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Application of scanning electron microscopy to determination of surface recombination velocity: GaAs

L. Jastrzebski,* J. Lagowski,* and H. C. Gatos

Department of Materials Science and Engineering, and Department of Electrical Engineering and Computer Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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A method is reported for the determination of the surface recombination velocity by scanning electron microscopy; this method is based on an established relationship between the effective diffusion length of the minority carriers, the penetration depth of the electron beam, and the surface recombination velocity. Values of surface recombination velocity, up to about 2.5×10^6 cm/sec, were determined in n-type GaAs with a bulk minority-carrier lifetime of the order of 10^{-8}–10^{-10} sec; in GaAs, with carrier concentrations exceeding 10^{18} cm^{-3}, recombination velocity of about 3×10^6 cm/sec represents a saturation value.

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Employing virtually "point" excitation of excess carriers by an electron beam in conjunction with high-resolution scanning, a number of investigators have achieved the determination of the diffusion length of minority carriers having extremely short lifetimes[1–5]: Excess minority carriers generated at the desired distance from a Schottky barrier (or p-n junction) diffuse to the barrier and produce an electric current; for a constant accelerating voltage applied to the electron beam, the current I is a function of the distance x between the impinging beam and the barrier, i.e., $I \simeq \exp(-x/L_{\text{eff}})$, where L_{eff} is the effective diffusion length of the minority carriers. It has been recognized that with decreasing accelerating voltage (i.e., decreasing penetration depth of the electron beam) L_{eff} decreases, apparently due to the increasing influence of surface recombination.[3]

In the present investigation the effect of surface recombination on the effective diffusion length was quantitatively analyzed. Single-crystal samples of n-type GaAs, with carrier concentrations 6×10^{16}, 2.4×10^{17}, and 1.8×10^{18} cm^{-3}, were used. Schottky barriers were obtained by evaporating gold onto GaAs "real" surfaces (prepared by chemical etching, chemical polishing, or by cleaving). The experiments were carried out in the standard configuration for diffusion length measurements[1,6] (see Fig. 1), with no bias applied on the barrier contact.

For a given (constant) accelerating voltage, a typical linear region of $\ln I$ vs x was obtained,[1,6] from which the effective diffusion length was evaluated. The measured current changes ranged over about 3 orders of magnitude. From a family of $\ln I$ vs x plots measured at different accelerating voltage values (ranging from 5 to 30 kV) effective diffusion length was determined as a function of the accelerating voltage and, thus, as a function of the penetration depth of the electron beam. Typical results obtained on n-type samples with a carrier concentration of 2.4×10^{17} cm^{-3} are shown in Fig. 1. It is seen that with increasing accelerating voltage V from 5 to 30 kV, L_{eff} increases by a factor of about 3 and then approaches the saturation value. These results reflect the increasing influence of surface recombination on L_{eff} with decreasing penetration depth ξ of the electron beam; it should be noted that $\xi \sim V^{1.7}$.[5,7]

The effect of surface recombination on the effective diffusion length will now be considered on a quantitative basis. In the first order of approximation the surface recombination velocity will be taken as a constant parameter, independent of the penetration depth of the electron beam. In this respect, it should be noted that, in general, the surface recombination velocity depends on the surface potential which varies with the excitation of excess carriers. In GaAs, however, the surface barrier is associated with a depletion region, and it essentially vanishes upon relatively low electron-hole

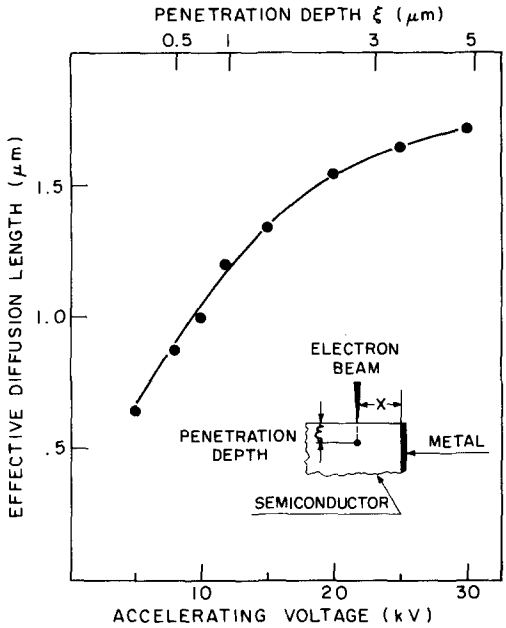

FIG. 1. Experimental configuration and typical results showing the dependence of the measured diffusion length on the accelerating voltage of the electron beam or penetration depth.

excitation.[8] Thus, in the present case of electron beam excitation—i.e., high level of excitation—there is virtually no surface barrier present.

On the basis of previous theoretical treatments of electron-hole pair excitation by an electron beam,[5] the electron beam is approximated by a steady-state point source $G\delta(x, y, z-\xi)$, with strength G, located at a distance ξ beneath the surface ($z=0$) of an n-type semi-infinite semiconductor. The steady-state concentration of excess minority carriers, $\Delta p(x, y, z)$, can be obtained from the continuity equation with the surface boundary condition

$$D\frac{\partial \Delta p}{\partial x}\bigg|_{x=0} = S\Delta p\bigg|_{x=0}, \tag{1}$$

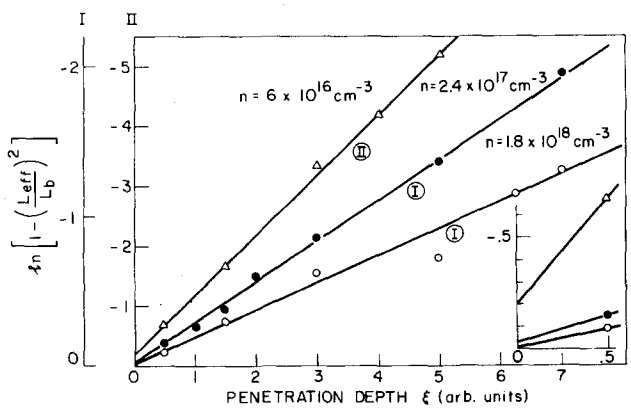

FIG. 2. $\ln[1-(L_{eff}/L_b)^2]$ as a function of the penetration depth of the electron beam, in arbitrary units. Curve I corresponds to the expanded scale (I), curves II correspond to the scale (II).

TABLE I. Measured surface recombination velocities of GaAs single crystals together with calculated values of τ_b and L_b and values of L_{eff} measured for an electron-beam accelerating voltage of 25 kV.

n (cm^{-3})	S (cm/sec)	τ_b (sec)	L_b (μm)	L_{eff}(25 kV) (μm)	Material
6×10^{16}	5×10^{5}	4×10^{-10}	0.5	0.45	boat grown, undoped
2.4×10^{17}	2×10^{6}	5×10^{-9}	1.8	1.65	LPE
1.8×10^{18}	2.5×10^{6}	1.5×10^{-8}	2.5	2.1	boat grown, Si doped

where D is the diffusion coefficient of the minority carriers and S is the surface recombination velocity. On the basis of Hackett's results[5] it can be readily shown that the total steady-state concentration of the excess holes,

$$\Delta p(\xi) \equiv \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \int_{0}^{\infty} dz\, \Delta p(x, y, z),$$

be reduced to

$$\Delta p(\xi) = (GL_b^2/D)\{1-[s/(s+1)]\exp(-\xi/L_b)\}, \tag{2}$$

where L_b is the bulk diffusion length of the minority carriers and $s = S\tau_b/L_b$; τ_b is the bulk lifetime of the minority carriers.

Under steady-state conditions, $\Delta p(\xi)$ can be related to the measured L_{eff} as follows:

$$\Delta p(\xi) = G\tau_{eff}, \qquad L_{eff} = (D\tau_{eff})^{1/2}, \tag{3}$$

where τ_{eff} is the effective steady-state minority-carrier lifetime.

From Eqs. (2) and (3) one obtains

$$L_{eff}^2 = L_b^2\{1-[s/(s+1)]\exp(-\xi/L_b)\}. \tag{4}$$

According to Eq. (4), for $\xi \le L_b$, L_{eff} can be significantly reduced due to surface recombination. L_{eff} remains sensitive to S for an intermediate range of S values, depending on the values of τ_b and L_b; in GaAs this range is about 10^4–10^6 cm/sec. For higher values of S, L_{eff} approaches a saturation value

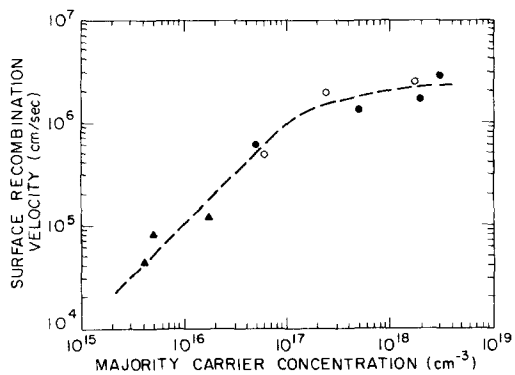

FIG. 3. Surface recombination velocity in GaAs vs majority-carrier concentration; ○, present results; ●, Ref. 7; ▲, Ref. 8.

$$L_{eff}^{sat} = L_b[1 - \exp(-\xi/L_b)]^{1/2}. \quad (5)$$

The experimental results will now be analyzed on the basis of Eq. (4). In Fig. 2, $\ln[1-(L_{eff}/L_b)^2]$ is plotted against ξ (or $V^{1.7}$); consistent with Eq. (4) a straight line is obtained (using the least-squares method) for a given value of carrier concentration. From the intercept of the line with the ordinate one can determine $s/(s+1)$, and therefore the surface recombination velocity. The values of the surface recombination velocities obtained for the three GaAs crystals are shown in Table 1.

From Eq. (4) it is also possible to evaluate L_b (and τ_b). The calculated values of L_b and τ_b are given in Table I together with the measured L_{eff} values for 25 kV. It should be noted that even for high values of accelerating voltage the measured L_{eff} is still noticeably reduced by surface recombination. The values of τ_b cannot be satisfactorily related to the corresponding carrier concentrations; however, the GaAs crystals used in this study were grown by different techniques and at different laboratories, and thus they may contain different types and concentrations of active recombination centers.

The present surface recombination velocity together with earlier results obtained by other methods[9,10] are plotted in Fig. 3 as a function of carrier concentration. As seen in Fig. 3, the agreement between the present results and those previously reported is very satisfactory. It should be pointed out that all results shown in Fig. 3 were obtained at high excitation levels, and, thus, the uncertainty associated with possible effects of the excitation intensity on the measured values of surface recombination is minimized. It is further seen in Fig. 3 that the surface recombination velocity in GaAs increases with increasing carrier concentration and approaches a saturation value of about 3×10^6 cm/sec for a carrier concentration of approximately 10^{18} cm^{-3}.

In summary, the scanning electron microscopy technique for determining the diffusion length of minority carriers in semiconductors was extended to the determination of surface recombination velocities. This new approach, based on the established quantitative relationship between the effective diffusion length and the penetration depth of the electron beam, is effectively applied to semiconductors with high surface recombination and short minority-carrier lifetime; standard methods for surface recombination measurements are not readily applicable to such materials.

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*On leave from Institute of Physics, Polish Academy of Sciences, Warsaw, Poland.

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Excitation of transversely excited CO_2 waveguide lasers

O. R. Wood II, P. W. Smith, C. R. Adams, and P. J. Maloney

Bell Telephone Laboratories, Holmdel, New Jersey 07733
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Using a preionization scheme based on the Malter effect, small-signal gains > 5%/cm at 10.6 μm have been produced in a 1-mm^2-cross-section waveguide CO_2 amplifier at total operating pressures of 100–760 Torr. Comparisons are made between this preionization scheme and those using electron beams.

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A highly controllable transverse excitation technique for use with waveguide CO_2 lasers[1,2] has been developed. By applying this excitation technique to a 1-mm^2-cross-section waveguide amplifier filled with CO_2-N_2-He mixtures, small-signal gains of peak value greater than 5%/cm on the $P(20)$ line of CO_2 at 10.6 μm have been produced at total operating pressures of 100–760 Torr. The performance achieved with this technique is comparable to previously published results using more complicated electron-beam preionization.[3,4] A 10-cm-long

