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Determination of Material Parameters From Regions Close to the Collector Using Electron Beam-Induced Current

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***Abstract*—The conventional method of extracting the minority carrier diffusion length using the electron beam-induced current (EBIC) technique requires that the electron beam be placed at region more than two diffusion lengths away from the collector. The EBIC signals obtained under this condition usually has low signal to noise ratio. In addition, the true diffusion length of the sample is initially unknown and hence it is difficult to estimate how close the beam can be placed from the collector. To overcome all these difficulties, a new method of extracting minority carrier diffusion length from the EBIC signal is proposed. It is shown that this method can be applied to EBIC signals obtained from regions close to the collector. It is also shown that the surface recombination velocity of the sample can also be obtained using this method. This theory is verified using EBIC data generated from a device simulation software.**

***Index Terms*—Electron beam applications, electron microscopy, finite difference methods, microscopy, semiconductor materials measurements, simulation.**

NOTATION

D	Minority carrier diffusion coefficient.
E_b	Beam energy.
I_b	Beam current.
I_o	EBIC current at $x = 0$.
$I(x)$	EBIC current.
I_{xx}	Second-order derivative of $I(x)$ with respect to x.
I_{zz}	Second-order derivative of $I(x)$ with respect to z.
k	Proportionality constant defined in (1).
L	Minority carrier diffusion length.
L_{ext}	Extracted minority carrier diffusion length.
q	Electronic charge (1.602 $\times 10^{-19}$ C).
R	Electron range.
s	Semi-normalized surface recombination velocity ($s = v_s/D$).
v_d	Diffusion velocity.
v_s	Surface recombination velocity.
$v_{s,\text{ext}}$	Extracted surface recombination velocity.
x	Distance between the junction and the generation volume (refer to Fig. 1).
z	Minority carrier generation source effective depth.
α	Constant in the modified EBIC equation.
λ	Reciprocal of the minority carrier diffusion length.
ρ	Material density of silicon.

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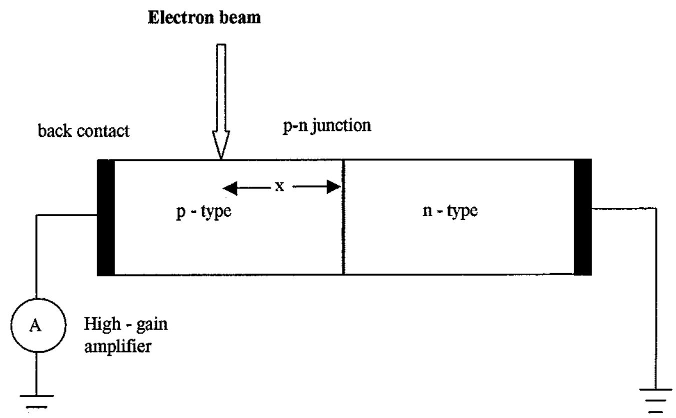


Fig. 1. Schematic diagram of the EBIC experiment setup.

I. INTRODUCTION

SEMICONDUCTOR material properties such as minority carrier diffusion length and surface recombination velocity can be determined using the scanning electron microscope (SEM) operating in the electron beam-induced current (EBIC) mode. This method is very popular due to its simple experimental setup. The theories that explain the EBIC phenomenon have been successfully verified both by numerical and empirical means [1]–[7].

One of the common experimental configurations in demonstrating the EBIC theory is illustrated in Fig. 1. The sample consists of a p–n junction, which is perpendicular to the electron beam incident surface. The high-gain amplifier measures the current signal induced within the sample due to the electron bombardments. The conventional method of evaluating the diffusion length is by plotting the EBIC signals against the beam–junction distances on a semi-logarithmic graph. The diffusion length can then be obtained from the negative reciprocal of the slope of the graph. However, the accuracy of the extracted diffusion length is affected by the surface recombination rates at the beam entrance surface. This surface recombination rate depends on the treatment of the surface [8].

Accurately extracted diffusion length for samples with substantial surface recombination rates can still be obtained by fitting the experimental data to the theoretically derived mathematical expressions [9], [10]. However, these mathematical expressions often involve special functions [10] or integrals with no closed form solutions [9]. In addition, there are usually more than one set of parameters that can fit the EBIC data. Hence, the curve fitting method is both laborious and unreliable.

A simple method of estimating the minority carrier diffusion length of a sample consisting of a p–n junction was proposed by one of the authors of this paper and the method was published in [11]. In a subsequent paper, it was shown that the same technique could also be used on the planar configuration [12]. This method involves fitting the experimental data to a modified EBIC equation as shown in the following equation:

$$I(x) = kx^{\alpha} \exp\left(-\frac{x}{L}\right) \tag{1}$$

where $I(x)$ is the EBIC current, x is the beam–junction distance and α is a constant, the value of which depends upon the surface recombination velocity. L is the minority carrier diffusion length and k is a proportionality constant. It was shown by numerical means that the error in the extracted diffusion length using this method was within a few percent provided that the x is kept larger than $2L$. A rough estimation of $2L$ can be obtained by measuring the distance for the EBIC signals to decay one order in magnitude. However, larger error is anticipated in practice due to the relatively small signal to noise ratio of the EBIC currents collected in that part of the region.

In this paper, a new method of determining the minority carrier diffusion length is proposed. This method is based upon the generalization of the approach that was used in the work published in [13]. The method of [13] is useful only for samples with negligible surface recombination velocity, whereas this method can be used for samples with all values of surface recombination velocity. The method proposed here can be applied to any arbitrary x values, including those that are less than two diffusion lengths from the junction. The advantage of placing the electron beam close to the junction is that the EBIC current obtained under this condition has better signal to noise ratio. It will be shown that the surface recombination velocity can also be extracted using this method.

II. Theory

In [13], it was shown that, if the surface recombination effect is negligible, the relationship between the EBIC current and its second-order derivative with respect to x is linear. The proportionality constant of this relationship is the square of the diffusion length

$$I(x) = L^2 \frac{\partial^2 I(x)}{\partial x^2} = L^2 I_{xx}(x). \tag{2}$$

This relationship is true for all values of x, except in the case of the extended generation source, where it is true only when x is greater than half of the primary electron range in the sample. This range, however, is known and controllable since the primary electron range is a function of the beam energy.

The relationship between the EBIC current and its second order derivative is no longer linear when the surface recombination velocity of the beam entrance surface is nonzero, as shown in Fig. 2. In this graph, the EBIC current, $I(x, z)$, is obtained by numerically solving Donolato's point-source based EBIC equation [9] and the second order derivative of $I(x, z)$ is calculated using the same technique as those published in [13].

It can be observed that the greater the surface recombination velocity (v_s), the larger the curvature of the graph will be, hence

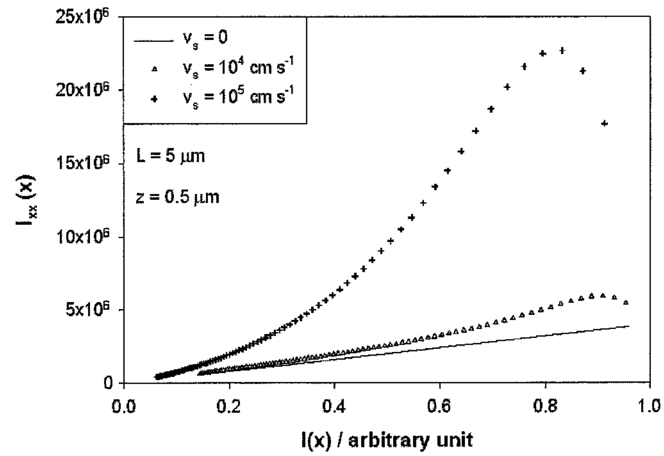


Fig. 2. Effect of the v_s on the $I_{xx}(x)$ against $I(x)$ relationship.

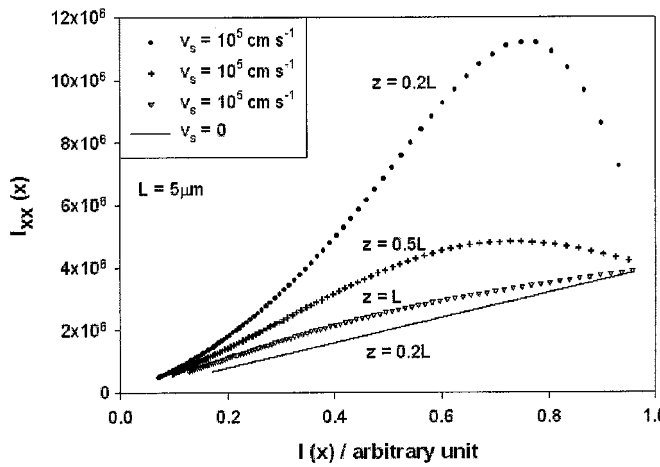


Fig. 3. Effect of the beam penetration depth on $I_{xx}(x)$ against $I(x)$ relationship.

the larger the error in the extracted diffusion length. However, for a particular value of v_s, say $v_s = 10^5$ cm s^{-1}, the curvatures of the graphs decrease with increases in the generation source effective depth (z), as shown in Fig. 3. This shows that the effect of the surface recombination on the EBIC current decreases with the increases in the primary electron range (R). When $z = L$, the curve corresponding to $v_s = 10^5$ cm s^{-1} is close to that with $v_s = 0$. Using this observation, the diffusion length of a sample with nonzero surface recombination velocity can be extracted fairly accurately by increasing the beam energy until the plot of $I_{xx}(x, z)$ against $I(x)$ is approximately linear. This means that the beam energy has to be increased until z is greater than L.

The z parameter mentioned above is the effective depth of the generation volume, which is taken to be the same as its centre of gravity. If the excess charge distribution within this volume is governed by a Gaussian function, then z is approximately 0.3 of the beam penetration range (R). The assumption that $z = 0.3R$ can also be found in works published by Donolato [9], Berz *et al.* [10], Hakimzadeh *et al.* [14], and Luke [15], [16].

Since, $z = 0.3R$ and the electron beam has to be placed $R/2$ from the junction, the minimum beam–junction distance is $1.5L$, which is $0.5L$ closer to the junction than in the case of the conventional method. This is not a great improvement and this method is not feasible for the case of samples with minority carrier diffusion lengths longer than the penetration depth of the electron beam. For instance, if the minority carrier diffusion length of a silicon sample is 10 μm, then $z > 10$ μm and $R > 30$ μm. It can be shown by calculation that the energy of the primary electron required to achieve this effective penetration depth is 66 KeV.

One way to overcome these problems is as follows. Using Donolato's point-source based EBIC equation [9], it can be shown, referring to Appendix I, that the relationship between $I(x,z)$ and its second order derivative is as follows:

$$I_{xx}(x,z) = \lambda^2 I(x,z) + \frac{2I_o s}{\pi}\int_0^\infty \frac{k}{\sqrt{k^2+\lambda^2}+s} \times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)dk \quad (3)$$

where $\lambda = 1/L$, I_o is the maximum EBIC current (occurring at $x = 0$), $s = v_s/D$ and D is the diffusion coefficient. The integral part at the right hand side of the equation is a measure of the surface recombination effect and it is also the term that causes nonlinearity in the plots illustrated in Figs. 2 and 3. However, (3) can also be written as follows:

$$I_{xx}(x,z) = \lambda^2 I(x,z) + \frac{2I_o s}{\pi}\int_0^\infty \frac{\partial^2}{\partial z^2} \times \left[\frac{k}{(k^2+\lambda^2)\left(\sqrt{k^2+\lambda^2}+s\right)} \times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)\right]dk. \quad (4)$$

Using the integration property [17] as shown in the following:

$$\int_a^b \frac{\partial}{\partial y} f(x,y)dx = f(a,y)\frac{\partial a}{\partial y} - f(b,y)\frac{\partial b}{\partial y} + \frac{\partial}{\partial y}\int_a^b f(x,y)dx \quad (5)$$

the $(\partial^2/\partial z^2)$ in (4) can be moved out of the integral. Donolato's point-source based EBIC equation given in [9], when rearranged gives

$$I_o \exp\left(-\frac{x}{L}\right) - I(x,z) = \frac{2sI_o}{\pi}\int_0^\infty \frac{k}{(k^2+\lambda^2)\left(\sqrt{k^2+\lambda^2}+s\right)} \times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)dk. \quad (6)$$

Taking the second-order derivatives of (6) with respect to z give

$$-I_{zz}(x,z) = \frac{2sI_o}{\pi}\frac{\partial^2}{\partial z^2}\int_0^\infty \frac{k}{(k^2+\lambda^2)\left(\sqrt{k^2+\lambda^2}+s\right)} \times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)dk \quad (7)$$

where $I_{zz}(x,z) = (\partial^2/\partial z^2)I(x,z)$. Substituting (7) into (4) with the use of (5) gives

$$I_{xx}(x,z) + I_{zz}(x,z) = \lambda^2 I(x,z). \quad (8)$$

Therefore, the slope of the graph of $I_{xx}(x,z)+I_{zz}(x,z)$ against $I(x,z)$ gives the square of the reciprocal of the minority carrier diffusion length.

It is now realized that the work published in [13] is actually a special case of (8) where $I_{zz}(x,z)$ is zero. If v_s is zero and the electron beam direction is parallel to the junction plane, then $I_{zz}(x,z)$ is negligible. The reason for this is as follows. If the amount of minority carriers that recombine at the surface is negligible, then the EBIC current collected by a junction which is perpendicular to the beam entrance surface, is almost unaffected by the beam penetration depth, provided that the minority carrier generation rate remains constant.

Estimation of the value of $I_{xx}(x,z)$ has been described in detail in [13] and the value of $I_{zz}(x,z)$ can be obtained in a similar fashion. Three EBIC line scans obtained using slightly different primary beam energies are required. Consider that $I^-(x)$, $I(x)$ and $I^+(x)$ are the EBIC currents when the beam is x μm from the junction but the effective beam penetration depths are z^-, z and z^+ μm respectively. The $I_{zz}(x,z)$ is estimated as follows:

$$I_{zz}(x,z) \approx \frac{I_{z1}(x) - I_{z2}(x)}{\frac{1}{2}(z^+ - z^-)} \quad (9)$$

where

$$I_{z1}(x) = \frac{I^+(x) - I(x)}{z^+ - z} \text{ and}$$
$$I_{z2}(x) = \frac{I(x) - I^-(x)}{z - z^-}. \quad (10)$$

The values of I_{xx} and I_{zz} in (8) depend on the minority carrier generation rate in the specimen. Hence, it is a function of both E_b (beam voltage) and I_b (beam current). Since this technique requires E_b to be varied slightly after each successful line scan, any one of the following procedures can be used to ensure that the values of both the I_{xx} and I_{zz} are independent of E_b.

1) Whenever the E_b is changed, I_b is adjusted such that the product of E_b and I_b remains constant. This will ensure that the minority carrier generation rate remains constant throughout the experiment. The total minority carrier generation rate (G_o) is given by [18]

$$G_o = \frac{E_b I_b}{eE_i}(1-\kappa) \quad (11)$$

where e is the electronic charge, E_i is the energy required to generate an electron-hole pair, and κ is the fraction of beam energy that loss due to backscattered electron.

2) The I_b is kept constant throughout the experiment. All measured current signals are normalized with respect to I_o. The value of I_o can be obtained by using either one of the following methods.
   a) The value of I_o can be obtained by extrapolating plots of $\ln[I(x,z)]$ versus x back to the junction [14].
   b) The beam position is placed at the junction such that the entire carrier generation volume is confined to within the depletion region. Since carrier recombination process is negligibly low in the depletion region, the current measured at the external circuit is the rate at which the minority carrier is generated by the electron beam.

A. Evaluating the Surface Recombination Velocity

After the minority carrier diffusion length is obtained using the above method, the semi-normalized surface recombination velocity of the sample s can also be determined.

Equation (3) can also be expressed as

$$\begin{aligned} I_{xx}(x,z) - \lambda^2 I(x,z) =& \frac{2I_o s}{\pi}\int_0^\infty \frac{k}{\sqrt{k^2+\lambda^2}} \\ &\times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)dk \\ &- \frac{2I_o s}{\pi}\int_0^\infty \frac{k}{\sqrt{k^2+\lambda^2}} \\ &\times \frac{s}{s+\sqrt{k^2+\lambda^2}} \\ &\times \exp\left(-z\sqrt{k^2+\lambda^2}\right)\sin(kx)dk. \end{aligned} \quad (12)$$

The solution for the first integral at the righthand side of the equation can be found in [17, p. 456]. The second integral is the product of the s and the first order derivative of the EBIC current with respect to z. Hence

$$\begin{aligned} &I_{xx}(x,z) - \lambda^2 I(x,z) \\ &\quad = s\left[\frac{2}{\pi}\frac{\lambda x I_o}{\sqrt{z^2+x^2}}k_1\left(\lambda\sqrt{z^2+x^2}\right) - I_z(x,z)\right] \end{aligned} \quad (13)$$

where $I_z(x,z) = (\partial/\partial z)I(x,z)$ and k_1 is the modified Bessel function of the second kind. Since λ is known and x as well as z are measurable parameters, the numerical value of the modified Bessel function can be calculated numerically. The values of $I_z(x,z)$ can be obtained from any two of the three adjacent EBIC line scans obtained earlier, using the following equation:

$$I_z(x,z) = \frac{1}{2}(I_{z1}(x) + I_{z2}(x)). \quad (14)$$

When the left-hand side of (13) is plotted against the terms inside the square bracket on the righthand side, the slope of the graph will give the value of s.

III. Verification

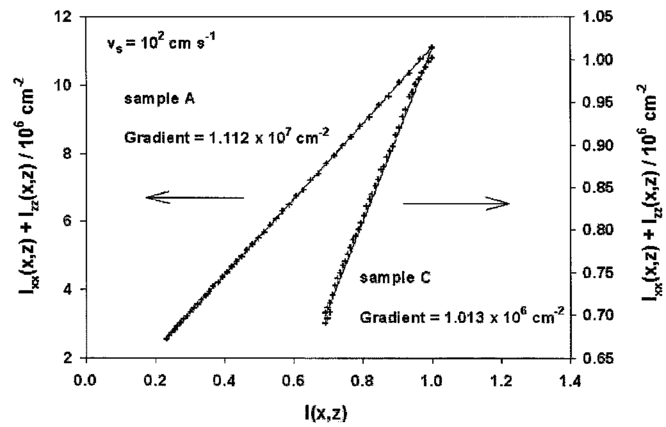
This theory was verified using EBIC data generated by MEDICI [19], a device simulation software. The experimental set up in this simulation is similar to that shown in Fig. 1. The sample used consists of a p–n junction and the direction of the electron beam is parallel to the junction plane. Four silicon samples were created in this simulation, namely, sample A, sample B, sample C, and sample D. The minority carrier diffusion length of samples A and B were 3 μm, while that of samples C and D were 10 μm. The doping levels of the n-type regions were 1×10^{15} cm^{-3} for all samples. The p-type regions of samples A and B were uniformly doped with 6.7×10^{17} cm^{-3} of impurity atoms. Those for samples C and D were doped with 7.9×10^{16} cm^{-3} of impurity atoms. The material parameters of these samples are shown in Table I. The depletion widths at the p-type regions are negligible since they were much more heavily doped than the n-type region.

In this simulation, the minority carrier diffusion lengths of the p-type regions were to be determined. The electron beam was set to scan from the junction to a region that was less than $2L$ away. Since the diffusion lengths of the samples were assumed to be unknown during the experiment, the beam–junction distances were varied from $x = 0$ to $x = 5$ μm for all the samples. Hence, for samples A and B, the EBIC measurements used in the material parameters extraction were obtained from regions less than $1.6L$ from the junction. For samples C and D, EBIC measurements from regions less than $0.5L$ from the junction were used. This experiment shows that the proposed method does not have the limitation where the EBIC measurements have to be taken from regions more than $2L$ from the junction.

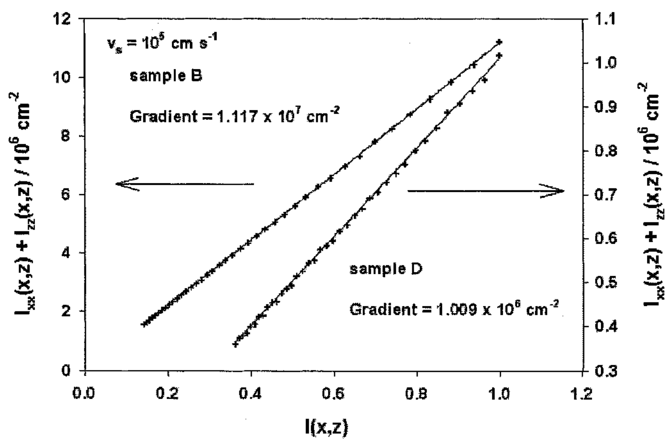
When the surface recombination velocity of a specimen is less than 10^2 cm s^{-1}, the $\ln[I(x)]$ versus x plot (EBIC line scan profile) is linear. As the value of surface recombination velocity is increased to beyond 10^2 cm s^{-1}, the EBIC line scan profile concaves upward. However, the curvature of the profile ceases to increase when the surface recombination velocity is more than

TABLE I
MATERIAL PARAMETERS OF THE SAMPLES USED IN THE SIMULATION

Sample	L / µm	v_s / cm s^{-1}	D / cm^2 s^{-1}
A	3	10^2	12.926
B	3	10^5	12.926
C	10	10^2	25.852
D	10	10^5	25.852



(a)



(b)

Fig. 4. (a) $I_{xx}(x,z) + I_{zz}(x,z)$ against $I(x,z)$ plots for samples A and C. (b) $I_{xx}(x,z) + I_{zz}(x,z)$ against $I(x,z)$ plots for samples B and D.

TABLE II
COMPARING RESULTS FROM THE PROPOSED METHOD WITH THOSE OBTAINED USING THE METHOD USED IN [11]

Sample	Proposed method				Method used in Ref. [11][1]		Method used in Ref. [11][2]	
	L_{ext} / μm	error in L_{ext} / %	$v_{s,ext}$ / cm s^{-1}	error in $v_{s,ext}$ / %	L_{ext} / μm	error in L_{ext} / %	L_{ext} / μm	error in L_{ext} / %
A	3.0	0.0	101	1.4	3.0	-1.1	3.0	0.0
B	3.0	-0.3	1.02 x 10^5	2.0	4.1	36	3.0	-0.2
C	9.9	-0.6	104	3.7	9.6	-3.9	10	0.8
D	10	-0.5	1.0 x 10^5	-0.2	6.1	-39	9.9	-0.6

1. Applied to EBIC data obtained under the condition that x < 2L
2. Applied to EBIC data obtained under the condition that x > 2L

10^6 cm s^{-1} [20]. Hence, the surface recombination velocities (v_s) of 10^2 and 10^6 cm s^{-1} were chosen in our simulation because these two values represent the lower and upper limit of the surface recombination effect on the EBIC line scan profile.

The primary electron energy E_b was 12.7 keV and the beam current I_b was 1.5 nA. The primary electron range R can be calculated using the following expression [18]

$$R = \frac{4.57 \times 10^{-6}}{\rho} E_b^{1.75} \tag{15}$$

where ρ is the density of silicon in gm/cm^3 and the R is given in cm. The z is 30% of this value, i.e., z is 0.5 μm in this case.

The position of the electron beam was stepped at 0.1 μm along the x direction, from the junction to $x = 5$ μm. The normalized EBIC current, $I(x)$ was recorded for each beam position. The $I^+(x)$ and $I^-(x)$ were obtained similarly except that the E_b was adjusted such that z deviates from the proposed method by $\pm 10\%$. The same procedure was used on all four samples.

In this simulation, the minority carrier generation volume, i.e., the region excited by the electron beam, is created based on the analytical expressions used in the work by Yakimov [18]. The distribution of the minority carrier within the generated volume is governed by a Gaussian function. Hence, the effective depth of the generation volume (value of z) is taken as 0.3 of the value obtained using (15).

The method described in [11] was also used with the EBIC currents collected at both $x < 2L$ and $x > 2L$, and the results were then compared with those obtained using the proposed method.

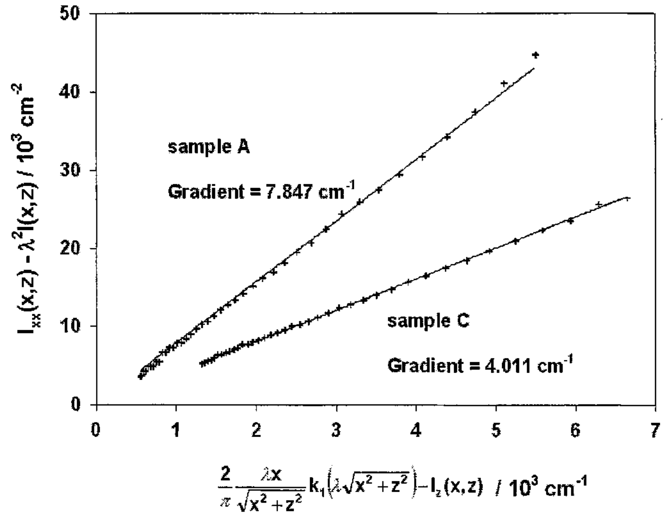
IV. RESULTS AND DISCUSSION

It was shown in [13] that the EBIC data obtained when x is less than $R/2$ produces inaccurate results. Hence, the EBIC data obtained from $x < R/2$ (i.e., $x < 0.8$ μm in this case) were excluded in our calculations. This means that the minimum beam–junction distance is $R/2$ in the proposed method. This distance is solely a function of the beam energy and not of any of the material parameters. In cases where the depletion widths are comparable to the primary electron range, the minimum beam–junction distance should be the sum of the depletion width and $R/2$.

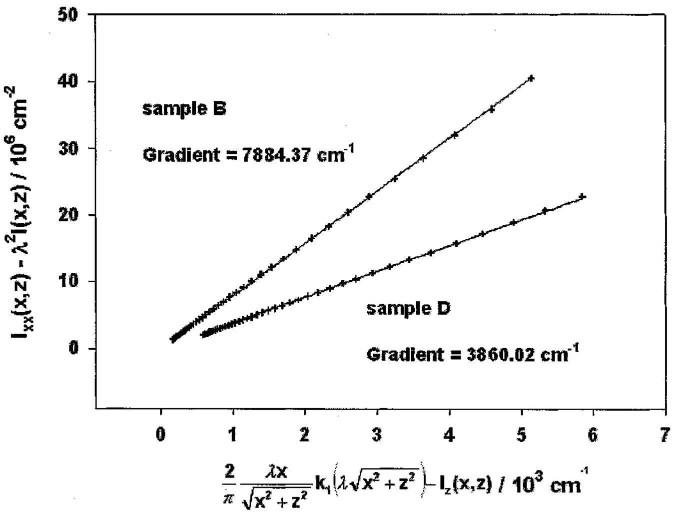
Fig. 4 show the plots of the $I_{xx}(x,z)+I_{zz}(x,z)$ against $I(x)$ for samples A, B, C, and D. The graphs are linear as predicted by (8). Linear regression was used to obtain the gradient of the graphs. The results are tabulated in the column 2 of Table II, where the L_{ext} is the extracted minority carrier diffusion length whereas the $v_{s,\text{ext}}$ is the extracted surface recombination velocity. The results in columns 6 and 8 are those using the method proposed in [11]. It can be observed that the errors in the extracted minority carrier diffusion lengths obtained using the proposed method are all within $\pm 1\%$. The method proposed in [11] can attain similar accuracies only when the minimum beam junction distance is at least $2L$. When the minimum beam–junction distance is less than $2L$, the errors in the diffusion lengths obtained using the method in [11] are within $\pm 4\%$ only for the case of $v_s = 10^2$ cm s^{-1}.

The earlier observations can be summarized as follows. The proposed method of determining the minority carrier diffusion length can be used on any arbitrary value of x including those that are less than $2L$ provided that the minimum beam–junction distance is $R/2$. This statement is supported by comparing the plots (in Fig. 4) for sample A with sample C and sample B with sample D. Both samples have different minority carrier diffusion lengths but the EBIC data used to evaluate the L_{ext} are from the same range of x, i.e., between $R/2$ and 5 μm, and this range satisfies $x < 2L$ for both samples. For the method proposed in [11], the L_{ext} is accurate for the case when $x > 2L$. Moreover, when v_s is small (i.e., $v_s < 10^2$ cm s^{-1}), this method produces reasonably accurate results even for the case of $x < 2L$. Since the value of v_s is unknown during the experiment, the method of [11] can only be used for the case where $x > 2L$.

Fig. 5 show the plots for determining the surface recombination velocities of the samples A, B, C and D. All the plots are linear as predicted by (13). The slopes of the plots give the value of s. The values of v_s are obtained by multiplying these values with the diffusion coefficient D of the respective samples, as given in Table I. These results are tabulated in the fourth column of Table II. It can be observed that the errors in the results are all



(a)



(b)

Fig. 5. (a) Determination of v_s of samples A and C. (b) Determination of v_s of samples B and D.

within $\pm 4\%$. In the case where the values of v_s cannot be calculated due to the unknown value of D, the value of s can still provide valuable information regarding the surface state at the beam-entrance surface. For instance, the product of s and the L gives the ratio of v_s and v_d, the diffusion velocity $(v_d = D/L)$.

V. Conclusion

The conventional method of extracting the minority carrier diffusion length requires the minimum beam–junction distance to be more than $2L$. It is difficult to determine the closest distance between the beam and the junction because the diffusion length is initially unknown. Accurate results can be obtained for the case of $x < 2L$ only if v_s is less than 10^2 cm s^{-1}. Since the value of v_s is also unknown initially, the minimum beam–junction distance has to be kept at $2L$. A new method of determining the minority carrier diffusion length from regions close to the junction is presented in this paper. It was shown that this technique does not require the minimum beam–junction distance to be $2L$, regardless of the surface recombination velocities of the samples. The advantage of using EBIC measurements close to the junction is noticeable only in practice. The EBIC signals from this region have better signal to noise ratio and hence, a relatively accurate result can be obtained. It was also shown that the surface recombination velocity of the samples could be found if the diffusion coefficient is known. The errors of the extracted v_s are all within $\pm 4\%$ in our simulation. I_{zz} is a measure of the surface recombination effect on the EBIC line scan profile. In practical EBIC experiments, the value of I_{zz} may be difficult to extract accurately, especially if the specimen has a small surface recombination velocity, e.g., $v_s < 10^2$ cm s^{-1}, at the beam entrance surface. In this case, however, the value of I_{zz} can be approximated as zero. Using method proposed in this paper, the value of z is needed to evaluate the semi-normalized surface recombination velocity (s) of the specimens. Usually, only the order of magnitude of this parameter is of interest and hence an accurate value of z is not required.

Appendix
Derivation of (3)

Donolato's EBIC equation [1] is given as follows:

$$I(x,z) = I_o\left[\exp(-\lambda x) - \frac{2}{\pi}s\int_0^\infty \frac{k}{\mu^2(\mu+s)} \times \exp(-\mu z)\sin(kx)dk\right] \quad \text{(A1)}$$

where $I(x,z)$ is the EBIC current, I_o is the maximum current, λ is the reciprocal of the minority carrier diffusion length, s is the semi-normalized surface recombination velocity and

$$\mu = \sqrt{k^2+\lambda^2}. \quad \text{(A2)}$$

Differentiate $I(x,z)$ with respect to x

$$\frac{\partial}{\partial x}I(x,z) = I_o\left[-\lambda\exp(-\lambda x) - \frac{2}{\pi}s\int_0^\infty \frac{k^2}{\mu^2(\mu+s)} \times \exp(-\mu z)\cos(kx)dk\right]. \quad \text{(A3)}$$

Differentiating(A3) with regard to x, we obtain

$$\frac{\partial^2}{\partial x^2}I(x,z) = I_o\left[\lambda^2\exp(-\lambda x) - \frac{2}{\pi}s\int_0^\infty \frac{-k^3}{\mu^2(\mu+s)} \times \exp(-\mu z)\sin(kx)dk\right]. \quad \text{(A4)}$$

From (A2), we know that $-k^2 = \lambda^2 - \mu^2$. Hence, (A4) can also be expressed as

$$\frac{\partial^2}{\partial x^2}I(x,z) = I_o\left[\lambda^2\exp(-\lambda x) - \frac{2}{\pi}s\int_0^\infty \frac{k(\lambda^2-\mu^2)}{\mu^2(\mu+s)} \times \exp(-\mu z)\sin(kx)dk\right]. \quad \text{(A5)}$$

Separating the integral part of (A5), we obtain

$$\frac{\partial^2}{\partial x^2}I(x,z) = I_o\left[\lambda^2\left(\exp(-\lambda x) - \frac{2}{\pi}s\int_0^\infty \frac{k}{\mu^2(\mu+s)} \times \exp(-\mu z)\sin(kx)dk\right)\right] + \frac{2I_o}{\pi}s\int_0^\infty \frac{k}{\mu+s}\exp(-\mu z)\sin(kx)dk. \quad \text{(A6)}$$

Substitute (A1) into (A6)

$$\frac{\partial^2}{\partial x^2}I(x,z) = \lambda^2 I(x,z) + \frac{2I_o}{\pi}s\int_0^\infty \frac{k}{\mu+s} \times \exp(-\mu z)\sin(kx)dk \quad \text{(A7)}$$

or

$$\frac{\partial^2}{\partial x^2}I(x,z) = \lambda^2 I(x,z) + \frac{2I_o}{\pi}s\int_0^\infty \frac{k}{\sqrt{k^2+\lambda^2+s}} \times \exp\left(-\sqrt{k^2+\lambda^2}z\right)\sin(kx)dk. \quad \text{(A8)}$$

REFERENCES

[1] J. W. Orton and P. Blood, *The Electrical Characterization of Semiconductors: Measurement of Minority Carrier Properties*. New York: Academic, 1990, pp. 185–276.

[2] H. J. Leamy, "Charge collection scanning electron microscopy," *J. Appl. Phys.*, vol. 53, pp. R51–R75, 1982.

[3] D. B. Holt, "The conductive mode," in *SEM Microcharacterization of Semiconductors*, D. B. Holt and D. C. Joy, Eds. New York: Academic, 1989, pp. 241–338.

[4] K. L. Luke, "Evaluation of diffusion length from a planar-collector-geometry electron-beam-induced current profile," *J. Appl. Phys.*, vol. 80, no. 10, pp. 5775–5785, 1996.

[5] K. L. Luke, O. von Roos, and L. J. Cheng, "Quantification of the effects of generation volume, surface recombination velocity, and diffusion length on the electron-beam-induced current and its derivative: Determination of diffusion lengths in the low micron and submicron ranges," *J. Appl. Phys.*, vol. 57, no. 6, pp. 1978–1984, 1985.

[6] V. K. S. Ong, "A direct method of extraction surface recombination velocity from an electron beam induced current line scan," *Rev. Sci. Instrum.*, vol. 69, no. 4, pp. 1814–1816, 1998.

[7] T. E. Everhart and P. H. Hoff, "Determination of kilovolt electron energy dissipation versus penetration distance in solid materials," *J. Appl. Phys.*, vol. 42, pp. 5837–5846, 1971.

[8] M. Levinshtein, S. Rumyantsev, and M. Shur, *Handbook Series on Semiconductor Parameter*. Singapore: World Scientific, 1996, vol. 1.

[9] C. Donolato, "On the analysis of diffusion length measurements by SEM," *Solid-State Electron.*, vol. 25, no. 11, pp. 1077–1081, 1982.

[10] F. Berz and H. K. Kuiken, "Theory of life time measurements with the scanning electron microscope: Steady state," *Solid-State Electron.*, vol. 19, pp. 437–445, 1976.

[11] V. K. S. Ong, J. C. H. Phang, and D. S. H. Chan, "A direct and accurate method for the extraction of diffusion length and surface recombination velocity from an EBIC line scan," *Solid-State Electron.*, vol. 37, no. 1, pp. 1–7, 1994.

[12] D. S. H. Chan, V. K. S. Ong, and J. C. H. Phang, "A direct method for the extraction of diffusion length and surface recombination velocity from an EBIC line scan: Planar junction configuration," *IEEE Trans. Electron Devices*, vol. 42, pp. 963–968, May 1995.

[13] V. K. S. Ong and D. Wu, "Determination of diffusion length from within a confined region with the use of EBIC," *IEEE Trans. Electron Devices*, vol. 48, no. 2, 2001.

[14] R. Hakimzadeh, H. J. Moller, and S. G. Bailey, "Evaluation of the minority carrier diffusion length and edge surface—Recombination velocity in GaAs p/n solar cells," *J. Appl. Phys.*, vol. 72, no. 7, pp. 2919–2922, 1992.

[15] K. L. Luke, "Choice of a range-energy relationship for the analysis of electron-beam-induced-current line scans," *J. Appl. Phys.*, vol. 76, no. 2, pp. 1081–1091, 1994.

[16] ——, "Evaluation of diffusion length from a planar-collector-geometry electron-beam-induced current profile," *J. Appl. Phys.*, vol. 80, no. 10, pp. 5775–5785, 1996.

[17] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marichev, *Integrals and Series Volume1: Elementary Function*. New York: Gordon and Breach, 1988.

[18] E. Yakimov, "Electron beam induced current investigations of electrical inhomogeneities with high spatial resolution," *Scanning Microsc.*, vol. 6, no. 1, pp. 81–96, 1992.

[19] *TMA MEDICI User Manual*, Technol. Modeling Assoc., pp. 2-1–2-96 vol. 1, 1996.

[20] L. Jastrzebski, J. Lagowski, and H. C. Gatos, "Application of scanning electron microscopy to determination of surface recombination velocity: GaAs," *Appl. Phys. Lett.*, vol. 27, no. 10, pp. 537–539, 1975.

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