

**SEM CONDUCTIVE MODE ANALYSIS
OF MICROELECTRONIC MATERIALS**

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ABSTRACT

The scanning electron microscope (SEM) conductive mode of analysis is useful for both qualitative and quantitative characterization of defects, surface phenomena and minority carrier behaviour in semiconducting materials. For the present work certain silicon materials were especially designed and fabricated for the purpose of determining the surface recombination velocity and minority carrier diffusion length using Donolato's equations. In addition a commercially fabricated GaAs bipolar transistor was examined using the conductive mode. This structure revealed new conductive mode phenomena that are significant for devices with more than one charge collection barrier.

Conductive mode (or electron beam induced current, EBIC) studies on silicon p-n junctions revealed a strong beam induced change in the form of the EBIC linescan across cleaved, p-type Czochralski silicon. An apparent dose rate dependent effect resulted in collection of almost all the generated electron-hole pairs at distances far from the junction. This is explained by a beam induced surface charge which produces a surface inversion layer that acts as a charge collection barrier. An experimental method was developed whereby beam induced surface effects can be systematically minimized.

EBIC linescans over cleaved silicon p-n junctions revealed that Donolato's models can be fitted to experimental data quite satisfactorily for 2, 3 and 8.5 ohm-cm p-type Czochralski silicon for beam voltages in the range 6-25 kV. Donolato's equations were solved numerically by writing a Pascal computer program.

Further experimental work is reported which characterizes in detail the shape of EBIC linescans under high magnification at the p-n junction for conditions of reverse bias up to 20 volts. A new theoretical model is proposed to describe this behaviour which uses both a Monte Carlo simulation and Donolato's equations. The new model resulted in a good

approximation to experimental data when the beam voltage ≥ 15 kV.

Conductive mode analysis of a GaAs bipolar transistor led to new techniques for examining defects in devices with more than one charge collection barrier. This resulted in an improvement in both spatial resolution and depth resolution of recombination centres.

Dedication

To the most Senior Engineer, the Master Craftsman who has designed and fabricated everything, seen and unseen.

For since the creation of the world God's invisible qualities - His eternal power and divine nature - have been clearly seen, being understood from what has been made, so that men are without excuse.

Romans 1:20

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INTRODUCTION

The scanning electron microscope (SEM) is an established analytical tool that is common in the microelectronics industry. The most familiar kind of electron micrograph is the emissive mode image produced by collecting secondary electrons from the specimen. This is principally used as an extension to optical microscopy whose magnification is limited due to the wavelength of visible light.

Instead of secondary electrons, the SEM conductive mode uses electron-hole pairs, generated in the specimen, as a signal to construct an image. Many electron-hole pairs are generated per incident primary electron since the electron-hole pair formation energy is much less than the SEM accelerating voltage.

Conductive mode microscopy takes advantage of a minority carrier detector in the specimen itself, referred to as the charge collection barrier. Charge collection barriers are usually p-n junctions or Schottky barriers. The electrons and holes created by the electron beam can induce a voltage or current across the charge collection barrier which is amplified in an external circuit. This induced signal is commonly referred to as the electron beam induced current (EBIC) or electron beam induced voltage (EBIV) depending on whether the short circuit current or open circuit voltage is the signal of interest.

Conductive mode microscopy is of considerable interest since contrast arises from non-uniformity in the generation and recombination of electron-hole pairs. Therefore it can be used for determination of minority carrier lifetime and diffusion length. It is also capable of imaging recombination centres such as precipitates and decorated dislocations not visible with either optical or emissive mode microscopy.

SEM conductive mode analysis is an attractive analytical technique because it is easy to

implement and does not require complicated specimen preparation. It is also convenient since it is done using the same SEM that is used for emissive mode microscopy, needing only an additional current amplifier.

Although the conductive mode has been used for nearly 25 years (Lander *et al*, 1963), it is not widely used as an aid to device fabrication and failure analysis in the microelectronics industry. This may be due in part to the fact that much of the published work concerning conductive mode analysis deals with devices that have only a single charge collection barrier. In addition, some workers report that determination of the minority carrier diffusion length is dependent on SEM parameters such as beam power, scan speed and dose rate (Bresse 1977, Davidson 1982, Marten and Hildebrand 1983, Hungerford and Holt 1987, and Castaldini *et al* 1987).

In the work that follows, the SEM conductive mode analytical technique has been extended in two ways. First, a thorough investigation of minority carrier diffusion length was undertaken for the purpose of determining the validity of a particular theoretical approach by Donolato (1982). His mathematical treatment is an easier method of finding diffusion length and surface recombination velocity than those previously proposed (van Roosbroeck 1955, Berz and Kuiken 1976). During this investigation special attention was paid to any effects that might yield variable results in the determination of diffusion length and surface recombination velocity.

In addition, a detailed conductive mode characterization of a GaAs bipolar transistor was done in order to establish a basis for predicting EBIC behaviour in devices with more than one charge collection barrier. These principles were then applied to qualitative analysis of process induced defects in the GaAs material which was fabricated using molecular beam epitaxial deposition (MBE).

1.0 PRINCIPLES OF CONDUCTIVE MODE ANALYSIS

1.1 Specimen Properties

1.1.1 Charge Collection Barriers

The most common charge collection barriers for the SEM conductive mode are p-n junctions or Schottky barriers. When a p-type and n-type material are brought into contact, bending in the conduction and valence band provide an electric field in the depletion region. This is called the diffusion potential and is shown in figure 1.1.1. Minority carriers that drift or diffuse to the depletion region will be accelerated across due to the built-in electric field. If there are an excess number of minority carriers arriving from one side of the junction, there will be a net current flow in the same direction as reverse leakage current.

Excess minority carriers will be produced when a high energy electron beam is focussed onto material on one side of the junction. If the p-type and n-type regions are short circuited externally, a short circuit current, I_{sc} , is obtained. This process is due to the electron voltaic effect which is analogous to the photovoltaic effect.

The diffusion potential, V_{bi} , of a p-n junction can be calculated from the doping densities and is given by

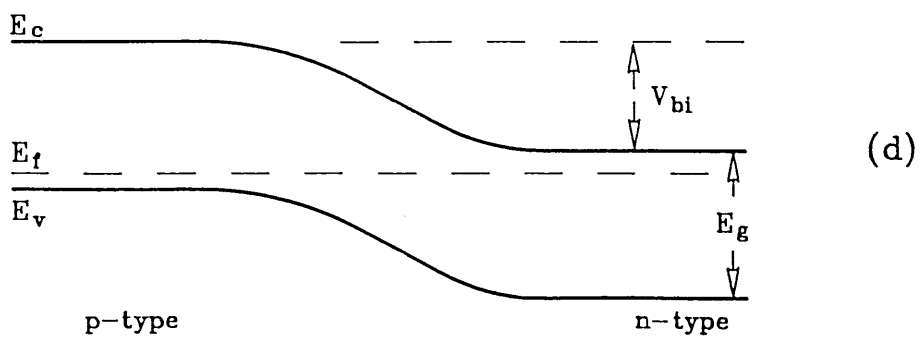
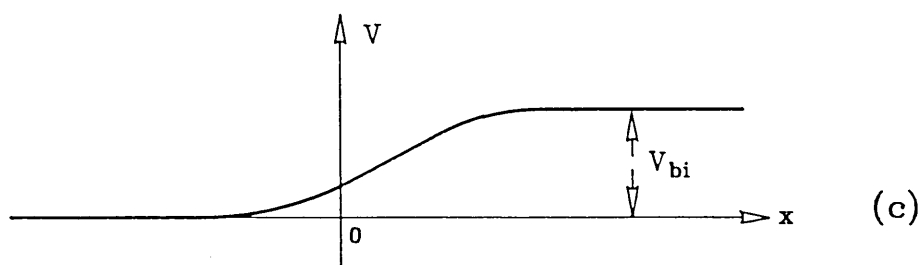
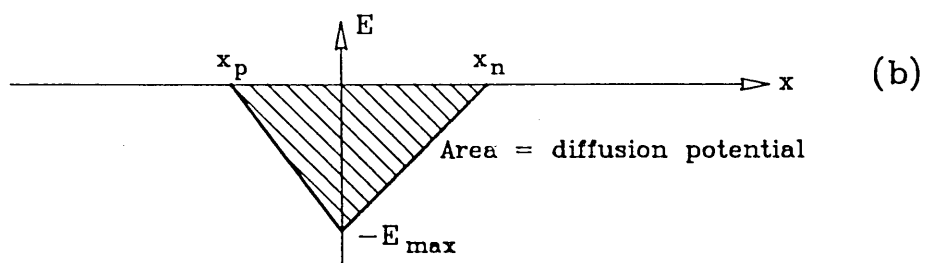
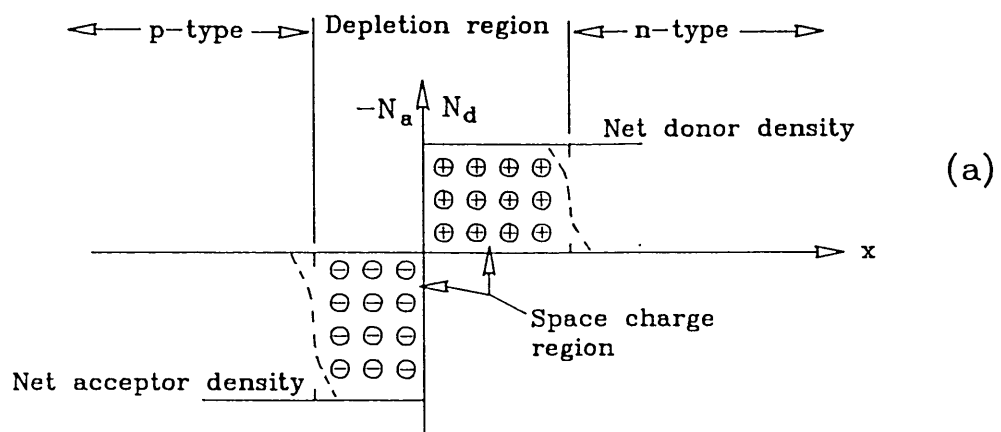
$$V_{bi} \approx kT/q \ln(N_a N_d / n_i^2) \quad (1.1.1)$$

where kT/q = thermal voltage = 0.026 V at 300° K

N_a = acceptor impurity concentration

N_d = donor impurity concentration

Figure 1.1.1. Abrupt p-n junction. (a) Space charge region; the dashed lines represent the majority carrier distribution tails. (b) Electric field distribution. (c) Potential variation with distance, where V_{bi} is the built-in potential. (d) Energy band diagram showing band bending.



n_i = intrinsic carrier concentration, cm^{-3}

The intrinsic carrier concentration is a function of the temperature and the bandgap, E_g , and is given in silicon by (Ong, 1986)

$$n_i = 3.9 \times 10^{16} T^{3/2} \exp(-E_g/2kT)$$

The depletion region width for a two-sided abrupt junction will be increased under reverse bias. This can be found from the diffusion potential by (Sze, 1981)

$$W = [2\epsilon_0\epsilon_s/q ((N_a+N_d)/(N_aN_d)) (V_{bi} - 2kT/q + V_r)]^{1/2} \quad (1.1.2)$$

where ϵ_s = dielectric constant of the semiconductor

ϵ_0 = permittivity of free space = 8.85×10^{-12} F/m

V_r = bias voltage, positive if reverse bias.

k = Boltzmann's constant

q = charge on an electron

T = temperature, °K

The $-2kT/q$ term arises due to the majority carrier distribution tails (see figure 1.1.1 (a)). The position of the depletion region edges can be calculated from a simple proportion which depends on the relative doping densities of the two materials according to

$$W_n = W (N_a/(N_a+N_d))$$

where W_n is the width of the depletion region on the n-type side of the junction

Table 1.1.1 shows some depletion region widths for selected semiconductor materials calculated according to equation 1.1.2.

Table 1.1.1. Depletion region widths for selected homojunctions at zero volts bias.

<u>Material</u>	<u>p-type doping</u>	<u>n-type doping</u>	<u>W, μm</u>
Si	1.5×10^{15}	6×10^{14}	1.25
Si	5.0×10^{15}	6×10^{14}	1.15
Si	6.7×10^{15}	6×10^{14}	1.14
GaAs	1.0×10^{18}	2×10^{17}	0.11
GaAs	1.0×10^{18}	1×10^{16}	0.42

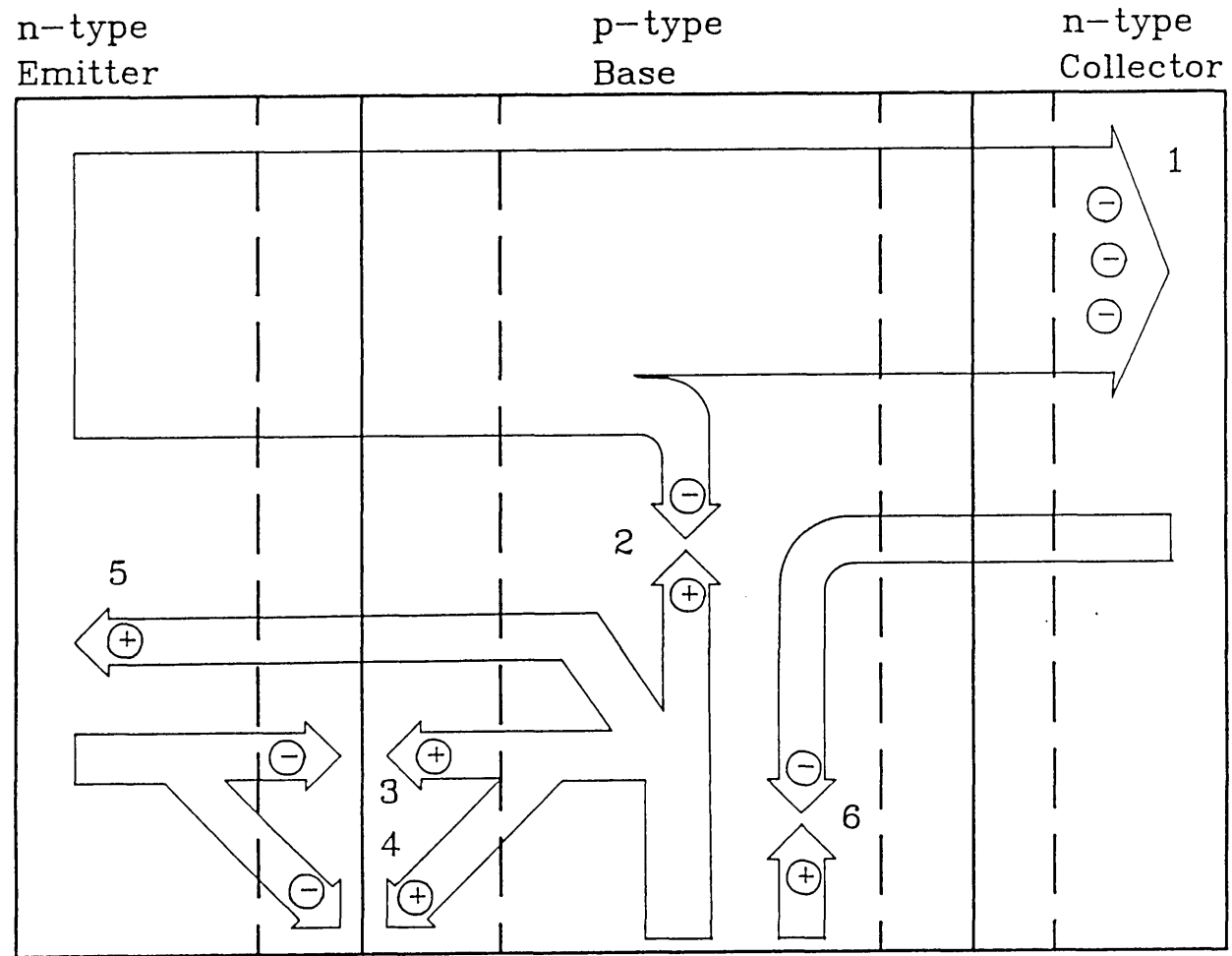
The principles of straightforward conductive mode analysis of devices with a single charge collection barrier is outlined in section 1.2 and reviewed in detail by Leamy (1982) and Holt and Lesniak (1985).

In practice, microelectronic devices rarely come in the form of a simple power diode. Conductive mode analysis of more complex electronic structures is useful. However theoretical treatments of electron beam induced carrier behaviour in devices with two or more charge collection barriers are rare (Gonzales, 1974).

Planar bipolar transistors are a good example of a structure that abounds with charge collection barriers, but the behaviour of its conductive mode signal has not been well characterized. Bipolar transistors are frequently plagued with recombination centres that consume power and degrade the gain. Conductive mode analysis is ideally suited for identifying the location and strength of subsurface recombination centres.

The basic DC operation of a bipolar transistor can be explained briefly with the aid of the schematic diagram in figure 1.1.2. The bipolar transistor relies for its operation on the

Figure 1.1.2. Schematic diagram of bipolar transistor operation.
Components of current flow labeled 1-6. Holes = '+', electrons = '-'
[after Hayes, 1984].



transport of minority carriers. The main components of current flow are labeled 1 through 6 in figure 1.1.2 which shows an n-p-n device. When a forward bias is applied to the emitter-base junction, electrons are injected over the potential barrier into the base region. Most of these electrons move under the influence of drift and diffusion to the edge of the depletion region at the collector end of the base. These are immediately swept into the collector by the high electric field of the depletion region. A simple relationship between the emitter-base voltage and the collector current is given by

$$I_C = I_S \exp(qV_{be}/kT)$$

where I_C = collector current

V_{be} = emitter-base forward bias voltage

and I_S is some saturation current that is characteristic of the device and the operating temperature.

Therefore small variations in the emitter-base voltage control large variations in the flow of current from emitter to collector labeled as current 1 in figure 1.1.2. The penalty to be paid for this control is the flow of current into the base region through the base contact. Normally this current is smaller than the collector current so the device provides current amplification. The gain of the device is defined as $\partial I_C / \partial I_B$; essentially the collector current over the base current. The device is designed so that this is a constant in the active region of operation and amplification is virtually linear.

The base current originates from several processes the most important of which are labeled as 2, 3, 4, 5 and 6 in figure 1.1.2. Current 2 represents a flow of holes recombining in the base with some of the electrons from the main collector current flow. 3 and 4 represent recombination processes occurring in the bulk and at the surface of the emitter-base depletion region. Current 5 is due to the injection of holes into the emitter across the forward biased

depletion region. This is the most important process and is the limiting constraint on DC performance.

Schick (1981) reports a successful conductive mode examination of a piped planar silicon bipolar transistor leading to the identification of the emitter-collector pipes. These appeared as dark spots when observing the EBIC signal across the base-collector junction. According to Schick they occur mainly in pairs. Subsequent transmission electron microscopy indicated dislocation loops associated with the pipes, originating at or near the surface, and extending more than 5 μm below the surface.

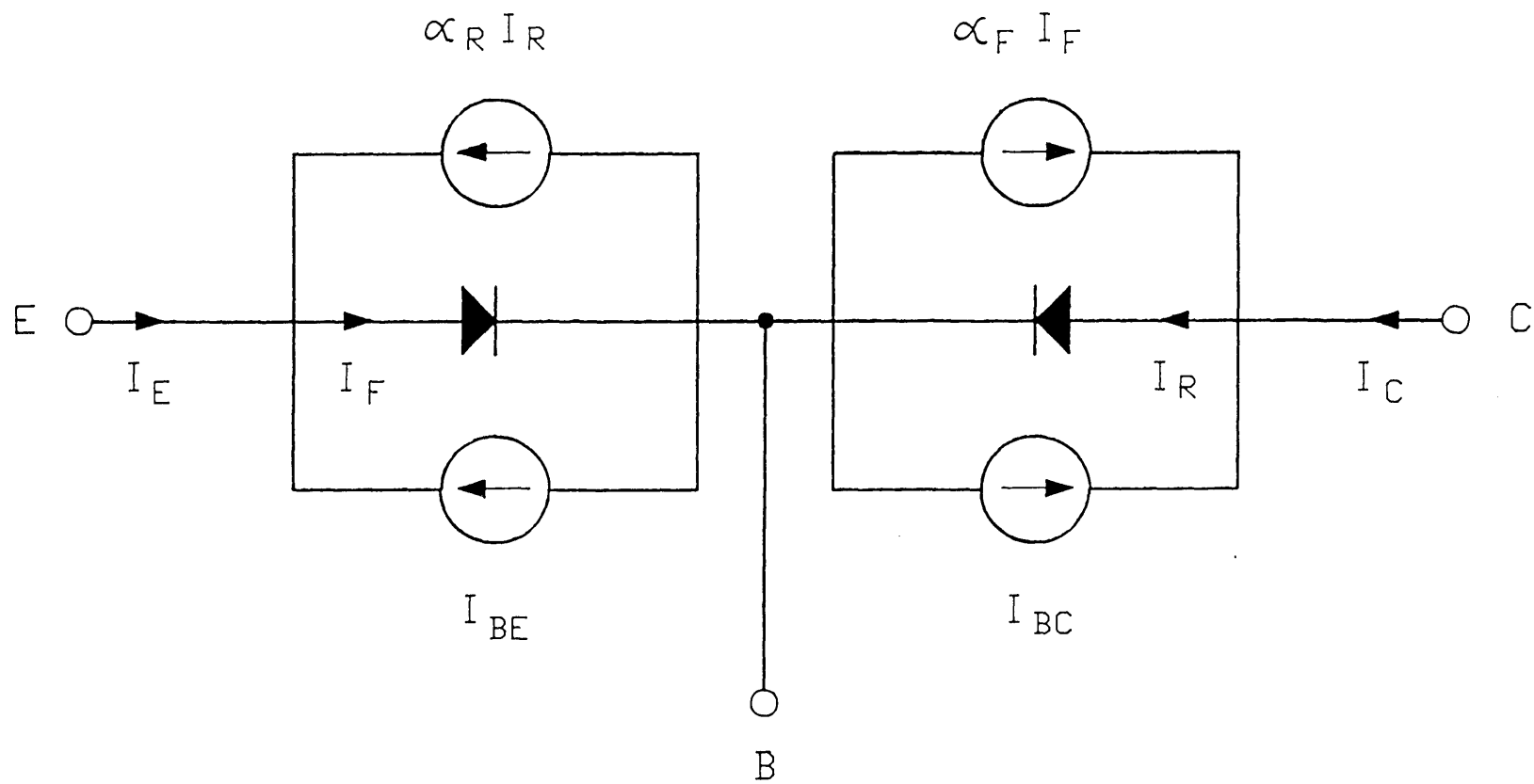
Gonzales (1974) predicts general quantitative trends for the various wiring permutations for extraction of the conductive mode signal from a planar bipolar transistor. He points out that that for the case where the EBIC is taken across the base-collector junction with the emitter shorted to the base (abbreviated C-EB), a signal should not be seen until the beam voltage is high enough to penetrate to the base-collector depletion region. Gonzales also asserts that an EBIC signal can be induced by a neighbouring junction. For example if the EBIC is taken across the base-collector junction (as above) except the emitter is allowed to float, (abbreviated B-C), the resulting EBIC signal will be composed of the normal collector EBIC signal, I_{bc} , plus an injected signal from the emitter, I_{be} , where

$$\text{C-B EBIC} = I_{bc} + \alpha_f I_{be} \quad (1.1.3)$$

This equation is derived from Gonzales' modified Ebers-Moll model shown in figure 1.1.3. The second term of equation 1.1.3 arises from the floating emitter as it becomes forward biased by the carriers collected at the emitter-base junction. This in turn results in the normal forward injection of carriers into the base region and subsequent collection by the base-collector junction.

Another configuration treated by Gonzales (1974) is that where two junctions are in series

Figure 1.1.3. Modified Ebers-Moll diagram showing current components of a transistor when irradiated with an electron beam. $\alpha_R I_R$ and $\alpha_F I_F$ are components of EBIC current induced by the open circuit voltage on the opposite diode. One of these components will be significant when either the emitter or collector contact is allowed to float. [after Gonzales, 1974]



such that the same type material is found in the common connection. This could occur when two Schottky diodes are in series or in observing the current between the collector and emitter contacts of a bipolar transistor. Gonzales gives a complex mathematical expression for the emitter-collector EBIC current as a function of several transistor parameters which is beyond the scope of the present work. However, he does point out that the contribution to the EBIC signal by each of the junctions is in the opposite direction and the overall signal will be greatly reduced. This means that one junction will be forward biased and its contribution reduced while the other is reverse biased and will produce a normal EBIC signal.

This configuration is interesting since the two junctions are effectively 'competing' with each other for domination of the direction of the EBIC signal. It is proposed in the present work that the dominating junction is determined by two factors; the diffusion potentials and the volume of excess minority carriers reaching the respective depletion region edges. A simple application of this should be observed at low beam voltages when electron-hole pairs are created in the emitter only. The direction of the EBIC should be determined by the emitter-base junction since it is the only junction collecting excess minority carriers. The direction of the EBIC should change as the electron beam voltage increases and more electron-hole pairs are generated nearer to the base-collector junction.

Ultimately it should be possible to qualitatively examine a device at the beam voltage where both junctions contribute the same amount to the EBIC signal whose net value should be about zero. Under these conditions the contrast of recombination centres in either the emitter or collector will be greatly enhanced because they will result in a sharp change in the direction of the conductive mode signal and not simply a fractional reduction. Moreover, the approximate location of these defects can be identified by the polarity of the resultant EBIC signal.

1.1.2 Properties of Silicon

Certain important properties of silicon can be either measured or predicted based on empirical relationships. The primary parameter of interest in single crystal semiconductor device quality silicon is the doping density. Assuming that the doping is uniform, it can be measured indirectly by measuring the bulk resistivity using a four point probe. The four points of the probe are equally spaced in a straight line about 0.5 cm long. A small current from a constant current source is passed through the outer two probes and the voltage is measured between the inner two probes. The bulk resistivity is found from (Sze, 1985)

$$\rho = (V/I) \times (d) \times (CF)$$

where I = current across outer probes

V = voltage measured across inner probes

d = substrate thickness

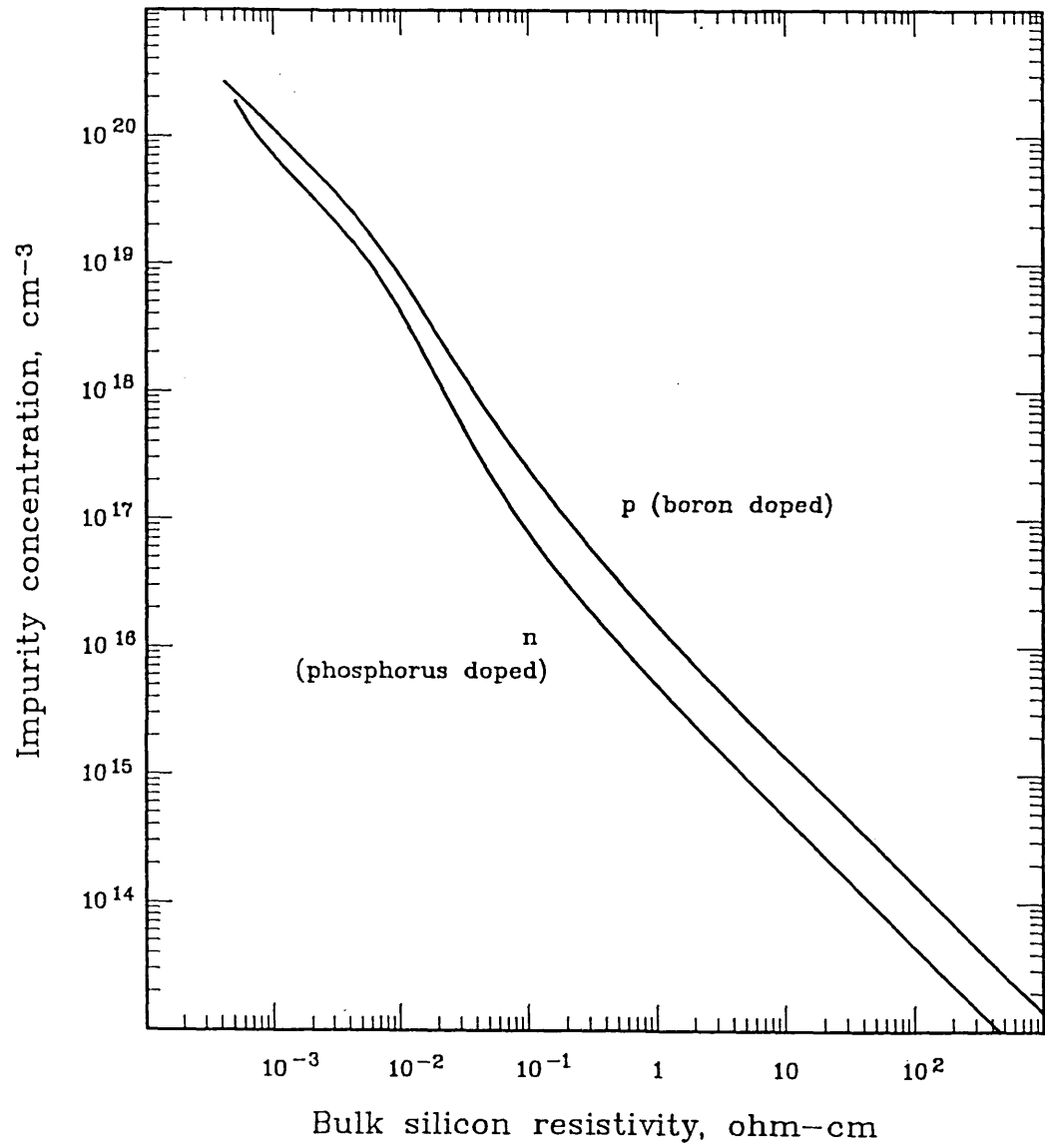
CF = correction factor

The correction factor is a function of the probe spacing and the distance from the probes to the edge of the silicon. This correction factor is given by Sze (1985, figure 6, p. 37) but is generally included in the literature supplied with the purchase of a four point probe. More commonly the correction factor is included in the resistivity reported by the four point probe. This will be the case if the wafer diameter is required as input by the probe before a measurement is made.

The ionized impurity concentration or doping density can be determined from the bulk resistivity from empirical data like that of figure 1.1.4. This is sometimes referred to as Irvin's curve after the man who first published an empirical curve of this sort (Irvin, 1962)

The majority of all single crystal bulk silicon substrates intended for microcircuit fabrication

Figure 1.1.4. Silicon ionized impurity concentration as a function of resistivity, sometimes called Irvin's curve. [after Thurber, Mattis, Lin, and Filliben, 1981]



are produced by the Czochralski process (abbreviated Cz). In this process a long boule of silicon is slowly pulled from a molten crucible using a seed crystal. Impurities such as phosphorus or boron are introduced into the melt to give very uniform doping densities. This process has been well characterized and wafers cut from a Cz boule have predictable properties.

One such property is the minority carrier lifetime, τ , given for electrons in p-type semiconductor (for example) by

$$\tau_e = 1 / (\sigma_e v_{th} N_t) \quad (1.1.4)$$

where v_{th} = thermal velocity

σ_e = trap cross-section, electrons in p-type

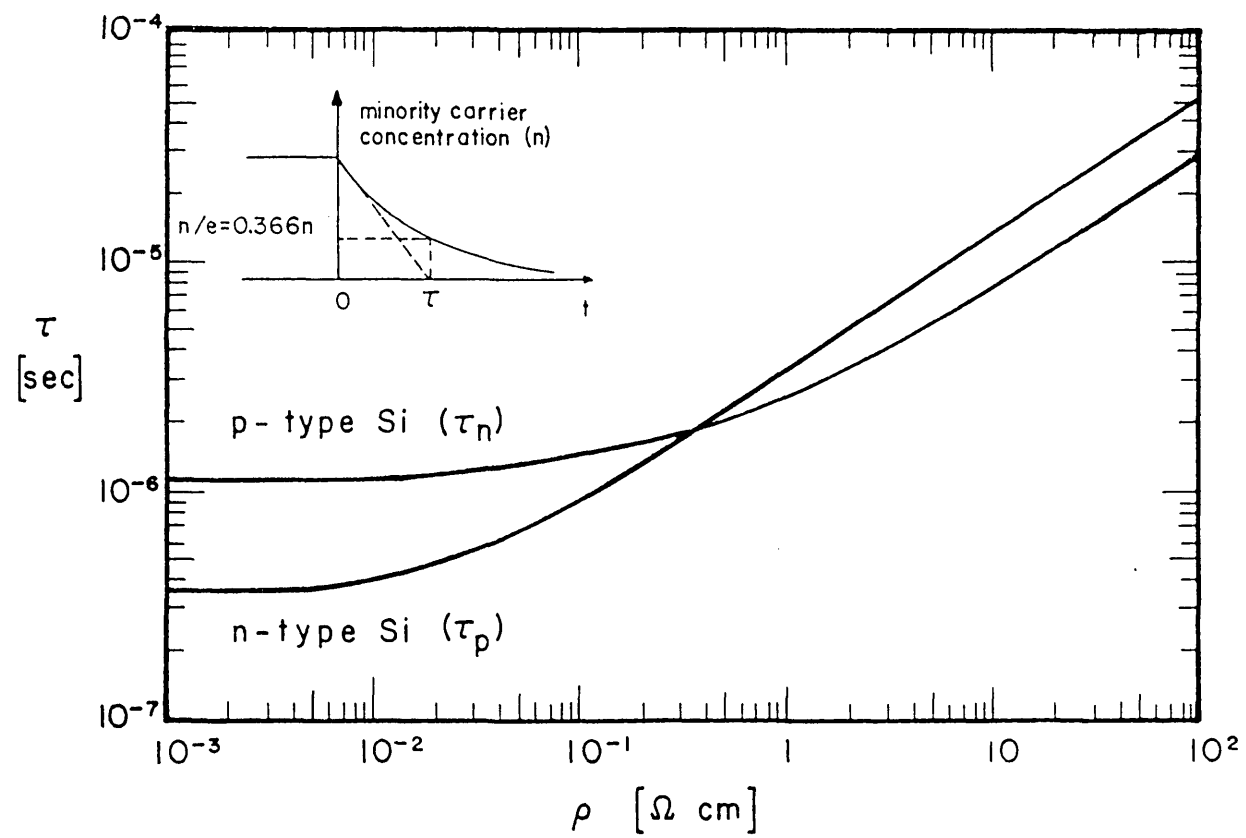
N_t = trap density, cm^{-3}

The minority carrier lifetime would be nearly infinity if it were not for localized states in the lattice that first capture the minority carrier and then capture a majority carrier. This is called a trap and recombination can take place at this location because the carriers do not have to overcome a difference in momentum as is the case for band to band recombination in an indirect gap semiconductor like silicon. Ionized impurity atoms act as traps as do imperfections in the crystal lattice. The traps in Czochralski grown silicon however, are almost entirely attributable to the impurity atoms due to the high degree of crystallographic perfection achieved by this process. Therefore the minority carrier lifetime can be obtained from the empirical data of Wolf (1969) shown in figure 1.1.5.

The minority carrier diffusion length is related to the lifetime by

$$L_e = \sqrt{D_e \tau_e} \quad (1.1.5)$$

Figure 1.1.5. Minority carrier lifetime as a function of bulk, Cz grown silicon resistivity. Lifetime, τ , is the time at which $1-1/e$ of the excess carriers have recombined. Curves based on empirical data from Wolf (1969).



where the subscript refers to the case of electrons in p-type material. The diffusion constant is found from Einstein's relation

$$D_e = \mu_e kT/q \quad (1.1.6)$$

The mobility, μ_e (for electrons in p-type material) or μ_h , in cm^2/Vsec can be found from the doping density, N , using an empirical relation for either n-type or p-type material at 300°K given by Bar-Lev (1984)

$$\mu_e = 1350 [1 - (0.933 N_a^{0.91}) / (N_a^{0.91} + 3.75 \times 10^{15})] \quad (1.1.7)$$

$$\mu_h = 480 [1 - (0.9 N_d^{0.76}) / (N_d^{0.76} + 5.85 \times 10^{12})] \quad (1.1.8)$$

Minority carrier lifetimes and diffusion lengths for some selected silicon materials are summarized in table 1.1.2. These were found from equations 1.1.5 through 1.1.8 using figures 1.1.4 and 1.1.5 and will be important later.

Table 1.1.2. Minority carrier lifetimes and diffusion lengths of selected silicon materials.

<u>Bulk resistivity</u>		<u>Doping density</u>	<u>Min. carrier lifetime</u>	<u>Min. carrier diff. length</u>
8.5 ohm-cm	(p)	$1.5 \times 10^{15} \text{ cm}^{-3}$	$5.53 \times 10^{-6} \text{ sec}$	138 μm
2.8	(p)	5.0×10^{15}	2.87×10^{-6}	98
2.0	(p)	6.7×10^{15}	2.55×10^{-6}	92
7.5	(n)	6.0×10^{14}	1.17×10^{-5}	130

The surface of a semiconductor also acts to promote recombination. As mentioned previously, a lattice defect can act as a recombination centre because it provides interband

energy levels that act as traps. The surface of a semiconductor is essentially one enormous lattice defect with a very high density of dangling bonds. In practice it is rarely atomically clean in that it will contain a host of other species such as silicon oxides on silicon. These arise from contact with the environment, such as the atmosphere for a cleaved silicon face.

Recombination at the surface is analogous to recombination in the bulk material except that the density of traps is thought of in units of traps/cm² instead of traps/cm³. The total number of carriers recombining at the surface per unit area per unit time is given for p-type silicon by (Sze, 1985)

$$U_s \approx (\sigma_e v_{th} N_{ts}) (n_s - n_{p0})$$

where v_{th} = thermal velocity

σ_e = capture cross-section for electrons

N_{ts} = trap density, cm⁻², at the surface

n_s = electron concentration at the surface

n_{p0} = equilibrium density of electrons in p-type Si

This is analogous to the bulk recombination rate which is expressed in numbers of carriers recombining per unit volume per unit time where the trap density is in units of cm⁻³. Thus the term $(\sigma_e v_{th} N_{ts})$ is the equivalent of the lifetime in the bulk, except it is in units of distance per unit time and is called the surface recombination velocity, v_s .

1.2 Electron Beam Induced Current (EBIC)

1.2.1 Principles of Qualitative Conductive Mode Analysis

A focussed electron beam scanning a specimen containing a p-n junction or Schottky barrier will generate electron-hole pairs. Some of these will be separated by the depletion region via the electron voltaic effect. This electron beam induced current can be detected and amplified in an external circuit. The amplified signal can then be used to drive the grid of a CRT that is scanned in rigid synchronization with the beam probe; the pixel intensity being proportional to the amplified short circuit current. As a result, an image is created whose source of contrast is the degree to which the amplified electron beam induced current is not homogeneous across the specimen.

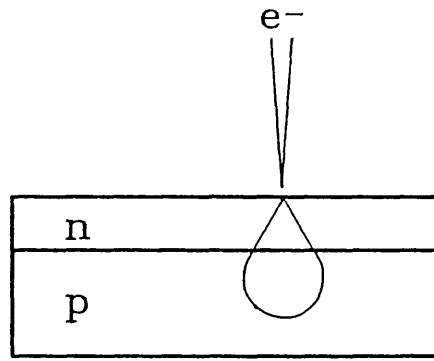
The electron voltaic effect was first reported by Ehrenberg and Gibbons (1951). The electron beam induced current was first used to drive a CRT and obtain an image by Lander, Schreiber, Buck and Mathews (1963). There are many sources of conductive mode contrast which are due to generation, recombination, multiplication, diffusion or separation of beam induced carriers.

The three most common specimen scanning geometries used in conductive mode analysis are shown in figure 1.2.1. The mechanisms for carrier generation, recombination and separation are essentially the same for conductive mode SEM as they are for normal photovoltaic operation of an optoelectronic device.

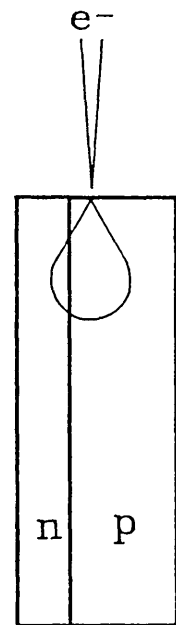
1.2.2 Principles of Quantitative Conductive Mode Analysis

When an electron beam is scanned across a p-n junction as shown in figure 1.2.1(b), an electron voltaic effect results. Minority carriers generated by the beam are subject to

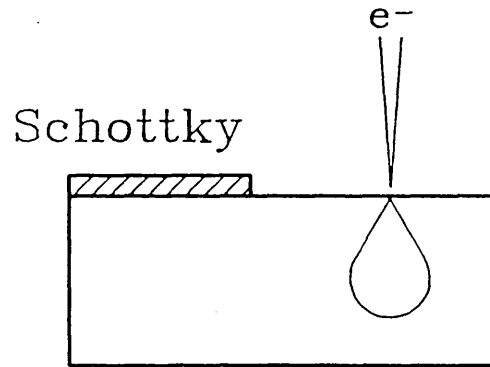
Figure 1.2.1. Three common specimen scanning geometries used for conductive mode analysis.



a)



b)



c)

recombination before they diffuse to the charge collection barrier. The carrier density at any location in the semiconductor is given (for electrons in p-type material) by the continuity equation

$$D\nabla^2(\Delta n) - \Delta n/\tau + G = 0$$

where Δn = injected electron density

G is the generation rate of electron-hole pairs per unit volume and is treated in more detail in section 1.3. The second term is the recombination rate of minority carriers due to their finite lifetime. The continuity equation is simply a way of accounting for the creation, recombination and collection of excess minority carriers.

By making the assumptions that the generation volume is a sphere of uniform generation rate and that there is no recombination at the surface, the continuity equation can be integrated over the plane of the junction to give (Wittry and Kyser, 1964)

$$I_{sc} = I_{max} \exp(-x/L_e) \quad (1.2.1)$$

where x = distance from incident beam to
edge of depletion region

L_e = minority carrier diffusion length

I_{max} is the total number of electron-hole pairs generated per unit time. It is important to adequately define this value since conductive mode experimental results are frequently reported in dimensionless units of I_{sc}/I_{max} . I_{max} is the current that would be obtained with 100% charge collection and can be expressed by

$$I_{max} = (V_b/e_i) I_b (1-\kappa f) \quad (1.2.2)$$

where V_b = electron beam accelerating voltage
 e_i = electron-hole pair formation energy
 I_b = electron beam current
 f = backscatter coefficient

κ represents the energy spectrum of backscattered primaries and is given by Sternglass (1954) as a function of atomic number;

$$\kappa = E_{bs}/V_b = 0.45 + 0.002 Z$$

where E_{bs} is the average energy of a backscattered primary. This expression is valid for $200 \text{ eV} \leq V_b \leq 32 \text{ keV}$. Czaja (1966) reports that f is a constant = 16.2% and that κ is not a function of V_b . The $(1-\kappa f)$ term determined in this way is 0.92 for silicon. More recently Hanoka and Bell (1981) report a $(1-\kappa f)$ term determined by Matsukawa *et al* (1973) and Goldstein (1977) as 0.90 for silicon and 0.77 for GaAs.

It is also possible to predict the $(1-\kappa f)$ term using the Monte Carlo simulation described by Napchan and Holt (1987) from the total backscattered energy calculated by the program. This was done for both silicon and GaAs where $(1-\kappa f)$ was found to be 0.89 and 0.78 respectively.

Fiebigler and Muller (1972) determined e_i using the Haynes-Shockley technique and found $e_i = 3.64 \pm 0.02 \text{ eV/pair}$ which is in good agreement with a host of other workers. Various experimentally determined values of e_i are reviewed briefly by Wu and Wittry (1978) who also determine e_i using the SEM conductive mode.

Another form of equation 1.2.1 that accounts roughly for recombination in the depletion region is

$$I_{sc} = I_0 \exp(-x/L_e) \quad (1.2.3)$$

where I_0 is the experimentally observed maximum in the short circuit current. However equation 1.2.3 still does not take into account recombination at the semiconductor surface. While some workers report experimental results in dimensionless units of I_{sc}/I_{max} , most report experimental results in units of I_{sc}/I_0 . This is done for the purpose of making a comparison to theoretical relationships that assume there is no recombination in the depletion region. There is an embedded assumption in equation 1.2.3 that a constant fraction of carriers that diffuse to the depletion region recombine inside of it. By expressing the short circuit current in terms of the observed maximum short circuit current, the relationship only attempts to describe carrier recombination outside the depletion region as the normalized maximum is 1.

The simple exponential relationships in equations 1.2.1 and 1.2.3 are not accurate models of carrier collection for small values of x (Marten and Hildebrand 1983, Kuiken and van Opdorp 1985) and when the energy dissipation volume overlaps one or both edges of the depletion region. Moreover, theoretical treatments that give I_{sc} as a function of x by taking surface recombination into account, incorporate inconvenient mathematical relationships such as Green's function and modified Bessel functions (van Roosbroeck 1955, Berz and Kuiken 1976). These models predict that v_s will have a proportionately greater effect at values of $x < L_e$. As a result a plot of $\log(I_{sc})$ vs. x should not be a straight line near the junction, but should be concave upwards (van Roosbroeck 1955, Davidson *et al* 1982, Donolato 1982)

Two such relationships for the short circuit current proposed by Donolato (1982) avoid the use of modified Bessel functions used by Berz and Kuiken (1976). Donolato's solution of the continuity equation is of the form

$$\int_0^\infty dx \int_0^\infty h(x,z) Q(x,z) dz \quad (1.2.4)$$

where $Q(x,z)$ is the carrier collection probability at depth z and distance x from the plane of the junction. $Q(x,z)$ is simply the probability that a minority carrier at some location will diffuse to the junction and appear as short circuit current. The short circuit current can be obtained by multiplying the number of minority carriers generated by $Q(x,z)$ at that point. If the electron beam is viewed as a point source at depth z_0 below the surface, the short circuit current as a function of x is given by

$$I_{sc} = Q(x, z_0) I_{max}$$

for the case when recombination in the depletion region is ignored. $h(x,z)$ is the two dimensional beam induced minority carrier distribution as a function of distance, x , from the plane of the junction and depth, z , below the surface. For the configuration of figure 1.2.1^(b), the continuity equation need only be solved for two dimensions.

Using p-type material as an example, Donolato gives the carrier collection probability as

$$Q(x,z) = \sinh[\lambda(d-x)]/\sinh(\lambda d) - \frac{2s/d}{\sum_{i=1}^{\infty}} [k_i/\mu_i^2(\mu_i+s) \exp(-z\mu_i) \sin(k_i x)] \quad (1.2.5)$$

where $k_i = \pi i/d$

d = distance from depletion edge to ohmic contact

$s = v_s/D_e$

v_s = surface recombination velocity

D_e = diffusion constant = $\mu_e kT$

μ_e = electron mobility

$\mu_i = \sqrt{k_i^2 + \lambda^2}$

$\lambda = 1/L_e$

L_e = minority carrier diffusion length, electrons

$\sinh x = 1/2 (e^x - e^{-x})$

Equation 1.2.4 is particularly convenient to use when $h(x,z)$ is known. $h(x,z)$ can be

calculated from the energy matrix produced by the Monte Carlo simulation program described by Napchan and Holt (1987) and treated in more detail in section 1.3.1. This gives the deposited energy as an 80 x 80 matrix. x and z can be calculated from the matrix coordinates and h is calculated by dividing the energy in each matrix element by q . However, the carrier collection probability, $Q(x,z)$, must then be calculated for each element in the array. This would require 6400 summations from 1 to ∞ ($Q(x,z)$, equation 1.2.5), to determine the short circuit current for only one beam position.

In equation 1.2.5 the summation need not be carried out to infinity. The term $\exp(-z\mu_i)$ grows smaller (as i increases) at a much faster rate than any other term. The summation can safely be terminated when $\exp(-z\mu_i)$ reaches some lower limit. The attractive feature of equation 1.2.5 is that the specimen thickness is taken into consideration which makes this a practical model for evaluating surface recombination velocity and diffusion length when L is comparable to d . L for silicon is usually very large with respect to specimen dimensions. This could explain why there are only a few treatments reported in the literature that attempt to fit theory to experiment for quantitative conductive mode analysis of silicon.

Instead of a Monte Carlo simulation, Donolato uses an approximation for $h(x,z)$ proposed by Fitting, Glaefke and Wild (1977) given by

$$h(x-x_0, z) = 1.14/(2\pi\sigma^2) \exp[-((x-x_0)^2 + (z-z_0)^2)/2\sigma^2] \quad (1.2.6)$$

where $z_0 = 0.3R$

$$\sigma = \sqrt{R/15}$$

x_0 is the beam position relative to the edge of the depletion region and must be greater than the lateral extension of the generation volume. In other words, the generation volume must lie completely outside the depletion region or expression 1.2.6 doesn't apply.

z_0 is the depth below which 50% of the electron-hole pairs are generated (and 50% above). This depth will also be mnemonically referred to as the location of the *centre of gravity of the generation volume*.

R is the Grün range and is obtained from a plot of electron beam energy dissipation versus penetration depth. It is the depth at which the straight line portion of the curve extrapolates to zero (Everhart and Hoff, 1971) and is given by

$$R = \beta / \rho_s V_b^{1.75} \quad (1.2.7)$$

where $\beta = 4.28 \times 10^{-6}$

ρ_s = density, g/cm³

From equation 1.2.6, taking into account surface recombination and the condition that the specimen is infinitely thick, Donolato gives

$$I_{sc}(x_0) = \frac{2}{\pi} \int_0^\infty (k/m^2) (\exp(-k^2\sigma^2/2) - 0.57 \exp(\lambda^2\sigma^2/2 - mz_0) s/(m+s) \operatorname{erfc}[(\sigma/\sqrt{2})(m-z_0/\sigma^2)]) \sin(kx_0) dk \quad (1.2.8)$$

where $m = \sqrt{k^2 + \lambda^2}$

$$\operatorname{erfc} x = 1 - \operatorname{erf} x$$

$$\operatorname{erf} x = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt \quad (1.2.9)$$

The integral in equation 1.2.8 can be approximated using Simpson's rule (Kreuzig, 1983) given by

$$\int_a^b f(x) dx \approx h/3 (f_0 + 4f_1 + 2f_2 + 4f_3 + \dots + 2f_{2n-2} + 4f_{2n-1} + f_{2n}) \quad (1.2.10)$$

where $h = (b - a)/2n$

$$f_j = f(x_j)$$

$$x_j = a + jh$$

$$j = 0, 1, \dots, 2n$$

Since equation 1.2.8 is periodic due to the $\sin(kx_0)$ term, h can be optimized for each solution by increasing $2n$ while integrating over a single period until the value of the integral does not change significantly. The total integral from 0 to ∞ can be evaluated by adding up integrals over each period until the total answer does not change significantly.

The erf may be evaluated using a Maclaurin series when the argument is less than 3.56 by

$$\operatorname{erf} x \approx (2/\pi) (x - x^3/1!3 + x^5/2!5 - x^7/3!7 + \dots) \quad (1.2.11)$$

or by an approximation to an asymptotic expansion when the argument is greater than 3.56 by (Kreyzig, 1983)

$$\operatorname{erf} x \approx 1 - (1/x\sqrt{\pi}) \exp(-x^2) \quad (1.2.12)$$

After the argument is greater than about 6, errors in the determination of erfc are significant but by that time the erfc term of equation 1.2.8 is the smallest term and can be approximated to zero.

1.3 Beam-Specimen Interactions

As the electron beam penetrates the sample the primary electrons lose energy and scatter, leaving behind a volume of ionized silicon. The energy lost by each primary electron goes, in part, to the creation of many electron-hole pairs. The conductive mode gain for a device with a charge collection barrier is defined in terms of the detected short circuit current, I_{sc} , as

$$\text{gain} = I_{sc} / I_b \quad (1.3.1)$$

where I_b = electron beam current

The primary beam energy loss as a function of penetration depth, z , is given by $g(z)$ in units of energy loss/cm per incident electron/sq cm, where

$$g(z) = \lambda(z/R) V_b(1-\kappa f)/R$$

where z = depth from the surface

R = Grün range (equation 1.2.7)

V_b = beam voltage

λ = normalized Grün function

The normalized Grün function can be represented by a polynomial given by Everhart and Hoff (1971)

$$\lambda(\psi) = 5.69\psi^3 - 12.40\psi^2 + 6.21\psi + 0.6$$

where ψ = the normalized depth, z/R

One practical implication of the electron energy loss function is that it is not peaked at the

surface. Therefore depth information can be extracted by comparing the shallow and deep penetration data. The photon energy loss function peaks at the surface and is therefore more sensitive to cumulative errors.

1.3.1 Monte Carlo Simulation

When the generation volume is small in relation to a feature being examined or when it is far away from a charge collection barrier, it can be approximated as a point source at $0.3 \times \text{Grün}$ range below the surface. However when the generation volume is comparable in size to features being examined or when it is close to or overlaps a charge collection barrier, a more precise description of the volume of deposited energy is needed to extract quantitative data from experimental results.

The energy imparted to the lattice by incident primary electrons can be determined as a three dimensional energy deposition matrix with the aid of a Monte Carlo simulation. As the primary electrons penetrate the specimen they both change direction and lose energy via elastic and inelastic collisions.

Elastic collisions are events which change the electron's trajectory but not its energy. These are simulated using a screened Rutherford cross section. This is a mathematical method of selecting a new angle and azimuthal direction at the beginning of each scattering event with the aid a random number generator such that the backscatter coefficient matches the experimentally determined value. The name *Monte Carlo simulation* is due to the element of chance which is associated with the notorious gambling casinos of Monte Carlo.

Inelastic collisions involve a transfer of energy from the primary electron to the lattice. The amount and location of the energy deposited is determined from the Bethe (1930) stopping power expression. For the decrease of electron energy, E , along the path length s , the

continuous slowing down approximation is given by (Reimer and Stelter, 1986)

$$dE/ds = - \sigma_0 N_{Av} / V_b Z \sum_i [f_i \ln(V_b/E_i)^2]$$

where $\sigma_0 = \pi e^4 / (4\pi\epsilon_0)^2$

N_{Av} = Avogadro's number

Z = atomic number

V_b = primary electron energy

s = path length in units of mass thickness, $\mu\text{g}/\text{cm}^2$

E_i = ionization energy of electron in i^{th} subshell

The summation is over all atomic electrons and f_i are the oscillator strengths that are equal to the number z_i of electrons in the i^{th} subshell in a first order approximation. The above relationship is a continuous expression for the energy loss however The Monte Carlo simulation computer program must view the energy loss as occurring at discrete points in order to produce a depth dose matrix.

These two types of interaction are treated as independent by the Monte Carlo simulation and the entire primary electron energy is arranged to dissipate over 50 elastic and 50 inelastic scattering events.

The Monte Carlo simulation described by Napchan (1987) was written in Pascal to run on an AT compatible microcomputer. This program was used in the present work to calculate the energy deposition matrix. In the application described in section 4.2 only a two-dimensional energy matrix was required since the charge collection barrier was assumed to be a semi-infinite plane.

1.3.2 Injection Levels

When a high energy beam of focussed electrons penetrates a semiconductor, it effectively injects carriers into the material due to the formation of electron-hole pairs. As long as the density of injected minority carriers is much less than the doping density, the minority carriers remain a true *minority* and this is referred to as the condition of low injection. When the injected carrier density is greater than the impurity concentration, the injection level is said to be high.

The minority carrier lifetime and diffusion constant are significantly affected by injection levels and are sometimes subscripted *l* or *h* to distinguish which value they refer to. Widespread conditions of high injection will seriously affect the short circuit current collected by a junction some distance from the generation volume. The values of diffusion length and lifetime for electrons in p-type Cz silicon reported in table 1.1.2 are for conditions of low injection.

Berz and Kuiken (1976) developed expressions for the injected carrier density to determine whether high or low injection conditions prevail. For the case of electrons in p-type material, the maximum injected carrier density, $\Delta n_{\max}$, at the centre of the generation volume (in this case assumed to be spherical) can be approximated by

$$\text{for } v_S = \infty, \quad \Delta n_{\max} \approx G/8\pi D (3/a - 1/h) \quad (1.3.2)$$

$$\text{for } v_S = 0, \quad \Delta n_{\max} \approx G/8\pi D (3/a + 1/h) \quad (1.3.3)$$

where a = width of the generation volume

h = depth of generation volume centre

G = minority carrier generation rate

If $\Delta n_{\max}$ at the centre of the spherical approximation to the generation volume is much less than the doping density, then the injected carrier concentration everywhere else will surely satisfy the conditions for low injection.

Berz and Kuiken point out that this condition of low injection is too restrictive. High injection, when sufficiently localized near the generation volume centre, should not affect carrier motion when the diffusion length is much greater than the diameter of the volume in which high injection conditions exist. Taking this into consideration Berz and Kuiken give

$$\text{for } v_s = \infty, \quad \Delta n_b = (5/2\pi) (G\tau_1/L_1^3) (h/L_1) \quad (1.3.4)$$

$$\text{for } v_s = 0, \quad \Delta n_b = (G\tau_1/L_1^3) \Theta[r_b/L_1, \tau_h/\tau_1] \quad (1.3.5)$$

where L_1 = minority carrier diffusion length at low injection

τ_1 = lifetime at low injection

Θ is a complex function of lifetime, diffusion length and radius of the volume dividing high and low injection. The details of this function are beyond the scope of the present work. However, according to Berz and Kuiken, typical values of Θ range between 0.01 and 0.2 which leaves equation 1.3.5 reasonably useful.

The relaxed condition for low injection, based on equations 1.3.4 and 1.3.5, is that the calculated Δn_b must be much less than the doping density.

1.3.3 Electron Beam Radiation Dose Rate

The radiation dose rate is especially important in the field of radiation hard microelectronic devices. However electron microscopists rarely mention the dose rate but more often refer to

the beam power, scan rate or even mistakenly refer to injection level when they mean dose rate. Bresse (1977) is a notable exception. He reports that determination of the surface recombination velocity is affected by the dose rate, although it is not clear how he calculates the dose rate.

The radiation dose is expressed in units of energy per unit mass, usually in *rads*. One rad is 0.01 joules/kg. Dose rate is rads/sec or more commonly Mrads/sec (10^6 rads/sec).

The radiation dose rate of a scanning electron beam is given by

$$\text{dose rate in rads} = 10^5 (V_b/q) I_b / \rho_s V_\phi \quad (1.3.6)$$

where V_ϕ = volume of specimen swept by beam

ρ_s = density

V_b = beam voltage

I_b = beam current

The definition of the volume is critical when comparing dose rates with other workers. In the present work we define the electron irradiated volume to be a spherical approximation to the generation volume with a radius of $0.5 \times \text{Grün range}$. The radiation volume swept out by a linescan is a cylinder, and the radiation volume of a scanned frame is a number of cylinders, equal to the number of linescans per frame.

1.3.4 Inversion Layers

An inversion layer is a volume of doped semiconductor that behaves as if it were doped in the opposite sense. For example, an inversion layer in p-type silicon behaves as n-type silicon. Inversion is the fundamental principle behind the operation of an MOS transistor as

shown in figure 1.3.1. For example, n-type source and drain are separated by a p-type channel preventing current flow by providing two back-to-back diodes. The transistor is turned on when the p-type material is inverted to n-type by an electric field provided by the gate located above the channel.

A cleaved silicon surface, upon contact with the atmosphere, reacts with oxygen to form a thin native oxide, SiO_x , where x is between 0 and 2. As with any silicon-silicon oxide interface, the dangling silicon bonds give rise to a surface states charge, Q_{ox} , which is positive. Holes have a much lower mobility in SiO_2 than do electrons yielding the possibility of trapped positive charge in the native oxide. Metal ion contamination such as sodium can also contribute to charge at the surface.

Positive charge trapped at the surface provides an electric field like that provided by the gate of an MOS transistor. This produces a corresponding negative charge, Q_{b} , in the bulk silicon near the surface and results in the band-bending represented by figure 1.3.2. This first produces a depletion region in p-type silicon. The depth of the depletion region due to the positive charge at the surface will increase as the surface charge increases until it reaches a maximum given by

$$W_{\text{max}} \approx [(4\epsilon_0\epsilon_s kT \ln(N_a/n_i)) / q^2 N_a]^{1/2}$$

(Lehovec and Fedotowsky, 1964 and Sze, 1983). It is assumed in the derivation of the above relationship that W_{max} is determined by the condition that the minority carrier concentration at the oxide interface equals the majority carrier concentration in the bulk. However, Lehovec (1985) has recently reported that this maximum depth is actually about 7% larger than previously thought. This is based on a correction to this assumption. According to Lehovec, the minority carrier concentration at the interface significantly exceeds the bulk majority carrier concentration when the maximum depletion width is reached

Figure 1.3.1. n-channel MOS transistor cross-section. The channel inverts to n-type when a voltage is applied to the gate which closes the circuit between source and drain.

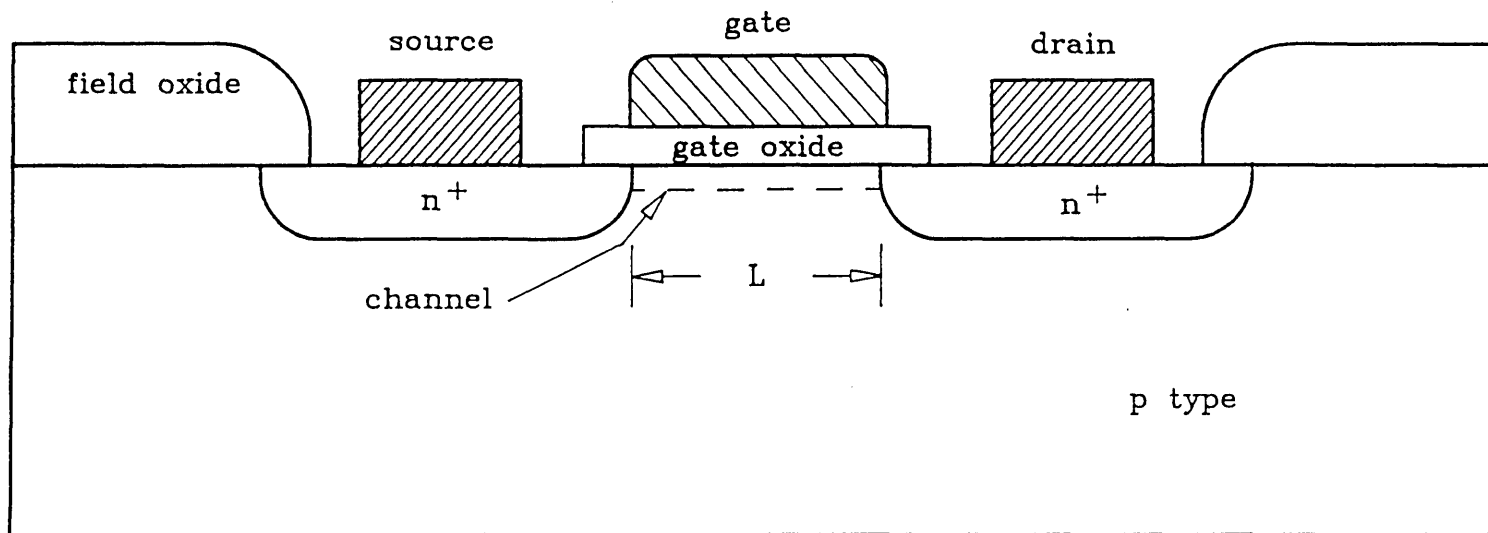
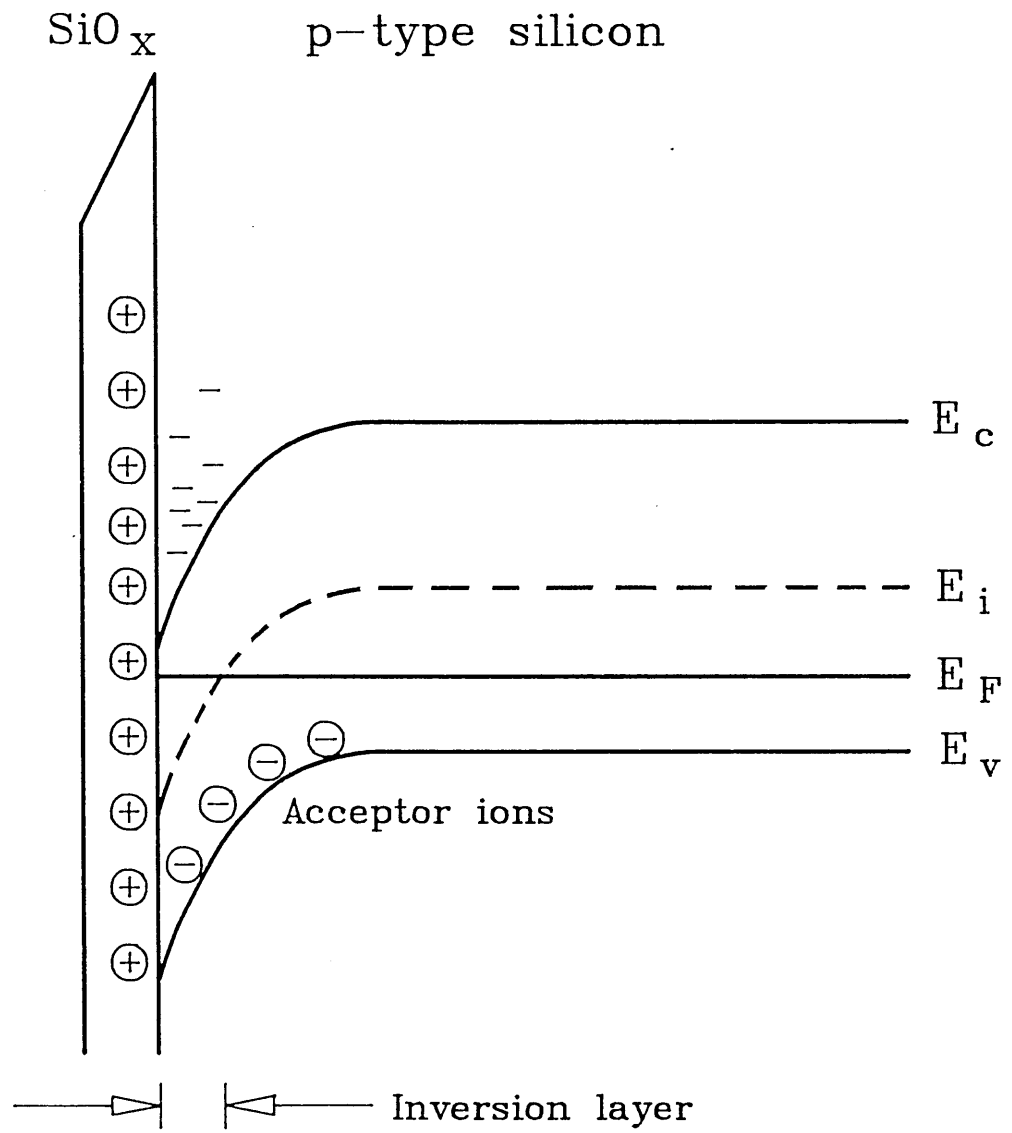


Figure 1.3.2. Band bending at the surface of p-type silicon due to positive charge at the surface. The maximum depletion region width will occur after the Fermi level crosses the conduction band at the surface.



$$W_m \approx [\epsilon_0 \epsilon_s / (2q^2 N_a / kT)]^{1/2} F(r) \quad (1.3.7)$$

$$\text{where } r = \sqrt{N_a / n_i}$$

and $F(r)$ is closely approximated by

$$F = 4.76 + 0.646 \log_{10} r - 0.009 (\log_{10} r)^2$$

Therefore an increase in Q_{ox} beyond that needed to produce a depletion width W_m ,

is compensated by an increase in the free electron density near the surface,

Q_c . Quantitatively this is given by (Bar-Lev 1984)

$$\bar{n} = N_c \exp\left(-\frac{E_c - E_f}{kT}\right)$$

where $\bar{n}$ = equilibrium carrier concentration

N_c = density of states

$E_c - E_f$ = difference in energy between Fermi level and conduction band

Since the free electron concentration is exponentially dependant on $E_c - E_f$, the free electron charge will increase very fast once effective inversion is reached.

It is well known (Gates and Griffith 1975, Keery *et al* 1976) that a scanning electron beam produces trapped positive charge at a silicon-silicon oxide interface. This space charge can be retained for long periods, even years (Hughes and Seager, 1983). In fact the silicon-silicon oxide interface is so sensitive to accumulation of trapped positive charge that inversion in the silicon underneath has been brought on by simple optical illumination by Abdou and Habib (1986). Hezel (1979) used an inversion layer as a charge collection barrier to produce qualitative EBIC images of dense dislocation arrays in (100) silicon.

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2.0 EXPERIMENTAL TECHNIQUES

The following section briefly discusses some selected aspects of experimental technique, particularly for EBIC linescans over silicon p-n junctions. The experimental configuration used for recording the conductive mode linescans is shown in figure 2.1.1.

2.1 Data Collection

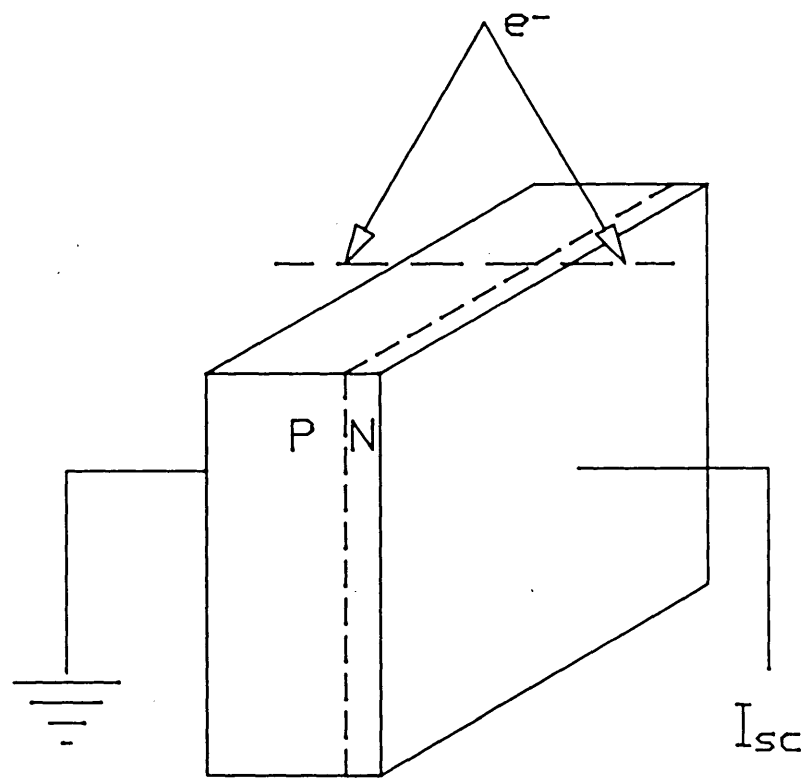
As shown in figure 2.1.1, the p-type contact was earthed when measuring the short circuit current. The contact to n-type semiconductor provided the input to a Keithley 427 current amplifier. A flow of electrons from the n-type silicon to the Keithley (i.e. the direction of I_{sc}) produced a positive (0 to +10V) output voltage from the Keithley.

The Keithley output drove the Y coordinate of an X-Y plotter. The signal for the X coordinate was the JSM-35 electron microscope X scan generator output voltage which varied from +10 to -10 volts as the beam scanned from left to right on the JSM-35 CRT. The junction was biased by inserting a DC power supply between the p-type semiconductor and earth.

Extracting the conductive mode signal in this fashion introduces certain limitations. The JSM-35 X scan output was investigated using an oscilloscope and found to be noisy, especially in the region +5 to -5 volts. This could be largely eliminated by using a filter on the X-Y plotter. Quantitative results were also subject to the accuracy with which the X-Y plotter acts as an analog voltmeter.

For some experiments it was necessary to perform a linescan over a region of silicon never before exposed to the scanning beam. This was done by positioning the JSM-35 stage at its extreme X and Y limits before mounting the purpose-built brass specimen holder. Aperture

Figure 2.1.1. Configuration for silicon linescan experiments. The electron beam scanned from left to right for most experiments. Scanning from right to left was tried, but results were identical.



alignment, filament current saturation, beam alignment and astigmatism were adjusted while the beam was directed at the brass holder. The electron gun was allowed to warm up at the desired accelerating voltage for 45 minutes or more. If this warm up was omitted, beam current and beam alignment would drift during the experiment. The beam current was checked before and after experimental data was taken. Normally the beam current would not change more than 3% over the course of the experiment but if it did, the experiment was repeated.

The end of the silicon specimen was brought into view at low magnification using the secondary electron image. The cross-section of the epitaxial layer was then viewed at high magnification and the stage was moved so that the specimen area under examination was far from the end. A conductive mode linescan was set up at the desired experimental magnification and optimum focus was determined for the sharpest EBIC peak as the beam scanned over the p-n junction. The JSM-35 was then set to selected area with a minimum width. The selected area position was directed well off the silicon cross-section onto the brass holder. Next, the Y image shift was adjusted in such a way as to direct the electron beam onto a previously unirradiated area of silicon once the selected area was turned off.

Unless dose rate effects were being investigated, linescans were taken at photographic speed horizontal 6, vertical 7. The photo button was engaged just prior to switching off selected area.

Unfortunately when multiple linescans were being performed over the same location, the beam position was changed slightly each time selected area was turned on and off. This was particularly crucial when many linescans were recorded on the same spot at different reverse biases. This introduced an uncertainty in the relative lateral position of the group of linescans to each other. This was largely overcome by using the sharp drop in the EBIC, as the beam dropped off the end of the specimen, as an edge reference.

Experimental linescans like those shown in figures 2.3.1, 2.3.2 and those presented in section 3.0, were constructed from the original EBIC trace produced by the X-Y plotter. This was done using a graphic computer aided design (CAD) package called Auto-CAD. The experimental trace was digitized using auto-CAD and the X and Y scales were determined from the specimen thickness and Keithley current range respectively.

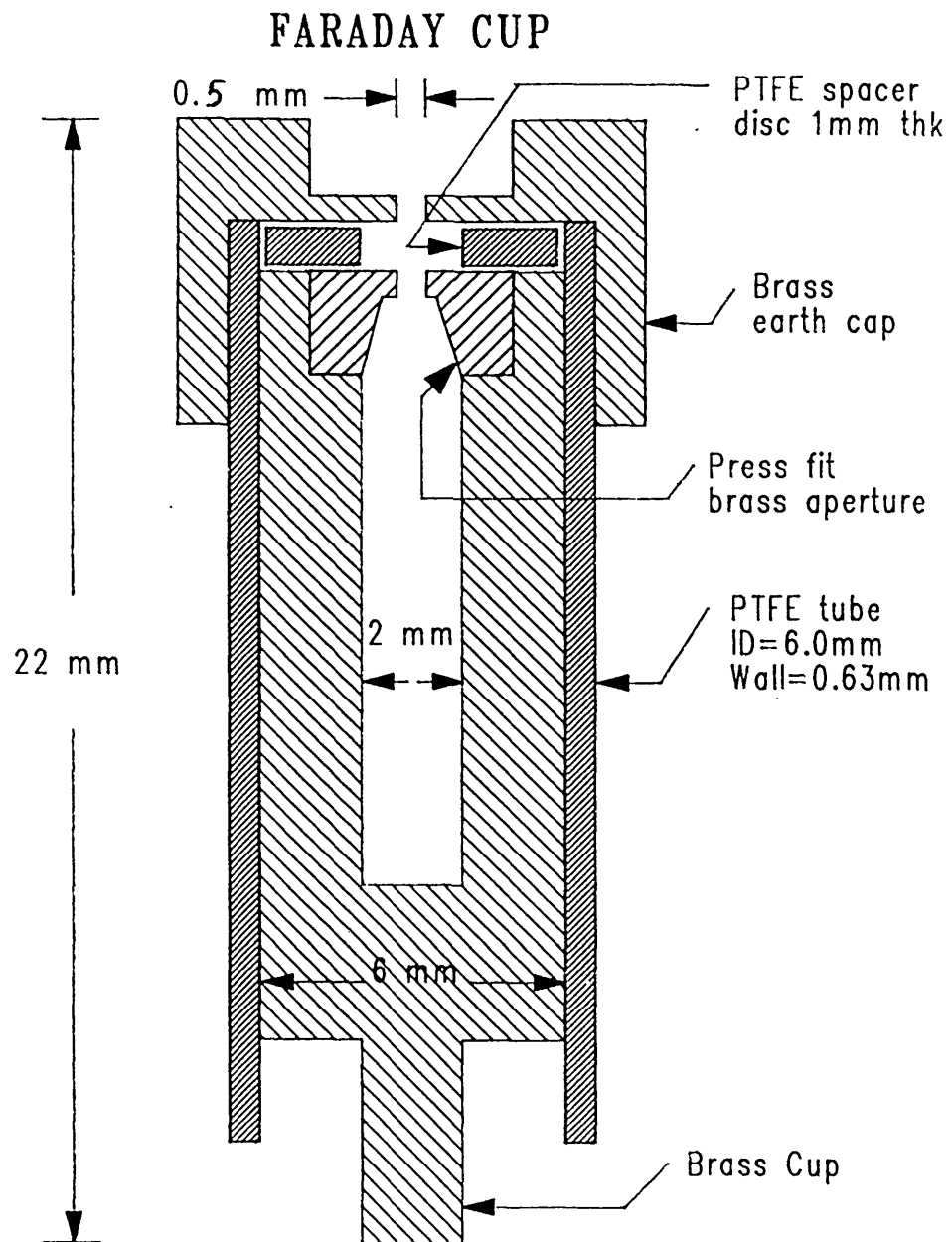
Unfortunately uncertainties are introduced during the process of copying the original EBIC trace or when manually extracting data from the graph paper used in the X-Y plotter. Ideally, the output from the Keithley should be recorded using a data logger or digital oscilloscope with a logarithmic input and transferred to a computer equipped with a graphics package for analysis and presentation.

The electron beam current was also measured using the Keithley 427 with a Faraday cup designed according to Joy's recommendations (1974). This is shown in cross-section in figure 2.1.2. A specimen holder was also constructed especially for examination of microelectronic materials mounted in T0-5 or T0-18 headers. This holder included a well for the Faraday cup located so that the beam current could be measured only a few microns from the specimen.

2.2 Specimen Preparation

10 microns of n-type epitaxial silicon, phosphorus doped to 7.5 ohm-cm, was grown on three p-type boron doped (100) silicon substrates with bulk resistivities of 2.0, 2.8 and 8.5 ohm-cm. Junction depth was determined by regular monitoring of epitaxial depositions in an AMS-1000 epi reactor. Epi resistivity was determined using a four point probe. The substrate thickness was measured to $\pm 2 \mu\text{m}$ using a μ -step 2000 thickness gauge. The substrate thickness was used to determine lateral dimensions on the SEM linescans. All three wafers were sputter coated front and back with 100 nm aluminium/30 ppm silicon and forming gas

Figure 2.1.2. Faraday cup design used for measurement of the electron beam current for both silicon and GaAs work.



annealed to give large ohmic contacts.

Diode specimens were prepared by cleaving the wafers into approximately 0.5 cm² rectangles. In order to obtain valid experimental results, a clean, flat cross-section was required. Wafers were cleaved upside-down to give a very flat cross-section near the p-n junction. The entire 400 µm cross-section of the substrate was also very flat and at 90° to the front and back face at one to two inches away from the start of the cleave.

The cleaved rectangles were mounted onto T0-5 headers using silver dag to bind the back contact to the gold coated base. A thin wire was soldered to a T0-5 post and bent to contact the front (epi) contact in the centre of the specimen. Electrical contact was made to the wire with a small drop of silver dag.

Once a specimen had been cleaved and mounted, it was placed in the SEM immediately for examination. Allowing for the silver dag to dry, the cleaved surface intended for examination was only exposed to the atmosphere for about 15 minutes. This was done to minimize native oxide growth.

For the experiments reported in sections 3.1.2 and 3.1.3, I-V characteristics of the prepared specimens were measured in the SEM under vacuum. Experimental data were only taken on specimens whose reverse leakage current was less than 10⁻⁵ amps at -20 V.

2.3 Carrier Multiplication Effects

In addition to acting as recombination centres, defects can also appear in normal polarity EBIC micrographs as bright regions where $I_{sc} \gg I_{max}$. Leamy *et al* (1978) report that precipitates and decorated dislocations, when situated in the depletion region, can concentrate the field lines such that beam induced carriers are accelerated and gain enough

energy to produce additional electron-hole pairs. These sites are thought to indicate areas of premature breakdown called microplasmas and are characterized by a reversal from a recombination centre to a current multiplication site at a well defined threshold voltage (Heydenreich, 1981). These will adversely affect quantitative EBIC linescans and therefore must be recognized and avoided when they occur.

There were two kinds of carrier multiplication observed when recording conductive mode linescans over silicon p-n junctions. Figure 2.3.1 shows a carrier multiplication effect in the right hand edge of the depletion region at reverse bias voltages of 16 and 20 V. Two linescans were recorded at $V_r = 16$ V and show that the carrier multiplication maximum is higher on the second linescan. This may indicate that electron beam irradiation plays a part in activating a carrier multiplication site.

A second type of carrier multiplication can be observed at the metal-semiconductor contact as shown in figure 2.3.2. In this example an EBIC signal is still detected long after the beam drops off the edge of the n-type epi onto the brass holder. This is not a transient, but is due instead to backscattered primaries from the brass which are reflected back towards the large face of the epi contact. What this means is that the region of carrier multiplication is not localized but covers a large area. Note that the gain of the EBIC peak due to current multiplication is over 6 times $I_{\max}$ ($I_b = 0.2$ nA for figure 2.3.2).

Figure 2.3.1. Carrier multiplication effect displayed in right hand portion of the depletion region for reverse bias voltages of 16 and 20 V. Microplasma effect is more pronounced for the second linescan at 16 V.

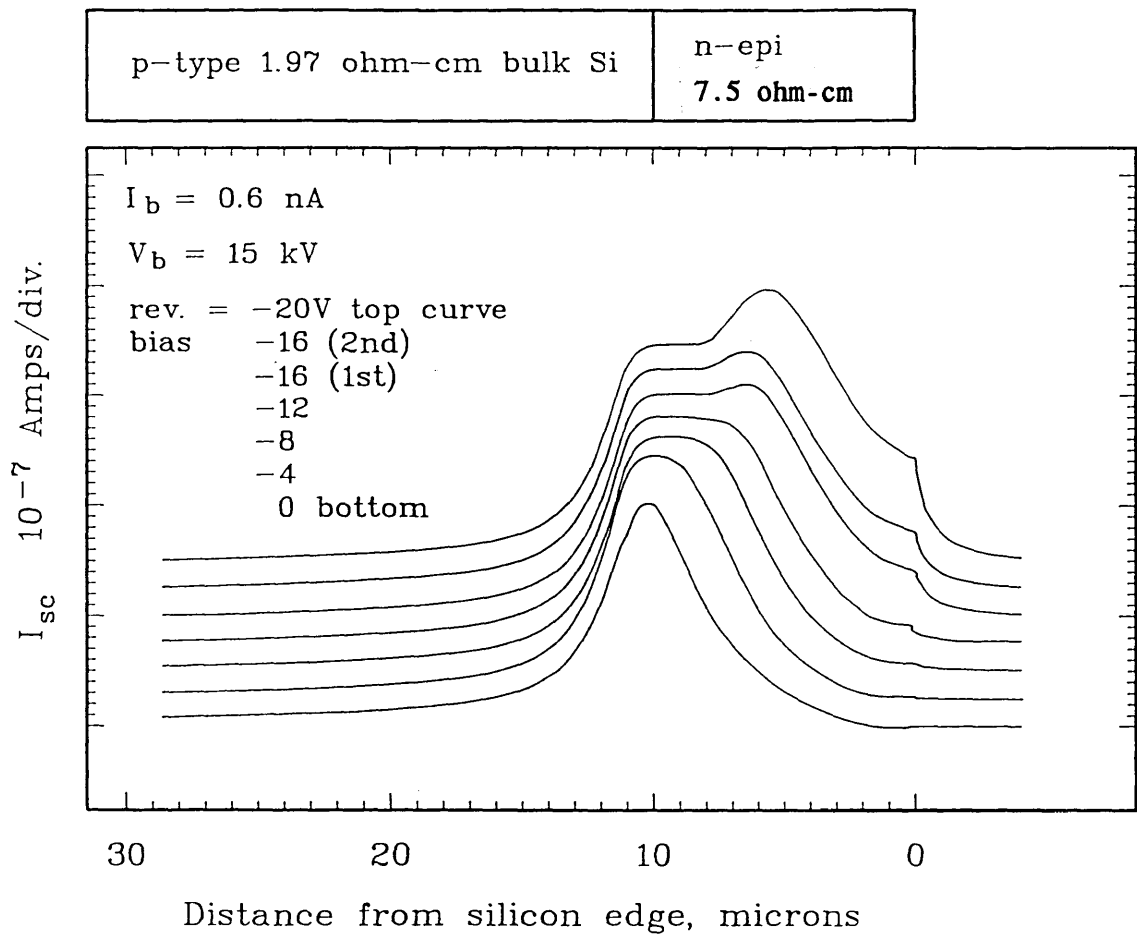
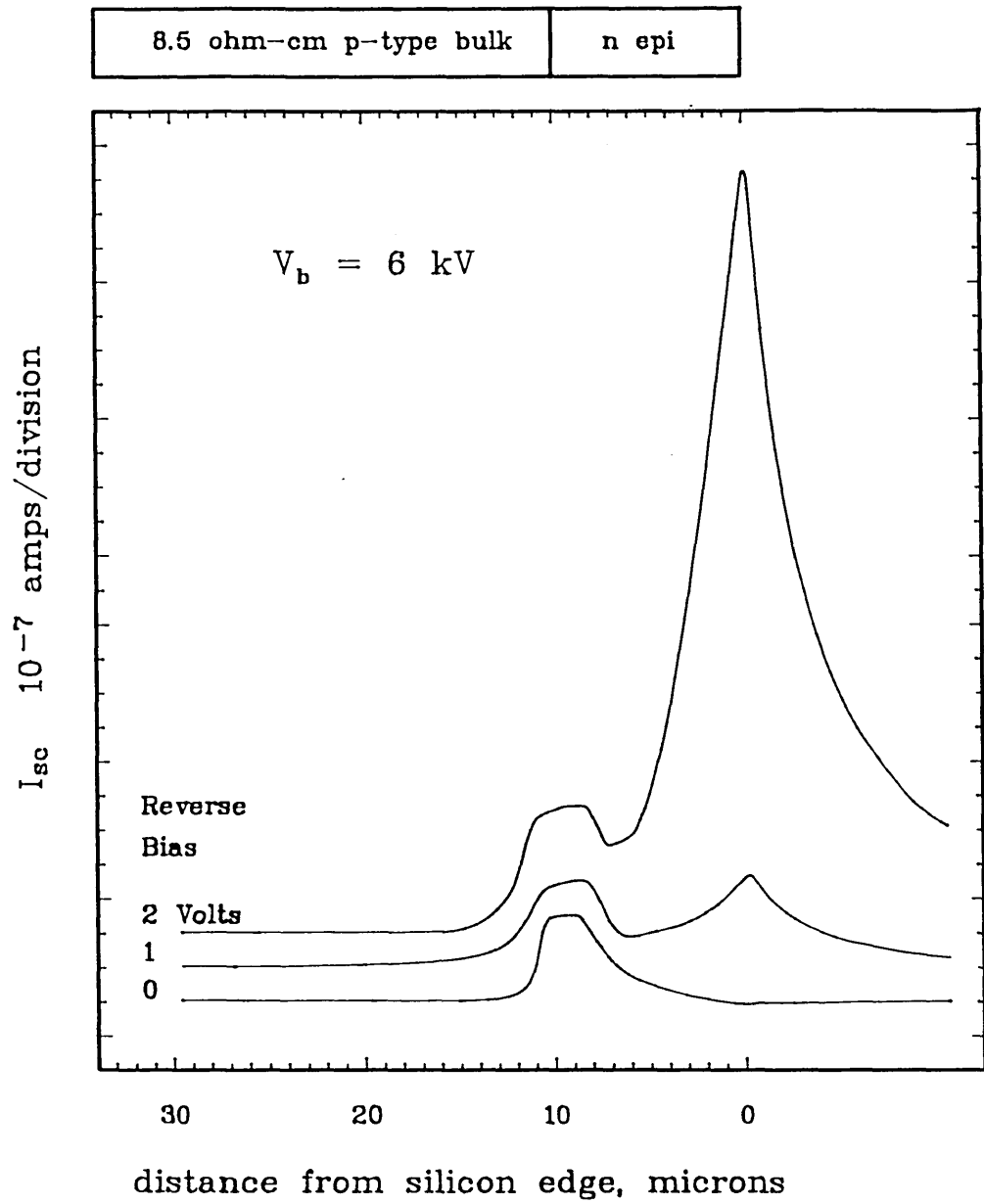


Figure 2.3.2. Carrier multiplication effect displayed over a large area of ohmic contact to 7.5 ohm-cm n-type epi. EBIC does not fall to zero when the beam drops off the edge of the specimen due to current multiplication of primary electrons backscattered from the brass specimen holder.



3.0 EXPERIMENTAL RESULTS

3.1 EBIC Linescans in Silicon

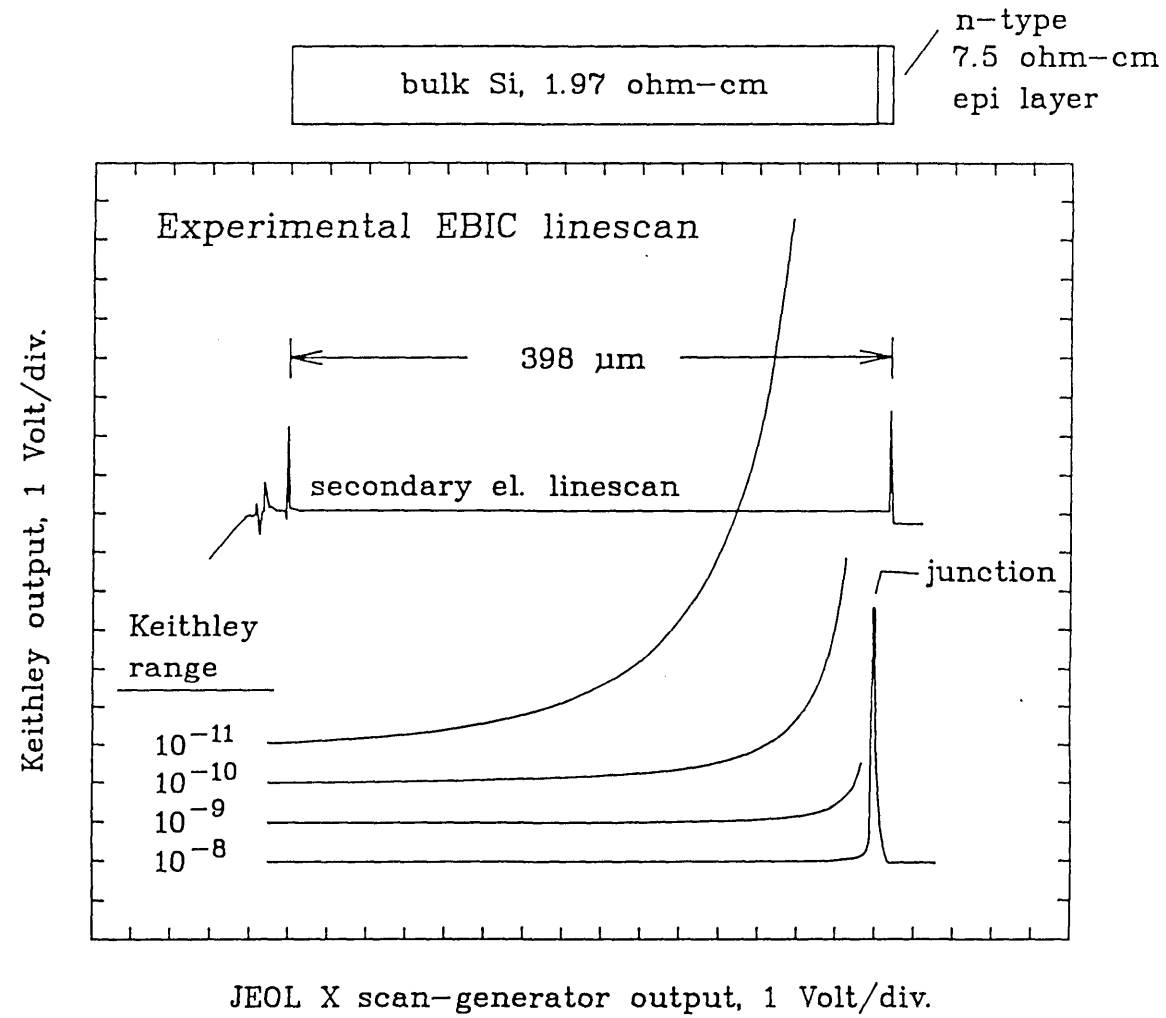
Several workers have recorded linescans over silicon p-n junctions for the purpose of fitting theory to experimental data (Bresse 1977, Davidson 1982, Hungerford and Holt 1987, Castaldini *et al* 1987). This is an attractive technique for determining the surface recombination velocity and minority carrier diffusion length. However some results reported so far indicate that the diffusion length and the surface recombination velocity vary with scan speed, beam power and dose rate.

A variety of EBIC linescans were performed on p-type silicon of three different doping concentrations for the purpose of establishing whether Donolato's expressions for the EBIC given in equations 1.2.5 and 1.2.8 are representative of data collected experimentally. A schematic diagram of the experimental configuration is shown in figure 2.1.1.

A typical EBIC linescan across the entire 400 μm silicon specimen thickness is shown in figure 3.1.1 (for several detector amplifications). The voltage from the JSM-35 X-scan generator is converted to microns with the aid of the secondary electron linescan which shows the front and back edges of the specimen as bright blips. The lateral scale for linescans performed at other magnifications were calculated using a simple proportion between the two magnifications.

In figure 3.1.1 the specimen was actually scanned four times while the sensitivity of the Keithley amplifier was increased by a factor of ten for each new scan. If this were not done a linear X-Y plotter could not resolve the EBIC signal from its maximum to its minimum. Data was read from the X-Y curves and replotted on a semi-log scale as a single linescan.

Figure 3.1.1. Typical experimental EBIC trace over entire thickness of a cleaved silicon substrate. $V_b = 6$ kV, $I_b = 0.52$ nA.

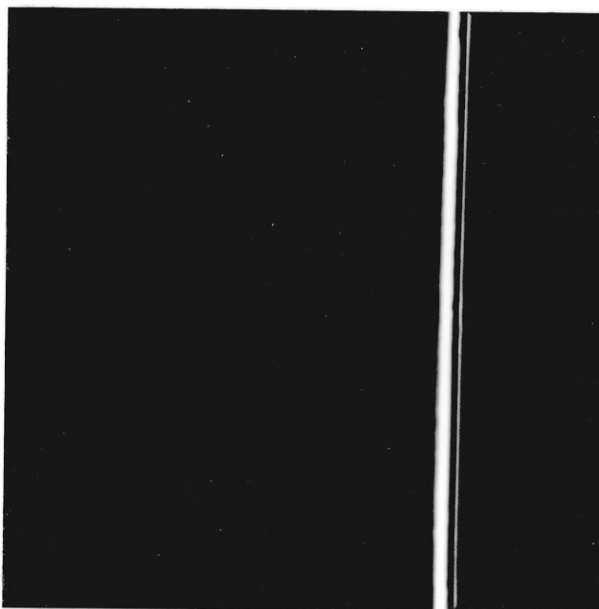


3.1.1 Electron Dose Induced Variations in Silicon Linescan Profiles

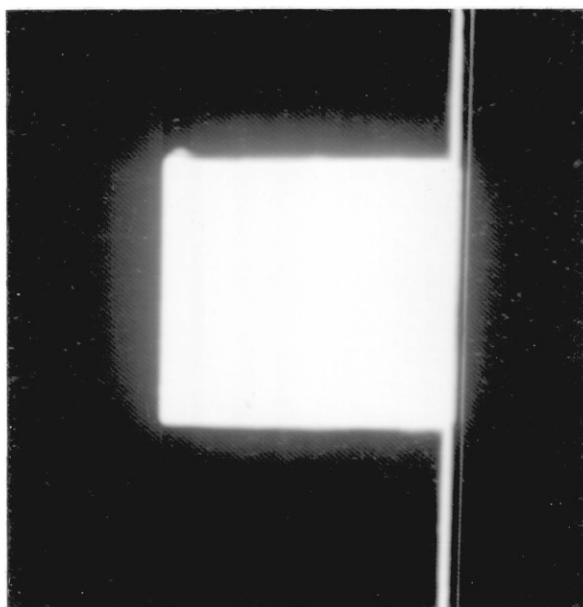
When a frame on the specimen was scanned at certain dose rates, the silicon was affected in such a way so as to allow collection of nearly 100% of the short circuit current at distances of up to 350 μm from the junction. This is clearly impossible if the simple exponential of equation 1.2.3 were valid. Figure 3.1.2(a) is a normal EBIC micrograph with a bright band at the p-n junction. This is due to very efficient excess minority carrier collection when the beam is near the charge collection barrier. In figure 3.1.2(b) the same area of silicon has had a rectangular region irradiated at a higher magnification. This area appears as a bright region where the EBIC signal has been induced to increase. This bright region extends across the entire 394 μm thickness of the wafer. EBIC images of the same area one or two hours later showed that the bright region could still be observed although the signal strength decays with time. For the 1.97 ohm-cm substrate, a wide range of radiation dose rates would bring a frame to the condition of figure 3.1.2(b). The 8.5 ohm-cm substrate however, had only a narrow band of dose rates that would bring the material to this condition and a linescan through a charged bright area showed that, at best, I_{SC} was considerably less than I_{max} at distances far from the junction.

Repeated EBIC linescans through a region such as the frame in figure 3.1.2(b) are shown in figure 3.1.3. The radiation dose rate of the linescan used to measure the short circuit current was approximately 400 times greater than in the frame scan. As the beam repeatedly scanned over the same line in the frame, I_{SC} steadily decayed with each successive linescan as shown. The experiment reported in figure 3.1.3, where linescans were repeatedly recorded through an enhanced frame like that in figure 3.1.2(b), was repeated over a range of beam voltages. The short circuit current was measured (on the first scan) at 200 μm from the junction. This value was normalized to I_{max} and plotted as a function of V_b in figure 3.1.4.

Figure 3.1.2. EBIC micrographs showing the same area before and after a frame was irradiated at 8 Mrads/min at higher magnification. (a) Bright EBIC band collected at the p-n junction [*before*]. (b) EBIC image of the same area as a) showing a strong conductive mode signal in the irradiated frame 394 μm wide [*after*].



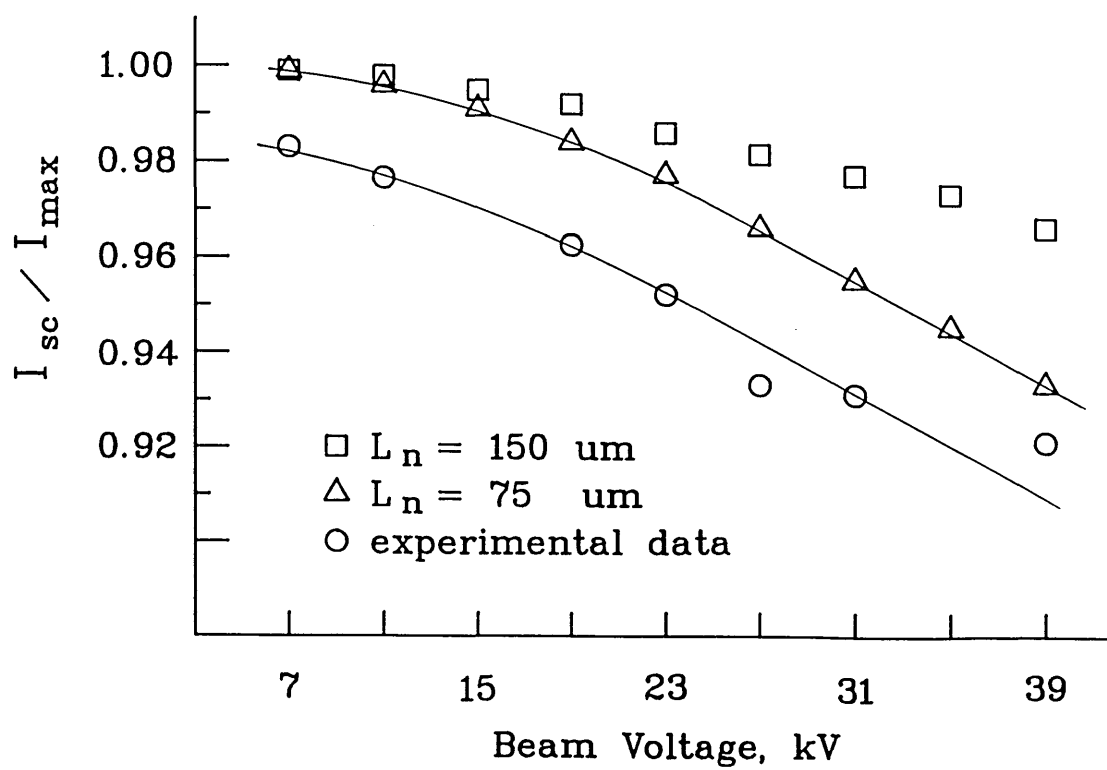
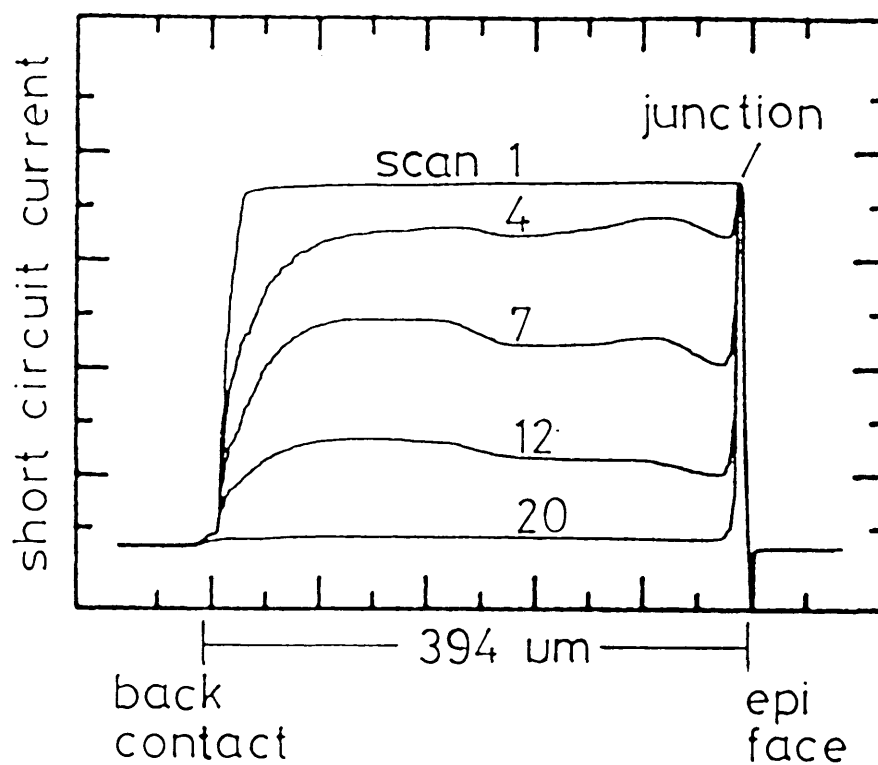
a



b

Figure 3.1.3. Repeated linescans over a bright area such as that in figure 3.1.2 (b). The area of enhanced short circuit current steadily loses its charge collection properties with subsequent scans. Time for one scan is 20 seconds. The bulk resistivity of the specimen was 1.97 ohm-cm.

Figure 3.1.4. Experimental data showing I_{sc} versus V_b measured at 200 μm from the junction on the first linescan through an enhanced frame such as figure 3.1.2 (b). The top two curves were calculated using a Monte Carlo simulation where a surface depletion region calculated according to equation 1.3.7 acted as the charge collection barrier.



Two theoretical curves of I_{sc}/I_{max} are also shown for the case of a depletion region of infinite area parallel to the surface. These were calculated using equation 1.2.1 applied to elements the depth dose energy matrix produced by the Monte Carlo simulation program. Diffusion lengths for these two curves were taken to be 75 and 150 μm and the depth of the depletion region was taken to be the maximum value for silicon at high inversion calculated using equation 1.3.7.

The data in figure 3.1.5 are from two linescans performed on a region of 8.5 ohm-cm p-type silicon. The beam was allowed to scan a line continually for a few minutes at constant I_b and V_b . The difference between the two is the scan speed. $\ln(I_{sc})$ is plotted against x , and the minority carrier diffusion length was calculated from the negative reciprocal of the slope according to equation 1.2.3. This was found to be 220 μm for the slower scan rate and possibly higher for the faster scan. This is not in good agreement with the data from table 1.1.2 where the maximum value of L_c for 8.5 ohm-cm p-type Czochralski silicon is given as 138 μm .

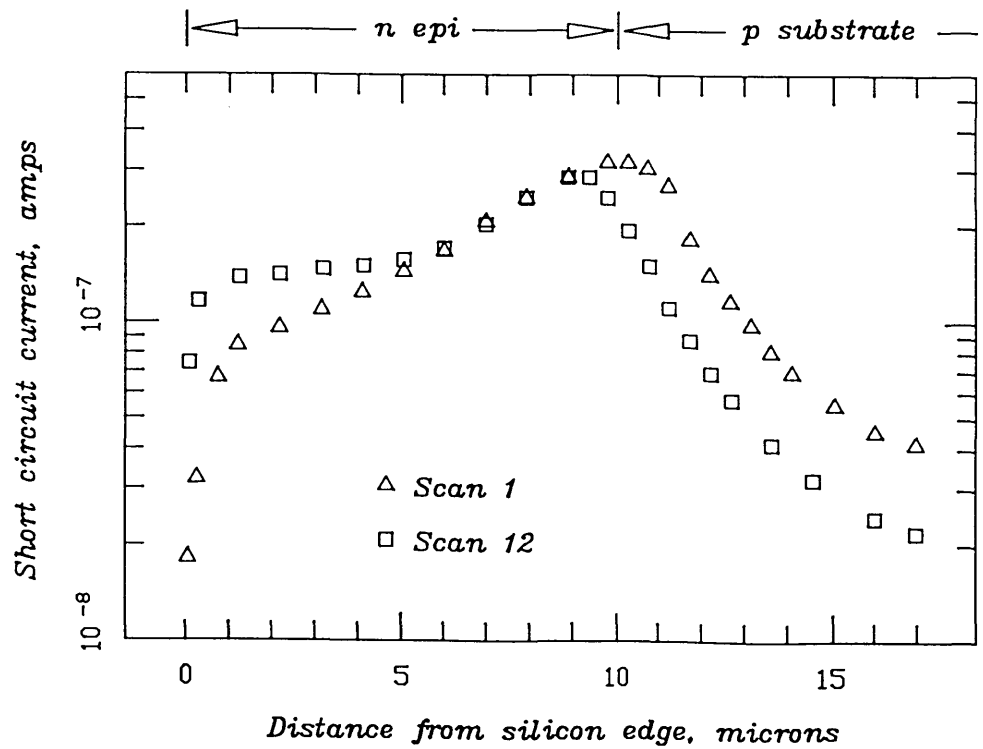
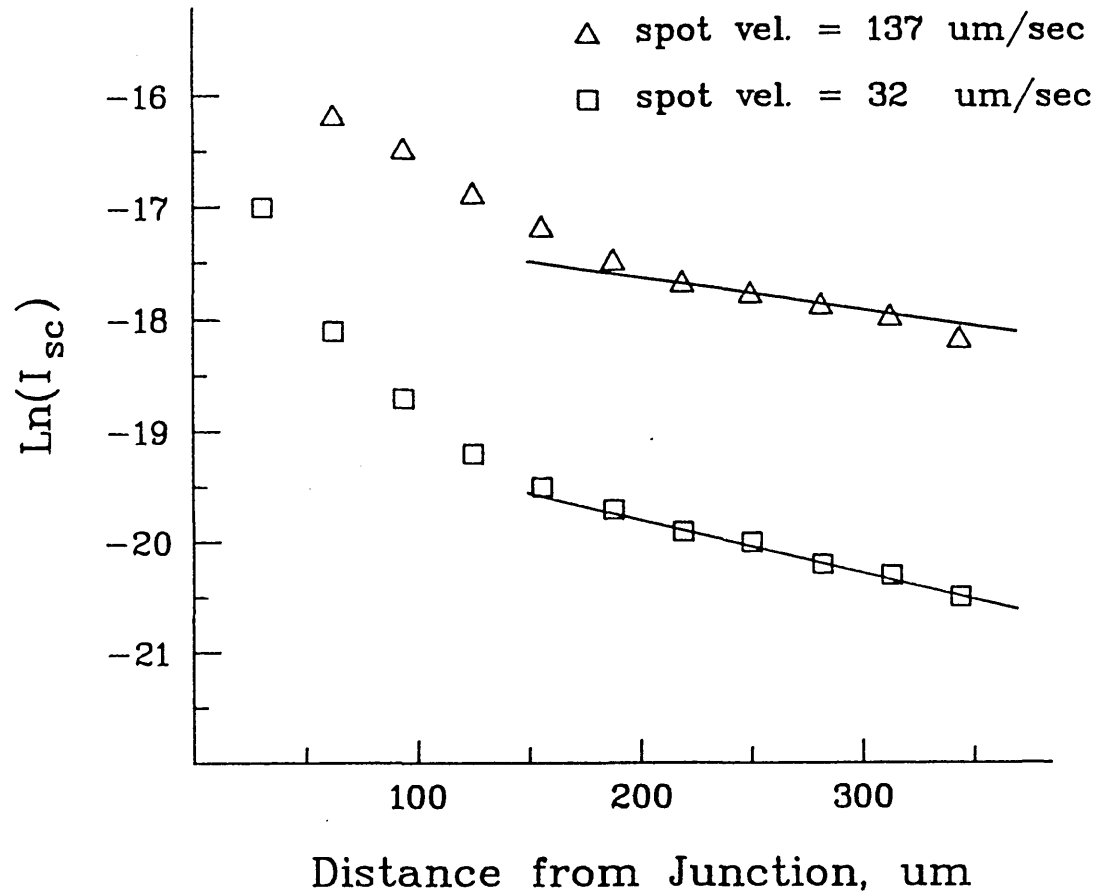
Figure 3.1.6 shows two linescans over a fresh region of 1.97 ohm-cm silicon. Data was taken for every linescan starting with the first. Although I_{sc} on the p side of the junction decreased with subsequent scans as in figure 3.1.3, the specimen area had not previously been exposed to the electron beam. After the twelfth linescan the shape and magnitude of the EBIC linescan did not change.

3.1.2 Macroscopic Experimental EBIC Linescans

Conductive mode linescan data were taken from three p-type Czochralski silicon substrates whose bulk resistivity was measured and found to be 1.97, 2.8 and 8.5 ohm-cm. These substrates each had 10 μm of 7.5 ohm-cm n-type epi deposited according to the procedure in section 2.2. Linescans were recorded over a range of beam voltages from 3 to 25 kV and the

Figure 3.1.5. Linescans across 8.5 Ω -cm silicon. Beam current, voltage and magnification are the same for both curves, only the scan speed differed. The bottom curve is for the slower scan. The beam was allowed to scan for a few minutes before data was taken.

Figure 3.1.6. Linescans across 1.97 Ω -cm silicon never before exposed to the electron beam. $V_b = 12$ kV, $I_b = 0.15$ nA, dose rate ≈ 7000 Mrads/min. The shape of the EBIC trace remained constant after the twelfth scan. Each linescan took 20 seconds and was about 20 μ m long.



experimental data appear in figures 3.1.7 through 3.1.9. This data is plotted as the normalized short circuit current for curve fitting using a computer program called EBICsim that is described in section 3.1.4.1. Only data from the p-type side of the junction is shown.

The distance between the edge of the depletion region and the back contact was taken to be the substrate thickness prior to epitaxial deposition. This was measured and found to be $388 \pm 3 \mu\text{m}$ for all three silicon specimens. Although it might appear from figure 3.1.9 for the 8.5 ohm-cm material, that the back contact was only 250 μm from the depletion region edge.

3.1.3 Experimental EBIC Linescans Over the Junction

As a p-n junction is reverse biased, its depletion region widens according to equation 1.1.2. An EBIC linescan over the p-n junction should tend to flatten out over the depletion region when most or all of the generation volume is enclosed by the depletion region. This was tested experimentally over a range of reverse bias and electron beam voltages using the materials described in section 3.1.2. The experimental configuration used to record EBIC linescans using reverse bias is described in section 2.1. The specimen thickness was used to determine the lateral scale. For each beam voltage and p-type bulk resistivity a linescan was recorded at reverse bias voltages from 0 to 20 volts in intervals of 4 volts. These results are shown in figures 3.1.10 through 3.1.17.

Reverse biasing beyond 20 volts was not desirable for two reasons. The reverse breakdown voltage for most specimens was around -25 volts. Also the reverse leakage current at -20 volts was usually equal to or greater than the short circuit current which made the linescan intolerably noisy. To overcome the noise problem due to reverse leakage current, smaller area specimens were prepared.

Figure 3.1.7. Experimental EBIC linescans across 400 μm of p-type, 1.97 $\Omega\text{-cm}$ bulk silicon for four beam voltages. Linescan time = 60 sec.

25 kV: $I_b = 2.4 \text{ nA}$

15 kV: $I_b = 0.6 \text{ nA}$

10 kV: $I_b = 1.4 \text{ nA}$

6 kV: $I_b = 0.52 \text{ nA}$

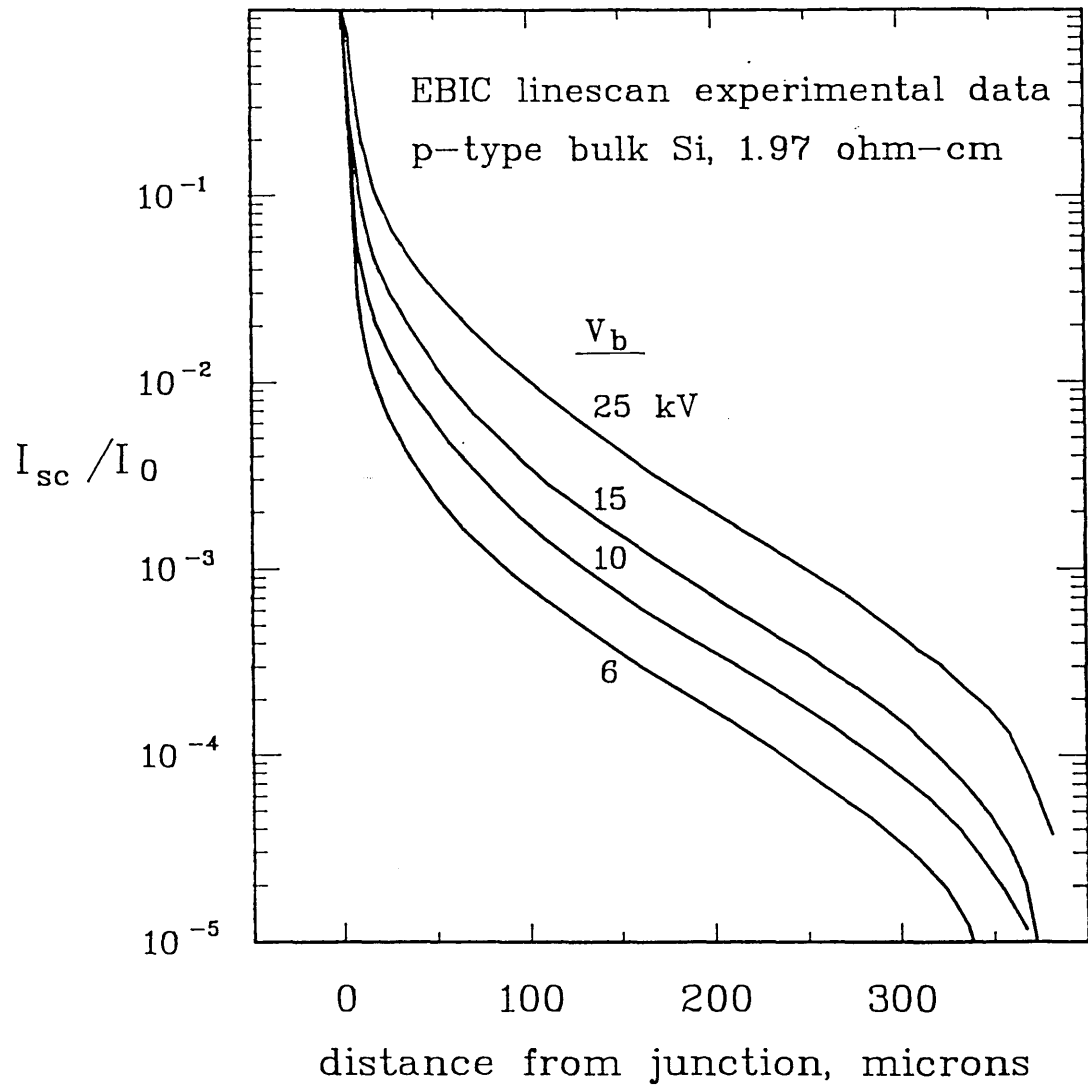


Figure 3.1.8. Experimental EBIC linescans across 400 μm of p-type, 2.8 $\Omega\text{-cm}$ bulk silicon for six beam voltages. Linescan time = 60 sec.

25 kV: $I_b = 1.3 \text{ nA}$

20 kV: $I_b = 0.46 \text{ nA}$

15 kV: $I_b = 0.42 \text{ nA}$

8 kV: $I_b = 1.1 \text{ nA}$

6 kV: $I_b = 0.72 \text{ nA}$

3 kV: $I_b = 0.08 \text{ nA}$

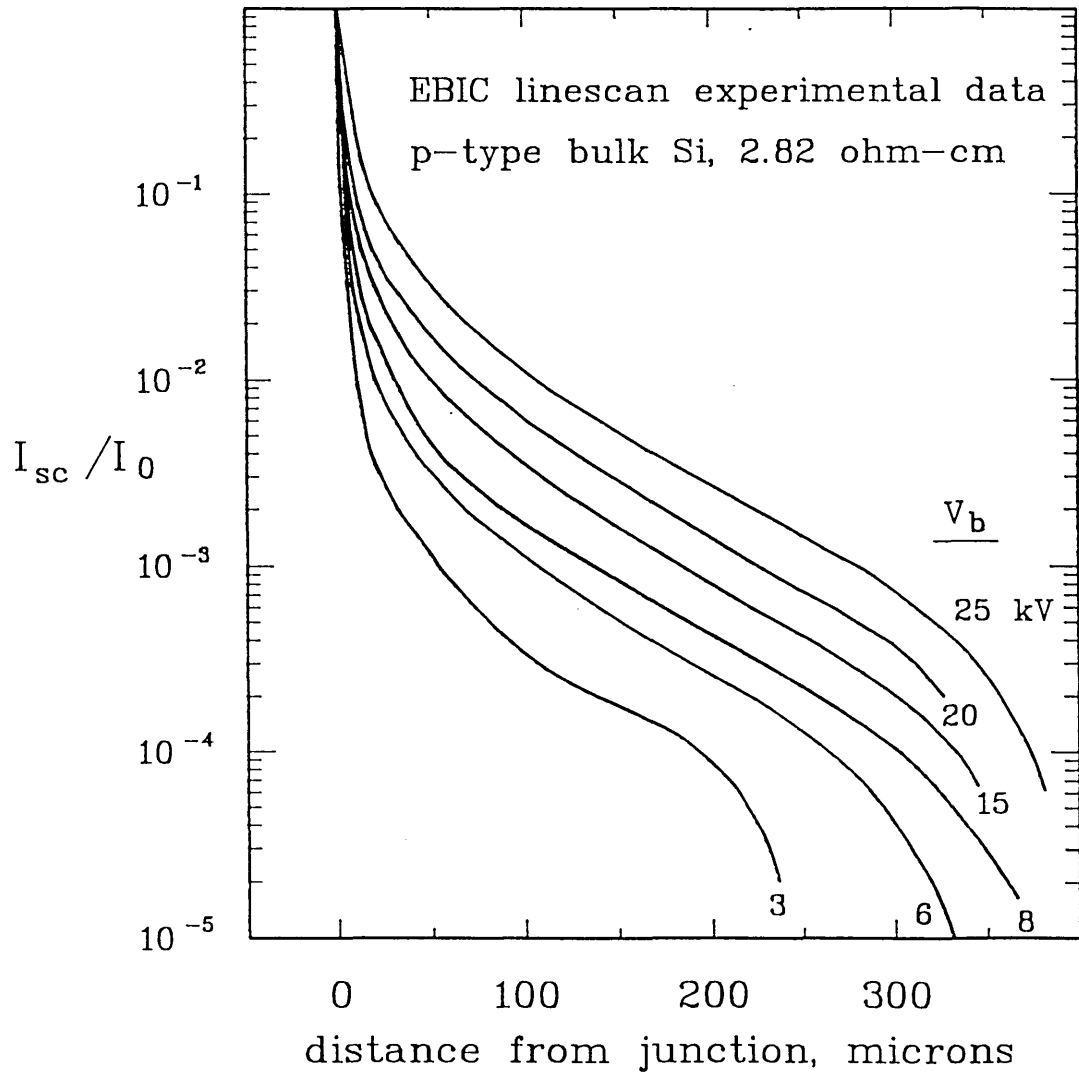


Figure 3.1.9. Experimental EBIC linescans across 400 μm of p-type, 8.5 $\Omega\text{-cm}$ bulk silicon for four beam voltages. Linescan time = 60 sec.

25 kV: $I_b = 2.5 \text{ nA}$

15 kV: $I_b = 1.5 \text{ nA}$

10 kV: $I_b = 2.3 \text{ nA}$

6 kV: $I_b = 1.5 \text{ nA}$

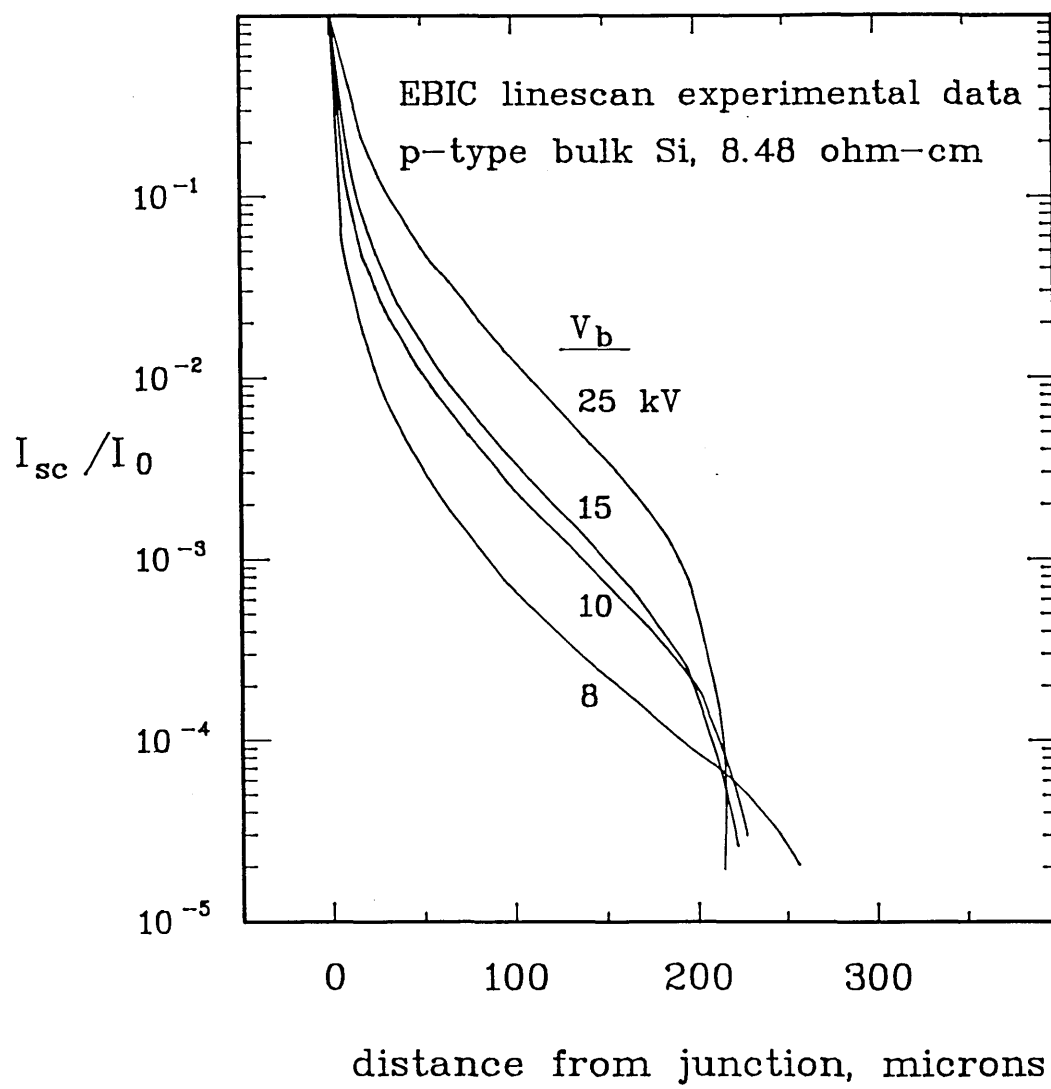


Figure 3.1.10. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 25$ kV, p-type bulk silicon resistivity = $1.97 \Omega\text{-cm}$.

Figure 3.1.11. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 15$ kV, p-type bulk silicon resistivity = $1.97 \Omega\text{-cm}$.

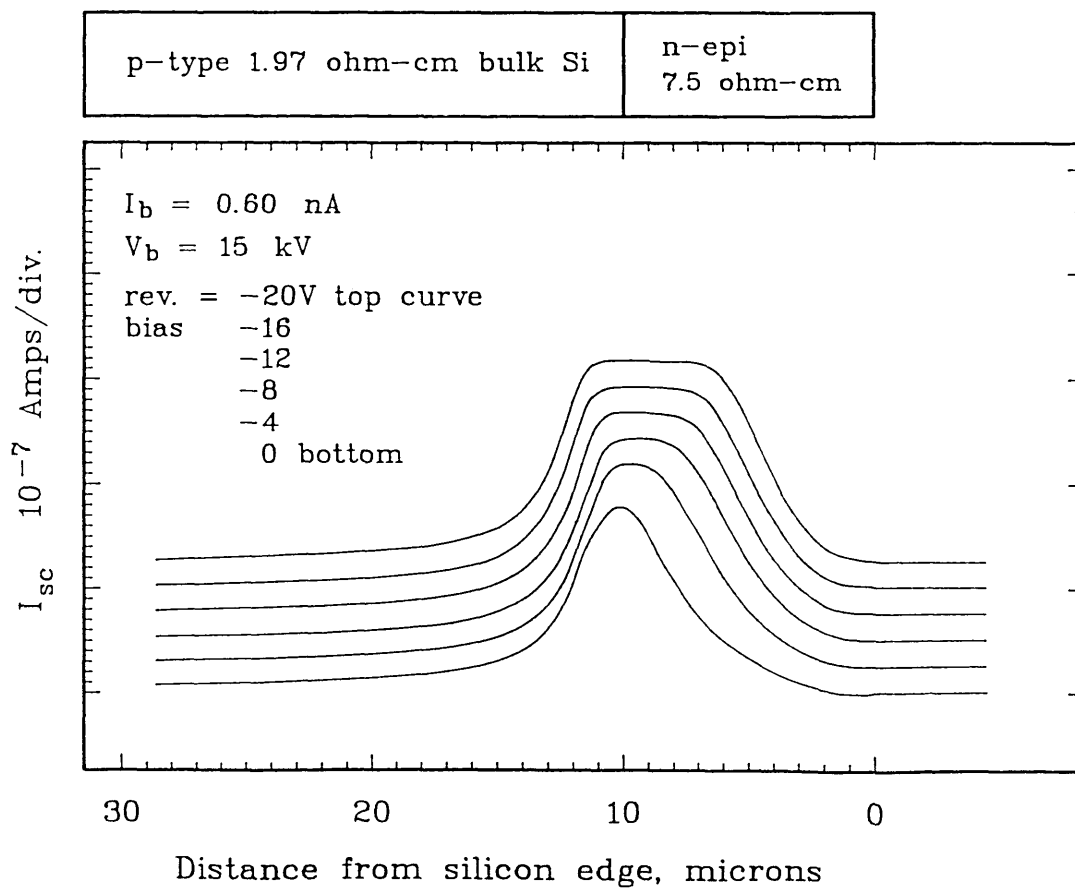
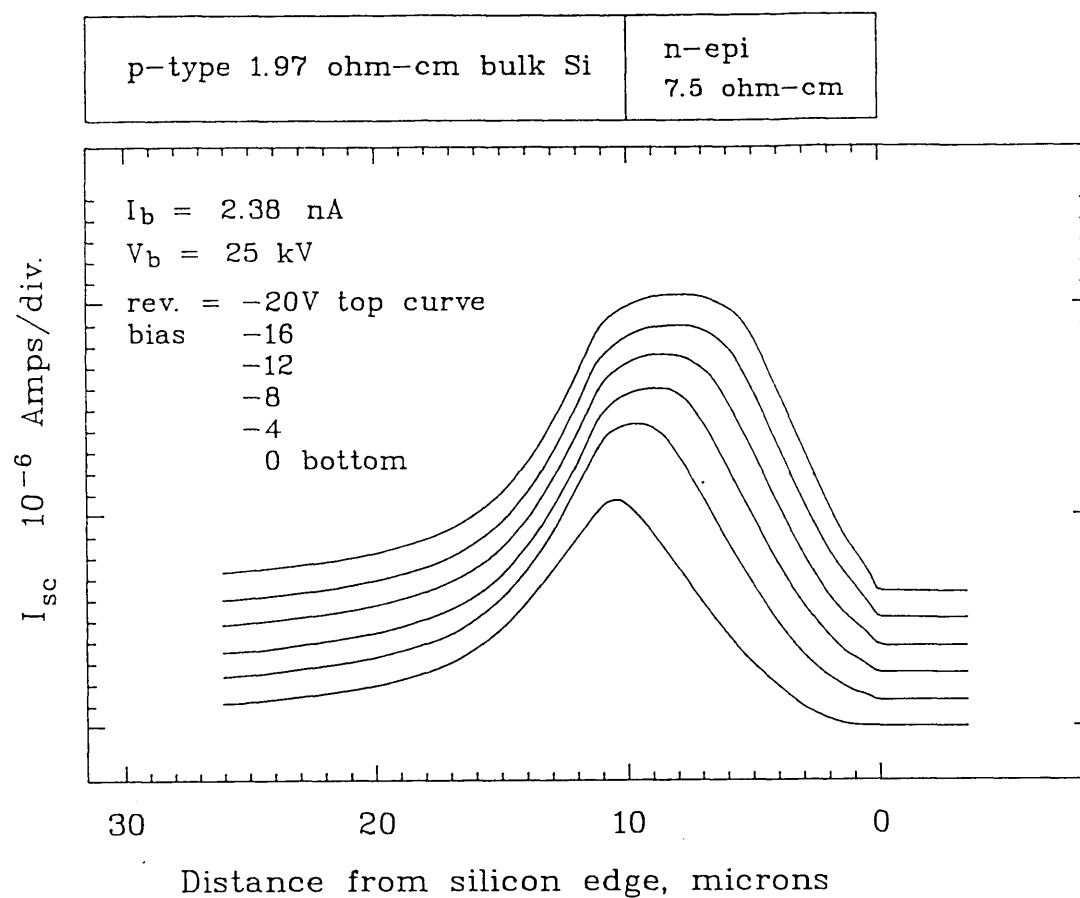


Figure 3.1.12. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 10$ kV, p-type bulk silicon resistivity = $1.97 \Omega\text{-cm}$.

Figure 3.1.13. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 6$ kV, p-type bulk silicon resistivity = $1.97 \Omega\text{-cm}$.

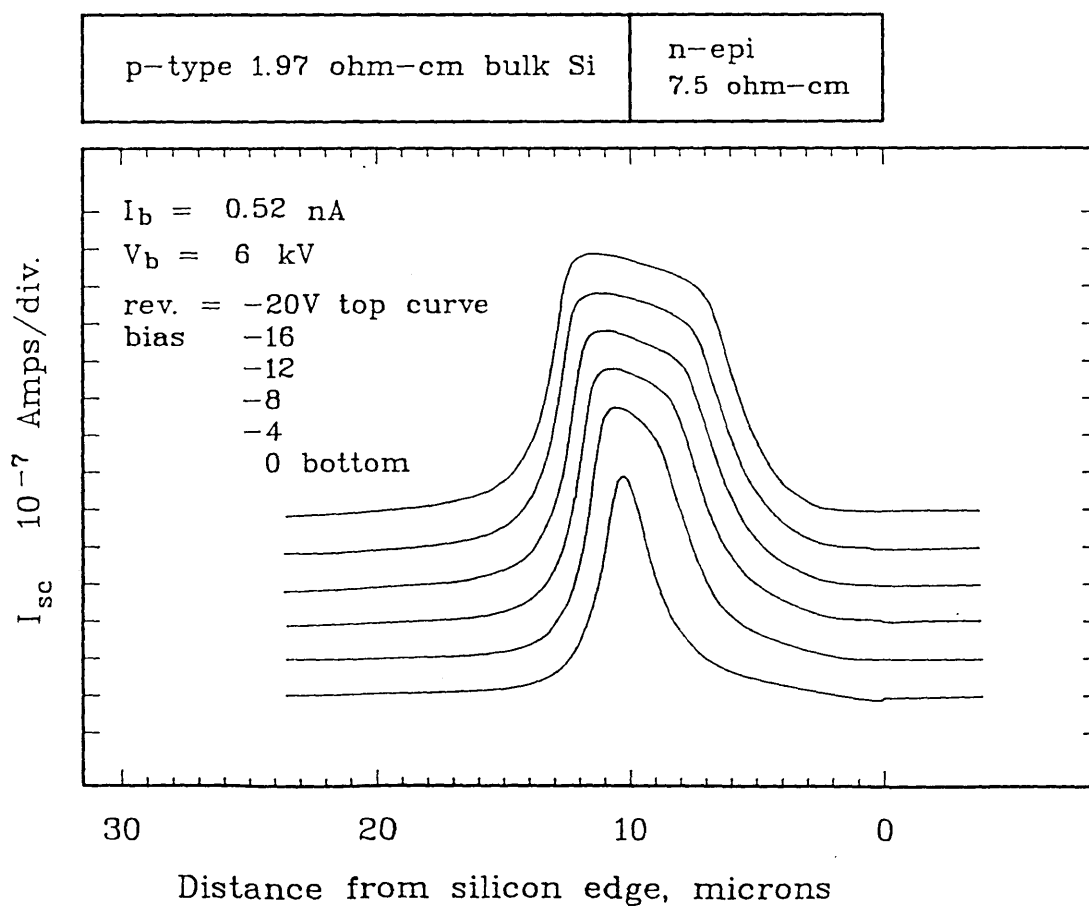
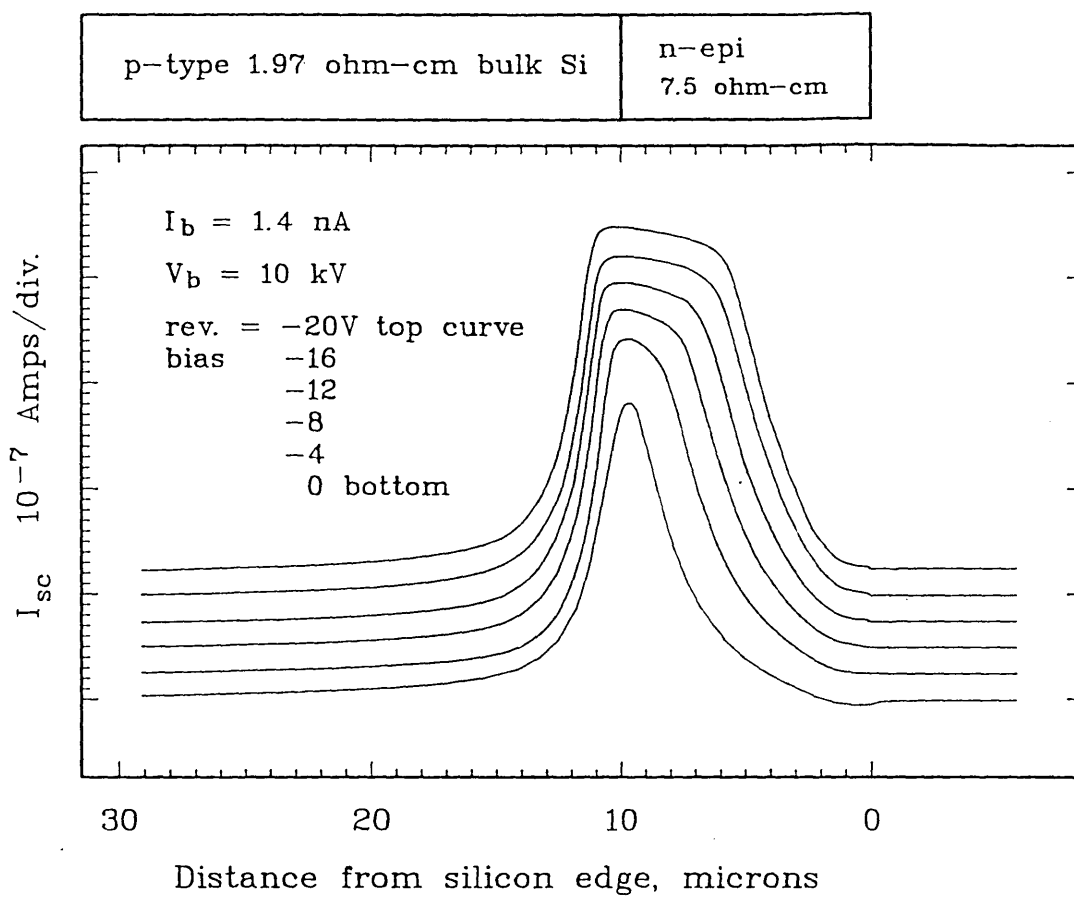


Figure 3.1.14. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 25$ kV, $I_b = 2.5$ nA, p-type bulk silicon resistivity = $8.5 \Omega\text{-cm}$.

Figure 3.1.15. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 15$ kV, $I_b = 1.5$ nA, p-type bulk silicon resistivity = $8.5 \Omega\text{-cm}$.

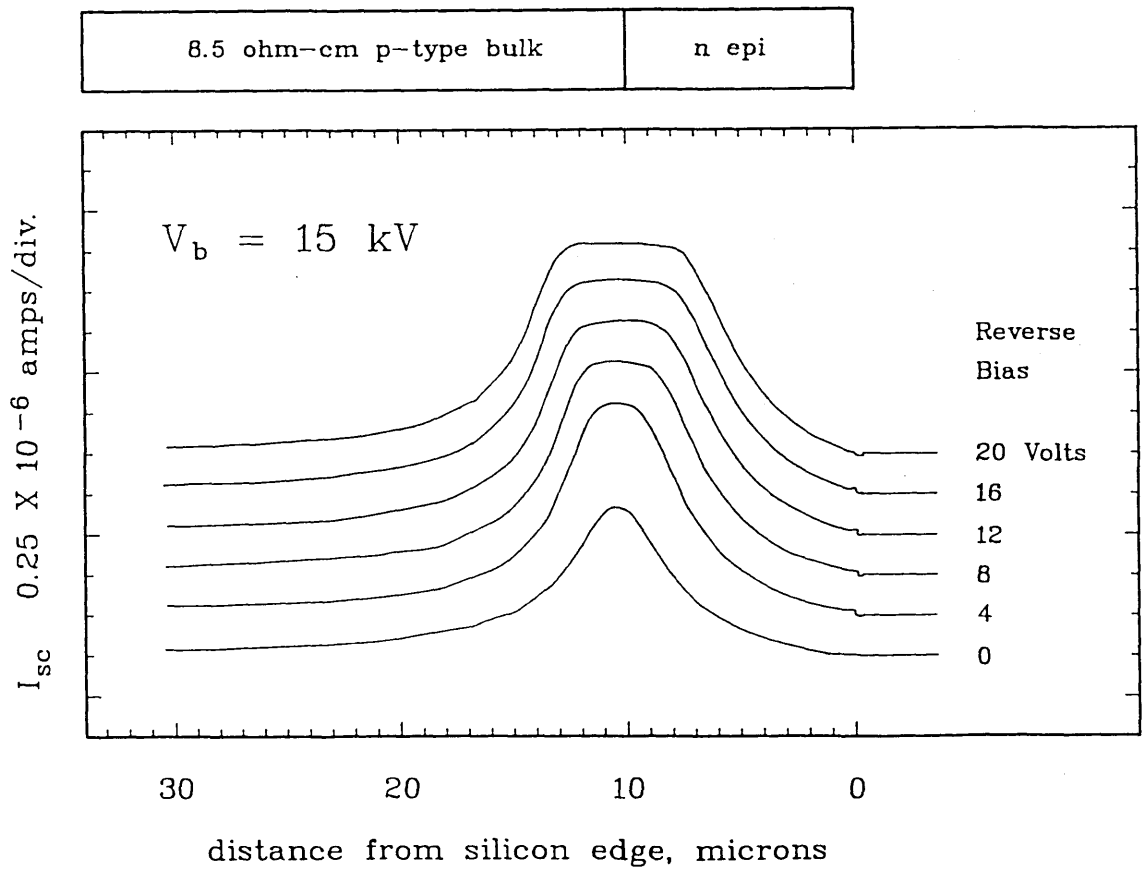
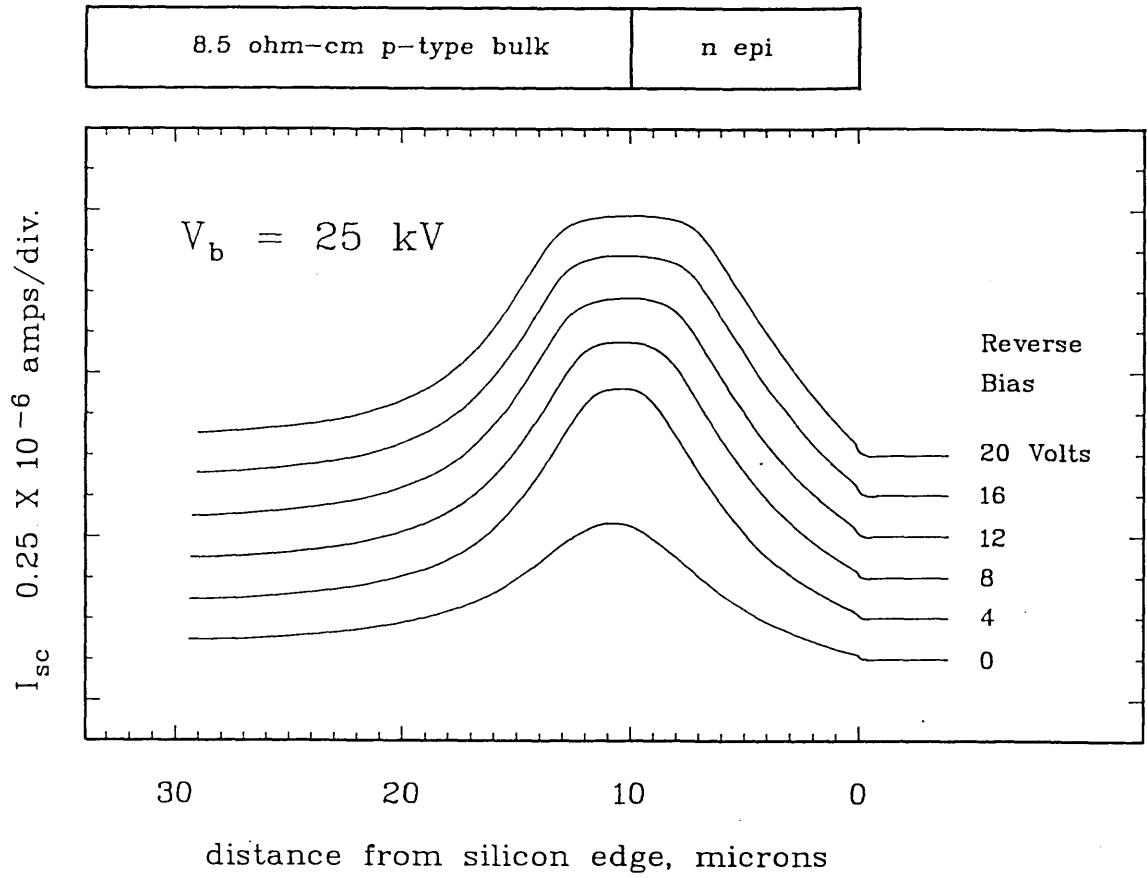
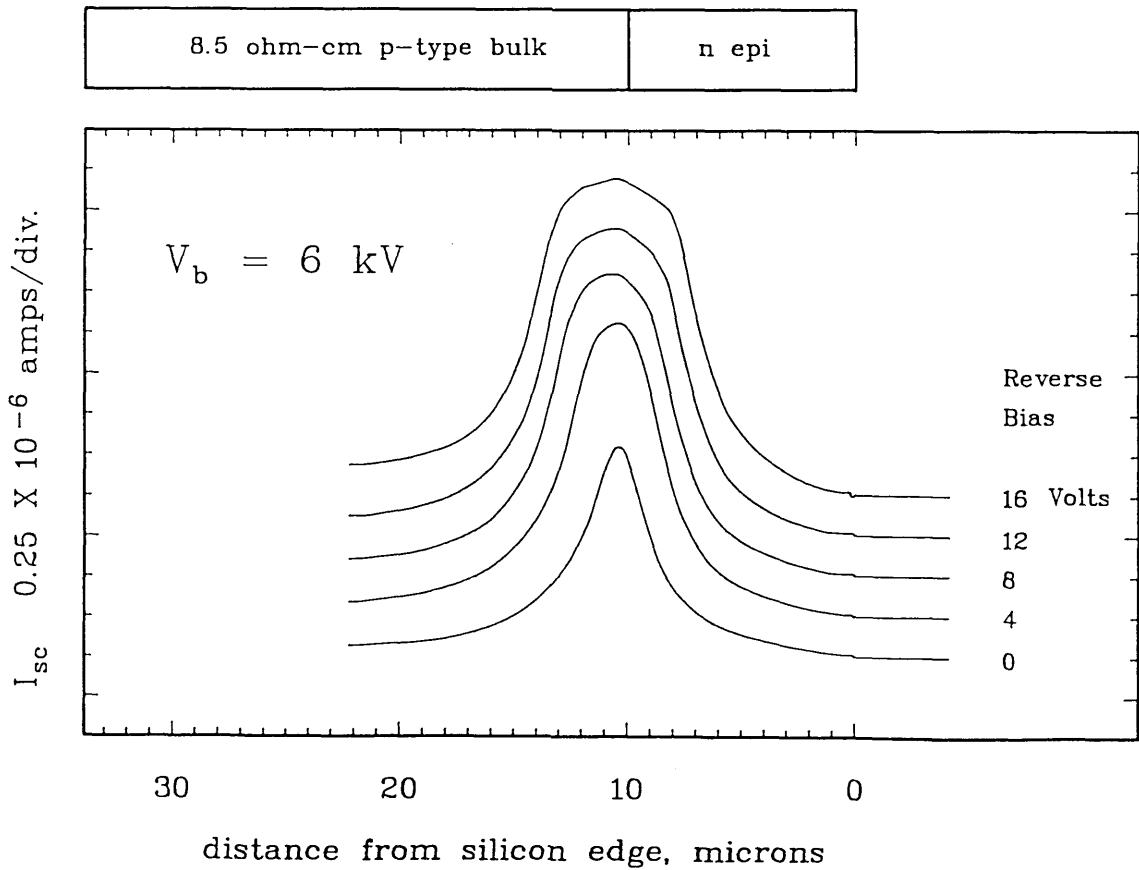
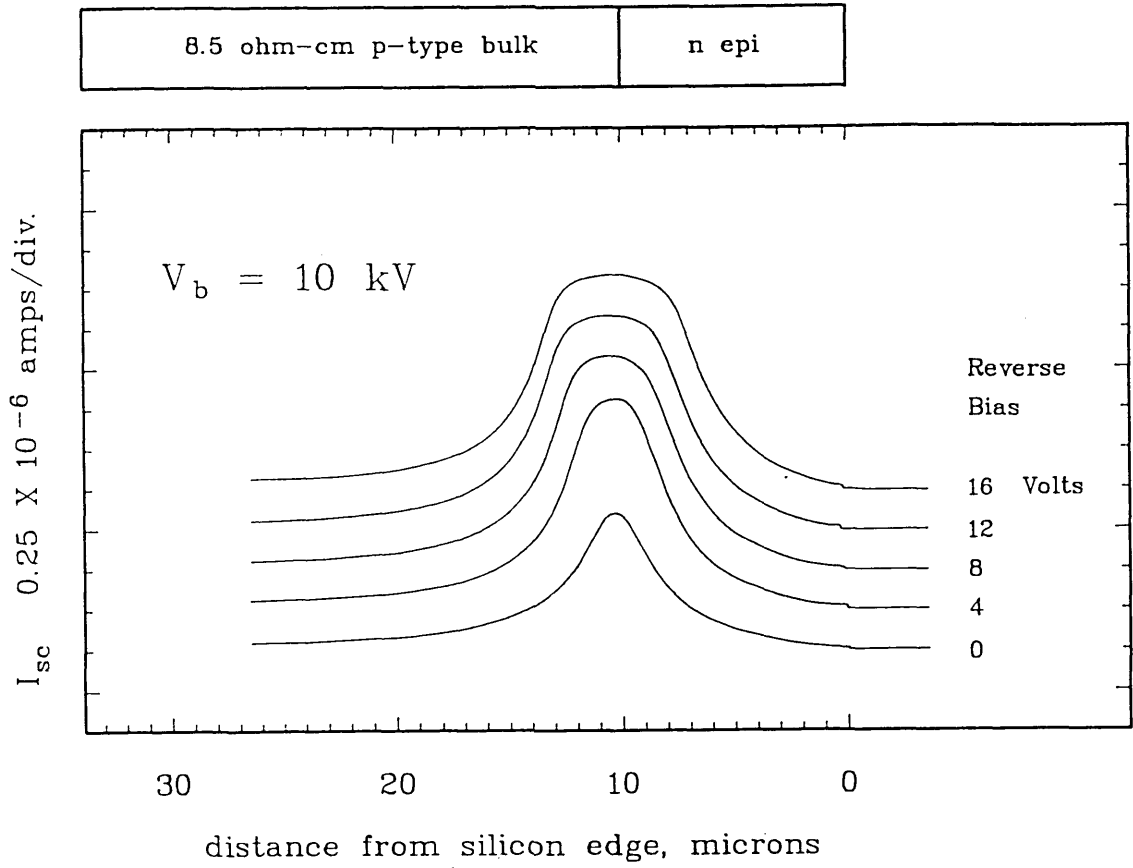


Figure 3.1.16. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 10$ kV, $I_b = 2.3$ nA, p-type bulk silicon resistivity = $8.5 \Omega\text{-cm}$.

Figure 3.1.17. High magnification EBIC linescans over a silicon p-n junction at various values of reverse bias. $V_b = 6$ kV, $I_b = 1.5$ nA, p-type bulk silicon resistivity = $8.5 \Omega\text{-cm}$.



3.1.4 Computer Solutions to Donolato's Equations

3.1.4.1 Macroscopic model

Equation 1.2.8 obtained by Donolato (1982) for a silicon specimen of infinite thickness was solved numerically using an IBM PC/AT computer fitted with an 80287 co-processor by writing a Pascal program called EBICsim. A copy of this program is included in Appendix B. EBICsim simulates an EBIC linescan by calculating the short circuit current for the beam incident at various distances from the depletion region edge.

The input parameters required by EBICsim are the following:

- (1) accelerating voltage, V_b
- (2) L_e or τ_e (p-type Si), or L_h or τ_h (n-type Si)
- (3) ionized impurity concentration, N_a or N_d
- (4) distance of the incident electron beam from
the depletion region edge
- (5) temperature
- (6) surface recombination velocity

Although temperature is required as input, EBICsim uses equations 1.1.7 or 1.1.8 to calculate the mobility. These empirical relationships are for silicon at 300° K. Therefore any significant deviation in the temperature input will result in calculations based on a questionable value for the mobility.

The EBICsim solution to equation 1.2.8 (referred to as the infinite specimen thickness model) uses equation 1.2.6 as an approximation to the function $h(x,z)$. This is a satisfactory assumption only for values of $x_0 \gg R$ and $L \gg R$ where x_0 is the distance from the incident electron beam to the depletion region edge.

The integral in equation 1.2.8 was evaluated using equation 1.2.10 and the error function was evaluated using equations 1.2.11 and 1.2.12. The numeric integration was divided into steps according to

$$\int_0^{\infty} f(x) dx \approx \int_0^{a_1} f(x) dx + \int_{a_1}^{a_2} f(x) dx + \dots + \int_{a_{n-1}}^{a_n} f(x) dx \quad (3.1.1)$$

where the bounds of integration for each term were such that the $\sin(kx_0)$ term of equation 1.2.8 was evaluated over one period (2π radians). The integration from 0 to ∞ was approximated by integrating from 0 to a_n on the condition that the last term in equation 3.1.1 was less than 0.05% of the sum of the previous terms. The 0.05% limit was determined by trial and error as the point where precision to the third significant digit did not change as the limit decreased; i.e. the point where precision was not significantly improved as a_n increased.

Fig 3.1.18 shows curves generated using values of the short circuit current calculated by EBICsim. These data are reported in dimensionless units of S ($= v_s L/D$), R/L and X_0 ($= x_0/L$). Figure 3.1.18 was constructed for comparison to Donolato's figure 2 (1982) as evidence that the equations had been solved correctly.

EBICsim also solves equation 1.2.4 by using equation 1.2.5 for a specimen of finite thickness. In this case the function $h(x,z)$ is approximated to a point source at $0.3 \times R$ below the surface. This is a satisfactory assumption only for values of $x_0 \gg R$ and $L \gg R$. In addition to the input parameters listed above, the specimen thickness is also required. The summation in equation 1.2.5 is terminated when the term $\exp(-z\mu_i) < e^{-2.5}$ since at this point the product within the summation is nearly 0.

Figure 3.1.18. Normalized short circuit current versus beam position for different surface recombination velocities and electron ranges calculated from equation 1.2.8 using the Pascal computer program EBICsim. $S = v_s L/D$

Figure 3.1.19. Normalized short circuit current versus beam position for different surface recombination velocities and electron ranges calculated from equation 1.2.5 using the Pascal computer program EBICsim. Specimen thickness was taken to be $4L$.

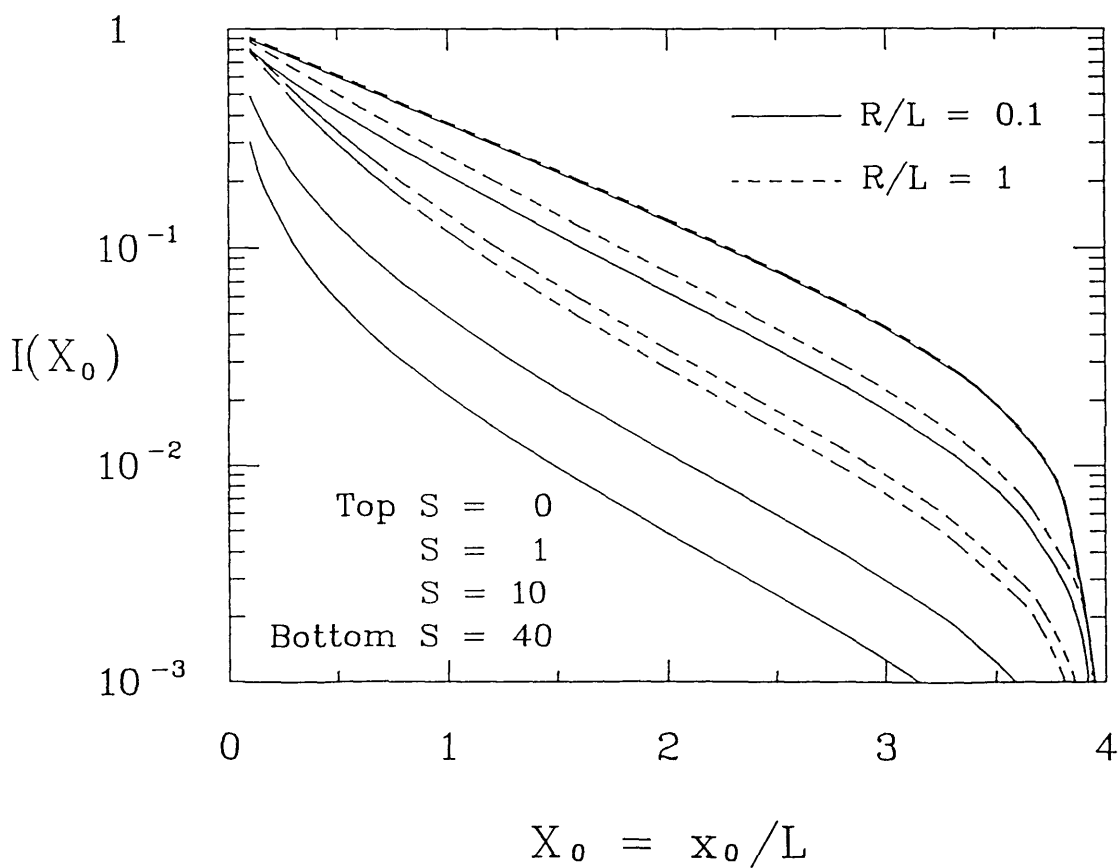
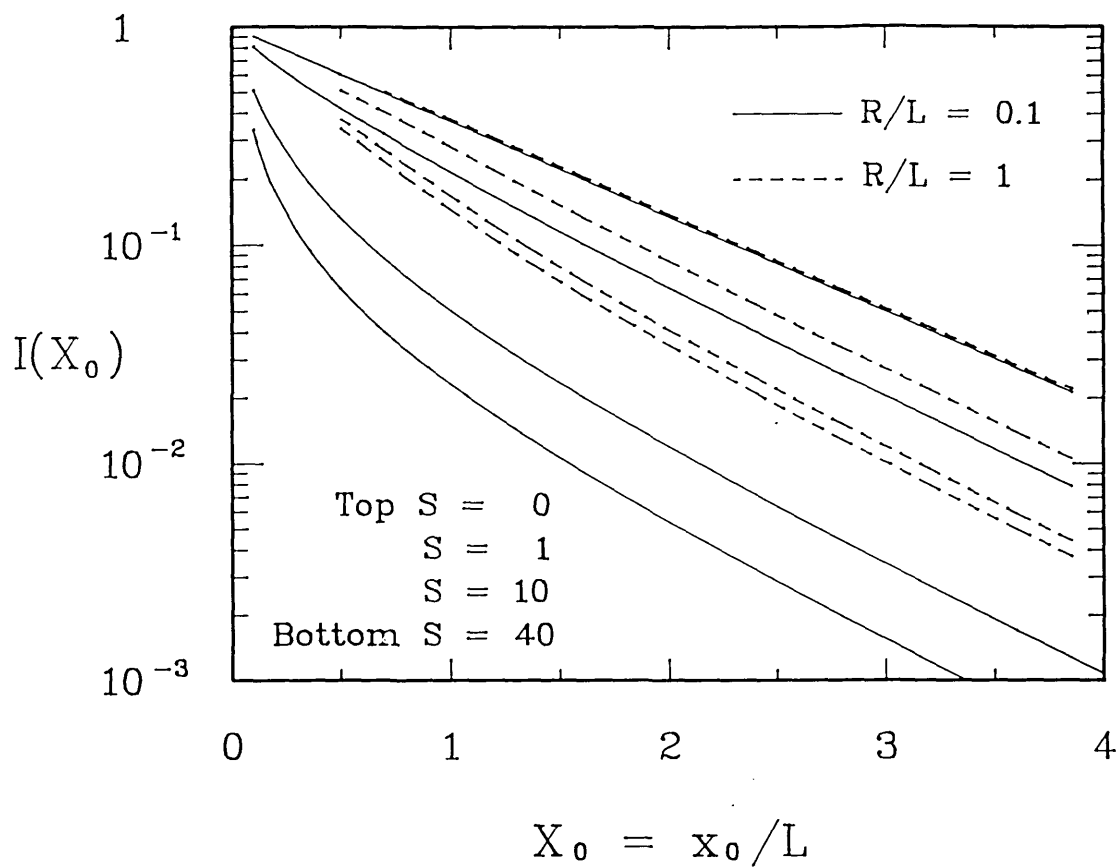


Figure 3.1.19 shows the EBICsim solution of the finite specimen thickness model assuming there is an ohmic contact on the back face which is 4 diffusion lengths from the edge of the depletion region.

3.1.4.2 Simulation of EBIC Linescans Over the Junction

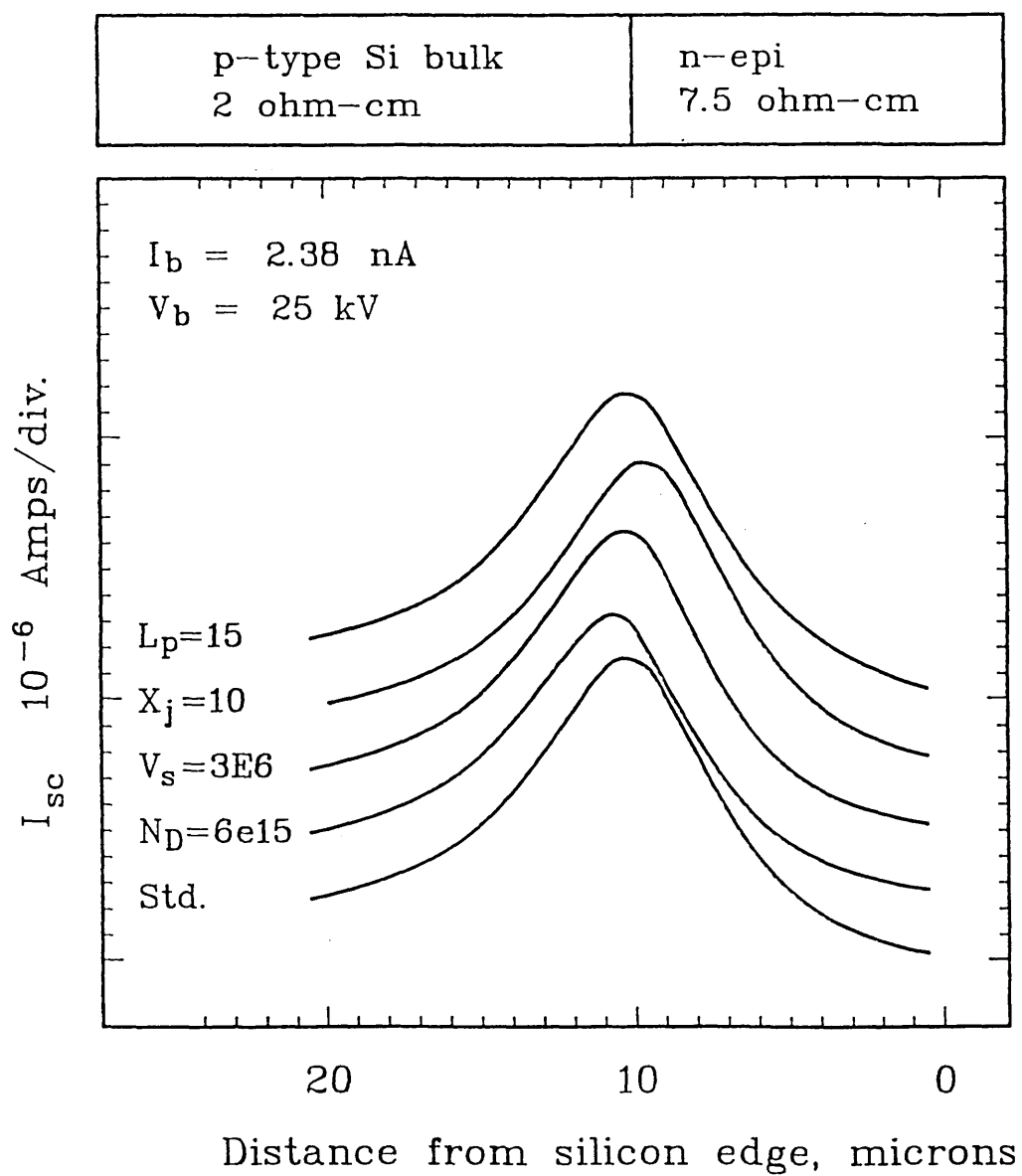
A Pascal computer program called nearEBIC was written to solve equation 1.2.4 when the conditions $x_0 \gg R$ and $L \gg R$ are not met. This is particularly useful for the case when the beam scans directly over the p-n junction and the generation volume is partly included within the depletion region. To do this, nearEBIC calculates the carrier collection probability $Q(x,z)$, given in equation 1.2.5, in the same fashion as does the program EBICsim. However, instead of assuming $h(x,z)$ is a point source, nearEBIC operates on the output file containing the lateral dose energy array produced by the Monte Carlo simulation program described by Napchan (1987).

nearEBIC cannot solve for $Q(x,z)$ for each of the 6400 elements in the energy array as described in section 1.2.2 because the computation time is excessive. Instead the energy array is approximated to 80 planes of deposited energy parallel to the charge collection barrier. The depth of the electron-hole pairs generated within each plane is taken to be the average value of $0.3 \times R$.

A copy of nearEBIC is included in Appendix C. An example of EBIC linescans calculated by nearEBIC is shown in figure 3.1.20. In this set of curves, all at 0 volts bias, the effect on the shape of the EBIC linescans can be seen as only one parameter is varied at a time from the values used for a standard curve shown at the bottom. The input parameters for the standard curve are from the 1.97 ohm-cm silicon material with a 10.6 μm epi layer prepared as described in section 2.2.

Figure 3.1.20. A comparison of solutions to equation 1.2.4. $h(x,z)$ found from Monte Carlo simulation. One parameter was varied at a time from a standard linescan. Calculated using the Pascal computer program nearEBIC.

Standard linescan parameters: v_s epi = 3×10^5 cm/sec, v_s substrate = 3×10^5 cm/sec, $N_d = 6 \times 10^{14}$ cm $^{-3}$, $N_a = 6.7 \times 10^{15}$ cm $^{-3}$, $L_h = 5$ μ m, $L_c = 90$ μ m, $X_j = 10.6$ μ m, $V_r = 0$ volts.



3.2 Conductive Mode Analysis of GaAs Bipolar Transistor

A commercially fabricated GaAs bipolar transistor was examined for the purpose of extending the fundamental principles of conductive mode analysis to complex device structures. The bipolar transistor examined was a large area device of circular geometry mounted in a T0-18 header with contacts to emitter, base and collector regions. The (100) GaAs material used for the active area of the device was grown over semi-insulating single crystal Czochralski GaAs using molecular beam epitaxy (MBE). A cross-section of the MBE material used to fabricate this device is shown in figure 3.2.1. The specimen is identified as MBE 193 and is a homojunction device. The number 193 identifies the MBE deposition at the GEC Hirst Research Centre, Wembley, where the device was fabricated.

The final structure was produced by photo-masking and etching the MBE material and a cross-section of the final multi-tiered structure is shown in the schematic diagram of figure 3.2.2. The emitter cap and the collector 2 materials were highly doped to provide contacts to the emitter and collector 1. Emitter and collector metallization is composed of 0.3 μm of Au/Ni/Ge with a 0.4 μm gold cap. Base metalization is 0.3 μm of Au/Ti with an identical gold cap. Metallization was patterned using a lift-off process as opposed to etching which would destroy the GaAs material.

An emissive mode micrograph of MBE 193 is shown in figure 3.2.3 and an EBIC micrograph of the same area is shown in figure 3.2.4. The diameter of the emitter region is approximately 100 μm . It can be seen from these micrographs that the MBE 193 specimen suffered from poor metal adhesion, especially over the emitter region. This led to complications in making the thermocompression wire bond which resulted in some mechanical damage to the relatively soft unpassivated GaAs material.

Figure 3.2.2 shows generally how the EBIC signal was collected from the transistor. It also shows a mnemonic key to abbreviations used to describe the six possible wiring

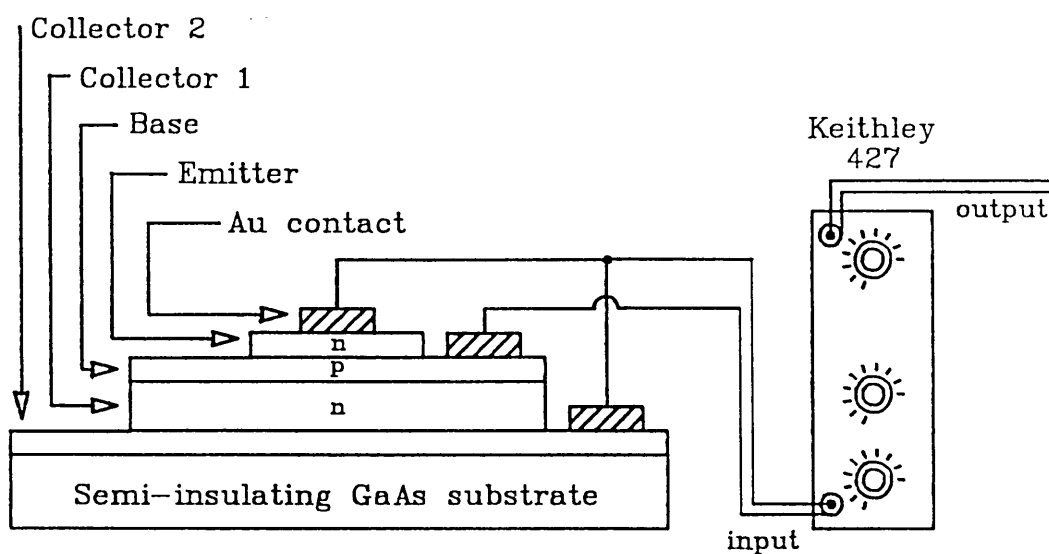
Figure 3.2.1. Cross-section of MBE GaAs material used to fabricate specimen MBE 193.

Material: MBE 193

Emitter Cap	n+ GaAs 2E18 Si, 0.19 um	
Emitter	n GaAs 2E17 Si, 0.30 um	
		intrinsic GaAs, 0.01 um
Base	p+ GaAs 1E18 Be, 0.30 um	
		intrinsic GaAs, 0.01 um
Collector 1	n- GaAs 1E16 Si, 1.0 um	
Collector 2	n+ GaAs 1E18 Si, 0.50 um	
		intrinsic GaAs, 0.05 um
Super Lattice Buffer	0.195 um intrinsic	
		intrinsic GaAs, 0.055 um
Semi-Insulating Cz (100) GaAs substrate		

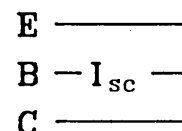
Figure 3.2.2. Schematic representation of how the EBIC signal was collected for examination of planar GaAs bipolar transistor.

Experimental Configuration for MBE 193



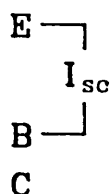
Wiring abbreviation for configuration above:

Mnemonic: B-EC

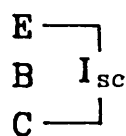


Other wiring configurations used:

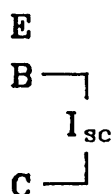
E-B



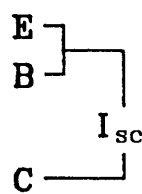
E-C



B-C



C-BE



E-BC

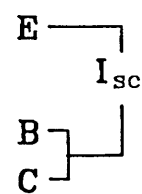


Figure 3.2.3. Emissive mode micrograph of MBE 193 showing the position of quantitative EBIC linescans. The gold bonding wire is 12.5 μm thick. Emitter, base and collector are marked E, B and C. $V_b = 25 \text{ kV}$.

Figure 3.2.4. EBIC micrograph of figure 3.2.3 showing position of quantitative linescans. $V_b = 9 \text{ kV}$.



100 μ m



permutations used to collect the EBIC signal. The " I_{sc} " stands for the short circuit current measured across the indicated contacts. If a letter E, B or C has no wire going to it this means it was allowed to float electrically and the short circuit current was taken across the other two contacts alone, as is the case for configurations E-B, E-C and B-C. For configuration C-BE, emitter and base were commoned (i.e. shorted together) while the base-collector junction alone provided the charge collection barrier. For configuration E-BC base and collector were commoned in a similar fashion.

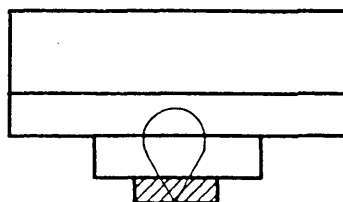
In addition to the six wiring configurations there were four basic beam positions on the transistor that gave conductive mode signals of interest. These are shown schematically in figure 3.2.5 and are referred to later as results are presented. Two beam positions not shown are for the case when the beam is directed at bare collector 2 material or at collector metal. No conductive mode signal could be detected experimentally with the beam at these locations which is not surprising. The thin, highly doped collector 2 material probably has a short diffusion length making it unlikely that minority carriers could diffuse large distances laterally to reach a charge collection barrier. Also at higher beam energies most of the energy will be deposited in the semi-insulating GaAs below.

3.2.1 Quantitative EBIC of GaAs Bipolar Transistors

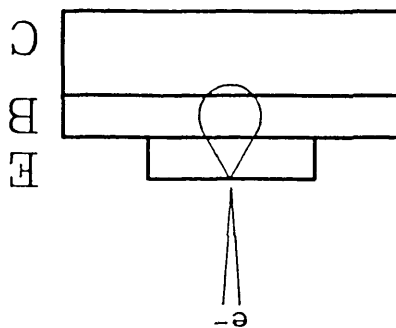
Macroscopic, low magnification EBIC linescans across the GaAs bipolar transistors were recorded using the six wiring configurations of figure 3.2.2 for a host of accelerating voltages from 3 to 25 kV. The position of these linescans is shown in figures 3.2.3 and figure 3.2.4 as a white line across the electron micrographs. The exact position of the linescan was not preserved from scan to scan intentionally to avoid a build up of a beam induced contamination layer on the surface. A single linescan was recorded for each wiring configuration at each beam voltage. Each linescan contained a conductive mode signal for each of the four beam positions shown in figure 3.2.5. A summary of this data for the MBE

Figure 3.2.5. Four types of conductive mode signal for examination of MBE 193. The transistor was unpassivated. (e) Electron beam over exposed emitter. (b) Electron beam over exposed base. (em) Electron beam over emitter metalization. (bm) Electron beam over base metalization.

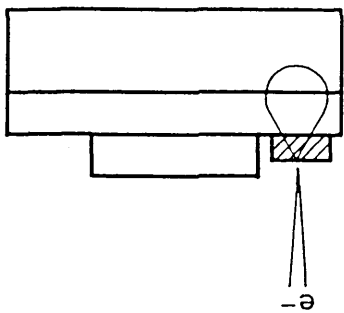
e_m)



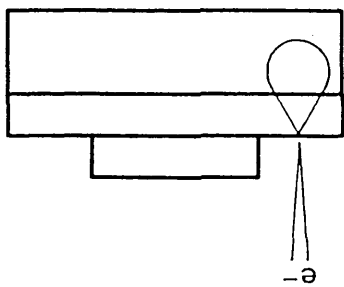
e)



b_m)



b)



193 homojunction device appears in table 3.2.1.

Values in table 3.2.1 are reported as the fraction I_{sc}/I_{max} where I_{max} is calculated according to equation 1.2.2.

Table 3.2.1

Configuration E-B; Values of I_{sc}/I_{max}

V_b	base	base <u>metal</u>	emitter	emitter <u>metal</u>
25 kV	.64	.56	.83	0
15	.68	.41	.86	0
12	.55	.26	.80	0
9	.39	.10	.65	0
7	.27	.03	.51	0
5	.18	0	.30	0
4	.11	0	.20	0
3	.06	0	.12	0

Configuration E-C; Values of I_{sc}/I_{max}

V_b	base	base <u>metal</u>	emitter	emitter <u>metal</u>
25 kV	-.29	-.23	-.08	.11
15	-.20	-.07	.42	.03
12	-.09	-.02	.58	0
9	-.02	-.002	.59	.008
7	-.01	-.003	.48	0
5	-.008	-.002	.30	0
4	-.01	-.0008	.21	0
3	-.007	0	.11	0

Configuration B-C; Values of I_{sc}/I_{max}

V_b	base	base <u>metal</u>	emitter	emitter <u>metal</u>
25 kV	.70	.60	.87	0
15	.74	.45	.88	0
12	.62	.27	.80	.01
9	.43	.11	.66	0
7	.30	.03	.50	0
5	.19	0	.31	0
4	.12	0	.21	0
3	.07	0	.12	0

Configuration B-EC; Values of I_{sc}/I_{max}

V_b	base	base <u>metal</u>	emitter	emitter <u>metal</u>
25 kV	.70	.62	.88	0
15	.74	.45	.88	0
12	.62	.27	.80	0
9	.43	.11	.66	0
7	.30	.03	.50	0
5	.19	0	.31	0
4	.12	0	.21	0
3	.06	0	.12	0

Configuration C-BE; Values of I_{sc}/I_{max}

V_b	base	base <u>metal</u>	emitter	emitter <u>metal</u>
25 kV	.72	.62	.53	0
15	.73	.44	.18	0
12	.62	.27	.04	-.02
9	.43	.11	0	-.01
7	.30	.04	0	0
5	.18	0	0	0
4	.12	0	0	0
3	.07	0	0	0

Configuration E-BC; Values of I_{sc}/I_{max}

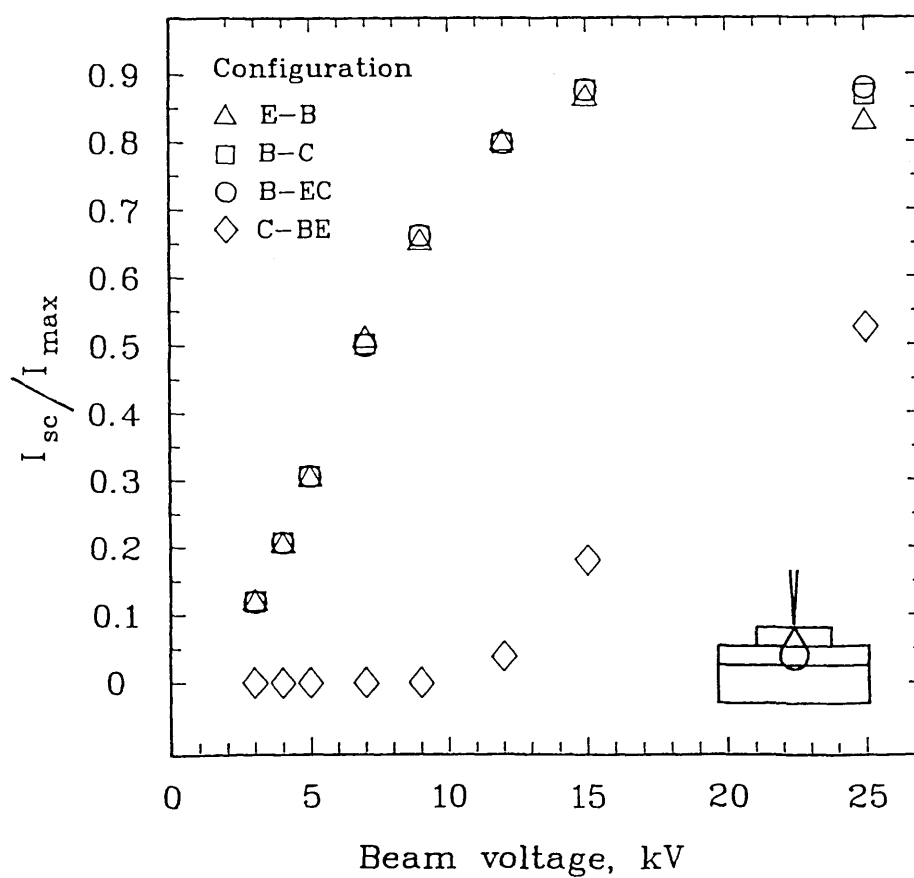
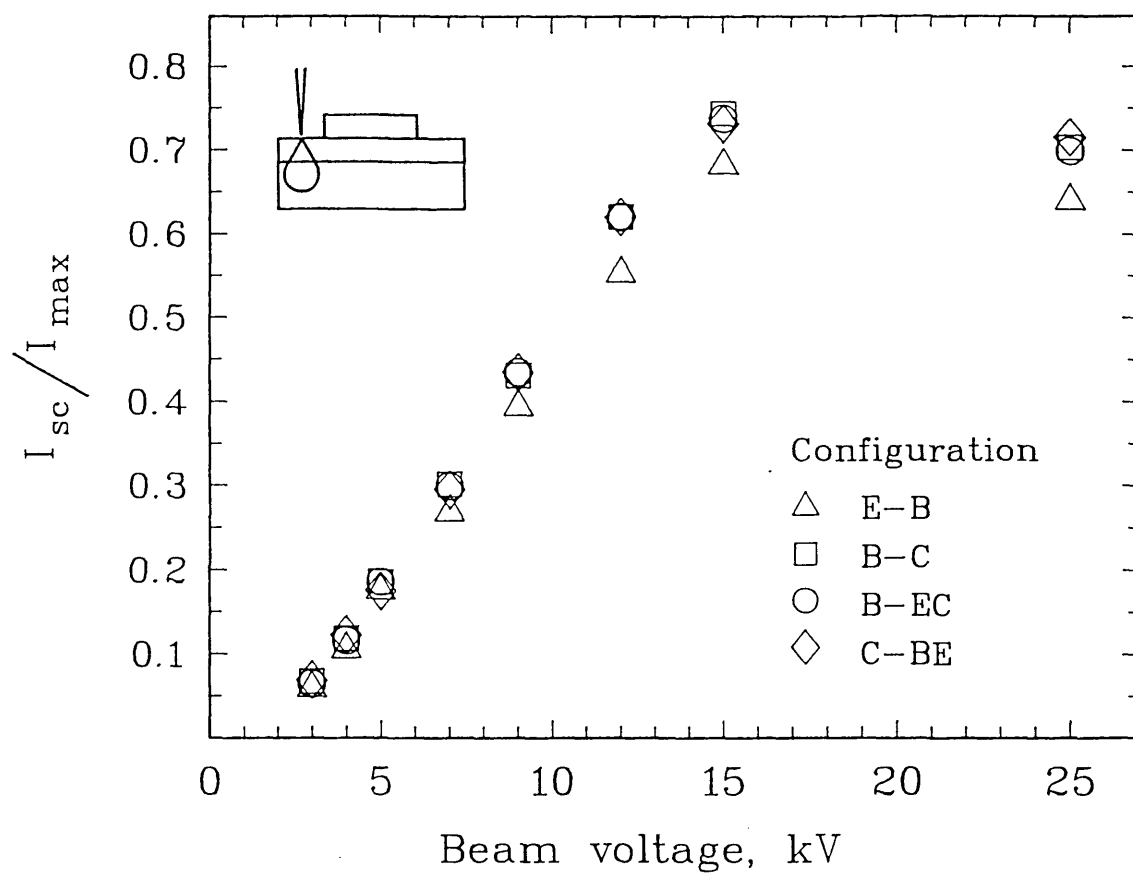
V_b	base	base metal	emitter	emitter metal
25 kV	0	0	.34	.02
15	0	0	.69	.02
12	0	0	.76	.01
9	0	0	.66	.006
7	0	0	.50	.004
5	0	0	.30	0
4	0	0	.20	0
3	0	0	.11	0

Figures 3.2.6 and 3.2.7 are constructed from the data in table 3.2.1 and show some unexpected similarities between wiring configurations E-B, B-C, B-EC and C-BE. In figure 3.2.6, I_{sc}/I_{max} is reported as a function of beam voltage for the case where the beam is directed at the exposed base. Wiring configurations B-C, B-EC and C-BE all employ the base-collector junction as a charge collection barrier. If the EBIC signal from the emitter-base junction be small compared to the EBIC collected by the base-collector junction, this would explain why configuration B-EC is the same as B-C and C-BE. However the data from configuration E-B not only show that the signal collected by the emitter-base is not small, they suggest it is virtually equal to the other 3 configurations. It is noteworthy that in order for the emitter-base junction to amplify the conductive mode signal, the carriers must diffuse laterally, up to 40 μm , from the point where the beam injects high energy primaries into the base and collector region. Also the experimental linescans showed that the signal collected using configuration E-B was constant as the beam scanned across the exposed base material.

Figure 3.2.7 is a comparison, similar to figure 3.2.6, except it is for the case where the electron beam is directed at exposed emitter material. Again there is an unexpected similarity between configurations E-B and B-C. This graph reveals yet another surprise; suddenly there is a significant difference in experimental results between configurations B-C and C-BE that

Figure 3.2.6. EBIC linescan data from MBE 193. Electron beam directed at the base. Comparison of four wiring configurations that yield nearly identical results.

Figure 3.2.7. EBIC linescan data from MBE 193. Comparison of the same four wiring configurations of figure 3.2.6, except the electron beam is directed at the emitter.



wasn't observed in figure 3.2.6. This is surprising because configurations B-C and C-BE are the only two wiring configurations that use the base-collector junction alone as the charge collection barrier.

Configuration E-BC is worthy of consideration for the case when the electron beam is directed at exposed emitter. This data is plotted in figure 3.2.8 and shows a well defined maximum at $V_b \approx 12$ kV suggesting it may be possible to resolve the depth of the charge collection barrier by interpreting the depth dose distribution. Configuration E-BC is quite similar to configuration E-B since they are the two cases where the emitter-base junction is used as the only charge collection barrier. Therefore the data for configuration E-B over exposed emitter is replotted in figure 3.2.8 for comparison.

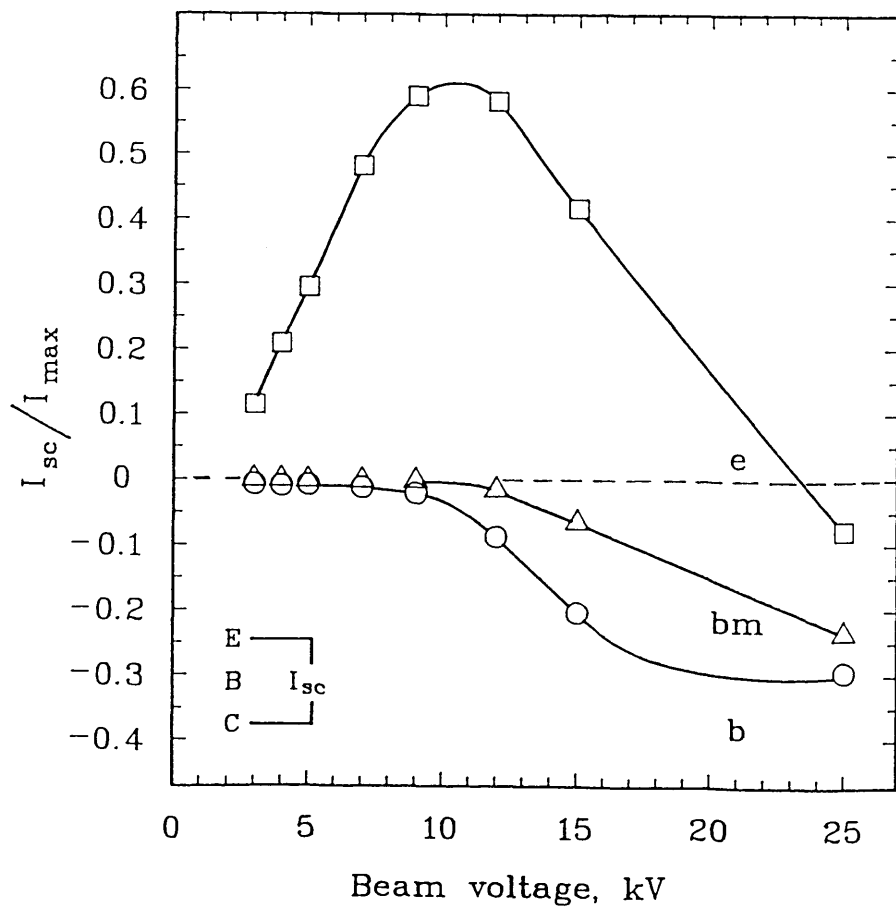
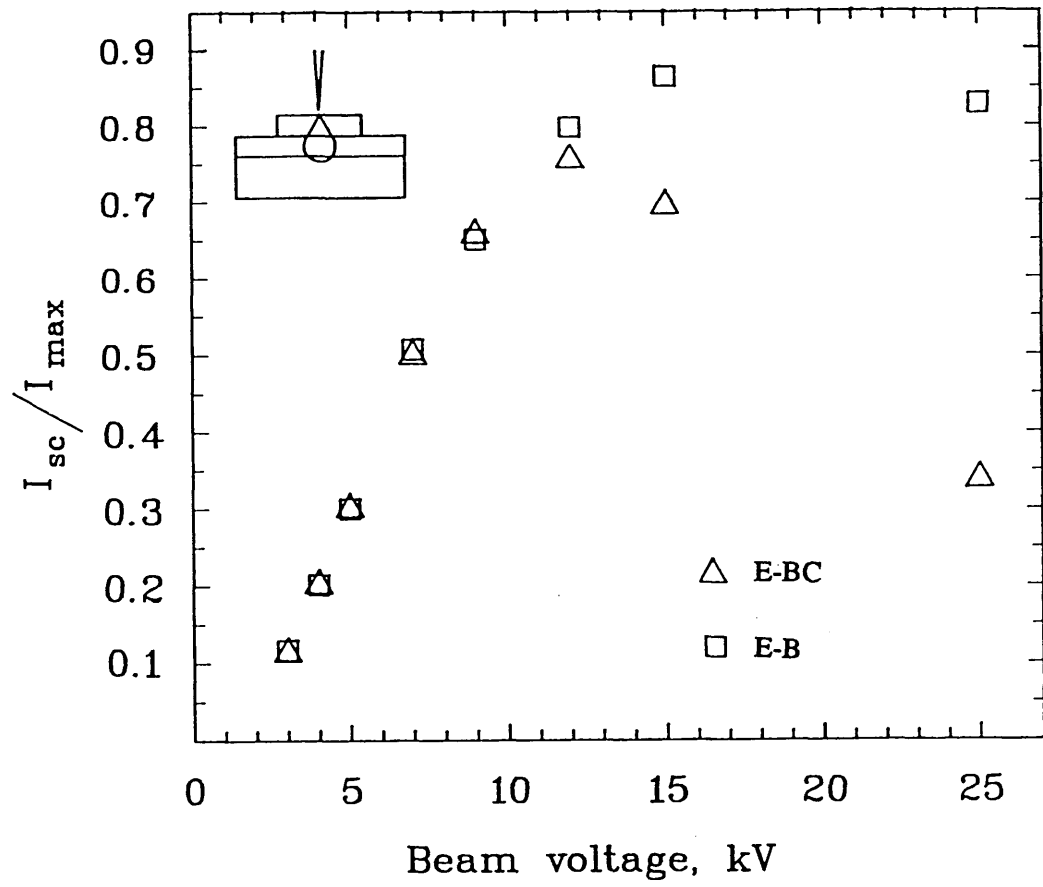
Intuitively, it would seem that configuration E-C might yield the most unusual results since the conductive mode signal is extracted from the specimen by two contacts to n-type semiconductor. Data for this wiring arrangement is reported in figure 3.2.9 for the experiments where the beam was over (e) exposed emitter, (b) exposed base and (bm) over base metal. It is important to note the reversal of the direction of the EBIC corresponding to whether the beam is over the emitter or base. Also there is a reversal of the direction of the short circuit current as the beam voltage increases when the beam is directed at the emitter. The sharp maximum in curve (e) again offers the possibility of resolving the depth of the charge collection barrier.

3.2.2 Qualitative Observation of Defects in GaAs Transistors

Fabrication of GaAs devices introduces defects which can be conveniently observed qualitatively with EBIC micrographs. Providing there is no thick passivation layer, fabricated devices can be ready for examination with little more preparation than prying the lid off the package. For the case of planar, bipolar transistors, the two charge collection barriers offer

Figure 3.2.8. A comparison of configuration E-BC to E-B for the case where the electron beam is directed at the emitter.

Figure 3.2.9. Three different conductive mode signals for wiring configuration E-C. (e) beam over emitter, (b) beam over base, (bm) beam over base metal.



six times as much information as a single charge collection barrier and can provide valuable depth related information as shown in the previous section.

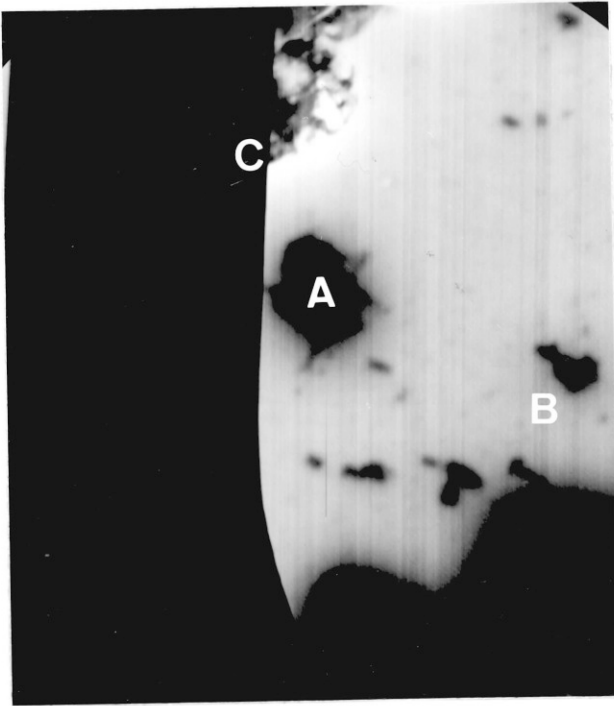
The EBIC micrographs in figure 3.2.10, taken on a JSM-35 SEM, show the exposed emitter region of MBE 193. The dark vertical band in the left half of the micrograph is a silhouette of the 12.5 μm gold wire that is bonded to (the remains of) the emitter metal. The polarity of the conductive mode micrograph is normal in the sense that bright areas correspond to charge collection by the electron voltaic effect and dark regions show areas where the electron-hole pairs generated by the scanning electron beam recombine before they can diffuse to the barrier.

The dark patch labeled A in figure 3.2.10 (a) is an area of enhanced recombination due to a defect. Of particular interest are the black spikes at right angles protruding mainly from the bottom and right hand side of the the dark region. Fig 3.2.10 (b) is an emissive mode micrograph of exactly the same area for comparison to the EBIC micrograph to see if there are any surface features that might explain the conductive mode contrast. In the case of figure 3.2.10 (b) there is a hint of an irregularity on the surface corresponding to defect A. Another emissive mode micrograph was taken of the area, this time using a JSM T-200 with the hope that resolution of surface features could be improved. This is shown in figure 3.2.10 (c) where a feature on the surface, about 1 μm wide, corresponds to the defect marked A. It is interesting to note that a second area of enhanced recombination labeled B in figure 3.2.10 (a) has no corresponding surface feature in figure 3.2.10 (c).

Another unusual phenomenon revealed by the EBIC micrograph of figure 3.2.10 (a) is identified as region C. The emissive mode micrographs of this area show some remains of emitter metal that may not have adhered properly. It would appear as if the EBIC signal were stronger around the perimeter of these emitter metal grains.

Figure 3.2.11 is an EBIC micrograph of reverse polarity where bits of metal on the surface,

Figure 3.2.10. (a) EBIC micrograph of emitter area near 12.5 μm gold wire. (b) Emissive mode micrograph of (a). (c) Emissive mode micrograph of area in (a) except taken on a JSM T-200. Reveals surface features corresponding to recombination centres in (a).

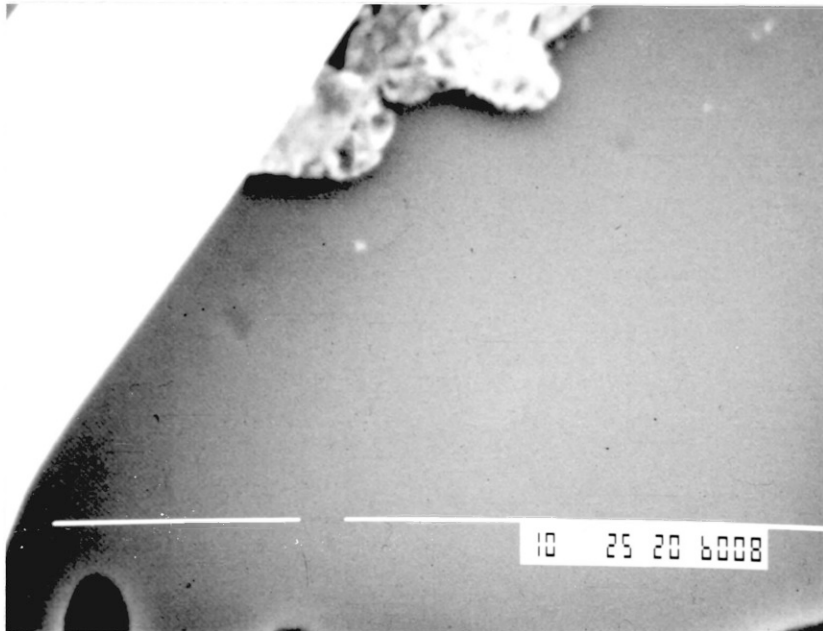


a

10 μm



b

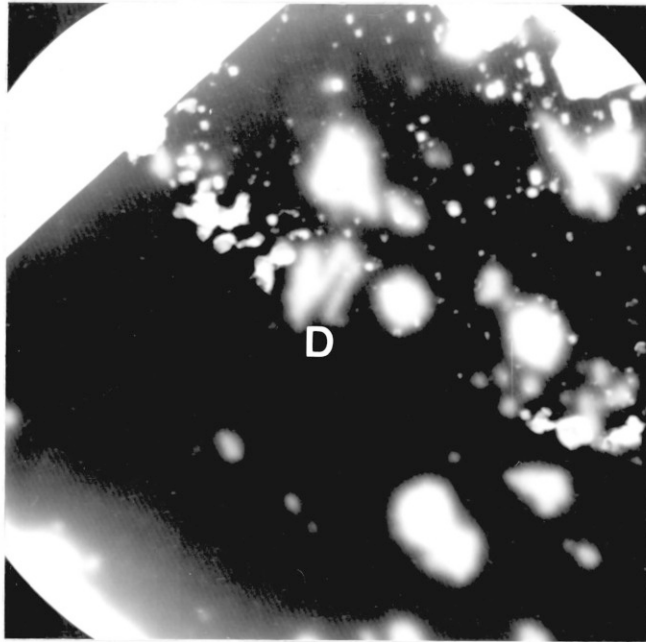


c

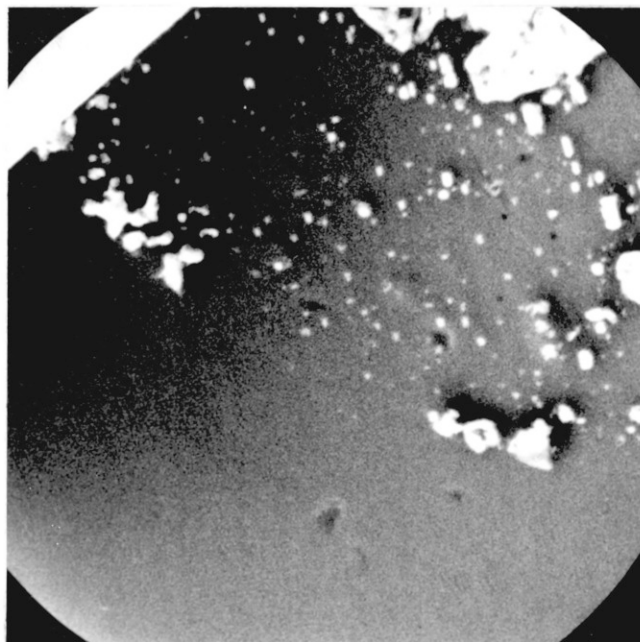
10 μm

Figure 3.2.11. Reverse polarity EBIC micrograph over emitter region of MBE 193. Brilliant white bits are specks of metalization. Dull, fuzzy white areas are recombination centres. Diagonal white patch in upper left-hand corner is a silouette of the gold bonding wire. $V_b = 20$ kV.

Figure 3.2.12. Emissive mode micrograph of figure 3.2.11 showing specks of metal on the surface and edge of gold wire in upper left-hand corner. $V_b = 20$ kV.



20 μm



as well as regions of enhanced recombination in the GaAs, appear as bright features. This EBIC image was taken using configuration B-EC. The defect labeled D is worthy of attention as it appears to display angles other than 90° . This is intriguing considering we are looking down on the (100) plane. Figure 3.2.12 is an emissive mode micrograph of the same area showing there is no corresponding surface irregularities.

Defect D, shown in figure 3.2.11, was investigated further by taking advantage of some of the lessons learned in section 3.2.1. Figures 3.2.13 and 3.2.14 are EBIC images taken under exactly the same conditions of beam current, beam voltage, magnification and scan speed. The only difference is that figure 3.2.14 had its conductive mode signal extracted according to configuration C-BE and figure 3.2.13 according to configuration B-C. By comparing the two micrographs it can be seen that the defect marked D in figure 3.2.13 has completely disappeared in figure 3.2.14. In addition some recombination centres in figure 3.2.13 change their appearance quite dramatically. The large black region marked E in figure 3.2.13 is resolved in figure 3.2.14 as two distinct recombination centres. Other features, such as the remains of emitter metal that can be identified in figure 3.2.12, seem to suffer a loss of resolution in figure 3.2.14. Both micrographs seem to display two white dots where the conductive mode signal is enhanced, although these two dots display a much higher contrast in figure 3.2.14.

3.2.3 Depth Resolved EBIC (DREBIC)

The depth of the defect identified as D in figure 3.2.11 was investigated using depth resolved EBIC techniques as described by Lesniak (1985). However the availability of two charge collection barriers, and thus a variety of charge collection configurations, introduces new sources of DREBIC information.

EBIC linescans over defect D were arranged so as to scan over the right hand 'leg' at about

Figure 3.2.13. EBIC micrograph at 12 kV. Conductive mode signal was extracted using configuration B-C. $V_T = 0$ volts.

Figure 3.2.14. EBIC micrograph at 12 kV.
Identical to figure 3.2.13 except the conductive mode signal was extracted using configuration C-BE.



10 μm

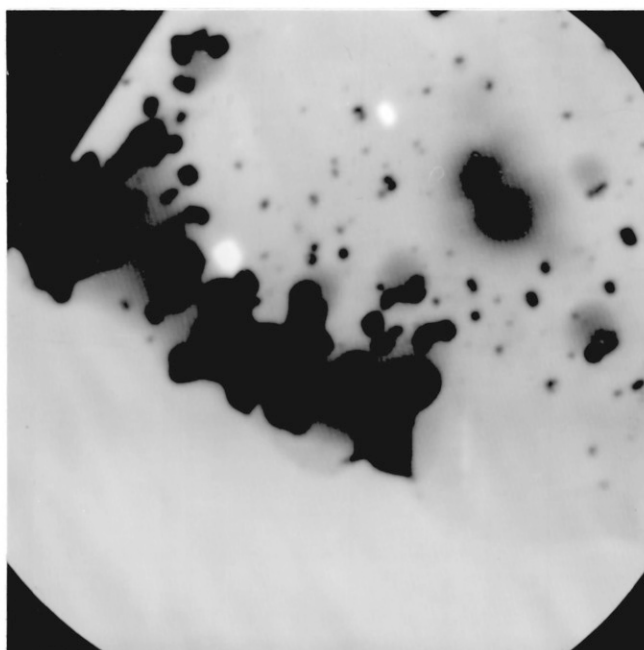
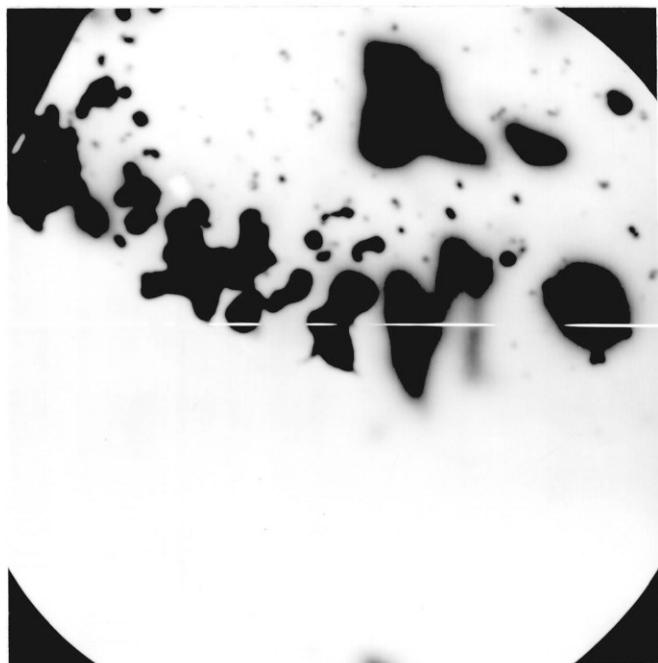


Figure 3.2.15. EBIC micrograph of defect D showing the position of linescans for the purpose of making contrast measurements ($V_b = 12$ kV, configuration B-EC).



10 μm

its midpoint as the white line shows in figure 3.2.15. Contrast was measured six ways at various values of accelerating voltage according to the six configurations of section 3.2.1. The contrast is defined in terms of $I_{\min}$ and I_0 and is normally given as

$$C = (I_0 - I_{\min}) \div I_0$$

However, I_0 is difficult to determine in this region of the specimen where defects and surface features are close packed. Figure 3.2.16 shows a typical linescan across defect D identifying $I_{\min}$ (called min), I_0 (called max) and a third level of EBIC called *high*.

For these experiments two contrasts were calculated; one in terms of I_0 , another in terms of the highest observed value of I_{sc} far from the defect according to:

$$C' = (\max - \min) / \max$$

$$C = (\text{high} - \min) / \text{high}$$

where the difference between the high and the max is shown in figure 3.2.16. The contrast C' will be referred to as the local contrast.

Both contrasts were calculated and are reported as a function of beam voltage and wiring configuration in table 3.2.2. The quantitative difference between C and C' can be seen immediately from inspection of table 3.2.2, especially at low accelerating voltages. The calculated values of the contrast are plotted in figure 3.2.17 for wiring configuration B-EC where a maximum can be observed in the C' curve.

Figure 3.2.16. Typical experimental EBIC linescan over defect D. Right hand leg of the defect corresponds to trough at the 'min' marker (configuration B-EC).

Figure 3.2.17. Contrast versus accelerating voltage showing a comparison of two ways to calculate the contrast.

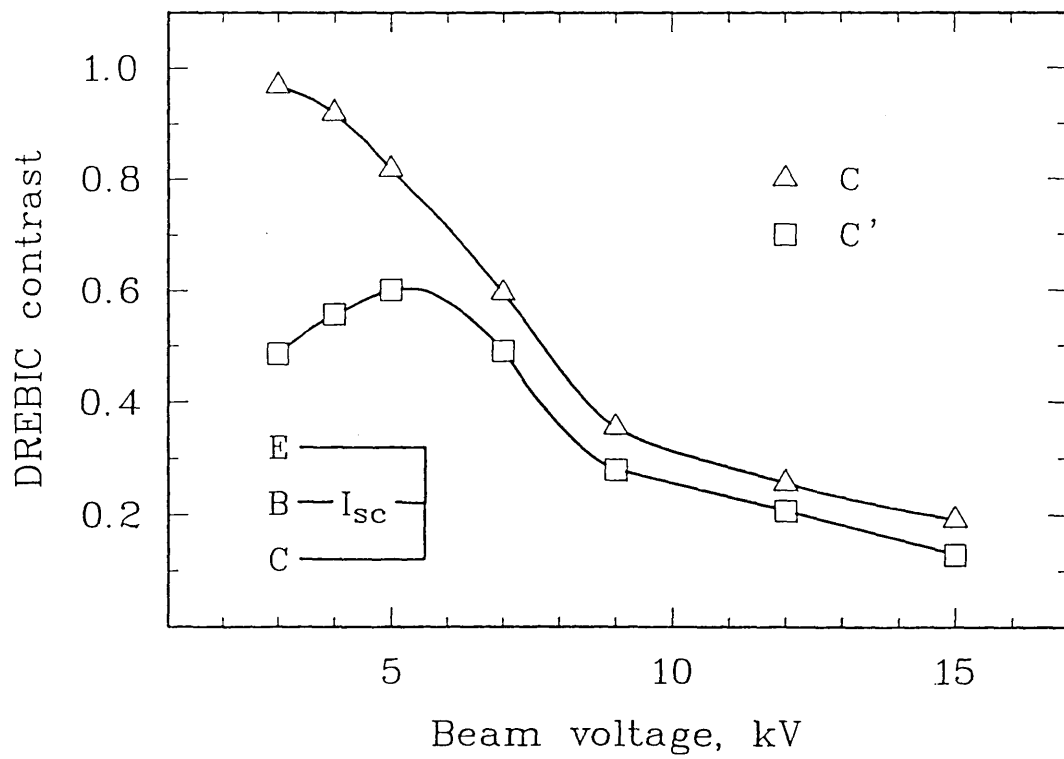
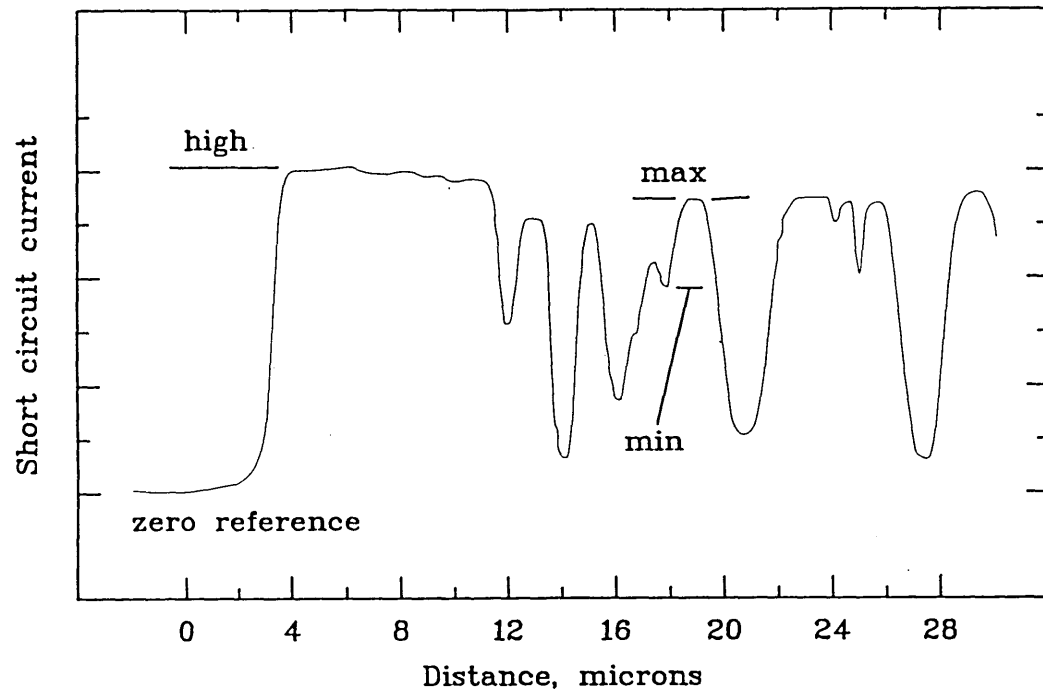


Table 3.2.2. Contrast measurements over defect D (see figure 3.2.16).

<u>C, (high - min)/high</u>						<u>V_b</u>
<u>E-B</u>	<u>E-C</u>	<u>B-C</u>	<u>B-EC</u>	<u>C-BE</u>	<u>E-BC</u>	
.987	.989	.991	.967			3 kV
.917	.915	.925	.918	.924		4
.786	.797	.812	.817	.782		5
.532	.557	.545	.595	.334	.552	7
.353	.367	.418	.355			9
.246	.324	.238	.256	0	.295	12
.200	.177	.095	.192	0	.231	15

<u>C', (max - min)/max</u>						<u>V_b</u>
<u>E-B</u>	<u>E-C</u>	<u>B-C</u>	<u>B-EC</u>	<u>C-BE</u>	<u>E-BC</u>	
.853	.750	.828	.485			3 kV
.485	.554	.589	.556	.567		4
.483	.542	.583	.600	.508		5
.442	.445	.435	.490	.207	.447	7
.290	.301	.348	.280			9
.197	.287	.193	.207	0	.217	12
.138	.125	.046	.129	0	.167	15

4.0 DISCUSSION

4.1 Electron Beam Induced Inversion Layers

In section 3.1.1 electron beam induced variations in silicon linescan profiles were reported. These can be explained by the presence of a surface inversion layer due to a fixed positive charge at the surface. This positive surface charge could be trapped in the native oxide or in slow states at the interface.

When silicon is cleaved and comes into contact with the atmosphere, a thin native oxide film is formed. At a Si/SiO_x interface, dangling silicon bonds give rise to a surface state charge, Q_s, which is positive. It is proposed that additional positive charge in the native oxide, and possibly at the interface as well, is produced by the scanning electron beam. It is also proposed that annihilation of positive charges near the interface occur during electron beam irradiation. The net positive charge density at the surface can be attributed to a number of competing mechanisms. Let dQ_s/dt be the rate at which fixed positive charge accumulates or disappears near the Si/SiO₂ interface and

$$dQ_s/dt = A - R_{th} - R_i \quad (4.1.1)$$

where A is the relatively fast rate of accumulation of fixed positive charges due to electron beam generation and trapping, and dominates for certain radiation dose rates resulting in a large surface charge that produces an inversion layer. R_{th} is the rate of relaxation of positive charge due to thermal annealing and is slow, taking about two hours for a frame to discharge at room temperature. R_i is the relatively fast rate of relaxation of positive charge due to annihilation of charge (or ionization) when the dose rate is high as displayed in figure 3.1.3.

Kato and co-workers (1975) first suggested that a surface inversion layer could act as a charge collection barrier for an EBIC signal, although they claimed that an π layer inverted

to p-type, implying that there must be trapped negative charge at the surface. Wilson et al (1981) reported that their measured value of $I_{\max}$ decreased by 12% over a period of 40 minutes during which time the beam scanned the specimen continually. In their experiments the thickness of a growing film of contamination was suggested as a possible explanation for the observed decrease in detected current. Their conclusion however, was that the contamination film was not nearly thick enough to account for the large decrease in short circuit current. The Wilson et al decrease in $I_{\max}$ is similar to the 10% decrease in $I_{\max}$ displayed in figure 3.1.6 and may be due to the slow erasure of a line or region of positive charge. This positive charge may exist at the surface before the specimen is irradiated. Or it could be built up during the period when the microscopist views the frame of interest as an emissive mode image.

Castaldini, Cavallini and Cavalcoli (1987) report that their measurement of the minority carrier diffusion length is not only a function of electron beam scanning speed, but that L displays a maximum when plotted against it (i.e. dose rate). This is in good agreement with the general trend of equation 4.1.1 and the results reported in section 3.1.1. Castaldini et al attribute this unusual behaviour to either variable surface recombination or changes in the injection level as the magnification changes. While changing the microscope magnification does change the radiation dose rate it does *not* change the injection level. The injection level is a function of beam voltage, beam current and the material being examined (Berz and Kuiken, 1976) and not the spot velocity as discussed in section 1.3.2. Since the lifetime is proportional to the thermal velocity (equation 1.1.4), the scanning spot velocity might reduce injection levels if it is comparable to the thermal velocity, but this is not asserted by any workers encountered in the literature review of section 1.0.

The thermal velocity is given by

$$v_{th} = (3kT/m^*)^{1/2}$$

where m^* = effective mass for electrons in a silicon lattice and is within an order of magnitude of m_0 (Sze, 1981), where m_0 is the rest mass of an electron. Therefore the thermal velocity is more than 250000 m/sec while the scanning speeds calculated from Castaldini's results were 0.0004 to 0.06 m/sec

While changes in surface recombination velocity may be able to account for Castaldini's calculated variation in L (an order of magnitude), it cannot account for a conductive mode signal like that of figure 3.1.3. However, the mechanism responsible for the behaviour observed in figures 3.1.2 to 3.1.6 could very well be the basis for variations in EBIC intensity and diffusion length reported by Castaldini *et al* (1987) and others as well (Zimmermann 1972, Bresse 1977, Wilson *et al* 1981, Marten and Hildebrand 1983).

Based on the presence of a surface inversion layer, L_e should be able to be determined with the aid of figure 3.1.4. The short circuit current in figure 3.1.4 decreases as V_b increases because electron-hole pairs are generated farther away from the depletion region which is near the surface. This increases the probability that they will recombine before being collected. It should be possible to bracket the experimental data between two curves of known diffusion length. Two theoretical curves were calculated under the assumption that there is a depletion region at the surface due to surface inversion. They were determined over a range of beam voltages by using the simple exponential (equation 1.2.1) applied to the the depth dose energy matrix produced by Napchan's (1987) Monte Carlo simulation program.

In reality there are resistive losses in the detection of I_{sc} and probably a certain degree of recombination in the depletion region giving the observed current offset between theory and experiment in figure 3.1.4. Also this is not a strictly valid comparison since an inversion layer near the surface produces a depletion region of finite thickness. A portion of the electron-hole pairs will be generated inside the depletion region and therefore will not be modeled in equation 1.2.1. The experimental value of about 75 μm from figure 3.1.4 is in reasonable agreement with the empirical value of 92 μm (table 1.1.2) for 1.97 ohm-cm

material.

The simple exponential of equation 1.2.1 is valid only if the surface recombination velocity is zero, which, as we shall see in the following section, is not the case. However the surface recombination velocity should not affect carriers diffusing to a depletion region edge that is located a finite distance from the surface. The maximum width of a depletion region due to strong inversion was calculated according to equation 1.3.7 and is tabulated for the three silicon p-type bulk resistivities of interest in table 4.1.1.

Table 4.1.1. Theoretical surface inversion induced maximum depletion region widths.

Bulk p-type <u>resistivity</u>	<u>W_m</u>
8.5 ohm-cm	0.481 μm
2.8	0.267
1.97	0.232

Determination of L_e from figure 3.1.4 is not a precise way to determine the diffusion length when L_e is much larger than the Grün range. Although determination of L_e in this fashion is not convenient, the ability to do so is strong evidence for a depletion region located at the surface due to surface inversion.

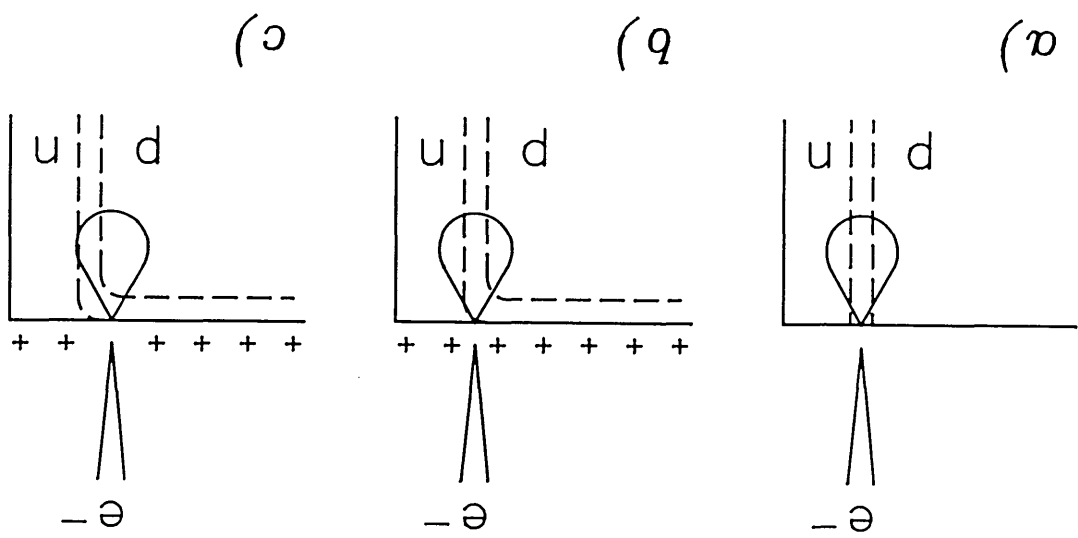
The first linescan of figure 3.1.3 shows that $I_{sc} \approx I_{max}$ up to a distance of 350 μm from the junction. Once the inversion layer has been created, it is only a few microns (depending on the Grün range) from the newly generated electron-hole pairs. Carriers are separated by the charge collection barrier before they can recombine and are conducted along the inverted silicon to the n-type epi layer. Linescans at higher magnification show a lateral shift in the maximum of the EBIC peak near the junction as seen in figure 3.1.6. Normally we would

expect this maximum where the focussed electron spot is over the p-n junction as in figure 4.1.1 (a). However, a surface inversion layer to one side of the junction (figure 4.1.1 (b)) means that more carriers will be collected there. Thus of the three configurations shown, figure 4.1.1 (c) will give the largest EBIC signal since the centre of gravity of the interaction volume is more efficiently surrounded by charge collection barriers. Evidence for this is shown in figure 3.1.6 where the EBIC signal was stronger on the p-type silicon before it was examined. As the beam reduced the positive surface charge density, and hence the short circuit current, the EBIC peak shifted away from the p-type side of the junction.

From figure 3.1.5 it appears that varying the spot velocity is sufficient to change the surface charge density enough to dramatically affect I_{sc} . It is important to note that the linescans not only display a different slope, but the absolute value of the short circuit current is wildly different for precisely the same beam voltage and beam current. The linescan will probably never flatten out to I_{max} when a linescan alone is used to charge up a surface region. The narrow, linescan induced inversion layer cannot act as a semi-infinite charge collection plane as in the case of a charged frame. The two linescans of figure 3.1.5 reflect the same dose rate over any time period greater than the time taken for the slowest scan. However an area of silicon in the path of these two linescans will receive its radiation in periodic doses. The more intense but less frequent dose of the slower scan will bring the local temperature higher on each pass than will the faster scan. If it is assumed for both scan speeds that the time between each radiation pulse is sufficient to dissipate the heat, the slow scan will result in more surface charges being annealed out. Thus there will be a less efficient charge collection barrier at the surface during a slow scan and I_{sc} will be lower than for the fast scan, as observed in figure 3.1.5.

Since the creation and erasure of the inversion layer can be explained satisfactorily by considering annealing effects alone, we would describe this as an *apparent* dose rate effect in agreement with the conclusions of Nichols' (1980) literature review that there are probably no true radiation dose rate related phenomena associated with the silicon-silicon oxide

Figure 4.1.1. Three configurations for considering the EBIC maximum. (a) Maximum occurs when the beam is directed at the junction. (b) The presence of a surface inversion layer provides an additional charge collection barrier on the p-type side which (c) shifts the maximum to the left side of the metallurgical junction.



interface at less than 10^5 rads/min, although the dose rates for the present work were in the range 10^6 to 10^7 rads/min.

A true dose rate effect is defined to be one that arises from an actual physical process occurring in the oxide. Its magnitude would depend on the instantaneous concentration of electron-hole pairs which depends in turn on the rate of ionizing radiation. An apparent dose rate effect is a manifestation of circuit effects, such as induced internal voltage changes, resulting from drift or diffusion of beam induced carriers.

The process of annealing mentioned in this context is the thermal process of untrapping holes that were deposited in the oxide or at the interface during a period of ionizing radiation. This would be expected to occur when the local silicon temperature in the proximity of the incident electron beam rises due to the rate at which energy is dissipated from the electron beam itself, ultimately in the form of heat.

Habing and Shafer (1973) report that positive charge trapped in the oxide of MOS devices can be eliminated at 0 bias by electron irradiation at dose rates less than 10^5 rads/min. They suggest that electrons generated in the silicon are injected into the oxide where they neutralize existing positive charge. This explains why the EBIC enhanced area of figure 3.1.2 (b), when left alone, takes up to two hours to lose its charge collection properties while at low dose rates (less than 10^5 rads/min) the enhanced area returns to 'normal' (3.1.2 (a)) in just a few minutes.

The minority carrier diffusion length determined from the data in figure 3.1.5 must be rejected since beam induced carriers are collected far from the junction due to a charge collection barrier not modeled in equation 1.2.1. In addition, the efficiency of this charge collection barrier is variable due to the unpredictable positive charge density at the surface according to equation 4.1.1.

Figure 3.1.5 shows that the value of the short circuit current is much lower for higher dose rates. This shows that the inversion layer might be eliminated for a sufficiently slow scan speed and high beam power. Also a charged frame may be prevented from forming if the specimen position and beam focus are set up far from the area of interest. The beam can then be deflected while the specimen is moved underneath the electron optical column and a previously unirradiated area can be examined.

Since the positive charge is associated with the native oxide, beam induced variations could be avoided by cleaving under vacuum. If this is not possible, they will be minimized if the specimen is cleaved and quickly placed into the SEM vacuum with a minimum of contact with the atmosphere.

4.2 Fitting Donolato's Equations to Experimental Data

4.2.1 Macroscopic EBIC Linescans

The linescans reported in section 3.1.2 (figures 3.1.7 to 3.1.17) were scanned slowly to increase the radiation dose rate. Each linescan was 500 μm long and took 75 seconds (5.3 $\mu\text{m}/\text{sec}$). The dose rate in Mrads/min for each experiment is shown in table 4.2.1. The reason that the dose rates are lower at higher beam voltages is that the mass of irradiated silicon increases faster than the beam power (see equation 1.3.6). These high dose rates did not display electron beam induced variations in the shape of the EBIC linescan.

Table 4.2.1. Dose rate in Mrads/min for EBIC linescans of figures 3.1.7 to 3.1.9

V_b	1.97 $\Omega\text{-cm}$	2.8 $\Omega\text{-cm}$	8.5 $\Omega\text{-cm}$
3 kV		2.1×10^3	
6	2.4×10^3	3.3×10^3	6.8×10^3
8		2.5×10^3	
10	1.8×10^3		3.0×10^3
15	2.8×10^2	2.0×10^2	6.9×10^2
20		1.0×10^2	
25	3.1×10^2	1.7×10^2	3.2×10^2

The linescans of figures 3.1.7 to 3.1.9 over approximately 400 μm of p-type bulk silicon were simulated using the EBICsim Pascal computer program described in section 3.1.4. The input parameters supplied to EBICsim were from measured values of beam current, beam voltage and doping density (from Irvin's curve).

Values for the surface recombination velocity and minority carrier diffusion length were supplied to EBICsim on a trial and error basis until the calculated theoretical EBIC linescans fitted the experimental data. This was done by first finding one value of L_e for each bulk resistivity that would give reasonable fits for all the curves at that bulk resistivity. A separate value of L_e is not reported for each curve because L_e should not change with beam voltage providing that conditions of low injection prevail throughout the experiment.

The assumption that L_e is not a function of V_b is justified by the experimental results in figures 3.1.7 to 3.1.9 where the slopes of the linescans do not vary with V_b for each bulk resistivity. 3 and 6 kV EBIC linescans had a more unrepresentative slope than for data taken at higher beam voltages so L_e was chosen to fit the results taken at above 6 kV. This was done because the data taken at lower beam voltages (when the generation volume is much closer to the surface) is more vulnerable to surface effects.

It was found that the low injection level condition of $N_a \ll \Delta n_b$ prevailed in the p-type bulk for all the experiments where Δn_b is the carrier concentration on the surface dividing regions of high and low injection (see section 1.3.2). The condition for low injection was calculated from equations 1.3.2 through 1.3.5 for the experimental worst case of a 25 kV, 2.5 nA beam. The results are shown in table 4.2.2 for the 2.8 ohm-cm p-type material. Calculations for the 1.97 and 8.5 ohm-cm materials were similar.

Table 4.2.2. Conditions for low injection for a 25 kV, 2.5 nA beam in 2.8 Ω -cm p-type Cz bulk Si; $L_e = 100 \mu\text{m}$, $\tau_e = 2.9 \times 10^{-6}$ sec.

	Δn_{max}	Δn_b
$v_s = 0$	1.9×10^{15}	$2.8 \times 10^{12} - 5.5 \times 10^{13}$
$v_s = \infty$	2.2×10^{14}	5.5×10^{12}

From the impurity concentrations given in table 1.1.1 where N_a of the 2.8 Ω -cm material is $5 \times 10^{15} \text{ cm}^{-3}$, it can be seen that worst case experimental conditions meet the low injection condition of $\Delta n_b \ll N_a$ for either $v_s = 0$ or $v_s = \infty$. This is not the case for the n-type epi whose impurity concentration is $6 \times 10^{14} \text{ cm}^{-3}$. Table 4.2.3 shows calculated low injection level conditions for the same beam voltage and beam current as table 4.2.2 but for n-type, 7.5 ohm-cm silicon. Since the calculation of Δp_b requires a diffusion length, two were tried. The values chosen were $L_h = 130$ and $L_h = 7.5 \text{ }\mu\text{m}$. The first value is the maximum possible L_h for Cz grown material (found in table 1.1.2). The value $L_h = 7.5 \text{ }\mu\text{m}$ will be important in later discussion.

Table 4.2.3. Conditions for low injection for a 25 kV, 2.5 nA beam in 7.5 Ω -cm n-type Si.

	Δp_{max}	$\Delta p_b, L_h = 130 \text{ }\mu\text{m}$	$\Delta p_b, L_h = 7.5 \text{ }\mu\text{m}$
$v_s = 0$	7.3×10^{16}	$5.1 \times 10^{12} - 8.5 \times 10^{13}$	$2.7 \times 10^{16} - 5.3 \times 10^{17}$
$v_s = \infty$	1.4×10^{16}	7.8×10^{12}	7.1×10^{17}

Initial guesses for L_c and v_s led to theoretical curves such as in figures 4.2.1 and 4.2.2. In figure 4.2.1 the effect of varying the diffusion length by $\pm 20\%$ can be seen. Once a diffusion length had been determined for each of the three different p-type substrates, the surface recombination velocity was determined for each beam voltage with the aid of constructions like figure 4.2.2. In this figure the effect of varying v_s over a factor of five can be seen. The surface recombination velocity, v_s , is labeled 's' in figure 4.2.2 and figures that follow. Theoretical curves were fitted by eye and the precision in v_s is thought to be only 1 significant digit. From figure 4.2.1 it appears that L_c can be determined with more precision, to 1 or possibly 2 significant digits.

These precision limits are comparable to those reported by Bresse (1977) where L was

Figure 4.2.1. Method of determining the minority carrier diffusion length using equation 1.2.8. $V_b = 25$ kV, p-type bulk resistivity = $1.97 \Omega\text{-cm}$ (infinite specimen thickness model).

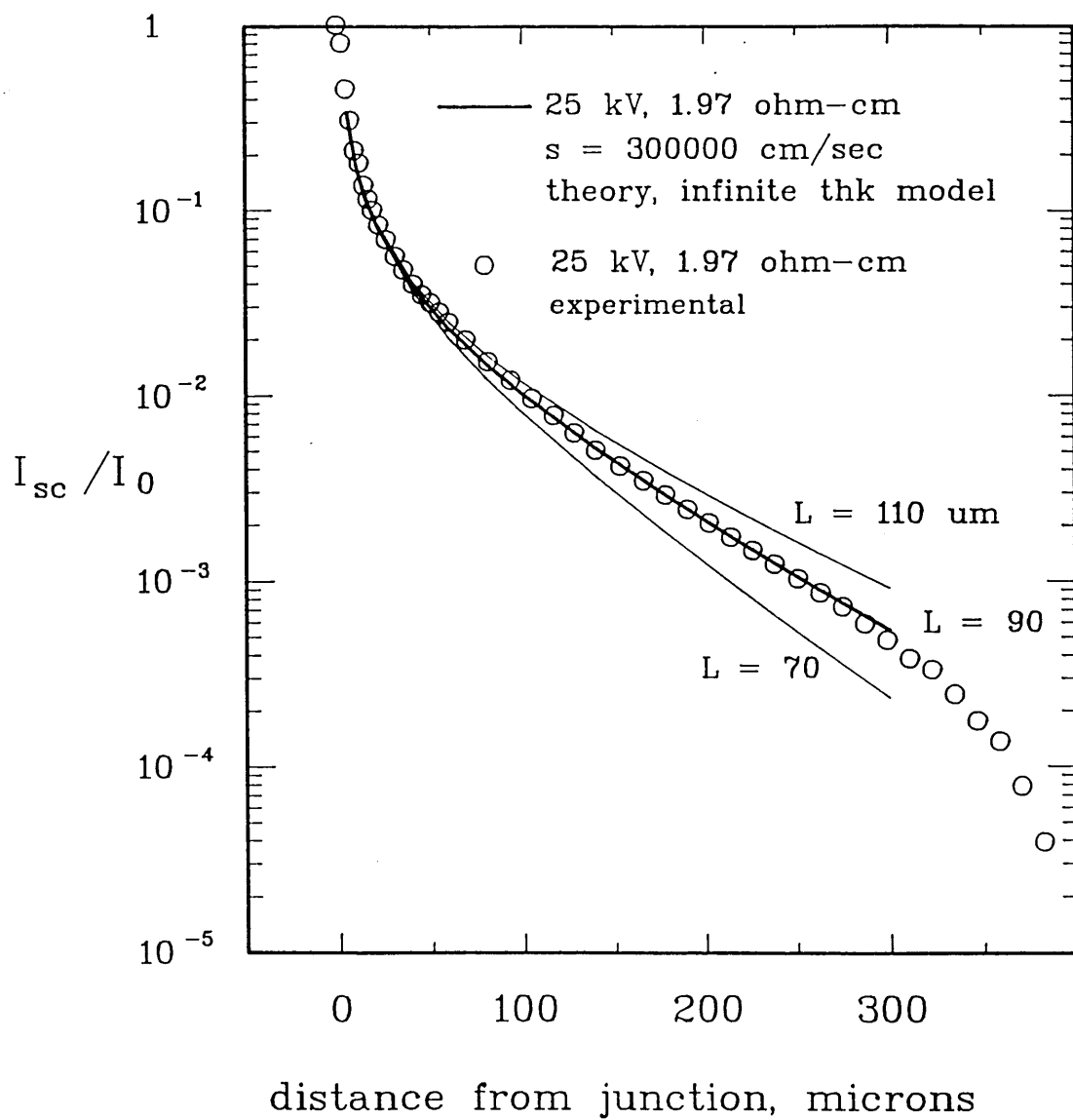
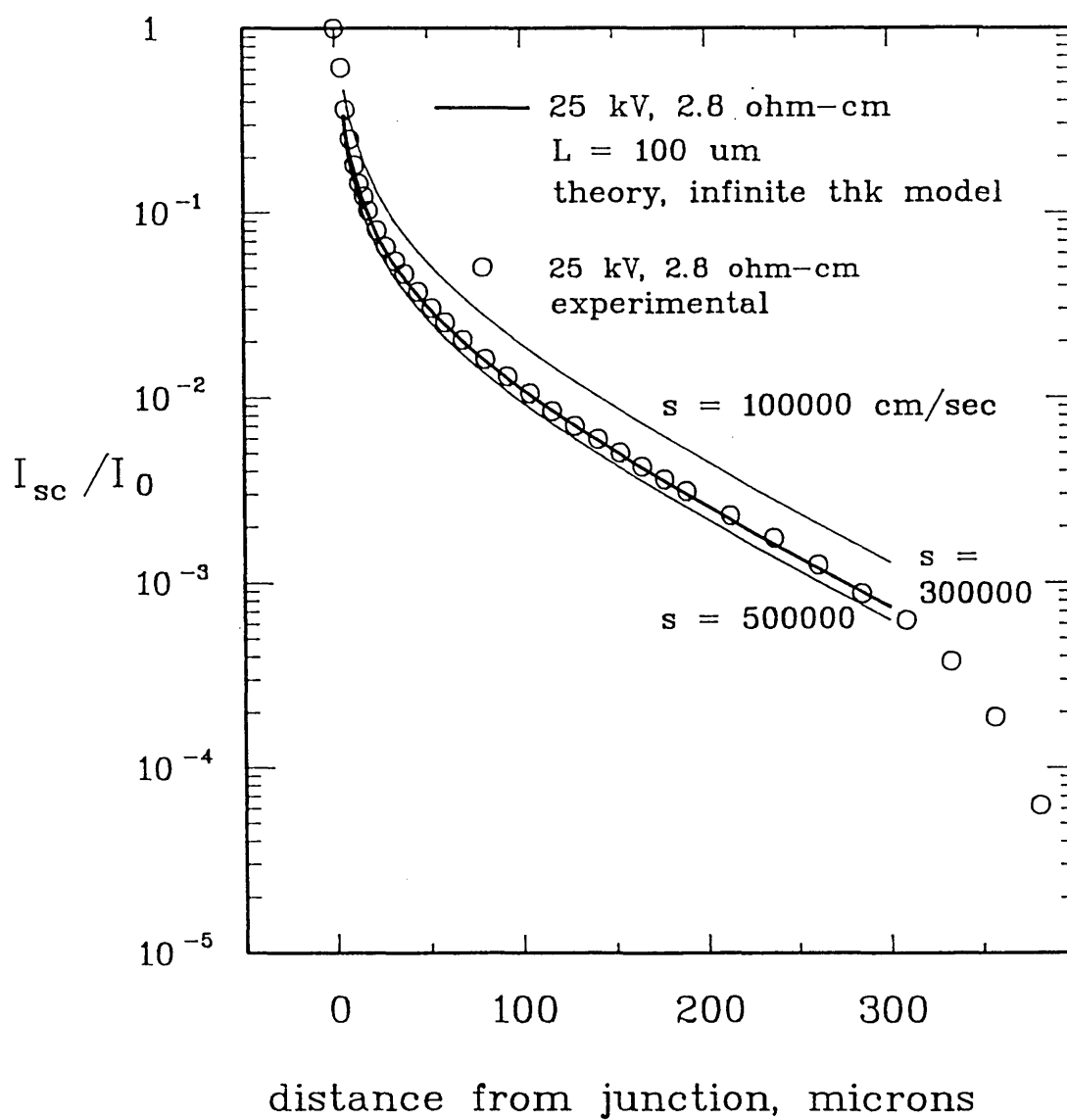


Figure 4.2.2. Method of determining the surface recombination velocity using equation 1.2.8. $V_b = 25$ kV, p-type bulk resistivity = $2.8 \Omega\text{-cm}$ (infinite specimen thickness model).



determined to $\pm 5\%$ and v_s to $\pm 30\%$. In that case L and v_s were determined by fitting van Roosbroeck's model (1955) to experimental EBIC linescans.

A numerical technique for curve fitting would probably be an improvement when determining L_e and v_s , however this would not be practical on an IBM PC. Calculation of one single point on a linescan using Donolato's models can take from 1 to 15 minutes. The time taken to find a solution increases as L_e and V_b decrease, and increases as distance from the junction increases. The theoretical curves in figures 4.2.1 to 4.2.9 contain 20 to 25 values of I_{sc} calculated by EBICsim.

Unlike the diffusion length, the surface recombination velocity was not expected to remain constant for different experiments using material with the same impurity concentration. Bresse (1977) determined the surface recombination velocity for three dose rates and found that the value of v_s varied by a factor of 3. Davidson (1982) also observed a variation in v_s that he associated with a transition from low to high injection conditions.

Once the minority carrier diffusion length was determined for each bulk resistivity, a surface recombination velocity was found for each beam voltage shown figures 3.1.7 to 3.1.9 such that calculated linescans fit the experimental ones.

The experimental data in figure 4.2.3 is the same as in figure 4.2.1 except the surface recombination velocity and diffusion length for the theoretical curve have been adjusted to give a better fit. The same data appear in figure 4.2.4 except the theoretical curve is calculated from equation 1.2.5 which is Donolato's model for a specimen of finite thickness. In this case the diffusion length found from the infinite width model was used but the surface recombination velocity had to be reduced slightly to give a good fit. This is reasonable since the back contact will produce a carrier concentration gradient due to the lack of reflected minority carriers. In the infinite specimen thickness model these unaccounted for carriers are assumed to recombine at the surface and therefore a fitted curve for the infinite width model

Figure 4.2.3. Optimum diffusion length and surface recombination velocity found in figure 4.2.1 fitted to experimental data. $V_b = 25$ kV, p-type bulk resistivity = $1.97 \text{ } \Omega\text{-cm}$ (infinite specimen thickness model).

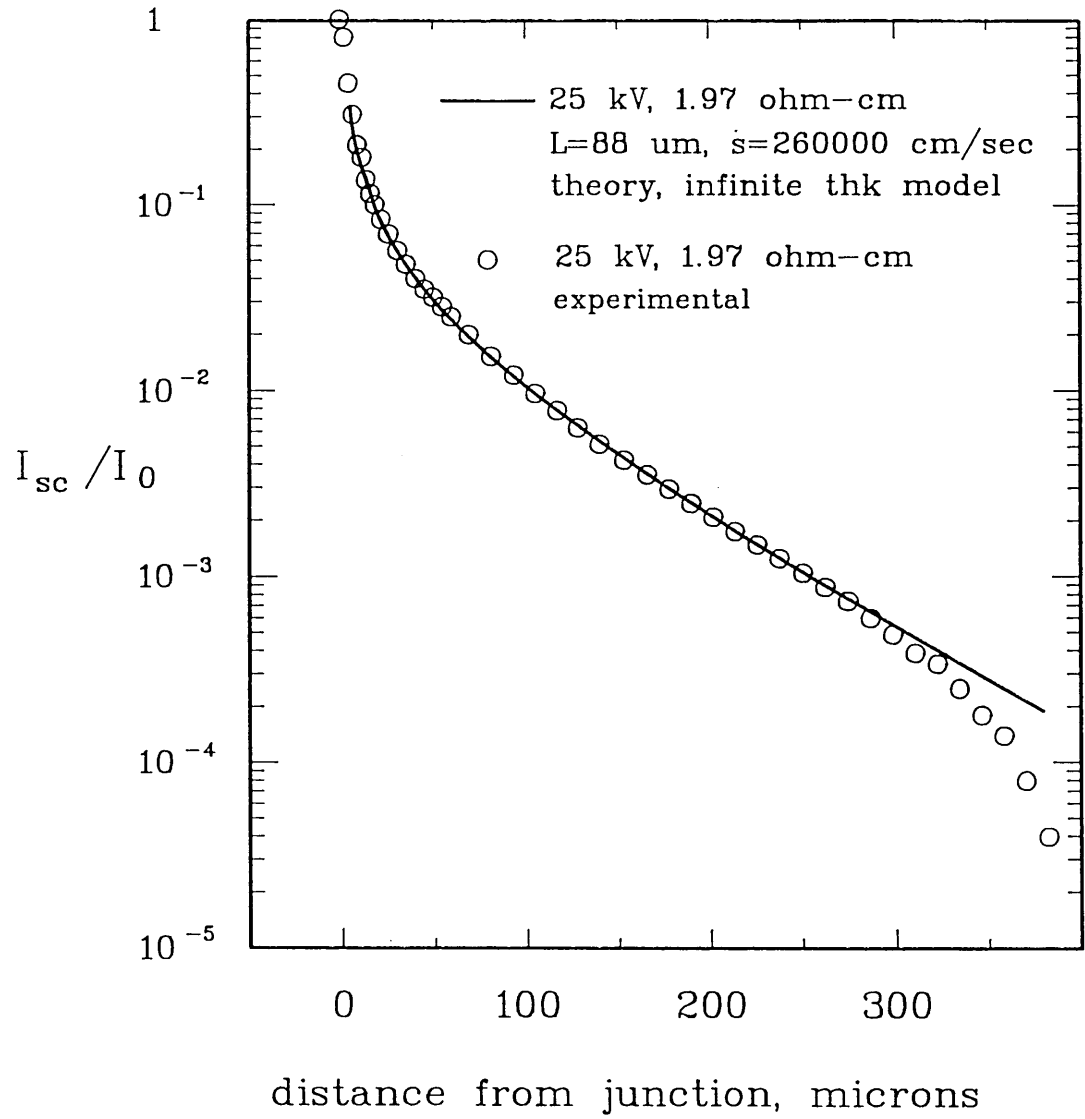
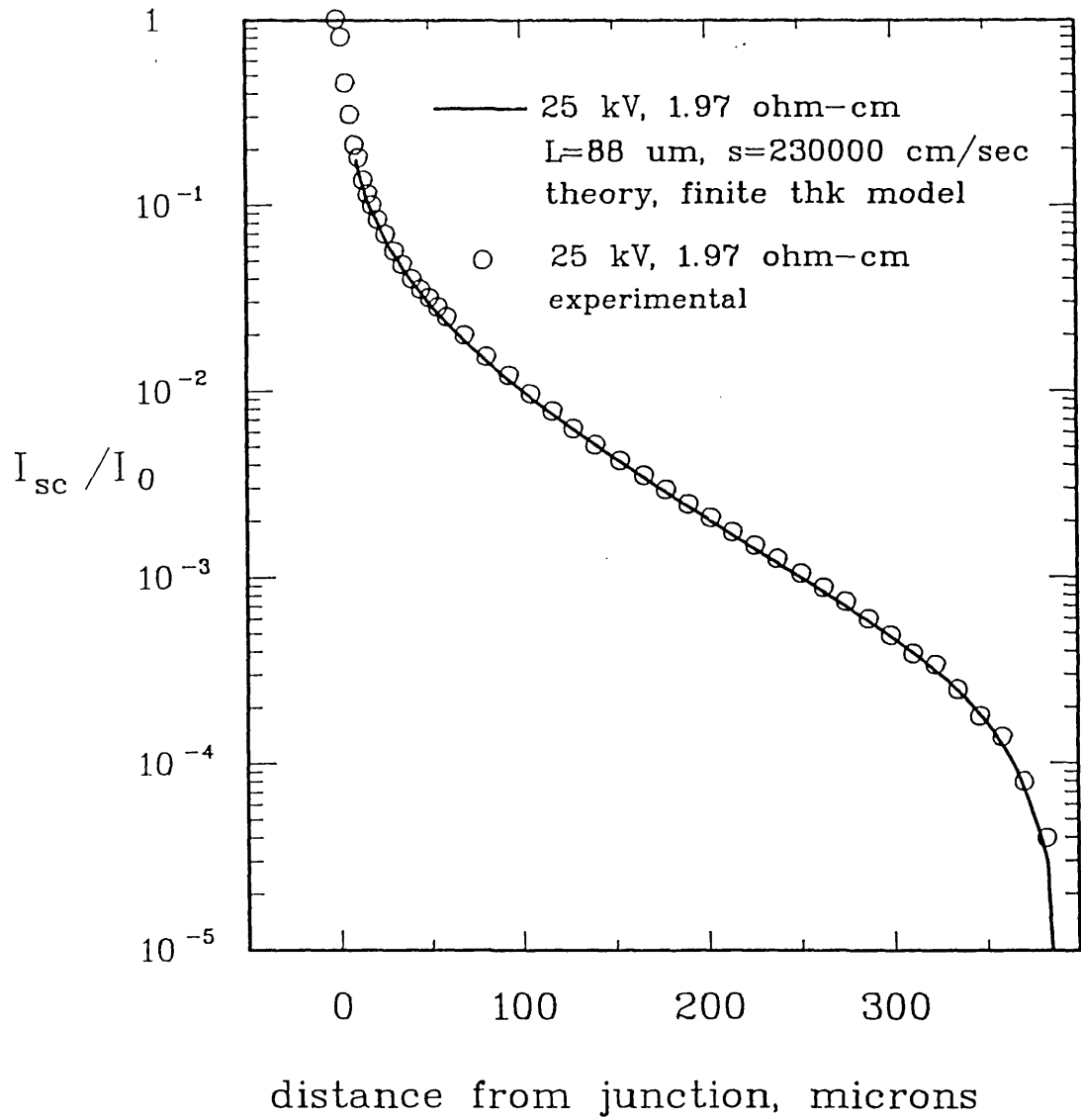


Figure 4.2.4. Theory compared to experiment. EBIC linescan calculated by EBICsim computer program using equation 1.2.5. Specimen thickness is 388 μm . $V_b = 25 \text{ kV}$, p-type bulk resistivity = 1.97 $\Omega\text{-cm}$ (finite specimen thickness model).



will indicate a higher v_s than is actually the case.

The majority of the experimental curves of figures 3.1.7 to 3.1.9 were fitted by the finite specimen width model as well as can be seen in figure 4.2.4. Figure 4.2.5 is the same experimental data of figure 4.2.2 for the 2.8 ohm-cm p-type bulk but it is more accurately fitted with the finite thickness model. EBIC linescans at 3 and 6 kV for the 2.8 ohm-cm silicon appear in figures 4.2.6 and 4.2.7. At 6 kV it is still possible to obtain reasonable agreement between experiment and theory, however at 3 kV it may be that surface effects not accounted for in equation 1.2.5 are affecting the shape of the linescan.

Another explanation for the unsatisfactory fit of figure 4.2.7 is that the maximum EBIC gain (equation 1.3.1) at 3 kV is less than 1000 times the beam current. The region where the experimental data deviate from theory is four orders of magnitude less than the observed maximum and therefore less than the beam current. It is likely that the current being measured at this point reflects the specimen current to a greater degree than the short circuit current. Therefore it is difficult to verify Donolato's models at low beam voltages.

Figure 4.2.8 shows an attempt to fit the finite specimen width model to experimental data from the 8.5 ohm-cm silicon. All four linescans on this material showed a sudden drop in the conductive mode signal at around 200 μm from the junction. This can be explained by the presence of an unwanted Schottky barrier instead of the intended ohmic contact on the back side of the wafer. In addition to a decreasing carrier concentration gradient toward the back contact, carriers that diffuse to the back contact actually contribute to the conductive mode signal, but in the opposite direction. Further evidence for this can be seen on the original linear experimental EBIC trace. This is not shown but is similar to figure 3.1.1 except the conductive mode signal dropped below zero when the beam scanned across the back contact. This was especially noticable on the sensitive ranges of the Keithley. The Schottky contact on the back face was not nearly as efficient a charge collection barrier as the p-n junction at the epi interface. The observed short circuit current maximum (or minimum, strictly

Figure 4.2.5. Theory compared to experiment. EBIC linescan calculated by EBICsim computer program using equation 1.2.5. Specimen thickness is 388 μm . As with figure 4.2.4 except for the 2.8 $\Omega\text{-cm}$ p-type substrate. $V_b = 25 \text{ kV}$ (finite specimen thickness model).

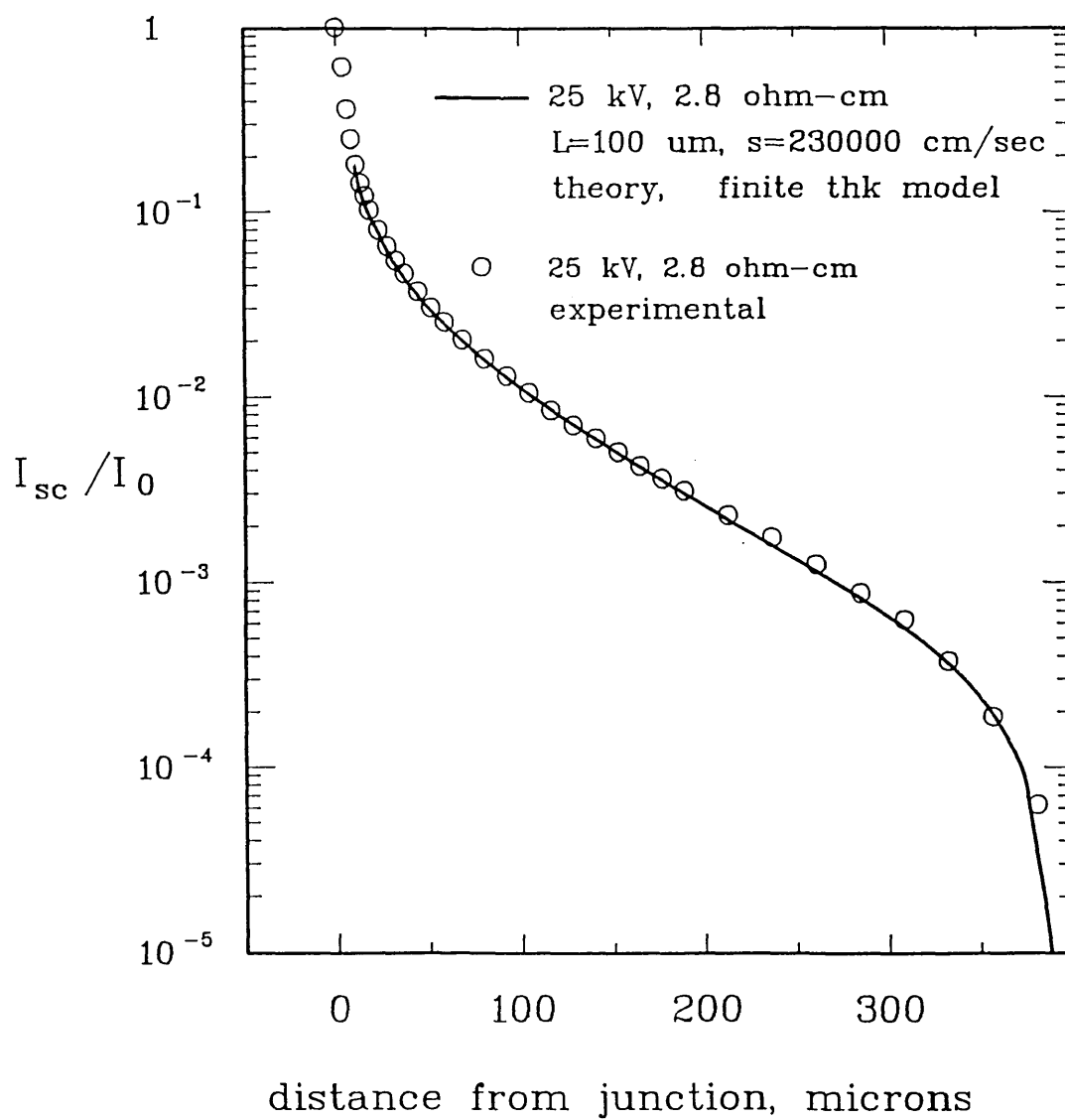


Figure 4.2.6. Theory compared to experiment. EBIC linescan calculated by EBICsim computer program using equation 1.2.5. Specimen thickness is 388 μm . As with figure 4.2.5 except for $V_b = 6\text{kV}$ (finite specimen thickness model).

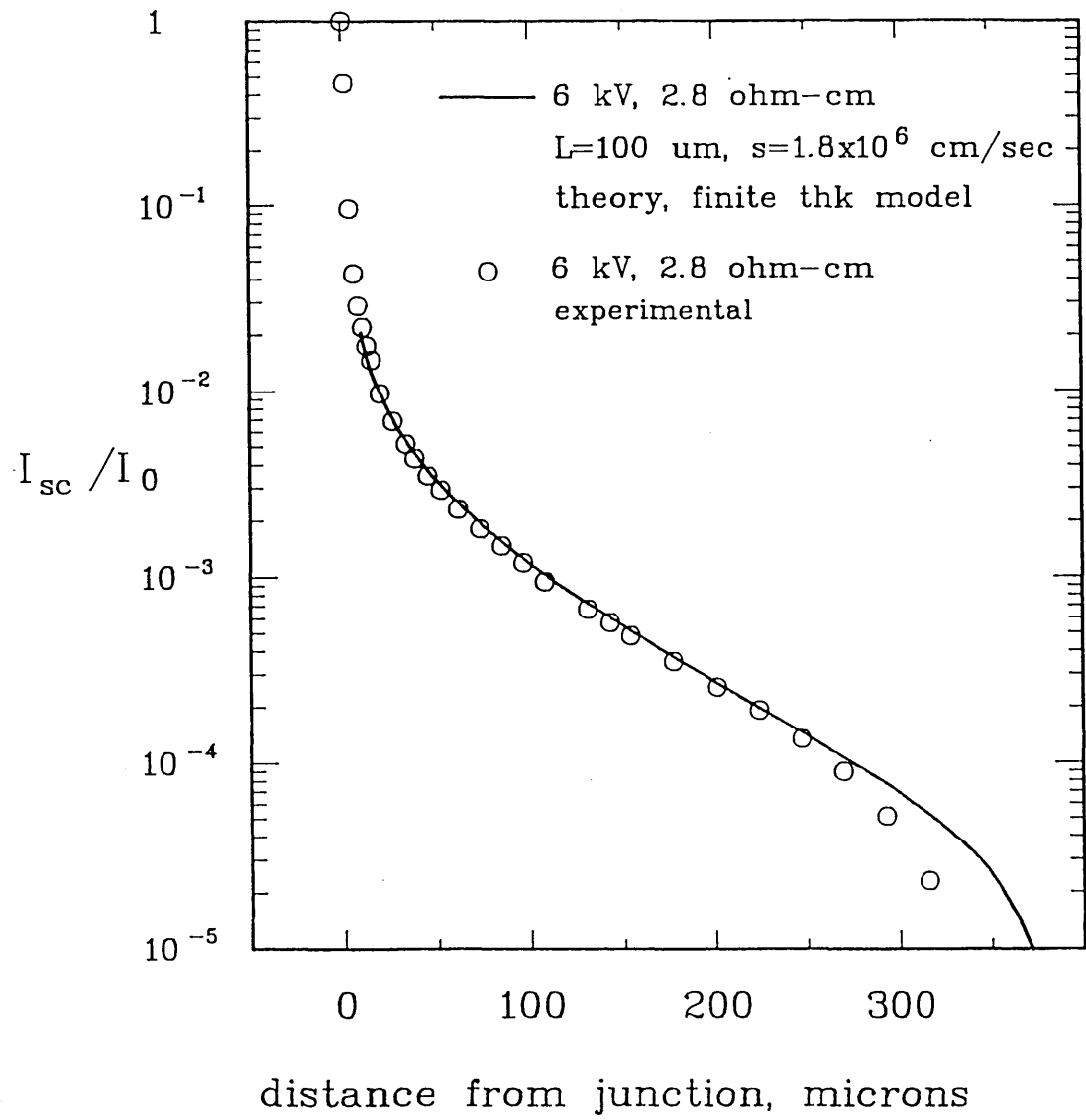


Figure 4.2.7. Theory compared to experiment. EBIC linescan calculated by EBICsim computer program using equation 1.2.5. Specimen thickness is 388 μm . As with figure 4.2.5 except for $V_b = 3$ kV (finite specimen thickness model).

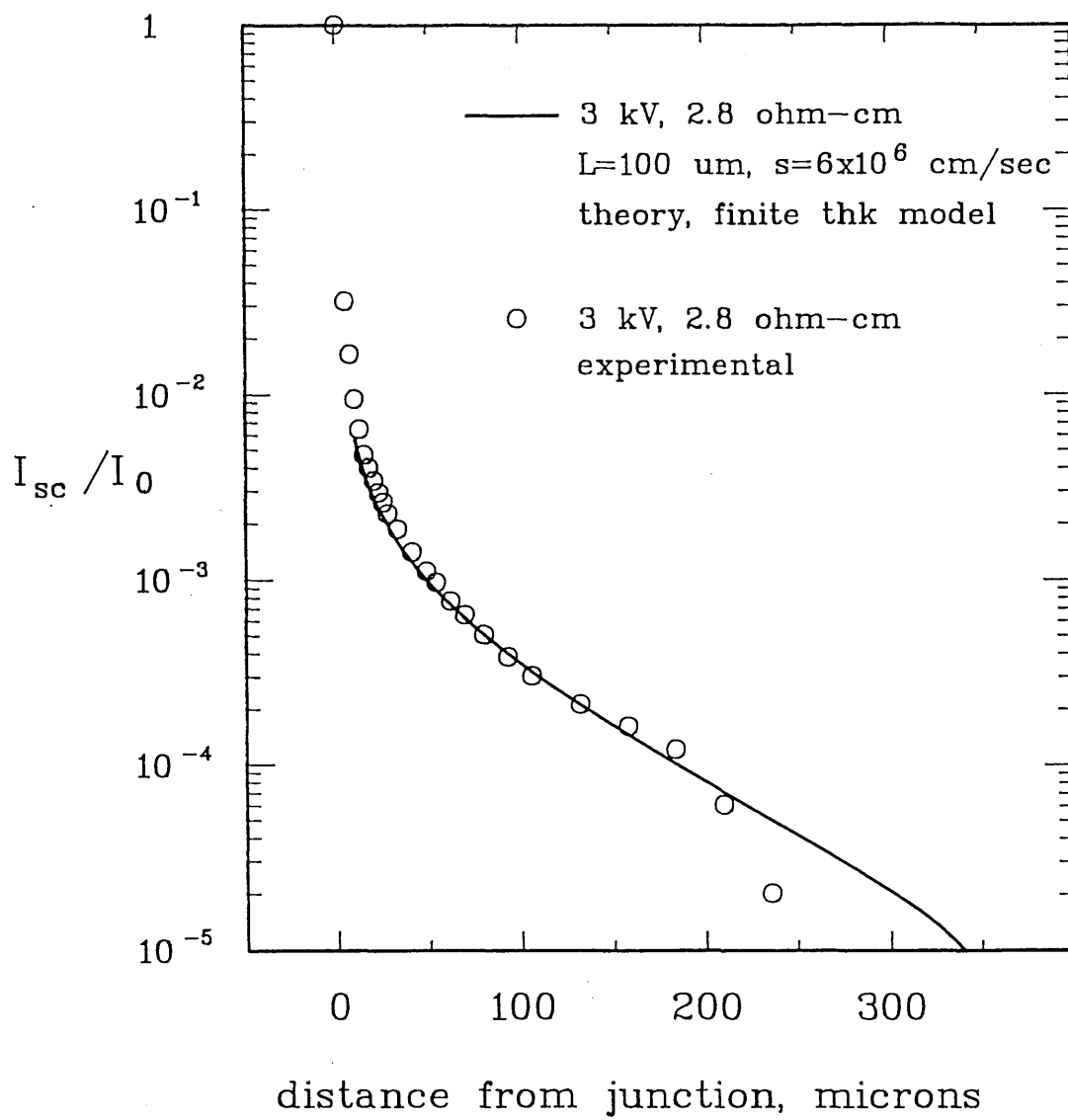
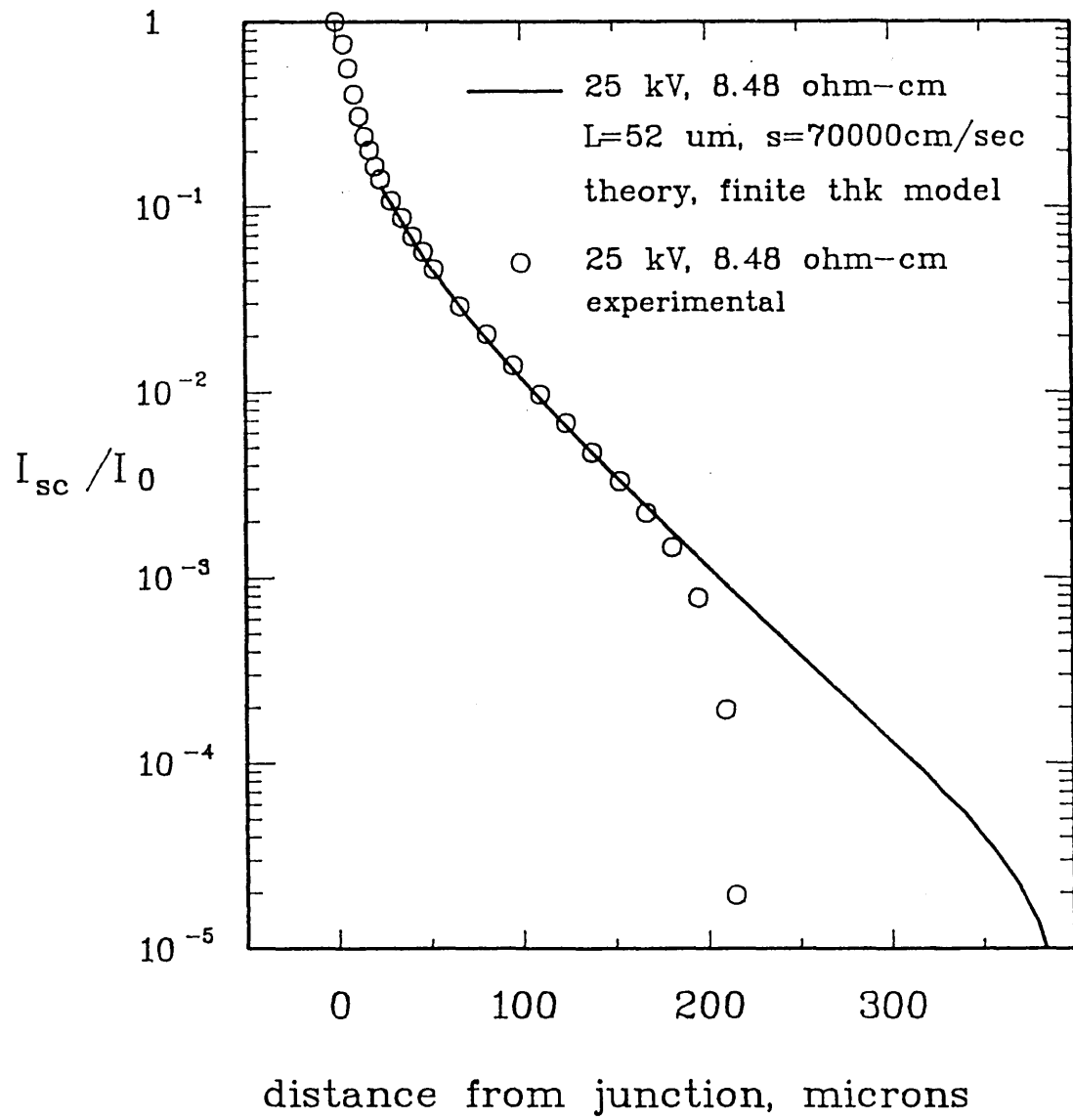


Figure 4.2.8. Theory compared to experiment. EBIC linescan calculated by EBICsim computer program using equation 1.2.5. Specimen thickness is 388 μm . As with figure 4.2.5 but for 8.5 $\Omega\text{-cm}$ p-type substrate (finite specimen thickness model).



speaking, as the signal was negative) was 10 times smaller for the back Schottky contact than for the p-n junction. This apparently is enough to cause a significant deviation in the EBIC linescan.

While the experimental data in figures 3.1.7 to 3.1.9 do not display inversion layers, it is likely that the surface charge density varies. Charge at the surface may not change the surface recombination velocity itself as much as provide an altered minority carrier depth concentration gradient due to an electric field near the surface. Such a feature is not accounted for theoretically but would appear as an increase in the surface recombination velocity if minority carriers (in this case electrons) were drawn to the surface by trapped positive charge.

The values of surface recombination velocity found by curve fitting are shown in table 4.2.4 and plotted in figure 4.2.9 as a function of V_b . Note that there is a general downward trend in v_s as the beam voltage increases. The dose rates shown in table 4.2.1 are plotted against v_s in figure 4.2.10. Bresse (1977) reported an increase in v_s as dose rate increased. This general trend can be seen in figure 4.2.10, although it is not a strong trend. Based on this it appears that trapped charge at the surface may not account for variations in v_s because if higher dose rates mean lower positive charge densities, as indicated in section 4.1.1, then v_s should decrease as dose rate increases which is not observed.

The beam power was calculated for each linescan and is plotted against v_s in figure 4.2.11. The correlation between beam power and surface recombination is much stronger than for either dose rate or accelerating voltage. It is significant that figure 4.2.11 shows a striking similarity to Davidson's figure 12 (1982, p. 270) where a linear relationship can be seen in the range 1 to 100 μW in both. In addition Davidson also shows that v_s begins to flatten out when the beam power is less than 0.1 μW which can also be seen in figure 4.2.11. Although Davidson attributes his observed variation in v_s to a transition from low to high injection, figure 4.2.11 was generated for experimental data taken at conditions of low injection. In

Figure 4.2.9. Surface recombination velocities found from curve fitting plotted against accelerating voltage.

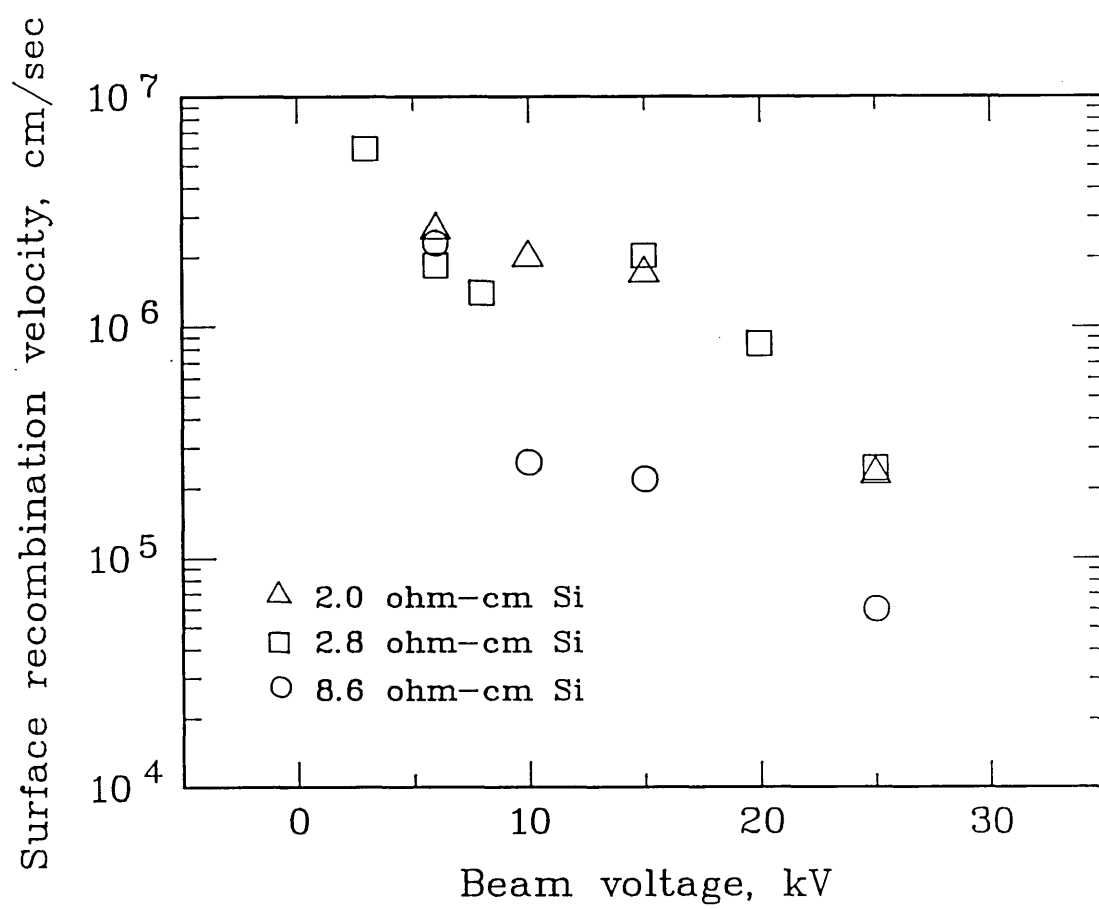


Figure 4.2.10. Surface recombination velocities found from curve fitting plotted against dose rate.

Figure 4.2.11. Surface recombination velocities found from curve fitting plotted against beam power.

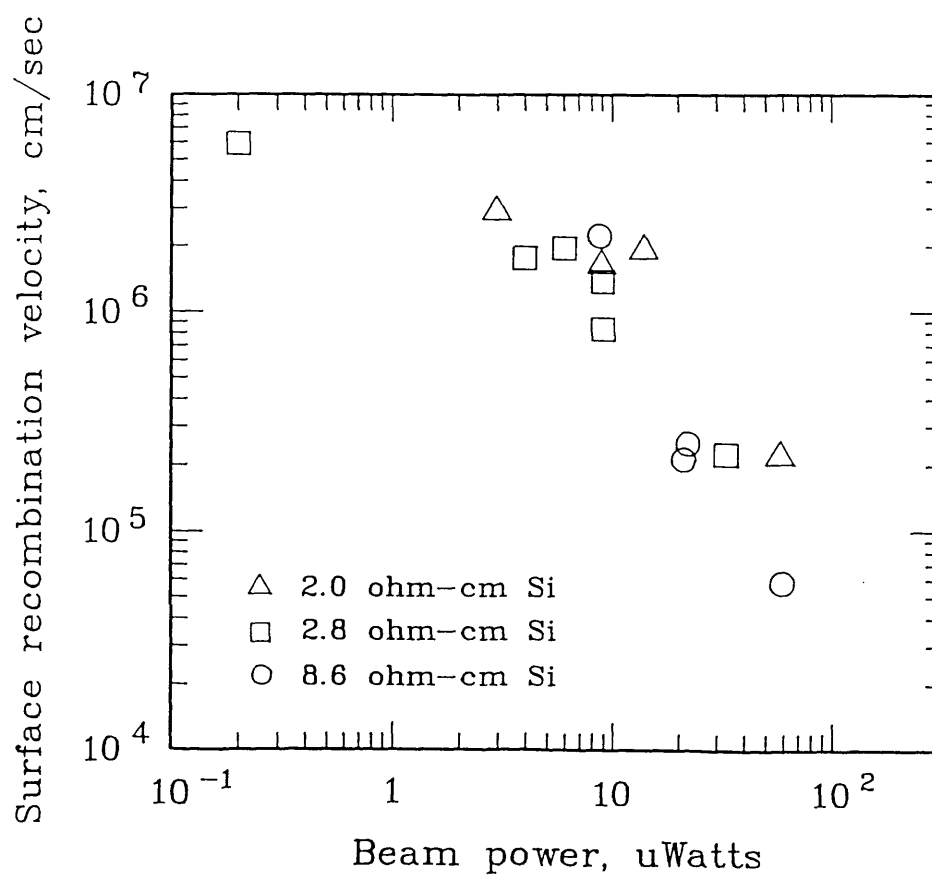
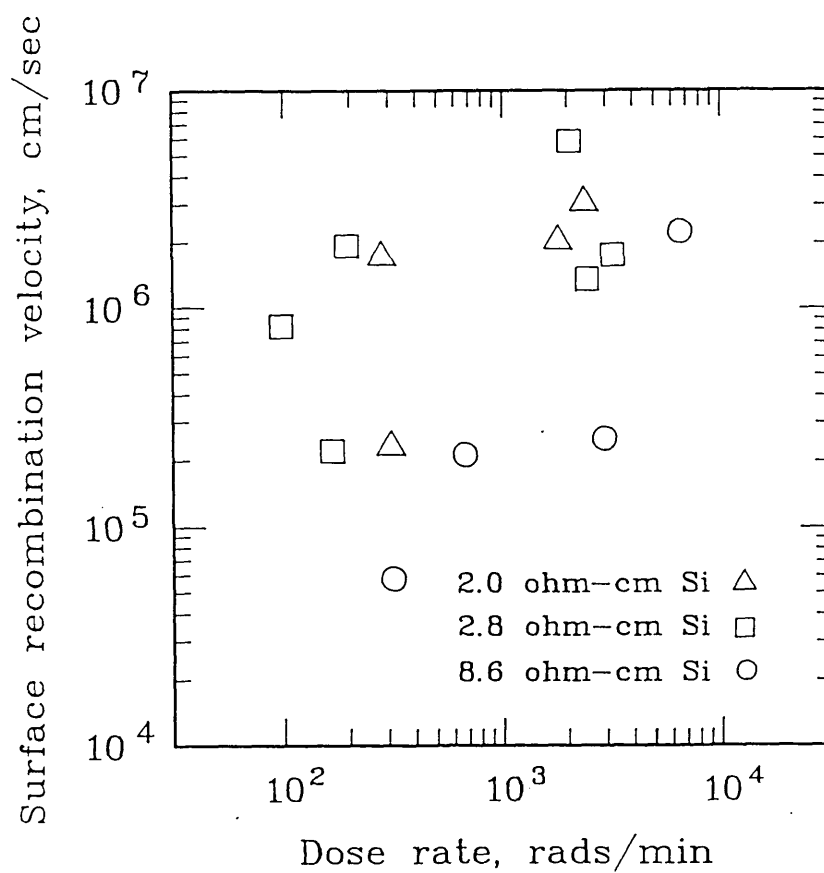


Table 4.2.4. Experimentally determined surface recombination velocities for experiments at various beam voltages and substrate resistivities.

V_b	v_s , cm/sec		
	<u>1.97 Ω-cm</u>	<u>2.8 Ω-cm</u>	<u>8.5 Ω-cm</u>
3 kV		6.0×10^6	
6	3.0×10^6	1.8×10^6	2.3×10^6
8		1.4×10^6	
10	2.0×10^6		2.6×10^5
15	1.7×10^6	2.0×10^6	2.2×10^5
20		8.5×10^5	
25	2.3×10^5	2.3×10^5	6.0×10^4

view of the close agreement between Davidson's variation in v_s and the present work, it seems that there is another explanation for the variation in v_s involving the beam power.

It could be argued that as the power increases, the silicon surface temperature could affect the surface recombination velocity. However, while the temperature may increase and change the surface recombination velocity in a localized area, this only represents a fraction of the total surface where recombination takes place.

The values of the minority carrier diffusion length determined by fitting Donolato's equations to experimental EBIC linescans are in good agreement with the empirically predicted values for 1.97 and 2.8 ohm-cm material as shown in table 4.2.5. For 8.5 ohm-cm material the value of 52 μm found by curve fitting is hopelessly astray. This is attributed entirely to the presence of a Schottky barrier at the back contact which make the experimental data unsuitable for determining the diffusion length.

Table 4.2.5. Comparison of experimentally determined values of L_e to empirically predicted ones.

<u>Bulk resistivity</u>	<u>L_e (predicted)</u>	<u>L_e (experimental)</u>
1.97 Ω -cm	92 μ m	88 μ m
2.5	98	100
8.5	138	52

4.2.2 Linescans Directly Over the p-n Junction

The numerical technique for modeling EBIC linescans over a p-n junction described in section 1.2.2 using equation 1.2.4 was solved by the Pascal computer program nearEBIC described in section 3.1.4. The input parameters required by nearEBIC were determined in the following way. The n-epi and p-type bulk doping densities were found by measuring the bulk resistivities and using Irvin's curve. The diffusion length and surface recombination velocity in the p-type silicon were simply taken to be those found in section 4.2.1. This is reasonable since the linescans of figures 3.1.7 to 3.1.9 (low magnification) were taken at the same time as those in figures 3.1.10 to 3.1.17 (high magnification). Beam currents, beam voltages and scan speeds were all identical except the dose rates were increased by a factor of 12 over those reported in table 4.2.1 since the magnification was twelve times higher. The junction depth was assumed to be 10.0 μ m by monitoring of the epitaxial growth rate from other depositions. The reverse bias was measured using a digital voltmeter and the depletion region edges were calculated according to equation 1.1.2.

The only two parameters not known for calculation of theoretical linescans over the p-n junction were the n-epi diffusion length and the surface recombination velocity on the cleaved epi surface. Determination of the minority carrier diffusion length in the epi layer was not as straightforward as with the p-type bulk because the epi was too thin to observe

simple exponential decay. Also the ohmic contact on the front epi surface affected the shape of the linescan in the same way as the back contact in figures 4.2.4 and 4.2.5. More importantly, the beam power was such that conditions of low injection did not prevail for all the experiments. For 7.5 ohm-cm n-type Czochralski the diffusion length could be as high as 130 μm . However n-type epitaxial silicon is not nearly as high quality as n-type Cz bulk so L_h is undoubtedly much less than 130 μm .

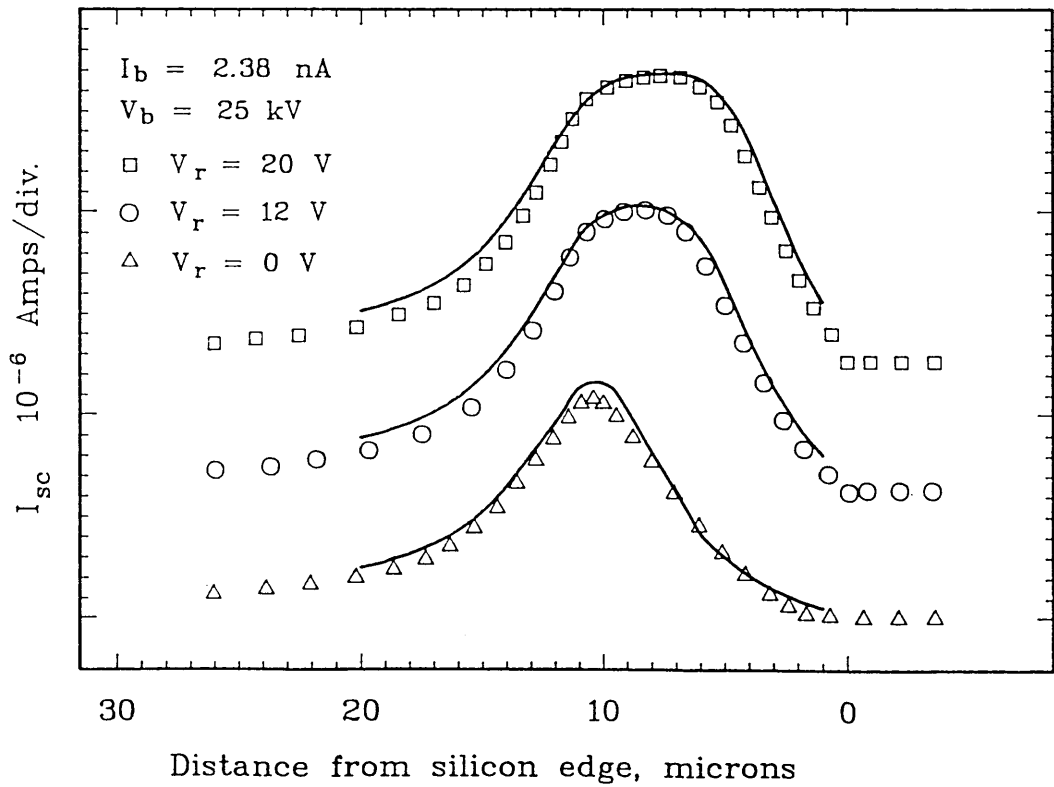
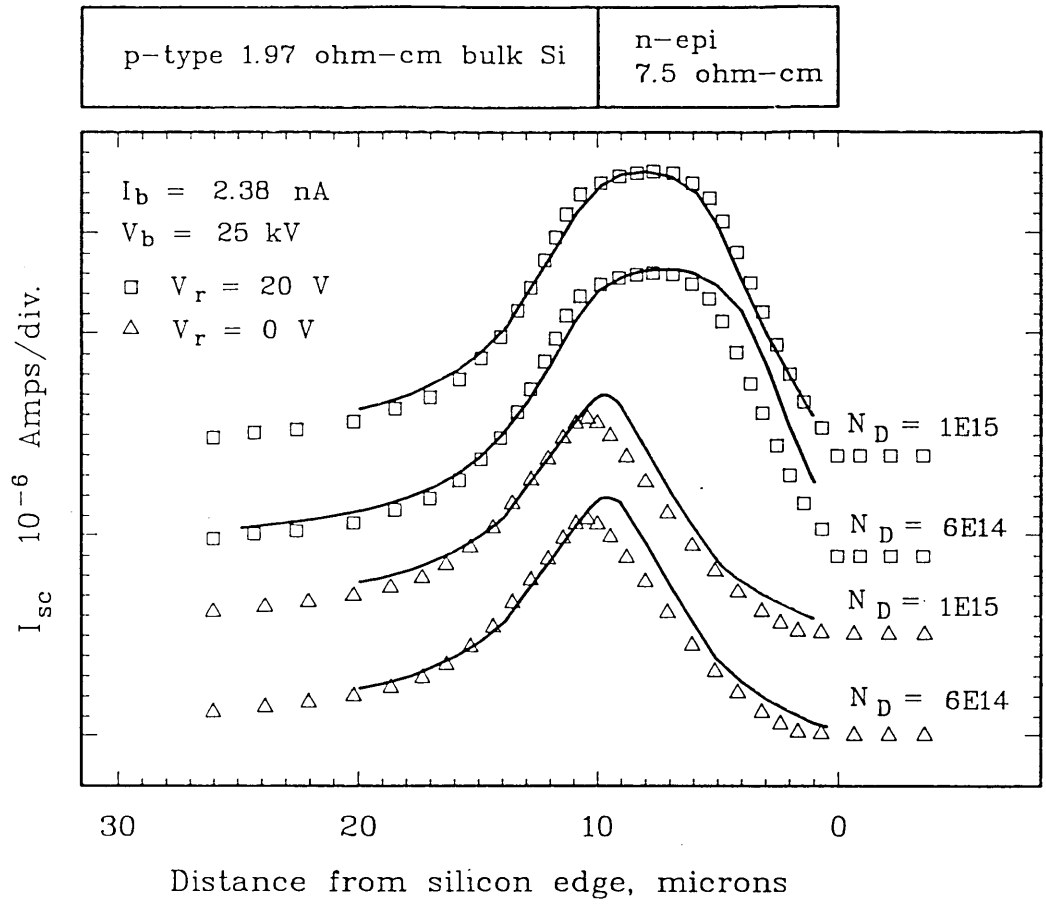
The minority carrier diffusion length in the epi layer was estimated by assuming that the surface recombination velocity over the epi was the same as that over the p-type bulk for the case where $V_b = 25$ kV. The 25 kV data was chosen to estimate L_h for the deep penetration conditions which minimize surface effects. nearEBIC then gave a reasonable fit over the epi layer for $L_h \approx 7.5$ μm . This value of L_h was then used for all subsequent calculations using nearEBIC as was the assumption that the surface recombination was the same over n-type and p-type silicon. Neither the estimate for L_h nor that for v_s in the n-epi are satisfactory, however they serve the purpose of providing some basis for establishing whether the approach (described in section 1.2.2) to modeling EBIC linescans near the junction is valid.

An example of fitting nearEBIC generated theoretical curves to experimental data can be seen in figure 4.2.12. The bottom two curves of triangles are identical and represent the experimental data taken at zero volts reverse bias ($V_r = 0$ V) on 1.97 ohm-cm material. The top two curves are also identical and represent experimental data taken at $V_r = 20$ V. The two continuous curves marked " $N_D = 6\text{E}14$ " are theoretical EBIC linescans for the nominal value of epi doping which is $6 \times 10^{14} \text{ cm}^{-3}$ from table 1.1.2. From these two curves it can be seen that nearEBIC has closely reproduced the shape of the experimental EBIC linescans, but appears to be shifted to the right with respect to the experimental data.

One possible explanation for this is that the doping in the epi layer is not uniform. During the beginning of an epitaxial deposition it is possible that the phosphine concentration in the $\text{PH}_3/\text{SiH}_4/\text{H}_2$ gas mixture can be higher than expected due to a contribution of phosphorus

Figure 4.2.12. Theory compared to experiment. EBIC linescans calculated by nearEBIC using equation 1.2.4 and a Monte Carlo simulation for $h(x,z)$. The result of changing doping in the epi layer is shown in 2nd and 4th curves from the bottom.

Figure 4.2.13. Theoretical EBIC linescans correctly fitted to experimental data of figure 4.2.12. Junction depth determined to be 10.6 μm by curve fitting.



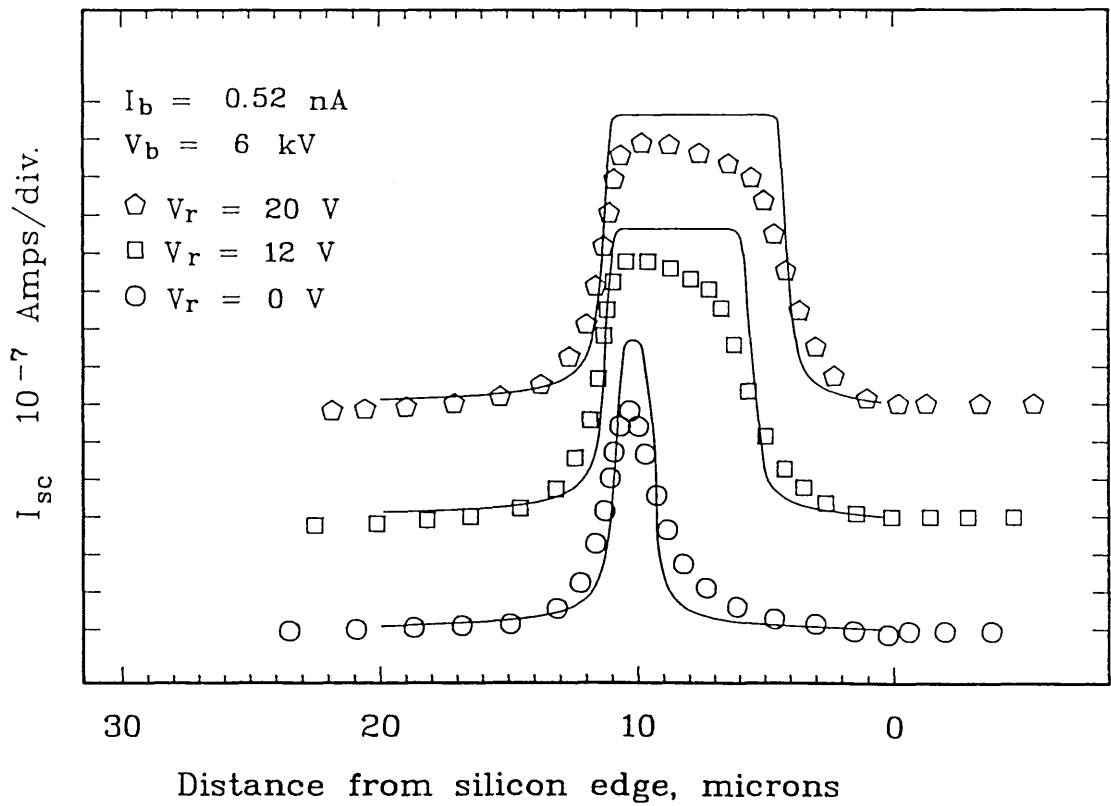
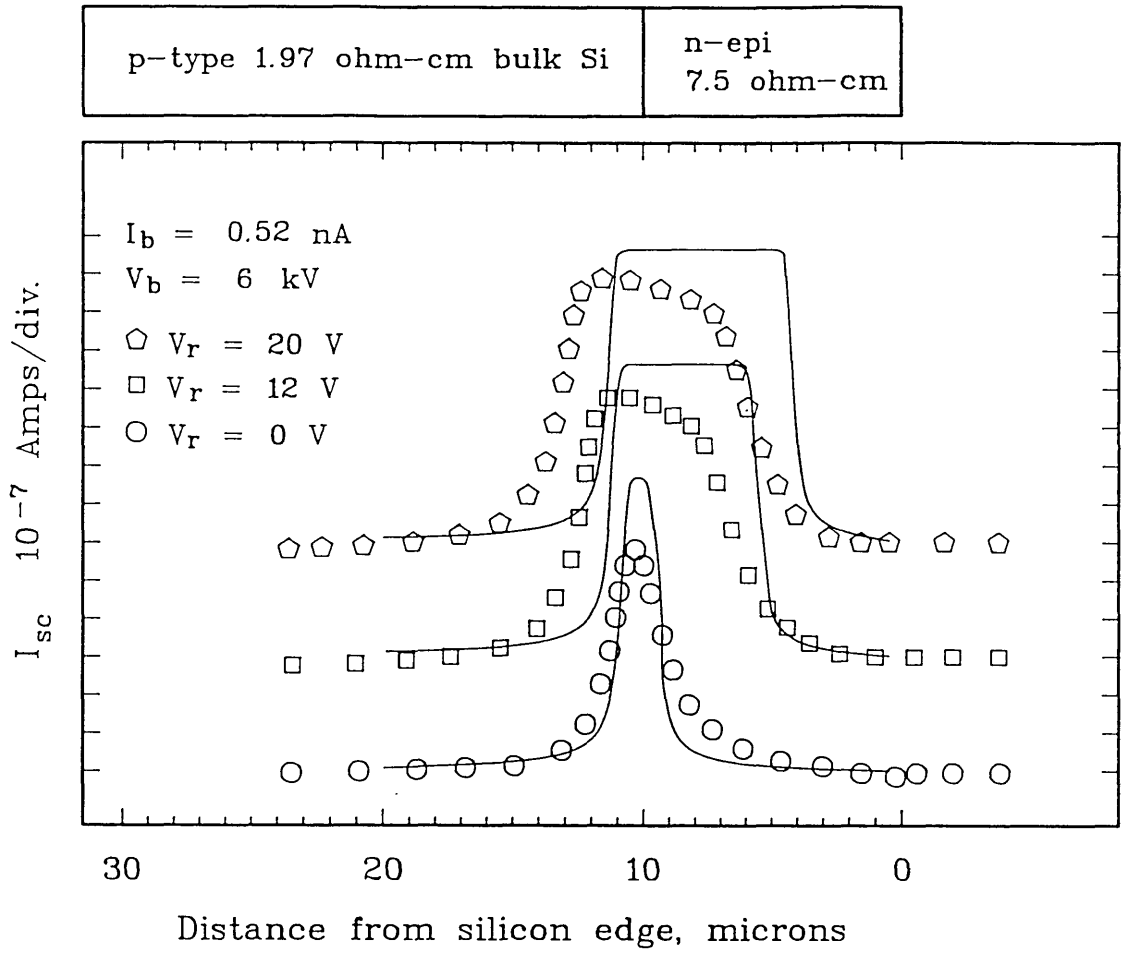
absorbed in the silicon carbide coated susceptors from a previous deposition. If this were so, the depletion region width would be narrower and the edges would be in a different position. Another two theoretical EBIC linescans were calculated using an epi doping level of 10^{15} cm^{-3} to see if this explains the lateral shift. From the continuous curves marked " $N_D = 1E15$ " in figure 4.2.12 it can be seen that this modification gives a much better fit for the case of $V_T = 20 \text{ V}$. However this change in epi doping does not correct the shift in the linescan at $V_T = 0 \text{ V}$. Therefore this explanation must be rejected in favour of something that explains the shift in both curves.

Since the junction depth is determined by merely a periodic monitoring of the epitaxial deposition rate, it is possible that the epi thickness is not $10.0 \mu\text{m}$. The bevel and stain technique used for determination of the junction depth is only good to about $\pm 5\%$. By changing the junction depth from 10.0 to $10.6 \mu\text{m}$ in the nearEBIC program, the theoretical curves of figure 4.2.13 were calculated for the 25 kV experimental conditions. The 25 kV data appear again in figure 4.2.13. This time an additional EBIC linescan at $V_T = 12 \text{ V}$ is included. A good fit between theory and experiment is obtained, especially in view of the assumption that there is no recombination in the depletion region. This may explain why nearEBIC calculates theoretical EBIC linescans that have slightly higher values for the short circuit current. One implication of the adjustment of the junction depth in nearEBIC to give a satisfactory fit to the experimental data is that curve fitting of this type could be used for determining junction depths to greater precision than present methods.

Theoretical EBIC linescans were also fitted to the experimental data for a 6 kV beam as shown in figures 4.2.14 and 4.2.15. The same input parameters as in figures 4.2.12 and 4.2.13 were used by nearEBIC except the junction depth was corrected to $10.6 \mu\text{m}$. Even with the adjustment to the junction depth, the calculated linescans are still offset. In this case the source of the lateral shift is thought to be due to drifting of the beam position from scan to scan over the course of the experiment.

Figure 4.2.14. Theory compared to experimental data, $V_b = 6$ kV. EBIC linescans calculated by nearEBIC using equation 1.2.4 and a Monte Carlo simulation for $h(x,z)$.

Figure 4.2.15. Theoretical EBIC linescans correctly fitted to experimental data of figure 4.2.14. Electron beam position had drifted while recording experimental EBIC linescans of figure 4.2.14



It may at first seem inconsistent to explain a lateral shift in the 25 kV data by inaccurate determination of the junction depth and then to attribute a similar lateral shift in the 6 kV data to a drifting electron beam. The experimental data for the 25 kV beam, used for plotting figure 3.1.12, clearly show the point at which the beam dropped off the epi edge onto the brass specimen holder. This appears as a sharp drop to zero in the conductive mode signal for all the scans (except for $V_T = 0$). Therefore it is easy to align the linescans laterally using this feature. This was done when the data was transferred from the original experimental X-Y trace to construct figure 3.1.12. During the 25 kV experiment, the beam had not drifted more than $0.7\text{ }\mu\text{m}$ over the time taken to record the six linescans.

On the other hand, for the 6 kV linescans used for plotting figure 3.1.13, only two of the six curves had any clear distinguishing mark indicating where the electron beam dropped over the epi edge. As a result the linescans could not be aligned with confidence. Also the problem of image drifting was observed to be more severe at low beam voltages. Therefore there is reason to question the lateral position of the 6 kV data but not the 25 kV data. When the position of the experimental data points are corrected, as in figure 4.2.15, a reasonable agreement between theory and experiment is obtained.

An unusual feature of the experimental EBIC linescans taken over the reverse biased p-n junctions at low beam voltages is the slope in the EBIC linescan over the depletion region. This is especially visible at high reverse biases when the depletion region is wide, such as can be seen in figures 3.1.12, 3.1.13 and 3.1.17. nearEBIC assumes that electron-hole pairs generated in the depletion region are collected with 100% efficiency and gives a flat top to the linescan wherever the generation volume is completely enclosed by the depletion region. For the data in figure 4.2.13 this was not a bad assumption. But this may only indicate that recombination inside the depletion region is negligible when carriers are generated far enough below the surface. The experimental data at low beam voltages as in figures 4.2.14 and 4.2.15 suggest that surface recombination or surface effects have a significant affect in the depletion region when the generation volume is closer to the surface.

The slope in the experimental data over the depletion region also shows that the surface is having a greater effect on carriers generated farther from the junction. For the case of the 1.97 ohm-cm p-type specimen the width of the depletion region at 20 volts reverse bias is 6.9 μm according to equation 1.1.2. As shown in figure 1.1.1, the electric field in this region is strongest at the metalurgical junction and becomes weaker nearer the depletion region edge. A carrier generated near the junction would accumulate more kinetic energy in the electric field as it was accelerated out of the depletion region than a carrier generated near the edge. Any surface condition providing a driving force for carriers would have a proportionally greater influence on the carriers generated in the weaker parts of the electric field. This explanation is consistent with the experimental data which shows that the conductive mode signal drops off and slopes downward away from the junction. This might explain why a higher proportion of carriers generated near the edges of the depletion region recombine.

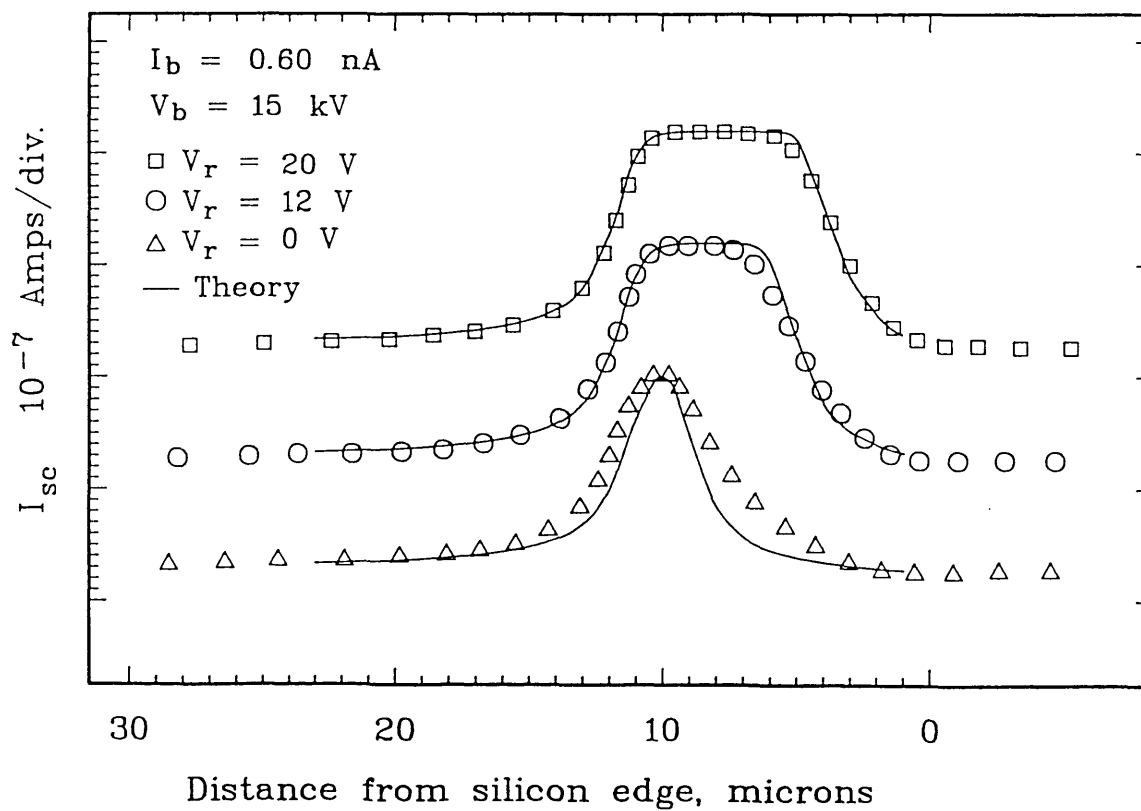
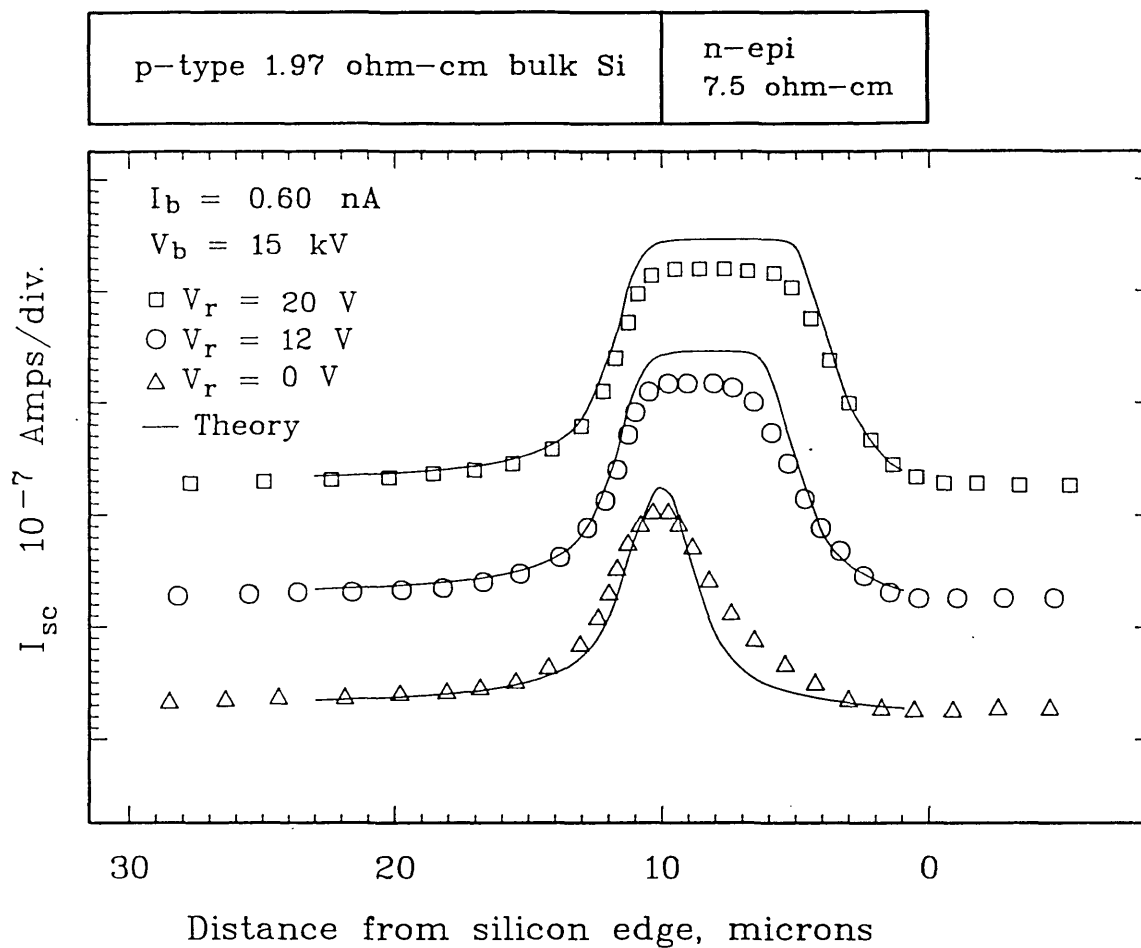
Finally in figure 4.2.16 theoretical EBIC curves were fitted to the experimental data for a 15 kV electron beam. Although there is no slope to the EBIC linescan, there is still a gap between the theoretical maximum and the experimental maximum. One possible explanation is that a certain percentage of carriers reaching the junction recombine inside the depletion region. This condition is easily incorporated into the theory as a constant 12% reduction in the EBIC at all points and gives a calculated theoretical EBIC linescan that is in good agreement with experimental data as shown in figure 4.2.17.

A fundamental weakness of the nearEBIC calculations is the assumption that the generation volume is essentially 80 *lines* of electron-hole pairs (see section 3.1.4.2) at a depth of 0.3R. This can be improved by implementing the computer program on faster processor and using all 6400 elements in the lateral dose energy array produced by the Monte Carlo simulation.

Another difficulty in modeling linescans of this type is that the shape of the curve near the

Figure 4.2.16. Theory compared to experimental data, $V_b = 15$ kV. EBIC linescans calculated by nearEBIC using equation 1.2.4 and a Monte Carlo simulation for $h(x,z)$.

Figure 4.2.17. Theoretical EBIC linescans more nearly fitted to experimental data of figure 4.2.16. Assumption was made in the computer model that 12% of the carriers diffusing to the depletion region recombine inside of the depletion region.



depletion region is very sensitive to the surface recombination velocity. This is unfortunate since in section 4.2.1 it was found that v_s is, as yet, not independent of the analytical technique.

The theoretical linescans calculated by nearEBIC could also be improved by taking high injection levels into account. Although the minority carrier lifetime and diffusion constant are defined at conditions of high and low injection, as yet mathematical relationships governing carrier behaviour in the transition region are not well established (Berz and Kuiken, 1976).

4.3 GaAs Bipolar Transistors

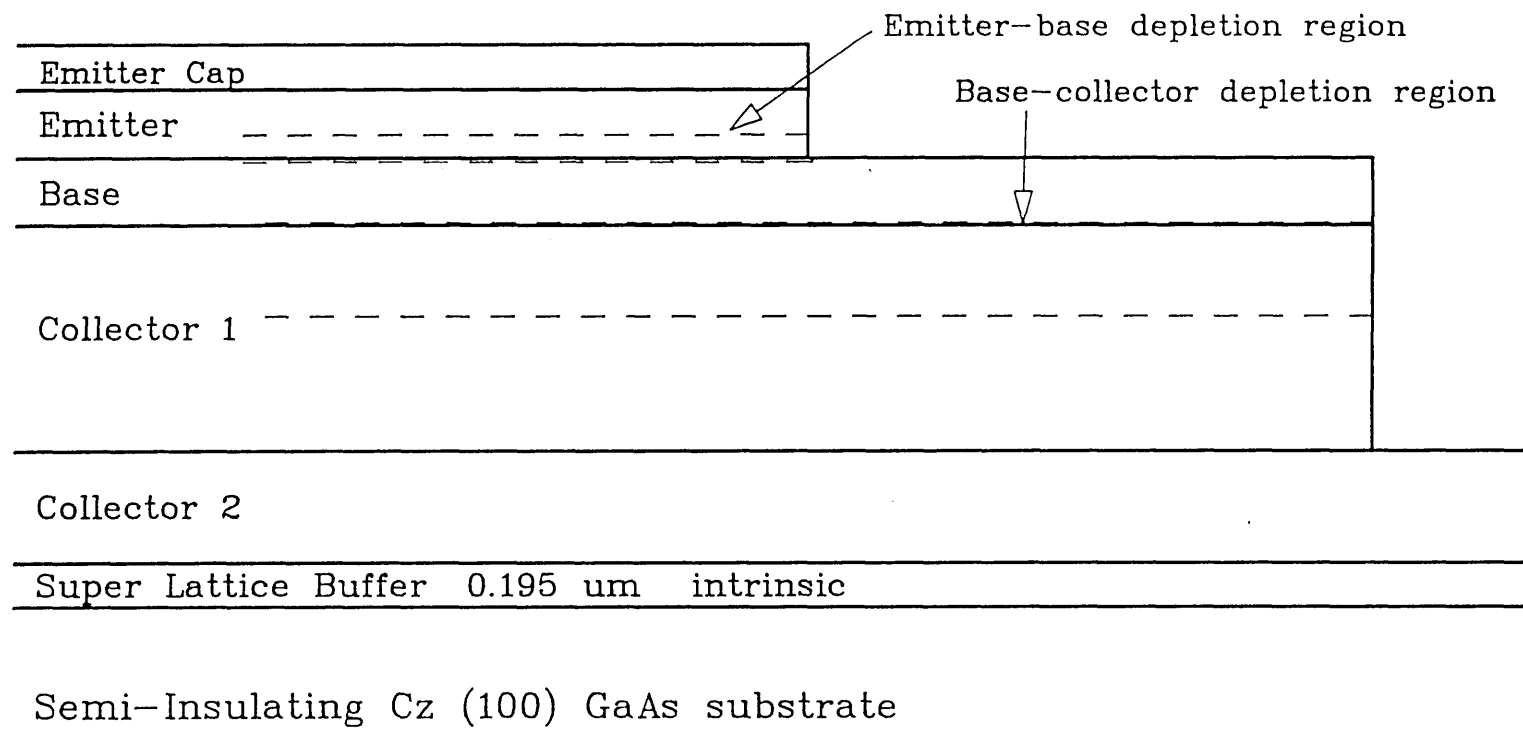
In section 3.2 experimental results for examination of GaAs bipolar transistors were reported as a function of accelerating voltage. Meaningful interpretation of conductive mode linescans and qualitative images requires information about the generation volume depth. The Grün range can be calculated from equation 1.2.7 and a table of calculated values of R as function of beam voltage is shown in appendix D for convenience.

4.3.1 Quantitative Conductive Mode Analysis

Depletion region widths were calculated for the GaAs planar bipolar transistor made from the material shown in figure 3.2.1 using equation 1.1.2. It was found that at zero bias the emitter-base depletion region extends $0.09\ \mu\text{m}$ into the emitter and $0.02\ \mu\text{m}$ into the base. The base-collector depletion region extends $0.42\ \mu\text{m}$ into the collector. There is only a very thin depletion region in the base at this junction since the base is 100 times more heavily doped. These depletion region locations are shown in the schematic diagram in figure 4.3.1.

The results of the quantitative EBIC linescans in section 3.2.1 suggest that the behaviour of two planar junctions is not simply the sum of the charge collection properties of two individual junctions at different depths. Figures 3.2.6 and 3.2.7 show quantitatively that wiring configurations B-C, B-EC and C-BE all yield the same conductive mode signal when the electron beam is directed at exposed base material. This is not surprising since these three configurations all use the base-collector junction as the charge collection barrier. For configuration B-EC the emitter-base junction would be expected to contribute to the conductive mode signal, however it is a long distance from the incident electron beam. It is interesting to note that the short circuit current displays a maximum at $V_b \approx 15\ \text{kV}$. The centre of gravity of the generation volume is at $0.31\ \mu\text{m}$ when $V_b = 16\ \text{kV}$ which is exactly the depth of the base-collector junction just below the surface of the exposed base. Since

Figure 4.3.1. Schematic diagram showing the location of the depletion region edges for the bipolar GaAs transistor specimen.



there is a sharp increase in the short circuit current as V_b increases from 3 to 15 kV, the surface recombination velocity must be very high or L_e in the base must be very short. This is supported by the data in figure 3.2.6 at 25 kV (Grün range = 2.25 μm) that is approximately equal to the data at 15 kV when most of the electron-hole pairs are generated in the collector. This shows that recombination in the collector (which has no exposed surface) does not vary with penetration depth as in the base.

In figure 3.2.7 where the electron beam is over the exposed emitter, the signal from configuration C-BE drops to almost zero when $V_b < 12$ kV. This is expected since electrons don't begin to penetrate to the base until $V_b > 11$ kV.

Figures 3.2.6 and 3.2.7 also contain some data whose interpretation is not immediately obvious. For example in figure 3.2.6 where the emitter-base junction alone is used to collect the conductive mode signal and the collector is left floating, one would not expect to see any signal at all since the electron-hole pairs are generated far from the emitter-base junction in the depletion region of the base. A clue to this behaviour lies in table 3.2.1 for configuration E-BC. This configuration also uses the emitter-base junction for charge collection but is zero for all V_b when the beam is over the base. The only difference between configurations E-BC and E-B is that the base is shorted to the collector in configuration E-BC and any electron-hole pairs generated in the base or collector are merely driven around the base-collector short and not detected. It appears that a conductive mode signal is obtained from the emitter-base contacts when the collector is floating due to an open circuit voltage across collector and base which forward biases the collector base junction. This is in agreement with equation 1.1.3 and Gonzales (1974) modified Ebers-Moll model shown in figure 1.1.3.

Further evidence for this type of mechanism can be found in figure 3.2.7 noting the difference between configurations B-C and C-BE. When the base-collector junction acts as the charge collection barrier while the emitter is shorted to the base (C-BE), the EBIC is

zero, as pointed out above, until the beam penetrates to the base-collector junction. However when the emitter is allowed to float (B-C), the base-collector junction yields a large conductive mode signal. Again this can be explained by the emitter-base open circuit voltage having an affect on the base-collector current. This is analogous to the previous case where the collector is floating (E-B versus E-BC).

This can be explained with the aid of figure 1.1.2 which shows the fundamental mechanisms of bipolar transistor operation. When electron-hole pairs are generated in the emitter or base region, minority carriers that diffuse to the depletion region are accelerated across in the same direction as reverse leakage current. If no external path exists for this current to go, there will be an open circuit voltage established across the emitter and base which will tend to forward bias the junction. This will begin to turn the transistor on, injecting carriers through the base into the collector.

Figure 3.2.8. shows a maximum at 12 kV in the conductive mode signal for configuration E-BC when the centre of gravity of the generation volume is at $0.19\text{ }\mu\text{m}$; precisely the depth of the emitter-emitter cap interface (figure 3.2.1). The maximum also occurs at the point where the Grün range is $0.62\text{ }\mu\text{m}$ and the generation volume extends into the base region about $0.12\text{ }\mu\text{m}$ below the emitter-base junction.

There is no fundamental reason why a maximum in the EBIC should occur when the centre of gravity of the generation volume is at the emitter cap interface aside from carrier collection via the bulk electron voltaic effect. This might be possible to detect if contact could be made independently to both layers since there is a sharp step in the silicon concentration from 2×10^{17} in the emitter to 2×10^{18} in the emitter cap. However configuration E-B of figure 3.2.8 shows that this maximum at the emitter cap interface is a coincidence. The E-B data does not display a maximum until $V_b \geq 15\text{ kV}$. This means that the short circuited base-collector junction in configuration E-BC collects a portion of the generated electron-hole pairs when the generation volume begins to extend into the base

region. Thus the short circuit current will increase for E-BC as the centre of gravity of the generation volume draws nearer to the emitter-base junction until the generation volume begins to penetrate into the base. At that point electron-hole pairs that diffuse to the base-collector junction will never be detected by the Keithley since they are EBIC that is driven around the base-collector short. This is not true for configuration E-B of figure 3.2.8 because when the collector is floating electron-hole pairs generated in the base region will be less likely to diffuse to, and be collected by, the base-collector junction since it is open circuit and probably forward biased.

In wiring configuration E-C the conductive mode signal is collected by connecting the current amplifier across the n-type emitter and collector contacts while the p-type base is allowed to float. Intuitively this is the least obvious way of collecting the conductive mode signal in a device with two charge collection barriers. The highest observed short circuit current for configuration E-C is 0.60 as opposed to the maxima of about 0.85 in figure 3.2.7. Although the conductive mode signal is reduced in this configuration as predicted by Gonzales (1974), it is hardly "greatly reduced" as he claims. This indicates that the EBIC signal from the forward biased junction is small. The diffusion potentials for the two junctions were calculated according to equation 1.1.2 and found to be 1.36 V for emitter-base and 1.28 V for base-collector.

In figure 3.2.9 when the electron beam is directed at exposed emitter, the short circuit current displays a maximum at about $V_b = 10$ kV. Although $R = 0.45 \mu\text{m}$ and the centre of gravity of the generation volume is in the emitter cap, there are still a quantity of electron-hole pairs generated up to 20% deeper than R (Everhart and Hoff, 1971). It would seem that as soon as any electron-hole pairs are generated in the base region ($0.5 \mu\text{m}$ below the surface) some of them diffuse to the base-collector junction inducing some current flow in the opposite direction which sharply reduces the emitter-base signal. As the beam voltage increases more electron-hole pairs reach the base-collector junction so the EBIC decreases until it reaches zero around 23 or 24 kV. At this point the centre of gravity of the generation volume

is 0.1 μm below the emitter-base junction, or about half way between the two junctions.

It would seem from the maximum observed for configuration E-BC in figure 3.2.8 (discussed previously), and from the point made from figure 3.2.9 where I_{sc} goes negative, that minority carriers generated deeper than 0.1 μm below the emitter-base junction (0.6 μm below the surface of the emitter) are collected by the base-collector junction. This is expected since carriers generated in the centre of the base region have roughly an equal probability of being collected by either junction.

In summary, the quantitative EBIC linescans reported in section 3.2 have lead to some important advances in the understanding of the use of conductive mode study of complex electronic structures.

(1) They confirm Gonzales' (1974) prediction that an EBIC signal will be produced by a neighbouring junction that injects carriers into the charge collection barrier. It was found that this EBIC signal is due to the EBIV of the neighbouring junction where images of recombination centres in the neighbouring junction could be clearly observed. In addition it was shown that junctions arranged back-to-back in series do not greatly reduce the conductive mode signal as Gonzales asserts. Although the EBIC signal is reduced by about 25%, this *competing junctions* arrangement holds much potential for improvements in both spatial resolution and depth resolution of recombinations centres.

(2) The open circuit voltage from neighbouring junctions can induce an apparent short circuit current in a junction that is not being irradiated as in the case for the signal collected by configuration E-B in figure 3.2.6. This implies that conductive mode signals could be extracted from regions on a microelectronic device that have no contacts such as p-wells or n-wells in CMOS devices.

(3) The experimental data of figure 3.2.9 show that a useful conductive mode signal can be extracted by two contacts to semiconductor of the same doping type. This could be useful when looking across source and drain or between two identical Schottky contacts.

(4) By interpreting the EBIC maximum as a function of V_b , (e.g. beam penetration), information about the diffusion potential and depth of the narrow base can be obtained, even in shallow devices. This is significant since this kind of depth resolved conductive mode analysis provides a convenient way to determine the depth of certain layers that are beyond the resolution limits of bevel and stain and FTIR techniques.

4.3.2 Qualitative Conductive Mode Images of Complex Structures

Figures 3.2.10 (a) through 3.2.10 (c) are a good illustration of the difference between recombination centres caused by surface damage and process induced defects embedded in the material during molecular beam epitaxy. Since (100) GaAs cleaves easily at right angles, it is not surprising that the surface damage of figure 3.2.10 (c) caused lattice damage that appears as recombination centres at 90° angles. Of more interest are recombination centres like defect B which degrade the performance of the device but cannot be seen on either an optical or emissive mode micrograph. Also features that show an increase in the conductive mode signal such as the bright perimeter of region C are important because this may identify the presence of an unwanted Schottky barrier. Napchan (1987) points out that this enhanced signal may be due to a critical thickness of metallization which brings the centre of gravity of the generation volume closer to a charge collection barrier that is nearer to the surface. This is unlikely however, considering that the wiring configuration used in figure 3.2.10 was B-EC. As the generation volume is brought closer to the surface, the short circuit current decreases sharply as shown experimentally in figure 3.2.7.

The depth the defect labeled D in figure 3.2.11 can be closely estimated using the principles

worked out in section 4.3.1. In the conductive mode micrograph of figure 3.2.13 the base-collector junction alone was used as a charge collection barrier while the emitter was allowed to float. Once the emitter was shorted to the base, the defect disappears from the image as shown in figure 3.2.14. Since the micrographs were taken at 12 kV, the centre of gravity of the generation volume was at the interface between emitter and emitter cap. The Grün range at 12 kV is $0.62\text{ }\mu\text{m}$ which means only a small fraction of electron-hole pairs diffuse to the base-collector junction to give a direct EBIC signal. The source of contrast for the image in figure 3.2.13 is almost entirely due to the effect of the open circuit voltage across the emitter and base.

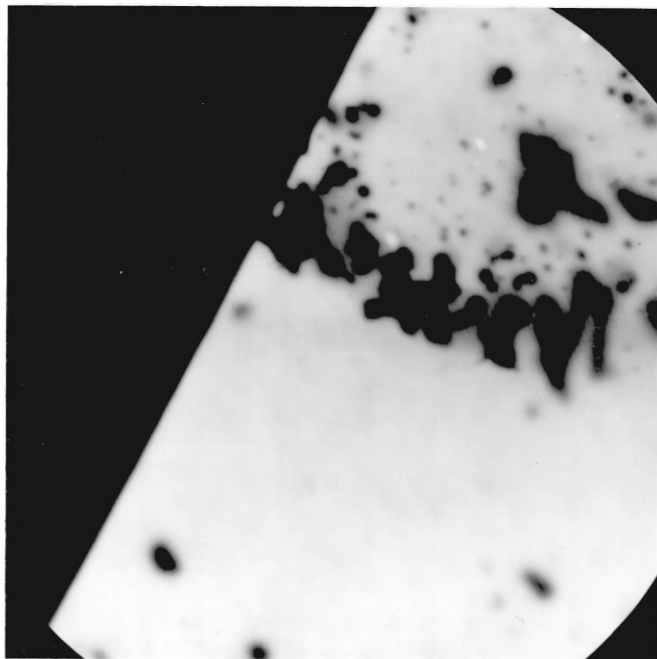
The disappearance of defect D in figure 3.2.14 indicates that it is located in the emitter or emitter cap. In the wiring configuration of figure 3.2.14, emitter and base are shorted and the only source of contrast is from electrons generated in the base that are collected across the base-collector junction. Thus figure 3.2.14 is an EBIC micrograph entirely due to minority carriers generated in the base. Since only a small part of the generation volume could reach the base, the Keithley current range required for figure 3.2.14 was ten times more sensitive than for 3.2.13.

From figure 3.2.14 it appears that the large black region marked E in figure 3.2.13 is almost certainly two recombination centres located (at least in part) in the thin base material. We know that features in the emitter do not appear because emitter and base are shorted to each other. Since the generation volume does not penetrate into the collector, the recombination centres must be in the base by the process of elimination.

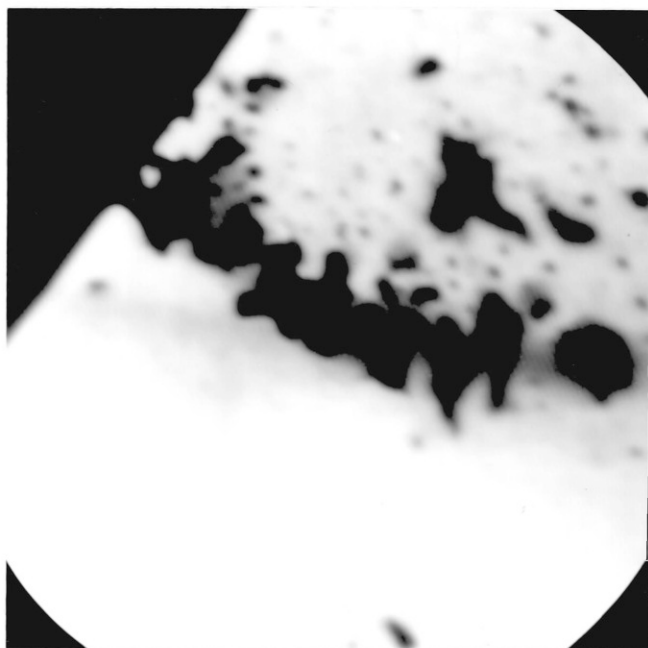
It is possible that the defect(s) marked E may extend vertically up into the emitter as well, since this region displays such high contrast in figure 3.2.13. Another possibility is that the odd shaped region marked E has nothing at all to do with the two dark circles at the same location in figure 3.2.14 since the resolution of defect E improves as the beam voltage decreases. This can be seen in figure 4.3.2 at 7 kV and figure 4.3.3 at 4 kV where the

Figure 4.3.2. EBIC micrograph of defect D when $V_b = 7$ kV. Conductive mode signal collected using configuration B-CE.

Figure 4.3.3. EBIC micrograph of defect D when $V_b = 4$ kV. Dark grey band across the defect is a reduction in the EBIC signal due to contamination build-up on the surface during SEM examination. Conductive mode signal collected using configuration B-CE.



10 μm



10 μm

conductive mode signal was collected using wiring configuration B-EC. Thus region E could be a defect very near the surface simply covering up the two dark areas of figure 3.2.14.

A more likely explanation lies in the striking similarity between region E and Schick's (1981) piped silicon transistors. Schick's defects came in pairs and were found to originate as dislocation loops at the surface (section 1.1). Even though the materials are quite different, the two dark recombination centres marked E occur as a pair and are associated with a feature near the surface since the resolution improves as V_b decreases.

To summarize, conductive mode analysis of a GaAs bipolar transistor has shown that devices with more than one charge collection barrier provide a means of identifying and characterizing a variety of process induced defects. The quantitative study discussed in section 4.3.1 has led to two important advances in qualitative imaging.

(1) By judicious choice of accelerating voltage and wiring configuration, the depth of some recombination centres can be determined, even in shallow devices as shown with defects D and E.

(2) A more thorough understanding of the conductive mode signal in a device with two charge collection barriers has lead to a striking improvement in defect resolution, as seen by comparing defect E between figures 3.2.13 and 3.2.14

4.3.3 Depth Resolved EBIC

The contrast data reported in section 3.2.3 all seem to indicate that the contrast improves as the beam voltage decreases. This is in agreement with the conclusion in the previous section that defect D is in the upper 0.5 μm of emitter or emitter cap material.

The EBIC micrograph of figure 4.3.3 shows a thick dark band across defect D that does not appear near the edge of the gold wire. The edge of the gold wire appears as a black silhouette diagonally oriented in the upper left hand corner of figures 4.3.2 and 4.3.3. The dark band is probably surface contamination due to prolonged SEM examination and linescans over the defect. For this reason the definition of C' in section 3.2.3 is the valid one, since any depth resolution would have to include the thickness of the contamination.

Although figure 3.2.17 shows a maximum in the local contrast C' at 5 kV for wiring configuration B-EC, it is the only configuration of table 4 to show a maximum. The contrast for all the other configurations increases steadily as the beam voltage decreases. Based on this it would appear that the defect is only just under the surface. A second method of determining defect depth is by plotting the half width resolution against $V_b^{1.75}$ as described by Lesniak (1985). This resolution was calculated for configurations B-C and B-EC and is summarized in table 4.3.1. Below 12 kV, configuration B-C is thought to be primarily an EBIV signal as discussed in the previous section. Since there is only a weak trend in the data in table 4.3.1, it is not reasonable to fit a straight line on a plot of resolution versus $V_b^{1.75}$ and determine the intercept, and hence the defect depth. This may mean that Lesniak's technique is not practical for determining very small defect depths.

Table 4.3.1. Depth resolved EBIC using defect resolution.

V_b	resolution B-EC	resolution B-C	$V_b^{1.75}$
3 kV	0.33 μm	0.59 μm	6.8
4	0.56	0.55	11.3
5	0.55	0.55	16.7
7	0.54	0.58	30.1
9	0.65	0.68	46.8
12	0.62	0.72	77.4
15	0.61	0.58	114.3

5.0 CONCLUSIONS

Advances in SEM conductive analysis have been made in several areas.

(1) It has been demonstrated that the thin native oxide on silicon can dramatically affect the conductive mode signal. This native oxide begins to form when silicon is brought into contact with the atmosphere. The signal variation is due to positive charge trapped either in the oxide or silicon-silicon oxide interface. Under certain conditions the charge density can be increased by the scanning electron beam to the point where an inversion layer is formed in the semiconductor under the native oxide. This inversion layer acts as a charge collection barrier that is not accounted for in theoretical relationships describing beam induced minority carrier behaviour. This offers an explanation as to why some workers have had difficulty interpreting diffusion length measurements found by fitting theory to experiment (Bresse 1977, Davidson 1982, Marten and Hildebrand 1983, Hungerford and Holt 1987, and Castaldini *et al* 1987).

(2) It was found that the surface inversion effect could be largely overcome by using electron radiation dose rates greater than 1000 Mrads/min. Under these conditions it is thought that the local silicon temperature in the path of the electron beam is brought high enough to anneal out the charge trapped in slow states at the interface. The effect of the native oxide can also be reduced by examining the silicon material immediately after cleaving, keeping contact with the air to a minimum.

(3) Once surface inversion effects were overcome, it was found that Donolato's equations (1982) were in good agreement with experimental data. These relationships are useful for determining the minority carrier diffusion length in p-type silicon using beam voltages over the range 6-25 kV. However the surface recombination velocity, determined by curve fitting, was observed to vary with beam power at conditions of low injection.

(4) A computer model was proposed to simulate an EBIC linescan over a silicon p-n junction when the interaction volume is partially enclosed by the depletion region. This model incorporated both Donolato's equations and a Monte Carlo simulation. Experimental EBIC linescans were recorded at a variety of beam voltages and conditions of reverse bias for two different silicon resistivities. A good agreement between theory and experiment was observed for $V_b \geq 15$ kV.

(5) A conductive mode investigation of a commercially fabricated GaAs bipolar transistor led to a basis for interpreting the conductive mode signal from a device with more than one charge collection barrier. The results confirmed some of Gonzales' predictions (1974) concerning EBIC analysis of planar bipolar transistors. As a result, an improvement in spatial resolution and depth resolution of process induced defects was achieved. It was found that the EBIV across a charge collection barrier without an electrical contact could be detected by a neighbouring junction. This should be useful for examining regions of fabricated devices that have no contacts.

APPENDIX A Key to notations

a	diameter of the generation volume
A	rate of accumulation of positive charge at the surface
C	defect contrast
C'	local defect contrast
CF	correction factor for four point probe
d	distance from depletion edge to ohmic contact
D, D_e, D_h	diffusion constant, cm^2/sec
e_i, E_i	electron-hole pair formation energy
E_{bs}	average energy of a backscattered primary
$E_c - E_f$	difference in energy between Fermi level and conduction band
f	backscatter coefficient
G	generation rate, electron-holes per unit volume
h	depth of generation volume centre
$h(x,z)$	two dimensional minority carrier distribution
I	current across outer probes (4 pt. probe)
I_0	experimental short circuit current maximum
I_b	electron beam current
I_{bc}	base-collector current
I_{be}	emitter-base current
I_c	collector current
I_{max}	total number of electron-hole pairs generated per unit time
I_s	saturation current
I_{sc}	short circuit current

k	Boltzmann's constant
L, L_e, L_h	minority carrier diffusion length
L_l	minority carrier diffusion length at low injection
m^*	effective mass of an electron
$\bar{n}$	equilibrium carrier concentration
n_i	intrinsic carrier concentration, cm^{-3}
n_s	electron concentration at the surface, cm^{-3}
n_{p0}	equilibrium density of holes in n-type, cm^{-3}
N_a	acceptor impurity concentration, cm^{-3}
N_{Av}	Avogadro's number
N_c	density of states
N_d	donor impurity concentration, cm^{-3}
N_t	bulk trap density, cm^{-3}
N_{ts}	trap density, cm^{-2} , at the surface
p_{n0}	equilibrium density of electrons in p-type Si, cm^{-3}
q	charge on an electron, C
$Q(x,z)$	carrier collection probability
R	Grün range, cm
R_i	rate of beam induced annihilation of positive charge at the surface
R_{th}	rate of thermal annealing of positive charge at the surface
s	path length in units of mass thickness, $\mu\text{g}/\text{cm}^2$
T	temperature, °K
U_s	surface recombination rate, $\text{cm}^{-2}\text{sec}^{-1}$
v_{th}	thermal velocity
V	voltage across inner probes (4 pt. probe)
V_b	electron beam accelerating voltage

V_{be}	emitter-base voltage
V_{bi}	diffusion potential
V_r	reverse bias voltage
V_ϕ	volume of specimen swept by beam
Q_s	surface state charge
W, W_n, W_p	depletion region width, in n-type or p-type
W_{max}, W_m	maximum inversion layer induced depletion region
x	distance from depletion region edge
x_0	distance from beam position to depletion region edge
z, z_0	depth below the surface
Z	atomic number
α_f	injected current in a transistor
$\Delta n, \Delta p$	injected minority carrier density
$\Delta n_{max}, \Delta p_{max}$	maximum injected minority carrier density
$\Delta n_b, \Delta p_b$	minority carrier concentration on sphere dividing low and high injection levels
ϵ_s	semiconductor dielectric constant
ϵ_0	permittivity of free space, F/m
κ	energy spectrum of backscattered primaries
λ	normalized Grün function
μm	micrometer or micron
μ_e, μ_h	mobility, $cm^2/Vsec$
ρ	bulk resistivity, $\Omega\text{-cm}$
ρ_s	semiconductor density, g/cm^3
σ_e	capture cross-section for electrons, cm^2
τ_e, τ_h	minority carrier lifetime, electrons, holes

τ_1	minority carrier lifetime at low injection
ψ	normalized depth, z/R
Ω	unit of resistance, ohm
CRT	cathode ray tube
Cz	Czochralski (abbreviation)
DC	direct current
DREBIC	depth resolved EBIC
EBIC	electron beam induced current
EBIV	electron beam induced voltage
FTIR	Fourier transform infrared spectroscopy
GEC	General Electric Company (UK)
IBM	International Business Machines Corp.
JEOL	Japanese Electron Optics Laboratory
JSM	JEOL scanning microscope
MBE	molecular beam epitaxy
PC	personal computer
SEM	scanning electron microscope

APPENDIX B

```
program EBICsim (input,output);
```

```
const pi = 3.14159265359;
      density_of_silicon = 2.33;           {g/cc}
      beta = 4.28E-6;
      k = 8.617E-5;           {Boltzmann's constant, eV/K}
      max_no_points = 100;
```

```
type state_of_completion = (complete, incomplete);
      significance = (significant, insignificant);
      state_of_determination = (determined, undetermined);
```

```
var two_pi, root_pi, root_2 : longreal;
    sigma_squared, lambda_squared : longreal;
    K1erf, K2erf, K1exp, K2exp : longreal;
    previous_Isc, next_Isc : real;
    lambda : real;           {1 / diffn length}
    sigma : real;           {0.3 * Grün range}
    mobility : real;
    s : real;           {vs/D }
    D : real;           {diffusion co-efficient}
    R : real;           {Grün range}
    Vb : real;           {electron beam voltage, kV}
    L : real;           {min. carrier diffn length}
    Temperature : real;
    z0 : real;           {Grün range / sqrt(15)}
    N : real;           {doping concentration}
    vs : real;           {surface recombination velocity}
    cap_S : real;           {s * L, dimensionless quantity}
    R_over_L : real;           {R / L, dimensionless quantity}
    length : real;           {length of linescan}
    x_offset : real;           {start point of linescan}
    h : real;           {integration stepsize}
    precision, fraction : real;
    lifetime : real;           {minority carrier lifetime in cm}
    specimen_thickness : real;
    LogIsc : real;
    i, j : integer;
    max_no_iterations : integer;
    points : integer;           {no. of points in linescan}
    periodno, div_per_period : integer;
    initial_term : integer;
```

```

x, Isc      : array [1..max_no_points] of real;
integration  : state_of_completion;
stepsize     : state_of_determination;
terms        : significance;
response     : char;
life_or_diff : char;
p_type       : boolean;

function xp(arg, exponent: real): real;
begin xp := exp(exponent*ln(arg)) end;

function Maclaurin(argument: real): longreal;
var number_of_terms, j, i, sign : integer;
    argument_squared, numerator, denominator, sum: longreal;
begin
    if argument < 2.0 then number_of_terms := 20
    else if argument < 2.4 then number_of_terms := 30
    else if argument < 3.0 then number_of_terms := 40
    else if argument < 3.56000 then number_of_terms := 55;
    sign := -1;
    sum := argument;
    numerator := argument;
    denominator := 1.0;
    argument_squared := sqr(argument);
    for i := 1 to number_of_terms do
        begin
            j := i * 2 + 1;
            numerator := numerator * argument_squared;
            denominator := denominator * i;
            sum := sum + sign * numerator/(denominator*j);
            sign := sign * (-1);
        end;
    Maclaurin := (2.0/root_pi) * sum;
end;

procedure integrate ( initial_term, iterations      :integer;
var h,x, Isc      :real);
var j              :integer;
    erfc, erf_argument :longreal;
    s0, s1, s2        :longreal;
    fj                :longreal;
    kj, mu             :real;
    no_of_periods, div_per_period :real;
    exp1, exp2         :real;

```

```

begin
  j := initial_term;
  max_no_iterations := initial_term + iterations;
  s0 := 0.0; s1 := 0.0; s2 := 0.0;
  while (j <= max_no_iterations) do
    begin
      kj := j * h;
      mu := sqrt(sqr(kj)+lambda_squared);
      erf_argument := K1erf * mu - K2erf;
      if erf_argument >= 5.0 then erfc := 0.0
      else if erf_argument <= -5.0 then erfc := -2.0
      else if erf_argument >= 3.56 then { solve erf by asymptotic expasion}
        erfc := exp((-1)*sqr(erf_argument))/(erf_argument*sqrt(pi))
      else if erf_argument <= -3.56 then { solve erf by asymptotic expasion}
        erfc := 2.0 + exp((-1)*sqr(erf_argument))/(erf_argument*sqrt(pi))
      else erfc := 1.0 - Maclaurin(erf_argument); { solve erf by Maclaurin series}
      exp1 := sqr(kj)*K1exp;
      if round(exp1) > -25 then exp1 := exp(exp1) else exp1 := 1.0;
      exp2 := K2exp - mu * z0;
      if round(exp2) > -25 then exp2 := -0.57 * exp(exp2) else exp2 := -0.57;
      fj := (kj/sqr(mu))*(exp1 + exp2*(s/(s+mu))*erfc)*sin(kj*x);
      if odd(j) then s1 := s1 + fj
      else if (j=0) or (j=max_no_iterations) then s0 := s0 + fj
      else s2 := s2 + fj;
      j := j + 1;
    end;
    Isc := (2.0/pi)*(h/3.0)*(s0+4.0*s1+2.0*s2);
  end; { integrate proc}

function sinh(arg: real): longreal;
begin sinh := (exp(arg)-exp((-1)*arg))/2 end;

procedure summation(d: real);
type      solutions      = (found, not_found);
var      sum, term       : longreal;
          kj, mu, pi_over_d : real;
          i, j, n         : integer;
          Q               : array [1..max_no_points] of real;
          solution        : solutions;

begin
  pi_over_d := pi / d;
  writeln(' x, microns   Isc, fraction   Log[Isc]   no. summations');
  for i := 1 to points do
    begin
      x[i] := i * (length/points) + x_offset*L;

```

```

sum := 0; solution := not_found; j := 1;
if x[i] < d then
  begin
    while solution = not_found do
      begin
        kj := j * pi_over_d;
        mu := sqrt(sqr(kj) + lambda_squared);
        term := (kj/(sqr(mu)*(mu+s)))*exp(-1*mu*z0)*sin(kj*x[i]);
        sum := sum + term;
        if (-1*mu*z0) < -25 then solution := found
        else j := j + 1;
      end;
      Q[i] := sinh(lambda*(d-x[i]))/sinh(lambda*d)-(2.0*s/d)*sum;
    end
    else Q[i] := 0.0;
    LogIsc := Ln(Q[i])/Ln(10);
    writeln((x[i]*10000.0):6:2,Q[i]:20:7,LogIsc:12:3,j:16);
  end;
end;

begin { ***** MAIN PROGRAM *****}
writeln('EBIC Linescan Simulation for Silicon    Version 1.0.0');
writeln('written by G A Hungerford              16 July 1987');
writeln('Dept of Materials, Imperial College, London SW7 2BP, UK'); writeln;
writeln('This program solves Donolato's models [1982] for electron beam');
writeln('induced carrier collection as a function of distance from a');
writeln('perpendicular charge collection barrier in silicon. '); writeln;
repeat { Parameter input }
  write('Specify lifetime or diffusion length? [t,L]: '); readln(life_or_diff);
  if (life_or_diff='t') or (life_or_diff='T') then
    begin write('Minority carrier lifetime [sec]: '); readln(lifetime); end
  else
    begin
      write('Minority carrier diffusion length [microns]: '); readln(L);
      L { cm} := L { microns} / 10000.0;
    end;
  write('Temperature [C]: '); readln(Temperature);
  write('Doping concentration [atoms/cc]: '); readln(N);
  write('p or n-type [p,n]: '); readln(response);
  if (response = 'p') or (response = 'P') then p_type := true;
{ preliminary calculations }
  root_2 := sqrt(2.0); root_pi := sqrt(pi); two_pi := 2.0 * pi;
  Temperature { K} := Temperature { C} + 273.0;

```

```

if p_type then
  mobility := 1350.0 * (1.0 - (0.933 * xp(N, 0.91))) / (xp(N, 0.91) + 3.75E15);
else mobility := 480.0 * (1.0 - (0.9 * xp(N, 0.76))) / (xp(N, 0.76) + 5.85E12);
D := mobility * k * Temperature;
if (life_or_diff = 't') or (life_or_diff = 'T') then L := sqrt(lifetime * D);
lambda := 1.0 / L;
writeln; write('Specify S and R/L? [y/n] '); readln(response);
if (response = 'Y') or (response = 'y') then
  begin
    write('S = ? '); readln(cap_S);
    vs := (cap_S * D) / L;
    write('R/L = ? '); readln(R_over_L);
    Vb := exp(ln(R_over_L * L * (density_of_silicon / beta)) / 1.75);
  end
else
  begin
    write('Beam Voltage [kV]: '); readln(Vb);
    write('Surface recombination velocity [cm/sec]: '); readln(vs);
  end;
s := vs / D;
R := (beta / density_of_silicon) * xp(Vb, 1.75);
z0 := 0.3 * R;
sigma := R / sqrt(15);
sigma_squared := sqr(sigma);
lambda_squared := sqr(lambda);
K1erf := sigma / root_2;
K2erf := z0 / (root_2 * sigma);
K1exp := sqr(sigma) / (-2.0);
K2exp := sqr(lambda) * sqr(sigma) / 2.0;
writeln; { Parameter check section }
if (life_or_diff = 't') or (life_or_diff = 'T') then
  writeln('Minority carrier lifetime           = ', (lifetime * 1E6) : 7 : 5, ' u-sec');
  writeln('Temperature                         = ', temperature : 4 : 2, ' K');
  writeln('mobility                               = ', mobility : 3 : 1, ' sq cm/Vsec');
  writeln('Electron beam voltage                   = ', Vb : 4 : 2, ' kV');
  writeln('Minority carrier diffn length, L       = ', (L * 10000) : 4 : 2, ' microns');
  writeln('Surface recomb. velocity, vs          = ', vs : 4 : 2, ' cm/sec');
  writeln('Diffusion constant, D                  = ', D : 5 : 3);
  writeln('Grun range, R                          = ', (R * 10000) : 6 : 3, ' microns');
  writeln('S = vs * L / D                         = ', (s * L) : 3 : 1);
  writeln('R/L                                     = ', (R / L) : 7 : 4);
  write('All values OK? [y/n] '); readln(response);
until not(response = 'n') and not(response = 'N');

```

```

while not(response = 'n') do
begin
  write('Number of points: '); readln(points);
  write('Length of linescan [in units of L] '); readln(length);
  length := length*L;
  write('Begin linescan at what distance from junction? [units of L] ');
  readln(x_offset);
  write('Use infinite or finite specimen width model? [i/f] ');
  readln(response);
  if (response='f') or (response='F') then
  begin
    write('What is your specimen thickness? [units of L] ');
    readln(specimen_thickness);
    summation(L*specimen_thickness);
  end
else
begin
  write('Integration precision? [recommend 0.0005] ');
  readln(precision);
  write('x [microns]   Isc, fraction   Log Isc   ');
  writeln('no. periods   div./period');
  for i := 1 to points do
  begin
    x[i] := (length/points) * i + x_offset*L;
    if not(x[i] >= R/2.0) then
      writeln(' ',(x[i]*10000):6:2,' Model not valid for x < R/2')
    else
      begin
        previous_Isc := 0.0; initial_term := 0;
        div_per_period := 8;
        stepsize := undetermined;
        while stepsize = undetermined do
        begin
          h := two_pi / (div_per_period * x[i]);
          integrate ( initial_term, div_per_period, h, x[i], next_Isc );
          fraction := abs((abs(next_Isc)-abs(previous_Isc))/(next_Isc));
          if fraction < precision then stepsize := determined
          else div_per_period := div_per_period + 4;
          previous_Isc := next_Isc;
        end;
        period_no := 1;
        Isc[i] := previous_Isc;
        integration := incomplete;
      end
    end
  end
end

```

```

while integration = incomplete do
begin
    period_no := period_no + 1;
    initial_term := initial_term + div_per_period;
    integrate(initial_term,div_per_period,h,x[i],next_Isc);
    Isc[i] := Isc[i] + next_Isc;
    fraction := abs(next_Isc/Isc[i]);
    if (Isc[i]>0) and (fraction<precision) then
        integration := complete;
    end;
    LogIsc := ln(Isc[i])/ln(10);
    write((x[i]*10000):8:2,Isc[i]:20:9,LogIsc:11:3);
    writeln(period_no:11,div_per_period:14);
end; { if x < R/2}
end; { for i:= 1 to points do}
end; { which model to use}
write('Repeat numeric solution? [y/n] ');
readln (response);
end; { while response <> 'no'}
end.

```

APPENDIX C

```
program nearEBIC (input,output);
```

```
{nearEBIC is an adaptation of profEBIC written by E. Napchan}
```

```
{but uses EBICsim maths to solve Donolato's equations}
```

```
type
```

```
    parameter_state = (unset,ntype,ptype);
    dEdZLR           = array[1..81] of real;
```

```
var
```

```
    sigma_squared,lambda_squared      : real;
    lambda : real; {1 / diffn length}
    sigma                               : real; {0.3 * Grün range}
    mobility                           : real;
    s                                  : real; {vs/D}
    D                                  : real; {diffusion co-efficient}
    R                                  : real; {Grün range}
    Vb                                 : real; {electron beam voltage, kV}
    L                                  : real; {min. carrier diffn length}
    Temperature                        : real;
    z0                                 : real; {Grün range / sqrt(15)}
    N                                  : real; {doping concentration}
    vs                                 : real; {surface recombination velocity}
    length                             : real; {total length of linescan}
    specimen_thickness                 : real;
    LogIsc                             : real;
    points                             : integer; {no. of points in linescan}
    response                           : char;
    parameters                         : parameter_state;
    ii                                 : integer;
    EBIC, beamposmat                   : array [1..40] of real;
    beampoints                         : integer;
    lastbeampos, origin, nearbeampos   : real;
    idata                             : array [1..15,1..9] of real;
    index                             : integer;
    noscans                           : integer;
    mACAD, bACAD, xACAD, yACAD        : real;
    ImACAD, ImMCS                     : real;
    FileName                           : string[20];
    DataFile, OutFile                  : Text;
    strDat                             : array[1..7] of string[14];
    strtemp                           : string[14];
    i, j,k,i1                         : integer;
    temp                              : real;
    dEdL, dEdLO                       : dEdZLR;
```

```

Dat                :array[1..7] of real;
quit, Inside_Depl_Region :boolean;
idpl               :integer; {index to layer number of depletion region}
zz                :real; {distance of point to nearest depletion edge}
Layer              :integer;
Found              :string[3];
dI                :real; {ebic current}
Q                 :real; {probability of collecting an electron}
ypos, beampos: real;
Z                 :array[1..2] of real;
Y                 :array[1..2] of real;

const
    pi              = 3.14159265359;
    density_of_silicon = 2.33; {g/cc}
    beta            = 4.28E-6;
    Boltz           = 8.617E-5;
    xj = 1; xn      = 2; xp      = 3; Lln  = 4; lp   = 5;
    nn = 6; np      = 7; Vsn     = 8; Vsp   = 9;

function xpp(arg, exponent: real): real;
begin xpp := exp(exponent*ln(arg)) end;

function sinh(arg: real): real;
begin sinh := (exp(arg)-exp((-1)*arg))/2 end;

procedure summation(d: real; var Q:real);
type solutions      = (found, not_found);
var sum, term       : real;
    kj, mu, pi_over_d : real;
    i, j, n          : integer;
    solution         : solutions;
begin
    pi_over_d := pi / d;
    sum := 0; solution := not_found; kj := pi_over_d;
    if length < d then
        begin
            while solution = not_found do
                begin
                    mu := sqrt(sqr(kj) + lambda_squared);
                    term := (kj/(sqr(mu)*(mu+s)))*exp(-1*mu*z0)*sin(kj*length);
                    sum := sum + term;
                    if (mu*z0) > 15 then solution := found
                    else kj := kj + pi_over_d;
                end
            end
        end
    end

```

```

        end;
        Q := sinh(lambda*(d-length))/sinh(lambda*d)-(2.0*s/d)*sum;
    end
    else Q := 0.0;
end;
Procedure LatDepDose;
var
    i,i2,i21,i40,i41,j: integer;
begin
    for i:= 1 to 81 do
        for j:= 1 to 81 do begin
            readln(DataFile,temp);
            if j=1 then dEdline[i] := temp;
            dEdL[j] := dEdL[j] + temp;
            dEdZ[i] := dEdZ[i] + temp;
            if dEdZ[i] > maxdE then maxdE:=dEdZ[i];
            if dEdL[j] > maxdE then maxdE:=dEdL[j];
        end;
    end;
    dEdLO[41] := dEdL[1];
    for i := 1 to 40 do
        begin
            i2 := 2*i; i21 := i2 + 1;
            i41 := i + 41; i40 := 41 - i;
            dEdLO[i41] := (dEdL[i2]+dEdL[i21])/2.0;
            dEdLO[i40] := dEdLO[i41];
        end;
    end;
end; {of proc LatDepDose}
procedure prelim_calc;
begin
    Temperature {K} := 20.0 {C} + 273.0;
    if parameters = ptype then
        mobility := 1350.0 * (1.0-(0.933*xpp(N,0.91)))/(xpp(N,0.91)+3.75E15))
    else mobility := 480.0 * (1.0-(0.9*xpp(N,0.76)))/(xpp(N,0.76)+5.85E12));
    D := mobility * Boltz * Temperature;
    lambda := 1.0/L; s := vs/D;
    R := ( beta/density_of_silicon ) * xpp(Vb,1.75);
    z0 := 0.3 * R; sigma := R / sqrt( 15 );
    sigma_squared := sqr(sigma); lambda_squared := sqr(lambda); end;
begin {***** MAIN PROGRAM BEGINS HERE *****}
    assign(OutFile,'a:outdata');
    rewrite(OutFile);
    writeln('Welcome to nearEBIC 1.0.0 Sept 1987, G.A. Hungerford ');
    write('Enter FileName of energy array: ');readln(FileName);
    assign(DataFile,FileName);

```

```

reset(DataFile);
for i:= 1 to 3 do
  begin
    readln(DataFile,strDat[i],Dat[i]);
    writeln(OutFile,strDat[i],'.',Dat[i]:7);
  end;
  writeln('Beam voltage = ',Dat[1]:4:1,' kV'); Vb := Dat[1];
idpl := trunc(Dat[3]) + 2; {index to depletion region layer number}
for j:=1 to trunc(Dat[3]) do
  begin
    readln(DataFile,strtemp,Sym);
    readln(DataFile,strtemp,Z[1],Z[2],Y[1],Y[2]);
    writeln(OutFile,'Layer ',j,' is ',Sym,'its coordinates are ',
      Z[2]:8:2,Z[1]:8:2);
  end;
for i:=4 to 7 do
  begin
    readln(DataFile,strDat[i],Dat[i]);
    writeln(OutFile,strDat[i],'.',Dat[i]:7);
  end;
LatDepDose;  close(DataFile);

write('Simulate how many beam positions? [40 max] ');
readln(beampoints);
if beampoints = 1 then write('Beam position? [um] '); readln(nearbeampos)
else
  begin
    write('Beam position nearest to Si edge? [um] ');
    readln(nearbeampos);
    write('Beam position farthest from Si edge? [um] ');
    readln(lastbeampos);
  end;
write('Xm for ACAD: '); readln(mACAD);
write('Xb for ACAD: '); readln(bACAD);
write('ACAD Imax: '); readln(ImACAD);
write('MCS Imax: '); readln(ImMCS);
writeln('No. of linescans to batch? '); readln(noscans);
for index := 1 to noscans do
  begin
    write('Position of jct. Scan no. ',index:1,'? ');
    readln(idata[index,xj]);
  end;

```

```

write('Near depl. region edge: '); readln(idata[index,xn]);
write('far edge: '); readln(idata[index,xp]);
write('n-epi doping: '); readln(idata[index,nn]);
write('p bulk doping: '); readln(idata[index,np]);
write('L of epi: '); readln(idata[index,Lln]);
write('L of p bulk: '); readln(idata[index,lp]);
write('Vs for epi: '); readln(idata[index,Vsn]);
write('Vs for p bulk: '); readln(idata[index,Vsp]);
end;
for index := 1 to noscans do
begin
  writeln(OutFile);
  write(OutFile,'Scan ',index:1,' Xj, Xn, Xp ');
  writeln(OutFile,idata[index,xj]:6:2,
    idata[index,xn]:6:2,idata[index,xp]:6:2);
  writeln(OutFile,'Nn, Np ',idata[index,nn],idata[index,np]);
  writeln(OutFile,'Ln, Lp ',idata[index,Lln]:6:1,idata[index,lp]:6:1);
  writeln(OutFile,'Vs epi = ',idata[index,Vsn], ' Vs p = ',
    idata[index,Vsp]);
for ii := 1 to beampoints do
begin
  parameters := unset;
  if beampoints > 1 then
    beampos := (ii-1)*(lastbeampos-nearbeampos)/(beampoints-1)
      + nearbeampos
  else beampos := nearbeampos;
  origin := beampos - (161/162)*Dat[4];
  dI:=0.0; k:=1; {start with the top layer}
  for i:= 1 to 81 do
begin
  if i < 40 then ypos := Dat[4]*((2*i-1)/81) + origin
  else if i > 41 then ypos := Dat[4]*((2*i-2)/81) + origin
  else {i=41} ypos := beampos;
  if (dEdLO[i] > 0.0) and (ypos>0) then
begin
  if ((ypos>=idata[index,xn]) and (ypos<idata[index,xp])) then
    Inside_Depl_Region := true
  else {else this layer lies outside the depl region}
begin
    Inside_Depl_Region := false;
    zz:=abs(ypos-idata[index,xp]); {dist. to one edge of depl reg.}
    temp:=abs(ypos-idata[index,xn]); {distance to other edge}

```

```

        if temp<zz then zz:=temp; {carriers diffuse to nearest edge}
    end;
    if Inside_Depl_Region then
        dI := dI + (0.27548) * dEdLO[i]
    else if dEdLO[i] > 0.0 then
        begin
            length := zz/10000.0; {cm}
            if (ypos<=idata[index,xj]) and (parameters<>ntype) then
                begin
                    parameters := ntype;
                    L := idata[index,Lln]/10000.0;
                    N := idata[index,nn];
                    vs := idata[index,Vsn];

                    specimen_thickness := idata[index,xn]/10000.0;
                    prelim_calc;
                end
            else if (ypos>idata[index,xj]) and (parameters<>ptype) then
                begin
                    parameters := ptype;
                    L := idata[index,lp]/10000.0;
                    N := idata[index,np];
                    vs := idata[index,Vsp];
                    specimen_thickness := 388.0/10000;
                    prelim_calc;
                end;
            summation(specimen_thickness,Q);
            dI := dI+(0.27548)*dEdLO[i]*Q;
        end;
    end;
end;
    beamposmat[ii] := beampos;
    EBIC[ii] := dI;
    xACAD := bACAD - beampos*mACAD;
    yACAD := ImACAD * (dI/ImMCS);
    writeln(OutFile,beampos:5:1,dI:15:1,xACAD:15:2,yACAD:15:3);
end; {for ii := 1 to beampoints do}
writeln(OutFile);
end; {multi linescan loop}
close(OutFile);
end.

```

APPENDIX D Table of Grün Ranges, in μm

<u>V_b</u>	<u>R, Si</u>	<u>0.3×R, Si</u>	<u>R, GaAs</u>	<u>0.3×R, GaAs</u>
3 kV	.126	.038	.055	.017
4	.208	.062	.091	.027
5	.307	.092	.135	.040
6	.423	.127	.185	.056
7	.553	.166	.243	.073
8	.699	.210	.306	.092
9	.859	.258	.377	.113
10	1.03	.310	.453	.136
11	1.22	.366	.535	.160
12	1.42	.426	.623	.187
13	1.63	.490	.717	.215
14	1.86	.558	.816	.245
15	2.10	.630	.920	.276
16	2.35	.705	1.03	.309
17	2.61	.784	1.15	.344
18	2.89	.867	1.27	.380
19	3.18	.953	1.39	.418
20	3.47	1.04	1.52	.457
21	3.78	1.14	1.66	.498
22	4.11	1.23	1.80	.540
23	4.44	1.33	1.94	.583
24	4.78	1.43	2.10	.629
25	5.13	1.54	2.25	.675

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