate current and has confirmed that the mechanism is photovoltaic.

It should be noted that a relatively large beam current for an SEM was used in this experiment (3nA) at 25 KV, yet the measured gate current was less than the beam current for most of the device. Much of the beam current was not collected by the gate junction but was dissipated either as backscattered electrons, secondary electrons or current to ground through the substrate

The low collection efficiency of the barrier and hence small increases in gate current are attributable to a short generated carrier diffusion length, relatively deep penetration of the beam into the semiconductor at 25 KV, and the low gate voltages and high doping levels in the active layer which create narrow depletion regions and hence inefficient collecting regions.

The various parameters affecting the magnitude of the induced gate current are discussed in the subsequent sections.

7.4 Effect of beam current on gate current

The EBS diode work [27,28] and preliminary results on GaAs FETs showed that increases in gate current were related to the incident electron beam current. Work performed to study this relationship is described here. The overall line scans of the type shown in Figure 7.3 indicated that some areas of the gate had a relatively homogeneous response to the electron beam. One such area was selected for detailed measurements of gate current as a function of the beam current for various accelerating voltages. Gate-source voltage was maintained at one volt throughout the experiments. The normal unstimulated leakage current at this voltage for the device used in these tests was approximately 1.3 nA. Beam current was measured by aiming the electron beam into a small Faraday cup attached next to the transistor on the sample holder. The beam current was measured by the same HP425A electrometer-picoammeter used to measure gate current. The value of the accelerating voltage was assumed to be accurate. Separate experiments indicated that the accelerating voltages as defined by the switch positions were consistent within 1%, however their absolute accuracy could not be determined.

After setting the beam current using the SEM condenser lens control, the 'spot' beam was directed onto the selected position on the gate metal and gate current was measured. Returning the beam to the same position was simple because

the stationary spot deposited a small amount of contamination on the gate metal that was visible on the SEM viewing screen. This contamination was caused by the electron beam which chemically breaks down diffusion pump oil. For the next measurement the beam was placed within 0.1 micrometers of the contamination spot. Figure 7.5 shows results for accelerating voltages between 8 and 35 KV. In all cases a linear relationship is clearly present over a beam current range of 0.01 nA to 0.5 nA.

Thus the relationship

$$I_{GS} = c I_B \quad (7.2)$$

has been experimentally established for GaAs FETs with c a complicated function of the accelerating voltage. This relationship is considered next.

7.5 Effect of accelerating voltage on gate current

The simple proportionality of device current to accelerating voltage for a constant beam current observed for EBS diodes [27] does not apply to GaAs FETs. This can be seen from the results shown in Figure 7.6, which shows the increase in gate current as a function of accelerating voltage for a beam current of 0.5 nA located on the gate metal. This section describes the work to investigate this relationship.

Figure 7.5 Measured increase in gate current as a function of electron beam current for various accelerating voltages

Figure 7.6 Measured increase in gate current as a function of accelerating voltage

It can be seen from Figure 7.6 that, initially, there is little induced gate current until a threshold value of the accelerating voltage of approximately 8KV is reached after which gate current rises rapidly. After peaking, the gate current decreases slowly. In similar experiments with the beam placed just off the gate metal there was no accelerating voltage threshold, indicating that the threshold results from attenuation of the beam by the gate metal. The sharp rise in current between the threshold and the peak approximates the EBS diode model.

Siekanowitz et al [27] in their development of the EBS diode model concluded that the induced current is proportional to the beam energy. Each beam electron is assumed to generate electron-hole pairs with an average energy of 4.6eV for gallium arsenide so that the induced current in the diode is proportional to the energy of the accelerated electrons divided by 4.6eV.

$$I_{\text{DIODE}} = \frac{V_B I_B}{4.6} \quad (7.3)$$

The peaking and subsequent decrease in gate current in the FETs tested in this work must result from less efficient carrier generation at higher beam voltages or fewer carriers reaching the collecting Schottky barrier gate. There is no evidence for the former, so far as the author is aware, in EBS diodes where measurements have been made to 50 KeV. The

latter would occur if the electron beam penetration range substantially exceeds the generated carrier diffusion length because fewer carriers per incident electron would reach the collecting Schottky barrier. Under circumstances where the generated carrier diffusion length is short, the overall induced gate current could decrease with increasing accelerating voltage. The experimentally measured diffusion lengths reported in the next section make this proposition feasible. The overall gate current increase depends upon the relative sensitivities to accelerating voltage of the terms in the model developed in Section 7.7.

7.6 Diffusion length measurements

Several workers have shown that the measurement of true diffusion lengths using electron beams [18, 19] is difficult and that anomalous results will occur if corrections are not made for surface recombination velocity and absorption coefficients. [20] Corrections must also be made if the diffusion length is short compared to the collecting junction depletion width. The assumption is usually made that the source of carriers is a point situated some depth from the surface. [18] However, in practice the beam energy is dissipated over a depth range that may be large compared with the minority carrier diffusion length.

Fortunately, an accurate value of the diffusion length is not required in this work. The measured "effective

diffusion length" is adequate because it is a practical measurement of the proportion of the beam stimulated carriers reaching the collecting junction as a function of distance along the surface. When carriers are generated within the semi-insulating layer below the Schottky barrier, they travel to the collecting junction first through the semi-insulating material and then through the active layer. By measuring the induced beam current as the beam slowly traverses from the source to the drain across the channel, data are accumulated which leads to the effective diffusion length. The initial measurements are reproduced in Figure 7.7 together with a SEI trace for reference.

Figure 7.8 is a semi-logarithmic plot of the induced gate current decay rate on the drain side. The data closely approximate an exponential decay rate despite the absence of corrections and justifies the use of an effective diffusion length in the subsequent model. The measured effective diffusion length is 0.26 micrometers.

An estimate of the effective diffusion length for a region of semi-insulating substrate alone has also been obtained. This was done by scanning the beam along the direction of the gate width as it crosses over the mesa edge from the semi-insulating substrate to the active area. This region corresponds to the site of the gate current peaks of Figure 7.3. The results shown in Figure 7.9 were obtained at much higher magnification with the beam held

Figure 7.7 Gate current increase and SEI linescan as the beam is scanned from source to drain

Figure 7.8 Semilogarithmic plot of beam induced gate current with distance from the gate edge towards the source

Figure 7.9 Change in gate current as beam is scanned across mesa edge for several gate voltages

stationary at a number of points for four different gate voltages (0, 0.5, 1.0, 2.0V). By holding the beam stationary and allowing the gate current to stabilize, non equilibrium effects of slow trapping states in the substrate were eliminated. The effective diffusion length is approximately 1.4 micrometers.

The edge of the active area (assumed to be the middle of the mesa) was used as the zero reference for the horizontal axis which corresponds to position measured along the width of the gate. The shape of the curve of induced current versus position of the beam corresponds to a relationship of the form

$$I_{GS}(z) = I_{GS}(0) \exp\left[-\frac{z}{L^*}\right] \quad (7.4)$$

where the gate current at $z=0$ is the induced gate current at the edge of the active area, the left hand side of the equation is the current at a distance z onto the semi-insulating layer, and L^* is the effective diffusion length of the induced carriers.

The change in shape found in Figure 7.9 when the edge of the gate metal is reached results from the effects of greater energy deposition in the semi-insulating substrate as the beam is no longer attenuated by the gate metal.

The similarity in the shape of the curves for the different gate voltages shows that the carrier diffusion

mechanism is independent of the voltage on the gate. This may be because the edge effects described in Section 5.3.2 ensure that the active semiconductor is fully depleted at the collecting region of the gate.

The downward slope in the curves between the mesa edge and the active region corresponds to an effective diffusion length of approximately 2 micrometers. This value is larger than the effective diffusion length obtained when the beam was on the substrate. It is believed that this is because carriers generated under the active layer are collected more efficiently than those generated beyond the mesa edge. The latter must pass close to the mesa edge which probably has a large surface recombination velocity.

7.7 Model of induced gate current as a function of the accelerating voltage

In this section a model is developed which explains the observed relationship between the induced gate current and the electron beam accelerating voltage.

7.7.1 Assumptions

- 1) The electron beam is assumed to impinge perpendicularly onto the samples from the -y direction so that penetration is in the +y direction as in Figure 7.10.
- 2) In the explanation of the model, the beam will be assumed to be far from perturbations to the induced gate

current caused by geometrical effects such as the edge of the mesa. It is, however, possible to model these regions by appropriate changes in parameter values.

3) The total deposited energy from the beam per unit time is proportional to the beam current at any specified accelerating voltage. All beam current electrons are assumed to have equal energy and beam current does not vary with time.

4) The average energy of the induced electron-hole pairs is independent of the energy of the primary electron which creates them. Only carriers which have an energy below the threshold energy required to create further electron-hole pairs will be considered.

5) All the beam energy is used to create electron-hole pairs which are assumed to have the threshold energy.

Assumptions 3 to 5 have been previously made for the EBS diode models [27].

6) The number of carriers generated at depth y in an element dy is assumed to be proportional to the deposited energy in that depth element.

7) The beam current electron-hole pairs spread out from the generation site evenly in all directions and do not interact with each other. Thus the proportion moving towards the Schottky barrier can be obtained from simple geometric calculations.

Figure 7.10 The four regions of the FET used in the model of gate current generation

Figure 7.11 a) Cross section of the simplified structure used in the model. b) Schematic view of the actual cross section

8) The proportion of carriers which reach the Schottky gate depletion region can be calculated by a simple exponential decay relationship characterized by the effective diffusion lengths, L^* which have been obtained experimentally.

9) The total number of generated carriers reaching the depletion region is the sum of the carriers reaching the depletion region from each depth element dy on the incident electron penetration path.

10) The total flux of carriers is not sufficiently great to create electric fields large enough to influence the diffusion behaviour of the carriers.

11) There is unimpeded flow of generated carriers across the semi-insulating to active layer interface. This assumption cannot be justified and will be discussed later.

12) For mathematical simplicity, all carriers generated at depth y will be assumed to come from a point on the beam penetration path. This assumption is not realistic physically, and probably is a reason why the model is in error at higher accelerating voltages.

13) The attenuating effect of the gate metal can be accommodated by replacing the aluminum in the model by an effective thickness of gallium arsenide.

14) Part of the beam current is lost as backscattered and secondary electron current. The fraction lost is assumed to be independent of beam voltage and is taken to be 0.3 of the beam current. [17]

15) A simplified structure is assumed for the model as shown in the cross section of Figure 7.11a. The structure of Figure 7.11b is closer to the real device structure. The two structures are essentially similar when the beam is on the gate metal. However, when the beam is off the gate metal there will be some additional error resulting from the extra gallium arsenide in the active layer where the trough for the gate has not been etched away.

7.7.2 Structure of the model

The incident electron beam is assumed to extend through four regions before being fully attenuated.

These regions are shown in Figure 7.10 and are:

Region 1 : The gate metal

Region 2 : The Schottky barrier depletion region

Region 3 : The undepleted active epitaxial layer

Region 4 : The semi-insulating layer.

The relevant characteristics of each region will be discussed in terms of the effects on the electron beam and the contribution each region makes to the gate current.

The beam induced gate current has two components. The first of these is the absorbed electron current in the gate metal of Region 1. The second is the contribution of all the electron-hole pairs which are generated within or diffuse into the Schottky barrier depletion region from Regions 3 and 4.

In the model the contributions from each region are separately calculated and added together to produce the total induced gate current as defined in equation (7.5)

$$I_{GS}(TOTAL) = I_{GS}(1) + I_{GS}(2) + I_{GS}(3) + I_{GS}(4) \quad (7.5)$$

The procedures adopted to obtain each component of the gate current follow a general pattern.

First, the thicknesses of each region are established. The thicknesses of the gate metal can be measured (Region 1). The depletion layer thickness, (Region 2) is obtained from the single sided step junction approximation for a Schottky barrier.[6] The thickness of the residual active layer (Region 3) is obtained by subtracting the depletion layer thickness from the total epitaxial layer thickness. This has been calculated from pinch-off voltage measurements and the one sided step junction approximation. Region 4 is defined as the penetration depth into the semi-insulating layer. It is obtained by subtracting the active layer thickness and the equivalent thickness of GaAs of the gate metal from the total penetration into GaAs calculated from equation (3.1). The GaAs equivalent thickness of the metal is discussed further when Region 1 is considered.

Once the thickness of each region has been established the proportion of the incident beam energy stopped in each region can be calculated using the Everhart and Hoff formula

(equation 3.2). To improve the accuracy of the model, Regions 3 and 4 are divided into appropriate sized depth elements (dy). The number of carriers generated in each depth element is then calculated. The fraction which diffuses towards the Schottky barrier is calculated using simple geometric factors defined in Figure 7.12. Finally, the number reaching the Schottky barrier depletion region boundary is calculated. All carriers reaching this boundary are assumed to generate gate current.

The regions will now be discussed in detail.

7.7.3 Region 1 : The gate metal

The gate metal of the experimental FETs is aluminum and is approximately 0.58 micrometers thick. As this region is metallic, not semiconducting, the contribution of this region to gate current consists only of primary electrons stopped in the aluminum. This contribution to gate current is small except for the lowest beam energies when most of the beam is attenuated by the metal. The metal however attenuates a significant portion of the beam at all beam voltages and reduces the energy reaching the other regions and hence it can significantly influence current generation in these regions.

The estimation of the attenuation can be greatly simplified if an equivalent thickness of gallium arsenide is mathematically substituted for the aluminum. A method to do

Figure 7.12 Geometrical relationship between the beam trajectory and elemental area $dxdz$ at depletion layer boundary

this has been described by Schumacher [22]. It has been experimentally established that the electron stopping power of a material is proportional to its density. Thus two materials will have the same stopping power if the products of their thickness and densities are equal. The aluminum can therefore be replaced in the model by an equivalent gallium arsenide thickness such that

$$d_{EFF}(GaAs) = \frac{\rho(Al)}{\rho(GaAs)} \cdot d(Al) \quad (7.6)$$

The induced gate current contributed by this region can now be calculated. Defining $Y(1)$ as the value of y in equation (3.4) for Region 1, by dividing the effective GaAs thickness of the metal by the penetration range,

$$Y(1) = \frac{d_{EFF}}{R_G} \quad (7.7)$$

so that the total fraction of the energy absorbed in Region 1 is

$$dE(1) = \lambda(Y(1)) \cdot V_B I_B (1-B) \quad (7.8)$$

where $\lambda(Y(1))$ is given by equation (3.2) and B is the electron backscattering factor. The fraction of gate current is therefore

$$I_{GS}(1) = \lambda(Y(1)) \cdot I_B (1-B) \quad (7.9)$$

7.7.4 Region 2 : The depletion region

The model postulates that all the energy absorbed in the depletion region contributes to the generation of gate current. The extent of the completely depleted region which is equal to the separation between $Y(2)$ and $Y(1)$, is derived from the single sided abrupt junction theory for the Schottky barrier.

$$W_{DEP} = \left[\frac{\epsilon \epsilon_0}{q N_D} (V_{BI} - V_{GS} - \frac{kT}{q}) \right]^{1/2} \quad (7.10)$$

The model therefore takes into account the applied gate voltage. The fraction of the beam energy absorbed in this region is calculated from the Everhart and Hoff equation (3.2)

$$dE(2) = V_B I_B (1-B) \int_{Y(1)}^{Y(2)} \lambda(y) dy \quad (7.11)$$

Each incident electron produces a large number of additional carrier pairs according to the Siexanowitz model for EBS devices (equation (7.3)) which all contribute to the gate current. The total current produced in Region 2 is therefore

$$I_{GS}(2) = \frac{V_B^2 I_B (1-B)}{4.6} \int_{Y(1)}^{Y(2)} \lambda(y) dy \quad (7.12)$$

This region produces a large fraction of the generated gate current because, unlike Regions 3 and 4, all of the carriers generated contribute to the gate current.

7.7.5 Region 3 : The active layer

This region is the active channel region between the edge of the depletion region and the interface of the epitaxial layer with the semi-insulating substrate. Only the carriers generated in this region which diffuse towards the depletion region contribute to the gate current. Of these, only the carriers which reach the depletion region without recombining actually produce gate current. Consider an element dy at a depth y below the depletion region but within the active epitaxial layer. The energy deposited in this region is

$$dE(y) = V_B I_B (1-B) \lambda(y) dy \quad (7.13)$$

This generates an increase in carriers per second at y

$$n(y) dy = \frac{V_B^2 I_B}{4.6q} \lambda(y) dy \quad (7.14)$$

These are assumed to diffuse outwards equally in all directions so that the number per second which would diffuse through an elemental area $dx dz$ positioned x from the centre line of the gate and z along the width of the gate as shown in Figure 7.12 will be

$$n(y, \theta) = \frac{n(y) dx dy \cos \theta}{4\pi r^2} \quad (7.15)$$

where dA is the area $dx dz$, r and y are given by

$$r^2 = x^2 + y^2 + z^2 \quad (7.16)$$

and

$$y = Y - Y(2) \quad (7.17)$$

and the angle θ is the angle between the y axis and the line joining the depth element dy to the centre of the elemental area dA .

The model assumes that the generated carriers decay exponentially with a characteristic diffusion length $L(3)$ in Region 3. The number of carriers per second arriving at the element dA is therefore

$$n(y, \theta, dA) = n(y) \frac{dx dz \cos \theta}{4\pi r^2} \cdot \exp \left[-\frac{r}{L(3)} \right] \quad (7.18)$$

from the depth element dy .

The total gate current generated by diffusion into the gate depletion region from element dy is therefore

$$I_{GS}(y)dy = \int_{-\frac{z}{2}}^{\frac{z}{2}} \int_{-x}^x \frac{(1-B)I_B V_B^2}{4.6} \frac{\lambda(y) \cos \theta}{4\pi r^2} \exp\left(-\frac{r}{L(3)}\right) dx dz \quad (7.19)$$

The practical limits of x and z are illustrated in Figure 7.13 and correspond to the coordinates of the four corners of the rectangle formed by the gate on the active region.

This value is then integrated over the active region between $Y(2)$ and $Y(3)$ to give the entire gate current generated by the beam in the active region

$$I_{GS}(3) = \int_{Y(2)}^{Y(3)} I_{GS}(y) dy \quad (7.20)$$

The integrals in equations (7.19) and (7.20) have been solved numerically in the program IGVEB, described in section 7.7.7.

7.7.6 Region 4 : The substrate

This region absorbs the majority of the beam energy

Figure 7.13 Cutaway section showing coordinates used in this model of the depletion layer

at all except the lower accelerating voltages. It is treated in a very similar way to Region 3. Carriers generated by the beam are assumed to diffuse to the active layer with a characteristic diffusion length $L(4)$. Carriers that reach the interface then diffuse towards the barrier with diffusion length $L(3)$. It is assumed that the high-low junction concentration gradient does not impede carrier flow into the active layer.

The mathematics of the model for Region 4 are similar to those of Region 3. Equations (7.13) through to (7.17) are used to describe the number of carriers diffusing towards area element dA from dy per second.

The number reaching dA per second is given by

$$n(y, \theta, dA) = n(y) \frac{dx dz \cos \theta}{4\pi r^2} \exp \left(-\frac{r(3)}{L(3)} - \frac{r(4)}{L(4)} \right) \quad (7.21)$$

where $r(4)$ is the distance the carriers travel in Region 4 and $r(3)$ is the distance they travel in Region 3 as they diffuse from dy to dA . The total distance they travel r is given by

$$r = r(3) + r(4) \quad (7.22)$$

The total gate current generated in Region 4 is given by replacing the simple exponential term in equation (7.19) by the more complex term in equation (7.21).

$$I_{GS}(y) dy = \int_{-\frac{Z}{2}}^{\frac{Z}{2}} \int_{-X}^X \frac{(1-B) I_B V_B^2}{4.6} \frac{\lambda(y) \cos \theta}{4\pi r^2} \exp \left(-\frac{r(3)}{L(3)} - \frac{r(4)}{L(4)} \right) dx dz \quad (7.23)$$

Finally, integrating for all depth elements in Region 4

$$I_{GS}(4) = \int_{Y(3)}^{R_G} I_{GS}(y) dy \quad (7.24)$$

The total induced gate current is the sum of the contributions from each of the regions (equation (7.5)).

The predictions of the model are presented and compared with the experimental results in section 7.8.

7.7.7 The computer program IGVEB

The program, developed in Fortran 4, to calculate the values of gate current as a function of beam voltage, current and position, is included as Appendix 2. The program closely follows the procedures described for the four regions.

It was necessary to divide the depth elements into 0.01 micrometer sections for the active layer and 0.1 micrometer sections for the SI layer to achieve the necessary accuracy because the elements should be small compared to the diffusion lengths.

The area elements also had to be smaller in each direction than the diffusion length. This meant that very lengthy and repetitious calculations were unavoidable. In order to reduce computing time, only area elements contributing one percent of the value of the closest area element to the depth element dy were counted. When the contribution of an area element dropped below one percent, calculations for area elements further from the beam axis were stopped.

By placing the beam at the centre of the gate, the computing time could be reduced by almost a factor of four by invoking symmetry.

The full program is capable of predicting the induced gate current at any beam position, on or off the active layer. However, this is very expensive in practice because of the larger number of computations caused by the small area and depth elements. It is recommended that for future work, more sophisticated programming techniques be adopted including analysis to obtain the optimum dimensions for area and depth elements. It is anticipated that these will vary with distance from the beam rather than be fixed as at present. A printout from the simplified version of the program IGVEB2 is included as Appendix 3.

7.8 Corrections for recombination at ohmic contacts

Above a certain accelerating voltage, a geometrical factor which has not been considered so far results in the induced gate current being overestimated. (Assumption 12 in section 7.1.)

This section shows how a correcting factor, f , can be derived which can be applied to improve the predictions of the model.

In Figure 7.14a it can be seen that the hemisphere in which it was assumed that carriers are generated overlaps the source and drain contacts when the beam is central between the source and drain. It has been explicitly assumed that the carriers generated at any particular depth act as if they come from a point directly below where the beam penetrates the surface. If this assumption is relaxed and the carriers are assumed to be generated uniformly throughout the volume, then it can be seen that the fraction generated below the ohmic contacts are likely to recombine at the ohmic contacts and not contribute to gate current.

The accurate calculation of the proportion of generated carriers reaching the gate depletion region is a complex three dimensional problem. To avoid mathematical complexity, a simple one dimensional approximation has been made together with geometrical simplifications for the case where the beam penetrates midway between the source and drain and away from the extremes of the gate width.

Figure 7.14 a) The total volume in which carriers are generated and b) the fraction from which carriers reach the depletion region

Figure 7.15 The correction factor f as a function of accelerating voltage

When the radius of the hemisphere of generation extends beyond the metal contacts as shown in Figure 6.1, only the carriers within the volume whose top surface is ABCD are assumed to contribute to gate current. This volume can be approximated without serious error to half a cylinder of height L as shown in Figure 7.14.

Thus the fraction of the carriers generated, f , contributing to gate current is given by

$$f = \frac{\pi}{2} r^2 \cdot \frac{3}{2\pi r^3} \cdot L = \frac{3L}{4r} \quad (7.25)$$

where L is the separation between source and drain contacts, and the value of r is obtained from equation (3.3):

Figure 7.15 shows how the value of f varies with accelerating voltage for a drain to source separation of 3 micrometers. The value of f is only meaningful when it is below unity. A value above unity indicates that the generating volume is such that all carriers are generated between the source and drain.

In the next section the predictions of the model with and without this correction will be compared with the experimental results.

7.9 Comparison with experimental results

The model reproduces the important features of the experimental results provided that suitable values for the generated carrier diffusion lengths are selected and the correction for the presence of source and drain contacts is made.

There is good similarity between the experimental results and the uncorrected model for accelerating voltages up to about 15KV where the model closely follows the electron beam stimulated diode model and the carriers are generated mainly in the depletion region.

The experimental results and uncorrected model predictions disagree above 15KV as the influence of the substrate (Region 4) increases. This is particularly apparent when relatively long diffusion lengths are used for the SI layer. With a diffusion length of 1.4 micrometers, the model predicts no gate current peak until well beyond 40KV whereas a peak exists at 17KV. Figure 7.16 shows the contributions of Regions 2, 3 and 4 for the case where the diffusion length is 1.4 micrometers.

At low accelerating voltages there is little or no induced gate current. The model predicts a sharp increase in gate current at about 6KV when the beam penetrates the metal. The experimental results show no significant increase until 8KV which indicates either that the measured

Figure 7.16 The uncorrected contribution of the four regions of the model to total gate current as a function of accelerating voltage

value of aluminum thickness is low or that the value of the penetration range is in error at low accelerating voltages.

The former is possible because of the difficulty in estimating the thickness accurately as the aluminum is recessed in a trough in the channel. However, the second is more likely as the Martinelli and Wang penetration range equation(3.2) adopted for the model predicts a greater range than the other formulae.[22,24] The difference is most significant at low accelerating voltages. It should be noted that the lowest accelerating voltage used by Martinelli and Wang was 3KV and that range was defined as the first evidence of penetration. This definition tends to give greater values of range than the other methods which compensate for enhanced diffusion. This error in the model is not considered fundamental and the reason for the discrepancy could be resolved with further experimentation.

In Figure 7.17 the predicted gate current increases for semi-insulating layer diffusion lengths of 0.01 to 1.4 micrometers are plotted. It can be seen that there is good agreement between the uncorrected model and experiment until the maximum gate current increase is reached when the diffusion length is set at 0.25 micrometers. At this diffusion length the uncorrected model predicts a shallow peak at a similar accelerating voltage to the experimental value. The peak becomes increasingly sharp as the diffusion length is made shorter but the rate of decay never matches

Figure 7.17 Total beam induced gate current for four different diffusion lengths in Region II as a function of accelerating voltage

the experimental value and the location of the peak moves to lower accelerating voltages. The reason the 1.4 micrometer diffusion length gives erroneous results is not known for certain. Several explanations are possible.

The 1.4 micrometer length was obtained in an area of the device where there was no overlying epitaxial layer. When diffusion lengths were measured at 15KV in the presence of an epitaxial layer, the effective diffusion length obtained was 0.26 micrometers. (Figures 7.7 and 7.8) At 15KV the beam penetrates almost 0.9 micrometers into the semi-insulating layer so that use of 0.25 micrometers for both the active and semi-insulating layer diffusion lengths has experimental justification.

A second possibility is that the electrons and holes produced in the substrate must diffuse into the depletion layer across a high-low junction which will hinder the flow of electrons. This mechanism is not included in the model. The holes however would be expected to cross this barrier more easily but enter a region of higher electron concentration where they would recombine very rapidly as GaAs is a direct recombination semiconductor.

The reason the induced gate current was experimentally observed to decrease more rapidly than the model predicts can be explained by the correction to the model described in section 7.8.

When the correction is applied by multiplying the total induced gate current by the geometrical correction factor f , very good agreement is achieved between the model and the experimental results for the higher accelerating voltages as can be seen from Figure 7.18. Agreement is within 15% over all accelerating voltages apart from the error at low voltages resulting from the metallization which has already been discussed.

The effect of gate voltage on the induced current can be seen from Figure 7.19 which shows the predicted gate current for four gate biases including the unbiased condition. The effect of changing the gate voltage is not large and results from an increased contribution from Region 2 and less from Region 3 as the gate voltage is increased.

A set of experimentally obtained values for the increase in gate current is presented in Figure 7.20. This confirms that the induced gate current does increase slightly with increasing gate voltage. A large increase in gate current occurs above the pinch-off voltage ($-1.8V$). Beyond pinch-off, the Schottky barrier depletion layer extends into the semi-insulating substrate and expands rapidly with increasing gate voltage. Thus Region 2 of the model now becomes much larger and many carriers that would have recombined before reaching the depletion region are now generated within this region and contribute to gate current.

Figure 7-18 The agreement between the experimental result and the uncorrected and corrected versions of

Figure 7.19 Predictions of the model for different gate voltages

Figure 7.20 Sensitivity of beam induced gate current to gate voltage at different accelerating voltages.

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At the lower gate voltages, the greatest gate current occurs at 25KV rather than at about 17KV as predicted by the model and experimentally confirmed on another device. This is not fully understood but is probably related to inaccuracies in the control of the beam current and errors in the placement of the beam. It should be noted that at gate voltages beyond pinch-off, the gate current increases most at the higher accelerating voltages.

7.10 Conclusions

The good agreement of the model with the experimental results makes it worthwhile to review the information gained

Firstly, from Figure 7.16 it can be seen that most of the induced current can be accounted for by the carriers generated in the depletion region and that those carriers generated in the substrate do not contribute significantly to the gate current. This means that the carriers generated in the substrate do not reach the depletion region unless the device is pinched off. Either they cannot surmount the high-low junction barrier or this region causes heavy recombination.

Secondly, the edges of the actual regions by the mesa step are more sensitive to the electron beam than the centre. This is almost certainly caused by the wider depletion region at the edges caused by the larger area of gate metal per unit volume of active layer near the mesa

edge. The model shows that when the depletion layer is wider as a result of higher gate voltages, more induced gate current is expected.

The wider depletion regions near the mesa steps imply that the edge of the channel is more nearly pinched off than the middle of the device so that less channel current will flow near the edges of the active layer. This effectively builds in protection against irregular channel current flow near the mesa which could have been the cause of noise or poor gate control.

The best agreement between theory and experiment occurs when the diffusion length in the substrate is the same as in the active layer and this occurs at a value close to the measured composite diffusion length of 0.26 micrometers.

With these values the model correctly predicts the following:

- 1) the point at which the gate current starts to rise rapidly as the beam penetrates the gate metal within 2KV.
- 2) the rapid rise in gate current caused by generation in the depletion region.
- 3) the peaking and slow decline of gate current as a larger proportion of the energy is deposited deeper into the semiconductor.
- 4) the more rapid decline in gate current at higher beam voltages caused by rapid recombination at the ohmic contact rather than diffusion to the gate.

5) the magnitude of the induced gate current to within 15% and the accelerating voltage at which the gate current peak occurs over almost the complete range of accelerating voltages.

6) the sensitivity of the effect to gate voltage.

The model is capable of predicting the induced gate current for any combination of epitaxial layer thickness, gate voltage, active and semi-insulating diffusion lengths. It is also in principle able to predict the induced gate current for any beam position.

In the next chapter the effect of the beam on the channel current is discussed. The knowledge of the device properties obtained from the induced gate current model is used in explaining some of the observed effects.

CHAPTER 8

BEAM INDUCED CHANNEL CURRENT CHANGES (1)

8.1 Introduction

In this and the next chapters the results of experiments designed to characterize the effects of the electron beam on the channel current are described. These effects can be summarized by the expression

$$\Delta I_{DS} = \Delta I_{DS}(L) + \Delta I_{DS}(S) + \Delta I_{DS}(t) \quad (8.1)$$

where L, S and t symbolize the contributions of the long and short range effects introduced in Chapter 6 and any time dependent mechanisms. In this chapter, experimental results are presented which show how the induced channel current (measured as changes in source current) varies with beam voltage, beam current, device bias and beam position. The complications in resolving the spatial dependence of the beam stimulated channel current caused by geometrical effects and differing beam attenuation by the metallic contacts are considered. Methods of overcoming these problems will be described.

8.2 Effects of large ohmic contacts

The interpretation of EBICC effects is complicated by

the fact that the drain current measured flows through the entire active channel but the region where beam-enhanced current flows may be considerably smaller. The short range effect has been found to extend over a region approximately 80 micrometers in diameter whereas the long range effect influences drain current over the entire 500 micrometer gate width of the HP devices.

Interpretation is further complicated by the gate metal attenuating the beam and by the geometry of the contact metal which makes the induced current sensitive to the beam position. Corrections must therefore be made when attempting to interpret results of how the induced current varies with distance. These complications will be considered in more detail in the next chapter. It will be shown that one effect can sometimes be isolated by careful experimentation and selection of the beam position.

8.3 Reducing the effects of device geometry

In normal two dimensional FET models, channel current is assumed to flow from source to drain homogeneously that is, each width element dz between the source and drain electrodes is assumed to carry an identical current $dI(z)$. However, when the electron beam acting on the device alters the channel current, the homogeneous current flow conditions are disturbed. The current flowing in each element will depend on the beam position and on the current mechanisms

involved but only the total current from all the width elements can be measured. This gives no direct information on the current distribution between the elements. Nevertheless, measurement of the changes in the total channel current as a function of beam position can, in principle, yield information on the current flow in individual elements. The actual achievement of this may be a very difficult and lengthy process, because of the many experimental variables. However, careful selection of the beam position can eliminate some of the variables and lead to approximate but general relationships between the induced current and the beam position or device parameters which are independent of individual device geometries.

For example, location of the beam on the channel midway between the source and drain but distant from the edge of the device yields results with an almost constant long range component. Advantage can be taken of the two separate source electrodes by monitoring each source current separately. The extent of the short range effect, its region of influence (ROI), can be estimated by moving the beam along the gate width across the device centre so that the distribution of the total induced current between the two sources will change.

The magnitude of the long range component of EBICC flowing into one source can also be studied as the beam is moved along the channel towards the monitored source. In

this example the potentials of the gate metal and the underlying channel are constant and are known accurately.

More information on the long range effect alone can be obtained by placing the beam on the semi-insulating substrate in line with the gate but well beyond the active region so that any short range effect can be safely neglected.

8.4 Estimating beam attenuation effects

The deposited metal layers forming the contacts have a significant effect on beam induced current and make the results sensitive to device geometry and manufacturing technology. The two areas of concern are the aluminum Schottky barrier and the gold-germanium-nickel ohmic contacts. Both types of metal attenuate the beam so that less beam energy reaches the semiconductor per unit time in metallized regions than in unmetallized regions. The reduction in absorbed energy can be calculated provided that the metal composition and thickness are known accurately, by using equation (3 2) to determine the energy absorbed in the metal and making an appropriate correction for material density. This correction is easy to make for the aluminum gate metal but the source and drain contacts are inhomogeneous on a microscopic scale and the individual thicknesses of the several layers of metal are not known accurately.

For this reason an alternative technique has been used whereby the measured channel current changes are corrected to allow for the contacts. The change in induced current as the beam crosses an interface was measured at the various boundaries and the appropriate additional current added for the ohmic contact regions. Examination of the line scans across the ohmic contacts in Figure 4.1 shows that the induced current fluctuates rapidly over short distances. This is attributed to the uneven contact alloying processes. Comparison of these results and the appropriate secondary electron image (e.g. Figure 4.2) shows that the regions of greater induced current correspond to the black areas of the secondary electron image and these have been shown by X-ray microprobe analysis to be where gold is absent or present in reduced quantities. The regions in the contacts where the induced current is least correspond to regions of greatest gold concentration and are relatively homogeneous. Thus the shape of the induced current curve is best approximated by the locus of the points of least induced current. An attenuation factor $A(Y)$ is used to correct the impinging beam energy for the attenuation of the contact metal in the empirical models. A value of $A(Y)$ is obtained from the steps in characteristics of linescans such as Figure 4.1 at interfaces where metal contacts end. The error introduced by changes in the backscattering factor are small and are absorbed in the value of $A(Y)$.

8.5 The beam position

8.5.1 The beam on the substrate

A series of experiments was performed to study the response of the channel to a fixed beam located on the substrate sufficiently far from the channel that the short range effect was insignificant. The beam was located in line with the gate stripe approximately 65 micrometers beyond the mesa step in the gate width direction. The transistor was operated with 2V drain bias and 0.5V negative bias on the gate. The induced channel current was measured at accelerating voltages between 10KV and 39KV using beam currents between 0.1nA and 10nA.

A series of calibration curves was first obtained to determine the correct condenser lens setting to give the required beam current at each accelerating voltage. The beam was then moved onto the device. Care was taken to avoid scanning the beam over the active region to minimize errors resulting from charge trapping effects with long time constants in or near the channel. This made precise location of the beam difficult and minor differences in beam position probably occurred at different accelerating voltages and caused some scatter in the results.

The induced channel current increased with both beam current and accelerating voltage, the increase, however, is non linear. Figure 8.1 shows that the channel current appears to increase as a function of the square root of the

Figure 8.1 Increase in channel current versus square root of beam current when the beam is on the substrate

beam current for various accelerating voltages. Figure 8.2 shows that the channel current also appears to increase as a function of the accelerating voltage which is plotted to the power of 1.5. Both power law relationships were established from log-log plots.

The results indicate an empirical relationship of the form

$$\Delta I_{DS}(L) = a V_B^{3/2} I_B^{1/2} \quad (8.2)$$

where the constant a depends on the individual device, the bias conditions, and the backscattering fraction. Figure 8.3 affords a measure of the generality of this relationship as it includes all the measured points. The reason for this relationship is not yet understood.

8.5.2 Beam on the active area

The beam was moved to a fixed point on the gate metal approximately mid way along one of the source electrodes where the beam stimulated channel current consists of a small long range component and a much larger short range component. Positioning the beam near the centre of the source electrode ensures that the short range current contribution is maximized and that slight errors in position will not produce significant changes in channel current.

Experiments described in Chapter 9 will show that the short

Figure 8.2 Channel current increase versus accelerating voltage to the power of 1.5 when the beam is on the substrate

Figure 8.3 Relationship between channel current increase and beam parameters when the beam is on the substrate

range effect extends approximately 40 micrometers from the beam whereas the beam was located over 100 micrometers from the edge of the source.

A further difference exists between this and the experiment described in the last section. Here, the gate metal absorbs a fraction of the incident beam energy whereas previously all the beam energy (apart from the backscattered fraction) was absorbed by the semi-insulating layer. With the beam on the gate metal, some energy is also absorbed in the depletion region and in the active layer.

The results of the calculations used in Chapter 7 to determine the fraction of the absorbed energy in the four regions of the device are reproduced in Figure 8.4. The fraction of the energy absorbed in the metal (Region 1) is greatest at low accelerating voltages and drops to about 4 per cent at 39KV.

The uncorrected results showing the beam induced channel current as functions of the beam current and the accelerating voltage are reproduced in Figures 8.5 and 8.6 which show that the induced current increases with both beam voltage and current but becomes less sensitive at higher energies. This tendency is more noticeable when the correction for absorbed energy is made.

The results include an unresolved component of the long range effect so that a simple relationship is unlikely to be determined from a purely experimental position. However,

Figure 8.4 Energy deposition in the four regions of the FET as a function of accelerating voltage

Figure 8.5 Increase in channel current as a function of beam current when the beam is on the gate metal

Figure 8.6 Increase in channel current as a function of accelerating voltage when the beam is on the gate metal

the results indicate a completely different relationship between induced channel current and beam parameters from the previous experiment.

Figure 8.7 shows the empirical relationship between the energy absorbed in the GaAs per unit time after correction for attenuation in the metal and the channel current increase. This has the form

$$I_{DS}(S) = k(V_B I_B)^{3.8} - I_{DS}(L) \quad (8.3)$$

where the constant k depends on device bias and n is between 3.5 and 4.7. Neither the physical significance nor the generality of this relationship have been established although order of magnitude similarities have been observed for devices from other manufacturers.

8.6 Effects of gate and drain voltage

The drain current was measured at several drain voltages with the beam first on and then blanked. A series of measurements was made at gate voltages varying between 2 volts reverse bias where the device was pinched off, through zero bias to a positive gate voltage of 0.3V to 0.5V depending on the limits imposed by safe power dissipation.

The results, shown in Figure 8.8, show that only a small EBICC increase occurs when the device is pinched off. The maximum increase occurs between -1.5V and -0.5V and the

Figure 8.7 Channel current increase versus beam energy when the beam is on the gate metal

Figure 8.8 Change in channel current caused by the electron beam as a function of gate and drain voltages.

amount of induced channel current decreases rapidly as the gate voltage becomes more positive.

This implies that the increase in EBICC is inversely related to the active channel width for conditions before pinch-off. (A positive gate voltage implies a narrower depletion region and therefore a wider channel). It can be concluded therefore that the induced current is not proportional to channel width insofar as it is controlled by the gate. Further, if the increase in drain current were proportional to an increase in carrier density in the active region, the EBICC would be expected to increase as the gate voltage became more positive and the channel widened. The carrier penetration depth of the beam at 20KV is significantly greater than the thickness of the metal and the active layer so that carrier generation will occur throughout the active region. At 20KV approximately 75 per cent of the absorbed beam energy is dissipated in the semi-insulating substrate, resulting in the possibility that enhanced substrate conduction or charge trapping is responsible for the increased channel current. However, if this were the case, the increase in drain current would have little sensitivity to the gate voltage and would be expected to increase with drain voltage as the substrate is not controlled by the gate.

The results of Figure 8.8 show however that the greatest increase occurs at a drain voltage of 0.5V and less increase.

occurs at higher drain voltages. Further, there is obvious sensitivity to gate voltage. It is proposed that the increased current flows in or near the substrate and is subjected to high fields between the gate and drain so that the carrier velocity is reduced by the presence of the stationary Gunn domain. This would explain the smaller observed increase in channel current at higher drain voltages.

The presence of the Gunn domain can also explain the smaller increase in channel current at the more negative gate voltages. The advanced two-dimensional models [9, 11, 14, 15] predict the presence of a space charge between the gate and drain because the carriers must pass through the narrow active region under the gate before emerging into the wider region between the gate and drain. As the carrier transport must be continuous, the carrier concentration will be greater under the gate compared to the region beyond the gate so that charge accumulation and depletion layers will develop. These in turn produce a high electric field which leads to carrier velocity reduction (Figure 2.5) and further enhancement of the space charge. The carrier concentration is however dependent upon the cross sectional area of the active channel where the current flows under the gate. Consider the effect of a small increase in depth of the active layer for an unspecified reason. The relative change in the channel area will be greater for an initially small

channel area (corresponding to the almost pinched off condition) compared to the relatively wide channel corresponding to zero or positive gate bias. Thus a small increase in active layer thickness could only appreciably reduce the mobile carrier concentration at high reverse gate voltages. The average carrier velocity and hence channel current would therefore be expected to increase more at higher reverse gate voltage and lower total drain currents. This proposed mechanism qualitatively explains the observations of Figures 8.7 and 8.8.

The possible explanation of how the increase in active layer width might occur will be described in Chapter 10.

8.7 The influence of substrate bias

During the early part of this work, it was realized that the substrate played an important part in the electron beam stimulation process. Therefore, in preparation for the beam stimulation studies, results were obtained which showed how substrate bias alters the channel current on an unstimulated FET. These results have been presented in Chapter 6 and a typical example shown in Figure 6.5. Additional positive substrate bias, after an initial small increase, produced no further increase in channel current whereas similar negative bias increases produced steadily greater decreases. The substrate bias acts like the bias on the gate of a junction FET which has a transconductance of about one tenth of that of the Schottky diode.

A series of experiments were performed to study EBICC at different substrate biases. A stationary beam was focussed on the channel midway along one of the source electrodes. The gate and substrate biases were varied while the drain current was monitored. The results are presented in Figure 8.9.

When the Schottky barrier is biased either positively or at low negative values, the depletion region narrows. Conversely, when the substrate bias has a large negative value, the back gate depletion region increases in width. Under these conditions the active channel is narrow and located further away from the substrate. In this situation, the electron beam produces the greatest increase in drain current. It is likely that the beam narrows the back gate depletion region which in turn reduces the Gunn domain between the gate and the drain for the reasons described in the previous section. The lateral electric field is therefore reduced and the carrier velocity correspondingly increases resulting in increased channel current.

It is noteworthy that similar active channel thicknesses can be achieved using different combinations of gate and back gate voltage. Two extreme biasing conditions provide an interesting comparison of channel current sensitivity to beam stimulation. It can be shown that an active channel width of approximately 0.011 micrometers is present both when the gate voltage is +0.2V and the substrate bias is

Figure 8.9 Change in channel current caused by the electron beam as a function of gate and substrate voltages

-22V and when the gate voltage is -1.5V with zero substrate bias.

These results were obtained by the use of equation (6.4) to calculate the Schottky barrier depletion layer width and subtracting this value and the estimated back gate depletion layer width from the epitaxial layer thickness. The back gate junction characteristics are not adequately known so that direct calculation of depletion layer thickness cannot be made. However, the empirical relationship of equation (6.16) was used to determine an equivalent Schottky barrier voltage for the back gate. Figure 8.10 was then used to calculate the change in depletion layer width when the substrate voltage was changed. The values for the ordinates of Figure 8.10 were obtained by subtracting the Schottky depletion layer thickness at zero applied volts from the depletion layer thickness at the required voltage and the abscissae values by the use of equation (6.16). When the gate bias was -1.5 and the active layer abutted the interface with the substrate the induced beam current was only 1.23mA whereas when the gate voltage was +0.2V and the substrate was biased at -22V, the induced current was approximately 13mA. This result provides further evidence that the beam more strongly influences the back gate than the Schottky gate. When the beam widens the channel towards or into the substrate, as in the case where the gate voltage is -1.5V, little additional current can flow because of the

Figure 8.10 Calculated change in depletion layer thickness in the active layer as a function of substrate voltage

tail off in doping which occurs during manufacture by outdiffusion of the n-type impurities into the substrate and partial compensation by diffusion of chromium from the substrate to the channel. However, when the gate bias is positive, the depletion region is narrowed, and the beam induced change in depletion layer thickness occurs in the more heavily doped region away from the substrate interface and the change in current is greater. This suggests that some other mechanism rather than substrate conduction is the main reason for EBICC generation.

The substrate bias influences the EBICC at all positions on the device as can be seen in Figure 8.11 which summarizes the results of linescans at right angles to the gatewidth for different substrate bias conditions. Four curves representing the beam on the drain, channel, source metal and source semi-insulating layer show that beam stimulation exists at negative substrate voltages for all parts of the device and that the drain and channel regions show increased EBICC for all substrate biases.

The results for no beam are included for comparison. This indicates that total channel current is reduced at negative substrate biases even though the beam induces greater changes under these conditions.

8.8 Summary and conclusions

In this chapter the basic responses of the channel

Figure 8.11 Channel current increase as a function of substrate voltage for different regions of the device

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current to the electron beam and to certain device bias conditions have been explored.

The experiments described have been concerned mainly with stationary beams situated on the device. Empirical relationships between the beam current, accelerating voltage and beam energy and the channel current increase have been established although the physical significance has not been determined.

The concepts of long and short range stimulation effects have been discussed together with possible means of separating these effects. Different sensitivities of the semi-insulating and active layers to beam parameters have been observed.

The sensitivity of the channel current to gate, drain and substrate bias when stimulated by an electron beam has been experimentally explored and it has been suggested that minor changes in the active channel thickness resulting from changes in the back gate depletion layer width account for the sensitivity. These changes in active layer width in turn, alter the electric field distribution within the channel and hence change the carrier drift velocity and the drain current. The suggested mechanism, although unproven, theoretically explains the experimentally observed results.

This chapter and previously Chapter 6 therefore lay the groundwork for Chapter 9, which details further experiments designed to separate the long and short range effects and to consider time dependent effects.

CHAPTER 9

BEAM INDUCED CHANNEL CURRENT CHANGES (2)

9.1 Introduction

This chapter extends the work described in Chapter 8 to situations where the electron beam is moving across the device so that the function of its position can be investigated. In the next section a general idea of the factors involved is obtained by studying the effects on the EBICC when the beam is scanned at right angles to the gate. This leads to studies of the short and long range effects and further consideration of the influence of drain and gate voltages.

9.2 Scanning the beam across the device

A considerable amount of information on the EBICC mechanisms can be extracted by detailed study of each part of the linescan reproduced in Figure 9.1. Positions A and M on this figure correspond to the edges of the die. The channel is situated between F and H. Between A and B, which is the edge of the aluminum gate bonding pad, the beam traverses semi-insulating gallium arsenide and creates a small increase in channel current. Between B and C, the beam penetrates through the gate bonding pad. The EBICC becomes increasingly negative as the beam moves towards the

Figure 9.1 Linescan of channel current from gate to drain bonding pads with associated SEI signals. Note the decrease in EBICC at the gate.

channel, and changes more rapidly even though the beam is focussed on the gate metal which is at a constant -1 Volt. This result shows that even negative beam induced channel current changes are inversely related to beam-channel separation. Between C and D, the beam again traverses a portion of the semi-insulating substrate. The change to an increase in channel current is attributed to the increasingly positive potential of the surface as the beam moves towards the source contact. The sudden change in slope at D corresponds to a position visible on the SEI linescan and in the SEM micrograph (Figure 9.2) as a change in signal contrast. The reason for this contrast change was not clear.

A separate series of experiments was undertaken to see if the contrast change could be attributed to voltage effects or to a change in material properties which would alter the secondary electron emission efficiency. Although brighter images normally occur when the substrate is negatively biased, the position of contrast change did not move nor did the bright and dark regions reverse position when the bias between the source and gate was varied between 4V and -4V. The change in contrast was therefore not a simple result of voltage contrast on a homogeneous surface. Under normal SEI operating conditions, a similar dark region is often observed around both ohmic contacts and is probably related to the mesa edge or to damage caused by the ohmic

Figure 9.2 SEI image and linescan of the region scanned in Figure 9.1. The length of the marker bar is 100 micrometers and the scan rate was approximately 3 micrometers per second

contacts. Changes in chromium concentration in SI GaAs have been reported by Magee et al [54] following alloying with gold contacts, so that this effect could be related to the chromium distribution.

As the beam traverses this darker region (DE in Figure 9.1), the induced channel current increases. At the interface with the edge of the source metal (which is also the mesa edge), there is a decrease in generated current thought to be mainly attenuation by the contact metal. The irregular changes in channel current between E and F correspond exactly to topographic detail on the ohmic contact as described in section 8.4. During this stage of the scan there is an overall increase in channel current which is caused mainly by the short range effect. The source was maintained at ground potential during this experiment so that no voltage sensitive effects occurred during this part of the scan. Between F and G, there is a sudden increase in induced current because the ohmic contact metal no longer attenuates the beam. The beam is centred over the channel where it is most effective insofar as the short range effect is concerned. During the later part of the scan over the channel (G to H) the induced current increases because the bias of the surface between the gate and drain becomes increasingly positive. The sudden change between H and I results from attenuation as the beam crosses onto the drain metal and this provides an important measure

of the attenuating effect of the ohmic contact. Between I and K the topographic irregularities seen when the beam was over the source are again evident. However, the induced current when the beam is on the drain differs from when it is on the source at an equal distance from position J. The difference is a measure of the influence of surface voltage on the overall effect. This is discussed in section 9.7.

Another important point emerges when the overall shape of the beam induced current versus beam position curve is studied. This is best done by ignoring the peak corresponding to the beam being over the channel and making corrections for the difference between source and drain voltages. The location of the peak (J) on the drain several micrometers from the channel (in this case, 6 micrometers) is a general characteristic that has also been observed for devices from other manufacturers. This result is attributed to the effects of the region of influence (ROI) of the electron beam. Consider the case of a circular ROI as described in more detail in section 9.6. When the beam is over the source most of the current induced is generated within an area of constant potential. However, parts of the regions may overlap the channel and the drain. The portions of the ROI in these two areas generate more current than equivalent areas on the source because of their more positive potentials. Thus, as the beam moves towards the drain, more current is induced. The peak occurs when most

of the ROI has passed beyond the source but before the beam has gone so far onto the drain that the EBICC decreases excessively. Thus in principle, measurement of the position of the peak provides valuable information about the size of the region of influence although in practice the extraction of such information is difficult because of the effect of the channel, and is unlikely to be as accurate as the method to be described in section 9.6 owing to the additional variables such as the irregular attenuation and non-uniform induced current generation over the active channel.

Between J and K the induced channel current decreases as the beam approaches the edge of the drain, due to decreases in both the long and short range EBICC effects. The sudden small increase in current between K and L is caused by contact metal attenuation and the presence of the mesa.

From L to M near the edge of the die, there is a decrease in the induced channel current which falls to about 0.5mA at the edge of the wafer. The potential of the gallium arsenide surface presumably decreases over this distance from drain potential near the mesa edge, to nearly substrate potential at the edge of the die.

9.3 Time dependent effects

Time dependent effects with long time constants have

been noticed throughout this work, resulting in slow changes in beam induced channel current. Thus it might be assumed that equilibrium is not reached at any point on the scan during rapid scans, so that the results of Figure 9.1 do not represent stable conditions. This hypothesis is investigated in this section.

During scanning of the FET, two limiting sets of results are possible, depending on the scan rate, with a range of possibilities between. In one extreme, the scan rate is so fast that no part of the scan deviates from its initial unstimulated position. In the other, the scan rate is so slow that all time dependent effects have reached equilibrium. The former test is not feasible with the available SEM scanning system, because even the fastest available scan rate, (i.e. TV scanning), is relatively slow compared with fast carrier recombination rates and also a single scan is not possible. The slowest scan rate available in the SEM (approximately 480 seconds) however, approaches the desired conditions for the second test. The results of such a test scan produced results similar to the 10 seconds per inch scan (scan rate 7) used in Figure 9.1. Scans produced at 1 second per inch were also essentially similar. An alternative means of checking the influence of the long time constant effects is to produce scans from opposite directions so that one scan starts at a position equivalent to M and continues towards A. This is easily

achieved by using the electronic scan rotation feature of the SEM. Thus any residual effects from, say, position C which would influence the beam at, say, position E in the original scan direction would not occur in the opposite direction scan. Rather, effects due to the beam at position F would affect the induced current, recorded when the beam was at position E. Experiments performed at 10 inches per second with scans in each direction were substantially the same. It therefore is concluded that the errors due to long time constant phenomena at the scan speeds used do not introduce serious errors so that it may be assumed that the results describe the situation where equilibrium has been reached.

Figure 9.3 shows a plot of the change in channel current as a 25Kv, 17pA beam current is switched on and then off after 175 seconds. The beam was stationary and located on the gate metal approximately midway between the device centre and the edge of the active region. The induced channel current rose to about 85% of its final value within half a second and then increased slowly over the next 174 seconds to close to its final value with a time constant of about 30 seconds. The decay after the beam was switched off was also initially fast until about 40% of its initial stimulated value before decreasing at a much slower rate to its unstimulated level with calculated time constants of about 80 and 500 seconds.

Figure 9.3 The change in channel current as a function of time when the beam is switched on or off. The associated time constants of each region are labelled

These results are insensitive to beam position provided that the beam is within a few micrometers of the channel. Similar results have been obtained for other HP devices, and previously for devices of other manufacturers. The different time constants are believed to represent the different trap filling and emptying rates of the chromium or oxygen centres and their measurement in terms of changes in channel current may provide a simple method of characterizing substrates for makers of FETs.

9.4 The results of removing the gate metal

Whenever instabilities in GaAs FET performance have been observed there has been speculation as to whether the Schottky barrier interface is responsible. [16.34 48] It is natural therefore to suppose that electron beam irradiation might change the barrier characteristics by altering the depletion width either through the high fields created within the device by the beam or by positive charge deposition in the thin insulating interface layer which may exist between the gate metal and the epitaxial layer.

A measure of whether the mechanisms causing channel current increase are sensitive to the presence of the gate metal can be obtained by etching the gate metal from a device and studying the sensitivity of the device to beam irradiation. The gate metal was successfully etched off one device using hot phosphoric acid after several earlier

unsuccessful attempts. X-ray microprobe analysis revealed some traces of residual gate metal in parts of the channel. However, no aluminum remained on the semi-insulating substrate and all results were obtained with the beam well away from the residual metal. Edwards [51] in similar studies, using laser stimulation, was able to remove all the gate metal and observed generally similar results. It is therefore believed that the small traces of residual metal do not invalidate the results reported in this work. Their effect reduces the saturated drain current below the maximum possible value. After etching the device used in this work passed about 10% more drain current in saturation than it did before etching.

The results obtained in the beam stimulation experiments lead to the conclusion that significant induced currents are still obtained in the absence of gate metal. The action of the beam on the back gate rather than the Schottky barrier is the main reason for the electron beam stimulated current. Comparison of results (Figure 9.4) obtained by scanning the beam across the gate on two different devices, one with and one without gate metal, shows that there is increased sensitivity to the beam in mid-channel when the gate is absent but the long and short range effects are otherwise very similar. Slightly different magnifications but similar beam voltages and beam currents were used. However, the similarities and differences in response in the active

Figure 9.4 The change in channel current as a function of beam position for similar devices with the gate present (top) and with it removed (bottom)

channel region can clearly be seen. The main difference is that the response is greater when the beam is on the channel with the gate metal removed. The increase is also greater than can be accounted for by attenuation of the beam energy by losses in the gate metal. The similarities include the overall shape and magnitude of the response curve in all other parts of the scan. In particular the following similarities exist:

- 1) The maximum response occurs with the beam over the drain region, not over the channel (ignoring the immediate channel region peak).
- 2) The response when the beam is over the drain is greater than when it is over the source.
- 3) The rates of decrease with increasing distance are similar when the beam is over the substrate beyond the drain.
- 4) The same step change in channel current response occurs at the drain metal edge. This is attributed to a change in beam attenuation.

It is therefore concluded that both the long and short range effects are present whether or not there is gate metal and hence they are not an artifact of the Schottky barrier. The response is however modified by the gate voltage as reported in Chapter 8. When the gate metal is absent the surface of the channel assumes a positive potential between

the source and drain which should reduce surface depletion and increase the drain current above the zero gate voltage condition. The small fraction of energy absorbed by the metal at 25KV (approximately 10 per cent as shown in Figure 8.4) indicates that reduced beam attenuation can only explain a fraction of the increased response when the gate metal is absent. The major contribution of the increase is believed to be caused by the reduction in electric field as the back gate depletion region becomes narrower under the influence of the beam.

The insensitivity of the long range effect to the presence of gate metal justifies its study using devices with or without gate metal. This has reduced the required amount of experimental work significantly

In the next section the response of the device to the movement of the beam along the channel is studied to investigate the short range mechanism in a region where the long range effect is almost constant.

9.9 Influence of the beam on substrate bias

The substrate voltage has already been shown to provide effective control of the channel current in the absence of the electron beam. Results described briefly in Chapter 6 and illustrated in Figure 4.16 showed that the substrate current and bias were also altered by the beam in devices where the substrate could be monitored independently. Such

changes correlate well with the EBICC changes as a function of beam position as can be seen by comparison of Figures 4.1a and 4.1b. In particular, the measured substrate current and bias always have the same polarity as the surface on which the beam is focussed, although the magnitude of the substrate voltage increases as the beam gets closer to the edge while the channel current decreases. No diode action was detected between any pair of contacts although at high substrate voltages. In independent experiments with no electron beam, evidence of trap filled space charge limited current flow and double injection was observed, as described by Mark and Lampert [55], particularly when the substrate was positively biased. However, this mode of current flow only occurred at substrate biases of 5V or greater. To avoid this, all beam stimulation experiments were performed below 5V. As saturation of the induced channel current also occurred below 5V, little information was lost by not exceeding 5V. It is believed that the long range increase in channel current is caused by the electron beam altering the injection efficiency of device contacts, thereby altering the substrate bias and hence the back gate potential. This is supported by Mark and Lampert [55] who report that light or electron beams can turn non-injecting contacts into good injectors by raising the energy of carriers above the built-in potential barrier caused by the difference in

Figure 9.7 Several possible EBIC profiles of the current monitored in one source as a function of beam position as compared with experiment

9.6 The short range stimulation effects

In this section a series of experiments utilizing the two separate sources of the HP FETs leads to evidence of the rate at which the short range EBICC effect decreases with distance from the collecting electrode (one of the sources).

The short range effect can be characterised by moving the beam through the centre of the device and measuring the current flowing into each source.

As the beam moves away from the source being monitored, a smaller fraction of the total short range EBICC flows into that source. The change in total measured EBICC with distance provides a means of determining how the induced current density changes in each part of the channel within the region of influence. The results of this experiment are shown in Figure 9.5. In this example the current in first one source, then the other, is recorded as the beam moves from left to right on successive sweeps. On the plot marked A, the right source (S2) is connected to the measuring apparatus. At the start of the scan, the beam is at the far left of the device, on the semi-insulating substrate and an initial increase in current of about 0.5mA caused by the long range effect, was recorded even though the beam was beyond the edge of the active region. An increase in the current through S2 occurred as the beam approached the centre of the device due to the short range effect. As the

Figure 9.5 Line scans along the gate width axis with the current generated in one source being monitored as a function of beam position

beam crossed the centre, the rate of increase in channel current in S2 decreased as the beam moved further onto the region between the drain and source S2.

Eventually, when the beam was sufficiently far beyond the centre, little further change in channel current was observed in S2 (scan A) indicating that all the short range effect of the beam now occurred between S2 and the drain. In scan B the reverse occurs. The sudden dip in the stimulated current, near the middle of S2, highlights a device defect and illustrates the value of this technique in device reliability analysis.

The short range effect can be characterized by the region of influence (ROI) within which the beam stimulates the channel current. The ROI will be defined more precisely later when the channel current stimulation profile has been investigated.

The results of fast dynamic scans of the type shown in Figure 9.5 are not as amenable to analysis as a series of stationary beams at different positions. The beam position can be more accurately identified when it is stationary because higher magnification can be used and there is no problem of the beam moving from the desired location during a scan because of any residual rotational error in the scan alignment. Furthermore, the system can be allowed to stabilize to eliminate errors due to the long time constant effect. However, a static scan experiment is more difficult.

to perform because it takes a considerable time, the number of experimental points is limited and electron beam instabilities or filament failure may occur. Significant amounts of contamination may occur where the beam strikes the sample causing charging up and possible beam movement. A slow scan taking about six minutes at X1000 magnification is a good compromise and provides data sufficiently accurate for analysis. The results of such an experiment are shown in Figure 9.6 where the beam crosses from between the drain and the unmonitored source S1 to between the drain and the monitored source S2, (Scan A).

From Figure 9.6, as the beam approaches the centre of the device from Source 1, the current in Source 2 starts to increase. Further increase occurs as the beam passes beyond the centre until all of the area influenced by the beam lies between the drain and the monitored source. It should therefore, in principle, be possible to determine the dimensions of this ROI in terms of its radius by observing the value of the induced current as the beam reaches the edge of the monitored source and measuring the distance at which the induced current rises to twice its value. This can be verified by measuring the distance back in the direction of the unmonitored source where the current induced in the monitored source falls to zero. These

Figure 9.6 High magnification linescan of the channel current increase measured in the two sources as a function of beam position. In Scan A, Source 2 is monitored, in Scan B, Source 1 is monitored

values, which equal the radius of the ROI, should be equal if no other effects are present.

Unfortunately, the long range effect occurs simultaneously and makes this relationship less obvious. The magnitude of the long range effect was found to be 0.41 mA under the experimental conditions used to produce Figure 9.6 at the edge of Source 1 based on separate static beam position results. The radius of the ROI can still be determined provided that the long range effect component is subtracted from the total beam induced current. This has been done but interpretation of the results is further complicated because changes of $dI(z)$ with distance from the beam are not measureable directly. However, experimental results indicate that the ROI in this case extends 40 micrometers from the centre of the beam for the specific experimental conditions.

The experimental results have been compared to several possible mathematical profiles in Figure 9.7 to obtain the best fit. These are:

- 1) A normal distribution of the total current with a standard deviation of 13 micrometers (curve 1 in Figure 9.7) since almost the entire normal distribution lies within 3 standard deviations and the ROI was found to be 40 micrometers.
- 2) A normal distribution with the same standard deviation of the elemental currents in dz such that the

Figure 9.7 Several possible EBIC profiles of the current monitored in one source as a function of beam position as compared with experiment

area under the curve at distance z is proportional to the increase in channel current. This is also known as the complementary error function (curve 2).

3) A decreasing exponential distribution of total current with diffusion length of 9.2 micrometers (curve 3).

4) The fractional portion of a circle of 40 micrometers radius that lies within the injecting region of the monitored source as the beam moves towards the monitored source (curve 4).

5) The fractional part of a hemisphere of 40 micrometers radius as its centre moves within the injecting region of the monitored source (curve 5).

Figure 9.7 also shows the experimental results. There is good agreement between the error function distribution and the experimental results apart from discrepancies where the short range effect is smallest and errors caused by inaccuracies in the magnitude of the residual long range effect contribution are most significant.

It is concluded therefore that, under the specific experimental conditions, the short range effect can be empirically modelled by a normal distribution of increased channel current with a standard deviation of 13 micrometers corresponding to a ROI of approximately 40 micrometers radius. The induced current density per micrometer gate

width in the centre of the distribution where the beam is located is approximately 72 microamperes per micrometer under the specific conditions of this experiment. Other experiments where the beam approaches the edge of the mesa also produce a decrease in induced channel current that begins about 40 micrometers from the mesa edge, (e.g. Figure 6.3). In addition, scans across the device such as Figures 4.1 and 9.1 indicate that this value is consistent with the observed decrease in channel current in these experiments.

9.7 The effects of drain bias

The action of drain bias on the beam induced channel current is complex and at least three separate effects are present. All the mechanisms involve the interface between the substrate and the active layer under the gate or between the gate and the drain.

The long range effect is especially influenced by drain voltage which generally creates greater induced current when the beam is on the drain contacts than when it is on less positively biased regions. However, the amount of beam induced current peaks sharply at comparatively low drain voltage. There is evidence that the back gate depletion width decreases under the influence of the beam and this, coupled with increased internal electric fields, causes reduced carrier velocity in the channel and hence the observed decrease in beam induced channel current above 1V drain bias.

In Figure 9.8, the influence of the drain bias is shown on four otherwise similar linescans of beam induced channel current. The results have been summarized in Figure 9.9, which shows how channel current increases change with increasing drain voltage.

Three distinct effects occur:

- 1) the overall shape of the curves remain the same over the short range ROI.
- 2) The difference between the induced current on the drain and source sides of the channel changes with drain voltage. This is part of the long range effect. A peak occurs at about 1 volt.
- 3) The shape of the sharp peak in the channel on the drain changes to a concave shape with increasing drain voltage. This is attributed to the change in internal electric field distribution which reduces beam induced channel current.

In an unstimulated GaAs FET, both the Schottky gate and back gate depletion layers widen and reduce the active channel thickness as the drain voltage increases. This causes the channel current to saturate for the reasons explained in Chapter 2. The stimulation produced by the electron beam, however, produces significant changes in the depletion layer width by altering the applied voltage

Figure 9.8 EBIIC profiles at different drain voltages as a function of beam position showing decreasing sensitivity with drain voltage and modification of the shape of the peak

Figure 9.9 Change in maximum EBICC as a function of drain voltage and the predictions of two possible models

between the drain side of the channel and the semi-insulating substrate.

In the case of the short range effect, it has been proposed in Chapter 6 that the beam may create positively charged traps which alter the potential across the interface. The voltage across the depletion region is thereby reduced so that the layer narrows and more current can flow through the channel. According to this simple concept, the drain current should steadily increase with increasing drain voltage. However, the experimental results shown in Figure 9.9 show that this is not the case.

Similarly, the simple explanation for the long range effect leads to the assumption that induced current will continue to increase with drain voltage. It has already been shown, however, that drain current does not increase continuously because the back gate depletion layer only extends a short distance into the active layer and when the substrate voltage has increased sufficiently to reduce the depletion layer essentially to zero, no further induced current increase can occur.

The assumption of equal current density at each depth element in the channel is initially made so that the change in channel current can be directly related to the change in back gate depletion layer thickness in the active channel.

In Figure 9.9 it can be seen that a 2.6 mA increase in channel current was observed when the drain voltage was 1V.

From Figure 6.6, in the drain current range between 40 and 60 mA of a similar unstimulated FET, it can be seen that a change in substrate voltage of 0.53V is required to produce a 2.6 mA change in channel current.

It is therefore assumed that the beam produces an equal change in substrate voltage and so a value of 0.53V can be assigned to the change in the back gate bias.

By substituting this value, and variable values of the drain to substrate voltage (which equals the drain source voltage since the substrate is grounded), an estimate can be made of how the depletion layer thickness changes with drain voltage. Using the data shown in Figure 6.8, the estimated change in channel current can be calculated.

This has been done and the results plotted in Figure 9.9. The prediction of the simple model underestimates the decrease in channel current. However, the decrease in mobility resulting from the increased electric field has not been taken into account. Assuming a constant field between gate and drain, a maximum reduction in saturated carrier velocity from $2E7$ to $1.2E7$ centimeters per second can be expected (Figure 2.6) as the drain voltage increases from 1 to 3V, which will reduce the induced channel current further. In Figure 9.9, a linear decrease in carrier velocity with field has been assumed for simplicity but the result still underestimates the observed change.

In view of the many simplifying assumptions made about FET back gate behaviour and in particular the assumptions of even current distribution with depth near the epitaxial layer, substrate interface and the known inaccuracy of the abrupt junction approximation for the depletion region in short gate FET models [7], this lack of good quantitative agreement is not unexpected.

The second of the effects mentioned at the beginning of this section is the increased channel current when the beam is on the drain rather than on the source. This is attributable to the long range effect. The substrate potential is changed when the beam makes the drain contact inject carriers into the substrate so that the substrate will assume a more positive bias. This in turn reduces the potential across the interface so that more of the active layer conducts as the depletion layer becomes narrower. This process is modelled in the next Chapter. The difference in induced current corresponds to the difference between the arrows in Figure 9.8a. The results of measurements of this difference for each drain voltage are shown in Figure 9.10. Again, the greatest beam sensitivity occurs at moderate drain voltages and suggests that the same basic mechanism controls both effects.

The final effect is the change in shape of the sharp peak in channel current when the beam is over the channel. The sample of results shown in Figure 9.8 shows how the peak

Figure 9.10 The change in EBICC between source and drain as a function of drain voltage

changes from a symmetrical shape at 0.5V when little or no high field carrier velocity decrease occurs. At higher drain voltages the shape of the source side of the peak remains unchanged, but the shape of the drain side becomes increasingly concave at higher drain voltages. This indicates that less induced current occurs when the beam is located between the centre of the channel and the drain metal at higher drain voltages.

This effect is clearly a very important discovery insofar as experimental distribution of current and electric field distributions within a FET are concerned, as it indicates the location of the Gunn domain, but the precise explanation of the mechanism involved needs further study.

The changes in the shape of the peak reflect the changes in EBICC as the beam traverses the region in which the Gunn domain forms at the higher drain voltages. This study of the fine detail of the peak may lead to an understanding of the fields within the device itself.

9.8 The effects of gate bias

It has been shown already (eg Figure 9.1) that when the electron beam is focussed on the gate bonding pad the channel current decreases. This has been attributed to the ability of the beam to make the gate pad inject more efficiently and hence make the overall substrate bias more negative. In this section the influence of the gate bias is

studied in more detail. The most suitable region of the device for these studies extends from the edge of the device to beyond the mesa along the line of the gate because the effect of gate bias on the active region and a semi-insulating material can be studied in a single linescan.

Figure 9.11 shows three typical superimposed linescans for different gate voltages. Two of the gate voltages are below pinch-off and the third is above pinch-off. The beam voltage was 20KV at a beam current of 0.03nA. Figure 9.12 summarizes the results of three linescans. The two curves represent the change in channel current at positions P and Q in Figure 9.11.

When the beam is on the gate metal over the substrate at position Q, there is a decrease in channel current initially. After a minimum, the channel current increases as pinch-off voltage is approached but it never reaches its unstimulated value.

The overall device current decreases as the gate voltage is increased at the same time as the beam is producing its effect. Thus, as the gate voltage increases the overall channel current is decreasing and the active channel moves away from the surface towards the substrate.

These beam current induced changes are superimposed on the overall device transconductance characteristic so that the drain-source current decreases to zero as the gate

Figure 9.11 The change in EBICC as a function of gate voltage shown in linescans from the substrate and onto the active layer when the beam is scanned along the gatewidth axis

Figure 9.12 Change in EBICC at the positions P and Q in Figure 9.11 as a function of gate voltage

voltage approaches pinch-off and the width of the active layer diminishes and its location approaches the interface with the substrate. When the beam is at P, the situation is the same as that described in Chapter 8 for a stationary beam on the gate metal.

The decreases in EBICC when the beam is at Q occur, however, because of the long range effect, in which the beam turns the segment of the gate on the substrate into an efficient injecting contact, thereby making the substrate more negative and increasing the potential across the depletion layer of the high-low junction. Thus the active channel region thickness is decreased by both the Schottky and back gates and the channel current is reduced as the gate voltage becomes more negative. As the Schottky gate voltage increase towards pinch-off, the total device current must decrease towards zero more rapidly in the presence of the back gate effect than in its absence. as both mechanisms reduce current. Thus the change in current caused by the gate must also decrease to zero.

9.9 Conclusions

This chapter has extended the study of the EBICC process to regions outside the active channel and shown how the effects at different positions can be explained by either the short or long range mechanisms. Consideration of the special case where the current is only one of the two source

electrodes has been monitored has led to an empirical description for the variation of the short range effect with distance from the collecting electrode. In the next chapter the possible mechanisms are studied and developed into models which are then compared with the experimental results.

CHAPTER 10

CHANNEL CURRENT MODELS

10.1 Introduction

Both the long and short range effects first described in Chapter 1 can be related to the change in depletion layer thickness extending into the active layer at the interface with the semi-insulating layer. Although the interactions between the beam and GaAs FETs are too complex to produce comprehensive models within the scope of this work, a series of simplifying assumptions leads to approximate models which are compared with experimental results with fair agreement. For practical use, empirical relationships are established based on results reported in earlier chapters which describe semi-quantitatively the range of interactions between the beam and channel current.

10.2 The short range beam stimulation model

It has already been proposed in Chapter 6 that the electron beam generates carriers in the substrate which account for some of the locally increased current flow contributing to the short range effect. There is, however, evidence to suggest that this mechanism cannot alone explain all the observed effects. For instance, the incorrect sensitivities to drain voltage have already been noted.

Additionally, in section 8.5.2, it was shown that the total increase in channel current was related to approximately the 3.8th. power of the beam energy per unit time and hence not to the number of electron-hole pairs generated by the beam per unit time which is proportional to the beam energy. The EBICC is therefore proportional to only an indirect effect of carrier generation. The radius of the volume in which carriers are generated (Figure 3.3) is at most 7.5 micrometers at an accelerating voltage of 39KV. At 20KV this radius is only about 2.8 micrometers. This is much shorter than the characteristic "diffusion length" of the unknown species responsible for the short range effect, described in Chapter 9. A "diffusion length" can readily be calculated from the experimentally established normal distribution of increased channel current with distance described in section 9.6. assuming the effect is caused by outward diffusion from the position of the beam. Comparison of the standard statistical and semiconductor diffusion notations for the normal or Gaussian distribution leads to a diffusion length of 9.2 micrometers at 20KV and 0.25nA beam current (assuming the 13 micrometer standard deviation found in section 9.6). This provides further evidence, at first sight, that the effect is unlikely to be caused by flow of generated carriers to the entire region of influence.

The alternative mechanism, hole trapping in the substrate causing changes in active channel width, also

outlined in Chapter 6, probably also contributes to short range EBICC. This mechanism is considered in more detail in the following sections and provides the basis for simple models which reproduce some of the observed features of the short range effects. The carriers generated by the beam in the back gate depletion region separate, with electrons flowing into the active channel and contributing to EBICC, and holes into the substrate. The holes either recombine or become trapped in one of the levels characteristic of compensated semi-insulating gallium arsenide and produce a fixed positive charge. When the hole generation rate is greater than the trap emptying rate, the traps under the beam become entirely filled and remain filled as long as the beam is still focussed on the same region. A smaller beam current will produce a lower hole flux diffusing outwards towards the edge of the ROI so that the critical distance at which the filling rate equals the emptying rate will be smaller and the ROI will be smaller. Thus the induced channel current will be weakly proportional to the beam current as is observed. When the traps near the beam have been filled, it is believed that their cross section diminishes and the hole diffusion length locally increases. Thus holes generated under the beam diffuse further and are able to fill more traps. The filled traps form a positively charged volume which reduces the bias across the back gate depletion layer. This in turn reduces the depletion layer

thickness and hence increases the active layer cross section and allows the device to pass more drain current over the region where the charge is trapped. Under some circumstances the increase in channel thickness may also reduce the electric field along the channel and hence further increase channel current because of increased carrier velocity for the reasons described in Chapter 8.

Consider the effect on current flowing in a width element of the channel dz at a distance z from the beam. The beam induced channel current increase in this element due to the short range effect. (signified by the letter S), can be attributed to an increase in channel thickness caused by depletion layer narrowing.

$$dI_{DS}(S,z) = nqv_s dW(S,z) \quad (10.1)$$

The change in back gate depletion width $dW(S,z)$ at position z is caused by the change in potential according to abrupt junction theory, such that

$$dW(S,z) = F \left[(V(BG) + dV(z))^{1/2} - V(BG)^{1/2} \right] \quad (10.2)$$

where $dV(z)$ is the voltage at position z caused by charge trapping in the vicinity of the beam, F is defined by

$$F = \left[\frac{\epsilon \epsilon_0}{qn} \right]^{1/2} \quad (10.3)$$

and $V(BG)$ is the sum of the built-in potential and the drain voltage.

$$V(BG) = V_{BI} + V_{DS} \quad (10.4)$$

Using the first terms of the binomial expansion to simplify (10.2) and combining with (10.1) gives

$$dI_{DS} = \frac{1}{2} nq v_s F dV(z) V(BG)^{-1/2} \quad (10.5)$$

The calculation of $dV(z)$ is not amenable to analysis even if the simplified hemispherical approximation of the volume in which carriers are generated is used (Figure 3.3). However, a solution can be obtained [56] if the even simpler approximation of Figure 10.1 is used. This approximation is physically equivalent to a sphere of charge with radius R equal to the half of the penetration range situated so that its surface is tangential to the interface between the substrate and the epitaxial layer.

The predicted induced current shows an almost reciprocal decrease in potential with increasing distance from the position where the beam is focussed on the device so that

MICROMETERS FROM BEAM

Figure 10.1 The simplified approximation of the region of induced positive charge (top) and predictions of EBICC and potential as functions of beam position

the change in EBICC varies with distance such that

$$\Delta I_{DS}(S) = \left[\frac{Qv_s}{8\pi} \cdot \frac{qn}{\epsilon\epsilon_0 V(BG)} \right]^{1/2} (R^2 + z^2)^{-1/2} \quad (10.6)$$

where Q is the total trapped charge. This expression yields a value of $2.8E15$ per cubic centimeter for Q when $V(z)$ is 0.5 volts and z is zero and R is 2.5 micrometers (corresponding to a beam voltage of approximately 35KV).

The value of Q is close to the usual doping level for chromium compensated material [5] assuming one hole-trap per atom.

In order to check the predictions of equation (10.6), the EBICC flowing into one source has been calculated for different beam positions on the gate between the other source and the drain. The predicted EBICC collected by the source is given by integration of (10.6) such that

$$\Delta I_{DS}(S) = \left[\frac{qn}{\epsilon\epsilon_0 V(BG)} \right]^{1/2} \sinh^{-1} \left[\frac{z}{R} \right]_{\frac{z}{2}}^z \quad (10.7)$$

The integration limits relate to the fraction of the tail of the induced current distribution that lies between the collecting source and the drain as illustrated in Figure 10.1. The predictions of equation (10.7) are plotted in

Figure 10.2. The EBICC at the edge of the monitored source has been normalized to unity. The experimental results derived from Figure 9.6 have also been plotted on this graph together with the results of the complementary error function curve described in the last chapter. (Figure 9.7)

It can be seen that the theory overestimates the EBICC at distances greater than 10 micrometers from the beam whereas the empirically determined normal distribution curve in Figure 10.2 gives a better working approximation of the experimental curve for engineering predictions.

The assumptions on which the short range models are based have been oversimplified. Nevertheless, even if the actual shape of the charge distribution were known more accurately, the simple model overestimates the EBICC because the reciprocal relationship between induced potential and distance implies too slow a decrease in EBICC with increasing distance. Thus both the proposed ~~short~~ range mechanisms, the hole trapping and the additional substrate current mechanism, individually are unable to explain all observed features of the short range EBICC. It is probable however, that a combination of the two mechanisms exists in practice. In the next section a model of the long range EBICC effect is developed, again based on simplified approximations of the very complex real conditions.

Figure 10.2 Predictions of the sensitivity of EBICC to beam position predicted by theory, by experiment and the normal distribution approximation.

10.3 The long range stimulation model

The model of the long range effect (i.e. EBICC changes which occur beyond the short range ROI) is based on the assumption that the electron beam improves current injection efficiency so that the potentials within the substrate are altered by the presence of the electron beam. These in turn alter the back gate depletion layer width. The potential at the position marked A in Figure 10.3 at the interface with the active layer can be calculated by analysis of the resistive network which is used to model the substrate. back gate depletion layer is represented by the capacitor at A. Region B is an unspecified 'general' region of the device used for illustrative purposes only.

The four resistors in the semi-insulating layer connecting the contacts to the capacitor in Figure 10.3 are lumped approximations of the distributed resistances to the contacts and all except $R(AS)$ are approximately one Gigaohm in value. The ability of the beam to make a contact inject current is modelled by on-off switches. Current flow through these resistors is normally injection limited when bias is applied to the terminal. This is represented by the open switch condition. When the beam is directed onto a contact it injects more efficiently and additional current flows from the external circuitry as if the switch were closed. Assume that the beam is focussed on region B whose

Figure 10.3 The lumped resistance approximation of the substrate when the beam is at the arbitrary location B

potential is $V(B)$. The resistance to the substrate from B decreases substantially as the current increases and the potential at the semi-insulating side of the capacitor becomes more negative as $R(BA)$ decreases. There will be a change in voltage $dV(z)$ such that

$$dV(z) = \frac{R(AS) V(B)}{R(AS) + R(BA)} - V(A) \quad (10.8)$$

across the capacitor at position A which is assumed to have a coordinate z in the gate width axis.

The resistances in Figure 10.3 cannot be measured accurately because of their distributed nature and the lack of information on the injection properties of each contact region during beam stimulation. However, $R(AS)$ will usually be small in comparison with $R(BA)$ simply because of the small separation between the source and channel. The unstimulated voltage $V(A)$ has been determined to be about +0.02V and so is negligible so that equation (10.8) reduces to

$$dV(z) = \frac{R(AS)}{R(BA)} \cdot V(B) \quad (10.9)$$

$R(BA)$ depends upon the device geometry but is roughly proportional to the distance between A and B. The voltage, $dV(z)$ determines the change in thickness of the part of the back gate depletion layer in the active region. Thus

$$dW(L,z) = F \left[(V(BG) + dV(z))^{1/2} - V(BG)^{1/2} \right] \quad (10.10)$$

assuming the step junction approximation and using the binomial expansion and neglecting higher terms, this expression can be simplified to an expression similar to (10.2) but where the letter L signifies this is a long range effect

$$dW(L,z) = \frac{1}{2} F V(BG)^{-1/2} dV(z) \quad (10.11)$$

Therefore using equation (10.8)

$$dW(L,z) = \frac{1}{2} F V(BG)^{-1/2} \frac{R(AS)V(B)}{R(BA)} \quad (10.12)$$

The only term that is dependent on position in this expression is R(BA) so that the change in EBICC is

$$dI_{DS}(L,z) = b' \left[\frac{qn\epsilon\epsilon_0}{V(BG)} \right]^{-1/2} \frac{R(AS)V(B)}{d(zB)} dz \quad (10.13)$$

where b' is a new constant incorporating the relationship between the resistance and the distance $d(zB)$ between positions A and B.

The accuracy of this model can be assessed by comparing its predictions with measurements of the total long range EBICC flowing through one of the two sources when the beam

is on the gate at position z far from that source (i.e. beyond the short range ROI). Figure 10.4 illustrates this situation with Source 1 being monitored. The total measured long range EBICC for the beam at any position z is the solution of equation (10.12) integrated from the mesa edge to the position z .

$$\Delta I_{DS}(L) = b'v_s \left[\frac{qn\epsilon\epsilon_0}{V(BG)} \right]^{1/2} R(AS)V(B) \left[\ln(d(zB)) \right] \frac{z}{\frac{z}{2} + z} \quad (10.14)$$

The result of this has been plotted in normalized form so that the long range EBICC corresponding to the whole of source 2 is made equal to unity. This is shown in Figure 10.5 which shows a slow decrease in EBICC with distance over the majority of source 1 apart from the region near the edge of the device. The experimental results for the stationary beam experiment reported in Figure 10.4 have also been plotted on this graph. These have been adjusted so that the value of the normalized theoretical curve and the normalized experimental value are equal at 150 micrometers from the device centre. Thus the shapes of the two curves can be compared. The agreement is good apart from the region where the short range effect becomes significant. The model correctly predicts the decrease in current at the edge of the active layer seen in Figure 10.4.

In view of the limitations of the theoretical models in their present stage of development, a pragmatic approach is

Figure 10.4 Increase in current measured at Source 1 for stationary scans showing the long range EBICC

Figure 10.5 Predictions of the long range EBICC model and experimental results in normalized form. The theory and experimental points were adjusted to be equal at 150 micrometers from the device centre

still the best means of predicting electron beam interactions with GaAs FET channel currents.

The simple one dimensional models for both the short and long range EBICC effects give fair qualitative estimates of the observed effects and provide the basis for further development. However, detailed two dimensional numerical modelling will be necessary to incorporate effects such as gate and drain voltage sensitivities just as such models have been found necessary for accurate modelling of unstimulated devices.

10.4 Empirical methods of estimating channel current increases

The induced channel current under equilibrium conditions is assumed to be the sum of short and long range terms which are described in separate expressions. The EBICC at any position on the device is given in the long range expression by

$$\Delta I_{DS}(L,z) = k'(1-B)A(Y)V_B^m I_B^n g(z)f(V_{DS},V_{GS}).V(B).d(zB)^{-1} \quad (10.15)$$

It was shown experimentally in Chapter 8 that the indices m and n varied according to whether the beam is focussed on

the substrate ($m = 1.5$ $n = 0.5$) or onto the active layer ($m = n = 3.8$). The amount of backscattering is determined by the factor B and the attenuation of the beam by metal (or glassivation) by $A(Y)$. The magnitude and polarity of the induced EBICC are accounted for by $V(B)$ and the distance between the beam and the position under the channel by $d(zB)$. The back gate transconductance factor $g(z)$ determines the effectiveness of the induced potential at z in altering the EBICC. This can be estimated from Figure 8.9. Finally, the induced current depends upon drain and Schottky gate bias in the relationship determined by the results displayed in Figure 8.8 in the last term in (10.14).

The short range effect can be estimated by inserting the appropriate values into the expression

$$\Delta I_{DS}(S,z) = k'' (1-B)A(Y)V_B^m I_B^n g(z)f(V_{DS},V_{GS})\operatorname{erfc} \frac{z}{\sigma} \quad (10.16)$$

where σ is one third of the ROI and where the terms have the same meanings and are determined in the same manner as in the expressions for the long range effect. Table 4 provides a list of sections and figures in this work which can be used to obtain parameter values for use in (10.15) and (10.16).

The value of the EBICC at position zero corresponds to the beam in a homogeneous region of the device away from both the edges of the active area and any electrodes. The

Table 4

Long and short range model parameters

Factor	Description	Section	Figure	Value	Comment
A(Y)	Attenuation factor **	8.4	10.7	0.3	
B	Backscattering factor	3.2	-	0.3	
V _B	Beam voltage #	8.5.1	8.2	m=1.5	on substrate
		8.5.2	8.6	m=3.8	on active layer
I _B	Beam current #	8.5.1	8.3	n=0.5	on substrate
		8.5.2	8.5	n=3.8	on active layer
g(z)	Back gate * transconductance	6.5.2	6.5		
f(V _{DS})	Effect of drain bias **	8.6	8.8		
f(V _{GS})	Effect of gate bias **	8.6	8.8		Gate and drain
		8.7	8.9		Gate and substrate
		9.8	9.11		
z	Position of beam	9.6	9.6		
	Std. deviation **	9.6	-		One third of ROI
d(zB)	Distance of beam from channel **	9.6	-		

* Depends upon individual device

** Depends upon device type

Long range effect only

Short range effect only

value of sigma in the complementary error function expression is obtained by the experimental methods described in section 9.6 or from the linescans across the gate as described in section 10.5. It is not very sensitive to beam parameters but is, however, very sensitive to substrate properties.

10.5 Linescans across the gate

The case where the beam is scanned at right angles to the gate width is different from when the beam is scanned along the gate. Consider a situation with the beam at position x which for simplicity is assumed to be on the source, under normal device bias conditions so that the long term component of the EBICC due to the position of the beam is negligible. This is represented by Figure 10.6. The induced current in the element of channel of width dz at z at a distance s from the location of the beam has been found experimentally to follow a normal distribution. The value of s is given by

$$s = (x^2 + z^2)^{1/2} \quad (10.17)$$

The current induced in dz is therefore

$$\Delta I_{DS}(x, z) = \int_{-\frac{z}{2}}^{\frac{z}{2}} C'' \exp\left(-\frac{s^2}{\sigma^2}\right) ds \quad (10.18)$$

Figure 10.6 Predicted EBICC at positions along the channel when the beam is 10 micrometers from the channel centre

Combining equations 10.17 and 10.18 gives

$$\Delta I_{DS}(x,z) = \int_{-\frac{z}{2}}^{\frac{z}{2}} C'' \exp\left(-\frac{x^2}{\sigma^2}\right) \exp\left(-\frac{z^2}{\sigma^2}\right) dz \quad (10.19)$$

The integration is assumed to extend over the entire gate width which is large compared with sigma so that

$$\int_{-\frac{z}{2}}^{\frac{z}{2}} \exp\left(-\frac{z^2}{\sigma^2}\right) dz = \sigma\pi^{1/2} \quad (10.20)$$

Therefore

$$dI_{DS}(x,z) = C''\sigma\pi^{1/2} \exp\left(-\frac{x^2}{\sigma^2}\right) \quad (10.21)$$

and so its magnitude in the z direction at each individual position of x is described by a one dimensional normal distribution function. The constant c includes the terms of (10.16) so that the induced channel current at position x is given by

$$dI_{DS} = c(1-B)A(Y)V_B^m I_B^n g(z)f(V_{DS}, V_{GS}) \exp\left[-\frac{x^2}{\sigma^2}\right] \quad (10.22)$$

10.6 Comparisons with experimental results

The empirical relationships can be used to synthesize the linescans generated during the experimental work.

Consider the example shown in Figure 10.7 which was produced

Figure 10.7 Experimental curve showing EBICC as a function of distance perpendicular to the channel with a corrected curve to allow for beam attenuation (top). Comparison of the predicted short range effect with the corrected result (bottom)

at 25KV and 0.4nA with one volt applied to the drain and -0.75V to the gate.

The positive difference between the drain and gate voltages ensures an overall positive substrate bias except when the beam is on the gate pad so that there is an almost constant long range EBICC component everywhere on the linescan being described. Its magnitude is the EBICC measured with the beam on the substrate beyond the source and beyond the ROI. The attenuation factor $A(Y)$, can be estimated by the relative change in EBICC at the channel edge of the source. The shape of the EBICC curve across the source is obtained from the locus of the lowest values of the EBICC as described in Chapter 8. The redrawn curve after correction for the attenuation on the source and drain is shown in Figure 10.7a. The observed EBICC increases as the beam goes onto the substrate beyond the drain. The corrected curve is reproduced in Figure 10.7b together with the predicted components of the two empirical models.

The peak value of the short range component can be measured from the corrected curve by subtracting the long range component. In the particular example of Figure 10.7 the short and long range components at the peak (position E) are 2.58mA and .67mA respectively. The magnitude of the short range component at each position is now calculated using the normal distribution function relationship of equation (10.20) and adding this to the long range component

which is assumed to decrease logarithmically with distance as in equation (10.14).

It can be seen that agreement between the corrected experimental curve and the empirical model (10.20) is quite good. The difference near the peak is attributed to the limited maximum total EBICC because only a small reduction in the back gate depletion layer thickness is possible in the active region due to its initial small thickness.

The results show that a good working approximation of the shape of the beam induced currents can be obtained from the established relationships.

10.7 Conclusions

The complexity of the EBICC processes has made the task of modelling EBICC difficult. Attempts have been made in this chapter to develop first order theoretical models with limited success. Complete models giving good quantitative accuracy have not been realized but the models as developed, together with the experimental results, have laid solid groundwork for a comprehensive approach to modelling. Some of the shortcomings of the present models are:

- 1) Some of the basic postulates may be inaccurate because the fundamental beam excitation processes in semiconductor materials have not been reported in adequate detail.

2) The inadequacy of the present models of unstimulated devices in treating back gate effects.

3) The inaccessibility of a simple method of determining potential anywhere within the substrate using only conventional transistors as test vehicles.

4) The difficulty in identifying the contribution of, and interactions between, the two possible short range mechanisms (i.e. increased substrate current and hole trapping) using only conventional transistors.

There is a general need for a more complete treatment of beam stimulation effects in semiconductor materials but this is, however, outside the scope of this thesis.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 Introduction

In this chapter the work reported is reviewed and conclusions drawn in terms of the objectives outlined in Chapter 1. Recommendations are made for future work and the implications for reliability analysis are discussed.

The interactions between SEM electron beams and GaAs FETs have been studied and the sensitivities of two important device characteristics, gate and channel current, to beam position, device biases and beam parameters have been investigated and relationships obtained. Wherever possible, models or possible explanations of the observed phenomena have been given. The work has been reviewed and suggestions for future work have been made.

11.2 Review and conclusions

Chapters 2, 3 and 4 set the scene for the original work by reviewing FET theory and how electron beams and photons stimulate semiconductors and GaAs FETs in particular. It was shown that photon transmission through the substrate was not the intermediate transport mechanism linking the effect of a remote beam to the increase in channel current.

After a discourse on the experimental equipment and techniques used in Chapter 5, Chapter 6 discussed the influence of the electron beam on the device parameters in terms of the Schottky barrier, the active channel and the substrate. It was concluded that both the Schottky gate current and the channel current were found to be sensitive to the electron beam but, rather surprisingly, the effects were independent under normal operating conditions so that they could be studied separately.

The possible causes of the induced changes in channel current were discussed in Chapter 6 in terms of the fundamental conductivity equation of a semiconductor. The possibilities of the beam causing changes in carrier concentration, mobility and channel dimensions were considered with the latter emerging as the most probable from a quasi-quantitative analysis of possible mechanisms.

The gate current stimulation process was studied in detail in Chapter 7 with good success. Methods were developed for measuring the effective diffusion lengths of beam generated carriers in both the active layer and in the semi-insulating substrate. A model was developed capable of predicting the induced current in each of four vertical regions of the device, the gate metal, the depletion region, the active layer and the substrate. Use was made of the in-situ measurements of the diffusion length generated carriers and allowance was made for the effects of the ohmic contacts.

The very complex channel current stimulation mechanism was studied in Chapters 8 to 10. In Chapter 8, the sensitivity of the induced current to the beam parameters in specific parts of the device were studied for the range of accelerating voltages and beam currents used in normal operation of the SEM.

When the beam was on the substrate the channel current increase was proportional to the square root of the beam current and the accelerating voltage to the power of 1.5 whereas when the beam was on the channel the channel current increase was proportional to the beam energy to the power of approximately 3.8 on the specific device measured.

The effects of drain and gate voltages on the beam stimulated current were found to be complex with peak sensitivities at intermediate voltages in each case. This further complicated the development of models to explain the beam stimulation process. Variations in the position of the active channel within the epitaxial layer caused by changes in thickness of both Schottky and back gate depletion layers resulted in significant differences in EBICC. It has been proposed that changes in the saturated carrier velocity resulting from changes in the internal electric field under the gate can explain these observations with fair success.

The long range effect has also been modelled in a way that explains all the major observed effects. The explanation involves beam induced carrier injection from

contacts into the substrate and consequent changes in the potential across the back gate resulting in changes in active channel width and hence channel current.

From the above, it is clear that the basic objectives of the thesis as outlined in Chapter 1 have been met although much additional work is necessary to put this work on a sound theoretical basis. This must await the development of better models of the unstimulated device. In particular, the back gate needs to be modelled in detail.

The results reported in this work can be used to test future models because the beam provides a means of locally modifying the characteristics of the back gate region. The work will also help reliability engineers and device designers to analyse devices more thoroughly in the SEM by pointing to the optimum biasing conditions to reveal defects, or to give the greatest amount of beam stimulation under any particular electron beam conditions. The results will also be useful in the rapidly advancing field of optically stimulated FETs. The possibility of utilizing the device as a high gain SEM detector which can provide direct amplification at low beam voltages should not be ignored. This work will provide a very useful basis for designing optimised devices in this field.

11.3 Suggestions for future work

The entire work in this thesis has utilized GaAs FET

devices. However considerable extra information could have been obtained if GaAs test structures made on FET wafers had been available. It is suggested that the following structures should be incorporated on a test wafer which would include normal FETs.

- 1) A large diameter Schottky diode to measure the active layer concentration profile.
- 2) Isolated electrodes on the substrate for localized control of substrate bias or monitoring substrate potential changes induced by the beam.
- 3) A region of epitaxial GaAs away from the channel which is not covered by contact metal, to study the sensitivity of n-type GaAs to beam stimulation.
- 4) A flip chip FET structure that can be irradiated by spectrally controlled light from the back (or by the electron beam).
- 5) A device with two channels, a common drain and multiple source electrodes. Only one channel would have a Schottky barrier gate. This would permit comparison of gated and ungated devices for electron beam and optical stimulation and allow more accurate measurement of short range effects.

Devices of these types with and without high resistivity epitaxial buffer layers up to 6 micrometers thick would help identify the sensitivity of the device to the chromium compensation process to beam current as 6 micrometers is the maximum electron beam penetration in GaAs at 40KV.

In view of the need for accurate knowledge of the sensitivities of channel current to beam parameters, further work is desirable to establish the validity of the relationships established in Chapter 8 for devices made by other manufacturers and with modified processing.

Other suggested future work should be concentrated on understanding the chromium compensation process in GaAs using the channel current changes as a monitor. A combination of electron beam stimulation and monochromatic light to stimulate or quench specific trap levels is thought to be a very suitable method. Further development of the two dimensional models of unstimulated GaAs FETs with concentration on the back gate and substrate effects is highly desirable.

11.4 Conclusion

It is believed that the work reported in this thesis provides a useful and practical source of information to both device designers and reliability engineers working in the fields of Failure Analysis and Destructive Physical Analysis. It will help them to observe how devices behave under different bias and stimulation conditions and to obtain the best experimental conditions to obtain the maximum beam stimulation effects.

Finally, it seems appropriate to repeat the preface to the excellent article by B. Schumacher[22] in which he quotes H.A. Lorentz, who said in 1906:

"The theory of electrons, on which I shall have the honour to lecture before you, already forms so vast a subject, that it will be impossible for me to treat it quite completely."

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APPENDIX 1

CHROMIUM DOPING AND THE SEMI-INSULATING SUBSTRATE

A good semi-insulating substrate is vital to satisfactory GaAs FET operation. Until recently, the only successful attempts to produce resistivities greater than 10 million ohm-centimeters in bulk GaAs involved the use of chromium doping to compensate for residual n-type impurities. These impurities are usually silicon or carbon, introduced from the crucible during crystal growth.

Little is known about the chromium trapping mechanism except that chromium in trivalent state substitutes for gallium in the lattice, producing a neutral level. The compensation process involves electron capture, reducing the overall positive charge in each trapped chromium atom to two. Chromium solubility limitations in GaAs reduce its overall ability to compensate to approximately 10^{16} atoms per cubic centimeter.

Before the discovery of chromium as a compensator by Cronin and Haisty,[5] oxygen doping was used to compensate. Oxygen is still almost always present and is found to play an important role in the compensation process.[35,36] The simple one trap mechanism is unable to explain the detailed changes in resistivity and mobility observed at different temperatures and a three or four level mechanism is

required, [36,39] involving shallow donors, deep donor and acceptor levels, and possibly a shallow acceptor. Photoconductivity studies [35 38-40] have shown that oxygen provides one of the levels and chromium two more.

The levels thought to be most important are shown in Figure A1.1. It seems to be generally believed that compensated chromium doped GaAs can be made photoconductive by light of greater than 1.25eV by promoting an electron from level 3 in Figure A1.1 to the conduction band. This leaves the substrate with a positive charge. Additionally, light of energy greater than 0.89eV is known to promote holes from the valence band to chromium level B at room temperature. [38]

Zucca [37] proposes that significant changes in electrical resistivity occur when the balance in occupancy of level 1 (oxygen, donor) and level A (chromium, acceptor) is altered. Lindquist [36] in his four level model proposes the same deep levels. Okamura et al [38] have found that the photoconductivity of SI GaAs depends on the ratio of chromium to oxygen with greater photoconductivity, when more chromium is present. They report instabilities in electric field within the crystal with long time constants following photoconductive stimulation which are attributable to charge trapping. Okamura et al derive expressions involving electron and hole, thermal and optical capture and emission rates for the chromium and oxygen sites to determine

Figure A1.1 Deep trap levels in chromium compensated GaAs including oxygen centres

photoconductivity. However, they point out that the individual photoconductivities depend upon individual crystal properties and that a competing process exists. Light of energy above 0.9eV generates holes which, because of their low mobility, only contribute slightly to increased conductivity. However, the increased hole concentration disturbs the balance of electrons and holes generated from oxygen level 1, reducing the number of electrons reaching the conduction band and hence reducing photoconductivity. (Electron mobility is much greater than hole mobility in GaAs.)

The author has been unable to find any detailed studies of the long time constant effects reported by several workers [35,38] who have treated the effects as an experimental inconvenience which should be eliminated by annealing at elevated temperatures. No mention has been made of electron beam induced effects either. The electron beam produces a spectrum of electron and lattice energies which will include energies below band-gap energy so that individual effects observed for light stimulation should also be present.

```
C      PROGRAM IGVEB2 . FORTRAN 4 ON SIGMA 9.
C      THIS PROGRAM CALCULATES THE ELECTRON BEAM
C      INDUCED GATE CURRENT OF A GALLIUM-ARSENIDE
C      FIELD EFFECT TRANSISTOR WHEN STIMULATED
C      BY AN ELECTRON BEAM.
C      REAL LDIF3,LDIF4
C      REAL LDIF,LDEP,NY
C      SET DIFFERENT GATE VOLTAGES
C      DO 100 NVG=2,4,1
C      VGS=-(NVG-1)/2.
C      SET DIFFERENT DIFFUSION LENGTHS FOR REGION 3
C      DO 100 LD3=4,6,1
C      LDIF3=LD3/20.
C      DEFINE RANGE OF DIFFUSION LENGTHS FOR
C      REGION4.
C      DO 100 LD4=1,5,1
C      IF(LD4.EQ.1) LDIF4=0.01
C      IF(LD4.EQ.2) LDIF4=.1
C      IF(LD4.EQ.3) LDIF4=.25
C      IF(LD4.EQ.4) LDIF4=.5
C      IF(LD4.EQ.5) LDIF4=1.4
C      DEFINE INITIAL CONDITIONS AND MATERIAL
C      DENSITIES.
C      DW IS ELEMENT OF GATEWIDTH; DX IS ELEMENT
C      OF LENGTH PERPENDICULAR TO GATEWIDTH.
C      ROAL=2.7
C      ROGAAS=5.32
C      DAL=0.57
C      DNPLUS=.195
C      EB=0
C      XB=0
C      ZB=0.0
C      DW=0.1
C      DX=.05
C      MAXWP=(250-ZB)/DW
C      MAXWN=ABS((-250-ZB)/DW)
C      H=0
C      PI=3.14159
C      SET CONDITIONS FOR BEAM BEYOND GATE
C      IF(ZB.GT.250.OR.ZB.LT.-250) H=.4
C      IF(ZB.GT.253.OR.ZB.LT.-253) DAL=0
C      DEFINE BEAM CURRENT
C      XIPI=.5E-9
C      BSF=.3
C      DDEP=.115*SQRT(.8726-VGS)
C      DACL=DNPLUS-DDEP
C      IF(ZB.GT.245.AND.ZB.LT.250) DDEP=.2
C      IF(ZB.LT.-245.AND.ZB.GT.-250) DDEP=.2
C      LDEP=1+2*DDEP
C      MAXXP=(0.5-LDEP-XB)/DX
C      MAXXN=(0.5-LDEP+XB)/DX
C      CALC GAAS EQUIV. THICKNESS OF AL GATE METAL
```

```

EFGAAS=DAL*ROAL/ROGAAS
OUTPUT(108)
XIPR9=XIPR*1E+9
WRITE(103,101)
101  FORMAT ('GAAS FET GATE CURRENT CAUSED BY ELECTRON BEAM')
      WRITE(108,102)
      WRITE(108,103)
      WRITE(108,104) DAL
      WRITE(108,117) EFGAAS
      WRITE(108,105)
      WRITE(108,106)VGS
      WRITE(108,107)DDEP
      WRITE(108,108)LDIF3
      WRITE(108,109)LDIF4
      WRITE(108,110)XIPR9
      WRITE(108,111)
      WRITE(108,112)
102  FORMAT(//, 'HEWLETT PACKARD EXPERIMENTAL GAAS FET',//)
103  FORMAT('  GATE LENGTH =1.0          GATE WIDTH =5.0')
104  FORMAT('  GATE METAL THICKNESS =',F5.2)
105  FORMAT('  EPI LAYER THICKNESS =0.20')
106  FORMAT('  GATE SOURCE VOLTAGE =',F5.2)
107  FORMAT('  DEPLETION LAYER =',F6.3)
108  FORMAT('  NPLUS DIFFN. LENGTH =',F7.4)
109  FORMAT('  S.I. DIFFN. LENGTH =',F7.4)
110  FORMAT('  BEAM CURRENT (NA) =',F8.2)
111  FORMAT('  BACK SCATTERING COEFF.=0.3')
112  FORMAT('  ALL LENGTHS ARE IN MICROMETERS')
117  FORMAT('  EFFECTIVE GAAS THICKNESS OF GATE METAL=',F5.2)
      OUTPUT(108)
C    WRITE QU? BEAM CURRENT,BEAM POSN(FROM CENTRE)AND DIFFN
C    LENGTH IN MICRONS
      WRITE(108,113)
      WRITE(108,114)
      WRITE(108,115)
C    INCREASE BEAM VOLTAGE
      DO 100 IEB=1000,40000,1000
      SCCGE2=0
      SCCGE3=0
      SCCGE4=0
      SCCGE=0
      EB=IEB/1000
C    CALCULATE RANGE RG
      RG=0.027*EB**1.46
C    ALLOW FOR BACKSCATTERING
      XI=XIPR*(1.0-BSF)
C    CALCULATE TOTAL CARRIERS GENERATED FROM EBS DIODE EQU.
      CCTOT=IEB*XI/(4.6*1.6E-19)
C    LOOP CALCS GENERATED CARRIER DENSITY AT DEPTH NY
C    REGION1 IS METAL GATE. YM IS FRACTION OF RANGE RG
C    IN METAL
      IF(RG.LE.EFGAAS) DELIG1=XI;GO TO35
      YM=EFGAAS/RG
      EDSM=.6*YM+3.105*YM*YM-4.13*YM**3+1.423*YM**4
      DELIG1=EDSM*XI
C    DELIG1 IS CURRENT IN GATE GENERATED BY BEAM

```

```

C   REGION 2 IS DEPL REGION .ALL CARRIERS ARE COLLECTED
    YD=(EFGAAS+DDEP)/RG
    IF(YD.GE.1.0) EDDEPL=1.0-EDSM;GO TO 27
    EDDEPL=.6*YD+3.105*YD*YD-4.13*YD**3+1.423*YD**4-EDS
27  CCGE=EDDEPL*CCTOT
    SCCGE2=SCCGE2+CCGE
    RY=RG-YD*RG
    IF(YD.GE.1.0) GO TO 35
82  CONTINUE
    DACL1=DACL+.1
    Y=0.0
    DO150 N=1,200,1
    IF(Y.GE.DACL1)/YINT=.1;GO TO 91
    YINT=.01
91  Y=Y+YINT
C   YR IS TOTAL FRACTION OF RANGE RG AT DEPTH Y
    YR=(Y-YINT/2.)/RG+YD
    IF(Y.GT.RY) GO TO25
    EYR=.6+6.21*YR-12.4*YR*YR+5.69*YR**3
    CCDY=EYR*YINT*CCTOT
    IF(Y.GE.DACL+.1) CCDY=EYR*.1*CCTOT
84  CONTINUE
    NP=0
C   CALCULATE FOR ALL GATEWIDTH ELEMENTS
    DO 300 NW=1,MAXWP,1
    CCDWTOT=0
    W=NW*DW
    DO 300 NX=1,MAXXP,1
    X=NX*DX
    R=SQRT(W*W+Y*Y+X*X)
    TH=ATAN(SQRT(W*W+X*X))
    SA=DX*DW*COS(TH)/(4*PI*R*R)
    IF(SA.GE.0.5) SA=0.5
    GCDW=CCDY*SA*2.
C   REGION 3OR 4, CALC EXPNT FOR REGION 3
    IF(Y.LE.DACL) EXPNT=EXP(-R/LDIF3); GO TO 41
C   CALC EXPNT FOR REGION 4
    RACL=DACL*R/Y
    RSI=(Y-DACL)*R/Y
    IF(RSI.LT.0.OR.RACL.LT.0)OUTPUT(108)NW, 'STOP2'
    CE=-RACL/LDIF3-RSI/LDIF4
    EXPNT=EXP(CE)
    GO TO 42
C   CALC TOTAL CONCS FOR REGIONS 3 AND 4
41  CCGE=CCDW*EXPNT
    IF(NW.EQ.1.AND.N.EQ.1) CCGE1=CCGE
    CCGE2=CCGE*100.
    IF(CCGE2.LT.CCGE1)GO TO 20
    SCCGE3=SCCGE3+CCGE
C   OUTPUT(108)SCCGE3
    GO TO 300
42  CCGE=CCDW *EXPNT

```

```

C      TOTAL CONC FOR REGION 4
      IF(NW.EQ.1.AND.N.EQ.1) CCGE1=CCGE
      CCGE2=CCGE*100.
      IF(CCGE2.LT.CCGE1)GO TO 20
      SCCGE4=SCCGE4+CCGE
C      OUTPUT(108)SCCGE4
300    CONTINUE
20     CONTINUE
25     CONTINUE
150    CONTINUE
C      CONVERSION OF NO. OF CARRIERS TO CURRENT
35     CONTINUE
      CCTOT1=CCTOT/1E+9
      SCCGE=SCCGE2+2.*(SCCGE3+SCCGE4)
      DELIG1=DELIG1*1E+9
      DELIG2=1.6E-10*SCCGE2
      DELIG3=1.6E-10*SCCGE3*2.
      DELIG4=SCCGE4*1.6E-10*2.
      DELIG=1.6E-10*SCCGE+DELIG1
113    FORMAT(T7,'ACCEL'  TOTAL',T23,'PENET',T30,'IG',T34,
&'IN',T38,'IG',
& T42,'IN',T47,'IG',T50,'IN',T55,'IG',T58,'IN',
& T63,'OVERALL',2X)
114    FORMAT(6X,28HVOLT E-H PAIR RANGE METAL,2X,
& 32HDEPL REG NPLUS SI LAYER INC IN)
115    FORMAT(6X,35H KV      E+9      E-6M      NA      NA,6X,
& 22HNA      NA      IG NA,2X,/)
      WRITE(108,116)EB,CCTOT1,RG,DELIG1,DELIG2,DELIG3,
&DELIG4,DELIG
116    FORMAT(7X,I2,3X,F8.2,3X,F4.2,2X,F4.2,2X,4F8.2)
100    CONTINUE
      STOP
      END

```

APPENDIX 3

GaAs FET GATE CURRENT CAUSED BY ELECTRON BEAM

HEWLETT PACKARD EXPERIMENTAL GAAS FET

GATE LENGTH = 1.0 GATE WIDTH = 500
 GATE METAL THICKNESS = .57
 EFFECTIVE GAAS THICKNESS OF GATE METAL = .29
 EPI LAYER THICKNESS = 0.20
 GATE SOURCE VOLTAGE = -1.00
 DEPLETION LAYER = .157
 NPLUS DIFF. LENGTH = .2500
 S.I. DIFF. LENGTH = 2500
 BEAM CURRENT (nA) = .50
 BACK SCATTERING COEFF. = 0.3
 ALL LENGTHS ARE IN MICROMETERS

ACCEL VOLT KV	TOTAL E-M PAIR E-9	PENET RANGE E-6M	IG IN METAL nA	IG IN DEPL nA	IG IN REG nA	IG IN NPLUS nA	IG IN SI LAYER nA	OVERALL IG IN nA
1	475.54	.03		.00	.00	.00		.35
2	951.09	.07		.00	.00	.00		.35
3	1426.63	.13	.35	.00	.00	.00		.35
4	1902.17	.20	.35	.00	.00	.00		.35
5	2377.72	.28	.35	.00	.00	.00		.35
6	2853.26	.37	.32	33.36	.00	.00		34.19
7	3328.80	.46	.23	104.45	.20	.00		104.93
8	3804.34	.56	.23	160.93	2.83	2.83		166.48
9	4279.89	.67	.19	193.39	4.73	12.09		210.41
10	4755.43	.78	.16	228.16	6.89	24.92		240.13
11	5230.97	.89	.14	212.01	8.77	38.71		259.63
12	5706.52	1.02	.12	209.54	10.40	51.42		271.47
13	6182.06	1.14	.10	203.63	11.78	63.19		278.70
14	6657.60	1.27	.09	195.97	12.97	73.86		282.90
15	7133.14	1.41	.08	187.59	14.00	83.47		285.15
16	7608.69	1.55	.07	179.07	14.90	92.02		286.07
17	8084.23	1.69	.06	170.73	15.69	99.69		285.17
18	8559.77	1.84	.05	162.76	16.40	106.55		285.76
19	9035.32	1.99	.05	155.24	17.04	112.72		285.05
20	9510.86	2.14	.04	148.20	17.62	118.32		284.18
21	9986.41	2.30	.04	141.54	18.16	123.41		283.25
22	10461.95	2.46	.04	135.56	18.65	128.07		282.32
23	10937.49	2.63	.03	129.92	19.12	132.37		281.44
24	11413.04	2.80	.03	124.69	19.56	136.36		280.64
25	11888.58	2.97	.03	119.85	19.98	140.08		279.94
26	12364.12	3.14	.03	115.36	20.38	143.57		279.33
27	12839.66	3.32	.03	111.19	20.77	146.87		278.85
28	13315.21	3.50	.02	107.31	21.14	150.00		278.47
29	13790.75	3.69	.02	103.70	21.50	152.98		278.21
30	14266.29	3.87	.02	100.34	21.86	155.84		278.06
31	14741.84	4.06	.02	97.20	22.20	158.59		278.02
32	15217.39	4.25	.02	94.27	22.55	161.25		278.08
33	15692.92	4.45	.02	91.52	22.88	163.82		278.25
34	16168.46	4.65	.02	88.95	23.21	166.33		278.51
35	16644.01	4.85	.02	86.54	23.54	168.77		278.87
36	17119.55	5.05	.02	84.26	23.87	171.17		279.31
37	17595.09	5.26	.01	82.12	24.19	173.51		279.84
38	18070.64	5.47	.01	80.11	24.51	175.82		280.45
39	18546.17	5.68	.01	78.20	24.84	178.09		281.14
40	19021.72	5.89	.01	76.40	25.15	180.33		281.90

GAAS FET GATE CURRENT CAUSED BY ELECTRON BEAM

HEWLETT PACKARD EXPERIMENTAL GAAS FET

GATE LENGTH = 1.0 GATE WIDTH = 500
 GATE METAL THICKNESS = .57
 EFFECTIVE GAAS THICKNESS OF GATE METAL = .29
 BACK SCATTERING COEFF. = 0.3

10FF

CPU = 1.5572 CDB = 00:23:00 INT = 81 CHG = 8 5.00

HONEYWELL CP-V AT YOUR SERVICE - CROC
 12:07 APR 24 '80 ID# 12 LINE# 22 USERS= 25 ETP# 4
 LOGON PLEASE:

END

1 7 1 2 8 1

FIN