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THE IMPLANTATION OF DONOR IONS INTO GALLIUM ARSENIDE FOR FIELD EFFECT TRANSISTORS

by

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Thesis presented for the Degree of Doctor of Philosophy

at

The Department of Electronic and Electrical Engineering,
University of Surrey,

1983
The purpose of the work described in this dissertation was to investigate the use of donor ion implantation into GaAs for the production of doped layers suitable for the manufacture of Schottky gated field effect transistors or MESFETs. The project had four main aims:-

(i) The establishment of a reliable method of encapsulation.
(ii) A study of the use of short thermal pulse annealing to activate donor ions implanted into GaAs.
(iii) An investigation of various ion implantation schedules to determine the most suitable for producing layers for MESFETs.
(iv) The manufacture and characterisation of MESFETs on ion implanted material. This area of the project was performed at the Allen Clark Research Centre (Plessey Research, Caswell).

Two sets of apparatus were constructed to achieve the rapid deposition of $\text{Si}_3\text{N}_4$ encapsulating layers. Both sets of equipment allowed the deposition of reliable encapsulating layers which protected the GaAs from decomposition during high temperature ($900^\circ\text{C}$) annealing. With the second apparatus uniform layers of $\text{Si}_3\text{N}_4$ could be deposited over one inch diameter slices.

The rapid thermal pulse annealing was also performed in the $\text{Si}_3\text{N}_4$ deposition equipment. The annealing temperature ($900^\circ\text{C}$) was reached in less than 10 seconds. It was found, by examining the degree of electrical activation of implanted ions, that a total of 30 seconds annealing was sufficient to achieve the maximum number of implanted ions that could be activated at $900^\circ\text{C}$.

Several species of ions, implanted at various energies, were studied as suitable donors using thermal pulse annealing. These included selenium, tellurium, germanium, tin and silicon. Additionally the implantation of dual ion combinations, and the co-implantation of selenium ions at two energies was investigated. The results of Hall measurements and profiling achieved in this study compare favourably with those reported in the literature for similar implants annealed in more conventional furnace annealing schedules.

The characterisation of MESFETs produced on implanted layers compare favourably with those manufactured on epitaxially grown material, both in terms of gain and noise figure. It was found also that characteristics of these MESFETs depended on the type of substrate used. The I-V characteristics of devices produced on bulk semi-insulating material were slightly inferior to those produced on epitaxial buffer layers, although the microwave performance was not significantly worse.
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This thesis is dedicated to my wife, children and parents.
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1. **THE GaAs MESFET**

1.1 **Introduction**

The superior high frequency performance of GaAs field effect transistors (FETs) compared with silicon bipolar transistors has resulted in their establishment as important devices in a variety of microwave and high speed logic applications. Two types of GaAs FET are of major interest. These are the MESFET (Metal-Semiconductor or Schottky Barrier gated FET) and the JFET (p-n Junction gated FET). The MOSFET (Metal Oxide FET) is also of interest, but suffers from difficulties associated with the oxide used to produce the gate.

MESFETs are generally operated in the depletion (normally on) mode. In this mode a current flows between source and drain unless a voltage is applied to the gate. MESFETs are of particular interest for very high frequency operation, for example Yamasaki et al have fabricated low noise MESFETs with 4.1dB gains at 29GHz\(^{(1)}\). MESFETs with very wide gates can be used to generate microwave power. S. Igi et al have fabricated MESFETs, operating at 5W with 5dB gains at 10GHz\(^{(2)}\). MESFETs have also been utilised in a variety of integrated circuit applications. The range of circuit applications is too wide to be reviewed here, but details may be found elsewhere\(^{(3)-(4)}\).

The JFET is inherently slower in operation than the MESFET due to minority carrier effects in the gate region. However, the JFET does offer the advantage of enhancement mode (normally off) operation. In this mode a source to drain current flows only when a voltage is applied to the gate. Thus the JFET offers lower power consumption than the MESFET, which makes it particularly attractive for integrated circuits where low power consumption per gate is vital. For example, Kasahara et al\(^{(5)}\) have fabricated a 15 stage oscillator with fully ion implanted JFETs. The power delay time product of these enhancement mode devices was 34fJ/gate, the lowest figure reported to date.
In this chapter the physical processes determining the operation of the MESFET are discussed. The theory presented here requires only slight modification to describe the operation of the JFET and MOSFET. Particular attention is paid to devices with gate lengths of 1 μm or greater, as these were chosen as suitable for experimental study. The major research interest worldwide is now in the production of FETs with submicron gate lengths. This is necessary in order to increase the maximum operational frequency. Submicron geometry devices are considered separately in section 1.8.

1.2 Electron Velocity Saturation in GaAs

The electrical characteristics of the GaAs MESFET are dictated by the phenomena of electron velocity saturation, and not by pinch-off as in more conventional FETs as described by the well known Shockley theory(6). This is because the small separation of electrodes needed for microwave operation produces high internal fields even under modest bias conditions, and at high field the electron velocity reaches a saturation value. To understand the dependence of electron velocity upon electric field it is necessary to consider the band structure of GaAs (figure 1). At low fields electrons with sufficient energy to escape the valence band are located in the lower valley of the conduction band. Here the relationship between velocity and applied field is given by

\[ \frac{dv}{dt} = -\frac{q \xi}{m^*} \]  

\[ (1) \]

where \( q \) is the electron charge, \( \xi \) the applied field, and \( m^* \) the electron effective mass in the lower valley.

\[ m^* = \frac{\hbar^2}{d^2E/dk^2} \]  

\[ (2) \]

where \( \hbar = \text{Planck's constant}/2\pi \), \( k \) = electron wave vector, \( E \) = electron energy.

Thus for constant electron mass the electron velocity is
Figure 1  Energy Band Structure of GaAs
v = \xi \mu \quad (3)

where \( \mu \) = electron mobility.

The dependence of velocity upon applied field is shown for electrons in silicon in figure (2). It can be seen that at low fields the electron velocity is proportional to the applied field, as predicted by equation 3. At high fields however the effective temperature of the electrons exceeds the lattice temperature, and the electrons lose energy to the lattice by phonon interactions. Consequently the electron velocity reaches a saturation value dictated by the silicon lattice temperature.

In GaAs the possibility of inter-valley transitions complicates the velocity field dependence, also shown in figure (2). At low fields the electron velocity increases linearly with increasing applied field, and attains a maximum velocity significantly greater than electrons in silicon, as the mobility of electrons in the lower valley of GaAs is approximately four times that of electrons in silicon. As the field is increased, however, the electrons acquire sufficient momentum to transfer to the upper valley. Here the effective electron mass is 17.6 times greater than in the lower valley, and the mobility is 40-80 times lower. The electron velocity therefore decreases and starts to obey a second linear dependence upon field. This is shown schematically in figure (3) for a theoretically possible semiconductor. At high fields, however, the electron energy again starts to exceed the lattice temperature, and phonon interactions result in velocity saturation at the same level observed in silicon, approximately \( 1 \times 10^7 \text{ cm s}^{-1} \).
Figure 2  Velocity-Field Dependence of Electrons in Silicon and GaAs.

Figure 3  Possible Velocity-Field Dependence of a Two Valley Semiconductor.
1.3 The GaAs MESFET - Physical Model

The basic GaAs MESFET structure is shown in figure (4). Essentially the device consists of two ohmic contacts (the source and drain electrodes) separated by a short, conducting channel. A rectifying contact (the gate electrode) is located between the source and drain electrode, and is used to modify the current between the ohmic contacts. The entire structure is formed by photolithographic techniques on a thin n-type layer on a semi-insulating substrate. Each device is usually isolated from neighbouring devices on the same substrate by MESA etching through the n-type layer. This also allows the gate contact pad to be located directly onto the semi-insulating substrate, and so reduce the gate capacitance.

1.3.1 Current Voltage Characteristics with no Gate Electrode

Prior to gate deposition the device consists of two ohmic contacts separated by a narrow resistive region. On the application of a bias between the two electrodes a uniform field is developed, and a current flows. The magnitude of this current is given by

\[ I_{DS} = W q N_D v d \] (4)

where \( W \) = channel width, \( N_D \) = donor density, \( v \) = electron velocity and \( d \) = conducting layer thickness.

At sufficiently high drain bias \( V_D \) the field between source and drain reaches the value producing the peak electron velocity. At this value the source-drain current reaches a maximum value, as shown in figure (5). Any subsequent increase in \( V_D \) leads to a decrease in current until the saturation velocity is reached, resulting in a saturation value of the source-drain current. Consequently, devices operated between the maximum current and the saturation current display negative dynamic resistance. A family of devices utilising this effect are termed Transferred Electron Devices (TEDs), the most significant being the Transferred Electron Oscillators (TEOs) sometimes known as Gunn oscillators.
Figure 4  MESFET Structure

Figure 5  Variation of Source-Drain Current with Voltage Prior to Gate Deposition
1.3.2 Effects of the Gate Electrode at Zero Bias

The introduction of a gate electrode in the channel region radically alters the field distribution between the source and drain. The field now decreases from its maximum value on the drain side of the gate, to a minimum value at the source. Also, because of the built-in potential of the Schottky barrier, a depletion region is set up beneath the gate electrode. Since there is a non-uniform field distribution, this depletion region extends deeper under the gate edge on the drain side than on the source side (fig. 6). The depletion region reduces the width of the conducting channel, and the magnitude of the current in the channel is now given by

\[ I_{DS} = W q N(y) v(y) d(y) \]  

where \( d(y) \) is the conducting channel width beneath the gate, \( N(y) \) is the carrier concentration. The dependence of \( N, v \) and \( d \) upon distance is incorporated to account for the variation due to the shape of the depletion region.

When the drain voltage is sufficiently large, velocity saturation starts to occur at the point of maximum field, which is also the point of maximum depletion. We shall denote the channel width at which saturation occurs as \( d_0 \). At higher drain voltages the depletion region extends further and the channel width becomes less than \( d_0 \) over a finite distance, as shown in figure (6b). As the velocity is saturated throughout this region any increase in applied field cannot be accommodated for by an increase in velocity. Consequently, in order to maintain constant current a negative space charge region is formed (where \( d < d_0 \)) in order to increase \( n(y) \) in equation (5). To compensate for the excess charge in this region a positive space charge region is formed by partial electron depletion between the gate and drain, commencing at the point where the channel width again exceeds \( d_0 \).
Depletion region

Figure 6 Effect of Bias Condition on Depletion Region

6A At onset of current saturation
   $V_g = 0$

6B Current Saturated
   $V_g = 0$

6C Current Saturated
   Gate reverse biased
Two dimensional computations\(^{(7)}\) show that almost the entire field is dropped between the positive and negative space charge regions. The predicted variation of field, mobility and drift velocity in the channel region of an FET with a 3\(\mu\)m gate length are shown in figure (7).

1.3.3 Effects of Gate Bias

For normal operation the gate electrode is reverse biassed, which increases the field in the channel region and increases the depth of the depletion region. At low drain bias, before velocity saturation occurs, the conducting cross-section is reduced due to the increase in depletion depth, and the resistance is increased. Velocity saturation occurs at lower drain bias because the field is increased by the gate voltage. The value of the saturated current is also reduced as less carriers are available because the conducting channel width is reduced. Thus, because the source drain current is dependent upon the applied gate voltage it is necessary to plot a series of I-V curves as a function of gate voltage to describe fully the behaviour of a MESFET, as shown in figure (8). The MESFET is normally operated in the saturation range, where the source drain current is independent of the drain voltage, \((V_{DS} > V_s)\).

At very large drain voltages avalanche breakdown of the gate-drain diode can occur, leading to a sudden increase in the source-drain current. This phenomenon provides the upper limit of drain bias \((V_{DS} = V_B)\).

At large gate voltages the depletion region extends completely through the n-type layer and no current flows between source and drain. This situation is referred to as pinch off, \((V_G = V_p)\).
Figure 7  Variation of Field, Mobility and Velocity across MESFET Channel
\[ V_G = -1\, \text{V}, \, l_G = 3\, \mu\text{m}, \, V_D = a) \, 0.5, \, b) \, 1, \, c) \, 3\, \text{V} \]

Figure 8  I-V Curve of MESFET
The relationship between the gate voltage and the source drain current is given by

$$g_m = \frac{dV_{DS}}{dV_g}$$  \hspace{1cm} (6)

where $g_m$ is defined as the TRANSCONDUCTANCE of the device. The importance of the transconductance in determining the noise and gain characteristics of the GaAs MESFET will be discussed in following sections.

1.4 Equivalent Circuit of the GaAs MESFET

The simple lumped-element circuit shown in figure (9) has been shown to represent the behaviour of the GaAs MESFET operating in the common-source configuration. The physical location of the circuit elements is shown in figure (9b).

$$(C_{dg} + C_{gs})$$ represents the total gate to channel capacitance.

$C_{dc}$ the capacitance of the space charge dipole.

$R_i$ and $R_{ds}$ represent the effect of channel resistance.

$R_s$, $R_d$ and $R_g$ represent the effects of contact and metallisation resistances, and the resistance of the n-type material.

The resistance $R_g$ is particularly important as the measured transconductance $g_m$ is related to the transconductance of the intrinsic device, $g'_m$, by the relationship (8)

$$g_m = \frac{g'_m}{1 + R_s g'_m}$$  \hspace{1cm} (7)

Thus, for high transconductance the source-gate resistance should be minimised.

$i_{ds}$ defines the value of the gate voltage controlled current source responsible for the saturated value of source-drain current.

The magnitude of $i_{ds}$ is related to the transconductance and the gate voltage by the equation

$$i_{ds} = \frac{v_c}{g_m} g_m \exp(-j\omega r_o)$$ \hspace{1cm} (8)
Figure 9  Circuit Elements of MESFET

9A Equivalent Circuit
9B Physical origin of Circuit Elements
where $V_c$ is the voltage dropped between the gate and channel, and $\tau_o$ represents the carrier transit time in the region under the gate.

\[\text{i.e. } \tau_o \propto \frac{L}{V_S} \]  

(9)

Thus, the frequency of unity gain $f_T$ is given by

\[f_T = \frac{1}{2\pi} \frac{V_S}{L} \]  

(10)

For a 1\mu m gate length the maximum frequency of a GaAs MESFET is $\sim 30$GHz.

In order to improve the high frequency performance it is necessary to decrease the gate length. Shorter gate lengths are not possible with conventional photolithographic techniques, and electron beam, X-ray or deep UV lithography can be used to reduce further device geometry, and increase the frequency range of operation.

1.5 Noise Behaviour of the GaAs MESFET

The noise behaviour of the GaAs MESFET has been discussed by Baechtold (9) and Pucel et al (10).

Basically the noise behaviour can be considered by representing the practical MESFET as a noiseless device, with noise generators connected across the input and output ports, as shown in figure (10).

The noise sources can be split into two major components:

1.5.1 Noise Current Generated in the Source Drain Region $i_{nd}$

The mean square noise drain current generated in the source drain path can be expressed by

\[i_{nd}^2 = 4kT_o \Delta f g_m P \]  

(11)

where $k$ = Boltzmann constant, $T_o$ = Lattice temperature

$\Delta f$ = bandwidth  

$g_m$ = transconductance

$P$ = a factor dependent upon device geometry and bias conditions.
Figure 10  Simplified Equivalent Circuit of MESFET used to Represent Noise Behaviour in Common Source Configuration
The factor $P$ takes into account

(i) Thermal noise generated in the channel.

(ii) Hot electron noise due to lattice phonon scattering.

(iii) Intervalley scattering noise.

(iv) High field diffusion noise in the velocity saturated region.

1.5.2 Noise Generated in the Conducting Channel Beneath the Depletion Region $- \mathbf{i}_{\text{ng}}$

A noise voltage generated beneath the gate causes modulation of the depletion width, resulting in a charge fluctuation in the depletion region. This results in an induced charge fluctuation at the gate electrode represented by

$$\mathbf{i}_{\text{ng}} = \frac{4k T \Delta f W^2 C_s^2 R}{g_m}$$  \hspace{1cm} (12)

$R$ is another factor dependent upon FET geometry and bias conditions.

Pucel has shown $^{(10)}$ that the minimum noise figure of the intrinsic FET can be expressed by

$$F_{\text{min}} = 1 + 2\sqrt{P R (1 - C^2)} \frac{f}{f_T} + 2g_m R_{\text{i}} P(1 - C/\sqrt{R}) \left(\frac{f}{f_T}\right)^2$$  \hspace{1cm} (13)

$F_{\text{min}}$ = minimum noise figure

$f$ = operating frequency

$C$ = a factor correlating the noise currents $\mathbf{i}_{\text{ng}}$ and $\mathbf{i}_{\text{nd}}$

In practice devices are normally operated at an optimised drain current ($I_{DS}/I_{DSS} \approx 0.15$) in order to reduce the noise component due to diffusion noise. Hewitt et al $^{(11)}$ have derived an expression to describe the optimum noise figure in terms of the MESFET geometry and the characteristics of the n-type layer. The effects of the parasitic resistances are incorporated in the expression, which gives excellent agreement with measured optimum noise figures. According to Hewitt
\[ F_0 = 1 + K_{FL} \left( \frac{5}{6} \right)^{1/6} \left( \frac{N_D}{a} \right)^{1/6} \left[ \frac{3.3}{L} \frac{R_C}{L} + \frac{1.8}{N_D} \frac{L_{SG}}{d} + \left( \frac{\frac{1.8}{N_D} \frac{R_C}{a} \right)^{1/2} \right] \]  

(14)

- **\( F_0 \)** = optimum noise figure
- Here \( L_{SG} \) = source-gate separation
- \( R_C \) = source contact resistance
- \( R_G \) = gate resistance
- \( K \) = coefficient depending on the quality of the GaAs material
- \( a \) = effective depth of n type layer beneath gate
- \( d \) = active layer thickness.

The above equation holds for frequencies significantly less than \( f_T \), where the linear term in equation (13) predominates. Also, the equation is only strictly true for uniformly doped n-type layers but can approximate the behaviour of layers produced by ion implantation, provided suitable average values of donor concentration and depth are chosen.

### 1.6 Choice of GaAs Material

#### 1.6.1 Material Quality

In equation (14) above, the factor \( K \) is used to account for the differences due to material quality and is derived empirically for any particular material. Variations in \( K \) are due to differences in deep level concentration, due for example to point defects within the GaAs.

For epitaxial material lowest noise figures have been measured in devices fabricated on GaAs grown by the trichloride technique \((12)\). In this process GaAs is formed by the reaction between \( \text{AsCl}_3 \) and Ga. Other vapour-phase techniques such as the hydride technique (where the GaAs is formed by reaction between \( \text{AsH}_3 \), Ga and HCl or \( (\text{CH}_3)_3\text{Ga and AsH}_3 \)) produce material with a greater number of defects. Consequently devices fabricated on GaAs grown by the hydride technique exhibit
higher noise figures.

Devices with the lowest noise figures to date have been produced on epitaxial material grown by the trichloride technique on epitaxial buffer layers (13). Here the buffer layer is undoped, and restricts the outdiffusion of chromium from the semi-insulating substrate into the n-type layer during growth. The effect of the buffer layer upon the electrical characteristics of the n-type layer is dramatic. The doping profile is sharpened, and high values of mobility are observed up to the interface between the n-type and buffer layers.

Butlin et al (13) have shown that I-V characteristics of MESFETs produced on material with a buffer layer exhibit low sensitivity to light and display virtually no hysteresis. The transconductance of these devices were less variable with gate voltage, and the noise figures were significantly less than devices produced on material grown with no buffer layer.

1.6.2 Active Layer Considerations

The two important parameters of the active n-type layer that need to be optimised are the doping level and depth. Pucel has shown (14) that the source-drain current and gate bias can be expressed, to a good approximation, by simple integral functions of the doping profile and the depletion layer depth.

\[ I_{DS} = q v_s W \int_s^d N_D(x) \, dx \]  

(15)

\[ V_g = \frac{q}{e_0} \int_s^0 x N_D(x) \, dx \]

(16)

where \( N_D(x) \) represents the donor concentration for an arbitrary doping profile

\[ x = \text{depth from surface} \]

\[ q = \text{electronic charge} \]

\[ v_s = \text{saturated velocity} \]
\[ W = \text{gate width} \quad d = \text{active layer thickness} \]

\[ s = \text{depletion depth} \]

Now since \( g_m = \frac{dI_{DS}}{dV_g} \) we have from (15) and (16)

\[ g_m = \frac{\varepsilon \varepsilon_o v_g W}{S(V_g)} \quad (17) \]

Hence the transconductance is related to the doping level by the gate voltage dependent depletion depth derived from equation (16).

For a uniformly doped layer equation (17) reduces to

\[ g_m = v_s W \left( \frac{q N_D \varepsilon \varepsilon_o}{2 \varepsilon_o} \right)^{\frac{1}{2}} \quad (18) \]

where \( N_D \) is the doping level.

Thus for the highest possible transconductance it is necessary to maximise the doping level. The maximum doping level possible in the active layer is however limited due to breakdown of the gate under reverse bias. Under normal operating conditions the source-drain bias is +5V, and the maximum source-gate bias at pinch off is about -3V. Thus the potential difference between the gate and drain is about 8V. Therefore the maximum doping level beneath the gate is about \( 3.10^{17} \text{ cm}^{-3} \), as layers of higher electron concentration cannot sustain fields of this magnitude (15). The maximum thickness of the doped layer is determined by both the breakdown field at the doping level of the layer, and the depletion layer thickness. In figure (11) the depletion layer width at breakdown is plotted as a function of doping level. Provided the doped layer is thinner than this thickness the layer may be fully depleted without breakdown occurring, and pinch off achieved. Also shown in figure (11) is the variation of depletion width with doping level, at zero and reverse biases. The depletion depth is calculated using the approximation:

\[ S = \sqrt{\frac{2 \varepsilon \varepsilon_o (V_{bi} \pm V_g)}{qN_D}} \]
Figure 11 Dependence of Depletion Depth Upon Carrier Concentration and Gate Bias
where $V_{bi}$ = Built-in voltage of the Schottky barrier.

Active layers produced by ion implantation are not normally uniformly doped because of the Gaussian nature of the implantation technique.

William and Shaw (16) have examined the dependence of transconductance upon doping profile, and concluded that a stepped profile would be the most desirable in that the transconductance would then be independent of gate voltage. The same authors (16) were able to approximate a true step function profile by growing layers with exponentially varying doping levels. Devices produced on these layers displayed an almost linear dependence of $I_{DSS}$ on gate voltage (constant $g_m$). Thus at optimum bias conditions (low $I_{DSS}$) the transconductance was not reduced from that obtained at zero gate voltage, and so high operational gains were measured.

The effects of variations in doping level upon FET characteristics have also been considered by Higgins et al (17). Their approach was to model the channel by a series of thin laminar layers of varying doping levels. Their conclusion was that peaked profiles obtained by ion implantation should enable the production of devices with characteristics superior to those fabricated in uniformly doped layers. Specifically it was concluded that the variation of transconductance with applied gate voltage would be reduced, which is in substantial agreement with the predictions of William and Shaw.
1.7 MESFET Fabrication Techniques

There are two basic gate fabrication techniques currently used for device production each developed specifically to reduce the source-drain resistance. These are the self aligned gate technique, and the etched gate technique. These will be considered below.

1.7.1 The Self Aligned Gate Technique

The basic fabrication steps used in this method are illustrated in figure (12). First a thin layer of gate metal (usually aluminium) is deposited uniformly over the slice. Areas where gates are required are then delineated by photolithography. The metal is then removed from around the photo-resist by etching. At this stage some of the metal beneath the photoresist is also etched away by undercutting. The width of metal remaining is observed by viewing through the photoresist, and etching is stopped when the desired gate length is achieved. The source and drain metallisation is then deposited by evaporation, using the remaining photoresist as a mask to define the width of the channel.

The main advantage of this method is that the source to gate separation is minimised without the need for difficult mask alignment techniques. However, the depth of the n-type layer must be accurately controlled prior to device fabrication, which makes ion implantation an attractive technique. In order to decrease the contact resistance of the source electrode \( (R_C) \) and the resistance of the region below the source electrode it is desirable to increase the doping level locally in this area. This can be achieved by the selective implantation of the source and drain regions, i.e. implanting this region with a large dose of donor ions whilst the channel region is masked off.
Figure 12  Fabrication Steps of Self Aligned Gate MESFET

12A  Gate areas defined in photo resist on uniformly evaporated gate metal
12B  Gate metal etched undercutting resist
12C  Ohmic contact metal evaporated
12D  Resist dissolved lifting off unwanted ohmic contact metal
1.7.2 The Etched Gate Technique

In this method the source and drain contacts are produced first. Using conventional photolithographic techniques a step is etched in the channel region. This step defines the area in which the gate is produced, the depth of the etch being chosen to leave the desired thickness of doped layer beneath the gate. The gate metal is then deposited, and the metal outside the gate region is then removed by the lift off technique. The etched gate technique offers several distinct advantages over the self aligned gate technique.

(i) The edge definition of the gates produced by this method are far superior to those obtained by the self aligned gate technique.

(ii) The spacing between the electrodes can be independently chosen.

(iii) Electron beam lithography can be successfully used to produce well defined gates at very small lengths (as little as 0.2μm).

(iv) The thickness and doping level of the n-type layers are no longer dictated by the requirements of the Schottky barrier. This enables the source-drain resistance \( R_S \) to be reduced by increasing the n-type layer thickness, and also allows the incorporation of an \( n^+ \) surface layer. An \( n^+ \) layer not only reduces \( R_S \) but also minimises the contact resistance \( R_C \). Epitaxial \( n^+ - n^- \) insulating layers have been used to fabricate devices, the noise and gain characteristics of which are considerably better than similar devices made on material without the \( n^+ \) layer (13).

The etched gate technique suffers from the practical disadvantage that the alignment of the gate mask is critical, and difficult to achieve with submicron geometries.
1.8 Submicron Gate Length FETs

In recent years there has been considerable research effort applied to the fabrication of MESFETs with submicron gate lengths. This has usually been achieved by direct slice writing with electron beams using a suitable resist. X-ray and deep UV lithography have also been utilised. It has been shown that the maximum usable frequency of an FET is directly related to the gate length and the electron drift velocity by equation (10):

\[ f_T = \frac{1}{2\pi L} \left( \frac{v}{L} \right) \]

therefore the maximum frequency of operation can be directly increased by decreasing the gate length. A secondary, although equally important effect of reducing the gate length is that the electron drift velocity can be increased to more than twice the saturation velocity. This is because the electrons require approximately 1ps to transfer from the lower to the upper band valley. Consequently in short gate length devices where the transit time is short the electrons may remain in their higher mobility state. Provided the distance travelled is less than about 0.6μm the electrons do not become thermally stabilised to their equilibrium condition, and \( f_T \) is increased accordingly.

The implications of increasing \( f_T \) are twofold. Firstly, this naturally means that devices can be produced for operation at higher frequencies. For example Oxley et al\(^{(18)}\) have produced FETs with 0.3μm gate lengths exhibiting maximum usable gains of 4dB at 40GHz. The noise figure of these devices was 3.6dB at 27GHz with an associated gain of 5dB. Kamei et al\(^{(19)}\) have produced devices with 0.25μm gates with 4dB noise figure at 30GHz and a similar associated gain of 5dB. The maximum available gain in this case was 8dB. Secondly, increasing \( f_T \) leads to a reduction in noise figure at lower frequencies (Equation 17),
and this is reflected in the noise performance of devices operating at 12GHz. For example Oxley has reported a 1.2dB noise figure at 12GHz with 0.3μm gate length\(^{(18)}\), Yamasaki et al have achieved 1.7dB with a 0.5μm gate length\(^{(1)}\), and Huang et al claim 1.29dB with gate lengths of 0.3–0.4μm\(^{(20)}\).
2. ION IMPLANTATION IN GaAs

2.1 Introduction

Ion implantation offers several distinct advantages over other methods of producing doped semiconductor layers. Among these advantages are:

(i) The ability to control accurately the quantity of dopant introduced - the ion dose.

(ii) The ability to accurately, uniformly and reproducibly control the depth of doped layers. The depth is governed by the ion mass and the energy at which implantation is performed.

Most of the general aspects of ion implantation have been adequately covered in the literature \(^{21,22}\) and only a brief summary will be given here. Particular attention will be paid to donor ion implantation, as n-type GaAs is of predominant interest for device applications because of its high electron drift mobility (approximately six times that of silicon).

2.2 Range of Implanted Ions

As an ion enters a solid it loses energy by two processes:

(a) Interactions with electrons of the target lattice - the ELECTRONIC or INELASTIC COLLISIONS.

(b) Collision with the target nuclei - the NUCLEAR or ELASTIC COLLISIONS.

The nuclear collisions cause the energetic ions to be deflected or scattered. Through the above processes the implanted ions slow down and come to rest in the host lattice. The distribution of implanted ions in amorphous substrates is approximately Gaussian, and described by the equation

\[
N(x) = \frac{N_i \exp \left(- \frac{(x - R_p)^2}{2(\Delta R_p)^2}\right)}{(2\pi)^{1/2} \Delta R_p}
\]

where \(x\) is the perpendicular distance into the substrate

\(N_i\) is the ion dose
\[ R_p \] is the theoretical projected range
\[ \Delta R_p \] is the standard deviation of the implanted profile.

Lindhard, Schaff, and Schiott \(^{(23)}\) have computed the projected range and the standard deviation of a variety of ions and substrate materials. Their predictions are frequently referred to as the LSS data. In figure (13) the projected ranges are plotted as a function of ion energies for the most commonly studied donor ions implanted into GaAs. The dependence of range upon ion mass and energy can be seen clearly.

In crystalline targets, such as GaAs, it is possible for the implanted ions to travel far greater distances than in amorphous targets, by moving along channels in major axis in directions, such as the \(<100>\) and \(<111>\). To achieve reproducible depth profiles crystalline targets are usually aligned a few degrees away from a channelling direction so the crystal appears randomly arranged to the main beam of ions. Even then, however, the implanted ions are scattered by collisions and some can be deflected along the channels, causing a long tail in the implanted profile.

Lee and Malbon \(^{(24)}\) have used secondary ion mass spectroscopy (SIMS) to determine the profile of silicon ions implanted at 50 - 500keV into GaAs in a random direction. Even after heat treatment at 800°C it was shown that the depth distribution of the implanted ions was close to the theoretical (LSS) profiles. Lidow et al \(^{(25)}\) have performed similar measurements on selenium ions implanted into GaAs with substantially the same result, although a longer tail in the profile was observed.

2.3 Radiation Induced Damage

As the energetic ions lose energy to the target lattice by collisions a large amount of damage is created, either by simple atomic displacement or through collision cascades.

The amount of lattice damage created depends upon the ion mass, ion dose, ion energy, the substrate type and the substrate temperature.
Figure 13. Dependence of Projected Range Upon Ion Species and Implant Energy
If GaAs is implanted at room temperature with a sufficiently high dose it can become amorphous. This has been demonstrated by Carter et al (26) for tellurium implanted GaAs using Rutherford Backscatter analysis (RBS). If the substrate temperature is increased during implantation the radiation induced damage becomes more mobile, and substantial annealing of the damage takes place during the irradiation. There is evidence to support the existence of an annealing stage at 150 - 180°C (27), and implantation performed above this temperature does not render GaAs amorphous. The amount of damage remaining in the GaAs affects the number of implanted ions which can sit on substitutional sites and act as donors. Takai et al (27) have shown by RBS measurements that whereas tellurium ions implanted at room temperature resided 0.3 - 0.8 Å off lattice sites, all of the implanted ions sat on lattice sites when the implant was performed at 300°C. Implantation at elevated temperatures is not sufficient, however, to produce high levels of activation of the implanted ions. A large number of stable defects still exist which only anneal out at high temperatures, typically 800 - 900°C.

2.4 Encapsulation

In order to anneal GaAs at high temperatures it is necessary to suppress the decomposition caused by preferential arsenic loss at temperatures above 640°C (28). Successful annealing has been achieved by several groups of workers using controlled atmosphere techniques. Annealing in an arsine (AsH₃) atmosphere has been shown to be a successful method of suppressing arsenic loss (29 - 30). This is usually performed in apparatus similar to that used for vapour phase growth of GaAs (30). Frequently the GaAs slices to be annealed are placed face down on another piece of GaAs to assist the suppression of arsenic loss. For example Grange et al (31) have achieved high levels of activation of low dose implants of Si, S and Se by annealing at 800°C in this way. Heated arsenic in flowing hydrogen (32), and arsenic saturated carbon powder (33) have also been used to provide overpressures of arsenic.
Decomposition is most frequently suppressed, however, by coating the GaAs with a suitable encapsulating layer, impermeable to the out diffusion of either gallium or arsenic. A variety of such materials have been investigated, and the merits of some of the most significant are discussed below.

2.4.1 Silicon Dioxide (SiO₂)

Silicon dioxide was the first reported encapsulant for GaAs\(^{34}\). In this instance the SiO₂ was deposited pyrolytically from silane and oxygen, although sputtered SiO₂ has also been examined. Gyulai et al\(^{35}\) has shown that significant out diffusion of gallium can occur through SiO₂ at temperatures as low as 750°C. It was postulated that gallium vacancies were created, which could form stable complexes with group VI donors (such as \(V_{Ga} - T_{As}\)), leading to a reduction in electrical activity. It is interesting to note that SiO₂ has been successfully used to anneal p-type implants. Here the group II ions need to reside on gallium sites to act as acceptors, as gallium loss tends to enhance the probability of activation. Whilst SiO₂ is still used by some investigators results tend to be variable, and SiO₂ is now generally accepted to be an unreliable encapsulant.

2.4.2 Silicon Nitride

It has been shown by Harris et al\(^{36}\) that the amount of Ga outdiffusion is significantly less through plasma deposited Si₃N₄ films than through SiO₂. The degree of electrical activation of Te implanted GaAs was considerably increased, and the number of \(V_{Ga} - T_{As}\) complexes significantly decreased in nitride encapsulated samples. The films used by Harris suffered from blistering and poor adhesion during the annealing. Lidow and Gibbons\(^{37}\) have shown that the mechanical damage in plasma deposited Si₃N₄ films can be eliminated by coating with an arsenic doped SiO₂ layer. Ion implanted material has been successfully annealed up to 1100°C with such a double layer encapsulant.
Difficulties due to non-adhesion have also been experienced using reactively sputtered Si$_3$N$_4$ films. This was probably due to the inclusion of uncombined nitrogen in the layers. Mogab et al.$^{(38)}$ have shown that the pressure of N$_2$ during growth is important in controlling the amount of free nitrogen. Eisen et al.$^{(39)}$ have used reactively sputtered Si$_3$N$_4$ to anneal implanted GaAs successfully, achieving high levels of activation of implanted ions.

Reactive sputtering and plasma deposition are attractive methods of applying Si$_3$N$_4$ as:

(a) They do not require sample heating to high temperatures, deposition is usually performed at less than 300°C.

(b) It is possible to produce layers of uniform thickness over large areas. This is particularly important if it is required to implant through the encapsulating layer.

Chemical vapour deposition (CVD) of silicon nitride has proved to be the most reliable and reproducible means of encapsulating. In this process the silicon nitride is formed by the pyrolytic combination of silane and ammonia. As this necessitates heating the GaAs to around 700°C, it is important to reach the growth temperature as quickly as possible. Bell et al. have shown that slow heating to the growth temperature is detrimental to the achievement of high percentage activation, which is also dependent upon the substrate being annealed.$^{(40)}$

Donnelly.$^{(41)}$ has developed a system where the growth temperature is reached in approximately 6 seconds. The nitrides produced using this method have been used to activate implanted GaAs to high levels reproducibly. An important factor in determining the efficiency of silicon nitrides as an encapsulating layer is the amount of oxygen contained in the film. Inada et al.$^{(42)}$ have proposed that highest levels of activation can only be achieved in implanted layers if the oxygen concentration is less than 0.1%. Sources of oxygen include outgassing from the carbon heater used to bring the GaAs
to the growth temperature, and residual water vapour in the deposition apparatus.

Donnelly also uses an overlayer of SiO₂ for mechanical protection, and has recently reported the use of such double layers for annealing up to 1140°C (43).

2.4.3 Aluminium Nitride (Oxynitride)

Electrical activities comparable to those obtained using CVD Si₃N₄ encapsulation have been measured using films sputtered from an aluminium nitride target. One reason for the success of aluminium nitride is that any oxygen in the films is stably bonded to aluminium in the form of Al₂O₃. Photoluminescence studies of heat treated GaAs with oxynitride encapsulation show the absence of a peak at 1.25eV which has been associated with a gallium vacancy, thus the encapsulant successfully inhibits Ga out-diffusion.

The adherence of aluminium oxynitride films is markedly better than many Si₃N₄ layers. Fashley & Welch (44) have suggested that this is due to the better match of thermal expansion. The respective expansion coefficients are:

\[
\begin{align*}
3.2 \times 10^{-6} \text{ °C}^{-1} & : \text{Si₃N₄} \\
6.8 \times 10^{-6} \text{ °C}^{-1} & : \text{GaAs} \\
6.1 \times 10^{-6} \text{ °C}^{-1} & : \text{AlN}.
\end{align*}
\]

Recently Okamura et al (45) have reported the successful use of reactively sputtered AlN caps to anneal up to 1000°C without any surface degradation or blistering of the encapsulating film. Also Bensalem et al (46) have reported the use of reactively evaporated AlN as a successful encapsulant up to a similar anneal temperature.

2.4.4 Aluminium

Sealy and Surridge (47) have used evaporated aluminium as an encapsulant for donor ion implanted GaAs. Aluminium was found to give more reproducible results than CVD Si₃N₄ (deposited with a slow rise to
growth temperature), but could not be used to anneal temperatures above 700 - 750°C as the amount of aluminium indiffusion into the GaAs substrate became appreciable. As a consequence of their studies Sealy and Surridge concluded that the most reproducible results were obtained in epitaxial material, and that semi-insulating material produced variable results.

2.4.5 Other Materials

A variety of other materials have been investigated to determine their suitability as encapsulants. Among these are thermally grown $\beta \text{Ga}_2\text{O}_3$ (48), $\beta \text{Ga}_2\text{O}_3$ plus aluminium (49), and polycrystalline silicon (50)(51). All have proved to be less successful at preventing dissociation of the GaAs, and $\text{Si}_3\text{N}_4$ is now by far the most widely used material. Despite its widespread use difficulties of reproducibility still exist and studies are still proceeding to improve the reliability of reactively sputtered and CVD silicon nitride layers.

2.5 Thermal Stability of Gallium Arsenide

It has already been mentioned that the electrical characteristics of ion implanted GaAs tend to be more variable when bulk grown semi-insulating material is used. Several workers have noted that semi-insulating material often becomes conducting after heat treatment, and a type conversion p or n type is frequently exhibited. With poor encapsulation type conversion could be due to Ga and As vacancy formation. It has been proposed that the loss of Ga and As from GaAs leads to a shallow n layer due to As vacancies, and a deeper p layer due to the more mobile Ga vacancies (52). It has also been proposed that chromium loss; due to migration to the surface, leads to a decrease in compensation allowing further, enhanced type conversion.
A comprehensive model incorporating all three of the above effects has shown to be in reasonable agreement with experimental observations\(^{(53)}\).

Type conversion after annealing has also been attributed to the presence of impurities in the GaAs. Zucca\(^{(54)}\) has identified the impurity manganese in p-type material; the source of the Mn being stainless steel components of the GaAs growth apparatus. Edmond\(^{(55)}\) and Huang\(^{(56)}\) have identified copper contamination from quartz furnace components as a source of type conversion. Huang has also observed a shallow acceptor level due to silicon.

Whilst there is still some ambiguity as to the cause of type conversion, it is also true that the exact nature of the mechanism whereby Cr doping renders GaAs semi-insulating is not fully understood. A variety of energy levels in the band gap, predominantly at 0.7eV, 0.4eV and 0.98eV above the valence band have been attributed to Cr doping. It has been proposed that chromium will exist in a variety of charge states in GaAs i.e. \(\text{Cr}^+, \text{Cr}^{++}, \text{Cr}^{+++}\), depending upon the number of electrons with which the Cr has combined\(^{(57)}\). Each of the charge states will have its own characteristic energy level. It is difficult, however, to ascribe unambiguously a particular charge state to a definite energy level. The situation is further complicated by the fact that chromium-vacancy and chromium-dopant complexes may also exist. The nature of such complexes, such as Cr-O and Cr-Si is likely to be dependent upon the annealing history of the GaAs.
Some measure of the complexity of the situation existing in Cr doped GaAs can be gained from the large variation of electrical results reported in the literature. It is generally agreed by most workers that reproducible results can only be achieved by

(i) Encapsulating with an effective encapsulating layer, both to prevent impurity indiffusion and Ga and As outdiffusion.

(ii) Carefully select the GaAs used. The group at Rockwell \(^{(58)}\) have used a two stage selection procedure to determine the suitability of particular ingots. This consists of annealing unimplanted material and monitoring changes in sheet resistivity, and similarly treating material implanted with krypton ions.

Only material which remained highly resistive after both the above tests were considered suitable for implantation with donor ions. A similar characterisation process was also used to select semi-insulating material as substrates for epitaxial buffer layers \(^{(58)}\). It was shown that thermally stable buffer layers could only be grown on semi-insulating material which had passed the above selection procedure. Thus, whilst undoped high resistivity buffer layers are attractive for ion implantation the problems associated with chromium doping are not completely alleviated, and it is still necessary to characterise the substrate in order to overcome fully the problem of type conversion during annealing.
2.6 Annealing

It has already been stated that maximum activation of implanted donor ions can only be obtained by annealing at 850 - 900°C. This is usually achieved by furnace heating in flowing nitrogen or H₂/N₂ for 15 - 30 minutes. Some workers have used an argon atmosphere for annealing, as there is some evidence that this tends to suppress GaAs decomposition \(^{(59)}\). Other methods of annealing have been investigated, and some of these are described briefly in this section.

2.6.1 Laser Annealing

The use of short, high energy pulses of laser radiation to anneal implantation induced defects in GaAs was first proposed by in 1976. To some extent laser annealing has failed to live up to its early promise of providing a simple means of achieving high electrical activities in ion implanted GaAs, without the need for prior encapsulation. To date the best results have been achieved only in substrates with near surface, high dose implants of donor ions; and often only when the surface was protected by an encapsulating layer. Pulsed ruby and neodymium lasers have both been used for irradiation, and some of the problems which needed, and to some extent still need, to be solved include:

(i) the prevention of oxygen/gas doping by the inclusion of ambient atmosphere atoms into the radiated surface.

(ii) the prevention of auto doping from an encapsulating layer - for example n-type doping by silicon from Si₃N₄ layers \(^{(60)}\).

(iii) maintaining good surface morphology - especially on recrystallisation of molten surface layers \(^{(61)}\).

(iv) achieving uniform illumination of the irradiated surface. To some extent this problem is solved by use of a beam homogeniser such as proposed by Gullis et al \(^{(62)}\).

(v) loss of substrate through evaporation \(^{(63)}\).

A full description of the achievements and problems of laser annealing is
beyond the scope of this dissertation, and the interested reader is referred to one of the many reviews already published (see for example references (64) (65):.

2.5.2 Electron Beam Annealing

Two methods of annealing implanted GaAs utilising high energy electron beams have been proposed:-

(i) Flood illumination, whereby the entire sample to be annealed is rapidly heated using a high current of energetic electrons.

(ii) Local heating using a scanned, focussed electron beam.

Electron beam annealing has been more successful than laser annealing in achieving electrical activation of low dose implants of donor ions suitable for FET channels (66)(67), however the technique is still not generally applicable to all implanted samples. As this technique was not used in this study a full description will not be given here.

2.5.3 Optical Irradiation

Flash tube, and high intensity c.w. irradiation have both been investigated as methods of annealing. Probably the most successful study to date was by Arai et al (68) who used halogen lamps to raise the temperature of the GaAs samples to 950°C. High levels of activation were achieved with un-encapsulated samples because both the time of rise to, and the time at the anneal temperature were so short (≈ 5 and ≈ 1 secs respectively).

Some evidence of decomposition of the surface, however, was observed. This technique does appear attractive and future studies may solve some of the outstanding problems.

2.5.4 Fast Graphite Strip Annealing

Surridge et al (69) have shown that as the annealing temperature is increased the time required to achieve maximum activation of any particular implant is decreased. Whereas at 700°C an anneal of about 20 minutes was required to achieve maximum electrical activation, the
anneal time could be reduced to less than 30 seconds if the anneal took place at 900°C. One of the aims of the present study was to show that thermal pulse annealing is a technique generally applicable to the production of n-type ion implanted GaAs layers, and further results will be given in the following chapters.

2.6 Donor Ion Implantation

2.6.1 Introduction

Whilst a great deal of effort has been devoted to obtaining high electrical activation of donor ion implants, it is only in the last few years that this has been possible. Prior to about 1978 the inefficiency of the encapsulants limited the maximum annealing temperature to about 700°C. Activation levels tended to be low and irreproducible. Recently, with the development of reliable encapsulants, annealing has been performed at temperatures between 800 and 1100°C, with a consequent rise in the percentage of implanted ions behaving as donors. In figure (14) the sheet carrier concentrations achieved for selenium implantations are compared for 700°C (70) and 900°C (71) annealing schedules.

It can be seen that a marked increase in electrical activation is produced by annealing at the higher temperature, and for low doses closely approaches 100%. The decrease in the level of activation at higher doses shown in figure (14) has been observed for most of the ions studied. These include the group IV elements S, Se and Te, and the group VI elements' Si, Ge and Sn.

To act as donors, group VI ions need to reside on arsenic sites. It has been proposed (72) that the principle cause of non-activation of implanted group VI ions is the formation of donor-gallium vacancy complexes, such as $V_{Ga} - Se_{As}$, which only dissociate after annealing to high temperatures. Surridge et al (69) have studied the annealing kinetics of ion implanted GaAs, and concluded that the dissociation energy of such complexes is approximately 1eV.
Fig. 14 Variation of Sheet Electron Concentration and mobility with Implanted Selenium Dose Annealed to 700°C (70) and 900°C (71).
The situation for group IV is more complicated because of their amphoteric nature. It is commonly accepted that when located on gallium sites they act as donors, and on arsenic sites as acceptors.

\[ \text{e.g.} \quad \text{Sn} + \text{V}_{\text{Ga}} \rightarrow \text{Sn}_{\text{Ga}}^+ + e^- \]
\[ \quad \text{Sn} + \text{V}_{\text{As}} \rightarrow \text{Sn}_{\text{As}}^- + h^+ \]

Thus, in addition to donor action there exists the possibility of acceptor action leading to compensation; and the formation of neutral-neighbour pairs of the form

\[ \text{Si}_{\text{Ga}}^+ - \text{Si}_{\text{As}}^- \]

Naturally the possibility of donor-vacancy complexes also exists, although the nature of such defects is not understood (73).

2.6.2 Sulphur Ion Implantation

Sulphur is the lightest group IV ion studied, and therefore at any given energy its range is greatest (see figure (13)). Sulphur was, therefore, considered initially an attractive ion as in any given accelerator the deepest n-type layers could be produced with this ion. It has been shown, however, that carrier concentration profiles obtained from sulphur implanted material exhibit long tails due to diffusion during the annealing stage (74)(75), and because of this tend to be very irreproducible. Eisen et al have shown that considerable outdiffusion of sulphur into the encapsulating layer also occurs (76), although Favennac has shown that the migration of implanted sulphur can be eliminated by the correct choice of encapsulant (77).

Sulphur also suffers from the disadvantage that beam purity is difficult to guarantee because its principle isotope has a molecular weight of 32, which corresponds to the commonly observed contaminant of many accelerators, $\text{O}_2^+$.  

2.6.3 Selenium and Tellurium

These group VI ions have been shown to produce similar levels of activation upon annealing. Because of the desire to produce deep layers
Donnelly et al (78) and Gamo et al (79) have both reported high levels of activation of selenium after annealing at 900°C using CVD silicon nitride, and sputtered Si$_3$N$_4$ and AlN encapsulating layers. The results of several studies of selenium and tellurium high dose annealed at 900°C implantations are compared in table (1). It can be seen that the highest levels of activation have been achieved in material implanted at elevated temperatures. Room temperature implantation has only been successful for GaAs implanted with low doses. It can also be seen that whilst peak electron concentrations tend to be similar, a considerable variation in the level of activation is observed. This can be attributed to variations in the width of the dopant profiles due to enhanced diffusion in the tail region. Several attempts to ascribe diffusion coefficients to implanted donors have been made. It is probable, however, that the diffusion of implanted ions is dominated by the damage created during the implantation; and the depth of the doped layers depends upon the efficiency of the encapsulating layer, and the length and temperature of the anneal.

2.6.4 Silicon

Silicon is the lightest of all the donor ions studied, and consequently has the largest available range. It has been shown that levels of activation similar to those achieved with elevated temperature implants of selenium can be achieved with silicon implanted at room temperature (78). Silicon is therefore a very attractive ion and has been widely studied (24, 81-83). The results of several investigations are summarised in table (2).

Silicon does suffer from the practical disadvantage that its principle isotope Si$^{28}$ has the same mass as the contaminants CO$^+$ and N$_2^+$. This can be overcome by implanting the isotope Si$^{29}$, but this requires the use of high current accelerators as the relative abundance of Si$^{29}$ is only 4.7%.
TABLE 1

Comparison of Electrical Results of GaAs Implanted with Selenium and Tellurium Ions at Doses $10^{14}$ - $10^{15}$ and Annealed at 900°C

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy keV</th>
<th>Implant Temp. °C</th>
<th>Encapsulation</th>
<th>Activity %</th>
<th>Peak Electron Conc. (cm$^{-3}$)</th>
<th>$\mu_H$ cm$^2$V$^{-1}$s$^{-1}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>400</td>
<td>RT</td>
<td>$Si_3N_4$</td>
<td>10</td>
<td>$10^{18}$</td>
<td>2200</td>
<td>78</td>
</tr>
<tr>
<td>Se</td>
<td>400</td>
<td>250</td>
<td>$Si_3N_4$</td>
<td>40</td>
<td>$2.10^{18}$</td>
<td>2300</td>
<td>78</td>
</tr>
<tr>
<td>Se</td>
<td>400</td>
<td>500</td>
<td>$Si_3N_4$</td>
<td>50</td>
<td>$3.6 10^{18}$</td>
<td>2300</td>
<td>78</td>
</tr>
<tr>
<td>Se</td>
<td>400</td>
<td>350</td>
<td>$Si_3N_4$</td>
<td>47</td>
<td>$3.10^{18}$</td>
<td>2300</td>
<td>71</td>
</tr>
<tr>
<td>Se</td>
<td>400</td>
<td>350</td>
<td>$Si_3N_4$</td>
<td>30</td>
<td>$1.10^{18}$</td>
<td>-</td>
<td>79</td>
</tr>
<tr>
<td>Se</td>
<td>400</td>
<td>350</td>
<td>AlN</td>
<td>60</td>
<td>$3.10^{18}$</td>
<td>-</td>
<td>79</td>
</tr>
<tr>
<td>Se</td>
<td>120</td>
<td>500</td>
<td>$Si_3N_4$</td>
<td>26</td>
<td>-</td>
<td>2200</td>
<td>37</td>
</tr>
<tr>
<td>Se</td>
<td>120</td>
<td>500</td>
<td>$Si_3N_4 + SiO_2$</td>
<td>20</td>
<td>-</td>
<td>2100</td>
<td>37</td>
</tr>
<tr>
<td>Se</td>
<td>100</td>
<td>400</td>
<td>$Si_3N_4$</td>
<td>38</td>
<td>$4.5 10^{18}$</td>
<td>-</td>
<td>42</td>
</tr>
<tr>
<td>Te</td>
<td>400</td>
<td>350</td>
<td>AlN</td>
<td>20 - 30</td>
<td>$2.10^{18}$</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>Te</td>
<td>400</td>
<td>350</td>
<td>$Si_3N_4$</td>
<td>10 - 15</td>
<td>$6.10^{17}$</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>Te</td>
<td>220</td>
<td>350</td>
<td>$Si_3N_4$</td>
<td>20</td>
<td>$10^{18}$</td>
<td>1500</td>
<td>44</td>
</tr>
<tr>
<td>Te</td>
<td>220</td>
<td>350</td>
<td>AlN</td>
<td>31</td>
<td>$7.10^{18}$</td>
<td>1371</td>
<td>44</td>
</tr>
</tbody>
</table>

TABLE 2

Comparison of Electrical Properties of High Dose Silicon Implants Annealed at 900°C

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Implant Temp. (°C)</th>
<th>Activity (%)</th>
<th>Peak Electron Conc. (cm$^{-3}$)</th>
<th>Mobility (cm$^2$V$^{-1}$s$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>RT</td>
<td>30</td>
<td>$2-7 10^{18}$</td>
<td>1000 - 2000</td>
<td>71</td>
</tr>
<tr>
<td>300</td>
<td>RT</td>
<td>60</td>
<td>$1-2 10^{18}$</td>
<td>-</td>
<td>81</td>
</tr>
<tr>
<td>400</td>
<td>RT</td>
<td>26</td>
<td>$8 10^{18}$</td>
<td>$\sim 2100$</td>
<td>78</td>
</tr>
<tr>
<td>170</td>
<td>340</td>
<td>25</td>
<td>$2.8 10^{18}$</td>
<td>$\sim 1000$</td>
<td>82</td>
</tr>
</tbody>
</table>
2.6.5 Germanium

Germanium is the least studied donor ion. Surridge and Sealy\(^{(84)}\) have compared the electrical characteristics of GaAs implanted with similar doses of Ge, Se, Te and Sn, and concluded that after annealing at 700°C the activity of Ge is similar to that of Se and Te, for a dose of around $2.10^{14}$ cm\(^{-2}\). At lower doses ($10^{13}$ - $5.10^{13}$ cm\(^{-2}\)) the measured sheet carrier concentration for Ge implanted GaAs was significantly less than selenium doped material. Surridge and Sealy also report that the electrical activity did not increase as the anneal temperature was increased to 750°C.

Kräutle\(^{(85)}\) and Park et al\(^{(86)}\) have also studied the behaviour of germanium as a dopant, with anneal temperatures between 700°C and 1000°C. Both of these groups determined p type activity for low dose (<$10^{15}$ ions cm\(^{-2}\)) at all anneal temperatures. The GaAs became n type, with a high level of compensation, only when higher doses were implanted. The difference between these results and those of Surridge and Sealy may be accounted for by the difference in implant temperature used; Surridge and Sealy performed their implantation into substrates held at 200°C, the other workers used no substrate heating. The difference in the damage levels created, coupled with possible differences in material and encapsulation no doubt caused the observed differences in the behaviour of implanted germanium.

2.6.6 Tin

Surridge and Sealy\(^{(84)}\) have reported that the highest activities achieved after annealing at 700°C were for tin implanted material. For a dose of $2.10^{14}$ ions cm\(^{-2}\) the measured sheet electron concentration was $\sim 9.10^{12}$ cm\(^{-2}\). The measured peak electron concentration was $7.10^{17}$ cm\(^{-3}\).

Donnelly\(^{(71)}\) has reported that for a $10^{14}$ cm\(^{-2}\) dose annealed at 900°C the measured sheet electron concentration was $\sim 2.10^{13}$ cm\(^{-2}\) which
is similar to the value reported by Sealy et al\(^{(84)}\) for samples annealed at \(\sim 720^\circ C\). Thus, for implanted tin ions a large increase in anneal temperature produces only a small increase in the activity of implanted tin ions in GaAs. This is possibly due to the amphoteric behaviour of tin, an increase in the anneal temperature producing no change in the relative concentration of donor and acceptor ions.

2.6.7 Dual Ion Im plantation

Heckingbottom and Ambridge\(^{(87)}\) proposed the use of dual ion implants to confine the location of implanted ions to the correct lattice site for electrical activation, and thus decrease the possibility of self-compensation. This is achieved by the preservation of stoichiometry by the co-implantation of ions which find it thermo-dynamically favourable to occupy different sites within the lattice.

Several studies of the effects of dual implantation have been performed\(^{(88)-(91)}\), and among the ion combinations that have been examined are Se + Ga, Te + Ga, Sn + S, C + Ga, Se + Ge and Si + Sn, Ge + Ga, Ge + As, Si + As, Si + Ga, Sn + As, Sn + Ga. Although some groups have reported a substantial increase in the level of activation of the donor ion when implanted with its complementary ion, other groups have reported only a slight or no increase. As an example of a successful dual implant Inada et al\(^{(88)}\) observed an increase in the peak electron concentration from \(6.10^{18}\) to greater than \(10^{19}\) cm\(^{-3}\) for high dose \((4.4 \times 10^{16}\) cm\(^{-2}\) \(100\) keV Se implants annealed at \(925^\circ C\) when co-implanted with \(5.10^{14}\) \(90\) keV Ga ions/cm\(^2\) at \(400^\circ C\).

Kräutle\(^{(85)}\) has shown that whereas Sn or Sn + As implants render GaAs n-type the co-implantation of Ga with tin results in p-type activity. The effect of Ga and As implants on the amphoteric behaviour of Ge has also been shown by Kräutle, and by Park et al\(^{(86)}\), which suggests
that the p-type activation observed samples implanted with low doses at room temperature may be related to arsenic vacancy formation (possibly through the formation of arsenic complexes).

Sealy et al.(89) have reported that dual ion implants tended to be less reproducible than single ion implants when annealed at 700°C. However this may be due to materials and/or encapsulant problems.

2.6.8 Application of Donor Ion Implantation to the Fabrication of GaAs MESFETs

Because of the advantages of ion implantation for producing uniformly doped n-type layers it has been widely investigated as a fabrication step for the production of a variety of devices in GaAs. For example, Mizutani et al.(92) have produced planar Gunn diodes by the implantation of sulphur ions and Bozler et al.(93) have produced IMPATT diodes by the implantation of silicon ions. Silicon ion implantation has also been implemented successfully by Toyoda et al.(94) to fabricate varactor diodes. In all cases an improvement in reproducibility and uniformity was reported compared with devices produced on epitaxially grown layers.

The first reported attempt to apply donor ion implantation to MESFET fabrication was by Hunspurger & Hirsch(95) in 1973, by the implantation of sulphur ions. Whilst FET action was displayed the transconductance and saturation current levels were low and no microwave results were reported. Characteristics of all early studies (96-99) were:-

(i) long gate lengths (2-4μm)
(ii) sulphur ion implantation
(iii) low transconductance of completed devices.
Improvements in the thermal stability of the semi-insulating substrates, better encapsulation and reduction in gate lengths have resulted in the fabrication of improved MESFETs. Also, most of the later studies used selenium or silicon implantation because of the reduction in diffusion of the tail region displayed by these ions.

Comparison of device characteristics is difficult because of the variety of geometries used. As shown in chapter 1, the gate length is a primary parameter in determining the microwave performance of the MESFET, and therefore only devices with similar gate lengths can be compared. In table (3) the published results of a number of devices with \( \approx 1.0\mu m \) gate lengths are given chronologically. Microwave results are given at 10GHz, the most commonly quoted value. It can be seen that the reported minimum noise figure has decreased steadily from a value of 4.6dB to 2.1dB whilst the associated gain (the gain measured under the bias conditions for minimum noise) has increased from 3.5dB to 8dB.

The results of Kung et al \(^{(102)}\) are worthy of extra comment, as they have several differences from the others quoted. The implantations were performed into epitaxial buffer layers, not semi-insulating material, and double energy implantation was performed to decrease the resistivity near the surface. Annealing was performed in a controlled arsenic atmosphere without an encapsulating layer. It is believed that the choice of dual energy implantation and buffer layer material resulted in the low noise devices produced. Devices produced by the same workers on epitaxial material had minimum noise figures approximately 1dB less, but with similar associated gains.
### TABLE 3

**Ion Implanted FET Results at 10GHz (1µm Gate Lengths)**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>Ion</th>
<th>Dose (cm$^{-2}$)</th>
<th>Energy (keV)</th>
<th>Material</th>
<th>Anneal Temp. (°C)</th>
<th>NF (dB)</th>
<th>Ass. Gain (dB)</th>
<th>MAG (dB)</th>
<th>$g_m$ (mA/V)</th>
<th>$I_{DSS}$ (mA)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>S</td>
<td>$7 \times 10^{12}$</td>
<td>100</td>
<td>SI</td>
<td>850</td>
<td>4.6</td>
<td>3.5</td>
<td>10</td>
<td></td>
<td></td>
<td>(100)</td>
</tr>
<tr>
<td>1976</td>
<td>Se</td>
<td>$2 \times 10^{12}$</td>
<td>400</td>
<td>SI</td>
<td>850</td>
<td>3.4</td>
<td>5</td>
<td>10</td>
<td></td>
<td>100</td>
<td>(101)</td>
</tr>
<tr>
<td>1977</td>
<td>Si</td>
<td>$5 \times 10^{12}$</td>
<td>175</td>
<td>EPI</td>
<td>800</td>
<td>2.9</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>(102)</td>
</tr>
<tr>
<td>1977</td>
<td>Se</td>
<td>$3 \times 10^{12}$</td>
<td>300</td>
<td>SI</td>
<td>850</td>
<td>3.5</td>
<td>7</td>
<td>11</td>
<td>20-30</td>
<td>70 - 100</td>
<td>(103)</td>
</tr>
<tr>
<td>1978</td>
<td>Se</td>
<td>$3 \times 10^{12}$</td>
<td>300</td>
<td>Selected SI</td>
<td>850</td>
<td>2.1</td>
<td>8</td>
<td>23</td>
<td>60</td>
<td></td>
<td>(104)</td>
</tr>
</tbody>
</table>

**NOTE**
All results produced with sputtered Si$_3$N$_4$ encapsulation except reference (102) which was unencapsulated and annealed in an arsenic atmosphere.
Results from the two sets of devices produced by the implantation of $3.10^{12}$ Se$^+$ ions at 300keV were both by the same group of workers\textsuperscript{(103,104)}. Here the semi-insulating substrates used were selected by electrical characterisation prior to device production. It is thought that the improvement in device characteristics reported (reduction in noise figure from 3.5 to 2.1dB) is due to improved encapsulation efficiency and material quality.

Ohata et al\textsuperscript{(105)} have selectively implanted the source and drain regions of devices produced on n-type epitaxial material to decrease the source-gate resistance. Silicon ions were implanted at 40keV and 100keV; the respective doses were $7.10^{13}$ and $10^{14}$ cm$^2$. The devices produced in this study had 0.5μm gates. The source resistance was reduced from 3.5 to 1.5Ω, which resulted in a reduction in the minimum noise figure of $\sim 0.5$dB and an increase in the associated gain of approximately 1.5dB. Thus high dose implantation in the ohmic contact region was effective in reducing the noise, as discussed in chapter 1.
3. EXPERIMENTAL PROCEDURE

3.1 Introduction

Three major areas of research were undertaken:-

(i) The development of a reliable and reproducible method of encapsulating and annealing

(ii) Measurement of the electrical profiles of a variety of implants in order to determine the most suitable implantation parameters for the channel region and the source and drain region of MESFETs. A number of variables had to be considered, including:-

(a) Ion species
(b) Ion dose
(c) Ion energy
(d) Implant temperature
(e) Anneal temperature
(f) Anneal time
(g) Material.

(iii) Manufacture of MESFETs from suitably implanted material, and the measurement of the electrical characteristics of complete devices. This area of the research was performed at Plessey Research (Caswell) Ltd. from material implanted at Surrey. A brief outline of the MESFET fabrication process will be given in this chapter.

3.2 GaAs Material Preparation

Prior to implantation it was necessary to clean all material. A variety of techniques were used because of the different types of GaAs used. These were:-

(i) Chromium Doped Bulk Semi-Insulating Material

This was obtained from two manufacturers, Mining & Chemical Products (MCP) and Metals Research Ltd. (MR). The MR material was pre-polished by the manufacturer and was supplied in discs up to 2 inches in diameter.
In order to remove any surface damage (due to polishing) this material was etched for 15 minutes in a solution of sulphuric acid, hydrogen peroxide and water. The relative concentrations of the constituents was

\[
\begin{align*}
H_2SO_4 & : 3 \\
H_2O_2 & : 1 \\
H_2O & : 1
\end{align*}
\]

During etching the etchant was maintained at a constant temperature of 40 ± 2°C by immersing the container in a water bath. This elevated temperature was required to increase the etch rate and decrease the viscosity of the solution. The solution was continuously agitated during etching to prevent the build up of a 'dead layer' at the surface of the GaAs. After etching the GaAs was rinsed thoroughly in distilled water and blown dry to prevent drying stains. (This technique replaced that of wiping the surface dry with a filter paper used initially in this study).

The material was subsequently cleaved into samples, usually 10 x 10mm in size, for implantation and annealing.

The material from MCP was obtained in ingot form. This was sawn into slices approximately 1mm thick using a rotating diamond saw. The sawn slices were then mounted upon quartz discs and polished on a rotating Hyprocel Pellon abrasive pad immersed in a 4% solution of bromine in methanol. The disc was continuously moved across the surface of the rotating pad, and also allowed to rotate freely. Initially this process was performed manually, however a machine was designed and constructed which performed the above operations automatically and produced highly polished, featureless surfaces. After polishing the samples were free-etched in a weak (½%) bromine in methanol solution to remove any damage produced during polishing.
The etch was continuously agitated during the final process, which was continued for ten minutes.

Because these slices were thicker than those supplied by Metals Research (approximately 0.25mm was removed during polishing) they could not be cleaved reproducibly and it was necessary to dice the polished slices into 1cm squares using a diamond impregnated wire saw. After sawing the samples were thoroughly degreased in hot toluene, rinsed in methanol and finally washed in distilled water and dried.

(ii) Epitaxial Material

Two types of epitaxial material were used: undoped buffer layers and n type doped layers, both grown on semi-insulating substrates. The epitaxial material was grown at Plessey Research (Caswell).

Prior to implantation these were cleaned by degreasing in hot toluene, immersed in hydrofluoric acid to remove any oxide or other contaminants, rinsed thoroughly in distilled water and dried.

It was not possible to etch the samples as the epitaxial layers were thin (1-3μm), but this was assumed to be unnecessary as the sample preparation prior to epitaxial growth was such that minimal damage would be present in the epitaxial films.

3.3 Ion Implantation

With the exception of silicon ions all implantations were performed in the Department's 500KeV heavy ion accelerator. This has previously been described in earlier reports and only a brief description will be given here. The major component parts, as shown in figure (15), are:-

(i) The Ion Source

This is a modified Nielson type. Solid source material is vaporised by electrical heating, and the gas produced ionised by electron collisions in crossed electric and magnetic fields.
Fig. 15. Schematic Representation of the Ion Implantation Facility
(ii) The Lens System

An Einzel lens system is used to extract the ions from the source, and focus the ion beam. Both the lens and the ion source are maintained at the accelerating potential by a SAMES generator.

(iii) Acceleration Stage

The ion beam is accelerated in a constant field region in which the terminal voltage is reduced to earth potential, in equal steps by a resistor chain. The number of stages in the resistor chain is varied according to the terminal potential, up to a maximum of 26 stages for the higher potentials.

(iv) Magnet

The high energy ion beam is deflected through 90° by a double focussing electro-magnet, with a field stability of better than 0.1%. At this stage unwanted constituents in the beam are eliminated, and only the component with the required momentum selected.

(v) Scanning Deflection

The ion beam is scanned in a raster by the application of a triangular waveform to orthogonal electrostatic deflection plates. The potential applied to the plates is varied according to the energy of the ions, and is sufficient to ensure that the ion beam was scanned completely over the samples.

A D.C. deflection system is also used to align the beam.

(vi) Specimen Holder

The specimen holder consisted of a carriage upon which up to five pairs of samples were mounted. The maximum size of these samples is 12 x 14mm, although other plates are available for samples with larger dimensions. Mechanical movement of the plate enables each of the pairs of samples to be radiated independently.
The carriage is oriented at 7° to the beam axis to minimise the possibility of channelling of the ions in crystalline samples. The sample holder can be heated to about 250°C by a resistive heater upon which the carriage is mounted, and the sample temperature is monitored by a thermocouple mounted in the carriage.

The size of the ion beam is determined by an earthed aperture plate mounted directly above the samples, and the emission of secondary electrons from the samples is limited by a suppressor plate, maintained at ~300V, located between the specimens and the aperture.

The ion beam was monitored electrically in two ways. Firstly, the beam emerging from the lens was scanned by a vibrating wire detector, the signal from which was displayed in an oscilloscope. This signal was used to monitor the width of the ion beam, and was used as a basis for determining the electrical parameters realised to focus the lens system. Secondly, the current between the sample holder and earth was monitored. This current, due to the ion beam, was processed as follows.

(i) **Direct display of current**

This enabled the machine conditions to be set up prior to implantation of the samples. All implantations were performed with a beam current of 0.2 - 1.0μA. As the aperture size used was 5 sq.cm., this corresponded to a flux of between 0.04 to 0.2μA cm⁻². The beam current was monitored throughout the radiation of samples in order to ensure the implantation conditions did not alter.

(ii) **Current Integration**

This enabled the implanted dose to be determined. The signal from the current integrator was fed to a counter which displayed the total charge implanted into the samples. Once the total charge reached a predetermined quantity corresponding to the dose required the beam was automatically shut off from the sample by a pneumatically operated shutter valve.
(iii) **Scanning mode**

As an alternative to (i) and (ii) above, the beam current could be processed to display the profile of the beam across the aperture. This was used to determine the voltages required for the scanning system, and the level of D.C. shift required to align the beam. The processing required was simply to convert the beam current to a voltage and apply it to the Y plates of an oscilloscope. The scanning waveform of either the X or Y scanning system, was fed into the X plates of the oscilloscope. As the magnitude of the scan voltage was proportional to the position of the beam, the resultant display upon the oscilloscope depicted the variation of beam intensity across the aperture. Thus it was possible to adjust the scan and deflection conditions to achieve a uniform beam across the sample.

It would, of course, be possible to simply overscan the beam in order to ensure uniformity across the sample. This, however, has two disadvantages. Firstly, a greater total beam current is required to produce the same sample current. This would be prohibitive when using 'difficult' ions where only low beam currents can be achieved. Secondly, and perhaps more importantly, the neutral component in the beam (due to charge exchange of the ions with residual gas molecules in the acceleration) is not deflected by the scanning system. Whilst the neutral component has been shown to be small, overscanning of the beam would lead to an increase in the relative concentration of the neutral component and could result in some areas of the sample receiving a significantly larger dose than expected.

It was observed that the profile of the beam across the samples could depend upon the focussing of the lens system, especially when doubly charged ions were being implanted. It was often found
necessary to re-focus the lens using the scanning uniformity display as a guide to the focus condition.

3.4 Encapsulation and Annealing

In order to prevent dissociation of the GaAs during annealing, all samples were coated with $\text{Si}_3\text{N}_4$ deposited by the chemical vapour deposition of silane and ammonia. Two sets of apparatus were used to deposit the $\text{Si}_3\text{N}_4$. The construction of the first apparatus was initiated as a final year undergraduate project, and completed by the author with the assistance of Mr. P. Davies (who was at that time a technician in the Department). This system was basically a copy of that used by Donnelly et al. (71), and is shown diagrammatically in figure (16).

The growth chamber was of stainless steel construction with a glass bell jar, sealed with an O ring compression seal. The reagent gases, $\text{NH}_3$ and $\text{SiH}_4$ (5% in $\text{N}_2$) were introduced into the chamber at controlled flow rates, along with a controlled flow of nitrogen carrier gas. The flow rates were measured using G.E.C. Elliot flow meters, and controlled by using the integral needle valves. After the gases had been flowing through the system for 5 minutes the GaAs samples were heated to the growth temperature by the passage of a high current through the graphite strip on which the sample sat. The temperature of the graphite strip was monitored by a thermocouple which was embedded in a small hole in the centre of the carbon strip. The temperature of the carbon strip was displayed on a COMARK digital thermometer and was controlled to within 1°C using a temperature controller designed and constructed by the department's Electronic Workshop, the signal from the thermocouple being used to provide the feedback signal. Prior to nitride growth the system was evacuated using a rotary pump. A liquid nitrogen fore-line trap was incorporated in the vacuum line to reduce the quantity of water vapour present.

A $\frac{1}{3}$ p.s.i. non return valve was incorporated in the outlet line so that a positive pressure was maintained in the chamber. In this way
Fig. 16 Construction of First Si₃N₄ Deposition Apparatus.
the effect of any leaks upon the composition of the nitride would be minimised. The non-return valve also had the effect of sealing off the outlet during pumping.

The complete growth schedule is summarised in Table (4).

Using this system the optimum growth temperature was determined to be 580°C, which was reached in about 8 seconds. Under the conditions given in table (4) a nitride film 400 - 600Å thick could be grown in five minutes, although the thickness varied from run to run. It was thought that this was due to heating of the growth chamber.

After the growth cycle was completed, the system was evacuated, and then flushed with flowing oxygen free nitrogen. The flow rate of the nitrogen was 8 l/min. The GaAs samples were then annealed at 900°C. This was achieved by reheating the samples to 580°C, and then increasing the temperature of the graphite strip to 900°C for 30 seconds (including ~ 6 seconds warm up time). The samples were then allowed to cool in flowing nitrogen and removed from the apparatus.

A second system was constructed to improve the uniformity of the Si$_3$N$_4$ layers grown, increase the size of samples, and improve the reliability and reproducibility of growth. This system shown schematically in figure (17) is of stainless steel construction, with very similar facilities to the original. The carbon heater strip was increased in size from 2" x ½" to 4" x 1⅜". The central area of the strip between the contacts, was milled down from 3mm to 1mm to increase the resistance. The current required to heat the strip was about 120 Amps to heat, and 60 amps to maintain a temperature of 700°C. Copper water pipes were soldered to the outside of the chamber for cooling and, reflector plates above and below the carbon heater were incorporated to reduce the heat loss to the walls of the reactor, and increase the temperature of the reagent gases in the vicinity of the sample. Other features of the system are that the top of the chamber was counter-balanced for easy
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Check all gas cylinder valves on and fore-line trap filled with liquid nitrogen.</td>
</tr>
<tr>
<td>2.</td>
<td>Open system and place sample in centre of graphite strip.</td>
</tr>
<tr>
<td>3.</td>
<td>Replace Belljar and open exhaust valve to evacuate system.</td>
</tr>
<tr>
<td>4.</td>
<td>Fasten Belljar Retaining screws.</td>
</tr>
<tr>
<td>5.</td>
<td>When pressure &lt; 0.1 torr close vacuum valve and open nitrogen valve.</td>
</tr>
<tr>
<td>6.</td>
<td>Preheat carbon strip to 150°C for 5 minutes.</td>
</tr>
</tbody>
</table>
| 7.   | Switch off nitrogen and introduce mixed gases. Set flow rates of gases to:  
|      | Nitrogen 1000 cc/min  
|      | Ammonia 400 cc/min  
|      | 5% Silane 200 cc/min. |
| 8.   | Leave gases flowing for 5 mins. |
| 9.   | Increase graphite strip current so that growth temperature (580°C) is reached, leave for 5 mins. |
| 10.  | Switch off current to carbon strip, turn off mixed gases and flush with nitrogen at 8 l/min for 5 mins. |
| 11.  | Check carbon temperature below 100°C. |
| 12.  | Switch on carbon strip heater and check growth temperature achieved. |
| 13.  | Switch graphite strip current to high - check annealing temperature (900°C) is achieved. |
| 14.  | Switch off graphite strip current after 30 seconds. |
| 15.  | Allow graphite strip to cool to below 100°C before turning off nitrogen gas. |
| 16.  | Evacuate chamber to release bell jar retaining screws - close vacuum valve and let system up to nitrogen. |
Figure 17  **Second Silicon Nitride Deposition Apparatus.**
Fig. 18 Second Silicon Nitride Apparatus and Close up View of Chamber Furniture.
removal, and the whole apparatus was enclosed in an airtight enclosure, with an exhaust fan for removal of any contaminant gases due to leakage. The Elliot flow meters had proved unreliable in the first apparatus, and were replaced with Brookes MID-RATE 150 flowmeters, which were more reliable and leak free. The apparatus is pictured in figure (18).

Because of the modifications it was found that the thickness of the nitride layers grown was very reproducible from run to run.

The growth rate of the new system was greatly increased - a 600Å thick film could be grown in 20 seconds at 580°C. However, after a great deal of experimentation the growth temperature in this system was set at 680°C. At this temperature a film of approximately 1000Å could be grown in 20 seconds. The growth/anneal schedule used in the second system was the same as that in the first, except for the growth temperature and time.

The experimental results which led to the establishment of the growth and anneal schedules used in each apparatus are discussed fully in the following chapter.

3.5 Sample Preparation

Apart from a limited amount of material which was delivered to Plessey Research for device production, all the implanted samples were measured by the Hall technique. For this clover-leaf specimens were prepared as outlined below. Each 1cm square sample was cut into four clover-leaf samples by affixing mild steel clover leaf masks to the nitride-coated surface with dental wax, and cutting away the un-masked material with a jet of nitrogen containing alumina abrasive powder. A COMCO INC. microblaster was used for this purpose, and the samples were mounted onto glass slides, again with dental wax, during this procedure. The clover leaf masks were made by etching steel sheet in hot ferric-chloride solution, the clover leaf pattern being delineated by photolithography.

After cutting, the samples were removed from the masks and the
glass slide by melting the wax, and then heated in toluene to remove any residual wax. The silicon nitride was then removed by immersing the samples in cold HF for five minutes. The samples were then thoroughly rinsed in distilled water and dried.

Electrical contacts were then alloyed to each corner. This was achieved by resting a small piece of 99.999% pure tin wire onto the GaAs, and heating the sample until the tin melted. A gas stream produced by bubbling 5% H₂ in N₂ through concentrated HCl was passed over the sample during the heating, to maintain cleanliness and prevent oxide formation. The tin dots were then contacted electrically using Silver Dag (a colloidal suspension of silver in a volatile organic medium). To ensure the contacts were ohmic (non-rectifying) the variation of current with voltage between each pair of contact was displayed on a curve tracer.

Electrical measurements performed on samples prepared as outlined above have shown the samples to be reasonably symmetric electrically, with

\[ \frac{R_{AB}}{R_{BC}} = \frac{R_{CD}}{R_{DA}} \] (see figure 19)

3.6 The Hall Technique

In 1958 van der Pauw (107) published the theory enabling Hall measurements to be performed on samples of arbitrary shape, provided the following criteria were fulfilled:

(a) Electrical contacts are located at the circumference of the sample.
(b) The contacts are small.
(c) The sample is of uniform thickness.
(d) The surface of the sample is singly connected (no pin holes).

According to Van der Pauw the following relationships apply for a sample with four contacts A, B, C and D, as shown in figure (19).
(i) **Sheet Resistivity** ($\rho_s$)

$$\rho_s = \frac{\pi}{\ln 2} \cdot \frac{R_{AB, CD} + R_{BC, DA}}{2} f$$  \hspace{1cm} (20)$$

$R_{AB, CD}$ = potential difference between contacts C and D for unit current through A and B

i.e. $R_{AB, CD} = \frac{V_{CD}}{I_{AB}}$

$f$ is a function given by

$$\frac{R_{AB, CD} - R_{BC, DA}}{R_{AB, CD} + R_{CB, DA}} = f \cdot \text{arccosh} \left[ \frac{\exp \left( \frac{\ln 2}{f} \right)}{2} \right]$$  \hspace{1cm} (21)$$

For a symmetrical sample

$$R_{AB, CD} = R_{BC, DA}$$ and $f = 1$.

(ii) **Sheet Hall Coefficient** ($R_{HS}$)

$$R_{HS} = \frac{\Delta R_{BD, AC}}{B}$$  \hspace{1cm} (22)$$

where $R_{HS}$ = sheet Hall coefficient

$B$ = magnetic field

$\Delta R_{BD, AC}$ = difference between the values of $R_{BD, AC}$ measured with and without applied magnetic field.

(iii) **Sheet Hall Mobility** ($\nu_{HS}$)

$$\nu_{HS} = \frac{R_{HS}}{\rho_s}$$  \hspace{1cm} (23)$$

where $\nu_{HS}$ is the sheet Hall mobility, which is related to the conductivity mobility $\mu$ by the relationship

$$r = \frac{\nu_{H}}{\mu}$$  \hspace{1cm} (24)$$

where $r$ = Hall scattering factor

$$\mu = \frac{1}{ne\rho}$$ where $n$ = carrier concentration.
The actual value of \( r \) depends on the scattering mechanisms and impurity concentration. As the exact value in any situation is not known \( r \) is assumed to be unity. This assumption, however, could lead to an error of up to 15% in \( n_s \). However, as this assumption is, of necessity, made by all workers using the Hall technique, direct comparison of results is possible and the error introduced is not considered a serious disadvantage.

The sheet carrier concentration is the total number of free electrons in the measured layer.

Thus the sheet electron concentration can be related to the implanted dose by the electrical activity or activation efficiency \( \eta \)

\[
\eta = \frac{n_s}{N_s} \times 100\% 
\]

where \( N_s \) is the implanted dose cm\(^2\).

To measure the electrical parameters required to calculate the properties of the implanted layers clover leaf samples were located between the pole pieces of a large electromagnet. The current supplied through the magnet was monitored continuously and controlled to within 0.1%. Hence the magnetic field, which was 5kG, was accurately determined, and corresponded to 141mV measured across a standard water cooled resistor.

A Keithley Instruments Model 225 current supply was used to provide a constant sample current accurate to ±0.5%, and the voltage between the other two sample contacts was monitored with a Solatron A200 digital voltmeter. In order to reduce the effects of slightly non ohmic contacts with respect to the magnetic field the quantities \( R_{AB,CD}, R_{BC,DA} \) and \( R_{BD,AC} \) were measured with the current flowing in each direction (e.g. \( A \to B \) and \( B \to A \)). To minimise the effects of sample misalignment
TABLE 5

Switching Sequence Used in Hall Measurements

<table>
<thead>
<tr>
<th>Switch Position</th>
<th>Constant Current</th>
<th>Measured Voltage</th>
<th>Magnetic Field</th>
<th>Measurement Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+ I_{AB}</td>
<td>V_{CD}</td>
<td>0</td>
<td>Resistivity</td>
</tr>
<tr>
<td>2</td>
<td>+ I_{BC}</td>
<td>V_{AD}</td>
<td>0</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>+ I_{BD}</td>
<td>V_{AC}</td>
<td>0</td>
<td>Hall</td>
</tr>
<tr>
<td>4</td>
<td>&quot;</td>
<td>&quot;</td>
<td>+B</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>&quot;</td>
<td>0</td>
<td>&quot;</td>
</tr>
<tr>
<td>6</td>
<td>&quot;</td>
<td>&quot;</td>
<td>-B</td>
<td>&quot;</td>
</tr>
<tr>
<td>7</td>
<td>- I_{AB}</td>
<td>V_{DC}</td>
<td>0</td>
<td>Resistivity</td>
</tr>
<tr>
<td>8</td>
<td>- I_{BC}</td>
<td>V_{DA}</td>
<td>0</td>
<td>&quot;</td>
</tr>
<tr>
<td>9</td>
<td>- I_{BD}</td>
<td>V_{CA}</td>
<td>0</td>
<td>Hall</td>
</tr>
<tr>
<td>10</td>
<td>&quot;</td>
<td>&quot;</td>
<td>+B</td>
<td>&quot;</td>
</tr>
<tr>
<td>11</td>
<td>&quot;</td>
<td>&quot;</td>
<td>0</td>
<td>&quot;</td>
</tr>
<tr>
<td>12</td>
<td>&quot;</td>
<td>&quot;</td>
<td>-B</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Fig. 19 Clover Leaf Sample used for Hall measurements.
with respect to the magnetic field, and eliminate the effects of hysteresis in the magnet pole pieces \( R_{BD,AC} \) was measured with the field applied in each direction, and also after the field had been switched off in each case. Thus a total of twelve measurements were required to completely characterise a layer. This was achieved by automatic switching of the connections to the magnet and sample. The sequence of switching is shown in table (5).

The measured voltages and the value of the constant current and magnetic field were fed into a calculator programmed to calculate the values of \( R_{HS} \), \( \rho_s \), \( n_s \) and \( \mu_s \) according to equations (22), (20), (25) and (23). The calculator also determined the value of \( f \) from the approximate equation

\[
f \approx 1 - \frac{R_{AB,CD} - R_{BC,DA}}{R_{AB,CD} + R_{BC,DA}} = \frac{2n_2^2}{4} \left( \frac{R_{AB,CD} - R_{BC,DA}}{R_{AB,CD} + R_{BC,DA}} \right)^4 \left( \frac{2n_2^2}{4} - \frac{(2n_2)^3}{12} \right) (27)
\]

which provides a sufficiently accurate value for \( f \) provided the ratio of \( R_{AB,CD} \) to \( R_{BC,DA} \) is less than 5. For samples where this ratio was greater than 5 further measurements were not made, as this only occurred with poor quality samples (non ohmic contacts, scratches etc.).

3.7 Electrical Profiling by the Differential Hall Technique

In order to determine the variation of the electrical properties with depth of the implanted layers the Hall technique was used in conjunction with chemical stripping. The theory which allows the determination of the volume values from successive sheet values was derived by Buehler(109). Buehler makes the assumption that the conducting layer is composed of a series of laminar layer each of thickness \( d_i \). Then the mobility \( \mu_i \) and the carrier concentration \( n_i \) of the \( i_{th} \) layer are given by:

\[
\frac{(R_s^2)}{\rho_s^2} - \frac{(R_s^2) + 1}{\rho_s^2} = e n_i \mu_i^2 d_i \] (28)
and \((\rho_s_i)^{-1} - (\rho_s_{i+1})^{-1} = e n_i \mu_i d_i\) \hspace{1cm} (29)

hence \(\nu_i = \frac{\Delta (R_s/\rho_s^2)_i}{\Delta (1/\rho_s)_i}\) \hspace{1cm} (30)

and \(n_i = \frac{\Delta (1/\rho_s)_i}{ed_i \mu_i}\) \hspace{1cm} (31)

where \((R_s)_i\) and \((\rho_s)_i\) are the sheet Hall coefficients and sheet resistivity which are measured following removal of the \(i^{th}\) layer and

\[
\Delta x_i = x_i - x_{i+1}
\]

Layer removal was achieved by successively etching for 1 minute periods in a solution of \(H_2SO_4, H_2O_2, H_2O\) in the ratios 1, 1, 100. The sample contacts were protected from the etch by coating with Apiezon W wax which was applied by painting with a solution of wax and toluene.

Electrical measurements on etched layers were performed with the sample immersed in de-ionised water. This not only reduced any temperature variation of the sample but inhibited the formation of the brown oxide which was observed to form on samples which were dried after etching.

The total number of layers removed varied from sample to sample according to the thickness of the active layer. (For very thin or very thick layers the etch time was changed to \(\frac{1}{2}\) or 2 minutes respectively to improve the accuracy of the results). Etching was discontinued when measurements became unstable or when the measured values of \(R_{AB.CD}\) and \(R_{BC.DA}\) under positive and negative current become different by a factor of two or more.

In order to determine the amount of material removed at each etch the total amount of material removed was measured using a Rank-Taylor Hobson Talystep, and this depth divided by the total number of etches performed. The accuracy of the step height measurement was \(\pm 5\%\). A total of eight heights were measured (two on each corner), and where
the scatter in these measurements was greater than 10% the etching was assumed to be non-uniform and the results were discarded. It was found that the amount of material removed per minute varied from 300-400 Å.

3.8 Errors of the Hall Technique

As already discussed the uncertainty in the numerical value of the Hall scattering factor is a source of error in the calculated value of the electron concentration. For reasons already discussed this error will be disregarded hereafter. Other sources of error are discussed below.

(i) Sample leakage current

Any current flowing between the contacts, either by leakage across the surface, through the bulk of the GaAs sample, or through the de-ionised water in which the sample is immersed, lead to an error in the calculation of the electrical properties of implanted layers. Hall measurements performed on high resistivity semi insulating material indicate that the leakage current is negligible in comparison with the typical measurement current of 70 - 500μA even at the maximum voltage supplied by the current source.

(ii) Sample Current

The Keithly current source used was capable of supplying the digitally selected current to within ± 0.5%. This was checked by monitoring the voltage dropped across a standard 1KΩ resistor. At no time was the observed current variation greater than this value.

(iii) Magnetic field

For a field of 5kG the required magnet current has been determined to correspond to a reading of 141mV measured across standard water cooled resistor incorporated in series with the magnet coils. The reproducibility of this voltage is better than 0.5%, and it is assumed that the reproducibility of the magnetic field is consistent with this value.
(iv) **Sample Voltage Measurements**

All voltage measurements were measured to ± 0.05mV. Where possible the sample current was adjusted to give voltage readings corresponding to the values of $R_{AB,CD}$, $R_{BC,DA}$ and $\Delta R_{BD,AC}$, of about 10mV or greater. Thus the error introduced by the voltage measurement is less than ± 0.1% for each reading taken.

(v) **Step Height measurement**

The major source of error in determining the electrical depth profiles is in the determination of the thickness of material removed by etching. The step height measurements performed using the Talystep were assumed accurate to within 5%. Care was taken with these measurements to ensure the most sensitive possible range of the instrument was used, in order to ensure the degree of accuracy.

(vi) **Other sources**

Other non quantifiable sources of error such as contact resistance and slightly rectifying contacts add to the error of the Hall measurements. The sources of error can only be minimised by care in sample preparation, and the possibility of such errors taken into account when considering electrical results.

By partial differentiation of equation (20) the error in the measurement of $R_{AB,CD}$ is given by

$$\frac{\delta R_{AB,CD}}{R_{AB,CD}} = \frac{\delta V_{CD}}{V_{CD}} + \frac{\delta I_{AB}}{I_{AB}}$$

where $\delta X$ represent the small error in $X$.

Because of the averaging technique used in the measurement the error in the sheet resistivity measurement becomes

$$\frac{\delta \rho_s}{\rho_s} = \frac{1}{2} \left[ \frac{\delta V_{CD}}{V_{CD}} + \frac{\delta I_{AB}}{I_{AB}} \right]$$

$$= 0.1\%$$
From equation (22)

\[ R_{HS} = \frac{\Delta R_{BD, AC}}{B} \]

By suitable choice of the sample current the error of determining the difference between the measured quantities of \( R_{BD, AC} \) with and without applied field can be made sufficiently large, so that

\[ \frac{\delta R_{BD, AC}}{\Delta R_{BD, AC}} \text{ is } << 1\% \]

Therefore, the error in \( R_{HS} \) is predominated by the error in the measurement of the magnetic field, i.e.

\[ \frac{\delta R_{HS}}{R_{HS}} = \frac{\delta B}{B} = \pm 0.5\% \]

From equation (23)

\[ \mu_H = \frac{R_{HS}}{\rho_s} \]

\[ \frac{\delta \mu_H}{\mu_H} = \frac{\delta R_{HS}}{R_{HS}} \frac{1}{\rho_s} + \frac{\delta \rho_s}{\rho_s} \]

\[ \approx 1\% \]

Similarly from equation (25)

\[ n_s = \frac{r}{e R_{HS}} \]

Ignoring the uncertainty in \( r \) we have

\[ \frac{\delta n_s}{n_s} = \pm \frac{\delta R_{HS}}{R_{HS}} \]

\[ \approx \pm 1\% \text{ (or } \pm 16\% \text{ in the absolute value of } n_s) \]

The errors introduced in the Hall profiling technique are more difficult to quantify, due to the differential nature of the method.

From equations (30) and (31) we have

\[ \mu_i = \frac{\Delta (R_s / \rho_s)^2}{\Delta (1 / \rho_s)} \]

and

\[ n_i = \frac{\Delta (1 / \rho_s)}{\epsilon d_i \mu_i} \]
Thus, the errors in the calculation of $\mu_i$ and $n_i$ depend upon the fractional change in the quantities measured and are greatest when the parameters measured vary little after etching. Therefore the error usually decreased with depth in profile measurement and needs calculating for each profile measured. This has been done for many of the profiles measured. In general, with the exception of the first point, where the error can exceed 100%, the error of each point is about $\pm 10\%$, decreasing to $\pm 6\%$ in the tail of the profile.

3.9 The Rutherford Backscatter (RBS) Technique

The Rutherford backscattering technique is a powerful method for the analysis of the surface and near surface composition of solid materials. The technique involves the measurement of the energy distribution of high energy ions which have been caused to undergo large-angle elastic scattering due to collision with target nuclei. In this study the RBS technique was used to analyse the composition of silicon nitride films.

A schematic diagram of the experimental apparatus used is shown in figure (20). A collimated beam of helium ions with an energy of 1.5MeV was directed at the sample under measurement which was mounted on a three axis goniometer. The beam current was limited to about 5nA and the ion beam diameter was about 1mm.

The energy of the backscattered ions was measured using a silicon surface-barrier detector with an energy resolution of about 15keV (FWHM) which was mounted at 150° to the incident beam. The amplified signal from the detector was fed into an 800 channel analyser which recorded the backscattered energy spectrum on a CRT screen, which was then transferred to hard copy on an X-Y chart recorder. An on line printer was used to print out the total number of counts in each of the analyser channels. The observed energy of a backscattered particle from a depth $x$ in the sample is given by (110):

$$E_{\text{obs}} = \left[ E - \int_{0}^{x} S^*(E) d \lambda_1 \right] \frac{K}{\cos \theta_1} - \int_{x/cos \theta_2}^{0} S(E) d \lambda_2$$

(33)
Fig. 20. Schematic Representation of the Rutherford Backscattering System

A) Diagram of Apparatus

B) Geometrical Relationship between $\theta_1$, $\theta_2$ and $\theta_5$. 
where $K$ is the fractional energy loss \( \frac{E_{\text{obs}}}{E} \) and is given by

$$K \approx \left( \frac{M_1 \cos \theta_s + M_2}{M_1 + M_2} \right)^2$$

(34)

$S^*(E)$ and $S(E)$ are the stopping powers of the incoming and outgoing beams.

$\theta_1$ and $\theta_2$ are the angles between the incoming and outgoing beams and the surface normal respectively (fig. (20b))

$\theta_s$ = the total backscattered angle (150°)

$E_{\text{obs}}$ = energy of backscattered particle

$E$ = energy of incident beam

$M_1$ = mass of incident ion

$M_2$ = mass of target atom.

Identification of impurities or constituents of the surface of a solid sample is most easily achieved by determining the highest energy of a peak in the backscatter spectrum (corresponding to the surface, $x = 0$), and calculating the mass of the atoms causing the peak using a known reference peak. This can either be an evaporated gold film, or as in this case the substrate material. In this study silicon nitride films were analysed on both GaAs and vitreous carbon substrates. Vitreous carbon was chosen as an attractive substrate because:-

(a) Carbon has a lower mass than the constituents, and most of the possible contaminants of the silicon nitride films. The backscatter peaks from the nitride films were therefore well resolved, enabling accurate integration of the number of counts in each peak to be made.

(b) As the vitreous carbon samples were non-crystalline the possibility of ion channelling was eliminated, and elaborate alignment techniques avoided.

The vitreous carbon samples were prepared by ultrasonic polishing with diamond paste. Five mm square samples were then cut using a stainless
steel wire saw in an alumina slurry. Immediately prior to nitride growth the carbon samples were thoroughly degreased in hot toluene, immersed in hot HF for five minutes, rinsed in distilled water and dried. Nitride growth took place in the nitride deposition apparatus, usually adjacent to GaAs samples, the electrical properties of which were also measured. In addition some carbon samples were coated with nitride after a 900°C pre-bake to ensure any adsorbed water was removed, and hence decrease any oxygen signal. The angular backscattering probability of an ion beam is given by the Rutherford backscattering formula

\[
\frac{d\sigma}{d\Omega} \propto Z_1^2 Z_2^2 \left(\frac{1}{E}\right)^2 \left(\frac{M_1 + M_2}{M_2}\right)^2 \frac{1}{\sin^4 \theta'/2} \ cm^2 \ sr^{-1}
\]

where \(\theta'\) = backscatter angle in centre of mass coordinates

\(Z_1\) = atomic number of incident ion

\(Z_2\) = atomic number of target nuclei.

Thus the number of counts in the peak due to a particular atom is proportional to the square of its atomic number. The relative concentrations of two constituents in a film can thus be determined using the approximation:

\[
\frac{N_A}{N_B} = \frac{Y_A}{Y_B} \frac{Z_B^2}{Z_A^2}
\]

where \(N = \) concentration

\(Y = \) integrated number of counts under a peak.

The above approximation is valid when the atomic masses of the constituents are significantly greater than the mass of helium. Using the above approximation the relative concentrations of silicon, nitrogen and oxygen were determined, and used as a basis for judging the quality of the films as a suitable encapsulant.
3.10 Silicon Nitride Film Thickness Determination

A limited number of silicon nitride layers were examined by ellipsometry, yielding both the thickness and refractive index of the films. Layers examined in this way were specially grown onto one inch diameter silicon slices, enabling the uniformity of large area films to be determined. All ellipsometric investigations were performed at the Plessey Research Centre. As ellipsometry did not form a major part of the investigation a full description of the technique will not be given here, but further details may be found in reference (111).

More generally silicon nitride thicknesses and uniformity were determined from the interference colours of the films using published data (112). Good agreement between ellipsometric results and the approximate values using interference colours was obtained.

3.11 Manufacture of MESFETs

A number of slices of implanted GaAs were selected as the substrates for the manufacture of MESFETs. The purpose of this aspect of the project was to produce devices with characteristics as near as possible to those of devices manufactured on highest quality epitaxial material; and examine the criteria which govern the behaviour of devices produced on ion implanted material.

The device structure chosen for this examination was the Plessey GAT-4 structure shown in figure (21). This device is a dual gate structure, with two separate MESFETs operated with a common drain. The source to drain separation of each device is 5μm, the gate length is 1μm and the total gate width 300μm. The device is isolated by a MESA etch, and the gate contact pad is located on the semi-insulating substrate to minimise the gate capacitance.

The processing steps used in device manufacture are described below.
Table 6

Variation of Colour of Si₃N₄ Films with Thickness

<table>
<thead>
<tr>
<th>ORDER</th>
<th>COLOUR</th>
<th>Si₃N₄ Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST</td>
<td>SILICON</td>
<td>0 – 0.020</td>
</tr>
<tr>
<td></td>
<td>BROWN</td>
<td>0.020 – 0.040</td>
</tr>
<tr>
<td></td>
<td>GOLDEN BROWN</td>
<td>0.040 – 0.055</td>
</tr>
<tr>
<td></td>
<td>RED</td>
<td>0.055 – 0.073</td>
</tr>
<tr>
<td></td>
<td>DEEP BLUE</td>
<td>0.073 – 0.077</td>
</tr>
<tr>
<td></td>
<td>BLUE</td>
<td>0.077 – 0.093</td>
</tr>
<tr>
<td></td>
<td>PALE BLUE</td>
<td>0.093 – 0.10</td>
</tr>
<tr>
<td></td>
<td>VERY PALE BLUE</td>
<td>0.10 – 0.11</td>
</tr>
<tr>
<td></td>
<td>SILICON</td>
<td>0.11 – 0.12</td>
</tr>
<tr>
<td></td>
<td>LIGHT YELLOW</td>
<td>0.12 – 0.13</td>
</tr>
<tr>
<td></td>
<td>YELLOW</td>
<td>0.13 – 0.15</td>
</tr>
<tr>
<td></td>
<td>ORANGE RED</td>
<td>0.15 – 0.18</td>
</tr>
<tr>
<td></td>
<td>RED</td>
<td>0.18 – 0.19</td>
</tr>
<tr>
<td></td>
<td>DARK RED</td>
<td>0.19 – 0.21</td>
</tr>
<tr>
<td>SECOND</td>
<td>BLUE</td>
<td>0.21 – 0.23</td>
</tr>
<tr>
<td></td>
<td>BLUE-GREEN</td>
<td>0.23 – 0.25</td>
</tr>
<tr>
<td></td>
<td>LIGHT GREEN</td>
<td>0.25 – 0.28</td>
</tr>
<tr>
<td></td>
<td>ORANGE-YELLOW</td>
<td>0.28 – 0.30</td>
</tr>
<tr>
<td>SECOND</td>
<td>RED</td>
<td>0.30 – 0.33</td>
</tr>
</tbody>
</table>
Fig. 21 Dual Gate FET used in this study.
(i) After removing the Si$_3$N$_4$ encapsulating layer, and washing the sample the active areas of the devices were delineated by contact photolithography and a mesa etch performed to isolate the individual devices.

(ii) The source and drain regions were exposed in a second layer of photo resist, and a light etch was performed to remove any damaged layer introduced during the annealing.

(iii) The source and drain metallisation was deposited by evaporation of In, Ge,Au. The unwanted metal was removed by the lift off technique. This step was aided by the etch step above which increases the resolution at the edges of the metallisation.

(iv) The contacts were alloyed into the GaAs by heating to about 450°C. The source-drain resistance was measured at this stage to ensure the suitability of the n-type layer for device production. Where slice resistance was high processing was discontinued at this point.

(v) The gate areas were exposed in a third photoresist layer, and subsequently etched to the required depth, which was varied according to the dopant profile of the n-type layer.

(vi) The gate metallisation, aluminium, was deposited by evaporation, and the unwanted metal removed, again by the lift off technique. Contact photolithography was used throughout. The processing required a set of three masks, and the alignment of each mask (which is critical) was assisted by the alignment marks on each mask. The gate length was observed to vary by about ±0.1μm from the nominal value of 1μm.

All device processing was performed by staff at the Plessey Research Centre as the techniques used are highly critical, and successful results can only be achieved by experienced processors.

3.12 Electrical Assessment of Device Performance

(i) D-C Measurements

Individual devices were contacted by probing the source, gate and
drain contact pads, and the I-V characteristics measured on a
transistor tester. The characteristics measured were

(a) Source-drain I-V characteristics, at zero gate volts, and
with incrementally increasing negative gate voltage.
(b) Forward and reverse characteristics of the gate Schottky
barrier.

The saturation current and transconductance of each device on the
slice were measured and recorded. The slice was then scribed and
cleaved into individual devices, and suitable devices selected for
microwave measurement.

(ii) Microwave Measurements

For the measurement of the microwave characteristics of the FETs
individual devices were bonded onto 1 x \(\frac{1}{4}\) inch alumina carriers
with a microwave stripline circuit. The source, gate and drain pads
were connected electrically to the copper contacts of the carriers
by wires connected by thermal-compression bonding. The carrier
was then connected into a jig which was then coupled into a waveguide
circuit by co-axial connectors electrically connected to the carrier.
The gain and noise characteristics of the devices were measured in a
calibrated apparatus working at 12.75GHz. The measurement technique
is shown schematically in figure (22). For the noise measurement
the signal from a calibrated noise source was fed into the FET.
The output from the FET was then amplified using a low noise
amplifier and mixed with the signal from a local oscillator at the
test frequency. The IF output from the mixer was then fed into a
noise figure indicator. The noise figure of the FET could then
be determined directly as the difference between the signals with
the noise source turned on and off.

For the gain measurements the output from an oscillator
was fed directly into the FET. The output of the FET was then
Fig. 22 Apparatus used for Measurement of
(A) Noise figure (B) Gain of FETs
fed into a power meter and compared with the signal from a separate line which bypassed the FET. The output power of the FET was attenuated, using a calibrated attenuator, so that the signal at the power meter was equal to that from the bypass line. The gain of the FET was then equal to the level of attenuation required to equalise the two signals.

The maximum available gain of the FET was determined with the gate zero biased. To match the FET to the measurement circuit small copper discs were placed onto the carrier, and their position adjusted until a minimum value of the FET noise was measured. The applied gate voltage was then increased to reduce the source-drain current until the noise signal was minimised.
4. **EXPERIMENTAL RESULTS**

4.1 **Introduction**

In this chapter the experimental results obtained will be presented under the three major classifications:

(a) Qualification of Silicon Nitride Encapsulant.
(b) Electrical Results of ion implanted layers.
(c) Electrical measurements of MESFETs.

The detailed discussion of the results is given in the following chapter.

4.2 **Qualification of Silicon Nitride Encapsulant**

4.2.1 **Rutherford Backscatter Analysis**

The RBS technique was used to determine the level of oxygen contamination and the stoichiometry of the nitride films deposited. The spectrum shown in figure (23a) was chosen as representative of several spectra obtained early in commissioning of the first nitride deposition apparatus. A large peak due to oxygen was observed. By integration of the counts in each peak the relative concentrations of the nitrogen, oxygen and silicon were determined to be

$$\frac{Si}{N} \approx 1, \quad \frac{O}{N} \approx 0.3$$

All of the nitride films examined at this stage contained large amounts (20-50%) of oxygen. As the carbon heater strip had been outgassed prior to growth, it was suspected that leaks were present in the apparatus. No leaks were discovered using conventional vacuum leak detection methods. Very small leaks were however detected by pressurising the equipment with ammonia to the supply pressure (112 psi) and probing the apparatus with wet Universal Indicator paper. As ammonia is alkaline and readily soluble the indicator paper underwent a rapid change in colour when located in the vicinity of a leak. It was found that the major sources of leaks were the seals in the flow meters used, and once these leaks were eliminated the amount of oxygen in the films was drastically reduced.
Figure 23. Typical RBS Spectra of $\text{Si}_x\text{N}_y$ Films Grown in Vitreous Carbon Substrates in First Apparatus.

A. showing large oxygen peak
B. showing reduced oxygen signal after leaks repaired.
The spectrum shown in figure (23b) has been selected as being more
typical of those obtained in the first apparatus after leaks were
eliminated, and a liquid nitrogen trap was incorporated in the vacuum
system. The relative concentrations of the components of these films
were:
\[
\frac{\text{Si}}{\text{N}} = 0.8, \quad \frac{\text{O}}{\text{N}} = 0.1
\]
Thus the films deposited were approximately stoichiometric \( \text{Si}_3\text{N}_4 \), with
an oxygen content of about 10\%. In some cases the amount of oxygen
was close to the detection level of the RBS system,
less than 5 at \%. 

One feature of both the spectra discussed above is the presence of
a peak due to a high arsenic content in the nitride films. This peak was
only observed when the nitride films were deposited simultaneously on carbon
and GaAs substrates. To discover the source of the As a series of
nitride layers were deposited as follows:

(a) A film was grown on a carbon substrate next to an uncoated GaAs sample.
(b) A film was grown on a carbon substrate next to a GaAs sample with its
back face (the face in contact with the carbon heater) previously
coated with silicon nitride.
(c) A film was grown as in (b) above, and subsequently annealed whilst
still adjacent to the coated GaAs sample.

In between each growth cycle the apparatus was purged of any residual arsenic
by heating the carbon strip to 900\(^\circ\)C with the system under vacuum.

A signal due to arsenic was only observed in sample (a) above;
thus the source of arsenic was identified as being the uncoated face in
contact with the carbon heater. Any arsenic lost during sample heating
in the growth cycle, or through the nitride layer during annealing was
below the detection limit of the technique.

The spectrum shown in figure (24) was obtained from a nitride film
grown on a carbon substrate in the second deposition apparatus. This
Figure 24. Typical RBS Spectrum of a Silicon Nitride Layer Grown in Second Apparatus with Indetectable Oxygen Signal.

Si$_3$N$_4$ film thickness $\sim$ 1000Å.
spectrum is typical of those obtained from layers deposited in this apparatus, in that little or no signal due to oxygen was obtained. The silicon to nitrogen ratio of this particular film was 0.75. Several samples grown at temperatures varying from 600-800°C, were examined by Rutherford backscattering. The silicon to nitrogen ratio measured in these samples was in the range 0.72 - 0.79. Within the error of the technique these results indicate that the layers examined were stoichiometric silicon nitride, and no variation was observed that could be correlated with growth temperature.

4.2.2 Electrical Measurements

The main criteria for judging the silicon nitride films was the effectiveness of the layers as encapsulants. The principle test for the nitride layers was to coat samples of semi-insulating GaAs with silicon nitride and anneal to 900°C for 30 secs. The nitride was then removed, and the electrical properties of the GaAs measured by the Hall technique. The results reported below were all obtained after the RBS technique had been used to confirm that stoichiometric Si$_3$N$_4$ was being deposited.

(a) Layers Deposited in First Apparatus

Initial measurements were performed on MCP semi-insulating material. A series of nitride layers were grown at temperatures of 650 - 900°C. The gas flow ratios were kept constant at

\[
\begin{align*}
\text{NH}_3 & \quad - \quad 400 \text{ cc/min} \\
5\% \text{ SiH}_4 & \quad - \quad 200 \text{ cc/min} \\
\text{N}_2 & \quad - \quad 1000 \text{ cc/min}.
\end{align*}
\]

Because the nitride growth rate increases with temperature the growth time was varied so that approximately 600\(\times\) as judged from the interference colour of the films were deposited. After deposition of the nitride the system was evacuated and then the samples were annealed at 900°C in
flowing nitrogen.

The resulting sheet carrier concentrations of the samples are given in table (7). In all cases the samples were p-type with hole concentrations varying from \( \approx 10^{12} \) to \( 3.4 \times 10^{14} \) cm\(^{-2}\).

A definite trend existed in these results, that is the encapsulation efficiency of the nitride layers was improved when the growth took place at the higher or lower temperatures.

Because it is not possible to divorce the effect of thermal instability of the semi-insulating material from the electrical results the experiment was repeated using MR material. Samples were prepared from ingot number A65R which was thought to be thermally stable, having been previously characterised by the manufacturer. The trend observed in the electrical results was similar for this material, and so the range of growth temperature was extended to lower temperatures. It was found that a nitride layer approximately 400 Å thick could be grown in 5 minutes at a growth temperature of 580°C, and the degree of type conversion measured in samples coated in this manner was the lowest observed.

The actual hole concentration determined after annealing was \( 1 - 1.4 \times 10^{11} \) cm\(^{-2}\) in four samples measured. Measurement of samples similarly coated but un-annealed was also attempted. Hall measurements were not possible as the samples were still highly resistive indicating that the type conversion observed occurred during the annealing and not the growth stage.

Because of the relative success of the nitride deposited at the low temperature it was used as the standard encapsulant in further studies of ion implanted material.

(b) Layers Deposited in Second Deposition Apparatus

Samples of A65R MR semi-insulating material were coated with silicon nitride on the second deposition apparatus. The growth temperature was varied between 580 and 900°C, and the samples were subsequently annealed
TABLE 7

Variation in Degree of Type Conversion Observed in MCP and MR Material after Annealing at 900°C for 30 Seconds in First Deposition Apparatus

<table>
<thead>
<tr>
<th>Growth Temp. (°C)</th>
<th>Growth Time (secs.)</th>
<th>Sheet Hole Concentration (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MCP</td>
</tr>
<tr>
<td>650</td>
<td>40</td>
<td>1.10¹³</td>
</tr>
<tr>
<td>700</td>
<td>20</td>
<td>1.10¹⁴</td>
</tr>
<tr>
<td>750</td>
<td>15</td>
<td>3.4 1.10¹⁴</td>
</tr>
<tr>
<td>800</td>
<td>13</td>
<td>4.7 1.10¹²</td>
</tr>
<tr>
<td>850</td>
<td>10</td>
<td>2.10¹²</td>
</tr>
<tr>
<td>900</td>
<td>8</td>
<td>1.10¹²</td>
</tr>
</tbody>
</table>

TABLE 8

Resistance of 10 x 2 mm Bars of MR Material after Annealing in Second Apparatus at 900°C for 30 Seconds

i. Flow Rates N₂ 1000 cc/min., NH₃ 400 cc/min., 5% SiH₄ 200 cc/min.

<table>
<thead>
<tr>
<th>Growth Temp. (°C)</th>
<th>Average Resistance (Ω)</th>
<th>No. of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>580</td>
<td>3.5 x 10⁷</td>
<td>4</td>
</tr>
<tr>
<td>630</td>
<td>10⁷</td>
<td>4</td>
</tr>
<tr>
<td>680</td>
<td>2 10⁷</td>
<td>3</td>
</tr>
<tr>
<td>700</td>
<td>4 10⁷</td>
<td>4</td>
</tr>
<tr>
<td>800</td>
<td>10⁷</td>
<td>4</td>
</tr>
<tr>
<td>900</td>
<td>5 10⁷</td>
<td>2</td>
</tr>
</tbody>
</table>

ii. Growth at 630°C

<table>
<thead>
<tr>
<th>Flow Rates (cc/min.)</th>
<th>Average Resistance (Ω)</th>
<th>No. of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>NH₃</td>
<td>SiH₄ (5%)</td>
</tr>
<tr>
<td>500</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>1,000</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>6,000</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>1,000</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>1,000</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>2,000</td>
<td>100</td>
<td>600</td>
</tr>
</tbody>
</table>
at 900°C for 30 seconds in flowing nitrogen. Hall measurements were not possible as the resistance of all the samples was too high. Instead cleaved samples approximately 10 x 2 mm were contacted at each end with tin dots. The resistance of these samples was measured on a curve tracer. No significant variation was observed in the resistance of these samples, whatever the growth temperature, and in all cases the resistance was greater than 10^7 Ω. Variation in the flow rates of the reagent gases also produced no significant variation in the resistance measured. These results are summarised in Table (8). Thus the efficiency of the encapsulant layers deposited in the second apparatus was independent of the growth temperature and the gas flow rates, within the range studied. The slight variations in the values of resistance were thought to be caused by the inaccuracies of the measurement technique and small differences in sample size; and not by any difference in encapsulation efficiency.

Samples measured after nitride growth but without annealing were of too high a resistance to be measured and appeared identical to untreated semi-insulating material.

4.2.3 Uniformity and Appearance of Films

(i) All the nitride films grown were assessed optically, both with the naked eye and microscopically. This examination was usually performed after annealing. With two provisos all of the films grown in the first apparatus were featureless and free of pin holes, blisters and cracks. The two exceptions to this were:

(a) GaAs surface insufficiently clean prior to nitride deposition

Drying stains in particular caused pin holes in the nitride layer which became decorated after annealing. Small particles of foreign matter, dust etc., also caused holes in the nitride films, leaving the GaAs uncoated. Special care was taken in assuring
the surfaces of the GaAs were rigorously cleaned prior to deposition.

(b) Excessive Thickness of Nitride Layers

Because of the difference in thermal expansion coefficient of the GaAs and the Si₃N₄, some films cracked or blistered after annealing. This effect was not observed in layers less than 1000Å thick where, presumably, the nitride layers were sufficiently elastic to accommodate stresses caused by the differential expansion. The uniformity of the silicon nitride layers grown in the first apparatus was assessed from the interference colour of the films. It was found that the film thickness could vary by over 50% on a 1cm square sample. For example, layers grown by the standard method (580°C for 5 minutes) varied from less than ~300Å at the edges of the sample to ~600Å at the centre. The observed non-uniformity was the principle reason for constructing the second redesigned deposition apparatus.

(ii) Silicon nitride layers grown in the second apparatus were found to be more susceptible to pin holes and blisters. Attempts to densify the films by annealing at 700°C for up to 30 minutes prior to annealing at 900°C were unsuccessful in preventing the blistering. The incidence of holes in the nitride layers also seemed to be independent of the gas mixture used for deposition and also the source of the GaAs.

A range of films of thickness varying from 300 - 1200 Å was grown in order to discover if the frequency of holes could be minimised by limiting the thickness of the layer, however there appeared to be no definite trend in these results.

A subjective comparison of films grown at various temperatures (the layers discussed in table (8)) indicated that the frequency of
hole formation seemed to be less when the films were grown at 680°C, although the number of films actually examined in this study was insufficient for a statistical analysis. Nitride layers grown subsequently at 680°C for protection during the annealing of implanted samples, did, however, produce hole free layers on the majority of occasions.

The thickness uniformity of nitride layers deposited in the second apparatus was remarkably good. No discernable variation in the colour of the films was observed in films grown on 1cm square GaAs samples. In order to determine the uniformity of layers over large areas films were grown on one inch diameter silicon slices which were readily available. A small variation in the interference colour of these films indicated that the films were slightly thicker in the central area.

Two layers grown under markedly different growth conditions were examined by ellipsometry at the Plessey Research Centre, and results are given in Table (9). The film thickness and refractive index were measured at nine points distributed over the area of the sample. Despite the difference in growth conditions the refractive indices measured in both cases are close to the ideal value of 1.97 expected for stoichiometric Si$_3$N$_4$. The thickness variation of both films was also very good, being less than ±5% over the 1 inch diameter slices. Also given in table (10) are the approximate thicknesses of nitride layers grown at different temperatures but with the same gas flow rates. It can be seen that the growth rate is dependent upon growth temperature. It is not possible to ascribe an exact growth rate for the nitride films as the time taken for the sample to reach the growth temperature is included in the growth time. The thermal cycles measured on the second apparatus are shown in figure (25). The rise time of the carbon strip is a function of its thermal capacity and electrical resistance of the carbon heater strip. It was observed
### TABLE 9

**Variation of Silicon Nitride Thickness and Refractive Index over one Inch Diameter Slices**

<table>
<thead>
<tr>
<th>Position</th>
<th>Layer A</th>
<th>Layer B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (Å)</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>1</td>
<td>1040</td>
<td>1.97</td>
</tr>
<tr>
<td>2</td>
<td>1040</td>
<td>1.98</td>
</tr>
<tr>
<td>3</td>
<td>1040</td>
<td>1.97</td>
</tr>
<tr>
<td>4</td>
<td>1026</td>
<td>1.97</td>
</tr>
<tr>
<td>5</td>
<td>1010</td>
<td>1.97</td>
</tr>
<tr>
<td>6</td>
<td>1070</td>
<td>1.96</td>
</tr>
<tr>
<td>7</td>
<td>1060</td>
<td>1.96</td>
</tr>
<tr>
<td>8</td>
<td>1010</td>
<td>1.97</td>
</tr>
<tr>
<td>9</td>
<td>980</td>
<td>1.97</td>
</tr>
</tbody>
</table>

**Growth Conditions**
- Layer A: 680°C for 20 seconds
- Layer B: 580°C for 15 seconds

### TABLE 10

**Dependence of Silicon Nitride Film Thickness upon Growth Temperature**

<table>
<thead>
<tr>
<th>Growth Temp. (°C)</th>
<th>Film Colour</th>
<th>Estimated Thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>580</td>
<td>RED</td>
<td>600</td>
</tr>
<tr>
<td>630</td>
<td>DARK BLUE</td>
<td>800</td>
</tr>
<tr>
<td>680</td>
<td>LIGHT BLUE</td>
<td>1000</td>
</tr>
<tr>
<td>700</td>
<td>YELLOW</td>
<td>1200</td>
</tr>
</tbody>
</table>

**Growth Conditions**
- N₂ 1000 cc/min., NH₃ 400 cc/min., 5% SiH₄ 200 cc/min.
- Growth time 20 seconds.
Fig. 25 Thermal cycles of graphite strip in second deposition apparatus.
that the time required for the heater strip to reach the growth temperature of 680°C was approximately 9 seconds (starting from 150°C).

4.3 Electrical Measurements of Ion Implanted GaAs

A large number of implanted samples were examined by the Hall technique in order to determine the most suitable implantation parameters for device fabrication.

Whilst all the devices manufactured were made by the etched gate technique, layers suitable for selectively implanted planar devices were also investigated.

In addition to the implantation of single ion species dual ion implantations were performed to determine the effectiveness of this technique in improving the activation efficiency of the implanted ions. Double energy implantations were also performed to enable the electrical depth profiles to be tailored to suit the specific requirements of the etched gate MESFETs. In order to achieve the profiles required, implants at energies up to 1 MeV were performed. This was achieved by using doubly charged ions. Although this technique is applicable to most ions only selenium was studied.

In the following sections the results of carrier concentration profiling are presented. In most cases several profiles were determined from each 1cm square sample, in order to examine the uniformity of the electrical characteristics. The experimental points from each sample are plotted on the same curve in each case, to enable a direct comparison of results to be made.

4.3.1 Comparison of Aluminium and Silicon Nitride Encapsulant Layers

Prior to the commissioning of the first silicon nitride deposition apparatus, evaporated aluminium films were used successfully as encapsulating layers for annealing implanted layers up to 750°C (47),(49). As a test of the effectiveness of the silicon nitride films as encapsulant layers it
was decided to compare the electrical results of implanted layers encapsulated with either aluminium or silicon nitride, and annealed at 700°C.

Several samples were measured by the Hall technique, and the results obtained using both encapsulants were identical within experimental error. The ions and doses studied were:

(a) Se - 390keV - \(2 \times 10^{14}\) ions \(\text{cm}^{-2}\)
(b) Se - 390keV - \(10^{13}\) ions \(\text{cm}^{-2}\)
(c) Sn - 300keV - \(2 \times 10^{14}\) ions \(\text{cm}^{-2}\)
(d) Se - 1MeV - \(10^{13}\) ions \(\text{cm}^{-2}\)
(e) Se - 1MeV - \(10^{14}\) ions \(\text{cm}^{-2}\)
(f) Se - 1MeV - \(5 \times 10^{14}\) ions \(\text{cm}^{-2}\)

The results obtained with each encapsulant are compared in table (11).

The depth profiles of the carrier concentration and Hall mobility for samples implanted with 1MeV selenium (500kV Se\(^{++}\)) are shown in figure (26). The experimental points determined from aluminium and silicon nitride encapsulated samples are shown. Good agreement between the experimental results produced by the two methods was achieved. Thus it is reasonable to assume that the silicon nitride layers were acting efficiently for 700°C anneals. The need for higher temperature annealing is apparent from the low activation efficiencies achieved after annealing at 700°C (table (11)). As no alternative encapsulant was available to compare with the silicon nitride after annealing at temperatures greater than 750°C its effectiveness had to be deduced by a comparison with published results.

As an indication of the reliability of the silicon nitride films at higher temperature the electrical profiles of two samples implanted with \(10^{13}\) 1MeV selenium ions and annealed at 825°C for 5 minutes are also shown in figure (26). It can be seen that the carrier concentration is
TABLE 11

Comparison of Electrical Results obtained after Annealing at 700°C with Aluminium and Silicon Nitride Encapsulation

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (keV)</th>
<th>Dose (cm⁻²)</th>
<th>Sheet Electron Concentration (cm⁻²)</th>
<th>Aluminium</th>
<th>Si₃N₄</th>
<th>AV. Activity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>390</td>
<td>2.10¹⁴</td>
<td>6.29 10¹² 6.96 10¹²</td>
<td>6.4 10¹² 6.51 10¹²</td>
<td>Al. 3.3</td>
<td>Si₃N₄ 3.2</td>
</tr>
<tr>
<td>Se</td>
<td>390</td>
<td>10¹³</td>
<td>3.31 10¹² 3.1 10¹²</td>
<td>3.2 10¹² 3.5 10¹²</td>
<td>Al. 3.2</td>
<td>Si₃N₄ 3.35</td>
</tr>
<tr>
<td>Sn</td>
<td>300</td>
<td>2.10¹⁴</td>
<td>1.1 10¹³ 1.3 10¹³</td>
<td>1.2 10¹³ 1.25 10¹³</td>
<td>Al. 6</td>
<td>Si₃N₄ 6.1</td>
</tr>
<tr>
<td>Se</td>
<td>1000</td>
<td>10¹³</td>
<td>4.2 10¹² 4.3 10¹²</td>
<td>4.3 10¹² 4.4 10¹²</td>
<td>Al. 42.5</td>
<td>Si₃N₄ 43.5</td>
</tr>
<tr>
<td>Se</td>
<td>1000</td>
<td>10¹⁴</td>
<td>2.06 10¹³ 1.99 10¹³</td>
<td>2.73 10¹³ 2.68 10¹³</td>
<td>Al. 20.3</td>
<td>Si₃N₄ 27.1</td>
</tr>
<tr>
<td>Se</td>
<td>1000</td>
<td>5.10¹⁴</td>
<td>1.63 10¹³ 1.69 10¹³</td>
<td>1.65 10¹³ 1.49 10¹³</td>
<td>Al. 3.3</td>
<td>Si₃N₄ 3.15</td>
</tr>
</tbody>
</table>
Figure 26. Electron concentration and mobility depth profiles of $10^{13} \times 1\text{MeV Se cm}^{-2}$ annealed at 825°C with silicon nitride encapsulation.

Also shown are the experimental points determined from samples annealed at 700°C with Si$_3$N$_4$ (+) and Aluminium (□) encapsulating layers.
increased markedly from that observed after annealing at 700°C, and is in fact close to that predicted by the LSS theory for 100% activation. The measured mobility values near the surface are also increased indicating that the degree of electrical compensation is reduced by annealing at higher temperatures. Similar results were also obtained after annealing at 900°C for 30 seconds, indicating that for this particular implant no improvement in activation efficiency is achieved at the higher temperature.

4.3.2 Comparison of High Dose Implants of Various Donor Ions

A series of implantations were performed to discover the relative effectiveness of the various donor ions for the production of highly doped n-type source and drain regions. Doses of $10^{14}$ ions cm$^{-2}$ of selenium, tellurium and tin were implanted into n on semi-insulating epitaxial GaAs. The energies were 200keV (Se) and 300keV (Te, Sn), which were chosen to give similar projected ranges of about 0.14μ. The implantations were performed with the substrates held at 200°C. The samples were encapsulated on the first Si$_3$N$_4$ deposition apparatus and pulse annealed at 900°C for 30 seconds. The average sheet values of Hall mobility, carrier concentration and resistivity obtained are given in table (12). Also shown in table (12) are the values obtained from samples which were later measured after encapsulation and annealing in the second deposition apparatus. There is good agreement between the two sets of results.

The depth profiles from the above samples are shown in figure (27). It can be seen that the carrier concentration level achieved by selenium implantation was greater than for either of the other ions.

The sheet electrical parameters measured following anneals to 1000°C are given in Table (13). It can be seen that, whilst the sheet carrier concentration values measured for selenium and tellurium implanted material are increased, the electron mobility is decreased, and the resistivity of
TABLE 12
Average Sheet Electrical Results obtained after Annealing Implanted Epitaxial Material at 900°C

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy</th>
<th>Electron Concn. cm⁻²</th>
<th>Mobility cm²V⁻¹s⁻¹</th>
<th>Sheet Resistivity Ω/□</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>200</td>
<td>3.2 \times 10^{13}</td>
<td>2200</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.2 \times 10^{13})</td>
<td>(1700)</td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>300</td>
<td>1.7 \times 10^{13}</td>
<td>2100</td>
<td>155</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.6 \times 10^{13})</td>
<td>(2000)</td>
<td></td>
</tr>
<tr>
<td>Te</td>
<td>300</td>
<td>2.6 \times 10^{13}</td>
<td>1700</td>
<td>110</td>
</tr>
</tbody>
</table>

Figures in brackets refer to results obtained after encapsulating and annealing in second apparatus.

TABLE 13
Average Sheet Electrical Results obtained after Annealing Implanted Epitaxial Material at 1000°C

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy</th>
<th>Electron Concn. cm⁻²</th>
<th>Mobility cm²V⁻¹s⁻¹</th>
<th>Sheet Resistivity Ω/□</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>200</td>
<td>5.2 \times 10^{13}</td>
<td>1450</td>
<td>83</td>
</tr>
<tr>
<td>Sn</td>
<td>300</td>
<td>1.8 \times 10^{13}</td>
<td>2000</td>
<td>180</td>
</tr>
<tr>
<td>Te</td>
<td>300</td>
<td>3.4 \times 10^{13}</td>
<td>1850</td>
<td>100</td>
</tr>
</tbody>
</table>
Fig. 27 Electron concentration and mobility depth profiles for 200keV Se and 300keV Te and Sn implants annealed at 900°C. Implant dose $10^{14}$ ion cm$^{-2}$.
the material remains substantially unchanged. It was therefore felt that 900°C annealing was sufficient for the production of high conductivity layers, particularly as the silicon nitride layers were pitted and cracked after annealing at the higher temperature.

The depth profiles of samples annealed at 1000°C are shown in figure (28). The changes observed in the sheet electrical values are reflected in the profiles shown - where an increase in the carrier concentration is obtained the mobility is decreased and the resistivity is essentially unchanged. For the tin implanted samples little difference was observed between the electrical depth profiles of samples annealed at the two temperatures.

One major difference between the selenium and tellurium profiles, which are in most other ways similar, is the reduction in mobility near the surface of the selenium implanted samples. This was observed after annealing both at 900 and 1000°C. In the tellurium (and tin) implanted samples the mobility values increase towards the surface, a minimum value being observed deeper in the sample.

The study of high dose implantations was extended to include cold implants of selenium and silicon, and 200°C implants of germanium. These implantations were performed into chromium doped semi-insulating material from ingots A65R and A84R. The energies of the implanted ions were 400keV for the selenium and germanium; and 120keV for the silicon. The projected ranges of these implants were 0.14µm for the selenium and germanium and 0.11µm for the silicon. The implanted dose was in all cases 10^{14} ions cm^{-2}. A similar dose of 400keV selenium was also implanted at 200°C for comparison. The sheet electrical results determined for these samples are given in Table (14). With the exception of germanium all the ions studied in the set of implants gave similar values of resistivity (85 - 107 Ω/□). High sheet carrier concentrations (>2 x 10^{13} els cm^{-2}) were obtained for the selenium and silicon implants.
Fig. 28. Electron Concentration and Mobility Depth Profiles of 200keV Se and 300keV Te and Sn Implants Annealed at 1000°C. Implant Dose 1.0 x 10^14 ions cm^-2
(Dotted line indicates results obtained after 900°C anneals)
Average Sheet Electrical Results obtained after 900° Anneals of Se, Si and Ge Implants. Implant Dose 10^{14} ions cm^{-2}.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Implant Temp. (°C)</th>
<th>Energy (keV)</th>
<th>Sheet Electron Conc. (cm^{-2})</th>
<th>Mobility (cm^2V^{-1}s^{-1})</th>
<th>Resistivity (Ω/Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>20</td>
<td>400</td>
<td>3.2 \times 10^{13}</td>
<td>1750</td>
<td>98</td>
</tr>
<tr>
<td>Se</td>
<td>200</td>
<td>400</td>
<td>2.61 \times 10^{13}</td>
<td>2264</td>
<td>107</td>
</tr>
<tr>
<td>Si</td>
<td>20</td>
<td>120</td>
<td>3.4 \times 10^{13}</td>
<td>2100</td>
<td>85</td>
</tr>
<tr>
<td>Ge</td>
<td>200</td>
<td>400</td>
<td>8.5 \times 10^{12}</td>
<td>950</td>
<td>820</td>
</tr>
</tbody>
</table>
The germanium implanted specimens exhibited the lowest sheet carrier concentrations and highest resistivity of all the high dose implanted samples examined. The sheet carrier concentration was only \( \sim 8.5 \times 10^{12} \text{cm}^{-2} \) (corresponding to an activation of 8.5% of the implanted ions), and the resistivity was nearly an order of magnitude greater than for the other ions studied.

The depth profiles of the electrical parameters for the above implants are given in figure (29). Two major aspects of these profiles worthy of particular emphasis are:-

(a) Low carrier concentration and mobility were measured in germanium implanted samples.

(b) Similar levels of activation, as indicated by the comparable volume values of carrier concentration, were obtained for the hot and cold implants of selenium. This is in contrast to previously published results (78) (113) where cold implantation of selenium produced appreciably lower levels of activation.

It should be noted that at this dose level the room temperature implants gave the higher values of electron concentration.

It was decided to investigate the dependence of implanted dose upon the electrical activity of Se, Ge and Si ions. Tin and tellurium implants were not investigated further as:-

(a) The range obtainable on our accelerator was insufficient for these ions for many practical applications.

(b) The results obtained from Te ions were similar to those of Se ions.

Whilst the low levels of activation achieved in germanium implanted specimens would seem to make it unattractive for the production of MESFETs it was felt that the results were sufficiently interesting, because of their uniqueness, to merit further study. It was hoped that an understanding of the reasons for the low activation achieved with germanium would result from such a study.
Fig. 29 Electron Concentration and Mobility Depth Profiles Measured in Samples Implanted with $10^{14} \times 400$keV Se, 120keV Si and 400 keV Ge ions cm$^{-2}$. 
4.3.3 Dose Dependence of Electrical Parameters of 200°C Implants of Selenium

Hot (200°C) implantations were performed into samples of chromium doped semi-insulating GaAs obtained from MCP and MR (ingot no. A65R). Various doses from $3.10^{12}$ cm$^{-2}$ to $10^{15}$ cm$^{-2}$ were studied. The samples were all annealed at 900°C for 30 seconds with silicon nitride encapsulant layers. The sheet Hall mobility and sheet carrier concentrations are plotted against implant dose in figure (30) for 400keV implants.

The activation levels achieved in the MCP material were significantly less than those in the MR material. In both cases the carrier concentration reached a maximum value as the dose was increased. For the MR material this saturation level was approximately $3.10^{13}$ cm$^{-2}$. At lower doses ($<10^{13}$ ions cm$^{-2}$) the activation level approached 100%. The measured mobility values decreased from a value of approximately $4000$ cm$^2$ V$^{-1}$.sec$^{-1}$ for the lowest dose implant to approximately $2000$ cm$^2$ V$^{-1}$.sec$^{-1}$ for the high dose implants.

The profiles for the MR samples (fig. (31)) are approximately gaussian with a peak near the theoretical range. The measured peak electron concentration increased with dose up to a value of about $1.5.10^{18}$ cm$^{-3}$ for a dose of $2.10^{14}$ cm$^{-2}$. Above this dose the peak electron concentration saturated and the peak in the profile occurred deeper in the sample.

Some values of sheet carrier concentration were determined in sets of samples implanted with $10^{14}$ ions cm$^{-2}$, and $2.10^{14}$ cm$^{-2}$, which did not correspond to the general trend. These values are shown in figure (30) as discrete points, with values considerably greater than those previously discussed. It is instructive to compare the depth variation of carrier concentration of these samples with those profiles normally measured for samples implanted at 200°C, as shown in figure (37) for the $10^{14}$ cm$^{-2}$ implants. It can be seen that the profiles measured are significantly deeper than those in samples
Fig. 30. Dependence of sheet electron concentration and mobility upon implanted dose of 400keV Selenium implanted at 200°C.
Fig. 31 Electron Concentration and mobility depth profiles of 200°C 400keV Se implants into MR substrates.

- $3 \times 10^{12} \text{ cm}^{-2}$
- $5 \times 10^{12} \text{ cm}^{-2}$
- $10^{13} \text{ cm}^{-2}$
- $2 \times 10^{14} \text{ cm}^{-2}$

Fig. 32 Anomalous profiles obtained for some $10^{14}$ 400 keV selenium implants.
giving the expected sheet concentration values. Also, the electron concentration profiles showed two discrete peaks in the profile. The mobility values measured in all the samples were similar, although higher in the 'anomalous' samples. The reproducibility of the activation of the implanted selenium at other doses can be judged from the scatter in the experimental points shown. The largest variation was observed at the lowest dose investigated - $3 \times 10^{12}$ cm$^{-2}$. The variation in sheet electron concentration for this dose was from 1.62 to $2.51 \times 10^{12}$ cm$^{-2}$.

Whilst 400keV was chosen as the implantation most studied, as it produced a profile of suitable depth for device production, it was considered desirable to examine the effects of implantation at higher and lower energies to produce broader, and shallower doped layers respectively.

Because of the desire to produce highly doped surface layers high dose ($10^{14}$ ions cm$^{-2}$) were performed at 100 and 200 keV. The electron concentration and mobility depth profiles from these samples are compared with the results obtained for 400 keV implants in figure (33). It can be seen that high volume electron concentrations ($> 2 \times 10^{18}$ cm$^{-3}$) are achieved, with peaks moving towards the surface as the energy is reduced.

Results obtained after the co-implantation of 100 keV and higher energy selenium ions are discussed in section (4.3.8).

High energy implants of selenium were achieved by the use of doubly charged ions. Initially doubly charged 500kV selenium ions, equivalent to 1MeV implants, were studied. Because of the instability of the accelerator at 500kV, attention was transferred to 800keV ions (400kV Se$^{++}$). It was felt that the depth achieved at this energy was sufficient for most applications. The particular interest of high energy selenium implants was the production of doped layers suitable for the gate area of devices ($< 2 \times 10^{17}$ electrons cm$^{-3}$). A range of implants covering the dose range
Fig. 33 Comparison of $10^{14}$ Se ions/cm$^2$ implants at 100, 200 and 400keV.

- ● 100keV
- ○ 200keV
- --- 400keV
1.5 \times 10^{12} \text{ to } 10^{13} \text{ ions cm}^{-2} \text{ was undertaken to determine the most suitable dose for the production of FETs. The carrier concentration and mobility profiles obtained are compared in figure (34), and the sheet results in table (15).}

Whilst it was not possible to determine the depth profiles of the electrical parameters for the samples implanted with the lowest dose (1.5 \times 10^{12} \text{ cm}^{-2}), and only two of the samples implanted with a dose of 2.5 \times 10^{12} \text{ cm}^{-2}, the spread in the results at the higher doses was within experimental error. For the 5.0 \times 10^{12}, 7.5 \times 10^{12} \text{ and } 10^{13} \text{ ions cm}^{-2} \text{ implants a steady increase in the peak electron concentration was observed, which was accompanied by a slight decrease in the measured value of the mobility. The samples implanted with a dose of 7.5 \times 10^{13} \text{ cm}^{-2} \text{ gave the required doping level of } \sim 2.1 \times 10^{17} \text{ cm}^{-3}, \text{ with an associated mobility of } \sim 3500 \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1}.

4.3.4 Dose Dependence of the Electrical Parameters of GaAs Implanted with Germanium at 200°C

The measured values of sheet mobility and sheet carrier concentration of samples implanted with 400keV Ge\textsuperscript{+} ions at 200°C and annealed at 900°C with silicon nitride encapsulant layers are shown in figure (35). All the germanium implants were performed into MR material (ingot no. A65R). For comparison the results obtained from samples implanted with selenium at 200°C (from fig. (30)), are also shown. It can be seen that the activity of the implanted germanium ions is significantly less than the selenium ions throughout the dose range studied. Also the mobility value at any dose is less for germanium implanted material. For a sheet carrier concentration value of 4.0 \times 10^{12} \text{ cm}^{-2} \text{ the respective doses required for selenium and germanium implants are 5.10^{12} and 4.5 \times 10^{13} \text{ cm}^{-2}. The mobility values for these doses are } \sim 4000 \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \text{ for the selenium implanted material and } \sim 2000 \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \text{ for the germanium implanted samples. The advantage of selenium for the implantation of the gate region of GaAs MESFETs is obvious.}
Fig. 34 Comparison of the depth profiles obtained from low dose 800keV Selenium implants.

+ $2.5 \times 10^{12}$ cm$^{-2}$

$5 \times 10^{12}$ cm$^{-2}$

$7.5 \times 10^{12}$ cm$^{-2}$

$10^{13}$ cm$^{-2}$
TABLE 15

Comparison of the Sheet Electrical Results obtained from Low Dose 800keV Selenium Implants

<table>
<thead>
<tr>
<th>Dose (x $10^{12}$ cm$^{-2}$)</th>
<th>Sheet Electron Concentration (x $10^{12}$ cm$^{-2}$)</th>
<th>Mobility (cm$^2$V$^{-1}$s$^{-1}$)</th>
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<tr>
<td>1.25</td>
<td>0.6                0.68</td>
<td>3691</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3472</td>
</tr>
<tr>
<td>2.5</td>
<td>1.22               1.27</td>
<td>4244</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4288</td>
</tr>
<tr>
<td></td>
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<td>4007</td>
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<td></td>
<td>4323</td>
</tr>
<tr>
<td>5</td>
<td>2.98               3.08</td>
<td>3486</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3026</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4131</td>
</tr>
<tr>
<td>7.5</td>
<td>3.37               3.53</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3287</td>
</tr>
<tr>
<td>10</td>
<td>3.8                3.71</td>
<td>3162</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4011</td>
</tr>
</tbody>
</table>
For higher dose implants suitable for the source and drain regions selenium is also the more attractive ion. For a sheet carrier concentration of \(3 \times 10^{18} \text{ cm}^{-2}\) the selenium implanted samples had a mobility of \(\sim 2000 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}\) whereas a value of \(\sim 850 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}\) was measured in the germanium implanted samples. Thus the resistivity of source and drain regions implanted with selenium would be less than half that of those implanted with germanium.

The depth profiles of carrier concentration and mobility for the germanium implanted samples are given in figure (36). It can be seen that the peak in the carrier concentration profile is located near the theoretical range of 0.14\(\mu\)m only for the lowest dose \((5 \times 10^{13} \text{ cm}^{-2})\). At the higher doses the peak is located at a depth of about 0.22\(\mu\)m. As the dose is increased from \(5 \times 10^{12}\) to \(10^{13}\) ions \(\text{cm}^{-2}\) the measured peak carrier concentration decreased from \(1.4 \times 10^{17} \text{ cm}^{-3}\) to \(1.1 \times 10^{17} \text{ cm}^{-3}\). Further increase in dose resulted in an increase in the measured peak carrier concentration. This behaviour is reflected in the observed change in sheet carrier concentration already shown in figure (35).

The mobility also changed with dose. For doses greater than \(10^{12} \text{ cm}^{-2}\) a distinct dip in the mobility was observed at a depth of about 0.075\(\mu\)m. At greater depths the mobility saturated at a level dependent upon the total implanted dose. As the dose was increased this saturation level decreased, from \(3500 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}\) for a dose of \(10^{13} \text{ cm}^{-2}\) to \(950 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}\) for a dose of \(7.5 \times 10^{14} \text{ cm}^{-2}\).

It was only possible to measure the profile of one sample implanted with the highest \((7.5 \times 10^{14} \text{ cm}^{-2})\) dose as all of the four samples implanted at this dose gave unstable readings. It is thought that this was due to the low electron mobilities of these samples. Whilst the profile measured is included here for completeness it should be emphasised that it was not possible to reproduce this result.
Fig. 35 Variation of sheet electrical results with implanted dose of 400keV Germanium ions.
Fig. 36 Variation of Electron Concentration and Mobility with Implanted Dose of 400keV Germanium ions.

- $5.10^{12}$ cm$^{-2}$
- $5.10^{13}$ cm$^{-2}$
- $5.10^{14}$ cm$^{-2}$
- $7.510^{14}$ cm$^{-2}$
4.3.5 Dose Dependence of the Electrical Parameters of Room Temperature Implants of Silicon

Several samples of MR semi-insulating GaAs from ingots no. A65R and A84R implanted with 120keV silicon ions at AERE Harwell were supplied by the Allen Clark Research Centre for encapsulation, annealing and measurement at Surrey University. This was accomplished in the manner previously described. The variation of sheet carrier concentration and mobility observed with implanted dose is shown in figure (37). The results for 200°C implants of 400keV Se⁺ ions are again shown for comparison.

(a) Low Dose Implants

The activity of the implanted silicon ions in samples implanted with 6 or 8.10¹² ion/cm² was markedly less than that achieved with implanted selenium ions. Also the measured values of mobility were lower for the silicon implanted samples and the variation in the results was considerable. Unfortunately no further samples were available: the tentative conclusion is that for low dose implantation silicon is less reproducible than selenium, and for channel type implants selenium implantation is preferable.

(b) High Dose Implants

For higher dose implants at the three doses studied; 6.10¹³, 10¹⁴ and 2.10¹⁴ ions cm⁻² the measured values of carrier concentration show far less scatter. The levels of activation of these implants was higher than that observed for 200°C implants of selenium. The maximum sheet carrier concentration measured was 4.10¹³ ions cm⁻² for an implanted dose of 2.10¹⁴ ions cm⁻². The values of mobility determined from these samples were very similar to those determined from the material implanted at 200°C with selenium ions.

To confirm that the pulse annealing for 30 seconds was sufficient to anneal the room temperature implants three samples were annealed for
**Fig. 37** Dependence of sheet electrical results upon dose of room temperature implants of silicon.
a longer period of \(2\frac{1}{2}\) or 4 minutes. The results obtained from these samples are also shown in figure (37). It can be seen that they agree very well with the values determined from samples annealed for only 30 seconds.

No profile measurements were possible on any of the samples implanted with either \(6.10^{12}\) or \(8.10^{12}\) Si\(^+\) ions \(\text{cm}^{-2}\), as the samples gave very unstable readings. The depth variation of carrier concentration and mobility determined the samples implanted with the high doses are shown in figure (38).

For doses of \(6.10^{13}\) \(\text{cm}^{-2}\) and \(10^{14}\) \(\text{cm}^{-2}\) the peak in the profile occurred at a depth of about \(0.08\mu\text{m}\), which is slightly nearer to the surface than the projected theoretical range (0.11\(\mu\text{m}\)). The peak in the profile of the samples implanted with \(2.10^{14}\) ions \(\text{cm}^{-2}\) was located at approximately the projected range. The value measured near the surface was less than that measured in the samples implanted with doses of \(6.10^{13}\) and \(10^{14}\) ions.\(\text{cm}^{-2}\). The peak value of the carrier concentration was not increased by doubling the dose from \(10^{14}\) to \(2.10^{14}\) \(\text{cm}^{-2}\), the slight increase observed in the sheet carrier concentration was caused by a broadening in the profile.

4.3.6 Dose Dependence of Electrical Parameters of Room Temperature Implants of Selenium

The implantation of selenium at room temperature was of interest as it was the only group of implantations studied which caused the GaAs to become amorphous. This was apparent by a visual inspection of the samples - the amorphous material having a changed reflectivity and hence appeared different to the naked eye. The variation of crystalline structure due to the transition to amorphous GaAs caused by the implantation of large doses of heavy ions has previously been reported (26), and was not further investigated here. In this study the interest was in achieving high levels of electrical activation, as this has not previously been achieved for room temperature implants of selenium ions above the dose required to render the GaAs amorphous (78).
Fig. 38 Electron Concentration and Mobility profiles of room temperature 120keV silicon implants.

- $6 \times 10^{13}$ cm$^{-2}$
- $1 \times 10^{14}$ cm$^{-2}$
- $2 \times 10^{14}$ cm$^{-2}$
The variation of sheet carrier concentration and sheet Hall mobility with dose, for samples implanted at room temperature with 400keV selenium ions is shown in figure (39). The results obtained for 200°C implantations are also shown for comparison.

It can be seen that at low and high doses (< $7.5 \times 10^{12} \text{ cm}^{-2}$, $7.5 \times 10^{14} \text{ cm}^{-2}$) the sheet carrier concentration values of the room temperature implants were less than that of the 200°C implants. For doses between $7.5 \times 10^{12}$ and $7.5 \times 10^{13} \text{ cm}^{-2}$ the sheet carrier concentration values of the implants at both temperatures are similar, although the room temperature implants were slightly more active.

The behaviour of the room temperature implants for doses around $2.1 \times 10^{14} \text{ cm}^{-2}$ was unusual. A large increase in activation over that observed in specimens implanted at 200°C was measured. The highest recorded sheet concentration was $5.5 \times 10^{13} \text{ cm}^{-2}$, which is over twice that observed in any of the samples implanted at 200°C. It was thought that the high levels of activation were anomalous and the measurements were repeated on samples implanted at a later date. The results obtained from these samples were in substantial agreement with those obtained previously. In only one sample was a carrier concentration level recorded similar to that expected ($3.3 \times 10^{13} \text{ cm}^{-2}$), which was thought to be caused by poor ohmic contacts.

The behaviour of the mobility of the samples implanted at room temperature is also shown in figure (39). At low doses (< $5.1 \times 10^{13} \text{ cm}^{-2}$) the mobility values measured were similar to those determined from samples implanted at 200°C. At higher doses the mobility values measured in the room temperature implanted specimens became increasingly lower than the hot implants as the dose was increased. This is indicative of increasing electrical compensation, and will be discussed more fully in the following chapter.

In figure (40a) the variation of carrier concentration with depth for the samples implanted at room temperature with 400keV Se$^+$ ions is shown
Fig. 39 Variation of sheet electrical results with implanted dose of 400keV Selenium ions implanted at room temperature.
for doses varying from $5.10^{12}$ to $10^{15}$ Se$^+$ ions cm$^{-2}$. For the low dose implants, $5.10^{12}$ and $10^{13}$ ions cm$^{-2}$, the carrier concentration profiles were approximately gaussian and centred at about the theoretical range. Whilst the peak carrier concentration was similar to that determined in samples implanted with selenium at 200$^\circ$C, the profiles were narrower for the room temperature implanted specimens. For samples implanted with higher doses the behaviour of the implanted ions was considerably more complicated. In samples implanted with $5.10^{13}$ ions cm$^{-2}$ the carrier concentration at a depth corresponding to the projected range was increased only marginally, but a large increase was observed deeper in the sample. A peak in the carrier concentration was found at a depth of approximately 0.25$\mu$m. The carrier concentration fell sharply at depths greater than this, and no further Hall measurements were possible to enable the profile of the tail to be determined. This deep secondary peak was observed in all the profiles determined for samples implanted with greater than $5.10^{13}$ cm$^{-2}$. For the specimens implanted with doses of $7.5 10^{13}$ to $10^{15}$ cm$^{-2}$ a peak was also observed at a depth of about 0.1$\mu$m. The height of this peak increased with increasing dose up to a maximum of $3.10^{18}$ cm$^{-3}$ for an implanted dose of $2.10^{14}$ cm$^{-2}$. For higher dose implants the height of the shallow peak decreased, and a value of $4.10^{17}$ cm$^{-3}$ was determined for samples implanted with $10^{15}$ ions cm$^{-2}$.

The variation of mobility with depth for the samples discussed above is shown in figure (40b). It can be seen that as the dose was increased the measured values of mobility decreased and very low values (600-900 cm$^2$V$^{-1}$sec$^{-1}$) were determined in the samples implanted with the highest doses, the lowest mobility values occurring at depths around 0.1$\mu$m.

As with 200$^\circ$C implants of selenium, irradiations were also performed at 800keV to produce doped layers deeper in the sample than those produced for 400keV implants.
Fig. 40 Variation of Electron Concentration and Mobility Depth Profiles with Implanted Dose of 400keV Selenium ions at Room Temperature.
Three doses were implanted, $5 \times 10^{12}$, $7.5 \times 10^{12}$ and $10^{14}$ ions cm$^{-2}$.

It can be seen that for the lower doses, the profiles determined by Hall measurements were very similar to those obtained from implants performed at $200^\circ$C, both for the carrier concentration and mobility (figure (41)). The major difference between the two sets of results was the sharp fall-off measured in the tail of the carrier concentration which is in agreement with that observed for the 400keV implants. The depth profiles of the electron concentration of samples implanted with $10^{14}$ ions cm$^{-2}$ displayed the same trend as the 400keV Selenium implants implanted with a dose of $10^{13}$ ions cm$^{-2}$. That is the peak in the profile was located deeper in the sample than the projected range, with a carrier concentration of approximately $10^{18}$ cm$^{-3}$.

4.3.7 Investigation of Selenium Implantation for MESFET Channel Regions

An investigation into the dependence of the electrical activity of low dose selenium implants upon the substrate material type was performed to determine the most suitable material for MESFET fabrication. It was decided to use $5 \times 10^{12}$ x 400keV ions cm$^{-2}$ as a standard dose for this comparison, as the study of the dose dependence of electrical activity had shown the carrier concentration of layers implanted with this dose were close to that required. The materials studied were:

(a) n on semi-insulating epitaxial material
(b) undoped epitaxial buffer layer grown on semi-insulating GaAs
(c) MCP semi-insulating GaAs
(d) MR semi-insulating material from ingots A84R and A65R.

Implantations were performed both at room temperature and at $200^\circ$C.

In figure (42) the depth profiles of electron concentration and Hall mobility determined after annealing at $900^\circ$C for 30 seconds are shown.

It can be seen that the highest levels of activation were achieved in the
Fig. 41 Electron Concentration and mobility depth profiles of 800keV Selenium ions implanted at room temperature.

- $5 \times 10^{12}$ cm$^{-2}$
- $7.5 \times 10^{12}$ cm$^{-2}$
- $10^{14}$ cm$^{-2}$
n on semi-insulating epitaxial material, where the peak electron concentration measured was \(2.5 \times 10^{17} \text{ cm}^{-3}\). Whilst this result is of interest n on semi-insulating material is not attractive for MESFET device fabrication. The depth profiles of MR semi-insulating material implanted at room temperature were very similar to those determined in the epitaxial material. The peak carrier concentration measured was \(\sim 2.3 \times 10^{17} \text{ cm}^{-3}\). The profiles from four samples implanted on separate occasions are shown to give an indication of the run to run reproducibility.

For samples implanted at 200°C a similar peak carrier concentration was observed in samples of A65R and A84R semi-insulating material, and in samples taken from one slice of epitaxial buffer layer material. Results from the other buffer layer slice gave lower values of electron concentration, especially near the surface. It was assumed that this slice was over-compensated in this region and was not used in further studies. The electron concentrations in MCP semi-insulating material were lower than in MR material throughout the implanted depth.

The measured mobility values were high (\(> 4000 \text{ cm}^2 \text{ V}^{-1} \text{ sec}^{-1}\)) throughout the implanted region. However, whereas in the epitaxial layers the mobility remained approximately constant throughout the depth, a distinct fall in the mobility was observed in the tail of the profiles in the semi-insulating material.

A comparison between the profiles determined from room temperature and 200°C implants in A65R emphasises the points made in previous sections:-

(a) Similar levels of carrier concentration are achieved near the theoretical range for implants performed at each temperature.

(b) The electron concentration profiles in material implanted at room temperature are narrower than in samples implanted at 200°C and have a sharper fall off in the tail.

It was decided to use A65R and selected buffer layers to produce implanted
Fig. 42 Comparison of $5 \times 10^{12}$ Se ions cm$^{-2}$ Implants into Different Substrate Materials.

- $200^\circ$C implant into n on semi insulating
- $200^\circ$C implant into A65R
- $200^\circ$C implant into rejected buffer layer
- $200^\circ$C implant into good buffer layer
- $200^\circ$C implant into MCP semi insulating
- $20^\circ$C implant into A65R
layers for MESFET production. The electrical characteristics of
MESFETs produced in such layers are discussed in section (44).

4.3.8 Dual Energy Selenium Implantation

A logical method of improving device characteristics of
MESFETs produced in implanted layers was to decrease the source to gate
resistance by increasing the carrier concentration near the surface of the
material. This approach was particularly relevant to the devices made
by the etched gate technique as the more highly doped region could be
removed in the channel by the gate etch step. In order to implement
this approach a number of samples were implanted with selenium ions at
two energies, 100 and 400keV. The dose of ions implanted at the higher
energy was standardised at $5 \times 10^{12} \text{ cm}^{-2}$, whilst the dose implanted at the
lower energy was varied from $1.25 \times 10^{12}$ to $10^{14}$ ions cm$^{-2}$.

A large number of samples were examined in this particular study
for the following reasons:

(a) The observed electrical profiles obtained after implantation
with the high energy ions first were different to that predicted
by LSS theory, and it was decided to implant a second set of
samples with the low energy ions first, to examine the dependence
of the profiles upon the order of implantation.

(b) This study was in progress during the commissioning of the second
silicon nitride deposition apparatus. It was decided, therefore,
to use the annealing of dual energy implanted samples to compare
the relative encapsulation efficiency of nitride layers grown in
the two different pieces of equipment.

(c) Whilst the majority of implantations were performed into substrates
heated to 200°C, some samples were also implanted at room temperature
for comparison.
The doses implanted at 200°C were:

(i) \(5 \times 10^{12} \text{ ions cm}^{-2}\) 400keV ions cm\(^{-2}\).
(ii) \(5 \times 10^{10} \text{ ions cm}^{-2}\) plus \(2 \times 10^{12} \text{ ions cm}^{-2}\) 100keV ions cm\(^{-2}\).
(iii) \(5 \times 10^{12} \text{ ions cm}^{-2}\) plus \(10^{13} \text{ ions cm}^{-2}\) 100keV ions cm\(^{-2}\).
(iv) \(5 \times 10^{12} \text{ ions cm}^{-2}\) plus \(10^{14} \text{ ions cm}^{-2}\) 100keV ions cm\(^{-2}\).

The experimental points determined from all the samples measured are plotted in figure (43). Instead of distinguishing the data points determined from each sample a different symbol is used for each of the implantation and annealing method used - e.g. high energy ions implanted first, annealed in second apparatus, etc. It can be seen that the depth profiles produced seem to be independent of this order of implantation, and also that the silicon nitrides deposited in the two deposition apparatus produced similar results. The samples implanted with two low doses (1.25 \(10^{12}\) and \(5 \times 10^{12}\), \(5 \times 10^{12}\) and \(5 \times 10^{12}\) ions cm\(^{-2}\)) displayed broad doping profiles, with an increase in electron concentration in the near surface region. Whilst only a slight decrease in resistivity was obtained compared with a single implant of \(5 \times 10^{12}\) 400keV ions cm\(^{-2}\) these specimens were interesting for device applications, as they offered a method of controlling the shape of the dopant profile.

Room temperature implants were only performed at low doses, as it was already known that at high doses the 200°C implanted samples exhibited higher mobilities. Only two dose combinations were considered:

(a) \(5 \times 10^{12}\) 100keV + \(5 \times 10^{12}\) 400keV ions cm\(^{-2}\)
(b) \(7.5 \times 10^{12}\) 100keV + \(5 \times 10^{12}\) 400keV ions cm\(^{-2}\).

The electrical profiles determined from these samples are compared with those obtained from samples implanted with a single \(5 \times 10^{12}\) dose of 400keV ions in figure (43). As with the 200°C implants an increase in the electron concentration was observed near the surface. However, the decrease in mobility observed in this region was far greater than that measured in the
Fig. 43  Electrical Depth Profiles of Dual (100keV and 400keV) Implants. Implant Temperature 200°C, 400keV Dose $5 \times 10^{12}$ cm$^{-2}$.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>$\text{Si}_3\text{N}_4$ Apparatus</th>
<th>100keV Dose (cm$^{-2}$)</th>
<th>Low Energy Implant</th>
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</thead>
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<td>•</td>
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<td>FIRST</td>
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<td>•</td>
<td>1</td>
<td>$1.25 \times 10^{12}$</td>
<td>FIRST</td>
</tr>
<tr>
<td>•</td>
<td>2</td>
<td>$1.25 \times 10^{12}$</td>
<td>SECOND</td>
</tr>
<tr>
<td>•</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 44  Selenium Dual Energy Implants

Performed at 100keV and 400keV.

100keV Doses 5.10^{12} and 7.5 10^{12} cm^{-2}.
400keV Dose 5.10^{12} cm^{-2}.

- 5.10^{12} x 400keV + 7.5 10^{12} x 100keV cm^{-2}
- 5.10^{12} x 400keV + 5.10^{12} x 100keV cm^{-2}
- 5.10^{12} x 400keV only
specimens implanted at 200°C. This is consistent with the behaviour, previously noted, of single energy room temperature implants.

As with single energy implants carrier concentration measurements were difficult to perform in the tail of the profile, as its sheet carrier concentration decreased very rapidly.

In order to separate the components of the doping profile due to the low and high energy implantations, a series of samples were implanted with various combinations of 100 and 800keV selenium ions, with the samples at both room temperature and 200°C.

The doses implanted at the low energy were 5.10^{13} and 10^{14} ions cm\(^{-2}\). At the higher energy 5.10^{12}, 7.5 10^{12} and 10^{13} ions cm\(^{-2}\) were studied. The choice of these doses was based upon the earlier study of single energy implantations.

The depth profile of carrier concentration and mobility determined from these samples are shown in figures (45) and (46). The near surface peak in the carrier concentration profiles in the samples implanted at 200°C was found to have a maximum value of about 2.10^{18} cm\(^{-3}\). A separate peak centred at about 0.3\mu m due to the higher energy implant was observed at all doses. The peak level of the samples implanted with 10^{13} ions cm\(^{-2}\) was suitable for FET manufacture (\approx 2.10^{17} cm\(^{-3}\)) and similar to that observed in samples implanted without the 100 keV ions. In the samples implanted at room temperature and electron concentration in the near surface region was 1 and 1.4.10^{18} cm\(^{-3}\) for the 10^{13} and 10^{14} ions cm\(^{-2}\) implants respectively. The peak due to the higher dose implant was observed to be wider than for the lower dose case. It can be seen by comparison with the profiles determined from single energy implants, that little interaction took place between the low and high energy implants, the little that did occur being confined to the narrow area between the peaks of the two implants. The profiles obtained were considered very suitable for
Fig. 45 Electrical Depth Profiles of Dual Energy Selenium Implants Performed at 200°C.

- $10^{14} \times 100$keV + $10^{13} \times 800$keV cm$^{-2}$
- $10^{14} \times 100$keV + $5 \times 10^{12} \times 800$keV cm$^{-2}$
Fig. 46 Electrical Depth Profiles of Dual energy Selenium Implants Performed at Room Temperature.

$+ 10^{14} \times 100 \text{keV} + 10^{13} \times 800 \text{keV cm}^{-2}$

$\circ 5 \times 10^{13} \times 100 \text{keV} + 7.5 \times 10^{12} \times 800 \text{keV cm}^{-2}$
device fabrication, as a deep region of nearly uniform doping was achieved, with a highly doped near surface region suitable for the formation of low resistance ohmic contacts.

An indication of the improvement in conductivity produced by the co-implantation of low and high energy runs compared with that determined from a single implantation suitable for MESFET fabrication, is given in table (16). Here the sheet electrical parameters determined from samples implanted with both single and dual energy ions is given, and it can be seen that the electrical parameters determined from the dual energy implants is markedly improved. For example, for an implant of $7.5 \times 10^{12}$ 800keV ions cm$^{-2}$ the sheet resistivity was about 220Ω/□, whereas the resistivity of a layer implanted with an additional $10^{14}$ 100keV ions cm$^{-2}$ was approximately 75Ω/□. Because of the possible improvement in MESFET operating characteristics afforded by such a decrease in resistivity, similar layers were implanted into both semi-insulating and buffer layer material for subsequent device manufacture.

4.3.9 Dual Ion Implantation

It was decided to undertake a limited investigation into the effects of dual ion implantation, because of the possibility of increased electrical activity afforded by this technique (85)-(91). One ion combination chosen for investigation was gallium plus selenium. Two doses of selenium were considered:

(a) $5.10^{12}$ 400keV selenium ions cm$^{-2}$, room temperature and $200^\circ$C implantation, suitable for channel region implants.

(b) $10^{14}$ 200keV selenium ions cm$^{-2}$ 200°C implantation, suitable for ohmic region implants.

Each of the above was co-implanted with an equal dose of gallium ions at the same energy to achieve similar doping profiles of the active ion (selenium) and the complementary ion (gallium).
Comparison of Sheet Resistivity Measurement of Single and Dual Energy Selenium Implants

(i) 200°C Implants

<table>
<thead>
<tr>
<th>800keV dose (ions cm(^{-2}))</th>
<th>100keV dose (ions cm(^{-2}))</th>
<th>Sheet Resistivity (Ω/□)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(7.5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(7.5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(10^{13})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(10^{13})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(-)</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
</tbody>
</table>

(ii) Room Temperature Implants

<table>
<thead>
<tr>
<th>800keV dose (ions cm(^{-2}))</th>
<th>100keV dose (ions cm(^{-2}))</th>
<th>Sheet Resistivity (Ω/□)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(7.5 \times 10^{12})</td>
<td>(-)</td>
<td>(5 \times 10^{13})</td>
</tr>
<tr>
<td>(7.5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(7.5 \times 10^{12})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(10^{13})</td>
<td>(-)</td>
<td>(5 \times 10^{13})</td>
</tr>
<tr>
<td>(10^{13})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(10^{13})</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
<tr>
<td>(-)</td>
<td>(-)</td>
<td>(10^{14})</td>
</tr>
</tbody>
</table>
The results of sheet Hall measurements on the dual implanted layers are compared in Table (17) with the results determined from material implanted with the same dose of selenium only, and encapsulated and annealed at the same time. The high dose implants are also compared with samples implanted with twice the selenium dose, to show the effect of a similar total dose of active ion.

It can be seen that in all cases the dual ion implants had greater sheet carrier concentrations than samples implanted with a similar dose of selenium ions only. Samples implanted with gallium ions only, at the two dose levels studied, had no measurable electrical activity. Thus it was concluded that the dual implant was having the desired effect, i.e. increasing the number of uncompensated selenium ions located on arsenic sites, except for 200°C low dose implants where the increase was minimal.

The profiles of carrier concentration and Hall mobility determined for the above samples are compared in figures (47) and (48). For the room temperature implants the variation of electron concentration with depth measured for the dual ion implant was similar to that determined for 200°C implants of selenium alone, both in the maximum electron concentration measured and in the shape of the tail of the profile. This is reflected in the similarity of the sheet electron concentration levels quoted in table (17).

For the 200°C low dose implants the measured profiles in the single and dual ion implanted specimens were identical within experimental error, whereas for the high dose case the increase in electrical activity was due to an increase in the electron concentration around the theoretical range of the ions (fig. 48).

Whilst a definite increase in electrical activity of the implanted selenium ions was observed for all doses studied, the extent of the increase was limited. It was felt that whilst the dual implant effect did cause
### TABLE 17
Sheet Electrical Results Determined from Samples Implanted with Gallium and Selenium Ions

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Gallium Energy (keV)</th>
<th>Gallium Dose (cm⁻²)</th>
<th>Selenium Energy (keV)</th>
<th>Selenium Dose (cm⁻²)</th>
<th>Electron Conc. (cm⁻²)</th>
<th>Mobility (cm²/Vs⁻¹)</th>
<th>Resistivity (ohm cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>400</td>
<td>5.10¹²</td>
<td>400</td>
<td>5.10¹²</td>
<td>3.28 x 10¹²</td>
<td>3756</td>
<td>473</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.47 x 10¹²</td>
<td>3930</td>
<td>458</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.36 x 10¹²</td>
<td>4125</td>
<td>451</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.41 x 10¹²</td>
<td>4320</td>
<td>441</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0 x 10¹²</td>
<td>4158</td>
<td>375</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>5.10¹²</td>
<td>3.3 x 10¹²</td>
<td>3817</td>
<td>497</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.8 x 10¹²</td>
<td>3979</td>
<td>564</td>
</tr>
<tr>
<td>200</td>
<td>400</td>
<td>5.10¹²</td>
<td>400</td>
<td>5.10¹²</td>
<td>4.07 x 10¹²</td>
<td>3952</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.29 x 10¹²</td>
<td>3930</td>
<td>371</td>
</tr>
<tr>
<td>200</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>5.10¹²</td>
<td>3.96 x 10¹²</td>
<td>3663</td>
<td>431</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.98 x 10¹²</td>
<td>3837</td>
<td>409</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>10¹⁴</td>
<td>200</td>
<td>10¹⁴</td>
<td>4.17 x 10¹³</td>
<td>2033</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.29 x 10¹³</td>
<td>2079</td>
<td>72</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.6 x 10¹³</td>
<td>2065</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.56 x 10¹³</td>
<td>2063</td>
<td>67</td>
</tr>
<tr>
<td>200</td>
<td>-</td>
<td>-</td>
<td>200</td>
<td>10¹⁴</td>
<td>1.15 x 10¹³</td>
<td>1617</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.45 x 10¹³</td>
<td>1815</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.38 x 10¹³</td>
<td>1857</td>
<td>244</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.53 x 10¹³</td>
<td>1745</td>
<td>234</td>
</tr>
<tr>
<td>200</td>
<td>-</td>
<td>-</td>
<td>200</td>
<td>2.10¹⁴</td>
<td>2.72 x 10¹³</td>
<td>1686</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.83 x 10¹³</td>
<td>1140</td>
<td>143</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>3.9 x 10¹³</td>
<td>1219</td>
<td>131</td>
</tr>
</tbody>
</table>
Figure 47  Depth Profiles Determined from Samples Implanted with $5 \times 10^{12}$ Se and $5 \times 10^{12}$ (Ga + Se) cm$^{-2}$ at Room Temperature.

- Gallium + Selenium
- Selenium only
Fig. 48 Comparison of Depth Profiles obtained after Dual (Ga + Se) and Single Selenium High Dose Implants.

- $10^{14}$ Se cm$^{-2}$
- $2 \times 10^{14}$ Se cm$^{-2}$
- $10^{14}$ Ga + $10^{14}$ Se cm$^{-2}$
an increase in the number of selenium ions located on correct lattice sites, the extra damage introduced by the electrically inactive gallium ions might be deleterious. For this reason it was decided to attempt the co-implantation of selenium with tin. In this case the tin would contribute to the overall carrier concentration, being a donor when located in a gallium site, and at the same time, act as a complementary ion and so increase the activity of the selenium ions by the dual implant effect.

The sheet electrical results determined from four samples implanted with $10^{14}$ 200keV Se$^+$ ions cm$^{-2}$ plus $10^{14}$ 300keV Sn$^+$ ions cm$^{-2}$ are given in table (18). The sheet electrical results determined from samples implanted with similar doses of selenium and tin only are also given for comparison.

The dual implant effect is definitely in evidence, as the electron concentration determined from the dual implanted samples was greater than the sum of the two single ion implants ($\approx 6.0 \times 10^{13}$ for the dual implant compared with $3.1 \times 10^{13}$ for the sum of the two single implants). The reduction observed in the resistivity achieved by dual selenium/tin implants is also marked. Thus implants of this type would seem to be advantageous. However, the depth profiles determined from the dual selenium/tin implants were very irreproducible as can be seen from figure (49). Because of this lack of reproducibility it was decided not to continue this particular study, although the effect is worthy of mention and may warrant future study.

4.4 MESPET Results

In table (19) the results from all the device slices processed are summarised. Where electrical results were obtained from completed devices these are also given

Initially samples for device fabrication were masked off prior to
### Table 18

Sheet Electrical Results Determined from Samples Implanted with Dual Selenium and Tin Ions at a Dose Level of $10^{14}$ ions cm$^{-2}$

<table>
<thead>
<tr>
<th>200keV Se dose (ions cm$^{-2}$)</th>
<th>300keV Sn dose (ions cm$^{-2}$)</th>
<th>Electron Conc. (cm$^{-2}$)</th>
<th>Mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)</th>
<th>Resistivity $\rho/\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14}$</td>
<td>$10^{14}$</td>
<td>$6.07 \times 10^{13}$</td>
<td>1860</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$6.25 \times 10^{13}$</td>
<td>1910</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5.8 \times 10^{13}$</td>
<td>1870</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$5.9 \times 10^{13}$</td>
<td>1940</td>
<td>55</td>
</tr>
<tr>
<td>$10^{14}$</td>
<td></td>
<td>$1.15 \times 10^{13}$</td>
<td>1620</td>
<td>335</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.45 \times 10^{13}$</td>
<td>1815</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.38 \times 10^{13}$</td>
<td>1860</td>
<td>244</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.53 \times 10^{13}$</td>
<td>1745</td>
<td>234</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
<td>$1.74 \times 10^{13}$</td>
<td>1900</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.79 \times 10^{13}$</td>
<td>2180</td>
<td>160</td>
</tr>
</tbody>
</table>
Figure 49  Depth Profiles Determined from Samples Implanted with $10^{14}$ (Se + Sn) ion cm$^{-2}$. 
implantation to enable only the required areas of the slice to be implanted. For example selective implantation of the source and drain regions and low dose implants over the area of the device were attempted. This was desirable as the devices could then be isolating and no mesa etch step could be required. This practice was later discontinued in favour of uniform implantations for the following reasons:

(a) The correct photo-alignment masks were not available for all the applications required, e.g. for an overall device implant the mesa mask could be used but only in reversal form.

(b) The extra photo-alignment processing steps required for designating areas for implantation increased the amount of transportation of slices between the two laboratories, and hence decreased the throughput.

(c) The alignment of slices subsequent to implantation was difficult, especially where only source and drain implants were performed and the critical gate alignment had to be carried out.

Most of the implantations were performed at 200°C, mainly with selenium ions. Some devices were processed on material implanted with germanium although no electrical measurements were obtained from these devices as all exhibited large source-drain resistances. This was expected from the Hall measurements of germanium implanted material and these samples were processed for comparison purposes only.

It can be seen from Table (19) that devices were fabricated on both epitaxial buffer layer and bulk semi-insulating material. The I-V characteristics shown in figure (50) were typical of samples fabricated on buffer layers (fig.50a) and semi-insulating (fig.50 b) material, although the actual magnitude of \( I_{DSS} \) and \( g_m \) varied from slice to slice according to the implantation parameters. In all cases where devices were fabricated on implanted buffer layer material the degree of light sensitivity, as estimated by the difference between the I-V characteristics
### TABLE 19

Summary of Implanted Slices Processed to Fabricate MESFETs

<table>
<thead>
<tr>
<th>Slice No.</th>
<th>Material</th>
<th>Implant Temp. (°C)</th>
<th>Ion/Dose/Energy ( /cm²/keV)</th>
<th>FET RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA3*</td>
<td>epi n</td>
<td>200</td>
<td>Se 10⁴</td>
<td>200</td>
</tr>
<tr>
<td>IA4*</td>
<td>BL</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Se 10¹⁴</td>
<td>400</td>
</tr>
<tr>
<td>IA5</td>
<td>BL</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA6*</td>
<td>SI</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA7*</td>
<td>SI</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA12</td>
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<td>Ge 5.10¹²</td>
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<td>IA13</td>
<td>SI</td>
<td>200</td>
<td>Ge 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA17</td>
<td>SI</td>
<td>200</td>
<td>Ge 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA18</td>
<td>SI</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA19</td>
<td>SI</td>
<td>200</td>
<td>Se 1.25 10¹²</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Se 5.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA20</td>
<td>SI</td>
<td>200</td>
<td>Se 3.10¹²</td>
<td>400</td>
</tr>
<tr>
<td>IA21</td>
<td>SI</td>
<td>200</td>
<td>Se 5.10¹²</td>
<td>800</td>
</tr>
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<td>IA30</td>
<td>SI</td>
<td>200</td>
<td>Se 10¹⁴</td>
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<td>Se 10¹³</td>
<td>800</td>
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<td>BL</td>
<td>RT</td>
<td>Se 5.10¹³</td>
<td>100</td>
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<td></td>
<td></td>
<td></td>
<td>Se 7.5 10¹²</td>
<td>800</td>
</tr>
</tbody>
</table>

* Selective Implants

<table>
<thead>
<tr>
<th></th>
<th>I_DSS (mA)</th>
<th>g_m (ma/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA3*</td>
<td>40-100</td>
<td>12-29</td>
</tr>
<tr>
<td>IA4*</td>
<td>45-70</td>
<td>20-24</td>
</tr>
<tr>
<td>IA6*</td>
<td>SLICE BROKE</td>
<td></td>
</tr>
<tr>
<td>IA7*</td>
<td>POOR OHMIC CONTACTS</td>
<td></td>
</tr>
<tr>
<td>IA12</td>
<td>PROCESSING FAULT</td>
<td></td>
</tr>
<tr>
<td>IA13</td>
<td>LOW S-D CURRENT</td>
<td></td>
</tr>
<tr>
<td>IA17</td>
<td>LOW S-D CURRENT</td>
<td></td>
</tr>
<tr>
<td>IA18</td>
<td>HIGH S-D RESISTANCE</td>
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</tr>
<tr>
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<td>HIGH S-D RESISTANCE</td>
<td></td>
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<tr>
<td>IA20</td>
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<tr>
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<td>20-30</td>
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<tr>
<td>IA30</td>
<td>50-70</td>
<td>29-36</td>
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</table>
Fig. 50 Typical I-V Characteristics of FETs on Ion Implanted Material

A. Implant into Epitaxial Buffer Layer
B. Implant into Bulk Semi-Insulating (A65R).
measured with and without external illumination, was good. Also little hysteresis was discernable in the characteristics. Devices manufactured on implanted semi-insulating material displayed inferior performance in both the above respects. The degree of sensitivity to light was greater, as was the amount of hysteresis observed in the characteristics. Another difference between the I-V characteristics of devices processed on the two different materials was the behaviour of the saturation current with varying drain voltage. In buffer layer material the saturation current level was independent of gate voltage (hard saturation), whereas in semi-insulating material an increase in drain bias increased the source drain current (soft saturation).

It can be seen, from the DC parameters given in table (19), that a large variation in device performance was observed. In most cases the DC parameters of devices varied according to the spatial position on the slice. An example of the variation observed is given in the figure (51) which is a map of the measured values of transconductance and $I_{DSS}$ for sample IA 30. Less detailed maps showing the variation observed in other samples are given in figure (52). In sample IA 33 the measured DC parameters did not vary in the same way, but a random variation within a small range was observed. The standard deviation in $I_{DSS}$, $g_m$ and $V_p$ were ± 14%, 5% and 16% respectively, which are comparable to the figures reported by Higgins et al (17) of ± 9%, 14% and 18%.

The RF results quoted in table (20) were determined from samples selected from each slice. The samples chosen for measurement were taken from areas of the slice yielding the highest transconductance, and therefore represent the best microwave performance possible from any particular specimen. Because the RF measurement is particularly time
Figure 51 Variation of Measured Values of $I_{DSS}$ (mA) and Transconductance (mA/V) over Slice no. 1A30.
Figure 52 Variation of $I_{DS}(mA)$ and Transconductance ($mA/V$) over Four Slices of Implanted Devices.
consuming only a few samples were measured from each slice. For comparison purposes the Plessey device specification for production epitaxial devices are included in table (20). The GAT4 specification is compared with the results obtained from samples implanted with a single dose of ions, and the GAT5 specification is compared with dual dose/energy implanted devices. This is a reasonable comparison as the devices all have the same geometry, the GAT4 having a uniform doping profile, the GAT5 having an n⁺ surface contact layer. Both GAT4 and GAT5 device layers are grown on semi-insulating substrates with an intermediate undoped epitaxial buffer layer.

It can be seen that with the exception of IA4 which had selectively implanted channel and ohmic contact regions, the noise figures obtained from the implanted devices were superior to those specified for the epitaxial devices. Device IA 33 is particularly noteworthy in that the noise figure is considerably reduced to 2.7dB at 12.75GHz. It should be noted that the implantations in this case were performed at room temperature.
### TABLE 20

Microwave Results from Implanted Device Slices  
(Test Frequency = 12.75GHz)

<table>
<thead>
<tr>
<th>Slice No.</th>
<th>MAG</th>
<th>NF</th>
<th>GASS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(dB)</td>
<td>(dB)</td>
<td>(dB)</td>
</tr>
<tr>
<td>IA4</td>
<td>9.9</td>
<td>4.1</td>
<td>5.7</td>
</tr>
<tr>
<td>IA18</td>
<td>6.6</td>
<td>3.3</td>
<td>4.9</td>
</tr>
<tr>
<td>IA30</td>
<td>7.6</td>
<td>3.4</td>
<td>4.5</td>
</tr>
<tr>
<td>IA33</td>
<td>8.8</td>
<td>2.7</td>
<td>5.6</td>
</tr>
<tr>
<td>GAT5 (spec.)</td>
<td>9.5</td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>IA5</td>
<td>7.8</td>
<td>3.1</td>
<td>5</td>
</tr>
<tr>
<td>IA21</td>
<td>8.2</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>GAT4 (spec.)</td>
<td>7.5</td>
<td>3.7</td>
<td>5.2</td>
</tr>
</tbody>
</table>
5. DISCUSSION OF RESULTS

5.1 Encapsulation and Annealing

5.1.1 Nitride Growth

The growth mechanism of the silicon nitride may be described by the reaction:

\[ 3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2 \]

Other reactions which can occur in the growth vessel include the formation of other nitrides, oxynitrides and oxides of silicon, and the pyrolitic deposition of silicon, i.e. reactions with the form:

\[ \text{SiH}_4 + \text{NH}_3 \rightarrow \text{Si}_{x\ y} + \text{H}_2 \]

\[ \text{SiH}_4 + \text{NH}_3 + \text{O}_2 \rightarrow \text{SiO}_{x\ y} + \text{H}_2 \]

\[ \text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + \text{H}_2 \]

\[ \text{SiH}_4 \rightarrow \text{Si} + 2\text{H}_2 \]

The possibility of all the above reactions exists, and it is only by the correct choice of gas mixture and growth temperature that non-desirable reactions are suppressed and a stoichiometric nitride achieved. The necessity of adequate precautions to eliminate oxygen (and water) from the growth container is evident from the above. Any oxide or free oxygen contained in the nitride film would enable the outdiffusion of either gallium or arsenic \(^{42}\), and could also lead to electrical compensation of the GaAs by the indiffusion of oxygen atoms.

The RBS and ellipsometer measurements performed indicate that near stoichiometric \(\text{Si}_3\text{N}_4\) films were grown in each apparatus. The ratio of the concentrations of \(\text{SiH}_4\) and \(\text{NH}_3\) is of particular importance in determining the stoichiometry of the silicon nitride films. By using premixed 5% silane it was ensured that the ratio of \(\text{SiH}_4\) to \(\text{NH}_3\) was always greater than 1:20. In this way the formation of uncombined silicon was suppressed. Some experiments were in fact performed
on the use of pyrolytically deposited silicon as an encapsulant, both with and without an intermediate silicon nitride layer. The silicon layers were deposited with identical growth parameters as the silicon nitride layers but without any ammonia gas flow. Whilst there were definite indications that silicon could be used as an effective encapsulating layer, and in fact improved the efficiency of silicon nitride layers when the silicon layer was deposited on top, the difficulties associated with the subsequent removal of the silicon layers made this approach unattractive.

It is believed that the difference in optimum growth temperature determined for each apparatus was caused by the difference in the construction of the apparatus. The second apparatus was designed specifically to improve the uniformity and growth rate of the silicon nitride films. Part of the design of this apparatus was the incorporation of heat reflector shields to increase the temperature of the reagent gases prior to reaching the heated sample. The effectiveness of this approach can be judged from the temperature measured on a second thermocouple which was located in the growth chamber approximately 2 cms. from the carbon strip. It was observed that the temperature recorded by this thermocouple achieved approximately the temperature of the carbon strip (to within 10°C) within 30 seconds of the carbon strip reaching the control temperature. Thus it is believed that the difference between the temperature of the reagent gases and the heated sample was probably minimised in this apparatus. Consequently it is likely that the nucleation rate of the deposited silicon nitride would be different in this apparatus, to that in the first apparatus where radiated heat from the carbon substrate was not contained, but was transmitted through the glass bell jar. Certainly the difference observed in the growth rates in the two apparatus was considerable.

For growth at 580°C a 400Å film could be grown in the first
apparatus in about five minutes. In the second apparatus a film equally thick could be grown at the same temperature in only 20 seconds. However, it was observed that the silicon nitrides grown in the second apparatus were more susceptible to blistering and cracking, and it is believed this may be a consequence of the fast growth conditions.

5.1.2 Sample Annealing

One interesting result of this study was that in all cases where type conversion of unimplanted material was observed the material displayed p-type activity. Other workers annealing for longer times, have observed predominantly n-type conversion. Whilst these results seem at first sight to be contradictory it is believed that the difference can be readily explained by the annealing system adopted. Chuang and Pearson have proposed that type conversion is caused by gallium and arsenic vacancy formation and migration. Their model involves the formation of p-type centres (arsenic vacancy complexes) due to arsenic loss, which are localised to the near surface region because of the low diffusion rate of arsenic vacancies (52). Gallium vacancies, on the other hand, have a higher diffusion rate and so have a greater effect deeper in the sample leading to n-type conversion at greater depths. In the pulse annealing schedule adopted it is thought that the time spent at elevated temperature is insufficient for any appreciable gallium vacancy diffusion to occur, and therefore only p-type centres have an observable effect, these being concentrated very near to the surface. By limiting the amount of arsenic loss by improving the quality of the nitride films the number of arsenic vacancies formed was reduced so that the samples remained highly resistive. One factor which may also limit the amount of arsenic out-diffusion is the inclusion of arsenic in the silicon nitride layer, as observed by RBS. No attempt was made to reduce this arsenic inclusion, for example by encapsulating the back face of the samples prior to annealing, as it
is known that the presence of arsenic ions at the surface can limit
the amount of arsenic loss. Indeed, Eisen et al (33) have successfully
annealed GaAs using powdered graphite saturated with arsenic as an encapsulant.

Having established a reproducible method of sample encapsulation
the choice of annealing conditions was not an arbitrary one. Studies of
annealing for different times showed that 30 seconds was sufficient to
produce maximum electrical activity. Times shorter than 30 seconds were
thought insufficient for completely homogeneous heating to the control
temperature. Annealing for 2 minutes and 4½ minutes produced no increase
in the degree of electrical activation. Annealing for 10 minutes actually
produced a slight decrease in the measured carrier concentration in some
instances, presumably due to encapsulation failure. It was felt that a
standard 30 secs. anneal at 900°C should be adopted for the following
reasons:—

(a) Maximum electrical activation of the implanted ions was achieved
    with this schedule.
(b) The probability of encapsulation failure was minimised.
(c) Reducing the time the sample heater remained at high temperature
    would prolong its life, and reduce the heating of the growth
    chamber — and hence the level of outgassing of components.
(d) The time the sample was at high temperature was minimised, and
    so the likelihood of appreciable diffusion of implanted ions,
    defects and contaminants was reduced.
(e) Whilst experiments showed that similar levels of activation could
    be achieved by annealing at lower temperatures (850°C) for low doses
    it was felt that a standard anneal, irrespective of dose,
    would be most attractive for device manufacture. This approach is
    also most directly relevant to dual dose implants.

In fact, the levels of carrier concentration achieved using this anneal
schedule compare favourably with those reported in the literature. These
values will be compared in the following section.
5.2 Electrical Measurements of Implanted Material

5.2.1 Comparison of Different Ions Studied

In table (21) the values of sheet and volume electrical parameters determined for samples implanted with high doses of the ions studied, are compared with the results reported in the literature by other workers for similar dose and energy combinations. It can be seen that there is considerable agreement between the peak electron concentrations determined in this study with the best of those reported in the literature. More variation was observed however in the level of electrical activation. This is probably due to differences in profiles width caused by diffusion during the annealing cycle. As anneals of only 30 secs duration were performed in this study the amount of diffusion the implanted ions could undergo was considerably less than that allowed by the longer anneals (typically 15-30 minutes) used by other workers. Inefficiency of the encapsulant can also lead to increased profile width. One possible explanation of this phenomenon is that if the encapsulant allows appreciable out-diffusion of gallium or arsenic; in-diffusion of the dopant species can be enhanced by an increase in the concentration of native vacancies.

5.2.2 Implantation of Selenium into GaAs at 200\degree C

(i) Peak Electron Concentration

It can be seen in table (21) that selenium implants were the most active of all the ions implanted at Surrey, and for this reason selenium was the most studied ion in subsequent investigation.

One outcome of the survey of the literature regarding donor ion implantation was that there existed no established method for predicting the resultant peak electron concentration resulting from any particular implantation. Most studies have taken place at only one energy, and thus if it is desirable to achieve doping at some depth different from that previously studied an investigation must be undertaken before the desired doping profile can be achieved. One of the achievements of this
TABLE 21
Comparison of the Electrical Activity of High Dose (> $10^{14}$ cm$^{-2}$) Implanted Various Ions

<table>
<thead>
<tr>
<th>Ion</th>
<th>Implant Energy (keV)</th>
<th>Implant Temp. (°C)</th>
<th>Activity (%)</th>
<th>Peak Conc. (cm$^{-3}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Se</td>
<td>100</td>
<td>200</td>
<td>20</td>
<td>$3.10^{18}$</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>400</td>
<td>38</td>
<td>$4.5 10^{18}$</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>500</td>
<td>20 - 26</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>200</td>
<td>26</td>
<td>$1.6 10^{18}$</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>250</td>
<td>40</td>
<td>$2.10^{18}$</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>500</td>
<td>50</td>
<td>$3.6 10^{18}$</td>
<td>78</td>
</tr>
<tr>
<td>Te</td>
<td>300</td>
<td>200</td>
<td>26</td>
<td>$2.8 10^{18}$</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>350</td>
<td>10 - 30</td>
<td>$6.10^{17} - 2.10^{18}$</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>350</td>
<td>20 - 31</td>
<td>$10^{18} - 7.10^{18}$</td>
<td>44</td>
</tr>
<tr>
<td>Si</td>
<td>120</td>
<td>20</td>
<td>34</td>
<td>$10^{18}$</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>340</td>
<td>25</td>
<td>$2.8 10^{18}$</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>RT</td>
<td>60</td>
<td>$1.2 10^{18}$</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>RT</td>
<td>30</td>
<td>$2.7 10^{18}$</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>RT</td>
<td>26</td>
<td>$8.10^{18}$</td>
<td>78</td>
</tr>
<tr>
<td>Sn</td>
<td>300</td>
<td>200</td>
<td>16 - 17</td>
<td>$1.6 10^{18}$</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>100-500</td>
<td>18</td>
<td>-</td>
<td>71</td>
</tr>
</tbody>
</table>
investigation is that it became possible to predict the peak electron
congestion resulting from an implant of any dose at any energy,
with a subsequent anneal at 900°C for 30 seconds. In figure (53) the
measured peak electron concentrations determined from a great number of
selenium implants with a variety of dose and energy combinations, are
plotted as a function of the theoretical peak atomic concentration.
This is determined from the implanted dose(Ni) and the theoretical
standard deviation (ΔR_p) by the use of the standard formula:

\[ N_v = \frac{0.4 \text{Ni}}{\Delta R_p} \quad \text{(from equation (19))} \]

It can be seen that at low theoretical peak concentrations the implanted
eons are approximately 100% active. As the peak concentration is
increased the level of activity decreases. It can be seen that the
log. carrier concentration varies linearly with log. peak concentration
up to a peak concentration of about \(4 \times 10^{18} \text{cm}^{-3}\). Above this concentration
the rate of variation changes, but the variation remained linear up to
a peak concentration of \(4 \times 10^{19} \text{cm}^{-3}\). Samples were not studied with
atomic concentrations greater than this value. It should be noted that
figure (53) includes results from samples implanted with energies within
the range 100keV to 1MeV, and that the relationship between peak electron
concentration and peak atomic concentration is obeyed throughout this range.
Thus it may be reliably concluded that the doping level achieved in
implanted specimens is related directly to the actual concentration of
atoms present at any depth in the sample. It is important to stress,
however, that the results shown in figure (53) apply only to the
concentrations at the actual peak in the doping profile. At depths
other than at the projected range the percentage of implanted ions is
greater, and approaches 100% in the tail of the profile. In the near
surface region the number of electrically active ions was also greater,
and in some cases actually exceeded the concentration of ions predicted
Figure 53  Dependence of Electron Concentration at Peak of Profile upon Concentration of Selenium Ions Implanted at 200°C.
using a simple Gaussian profile to approximate the LSS predictions. This is probably due to increased scatter in the surface region due to electronic stopping, which is not accounted for using a simple Gaussian approximation.

Thus it is possible to distinguish three major areas in the electron concentration profiles, as shown in figure (54) for $5 \times 10^{12}$ and $10^{14} \text{ cm}^{-2}$ 400keV selenium implants.

(a) The near surface region where out-diffusion of the implanted ions can cause the electron concentration to exceed that predicted by LSS theory.

(b) The region near the theoretical peak of the profile where the electron concentration is predicted from the theoretical peak concentration using the results of figure (53).

(c) The tail region of the profile where the theoretical and actual values determined correspond.

Also shown in figure (54) are the mobility profiles determined from these samples. These mobility profiles may be compared with those predicted from the carrier concentration profiles using the data of Sze and Irwin\(^{(114)}\), assuming 100% activation. It can be seen that the measured mobility values in the high dose sample are significantly less than the theoretical values except in the tail of the profile where the measured and theoretical values correspond more closely. This is consistent with an increase in compensation of the implanted ions towards the surface of the sample. In the sample implanted with the lower dose ($5 \times 10^{12} \text{ cm}^{-2}$) the theoretical and actual mobility profiles correspond closely throughout the implant profiles, indicating lower levels of compensation.

The use of theoretically generated mobility profiles is explored more fully in section (5.2.4.).
Fig. 54. Comparison of Measured and Theoretical Depth Profiles for 200°C Selenium Implants. Ion Dose $10^{14}$ cm$^{-2}$ and $5.10^{12}$ cm$^{-2}$.

- a Theoretical mobility profile $5.10^{12}$ cm$^{-2}$
- b Theoretical mobility profile $10^{14}$ cm$^{-2}$
In section 4.3.3 it was stated that several samples from two implanted slices, one implanted with a dose of $10^{14}$ cm$^{-2}$ the other $2.10^{14}$ cm$^{-2}$, gave anomalous electrical results. There are two possible explanations for these results.

Firstly, it is possible to achieve accidental channelling of the implanted ions. This can result from misalignment of the sample holder with respect to the ion beam, and can result in electrical profiles located deeper in the sample than expected. The carrier concentration of the channelled profiles has been shown to exceed that of random implants $^{(115)}$.

The second explanation is that the implantation was performed at a temperature less than the expected 200°C. This could be caused by poor thermal contact between the specimen holder and the sample holder. Comparison of the sheet electrical results of the 'anomalous' samples (fig. 30) and those of implants performed at room temperature (fig. 39) show a distinct similarity. Additionally, a comparison of the electron concentration and mobility depth profiles determined in the 'anomalous' and room temperature implanted samples shows distinct similarities between the depth and level of the peaks, as shown in figure (55). It is thought therefore that the explanation of the 'anomalous' results is that the samples were inadvertently implanted at a temperature less than the 200°C which was intended, and the resultant activation of the implanted ions is more similar to that produced in samples implanted at room temperature.

(ii) 'Anomalous' Implant Results
Fig. 55 Comparison of Electrical Depth Profiles of 'Anomalous' Samples and Room Temperature Implants of Selenium.

a $2 \times 10^{14}$ cm$^{-2}$ Anomalous sample
b $1 \times 10^{14}$ cm$^{-2}$ Anomalous sample
... $2 \times 10^{14}$ Se cm$^{-2}$ Room temp.
---- $1 \times 10^{14}$ Se cm$^{-2}$ Room temp.
5.2.3 Room Temperature Implantation of Selenium

The results obtained from the electrical measurement of samples implanted at room temperature with selenium ions were among the most interesting of this study. Several points are immediately apparent from the results presented.

(i) Higher levels of activation were achieved than those previously reported in the literature, particularly at high dose levels. It is thought that the principle reasons for this are the use of thermally stable GaAs, reliable encapsulation and high temperature annealing.

(ii) The doping level in the tail of the profiles falls off far more rapidly with depth in the room temperature implanted samples than in those implanted at 200°C. This is true for all the dose and energy combinations studied. It is thought that two major factors contribute to the observed effect:

(a) Wilson and Jamba\(^{(116)}\) have shown by SIMS measurements that long tails occur in the atomic distribution of selenium implanted at 250°C at high doses, whereas if similar implants are performed at 25°C diffusion of the tail is suppressed. For low dose implants the shape of the SIMS profiles are identical for implants performed at both temperatures. These authors conclude that the tail in the profile is caused by interstitial migration of the implanted ions during implantation, which is prevented when the material becomes amorphous due to high dose implantation at room temperature. Wilson and Jamba also show that the atomic distribution is unaffected by annealing at 840°C for 20 minutes.

Whilst the above accounts for the similarity of the tails of the profiles of high dose room temperature implants, it does not fully account for the observed behaviour, especially at low doses where amorphisation does not occur.
(b) Evans et al.\textsuperscript{(117)} have shown, also by SIMS investigations, that appreciable gettering of chromium occurs in the tail of room temperature implanted GaAs after annealing, which is not observed in samples implanted at 500\(^\circ\)C. It is proposed that this chromium causes increased compensation locally, giving a decrease in the number of implanted ions becoming electrically active.

(iii) High dose implants (\(> 7.5 \times 10^{12}/\text{cm}^2\) at 400keV) result in a complex, twin peaked profile, the reasons for which are not obvious. One possible explanation requires a consideration of the effects of ion implantation upon the lattice atoms. Christel and Gibbons\textsuperscript{(118)} have calculated the distribution of lattice atoms displaced by recoil implantation after a \(10^{15} \text{ cm}^{-2}\) implant of 400keV Se\(^+\). This results in an excess of Ga and As vacancies near the surface, and a distribution of displaced Ga and As atoms centred at about 0.2\(\mu\)m, as shown in figure (56). The following assumptions are now made.

(a) For high doses, where the GaAs starts to become amorphous, the imbalance in stoichiometry due to recoil implantation is maintained (for hot implantation interstitial diffusion may occur in order to return to the equilibrium, stoichiometric situation).

(b) The degree of amorphisation at any given depth is governed by the total number of excess atoms present at that depth – the sum of the implanted Se ions and the displaced Ga and As atoms.

(c) The degree of electrical activation of the implanted Se ions is determined by the ease of recrystallisation (allowing the Se to sit on the correct lattice site) which in turn depends on the degree of amorphisation at that depth.

(d) Electrical activation of the implanted Se is most favourable where the number of implanted Se ions exceeds the total number of displaced atoms.
Figure 56  Calculations of Stoichiometric Disturbances in GaAs Implanted with 400keV Se to a dose of $10^{13}$ cm$^{-2}$

- - - - Implanted Se atoms
--- net Ga and net As displaced (approx.)
------- net Ga and net As vacancies (approx.)
-------- excess Ga
---------- excess As
In figure (57) the total number of excess atoms (Se, Ga and As) are plotted as a function of depth for a $2.10^{14}$ cm$^{-2}$ implant. According to the assumptions made above the minimum activation of the implanted Se should be observed at the depth of maximum excess atoms (0.12μm) which is in close agreement with the observed minimum in the electrical concentration profile shown previously in figure (55). It can also be seen in figure (55) that the shape of the near surface peak closely corresponds to the calculated profile of excess Se (produced by subtracting the profile of the displaced Ga and As distribution from the theoretical implantation profile of the selenium.

A twin peaked carrier concentration profile has been observed in GaAs implanted with Se at 200keV (69), after annealing at $\sim$ 600°C. On annealing at higher temperatures (700°C) the dual peak structure disappeared, and a single Gaussian profile was observed. It was found in this case that the shallow peak became active for short anneals, whereas the deeper ions only became active after longer anneals. This behaviour is consistent with the model proposed, in that the excess ions in the deeper regions would restrict the movement of the selenium ions onto arsenic sites within the lattice.

It is interesting to compare the results of this study with those of Donnelly (41) for room temperature implants of $1.10^{14}$ x 400keV Se$^+$ cm$^{-2}$ shown in fig. (58). It can be seen that the electron concentration profile observed by Donnelly is similar to that determined for a dose of $5.10^{13}$ ions cm$^{-2}$, in that a peak was observed deep in the sample, with a very sharp tail. The position of the peak observed by Donnelly is shifted towards the surface as the implant was performed through 700 $\AA$ of Si$_3$N$_4$.

(iv) Except for the lowest doses ($5.10^{12}, 10^{13}$ ions cm$^{-2}$), very low values of mobility were measured throughout the depth of the implant. It is proposed that this is due to localised compensation. This hypothesis is discussed in the following section.
Figure 57 Theoretical Profiles of Implanted 400keV Selenium, with calculated distribution of displaced lattice ions. Implant dose $2.10^{14}$ ions cm$^{-2}$ (after ref. (118)).
Fig. 58 Comparison of the Results of Donnelly et al (Ref. (41)) for a $10^{14}$ x 400keV Selenium ions cm$^{-2}$ Implant Performed at Room Temperature, with the Results of This Study.

Implant of ref. (41) Performed through 700Å of Si$_3$N$_4$. 

Electron Concentration (cm$^{-3}$)

$10^{16}$

$10^{17}$

$10^{18}$

$10^{19}$

Depth (μm)

0 0.1 0.2 0.3 0.4

$5 \times 10^{13}$ cm$^{-2}$

$10^{14}$ cm$^{-2}$
5.2.4 Compensation

The value of the mobility measured at any given carrier concentration has been shown to be dependent upon the implanted ion species, and the implantation conditions, especially temperature. Other factors, especially the anneal temperature are also important. It is proposed that the observed variation is caused by differing degrees of electrical compensation within the material.

In order to examine the variation in compensation a simple analytical procedure was developed. This consists of:

(a) Measuring the electron concentration and mobility depth profiles as outlined previously.

(b) From the measured electron concentration determining the expected value of Hall mobility (\( \mu_{TH}^\prime \)). The data of Sze and Irvin (116) (Fig. (59)) was used, as this directly relates the Hall mobility not the drift mobility, to the impurity concentration.

(c) Calculating the ratio of the expected value of mobility to the actual measured value \( \mu_m \).

\[
\frac{\mu_{TH}^\prime}{\mu_m}
\]

This ratio was used as a measure of the degree of compensation in the material and has a value of 1 when the measured electron concentration is equal to the number of ionised impurities. Values greater than 1 are obtained when the number of ionised impurities exceeds the electron concentration.

An alternative approach would have been to use the measured mobility to predict a value of ionised impurities present, and use this value to determine the ratio of electron concentration to ionised impurities - the true compensation ratio. This approach was not adopted because due to the very high levels of compensation exhibited in some instances, very low values of mobility, \(< 1000 \text{cm}^2\text{V}^{-1}\text{sec}^{-1}\), were determined. This is consistent with impurity concentrations in excess of \(10^{19} \text{cm}^{-3}\), and degeneracy effects make the values of expected mobility inaccurate(119).
Figure 59 Theoretical Variation of Hall Mobility with Donor Ion Concentration in n-type GaAs.
Using the approach adopted significantly lower values of electron concentration were used in the determination, and the data used was consistent with ionised impurity scattering being the major factor in determining the expected mobility.

Average values of electron concentration taken from all the samples studied were used to determine the values of $\mu_{TH}$, and the average values of mobility were also used.

It can be seen in figure (60) that for room temperature implants of selenium there was a considerable variation of compensation with depth which was dependent upon the implanted dose. For low doses ($3.10^{12} - 10^{13}$ cm$^{-2}$) the material was uncompensated ($\mu_{TH}/\mu_m \approx 1$) except very near the surface, where partial encapsulation failure was probably responsible for the small increase in compensation observed. As the dose was increased up to $2.10^{14}$ cm$^{-2}$ the level of compensation increased, with a maximum level ($\mu_{TH}/\mu_m \approx 2$) at about the theoretical range of the implanted ions. For higher doses ($5.10^{14} - 10^{15}$ cm$^{-2}$) the degree of compensation increased dramatically throughout the implanted depth, with a significant maximum value, once again at a depth around the theoretical range ($\mu_{TH}/\mu_m \approx 5$). To clarify the way in which the degree of compensation varies with dose the ratio ($\mu_{TH}/\mu_m$)$_p$ is plotted against the total number of implanted ions in figure (61). Here the ratio ($\mu_{TH}/\mu_m$)$_p$ was determined at the theoretical range. It is evident from figure (61) that the degree of compensation increased appreciably in the small dose range between $2.10^{14}$ and $5.10^{14}$ cm$^{-2}$. It is anticipated that annealing at higher temperatures may result in a shift in this range to higher doses, however because the encapsulant blistered and cracked appreciably at temperatures above 900°C this hypothesis was not proven.

Also shown in figure (61) are the values of the mobility ratio determined for samples implanted with selenium at 200°C. It can be seen that whilst there is a steady increase in the mobility ratio as the dose
Figure 60  Variation of Mobility Compensation Ratio with Depth in Samples Implanted with Selenium at Room Temperature.

- a: $5 \times 10^{12}$ cm$^{-2}$
- b: $10^{13}$ cm$^{-2}$
- c: $5 \times 10^{13}$ cm$^{-2}$
- d: $7.5 \times 10^{13}$ cm$^{-2}$
- e: $2 \times 10^{14}$ cm$^{-2}$
- f: $5 \times 10^{14}$ cm$^{-2}$
- g: $10^{15}$ cm$^{-2}$
Figure 61  Variation of Mobility Compensation Ratio Determined at Projected Range with Implanted Dose of Selenium Ions at Room Temperature.

... Results obtained from samples implanted at 200°C.

Implant Dose (cm$^{-2}$)

Mobility Compensation Ratio ($\mu_{TR}/\mu_m$)
is increased, the dramatic rise observed for the room temperature implanted samples does not occur. It is reasonable to associate the increased compensation in the room temperature implanted samples with the transition to an amorphous layer which of course does not occur in the samples implanted at elevated temperatures.

5.2.5 $5 \times 10^{12}$ cm$^{-2}$ Selenium Implantation

The effect of substrate quality upon the performance of implanted donor ions was emphasised by this part of the study of implanted selenium ions.

The highest activation efficiencies and mobilities were found in implanted low n-type epitaxial material. This is however the least attractive substrate for MESFET fabrication because of its relatively high cost. Epitaxial material is also difficult to grow accurately to a specified thickness, especially at the very low levels of doping suitable for use as implantation substrates for MESFET applications. As any excess carriers at depths below the maximum implanted depth would tend to increase the noise of final devices, the difficulties associated with this material rule it out for this application. One further problem associated with epitaxial material is the unavoidable inclusion of extra damage at the interface between the epitaxial layer and the semi-insulating substrate upon which it is grown.

A good alternative to n on semi-insulating material is the epitaxial undoped material used as part of this study. Whilst electron concentration values measured in this material were similar to those obtained in the best semi-insulating material, the improvement observed in the mobilities especially in the tail of the profile, make it a more attractive alternative. As the material has a very low residual donor concentration the depth of the epitaxial material is not restricted. Uniformity requirements are therefore relaxed considerably, and problems associated with the epitaxial layer to
substrate interface are overcome, as this interface can be adequately separated from the active layer of the device. The increased cost of epitaxial material, and the extra difficulties experienced in growth of the epitaxial layer must also be considered.

A considerable variation was also observed in the results achieved in the various semi-insulating substrates examined.

As shown in figure (42) the material grown by MCP exhibited lower activities and mobilities after implantation throughout the doping range investigated. Of the two MR ingots used A65R gave the more consistent results, whilst the activities determined from implanted slices of A84R material tended to be more variable.

As discussed in section (2.5) the reasons for poor results in chromium doped GaAs are still not understood. Recently high activities with high mobilities have been reported in implanted high resistance undoped material. To date the best results have been reported in material specially grown for experimentation, and not commercially available. Since the completion of the experimental work of this study undoped, high resistance material has become commercially available, and it would be an interesting area for further study to examine the levels of activation achievable in this material.

Because of the interest in producing MESFETs on material implanted at $5 \times 10^{12} \text{ cm}^{-2}$ a large number of samples were implanted with this dose throughout the course of this study. To indicate the degree of reproducibility the electrical results determined in samples of A65R are given in table (22). It can be seen that run to run reproducibility is very good, and the results to some extent reflect the uniformity and quality of this particular ingot of semi-insulating material.
### TABLE 22
Sheet Electrical Results Measured on Samples of A65R MR Semi Insulating GaAs Implanted at 200°C with 5.10^{12} Se^{+} cm^{-2}

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sheet Electron Conc. (cm^{-2} x 10^{12})</th>
<th>Hall Mobility (cm^{-2}v^{-1}s^{-1})</th>
<th>Sheet Resistivity (\rho/\Omega)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3</td>
<td>4.14</td>
<td>4018</td>
<td>376</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>4186</td>
<td>414</td>
</tr>
<tr>
<td>M3</td>
<td>4.03</td>
<td>3643</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>4.49</td>
<td>3687</td>
<td>378</td>
</tr>
<tr>
<td></td>
<td>4.63</td>
<td>3207</td>
<td>412</td>
</tr>
<tr>
<td></td>
<td>4.43</td>
<td>3587</td>
<td>374</td>
</tr>
<tr>
<td>O1</td>
<td>4.07</td>
<td>3952</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>4.29</td>
<td>3930</td>
<td>371</td>
</tr>
<tr>
<td></td>
<td>3.96</td>
<td>3663</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>3.96</td>
<td>3837</td>
<td>409</td>
</tr>
<tr>
<td>R1</td>
<td>4.3</td>
<td>4202</td>
<td>346</td>
</tr>
<tr>
<td></td>
<td>4.44</td>
<td>3745</td>
<td>376</td>
</tr>
<tr>
<td></td>
<td>4.26</td>
<td>3619</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>4103</td>
<td>339</td>
</tr>
<tr>
<td>W1</td>
<td>4.26</td>
<td>4150</td>
<td>351</td>
</tr>
<tr>
<td></td>
<td>4.35</td>
<td>3900</td>
<td>360</td>
</tr>
</tbody>
</table>
5.2.6 Implantation of Germanium

The behaviour of germanium as a dopant ion in GaAs is considerably more complex than that of the group VI ions Se and Te. Whilst the atomic size of germanium is the closest match to that of Ga and As, and should produce minimal distortion to the GaAs lattice when located on substitutional sites, it has the serious disadvantage of being an amphoteric dopant, that is it can act as a donor or acceptor depending on which site it resides.

The possibility of a multitude of dopant-vacancy complexes also exists, making the prediction of the behaviour of implanted germanium impossible. Examination of the variation of the degree of electrical activity of the implanted germanium with dose (fig. (35)) indicates that this drops rapidly from a high level at low doses (≈ 80% at $4 \times 10^{12} \text{cm}^{-2}$) to about 10% at $2 \times 10^{13} \text{cm}^{-2}$. The level of activation is then approximately constant until high doses (≈ $2 \times 10^{14} \text{cm}^{-2}$) are implanted. One explanation of this behaviour is that at low doses the germanium behaves almost exclusively as a donor. As the dose is increased a significant percentage of the germanium act as acceptors, leading to an increase in the level of compensation, and a nearly constant level of percentage activation. At very high levels of dose increased unannealed damage leads to a further reduction in the level of activation, similar to that observed with other ions. If this model is correct it would be expected that the compensation ratio would increase rapidly as the dose was increased from very low levels. In figure (62) the mobility ratio ($\mu_{TH}/\mu_m$) is plotted against dose. The mobility ratio is determined at three depths:

(a) The theoretical range - $R_p$

(b) The depth of the peak in the electron concentration for high dose implants - $1.5R_p$

(c) The depth of the observed minimum values of mobility - $0.5R_p$. 
Figure 62 Variation of Mobility Compensation Ratio Determined at Three Depths in Samples Implanted with Germanium Ions at 200°C.

- Depth = 1.5Rp
- Depth = 1.0Rp
- Depth = 0.5Rp
It can be seen that the mobility ratio increases rapidly in all three cases, the greatest increase being observed at the shallow depths, causing the apparent shift in the peak of the electron concentration profile (fig. (36)).

It is interesting to compare the results of this study with those of Krüntle (85) and Park et al (86), who observed n type activity only after high dose (> 10^{15} cm^{-2}) implantation of germanium, lower doses giving acceptor type activation. Both sets of workers reported that n type activity could be achieved for lower doses implants only when co-implanted with a similar dose of arsenic ions, causing the germanium ions to sit preferentially on gallium sites. It is important to note that both Krüntle and Park performed their implantation into samples held at room temperature, whereas the results reported in this study were from samples implanted at 200°C. The behaviour of germanium is obviously complicated, with n-type activation being achieved when the implant is:

(a) performed into heated substrates
(b) performed into room temperature substrates at doses sufficient to render the GaAs substrates amorphous
(c) performed into room temperature substrates with a co-implant of arsenic.

The importance of having an excess of arsenic to achieve donor type activity in germanium implanted material suggest that the high levels of compensation observed near the surface of samples in this study are perhaps due to loss of arsenic in this region. This could simply be due to slight arsenic loss through the encapsulating layer, although this would not tend to be implant dose dependent. An alternative explanation is that stoichiometric imbalances due to recoil of the atoms of the host lattice would result in a net distribution of excess arsenic vacancies at the surface, similar to that shown in figure 55 for implantation of selenium (which has a similar mass to that of germanium).
In the samples implanted at room temperature it is probable that the nature of the damage caused favours the location of germanium ions on arsenic sites giving p type activity. As this is thermo-dynamically nearly as favourable as gallium site location annealing will not tend to cause activation as donors. The co-implantation of arsenic would tend to assist gallium site location, however, giving n type activation.

5.2.7 Silicon Implantation

Silicon is becoming an increasingly important ion for GaAs doping because high levels of activation have been reported in room temperature implanted material. In order to achieve a pure silicon ion beam it is usually necessary to implant the Si$^{29}$ isotope to avoid possible contamination of Si$^{28}$ with N$_2^+$ or CO$_2^+$ ions. However the Si$^{29}$ isotope accounts for only 4% of the available silicon beam, and because the maximum current of the Surrey implanter is limited it is not possible to achieve suitable current levels of Si$^{29}$ ions. It was therefore necessary to obtain samples implanted at AERE Harwell in a high current accelerator for this study.

The electrical activities obtained from samples implanted at low doses were disappointingly low. Higher activities have been reported in the literature for similar dose implants performed at room temperature (78)(81). The semi-insulating substrates used were of the same type as for the highly active selenium implants, and therefore the reasons for the low activity are not immediately evident. One possibility is that the particular substrates used were slightly gallium rich (excess arsenic vacancies), either before or after annealing. This would tend to assist in the activation of selenium ions, which need to sit on an arsenic site for electrical activation, and hinder the activation of silicon implants which require gallium site location. Another alternative is that the dosimetry of the silicon implants was incorrect. This is certainly possible as the Si$^{29}$ isotope may be contaminated with
BF$_2^+$ ions, a common impurity in accelerators used for boron implants into silicon.

At higher doses the silicon implanted specimens displayed encouragingly high levels of activation with high electron mobilities. The peak electron concentrations measured were $\sim 2.10^{18}$ cm$^{-3}$, which exceeds the best results of Tandon et al for 300keV implants of silicon at dose levels up to $5.7 \times 10^{14}$ cm$^{-2}$, annealed at 850°C (81). No evidence was obtained for the profile broadening reported by these authors, in samples annealed at 900°C. It is thought that this effect was probably due to encapsulation failure in their case. The carrier concentration in these samples was $\sim 2.10^{18}$ cm$^{-2}$, but the mobility levels were approximately half that measured in the samples implanted at 120keV reported here.

Because of the necessity of performing silicon implantation at AEWE Harwell it was thought undesirable to extend the investigation of the behaviour of silicon implanted material, particularly as superior results were achieved with selenium implantation at low doses. Also, similar performance was achieved with the two ions at the higher dose levels, both in terms of carrier concentration and mobility levels achieved.

5.2.8 Dual Energy Selenium Implantation

The investigation of dual energy selenium implants was undertaken in order to produce a method of tailoring the dopant profile to meet device requirement, specifically in order to reduce the series resistance of MESFETs by producing a highly doped surface region. In this way not only can the resistance of the GaAs be reduced, but also the contact resistance of the source and drain ohmic contacts, as this is dependent upon the doping level of the semiconductor-contact interface. It has been shown experimentally that the specific contact resistance is inversely proportional to the GaAs electron concentration (120):

\[ R_c = f \left( \frac{1}{N_d} \right) \]

i.e. $R_c = f \left( \frac{1}{N_d} \right)$

where $R_c$ = specific contact resistance.
Of the profiles obtained from samples implanted at 100 and 400keV only two were of interest for device fabrication. These were obtained from samples implanted with $1.25 \times 10^{12}$ 100keV cm$^{-2}$ + $5.1 \times 10^{12}$ 400keV cm$^{-2}$ and $5.1 \times 10^{12}$ 100keV cm$^{-2}$ + $5.1 \times 10^{12}$ 400keV cm$^{-2}$. For the lower dose sample quoted the profile obtained was approximately flat at depths greater than about 0.05μm. The sample implanted with $5.1 \times 10^{12}$ 100keV and 400keV cm$^{-2}$ allowed the fabrication of devices on material with a doping concentration which continuously decreased with increasing depth, again assuming the first 0.05μm was removed.

These doping profiles were of interest because of theoretical prediction discussed in section (1.6.2). The device results obtained from these samples will be discussed in section (5.3.4).

The profiles obtained from samples implanted with the higher dose ($10^{14}$ cm$^{-2}$) of 100keV selenium ions plus $5.1 \times 10^{12}$ 400keV Se$^+$ cm$^{-2}$ were not directly applicable to device fabrication because the long tail of the 100keV ions completely encompassed the profile of the 400keV ions making it impractical to etch to the desired doping level for Schottky barrier formation. It is probable that the increased depth of the tail of the implant was due to enhanced diffusion caused by the selenium concentration exceeding the solubility limit, as discussed by Lidow et al.$^{(121)}$. No advantage could therefore be gained by implanting the high-dose surface implant at lower energies. Instead the active region of the device was separated from the contact region by increasing the depth of the region doped to $10^{17}$ cm$^{-3}$, by increasing the energy of the deeper implant to 800keV.

The doping profiles achieved by the dual implantation corresponded closely to that predicted by adding the profiles obtained from single energy implants.
The only major difference between the profiles of samples implanted at room temperature and 200°C is the relative sharpness of the tail of the unheated samples. As with room temperature single energy implants profile determination was again difficult in this region due to the rapid decrease in sheet electrical parameters on consecutive Hall measurement.

The only disadvantage of the high dose-low energy implant was considered to be the dramatic decrease in mobility (and consequently increased resistivity) observed very close to the surface. In practice a shallow etch was performed prior to the evaporation of the ohmic contact metallisation when manufacturing FETs, so that the ohmic contacts were actually alloyed onto low resistivity, highly doped material. Minimum contact resistance was therefore attained. It must also be borne in mind that during the alloying of ohmic contacts considerable diffusion of the germanium takes place, which tends to dope the surface of the material. The germanium in-diffusion is enhanced by the presence of indium or nickel in the two most common ohmic contacts used, In/Au/Ge and Ni/Au/Ge, causing the ohmic contact penetration to be 0.1 - 0.3μm (122).

5.2.9 Dual Ion Implantation

As only a limited investigation of dual ion implantation was possible the study was limited to two ions combinations:-

Ga + Se
Sn + Se.

Previous investigation of samples annealed at 700°C, where the damage remaining tended to mask the dual implant effect, had indicated that the Ga + Se combination was one of the most likely to yield enhancement of electrical activation. Since gallium has an exact match to the host lattice it is likely to produce the least lattice distortion of all the group IV ions, and os is the most attractive ion for co-implantation with selenium. Also, the results of Inada et al (88) have shown that
very high levels of carrier concentration (up to $\sim 10^{19}$ els cm$^{-3}$) could be achieved with this combination when annealed at 1000$^\circ$C.

In this study, with samples pulse annealed to 900$^\circ$C, the maximum observed carrier concentration was $3.3 \times 10^{18}$ cm$^{-3}$, with a similar dose combination to that used by Inada et al. One conclusion which may be drawn is that 900$^\circ$C is insufficient to remove all of the implantation induced damage, and the full advantages of dual implantation are not achieved. Because of the previously described instability of the Si$_3$N$_4$ encapsulant at 1000$^\circ$C it was not possible to reproduce the results of Inada.

For the lower dose implants of Ga + Se some increase in carrier concentration was also observed. The most significant increase was observed in the room temperature implanted samples, where the co-implantation of gallium resulted in an increase in the activity of the implanted selenium to $\sim 80\%$, with carrier concentration and mobility profiles almost identical to the results achieved with 200$^\circ$C implants of selenium. The increase was most marked in the tail of the profile, where room temperature implants of Se alone fall off more quickly than 200$^\circ$C implants. This indicates that the low activation level of the room temperature implants of Se in this area is caused by gallium depletion (or excess As). This may be caused by recoil implantation as proposed by Christel and Gibbons (118).

The other ion combination studied was Se + Sn. As already mentioned this pair of ions was particularly interesting because both ions act as donors when correctly located within the GaAs lattice. The only dose considered was $10^{14}$ ions cm$^{-2}$ of each ion, to produce an n$^+$ layer for the source and drain regions. Whilst a definite increase in the electrical activation was achieved, compared with Se or Sn only, the carrier concentration
profiles determined from the samples were very irreproducible. In order for correct site location of the implanted ions only short range diffusion is necessary, and it is probable that the determining factor in establishing the level of activation is the lattice location of the Sn ions, as these will tend to act as acceptors when located on Ga sites. It is thought, therefore, that local differences in rate of temperature rise and vacancy distribution may have caused variations in the incorporation of the Sn ions onto Ga sites, leading to the observed differences in electrical profiles.

Because of the variations from sample to sample the use of dual Sn + Se implants for device applications must be questionable, despite the observed decrease in resistivity observed in all of the samples measured.
5.3 Device Results

5.3.1 Selective Implants

Whilst the technique of selective implantation was not fully investigated due to fabrication difficulties, the attraction of this approach should not be overlooked. Two main advantages which selective implantation offers are:

(i) Selectively implanting the active region would avoid the need for mesa etching. This could lead to higher yields, avoiding the possible failure mechanism associated with metallising over the mesa edge. This technique would also allow FET fabrication in both the (100) and (010) directions, which is not possible with the current process as the selective etch used produces an undercut in the (010) direction due to preferential etching.

(ii) Selective n⁺ implantation of the source and drain regions would allow the ohmic contacts to be alloyed to highly doped material and provide a well defined edge to these regions. This technique would allow the ion dose in the channel region to be tailored so that no etching of the gate region would be necessary. This should lead to increased uniformity as it avoids the variable gate etch step, however it would lead to an increase in source-gate resistance, and would be most attractive only where the source to gate separation is minimised, for example with self-aligned gate technology.

A full investigation of selective implantation would require a re-designed mask set with additional masks to

(i) Define accurate alignment marks to ensure correct location of the metallisation and implantation masks.

(ii) Allow the source and drain, and active regions to be accurately defined, so that correct alignment of the ohmic Schottky metals could be achieved.
5.3.2 Device I-V Characteristics

The I-V characteristics of completed devices can be a useful guide to the quality of the implanted layers. In particular hysteresis (13), light sensitivity (13) and hardness of saturation (123) have been shown to be indicative of the deep level concentration present in the channel region, and an indication of the noise performance of FETs. In this study the devices produced on implanted buffer layers always displayed lower light sensitivity, harder saturation and less hysteresis than those fabricated on semi-insulating substrate material. It is believed that this reflects the somewhat poor quality of the Cr-doped semi-insulating material used, and highlights the need for the vast amount of research currently being undertaken in order to improve the quality of semi-insulating GaAs. Several workers have recently shown that improved device characteristics can be achieved using undoped semi-insulating material (124)(125), or chromium doped material grown under very well controlled conditions (126).

5.3.3 Uniformity of DC Characteristics

Whilst several slices demonstrated the possibility of achieving usable levels of transconductance ($g_m$) at suitable source-drain current levels ($I_{DSS}$) a considerable variation in $I_{DSS}$, $g_m$ and pinch off voltage was observed across most slices. In many cases the degree of variation was disappointingly high, as one of the major advantages offered by ion implantation as a doping technique is reduced spatial variation of doping level compared with epitaxial growth. Some of the possible causes of the observed non-uniformity are:-

(a) Non uniform implantation

(b) Non uniform heating during annealing.

(c) Poor alloying of ohmic contact, specifically mis-location of ohmic contact deposition with respect to highly doped/doped layers.
(d) Non uniform etching of gate recess.
(e) Variation of compensation levels across semi-insulating material.

RBS measurements of dose levels across large slices have shown the Surrey 500kev implanter to be capable of uniformities to within about 2%, and therefore any contribution to the observed variation may be considered to be negligible.

Non-uniform heating of slices is also thought to be of secondary importance. The thickness of nitride layers grown at the anneal temperature (900°C), would indicate gross variations in temperature, but in fact such layers were very uniform in thickness. Also as the material on which devices were processed was usually one centimeter square it is not thought possible for large variations in temperature to occur. It should be remembered that the electron concentration after annealing is relatively insensitive to temperature, as similar values of doping can be achieved after annealing in the range 850 - 1000°C.

Although non-reproducible alloying of ohmic contacts could have a contributory effect, this technology is well understood at Plessey, and it must be assumed in the first instance that any contribution from this source is small. Also, if this phenomenon was present it is more likely to result in a variation from slice to slice than a non-uniformity across a single slice. (For example slice IA7 did exhibit poor ohmic contacts, resulting in a complete loss of devices.) Non-uniform etching at the gate recess stage is a very definite possible cause of the observed variation. The etch used at this stage is very fast, the gate etch being performed in etch steps of only a few seconds duration. Problems associated with surface wetting, particularly through 1μm wide windows, and etchant removal would tend to aggravate what is already accepted to be a non-uniform process.
In order to separate non-uniformities caused by this step in the fabrication the saturated source drain current was measured prior to gate recessing on several later slices. Whilst this demonstrated that some slices were still non-uniform this technique could not be used where an n$^+$ implant was also performed, as the saturation levels were too high and burn out resulted. Measurement of the low field resistance (before saturation) was also attempted on these slices, but difficulties of achieving low probe resistances obscured the results.

The best uniformities produced in this study were on slice IA33 which was a buffer layer slice, and this perhaps is an indication of the main cause of the observed non-uniformities, that is variations in compensation levels across the semi-insulating material used. Superior uniformity results have recently been reported in the literature$^{(124)(125)}$, and in all cases it has been emphasised that the major contributing factor to the attainment of highly uniform implanted layers has been the careful selection of the substrate material. Furthermore, several authors have stated that good uniformities could not be achieved with commercially available GaAs, and stressed that in order to achieve the levels reported it was necessary to grow their own ingots under very carefully controlled conditions.

5.3.4 Microwave Results

The results of this study (Table (20)) indicate that the performance of MESFETs fabricated on implanted GaAs can be similar to, if not superior to, devices produced on good epitaxial material. In particular the noise figures of devices manufactured on implanted buffer layer material are significantly better than typical production devices. (2.7dB for implanted n$^+$/n devices compared with 3.5dB for similar epitaxial material, and 3.1dB for implanted n layers compared with 3.7dB for uniformly doped epitaxial material). The noise figures of devices
produced by direct implantation of bulk semi-insulating material tend
to be about 0.5dB worse than those produced on similarly implanted
epitaxial buffer layer material, although this is likely to depend significantly
upon the quality of the semi-insulating material. It is thought that
the high quality undoped material currently becoming available commercially
is likely to give superior results to that obtained with the chromium
doped substrates used in this study.

The maximum available gain levels achieved with implanted devices
tended to be slightly greater than those of uniformly doped epitaxial
material (8.2dB compared with 7.5dB) which is probably due to a slightly
higher doping level in the implanted slices, giving a slightly higher $g_m$.
In the $n^+$ on $n$ doped layers this situation was reversed, the epitaxial
material giving larger MAGs, (9.5dB compared with the best result of
8.8dB). This was almost certainly because the $n^+$ layer grown epitaxially
is usually about 0.5$\mu$m thick compared with only about 0.1$\mu$m in the
implanted material, giving a lower source-drain resistance. The exception
to this is the case of the selectively implanted devices where it is
thought alignment difficulties resulted in the gate being located very
close to the source.

The best measured associated gains in the implanted devices were
very similar to those expected from devices on good epitaxial material,
(5.2 and 5.5dB for the uniformly doped and $n^+$ on $n$ layers respectively).

To summarise it would appear that it is possible to produce devices
on implanted material with performance at microwave frequencies similar
to that achieved in good epitaxial material, provided good quality
substrates are used. The use of an implanted $n^+$ contact layer results
in improved performance, similar to that achieved with an epitaxial
highly doped layer.
The experimental work described in this thesis has been successful in three main areas.

(i) A reliable method of encapsulating ion implanted GaAs was developed. This was based on the chemical vapour deposition of silicon nitride using the pyrolitic decomposition of silane and ammonia. The substrate was heated to the growth temperature in about 6 seconds. Layers of Si$_3$N$_4$ approximately 1000 Å thick could be deposited in about 20 seconds. The variation of thickness of these layers over a one inch slice was ± 5%.

(ii) Fast thermal annealing (30 seconds at 900°C) was shown to be a reproducible and reliable method of annealing GaAs implanted with a variety of donor ions. High levels of activation, comparable with those reported in the literature for conventional furnace annealing, were achieved with several implanted species. The ions chosen for comprehensive study were:

(a) Selenium into substrates at room temperature and 200°C.
(b) Silicon into room temperature substrates.
(c) Germanium into substrates at 200°C.

Among the variables which were considered were implant energy and dose.

High dose implants of tin and tellurium were also studied. Dual ion implantation (Ga + Se, Se + Sn), and dual energy implants of selenium were examined as a means of producing tailored profiles suitable for FETs.

Whilst the majority of the experimental work was performed on chromium doped semi-insulating material from Materials Research, similar material from MCP, and epitaxial buffer layer material was also used. In general it was found that the MR material from ingot
A65R gave the best results, comparable to that obtained from n on semi-insulating epitaxial material.

(iii) It was shown that direct ion implantation into semi-insulating substrates could be used to provide the active layer for microwave MESFETs. The DC characteristics and microwave performance of these devices were similar to that achieved from devices fabricated on good epitaxial material. The best results achieved were from FETs fabricated on substrate material implanted with selenium at 100 and 800keV, giving a noise figure of 2.7dB with an associated gain of 5.6dB at 12.75GHz.
APPENDIX I

Comparison of $5 \times 10^{12} \text{cm}^{-2}$ Silicon Implants into Different Semi-Insulating Substates

Subsequent to the completion of the experimental work described in this thesis the author was involved in a pre-development exercise examining the use of implantation for the production of GaAs MESFETs, at the Philips Research Laboratories. The implantations were performed on a Lintott III accelerator, which has a maximum accelerating voltage of 200kV. This energy limitation, together with the necessity of room temperature implantation led to the necessity of investigating silicon as a donor ion. The implant dose was $5 \times 10^{12} \text{cm}^{-2}$ at 200keV.

A variety of substrates were chosen for study. These included MCP and MR chromium doped, MR undoped and epitaxial buffer layers. After implantation the substrates were coated with $\text{Si}_3\text{N}_4$ on an apparatus similar to that already described. One major difference is that the size of the carbon heater strip was 6" x 2½", and capable of producing uniform $\text{Si}_3\text{N}_4$ layers on complete 2 inch diameter slices. Annealing of the implanted material was also performed in the $\text{Si}_3\text{N}_4$ apparatus in the manner already described, i.e. $900^\circ\text{C}$ for 30 secs.

The results of this investigation are interesting in that in all the material studied high levels of activation (60-80%) of the implanted silicon ions was achieved, although the actual level was observed to vary from substrate to substrate. The lowest levels were measured in the MCP Cr-doped material. This high level of activation is in contrast to the results reported for low dose Si implants reported previously in this study. It is significant that great care was taken in ensuring the purity of the silicon beam, in one case three days of constant running of the silicon source in a hydrogen discharge was required to obtain the correct abundances of the $\text{Si}^{28}$, $\text{Si}^{29}$ and $\text{Si}^{30}$ isotopes.
The Si$^{29}$ isotope was then implanted to the required dose.

In figure (63) the I-V curves measured on FETs fabricated on three different substrates are shown. The FETs processed on MCP Cr doped material were similar to those on MR Cr doped material, displaying hysteresis, light sensitivity and soft saturation. The devices processed on implanted buffer layers, and MR undoped semi-insulating material displayed improved results for all the above parameters, indicating that undoped material can be used as an effective substrate for implanted FETs.
A. MCP Cr Doped

B. MR undoped

C. Epitaxial Buffer Layer

All curves
5mA/div vert.
1V/div horiz.
1V gate steps.

Fig. 63 I-V Characteristics of Si Implanted FETs on Different Substrate Materials.
APPENDIX II

Device Uniformity over 2" Implanted Slices

As part of a development exercise at the Philips Research Laboratories slices from a large number of different MR undoped GaAs ingots have been investigated for uniformity of device results. The implant dose was \( 5 \times 10^{12} \text{ Si}^+ \text{ cm}^{-2} \). The samples were encapsulated with \( \text{Si}_3\text{N}_4 \) and annealed at 900°C in the same coating unit. Because of the large thermal capacity of two inch slices it was necessary to increase the total anneal time to two minutes to ensure complete annealing over the entire slice.

After annealing pairs of ohmic contacts (the source and drain of the final FETs) were deposited over the entire slice and annealed. After MESA etching to isolate individual devices the saturation current \( (I_{DSS}) \) between the contact pairs was measured. These were then plotted as across slice distributions, and histograms. The amount of variation of \( I_{DSS} \) across two inch slices was observed to vary significantly from ingot to ingot. The results shown in figure (64) were obtained on a slice from a 'good' ingot, and not only displayed a high level of uniformity over a two inch diameter slice but gave good microwave results.

It is significant that comparable results were not obtained from any chromium doped material, the results obtained in this case being more similar to those reported previously in this thesis. This tends to support the hypothesis, proposed in Chapter 5, that the degree of non-uniformity observed in devices produced in Cr doped semi-insulating material was largely caused by the quality of the material itself.
SCATTER DIAGRAM

Test No. 767/1  Ideo @ 5 volts (mA)

KEY
1. <80
2. 80-<83
3. 83-<100
4. 100-<120
5. 120-<150
6. 150-<170
7. 170-<200
8. 200-<220
9. 220-<250

Fig. 64 Uniformity of $I_{DSS}$ Results over 2 Inch Diameter Undoped GaAs Slice.
REFERENCES

3. 1982 GaAs IC Symposium Technical Digest.


124. C.A. Stolte, ibid. p.93.