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Diffusion Length Measurements in Bulk and Epitaxially Grown III-V Semiconductors Using Charge Collection Microscopy

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DIFFUSION LENGTH MEASUREMENTS IN BULK AND EPITAXIALLY GROWN III-V SEMICONDUCTORS USING CHARGE COLLECTION MICROSCOPY

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SUMMARY

Diffusion lengths and surface recombination velocities were measured in GaAs diodes and an InP finished solar cell. The basic technique used was charge collection microscopy also known as electron beam induced current (EBIC). The normalized currents and distances from the pn junction were read directly from the calibrated curves obtained while using the line scan mode in an SEM. These values were then equated to integral and infinite series expressions resulting from the solution of the diffusion equation with both extended generation and point generation functions. This expands previous work by examining both thin and thick samples. The surface recombination velocity was either treated as an unknown in a system of two equations, or measured directly using low e- beam accelerating voltages. These techniques give accurate results by accounting for the effects of surface recombination and the finite size of the generation volume.

An accurate method to measure minority carrier diffusion length (L) is exremely important in III-V semiconductors. These promising and already widely used materials in photovoltaic and transistor devices present serious challenges in the use of charge collection to make quantitative measurements. While the diffusion lengths tend to be small, the surface recombination velocity (S) is usually quite large.

In an idealized case with point generation of minority carriers, and zero surface recombination velocity, the collected current follows a simple exponential decay form:

$$I_{cc} = I_o e^{-x/L} \tag{1}$$

where

I_o maximum current collected PN junction

L diffusion length

x distance from PN junction

which describes the variation of the collected current as an electron beam impinges in the vicinity of a region with a nonzero electric field in a semiconductor.

However, for cases where $S >> 0$, equation (1) does not give accurate results. This is why in this work, the integral solution of the two-dimensional diffusion equation has been used to extract the values of L in thick samples (see fig. 1, ref. 1):

$$\frac{I_{cc}(x_o)}{I_o} = \frac{2}{\pi}\int_0^\infty \frac{udu}{(u^2+1)} \left\{ \exp\left(-\frac{u^2\sigma^2}{2L^2}\right) - 0.57 \exp\left(\frac{\sigma^2}{2L^2} - \sqrt{u^2+1}\ \frac{z_o}{L}\right) \right.$$

$$\left. \times \frac{\eta}{\eta + \sqrt{u^2+1}} \operatorname{erfc}\left[\frac{\sigma}{\sqrt{2L}}\left(\sqrt{u^2+1} - \frac{z_o}{L}\frac{L^2}{\sigma^2}\right)\right] \right\} \sin\left(u\frac{x_o}{L}\right) \quad . \tag{2}$$

where

$z_o = 0.3\ R_e$

$\sigma = \frac{R_e}{15}$

$\eta = \frac{LS}{D}$

R_e = electron range

D = diffusivity

An extended generation function (ref. 2) in the form of a three-dimensional Gaussian has been suggested as the most appropriate analytical expression to simulate the region of interaction of an electron beam and a semiconductor, and it is included in equation (2), as well as the boundary conditions:

$$\text{at } z = 0\ , \quad \frac{\partial q}{\partial z} = \frac{S_q}{D}$$

$$\text{at } x = 0, \quad q = 0$$

where q = excess hole or electron density.

While the above mentioned analysis is the most appropriate to characterize the base of a solar cell, often times it becomes desirable to evaluate the electrical properties of epitaxially grown thin films, that would eventually be used for photovoltaic or other devices in order to optimize material growth. One then has to contend with a third boundary condition:

$$G = 0 \quad \text{at} \quad x = d$$

where d is the thickness of the epilayer and G is the Green's function required for the calculation of the carrier collection probability.

This condition holds for an ohmic contact, and the carrier collection probability becomes (ref. 1):

$$Q(x,z) = \frac{\sinh[\lambda(d - x)]}{\sinh(\lambda d)} - \frac{2}{d}\frac{S}{D}\sum_{n=1}^{\infty} \frac{k_n}{\mu_n^2\left[\mu_n + \frac{S}{D}\right]} \exp^{-\mu_n z} \sin(k_n x) \qquad (3)$$

where

$$\lambda = \frac{1}{L}$$

$$k_n = \frac{\pi n}{d}$$

$$\mu_n = \left(k_n^2 + \lambda^2\right)^{1/2}$$

Two different methods have been used here in order to account for the effects of the surface recombination velocity. One of them uses the result (ref. 3):

$$\left.\frac{\partial}{\partial z} \ln I_{cc}\right|_{z\to 0} = \frac{S}{D} \qquad (\text{as } E\to 0) \qquad (4)$$

which allows a direct determination of the value of S while the sample is in the SEM specimen chamber. Figures 2 and 3 show the measured values of S/D for two of the specimens that were used in this study. Using equation (4) to measure the surface recombination velocity requires careful quantitative handling of the data. Since it is assumed that the decrease in the collected current will only be caused by a decrease in the accelerating potential, one must make sure that the e^- beam current does not vary with accelerating potentials, or else measure it (Faraday cup method) to account for it. Since both the surface recombination velocity and the diffusion length can vary spatially in a given sample, finding the exact same spot where the line scan mode was used can be difficult. In a field emission gun, the beam current does not change significantly with accelerating voltage, but the emission current is unstable, so it must also be monitored.

The second method requires a little more computer time, but it is recommended for researchers wary of spending many hours in a dark SEM room. If one uses two different accelerating potentials (E1 and E2) for the electron beam impinging on the semiconductor, both equations (2) and (3) can be written in schematic form:

$$I_{cc1}(x)/I_{01} = f(E_1,L,x,S,D\ .\ .\ .) \qquad (5)$$

$$I_{cc2}(x)/I_{02} = f(E_2,L,x,S,D\ .\ .\ .) \qquad (6)$$

Figure 4 shows two experimentally obtained charge collection curves at two different potentials. If the same x is used, and the same spot is used for the line scan, both the diffusion length and the surface recombination velocity will have the same value at that particular x (there is a very small variation in z). This allows the treatment of equations (5) and (6) as two equations with two unknowns. The value of S can be obtained using an iterative process, where an initial value for S is "guessed". Holding S constant in equation (5), an L is found that satisfies the condition:

$$|I(\text{measured}) - I(\text{calculated})| < \text{tolerance} \tag{7}$$

This value for L is then used in equation (6), where S is now varied to satisfy equation (6). This process is repeated until an L and an S are found which satisfy both equations (5) and (6). A flowchart for the numerical computations used in the semi-infinite sample approximation involving the integral equation (2) has been given elsewhere (ref. 4).

Figure 5 is an electron micrograph showing the cross section of a GaAs n/p/p+ diode with a line scan of the collected current. Figures 6 and 7 show the results obtained for a highly doped GaAs base and for an irradiated InP solar cell. Figures 8 and 9 show the spatial distributions of both the minority carrier diffusion length and the surface recombination velocity (at the cleavage plane) for two epilayers that were grown using MOCVD.

Low accelerating voltages (1 - 7 keV) were used in all these measurements. An effort was made to keep the electron range as small as possible given that the generating function is still just an approximation. Ohmic contacts were used with evaporated thin films of gold, for all samples. In the epitaxial samples, the beam was scanned along a line under a contact, so as to maintain ohmic boundary conditions in the front of the sample. A fast responding, low noise and low input impedance current amplifier was used. The gain was calibrated when the surface recombination velocity was measured using equation (4), leads were shielded, and the SEM and circuit grounds were separated from each other.

Since equations (2) and (3) are not valid when considerable recombination occurs within the depletion region, beam currents were measured the bandgap dependent required ionization potentials (ref. 5) were used to predict the magnitude of the currents that should be collected at the junction. Figure 10 shows the case of a poor junction and an acceptable junction within the same sample (the irradiated InP cell).

In summary, accurate evaluations of diffusion lengths in thin films and in substrates of high quality, heavily doped and/or irradiated III-V materials have been made possible using the experimental and numerical techniques described here.

N. Fatemi's contribution in the formation of ohmic contacts to the GaAs diodes is very much appreciated. We are also indebted to the Magnetics Technology Center at Carnegie Mellon University for letting their field emission SEM be used for part of this work and to S. Santhanam for lending his expertise in its operation.

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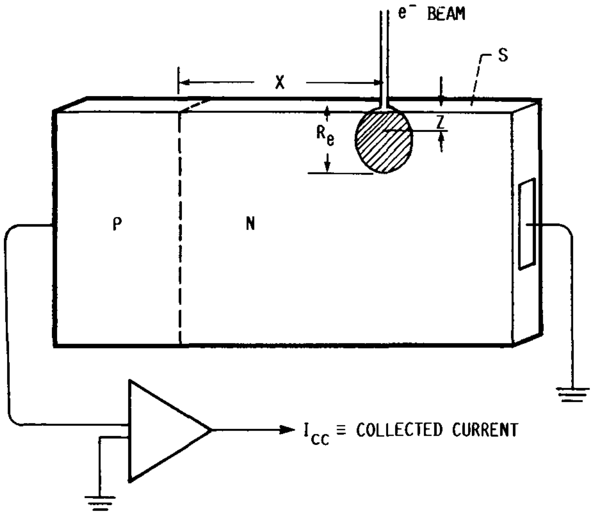

FIGURE 1. - GEOMETRY THAT WAS USED IN THE CHARGE COLLECTION SETUP. DIAGRAM SHOWS MEASUREMENT DONE ON A THICK BASE OR SUBSTRATE MATERIAL.

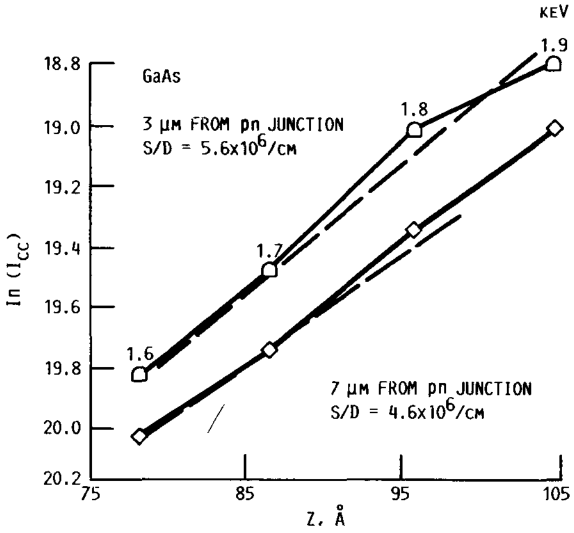

FIGURE 2. - DIRECT MEASUREMENT OF THE SURFACE RECOMBINATION VELOCITY ON A GaAs DIODE.

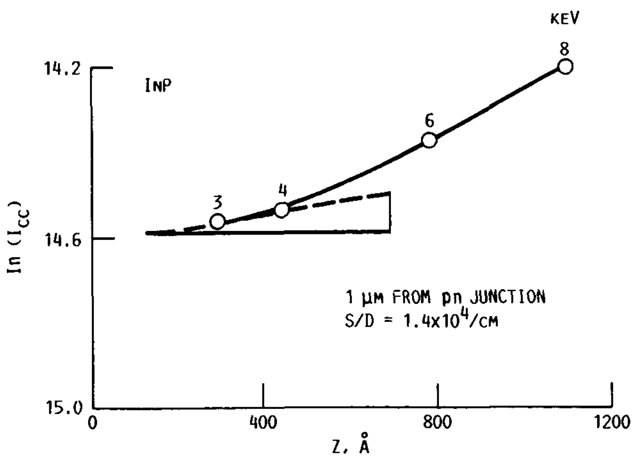

FIGURE 3. - SAME MEASUREMENT ON AN INP SOLAR CELL.

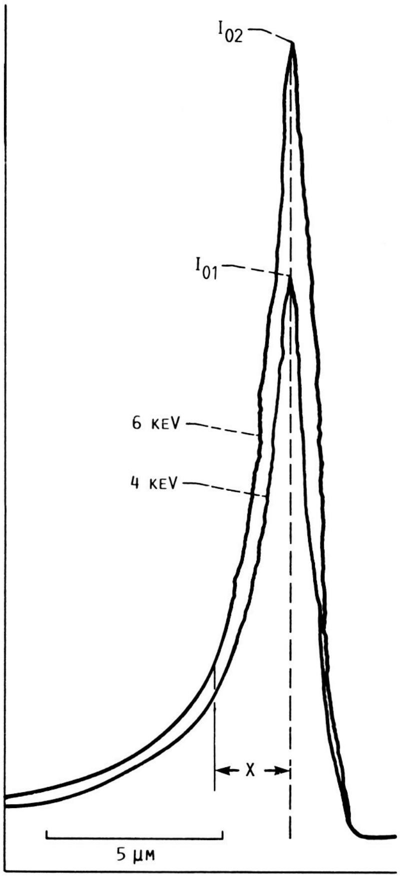

FIGURE 4. - CURVES OF THE CURRENTS COLLECTED AT 4 AND 6 keV IN A GaAs DIODE.

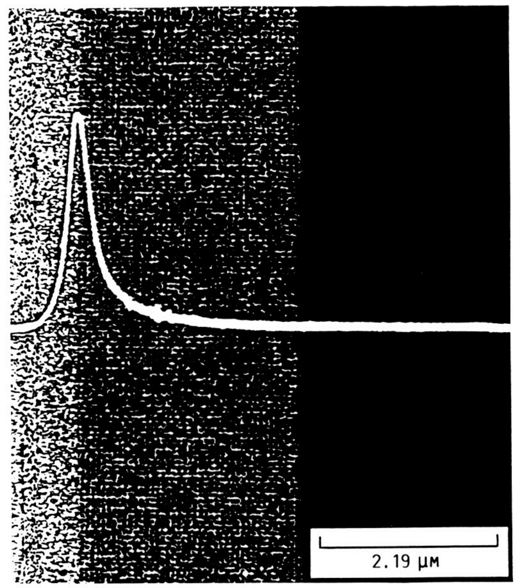

FIGURE 5. - LINE SCAN OF EBIC IN AN n/p/p$^+$ GaAs DIODE. MICROGRAPH SHOWS CONTRAST IN BETWEEN REGIONS OF DIFFERENT DOPING TYPE OR CONCENTRATIONS.

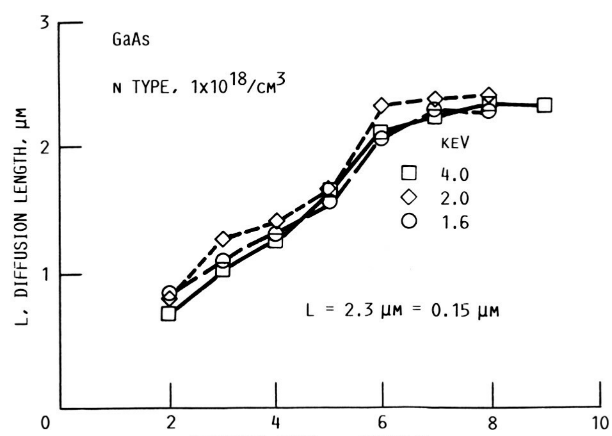

FIGURE 6. - DIFFUSION LENGTH IN HEAVILY DOPED (n TYPE, SILICON, 1x10^{18}/cm^3) GaAs DIODE.

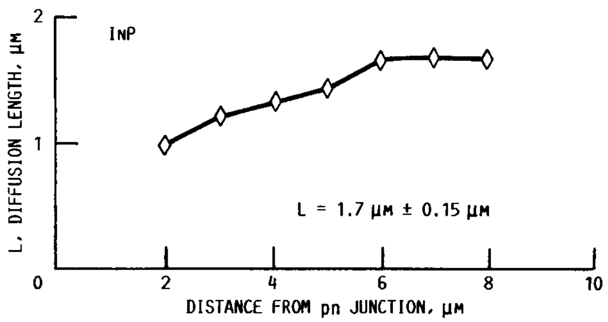

FIGURE 7. - DIFFUSION LENGTH IN THE BASE OF AN N/P INP SOLAR CELL AFTER $10^{12}/CM^2$ 10 MEV PROTON IRRADIATION.

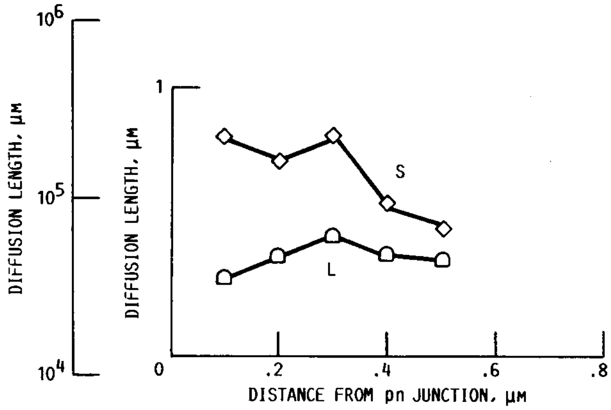

FIGURE 8. - DIFFUSION LENGTH AND SURFACE RECOMBINATION VELOCITIES IN A 0.8-μM THICK OMCVD GROWN GaAs FILM THAT HAD POOR MORPHOLOGY.

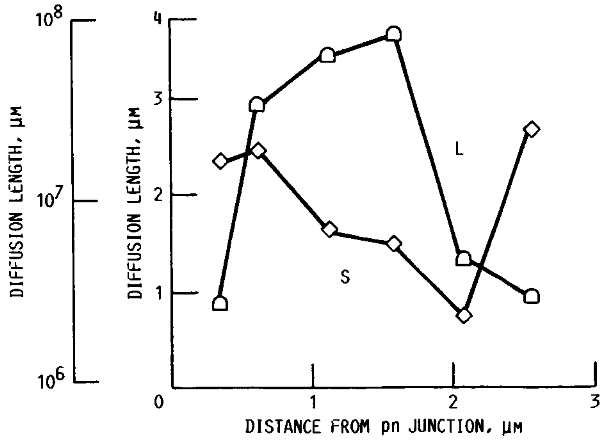

FIGURE 9. - DIFFUSION LENGTH AND SURFACE RECOMBINATION VELOCITIES IN A 3.9-μM OMCVD GROWN GaAs FILM.

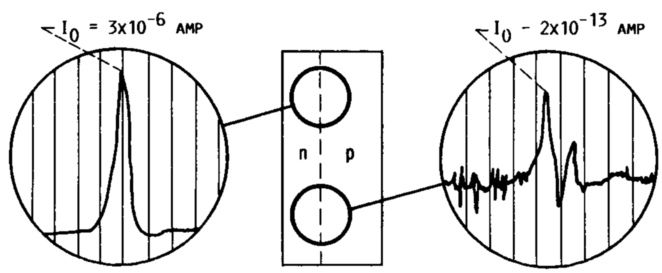

FIGURE 10. - MAXIMUM COLLECTED CURRENTS AT DIFFERENT PARTS OF THE JUNCTION IN AN IRRADIATED INP SOLAR CELL.

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16. Abstract

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