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ABSTRACT

Measurements of minority carrier diffusion lengths for p-type and n-type GaAs were carried out using an electron beam induced current (EBIC) technique. The GaAs material was grown by Liquid Phase Epitaxy (LPE) at the Australian Nuclear Science and Technology Organisation. The diffusion lengths measured for the n-type materials show good agreement with past results for material of similar purity. For higher purity p-type and n-type samples, diffusion lengths were observed which are larger than any previously reported.

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ANSTO; carrier mobility; diffusion length; electron beams; epitaxy; experimental data; gallium arsenides; n-type conductors; p-type conductors; purity; radiation detectors; scanning electron microscopy; Schottky barrier diodes.

EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation replaced the Australian Atomic Energy Commission on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

CONTENTS

1. INTRODUCTION

The potential for room temperature operation has made high atomic number, large bandgap compound semiconductors an attractive alternative to the more common silicon and germanium detectors - which normally operate at liquid nitrogen temperatures. GaAs, CdTe and HgI_2 have all shown some degree of promise in this area [1]. GaAs is of particular interest because of its high carrier mobility, and because of the high quality of the material which can be produced. In fact there has been a considerable amount of research aimed at producing high purity n-type GaAs for use as X-ray and low energy gamma ray, surface barrier detectors [2,3,4,5,6,7,8].

One parameter which plays an important role in the suitability of any radiation detector is the purity of the material being used. For material with a high total impurity concentration (N_D+N_A - where N_D is the concentration of donor atoms and N_A is the concentration of acceptor atoms), charge collection efficiency may be degraded by high concentrations of deep level traps. A low net impurity concentration (N_D-N_A for n-type material; N_A-N_D for p-type) is also important if wide depletion regions are to be attained with a reasonably low bias voltage [2].

The measurement of the diffusion length of minority carriers is useful in characterising the purity of detector material because, as well as being dependent on intrinsic semiconductor properties, the diffusion length is also dependent upon the density of traps within the semiconductor [9,10].

For the experiments reported here the diffusion lengths (L) of p-type and n-type GaAs, grown at the Australian Nuclear Science and Technology Organisation, were measured. The results are compared to values of L previously reported by others [9,11,12].

2. EXPERIMENTAL PROCEDURE

2.1 Material Preparation

Diffusion length measurements were carried out with the GaAs samples configured as surface barrier diodes. These Schottky diodes were prepared at the Australian Nuclear Science and Technology Organisation by first growing an epitaxial layer, from the liquid phase, onto a commercially available GaAs (100) substrate. The LPE GaAs was then etched and masked, so that a 1 mm diameter aluminium surface barrier could be evaporated onto it. A gold ohmic contact was also evaporated onto the diode substrate.

2.2 Measurement Method

The actual diffusion length measurements were made using an electron beam induced current (EBIC) technique. Although several variations of the technique exist [10,12,13] the method used here was basically that employed by Ryan and Eberhardt [9]. Following their work a steady electron beam is scanned across the GaAs surface in a direction which is normal to the Schottky barrier. The electron beam acts as a point source of excess carriers which diffuse through the epitaxial layer. The minority carriers which reach the zero bias depletion region of the Schottky barrier are collected by the electric field of the depletion region. The short circuit current thereby induced in the diode is measured as a function of distance from the surface barrier. Figure 1 shows the situation being described.

The relevant equation for this measurement procedure [9] is

$$I_j \alpha \exp(-x/L) \tag{1}$$

where x is the distance from the depletion region, and I_j is the measured short circuit current. L can therefore be calculated from a plot of $\ell n|I_j|$ vs x, since the slope of the plot will be -1/L.

2.3 Technical Aspects

Experiments were carried out using a Joel JXA-840 Scanning Electron Microscope (SEM). The SEM provided an electron beam which focused to a 0.1 - 0.01 μm spot (though the penetration of electrons below the sample surface would have been over a substantially wider area [10]) and could be moved laterally across the diode surface towards the rectifying barrier. The rectifying contact itself was connected to a Keithley 614 Electrometer which was shorted to the SEM case through its current metering circuitry.

Care was taken to shield the connections to the Keithley, both inside and outside of the SEM, and to keep the connections as short as possible [10,13]. Also the Keithley was operated with its own internal battery. This was done in order to eliminate ground loops between the Keithley and the SEM casing.

The ohmic contacts of the diodes studied were grounded to the case of the SEM. This was no trivial task. Although the ohmic contacts were easily connected to an aluminium sample holder via an indium pad, it turned out that the section of the SEM to which the sample holder is secured is not normally grounded. This is a deliberate design on the part of the manufacturer which allows an alarm to be activated when the sample holder accidently comes in contact with the SEM casing.

For our purposes the external connection of the SEM to this alarm circuit was disconnected. In its place an electrical short to the SEM casing was installed thus grounding the ohmic contact of each of the diodes examined.

The distances across the specimen were worked out from photographs of the diodes which gave a calibrated reference bar for the magnifications used. The distances on the photographs could then be related back to the beam positions measured on the SEM screen.

Some difficulty was apparent in ascribing an absolute distance in relation to the barrier edge (which was used as a reference point for distance calibration). Although the barrier edge could be easily identified for the slow scan rate at which the calibration photographs were taken, the sample image shifted by a significant amount with a change in scan rate. This was not a problem for these measurements since an absolute knowledge of the barrier position was not essential for the calculation of diffusion lengths.

3. RESULTS

Measurements of short circuit current were made for electron beam voltages of 15kV, 25kV and 35kV, and with an electron beam current of 6nA. Plots of the resulting data are shown in Figures 2 and 3. Different electron beam voltages were used for the measurements so that the variation in electron beam penetration could indicate if surface recombination had any significant effect on the results. The effect of surface recombination is reviewed in detail by Leamy [10], but basically it acts to reduce the observed value of L.

The diffusion lengths were calculated for each set of data shown in Figures 2 and 3 (except for sample GaAs-89-53-2). The points nearest the Schottky barrier were used for this because at greater distances from the barrier some of the plots show a decrease in the slope of the data which is not governed by diffusion processes. Wittry et.al. [14] and Ryan et.al. [9] also noted a change in slope far from the barrier. The mechanisms which determine the diode current at large distances are not precisely known. It is, however, believed that re-emitted radiations (e.g. X-rays, backscattered electrons, cathodoluminescent radiation, etc), generating excess carriers near the barrier edge are likely to be the dominant feature [14].

The results of the diffusion length measurements are given in Tables 1 and 2, along with some past measurements of L given by others [9,11,12].

No L values were calculated for sample GaAs-89-53-2 because of the flatness of its slope. A similar result was obtained for two other samples (data not shown), however, these two diodes were damaged by excessive currents generated in them by the electron beam. This damage was indicated by a large increase in the zero bias dark current of the diodes, measured before (< 1pA) and after (> 100pA) the electron beam was incident on them.

It is believed that on some previous occasion sample GaAs-89-53-2 may also have been damaged by excessive currents. It had a notably large zero bias dark current before the EBIC measurements were made.

The possibility that the beam current may have been influencing the results was checked by measuring the short circuit current at two different beam currents, (i.e. 6nA and 30pA) for sample GaAs-90-89-7. Those results are shown in the graph of Figure 4, and little difference is seen in the slopes of the different data of that graph.

4. DISCUSSION

4.1 Surface Recombination

As has already been mentioned, the effect of surface recombination was of some concern during these measurements because it can act to reduce the observed value of L. Measurements made at the three different electron beam voltages showed little difference in the values of L calculated for each sample. This would seem to indicate that the effect of surface recombination has been insignificant for these measurements. The lesser electron beam voltages provide a less penetrating electron beam (1.5μm for 15kV, 3.5μm for 25kV and 6.0μm for 35kV), and so a reduction in the measured value of L would have been expected if surface recombination had been severe. The fact that surface recombination effects are not observed would seem to indicate that the surface recombination velocity is very low, which is to be expected for very pure GaAs [16].

One factor that seemed to indicate higher recombination velocities was the fact that the measured values of I_j were much smaller than would normally be observed for a p-n junction, given the electron beam currents used [13]. Surface recombination is known to reduce the currents generated in samples [10], however, the geometry of this technique is such that the EBIC currents collected at the Schottky barrier would be much less than that expected for a planar junction. The observed values of I_j were therefore thought to be of a reasonable magnitude given the geometries employed - and not an indication of large surface recombination velocities.

4.2 Theoretical Diffusion Lengths

In Tables 1 and 2 of this report the measured minority carrier diffusion lengths, for the GaAs samples, are compared with theoretical values of diffusion length calculated from the recombination theory given by Hall [15]. Since GaAs is a direct bandgap semiconductor the upper limit of minority carrier lifetime is primarily determined by the probability of direct radiative recombination (B_{dr}). Using Hall's equation 10 [15]

$$B_{dr} = 0.58 \times 10^{-12}\ \bar{n}(1/(m_n+m_p))^{3/2}$$

$$\times\ (1+1/m_n+1/m_p)(300/T)^{3/2}W_g^{\,2} \qquad (2)$$

where, for the semiconductor of interest, $\bar{n}$ is the refractive index, W_g is the bandgap, T is the temperature in Kelvin, and m_n and m_p are the density of state effective masses of the electrons and holes. For GaAs at 300K $\bar{n} = 3.6$, $m_n = 0.068$, $m_p = 0.5$ and $W_g = 1.43$eV so that

$$B_{dr} = 1.7 \times 10^{-10}\ \text{cm}^3/\text{sec} \qquad (3)$$

An approximate value for the minority carrier lifetime (τ_{dr}) is obtained from the equation

$$\tau_{dr} \approx 1/(N_x B_{dr}) \qquad (4)$$

where N_x is the net carrier concentration, which was found independently by Capacitance-Voltage measurements for each of the samples given in Tables 1 and 2. A theoretical value of diffusion length (L_{dr}) is obtained from the equation

$$L_{dr} = (D\tau_{dr})^{1/2} \qquad (5)$$

where D is the diffusion coefficient of the minority carrier.

Along with the theoretical values of L_{dr}, found from the above analysis, the values of τ_{dr} and N_x which were used to calculate L_{dr} are also given in Tables 1 and 2.

4.3 Measurement Evaluation

The theoretical and measured values of L, given in Tables 1 and 2, are in reasonable agreement with each other considering the large errors usually attributed to this method of measuring diffusion length. Surface recombination is often identified as a major source of error [9,10], however, for these measurements the effect of surface recombination was negligible. This result would be expected if the surface recombination velocities were very small, and indeed Jastrzebski [16] shows that the surface recombination velocity of GaAs decreases substantially with higher purities of material. This is consistent with the results seen here.

Another potential source of error, and one which was evident for this data, is the effect which infrared and X-ray radiations have when they are absorbed near the barrier junction [14]. For the data presented here these secondary radiations were thought to be the dominant factor in determining the value of I_j far from the barrier. Internal absorption of recombination radiation has also been cited as a mechanism which increases the observed lifetime of the minority carrier [17]. This would likewise tend to increase the observed minority carrier diffusion lengths. The above effects were minimised by calculating the minority carrier diffusion lengths from the data closest to the barrier.

5. CONCLUSIONS

The diffusion length measurements reported here indicate that the LPE GaAs samples being produced by the Australian Nuclear Science and Technology Organisation's Radiation Detectors Project are of the highest quality for producing X-rays and low energy gamma ray radiation detectors. Values of diffusion length were measured for both p-type and n-type GaAs which were larger than any others previously reported. The results were in agreement with theoretical values of diffusion length found using Hall's theory of recombination processes. The measurements confirmed that the GaAs samples were very pure.

For different electron beam voltages the observed values of diffusion length were unaffected by surface recombination. This again indicates very pure material.

6. ACKNOWLEDGEMENTS

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TABLE 1

Measured and Theoretical Values of Minority Carrier Diffusion Length (L_p) for n-type GaAs

Specimen	N_x (cm^{-3})	Theoretical Values		Measured L_p (μm)		
		L_{dr} (μm)	τ_{dr} (μsec)	15 keV	25 keV	35 keV
GaAs-90-89-4	~ 1 x 10^{13}	~770	600	830	780	920
GaAs-90-89-5	2 x 10^{14}	174	29	270	260	260
GaAs-90-89-6	1 x 10^{15}	78	5.9	270	280	280
GaAs-90-89-7	~ 1.4x10^{14}	~ 208	42	230	210	200
GaAs-89-32				200	210	260
Ryan & Eberhardt	6 x 10^{13}	320	100	100	200	200
Alferov et. al.	5 x 10^{15}	34	1.1	11.1		
Wittry & Kyser	5.1 x 10^{16}	10	0.1	4		
Tansley	2 x 10^{18}	1.8	0.003	1.6		
Hwang	2 x 10^{16}	18	0.3	1.5		

TABLE 2

Measured and Theoretical Values of Minority Carrier Diffusion Length (L_n) for p-type GaAs

Specimen	N_x (cm^{-3})	Theoretical Values		Measured L_n (μm)		
		L_{dr} (μm)	τ_{dr} (μsec)	15 keV	25 keV	35 keV
GaAs-89-53-2	5×10^{14}	510	12	-	-	-
GaAs-89-47-2	5×10^{14}	510	12	490	340	300
Wu & Wittry	5×10^{17}	16	0.012	1.2		
Leitch et al	4×10^{18}	5.7	0.0015	3.1		
"	1×10^{17}	36	0.059	9.6		
"	2×10^{17}	25	0.029	3-14		

Figure 1

Schematic of GaAs sample showing the electron beam path and the current measurement path.

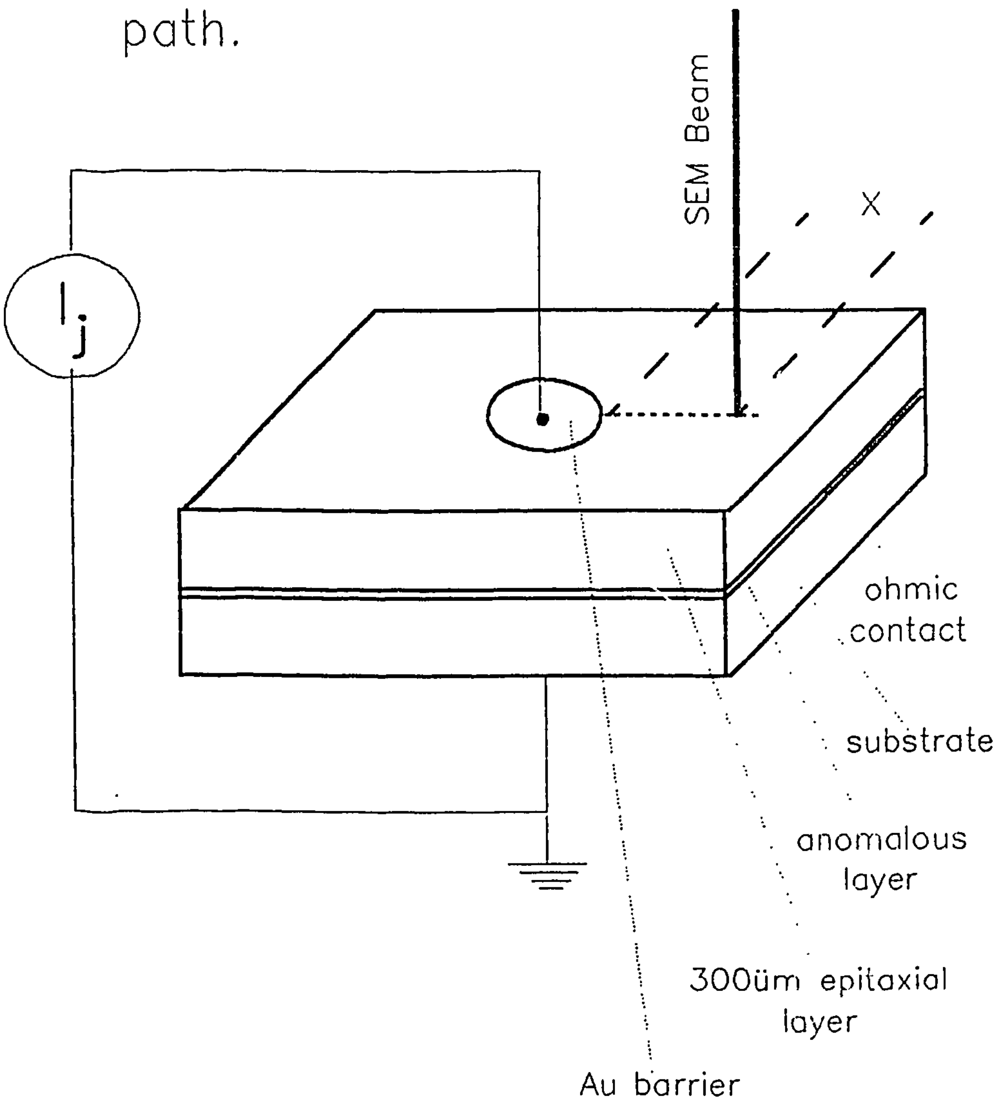
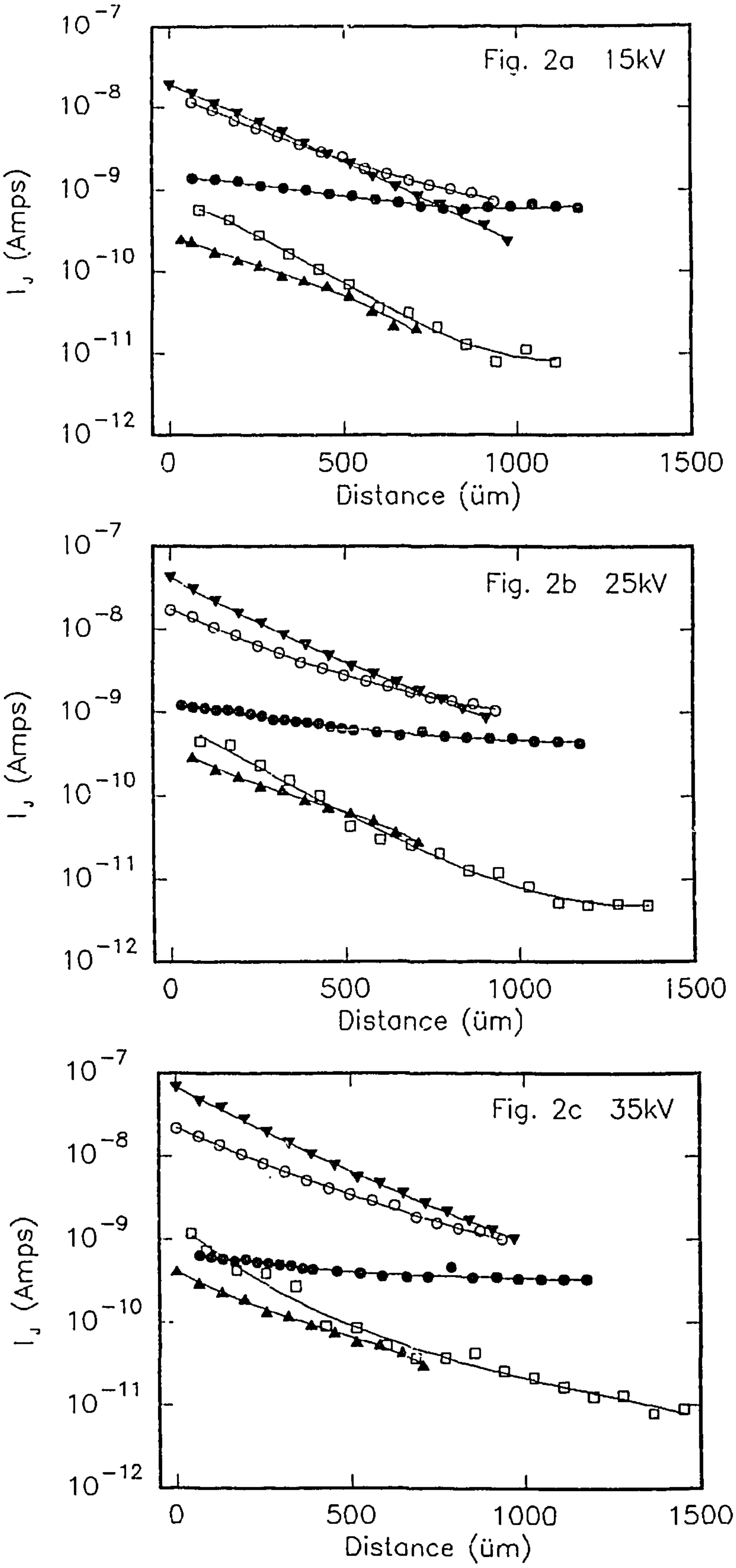


Figure 2

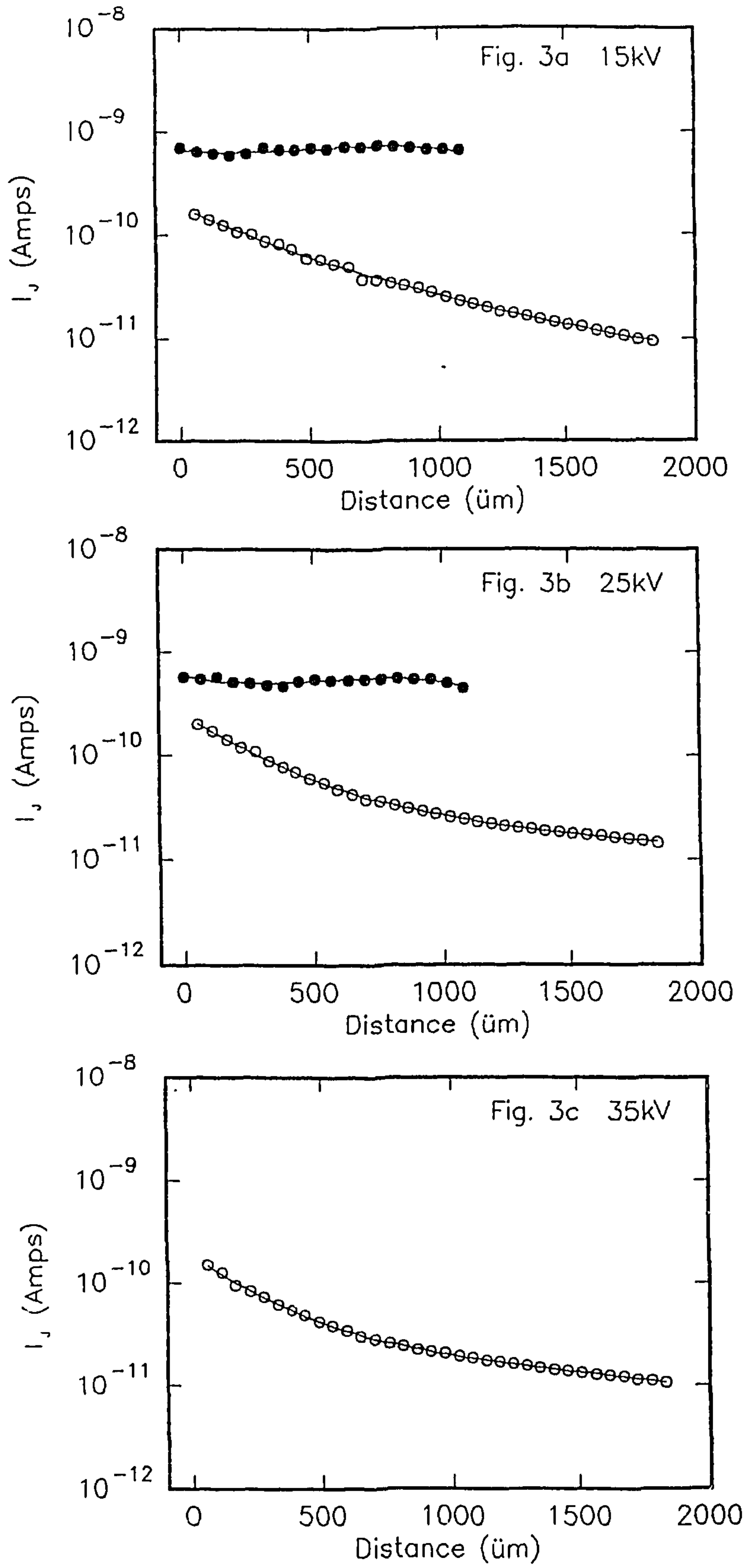
Measured EBIC currents for n–type GaAs samples, using different electron beam voltages.



- ● GaAs–90–89–4
- ○ GaAs–90–89–5
- ▲ GaAs–90–89–6
- ▼ GaAs–90–89–7
- □ GaAs–89–32

Figure 3

Measured EBIC currents for p−type GaAs samples, using different electron beam voltages.



○ GaAs−89−47−2

• GaAs−89−53−2

Figure 4

The EBIC currents measured in a GaAs sample, for different electron beam currents.