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Determining the Location of Localized Defect in the Perpendicular Junction Configuration With the Use of Electron Beam Induced Current

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Abstract—This paper describes a new method of determining the location of a localized defect in semiconductor materials using the perpendicular p–n junction configuration. The scanning electron microscope (SEM) operating in the charge-collection, or the electron beam induced current (EBIC) mode, is used for this. This method is based on the model used to calculate the contrast of a localized defect as suggested by C. Donolato and is known as the contrast $C_{\eta''}$ model. This model can be used to precisely extract the location of the localized defect and is unaffected by the value of the surface recombination velocity at the beam entrance surface. The model of the localized defect used in this paper is characterized by minority carriers with constant lifetimes that are lower than those in the bulk. An electron beam with an extended generation profile was used in a two-dimensional (2-D) device simulator, for the verification of the theory.

Index Terms—Electron beam application, electron microscopy, p–n junctions, semiconductor devices, semiconductor charge carriers, simulation.

NOMENCLATURE

c	EBIC contrast function given in [1].
c_{η}	EBIC contrast function expressed in terms of the charge collection efficiency.
C_{η}	EBIC contrast function expressed in terms of the η_{HE} and η_{LE} profiles.
$C_{\eta''}$	EBIC contrast function expressed in terms of the η''_{HE} and η''_{LE} profiles.
d	Electron beam diameter (cm).
D	Minority carrier diffusion coefficient (cm^2s^{-1}).
e	First curve fitting parameter.
E	Electron beam energy (keV).
E_i	Energy of electron–hole pair formation (eV).
f	Second curve fitting parameter.
$F(x, y, z, E)$	Radial distribution of the electron–hole pairs generation (cm^{-2}).
g	Third curve fitting parameter.
$G(\bar{r})$	Generation rate of the electron–hole pairs per unit volume (cm s^{-3}).
G_o	Total carrier generation rate (s^{-1}).
$h(z, E)$	Depth distribution of the electron–hole pairs generation (cm^{-1}).

I	Collected EBIC signal when the electron beam normal to the surface is on top of the defect in the planar p–n junction configuration (A).
I_b	Electron beam current (A).
I_o	Collected EBIC signal when the electron beam normal to the surface is far away from the defect in the planar p–n junction configuration (A).
L	Bulk minority carrier diffusion length (μm).
L_d	Effective diffusion length of the localized defect (μm).
Q	Total generation current (A).
R	Primary electron penetration depth as defined in (7) (μm).
x_0	Fourth curve fitting parameter.
x_b	Distance of the electron beam from the p–n junction (μm).
x_d	Distance of the defect from the p–n junction (μm).
y_0	Fifth curve fitting parameter.
y_d	Depth of the localized defect from the free surface (μm).
η	Charge collection efficiency.
η_{HE}	Charge collection efficiency at high beam energy.
η_{LE}	Charge collection efficiency at low beam energy.
η''_{HE}	Second derivative of the charge collection efficiency with respect to the beam–junction distance, x_b at high beam energy.
η''_{LE}	Second derivative of the charge collection efficiency with respect to the beam–junction distance, x_b at low beam energy.
ρ	Material density (g cm^{-3}).
κ	Fraction of the electron beam energy lost due to backscattering.
$\Lambda(\zeta)$	Normalized depth distribution of the electron–hole pairs.
τ	Bulk lifetime of the semiconductor (s).
τ_d	Lifetime of the localized defect (s).

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I. INTRODUCTION

IN A SEMICONDUCTOR junction structure, carriers created by the primary electrons of a scanning electron microscope (SEM) give rise to an electron beam induced current

(EBIC) which can be used for microscopy. The EBIC mode of the SEM enables defects which are present inside the junction structure to show up due to enhanced carrier recombination at the defect. As a result, this mode of the SEM has found wide applications in the study of the electrical activities of crystal defects in semiconductors [1]–[6].

The traditional method of using EBIC for defect characterization is to use the planar configuration. This makes use of either a very shallow junction, or a Schottky contact at the beam entrance surface. The present paper examines the possibility of using the perpendicular junction configuration as shown in Fig. 1, for defect characterization. This would be useful for the characterization of defects in the vicinity of a junction, such that the junction is perpendicular to the beam entrance surface. This is, therefore, an attempt at extending the use of the EBIC technique for defect characterization, to a wider range of configurations.

In the planar configuration, the presence of defects in the vicinity of a junction can easily be detected by line scanning the sample surface with the use of EBIC. The negative peaks of the EBIC signal reveals the location of the defects. However, in the perpendicular junction configuration, the detection of the defects is not as straightforward. This can be seen in Fig. 2. This figure shows two EBIC profiles, one is taken from a sample which contains a defect, while the other is from a sample which is free of defects. In the absence of defects, the electron-hole pairs generated by the electron beam diffuse over a distance before reaching the junction. If the EBIC signal were to be plotted against the beam-junction distance, an exponential profile which corresponds to the solid line in Fig. 2 will be produced. This exponential plot has been well analyzed in [7]–[11]. In the presence of a localized defect at a distance of, say $x_d = 1.0 \mu\text{m}$ from the p-n junction, the generated carriers will be reduced due to increased recombination at the defect. This will in turn cause a reduction in the collected EBIC signal. A plot of the EBIC signal against the beam-junction distance in this case produces an exponential curve which is indicated by the dotted line in Fig. 2. Comparing the two EBIC profiles in Fig. 2, it can be seen that the exponential profile of the sample with defect is simply more concave than the one without defect. Thus, the location of the defect cannot be determined directly from the plot in this case.

There is, therefore, a need to propose a new method of locating defects in the perpendicular junction configuration so that defects in the vicinity of the junction can be characterized.

II. METHOD

The proposed method is based on a model used to calculate the contrast of a localized defect as suggested by Donolato [1] for the planar p-n junction configuration. This contrast function is given by

$$c = \frac{I - I_0}{I_0} \quad (1)$$

where I_0 and I are the collected currents when the incident electron beam is far away from the location of the defect, and directly above it, respectively. Equation (1) can also be rewritten

Fig. 1. Simple localized defect-sample layout in the perpendicular junction configuration.

in terms of the charge collection efficiency. This is simply the ratio of the EBIC signal to the total carrier generation rate, and it represents the fraction of the injected carriers that is collected i.e., $\eta = I/Q$ (where Q is the total generation current). Thus, (1) becomes

$$c_\eta = \frac{\eta - \eta_0}{\eta_0}. \quad (2)$$

In the perpendicular p-n junction configuration, (2) is used to determine the position of the localized defect instead of (1). In the method proposed here, the p-n junction is first scanned with different beam energies. The ratio of the collected EBIC signal to the total carrier generation rate, or the charge collection efficiency, η is then computed. The excitation volume produced by a low energy electron beam has a small penetration depth R . If the depth of a defect y_d is much larger than R , then the defect will have very little effect on the charge collection efficiency of the low energy electron beam. This can therefore be used to compute the contrast profile by approximating (2) with the following equation:

$$C_\eta = \frac{\eta_{HE} - \eta_{LE}}{\eta_{LE}} \quad (3)$$

where η_{HE} and η_{LE} are the charge collection efficiency profiles obtained by line scanning the defect at high and low beam energies, respectively. Equation (3) can then be used to estimate the position of the defect which corresponds to the minimum of the contrast profile C_η . This method, however, is only accurate for the case where the surface recombination velocity v_s is negligible. For the case where v_s is not negligible, serious errors will arise. It is therefore proposed in this paper that the second derivative of η be used instead. Equation (3) then becomes

$$C_{\eta''} = \frac{\eta''_{HE} - \eta''_{LE}}{\eta''_{LE}} \quad (4)$$

where η''_{HE} and η''_{LE} are the second derivatives of the charge collection efficiency profiles with respect to the beam-junction distance x_b . The use of the second derivatives of the charge collection efficiency profiles helps to increase the sensitivity of the

Fig. 2. Simulated EBIC profiles obtained from line scanning the perpendicular junction with and without defects. The defect is located at $x_d = 0.1 \mu\text{m}$.

contrast profile and thus enabling the defect position to be located. It will be shown below that the extracted defect position from (4) corresponds exactly to the peak of the $C_{\eta''}$ profile.

III. DEVICE STRUCTURE

The device structure used is shown in Fig. 1. It consists of a piece of silicon semiconductor with both the p-type and the n-type doping concentration $= 10^{16} \text{ cm}^{-3}$, and the junction is abrupt. The simulation was carried out with the use of a two-dimensional (2-D) device simulator MEDICI [12]–[14]. MEDICI is a powerful device simulation program that can be used to model the 2-D distributions of potential and carrier concentrations in a device to predict its electrical characteristics at any bias condition. It solves the two fundamental equations that govern the electrical behavior of semiconductor devices. They are the Poisson's equation and the continuity equations. The Poisson's equation, which is derived from Maxwell's electrostatic equations, describes the electrostatic behavior of the semiconductor device and is given as follows:

$$\epsilon \nabla^2 \psi = q (N_D^+ - N_A^- + p - n) \quad (5)$$

where

ψ	electrostatic potential;
N_D^+ and N_A^-	ionized donor and acceptor impurity concentrations, respectively;
n and p	electron and hole concentrations, respectively;
q	electronic charge;
ϵ	dielectric constant, often written as the product $\epsilon_0 \epsilon_r$.

The continuity equations, which govern the carrier concentrations, are given below. For the electrons

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \vec{J}_n - U_n \quad (6)$$

where $\vec{J}_n$ is the electron current density and U_n is the net electron recombination rate. For the holes

$$\frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot \vec{J}_p - U_p \quad (7)$$

where $\vec{J}_p$ is the hole current density and U_p is the net hole recombination rate.

A localized defect is placed at a distance x_d from the p-n junction, and lying at a depth y_d from the free surface of the sample. The localized defect used in this simulation is a square defect with sides of $0.01 \mu\text{m}$. The defect is characterized by minority carriers with constant lifetimes that are lower than those outside the defect, i.e., $\tau_d < \tau$ where τ_d is the constant lifetime of minority carriers within the defect, and τ is the constant lifetime of minority carriers outside the defect. The values τ and τ_d used are 10^{-8} s and 10^{-10} s , respectively. The minority carrier diffusion coefficient D is given the same value of $1.0 \text{ cm}^2 \text{ s}^{-1}$ both inside and outside the defect. The corresponding minority carrier diffusion lengths are therefore $L \equiv \sqrt{D\tau} = 1.0 \mu\text{m}$ and $L_d \equiv \sqrt{D\tau_d} = 0.1 \mu\text{m}$, respectively.

An electron beam with an extended profile was simulated with the use of an analytical expression [15] given as follows:

$$G(\vec{r}) = G_o F(x, y, z, E) h(z, E) \quad (8)$$

where G_o is the total generation rate [16] which is given as

$$G_o = \frac{EI_b(1 - \kappa)}{qE_i} \quad (9)$$

Fig. 3. Normalized depth distribution of electron-hole pair generation for silicon.

where

- E electron beam energy;
- I_b electron beam current;
- q electronic charge;
- E_i energy required for the formation of an electron-hole pair;
- κ fraction of the electron beam energy lost due to backscattering.

The values of each of these parameters are selected as follows: $q = 1.6022 \times 10^{-19}$ C, $E_i = 3.65$ eV for silicon (according to Fiebigler and Muller [17]) and $\kappa = 0.08$ for silicon (according to Bishop [18]), a value which is independent of E [19]. Since these three parameters are constant and are independent of E and I_b , for the case of silicon, we can rewrite (9) as

$$G_o = 1.6 \times 10^{18} E I_b. \quad (10)$$

This is exactly the equation obtained by Berz and Kuiken in [20]. Therefore, for a given beam energy and current, e.g., $E = 16$ keV and $I_b = 10^{-11}$ A, respectively, the total generation rate G_o can be determined as 2.52×10^{11} EHPs $^{-1}$ where EHP stands for electron-hole pairs.

$F(x, y, z, E)$ describes the radial distribution of the electron-hole pair generation. For silicon, it is given by Donolato [21] as

$$F(x, y, z, E) = \frac{1.76}{2\pi\sigma^2 R} \exp \left[-\frac{(x^2 + y^2)}{\sigma^2} \right] \quad (11)$$

where

$$\sigma^2 = 0.36d^2 + \frac{0.11z^3}{R}. \quad (12)$$

where d is the electron beam diameter and R is the primary electron penetration depth. This depth depends on the electron beam energy E and can be determined from the relationship given by Everhart and Hoff [22]

$$R = \frac{3.98 \times 10^{-2} \times E^{1.75}}{\rho} \quad (13)$$

where ρ is the material density, and for silicon, $\rho = 2.33$ g cm $^{-3}$. From this expression, it can be seen that the electron penetration depth R increases at a rate which is proportional to the electron beam energy, E raised to the power of 1.75. This means that the penetration depth of the electron beam increases faster than the beam energy E .

The function $h(z, E)$ gives the depth distribution of the electron-hole pair generation. For silicon, this function can be approximated by a normalized expression proposed by Everhart and Hoff [22] as

$$\Lambda(\zeta) = 0.6 + 6.21\zeta - 12.40\zeta^2 + 5.69\zeta^3 \quad (14)$$

where ζ is the depth z , normalized by the electron penetration depth R , i.e., $\zeta = z/R$, and it has a range of $0 < \zeta < 1.1$. The graphical representation of $\Lambda(\zeta)$ is shown in Fig. 3.

The generation volume can be generated by incorporating (8) into the device simulator. Fig. 4 shows the density contours of the generated carriers for values of beam energy $E = 16$ keV, and beam current $I_b = 10^{-11}$ A, respectively. The beam diameter d used was 1% of R , which is 21.9 nm. From Fig. 4, it can be seen that the depth distribution of the carrier generation is similar to that obtained by Cohn and Caledonia [23]. A graphical comparison is done between the simulated generation current and the calculated values for $E = 2$ keV–20 keV and

$I_b = 10^{-11}$ A (see Fig. 5). The generation current Q is defined simply as

$$Q = qG_o \quad (15)$$

where G_o is the total generation rate, which can be approximated by (10). From Fig. 5, it can be seen that the graph of the simulated generation current matches perfectly with that obtained by calculation.

IV. RESULTS AND DISCUSSION

In this section, the results will be presented in two parts. In the first part, the effect of the application of the proposed method on a localized defect located at $x_d = 1.0 \mu\text{m}$ and $y_d = 1.0 \mu\text{m}$ will be discussed. The effect of using different contrast definitions, i.e., C_η and $C_{\eta'}$ in (3) and (4), respectively, to determine the position of the localized defect for the case of zero surface recombination velocity v_s will be discussed in detail. The contrast profile $C_{\eta'}$ will also be used to determine defect locations for cases with different values of surface recombination velocities v_s . In the second part of this section, the method will be tried out with the defect located at different distances from the junction, at different depths from the surface, and with the surface having different values of recombination. This is to test out the range of validity of the technique.

A. Localized Defect Located at $x_d = 1.0 \mu\text{m}$ and $y_d = 1.0 \mu\text{m}$

Fig. 6 shows the contrast profile C_η versus the beam-junction distance x_b for different values of beam energies. The surface recombination velocity v_s is zero. In this graph, the charge collection efficiency profile of the lowest beam energy, i.e., 2 keV, is used as η_{LE} to compute the C_η profiles for all the other values of beam energies. The entire line scan can be divided into five different sections with each section having a unique characteristic.

In the first section, where the electron beam is very near to the junction, a negative contrast is observed. This is due to different lateral sizes of the excitation volume at different beam energies. Fig. 7 shows the charge collection efficiency of two beam energies, i.e., 2 keV and 20 keV. Since the depletion width of the device is approximately $0.4 \mu\text{m}$, for the lower beam energy (2 keV), the lateral dimension of the excitation volume, which is calculated to be $0.06 \mu\text{m}$, is small enough for the whole of the excitation volume to fit into the space charge region. As a result, most of the charge carriers are collected as shown in Fig. 7. On the other hand, for the higher beam energy (20 keV), the lateral dimension of the excitation volume, which is calculated to be $0.912 \mu\text{m}$, is significantly larger, so that only a portion of the excitation volume falls within the space charge region while the rest of the generated charge carriers are in the bulk region where the recombination is relatively higher. This results in a lower charge collection efficiency, as can be seen in Fig. 7. At a higher beam energy, the defect point is also relatively closer to the excitation volume, causing more generated charge carriers to be drawn toward it and hence further reducing the collection efficiency. Thus, a negative contrast is seen in the first section.

In the second section, as the electron beam moves away from the junction, an increase in the contrast is observed. This is due

Fig. 4. Contours of carrier pair generation in silicon, computed using MEDICI. The beam energy used is 16 keV with beam diameter $d = 21.9 \text{ nm}$. The projected density of the contours shown are $1.151 \times 10^{21} \text{ cm}^{-3}$, $4.605 \times 10^{20} \text{ cm}^{-3}$, $2.303 \times 10^{20} \text{ cm}^{-3}$, $1.151 \times 10^{20} \text{ cm}^{-3}$, $4.605 \times 10^{19} \text{ cm}^{-3}$, $2.303 \times 10^{19} \text{ cm}^{-3}$, $1.151 \times 10^{19} \text{ cm}^{-3}$, $4.605 \times 10^{18} \text{ cm}^{-3}$, $2.303 \times 10^{18} \text{ cm}^{-3}$, $1.151 \times 10^{18} \text{ cm}^{-3}$, $2.303 \times 10^{17} \text{ cm}^{-3}$, $1.151 \times 10^{17} \text{ cm}^{-3}$, and $2.303 \times 10^{16} \text{ cm}^{-3}$.

to fact that the lower beam energy profile η_{LE} decreases at a much faster rate than the higher beam energy profile η_{HE} . This can be seen in Fig. 7. The reason for the faster decay of η_{LE} , as compared to η_{HE} , is again due to the difference in the sizes of the excitation volumes of each of the beam energies.

In the third section, where x_b is $0.5 \mu\text{m}$ beyond the junction, the electron beam is closer to the localized defect. As x_b increases, the excitation volumes with higher beam energies begin to come into contact with the defect point, causing more generated charge carriers to be recombined, hence decreasing the charge collection efficiency. Therefore, the η_{HE} profile decreases faster than the η_{LE} profile and a general decreasing in the C_η profile is observed.

In the fourth section, where the electron beam is about $1.0 \mu\text{m}$ from the junction, a minimum contrast value is observed at each contrast profile. This is where the effect of the localized defect is at its maximum. It can also be observed that the minimum contrast value decreases from 3 keV to 14 keV and then increases for beam energy E greater than 14 keV. This is due to the fact that the vast majority of the generated charge carriers in an excitation volume are located close to the center of gravity of the excitation volume [20]. As the beam energy increases from 3 keV to 13 keV, the center of gravity of the excitation volume moves closer to the defect point causing more charge carriers to recombine. When the defect point is exactly at the center of gravity of the excitation volume, where most of the generated charge carriers are (14 keV in this case), the largest fraction of the generated charge carriers will recombine. Increasing the beam energy further from 15 keV to 20 keV will cause the center of gravity of the excitation volume to move away from the localized defect, thus causing the contrast profiles increase again.

Fig. 5. Graphical comparison of the calculated generation current using (15) and the generation current simulated in MEDICI.

Fig. 6. C_η profile versus beam-junction distance x_b for different beam energies and zero surface recombination velocity.

Finally, as the electron beam moves away from the defect in the fifth section, the contrast levels all increases. This is because the smaller excitation volume associated with the lower beam energy will cause η_{LE} to decrease at a faster rate than η_{HE} . Thus, from this plot, one observes that the minimum contrast value occurs at $x_b = 1.11 \mu\text{m}$, which can be taken to be the location of the defect.

A major shortcoming of this method is its failure to correctly locate the precise position of defects. In the sample shown above, the actual defect is at $x_d = 1.0 \mu\text{m}$, but the technique locates it at $x_b = 1.11 \mu\text{m}$. The method also fails when it is used on samples with nonnegligible surface recombination velocities. An example of this is shown in Fig. 8, in which the technique is used on a sample with $v_s = 10^6 \text{ cm s}^{-1}$. It can be

Fig. 7. Charge collection efficiency η profile versus beam-junction distance x_b for 2 keV and 20 keV.

Fig. 8. C_η profile versus beam-junction distance x_b for different beam energies and surface recombination velocity $v_s = 10^6 \text{ cm s}^{-1}$.

seen in this figure that the graph does not have a minimum contrast at all.

It turns out that significant improvements to the method can be achieved by taking the second derivatives of the charge collection efficiency profiles η_{HE} and η_{LE} with respect to the beam-junction distance x_b , as given in (4). By doing this, the sensitivity of the contrast to the defects in both η_{HE} and η_{LE} are increased. This is illustrated in Fig. 9, which shows the $C_{\eta''}$ profile versus the beam-junction distance x_b for the surface recombination velocity $v_s = 0$. This graph is the same

as that in Fig. 6 except that the second derivative of the η_{HE} and η_{LE} profiles with respect to the beam-junction distance x_b are used instead. In this case, the position of the localized defect corresponds to the peak in the $C_{\eta''}$ profile rather than the minimum as in the case of the C_η profile. In Fig. 9, it can be seen that the peak for all the $C_{\eta''}$ profiles occurs at the beam-junction distance $x_b = 1.0 \text{ } \mu\text{m}$ which corresponds to the precise location of the defect. Thus, the location of the defect can be determined much more accurately with this method.

Fig. 9. $C_{\eta''}$ profile versus beam-junction distance x_b for different beam energies and zero surface recombination velocity.

Fig. 10. $C_{\eta''}$ profile versus beam-junction distance x_b for different beam energies and surface recombination velocity $v_s = 10^6 \text{ cm s}^{-1}$.

The main advantage of using the $C_{\eta''}$ profile over the C_{η} profile is that the position of the defect can be accurately determined for all values of surface recombination velocities v_s . It was shown in Fig. 8 that it was not possible to locate the position of a defect using the C_{η} profile for $v_s = 10^6 \text{ cm s}^{-1}$, while in the case of the $C_{\eta''}$ profile, this is possible, as illustrated in Fig. 10. From this graph, it can be seen that for beam energies greater than 7 keV,

the peak of the $C_{\eta''}$ profile appears quite prominently at about $x_b = 1.0 \mu\text{m}$. This corresponds to the exact location of the defect.

Fig. 11 shows the $C_{\eta''}$ profile versus the beam-junction distance x_b for a sample with infinite surface recombination velocity v_s . From this graph, the position of the defect, which corresponds to the peak of the $C_{\eta''}$ profile is found to be at $x_d = 1.04 \mu\text{m}$.

Fig. 11. $C_{\eta''}$ profile versus beam-junction distance x_b for different beam energies and infinite surface recombination velocity.

B. Localized Defect Located at Different x_d and y_d

This section examines samples in which the defect is located at different positions and at different depths. Four different positions of defects are selected for analysis. They are: $x_d = 0.5 \mu\text{m}$, $1.0 \mu\text{m}$, $1.5 \mu\text{m}$, and $2.0 \mu\text{m}$. For each lateral defect position x_d , the depth of the defect is also varied to the following values: $y_d = 0.5 \mu\text{m}$, $1.0 \mu\text{m}$, and $1.5 \mu\text{m}$. The results are tabulated in Table I for the case of zero surface recombination velocity. The beam energies which give the highest peak values are given in the parentheses in the table.

From this table, it can be seen that when the defect-junction distance is greater than the depth of the defect, i.e., $x_d > y_d$, the proposed method can be used to extract the position of the localized defect x_d quite accurately. However, when $x_d < y_d$, the value of the extracted defect position x_d becomes somewhat less accurate. This can be seen for the case of $x_d = 0.5 \mu\text{m}$ and $y_d = 1.5 \mu\text{m}$, where the extracted defect position x_d is $0.64 \mu\text{m}$. The reason for this is that when the defect junction distance x_d is less than the defect depth y_d , the lateral dimension of the generation volume is large enough for a part of it to be engulfed by the depletion region. This, in turn, affects the accuracy of the extraction process.

For the case where $x_d = 0.5 \mu\text{m}$ and $y_d = 1.5 \mu\text{m}$, the peak energy of the extracted x_d is 15.6 keV . At this beam energy value, the lateral dimension of the generation volume is $0.72 \mu\text{m}$, while the width of the depletion region is $0.43 \mu\text{m}$. Therefore, it is quite clear that part of the generation volume falls within the depletion region.

Tables II and III show the extraction of the defect-junction distance x_d for samples with $v_s = 10^6 \text{ cm s}^{-1}$ and ∞ , respectively. It can be seen from these tables that for both cases, the proposed method can also be used to extract x_d accurately when

TABLE I
RESULTS OF EXTRACTING DEFECT LOCATIONS AT DIFFERENT x_d AND y_d
FOR THE CASE OF ZERO SURFACE RECOMBINATION VELOCITY.
THE BEAM ENERGIES IN THE PARENTHESES ARE THE
PEAK ENERGY IN THE $C_{\eta''}$ PROFILE

$y_d \backslash x_d$	$0.5 \mu\text{m}$	$1.0 \mu\text{m}$	$1.5 \mu\text{m}$	$2.0 \mu\text{m}$
$0.5 \mu\text{m}$	$0.5 \mu\text{m}$ (10.1 keV)	$1.0 \mu\text{m}$ (10.2 keV)	$1.5 \mu\text{m}$ (10.2 keV)	$2.0 \mu\text{m}$ (10.2 keV)
$1.0 \mu\text{m}$	$0.56 \mu\text{m}$ (13.9 keV)	$1.0 \mu\text{m}$ (15.1 keV)	$1.5 \mu\text{m}$ (15.2 keV)	$2.0 \mu\text{m}$ (15.2 keV)
$1.5 \mu\text{m}$	$0.64 \mu\text{m}$ (15.6 keV)	$1.11 \mu\text{m}$ (17.6 keV)	$1.5 \mu\text{m}$ (18.8 keV)	$2.0 \mu\text{m}$ (19.2 keV)

$x_d > y_d$. For $x_d < y_d$, the accuracy of the extracted x_d is somewhat affected by the lateral dimension of the generation volume, as discussed above.

It can thus be summarized that the proposed method can be used to accurately extract defects anywhere in the vicinity of a junction, provided that the generation volume does not come into contact with the depletion region of the junction. The lateral dimension of the generation volume can be estimated from the beam energy. The surface recombination velocity of the sample at the beam entrance surface seems to have only a slight effect on the accuracy of the extracted defect position.

In this work, the verification of the proposed method is done only on data obtained from computer simulation, which is free of noise. Real EBIC experiments, however, are typically noisy. A fair amount of noise can be removed by over-sampling the data. However, since taking derivatives of noisy data tends to accentuate the noise, it is proposed that the experimental data first be smoothed out by curve fitting.

TABLE II
RESULTS OF EXTRACTING DEFECT LOCATIONS AT DIFFERENT VALUES OF x_d
AND y_d FOR $v_s = 10^6 \text{ cm s}^{-1}$

$y_d \backslash x_d$	0.5 μm	1.0 μm	1.5 μm	2.0 μm
0.5 μm	0.56 μm (10.4 keV)	1.0 μm (10.6 keV)	1.5 μm (10.7 keV)	2.0 μm (10.7 keV)
1.0 μm	0.60 μm (14.1 keV)	1.04 μm (15.3 keV)	1.5 μm (15.5 keV)	2.0 μm (15.5 keV)
1.5 μm	0.68 μm (15.9 keV)	1.24 μm (18.0 keV)	1.52 μm (19.0 keV)	2.0 μm (19.2 keV)

TABLE III
RESULTS OF EXTRACTING DEFECT LOCATIONS AT DIFFERENT VALUES OF
 x_d AND y_d FOR $v_s = \infty$

$y_d \backslash x_d$	0.5 μm	1.0 μm	1.5 μm	2.0 μm
0.5 μm	0.56 μm (10.5 keV)	1.0 μm (10.7 keV)	1.5 μm (10.7 keV)	2.0 μm (10.7 keV)
1.0 μm	0.60 μm (14.3 keV)	1.04 μm (15.3 keV)	1.5 μm (15.5 keV)	2.0 μm (15.5 keV)
1.5 μm	0.72 μm (16.2 keV)	1.24 μm (18.1 keV)	1.56 μm (19.1 keV)	2.0 μm (19.4 keV)

The Weibull equation has been found to be suitable for this purpose. It has been used successfully for a similar purpose in [24]. The equation is given as follows:

$$y = y_0 + e \left(1 - \exp \left(- \left(\frac{z}{f} \right)^g \right) \right) \quad (16)$$

with

$$z = \left| x - x_0 + f \times \ln 2^{1/g} \right| \quad (17)$$

where e , f , g , x_0 , and y_0 are the five parameters used for curve fitting. The curve fitted EBIC data will now be free of noise, and can be used to compute the second derivatives of the signals without giving rise to spurious results.

V. CONCLUSION

It has been shown that the contrast C_{η} model can be used to estimate the position of a localized defect in the perpendicular p-n junction configuration for the case of zero surface recombination velocity v_s . However, for $v_s > 0$, the method fails. This problem can be overcome by using the second derivative of the charge collection efficiency to compute the contrast profile. This gives the contrast $C_{\eta''}$ model. The position of the localized defect corresponds to the peak in the $C_{\eta''}$ profile. The accuracy of the contrast $C_{\eta''}$ profile to precisely extract the position of a localized defect x_d has been clearly demonstrated in this paper for all values of surface recombination velocities. The method,

however, loses some accuracy if the generation volume comes into contact with the depletion region of the junction.

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