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<td><strong>Author(s)</strong></td>
<td>Ong, Vincent K. S.; Tan, Chee Chin.; Radhakrishnan, K.</td>
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Extraction of Diffusion Length Using Junction-less EBIC

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Abstract—The electron-beam-induced current (EBIC) mode of the scanning electron microscope (SEM) has been widely used in semiconductor materials and devices characterization in particular the extraction of minority carrier properties. The conventional approaches require the sample to have a built-in electric field created by the charge collecting junction that separates the majority carriers from the minority carriers and drives the induced current into the external circuitry for detection. As a result, these conventional approaches are not applicable for samples without junctions, i.e. bare substrates. This paper discusses the feasibility of extracting the minority carrier diffusion length in junction-less sample using the junction-less EBIC technique with the use of a two-point probe method. A 2-D device simulator is used to verify this technique and it is found the accuracy depends on the location of the origin.

Index Terms—Charge carrier processes, electron beam applications, semiconductor materials measurements, simulation.

I. INTRODUCTION

The semiconductor’s minority carrier transport properties such as minority carrier diffusion length and surface recombination velocity play an important role in the performance of the semiconductor devices particularly the bipolar devices and the photodiode [1]. One of the widely used techniques for semiconductor materials and devices characterization is the electron-beam-induced current (EBIC) mode of the scanning electron microscope (SEM). This technique has become a favorable analytical tool as it requires minimum sample preparation and less destructive to the sample as compared to other techniques such as the ion-beam-induced current (IBIC). Its capability in controlling both the beam position and penetration depth precisely is another reason for its popularity.

The EBIC technique begins by the generation of charge carriers in a volume known as the generation volume when a focused energetic electron beam impinges upon the sample. These generated charge carriers tend to diffuse away from the generation volume and recombine. An electromotive force (e.m.f) in the sample is required in order to separate the majority charge carriers from the minority charge carriers, preventing them from recombining and to drive the induced current into an external circuit for detection. In general, this e.m.f can be either produced internally by built-in electric fields at electrical barriers such as the p-n junction or externally by external biasing. The former gives rise to the phenomenon known as electron voltaic effects (barrier or bulk voltaic effect) [2] and the latter gives rise to phenomenon refers to electron beam induced conductivity (β-conductivity) [3].

The relationship of the induced current $I_{EBIC}$ and the beam distance $x$ measured from the charge collecting junction for two widely used configurations, the normal-collector configuration and the planar-collector configuration, at any surface recombination velocity is generalized in [4, 5] and is given by

$$I_{EBIC} = kx^\alpha \exp(-x/L)$$  \hspace{1cm} (1)

where $k$ is the proportionality constant, $\alpha$ is the fitting parameter and $L$ is the minority carrier diffusion length. The $\alpha$ parameter is found to be dependent on the type of collector configuration as well as the surface recombination velocity $V_s$. For normal-collector configuration, $\alpha = 0$ if $V_s = 0$ and $\alpha = -1/2$ if $V_s = \infty$. On the other hand, for planar-collector configuration, $\alpha = -1/2$ if $V_s = 0$ and $\alpha = -3/2$ if $V_s = \infty$. For other finite values of surface recombination velocity, the $\alpha$ has a value ranges from the two extremes. The $\alpha$ can be used to extracted the surface recombination velocity [6] and the parameters affect the $\alpha$ value was studied in [7]. It is found that (1) is also applicable for a diffused junction with any values of junction depths [8].

Unfortunately, the aforementioned steady state method of minority carrier diffusion length extraction required the sample to have either a charge collecting junction or the built-in electric field which may not be readily available in bare substrate. An additional sample preparation procedure such as the fabrication of p-n junction or special probe [9] is required in order to extract the minority carrier properties of a junction-less sample using the conventional EBIC techniques.

The minority carrier diffusion length $L$ can be determined by the following equations

$$L = \sqrt{D\tau}$$ \hspace{1cm} (2)

$$D = \frac{KT}{q\mu}$$ \hspace{1cm} (3)

where $D$ is the diffusion coefficient, $\tau$ is the carrier lifetime, $K$ is the Boltzmann constant, $T$ is the temperature in Kelvin, $q$ is the elementary charge and $\mu$ is the carrier mobility. The photoconductance decay lifetime characterization proposed by...
theory

In this technique, one has to monitor the decay of electron hole pairs (ehps) generated by optical excitation or by high-energy electrons as a function of time once the excitation is turned off. The time-of-flight method [11] is used to determine the carrier mobility and hence the diffusion coefficient using (3). As a result, the minority carrier diffusion length can be extracted by using (2) with \( D \) and \( \tau \) are determined separately in the aforementioned technique. The extraction of the diffusion length using two separate experiments may be suitable for junction-less sample, however, it is difficult to implement the transient method for the extraction of carrier lifetime and it is less robust as two experiments are conducted for one parameter extraction.

Two-point probe method as shown in Fig. 1 is originally used for semiconductor spreading resistance profiling [12]. In our experiment, the two-point probe under some external voltage biasing is used to measure the change in the current due to the electron irradiation, and this change in the current is analogous to the induced current due to the electron beam in conventional EBIC technique. The biasing is necessary as it serves as the necessity e.m.f to drive the induced current into the external circuitry. Under equilibrium condition, i.e., both the probes are grounded; it is assumed that no potential barrier formed when the probes and the sample are in contact.

In this paper, we are going to study the feasibility of extracting minority carrier diffusion length in junction-less sample using the two-point-probe method and discuss how the accuracy is affected with the change of the origin, voltage bias and probe spacing.

II. THEORY

The current density in a semiconductor is given by the following equations

\[
J = \sigma E - q \left( D_p \frac{dp}{dr} - D_n \frac{dn}{dr} \right) \tag{4}
\]

\[
\sigma = q (\mu_p n + \mu_n p) \tag{5}
\]

where \( \sigma \) is the conductivity, \( E \) is the electric field, \( D_p \) and \( D_n \) are the diffusion coefficient for hole and electron respectively, \( p \) and \( n \) are the hole and electron density respectively, \( q \) is the elementary charge and \( \mathbf{r} \) is the real space vector. The first term in (4) corresponds to the drift current caused by electric field and the second term in (4) corresponds to the diffusion current caused by the carrier concentration gradient. In uniformly doped samples, the diffusion term can be neglected provided that there is no charge carrier generation by the electron beam.

If electron beam impinges upon the sample, (4) needs to be modified and is expressed as follows

\[
J' = (\sigma + \Delta \sigma) E' - q \left( D_p \frac{d(p + \Delta p)}{dr} - D_n \frac{d(n + \Delta n)}{dr} \right) \tag{6}
\]

\[
\Delta \sigma = q(\mu_p + \mu_n) \Delta p \tag{7}
\]

\[
\Delta p = \Delta n \tag{8}
\]

where \( E' \), \( \Delta p \), \( \Delta n \), and \( \Delta \sigma \) are the new electric field, excess hole concentration, excess electron concentration and change of conductivity due to electron irradiation respectively. If the voltage bias remains unchanged and the charge carrier generation has an insignificant effect on the electric field, then the electric field remains unchanged. The change in current density is then simply

\[
J' - J = \Delta \sigma E - q \left( D_p \frac{d\Delta p}{dr} - D_n \frac{d\Delta n}{dr} \right) \tag{9}
\]

Under steady state condition, the excess carrier concentration in a n-type sample can be determined by solving the continuity equation

\[
\nabla \cdot (D \nabla p - \mu_p E) - \tau^{-1} p = -G \tag{10}
\]

where \( G \) is the carrier generation rate.

If we assume the location in question is far from the probes, then generation volume location will have a small electric field. As a result, the first term of (9) i.e. the change in the drift current, can be neglected and the change in the current for such a case is dominated by the change in the diffusion current which is similar to the induced current in the conventional EBIC technique.

The generalized equation (1) used to describe the EBIC current can be re-expressed as follows

\[
\ln \left( \frac{I_{EBIC}}{x^\alpha} \right) = -\frac{x}{L} + \ln(k) \tag{11}
\]

A straight line is observed when \( \ln \left( \frac{I_{EBIC}}{x^\alpha} \right) \) is plotted against \( x \). The change in current, i.e., the induced current, is fitted into (11) and the alpha parameter is adjusted to yield the best fitted curve. The figure of merit of the curve fitting can be determined from the correlation coefficient, \( r^2 \). The negative of the reciprocal of the slope yields the diffusion length. The fitting parameter \( \alpha \) may carry information such as the surface recombination velocity.

III. VERIFICATION

The verification of a new proposed method has traditionally been done through experiment means. One of the main drawbacks of the experimental verification method is the
limitation on which the parameters of the materials can be varied. This may cause some restrictions on the generality of the proposed method. Besides this, the material fabrication process may also degrade the accuracy of the parameter to be extracted and the experimental environment may also introduce some degree of errors to the result. The computer simulation is expected to overcome these drawbacks. In this paper, MEDICI, a commercially available 2-D device simulator, is used to verify this junction-less EBIC technique.

The two-point probe junction-less EBIC configuration as shown in Fig. 1 is modeled using MEDICI. The n-type doping concentration is set to $10^{14}$ cm$^{-3}$ uniformly and the minority carrier diffusion length is set by adjusting the minority carrier lifetime. The thickness of the sample, $T$, the width towards the left of the probe 1, $x_l$, and the width towards the right side of probe 2, $x_r$, are arbitrary set to 19$\mu$m, 27.5$\mu$m and 10$\mu$m respectively.

It is found in [13] that it is insignificant whether a circle or a square generation volume is used if the size of the generation source used is sufficiently small. Thus the round generation source with radius 0.1 $\mu$m can be approximately modeled by a square generation area with sides of 0.2 $\mu$m without sacrificing the accuracy. The charge generation rate per unit volume is set to $2.52\times10^{53}$ EHP cm$^{-2}$s$^{-1}$ with its centre at 0.3 $\mu$m below the surface of the sample. This corresponds to a beam energy and an injected beam current of about 8.7 keV and 0.72 pA respectively. This generation rate per unit volume is chosen to minimize the simulation error [14] and to ensure the carrier injection is in the low injection regime [15]. The electron beam is scanned from a distance of 12.5 $\mu$m away from probe 1 to a distance of 7.5 $\mu$m away from the probe 1. The surface recombination velocity is set to zero. In practice, this can be achieved with the use of etching during the sample preparation.

IV. RESULTS AND DISCUSSIONS

Fig. 2 shows the percentage of extraction errors using (11) at different x-origin, i.e., the location where $x = 0$ with respect to probe 1, for minority carrier diffusion length $L$ of 3.146 $\mu$m, probe spacing $s$ of 2.5 $\mu$m, $V_f$ at 0.1 V, $V_s$ is grounded and other parameters are as described in Section III. It can be observed that if the x-origin is set far towards the right of probe 1 (negative x value), it will extract a larger value of $L$, and if the x-origin is set far towards the left of probe 1 (positive x value), it will extract a lower value of $L$. This poses a challenge to this method as it may be hard to determine the x-origin to yield an accurate extraction.

In the analysis, the x-origin location is varied until the best minority carrier diffusion length extraction occurs. This allows us to study on the location of the x-origins is required for a good extraction.

Table I shows the required x-origin location measured from probe 1 to achieve an accurate minority carrier diffusion length extraction and its corresponding $\alpha$ values for different value of $V_f$ bias with minority carrier diffusion $L$ of 3.146 $\mu$m, probe spacing $s$ of 2.5 $\mu$m, $V_s$ is grounded and other parameters are as described in Section III. It can be observed that the x-origin shift towards the left of probe 1 if the $V_f$ is increased. This may be due to the increase in the magnitude and locus of the strong electric field around the probe that analogous to the edges of built-in electric field in junction devices. This can be seen in Fig. 3, the electric field profile for different $V_f$ bias at depth $z = 0.3 \mu$m that generated using the MEDICI. Fig. 3 also verifies our assumption that the location far from probe has a negligible electric field. The $\alpha$ parameter also increased with $V_f$. This is because as $V_f$ increased, the locus of strong field enlarged and this enhanced the collection. This is similar to increasing the junction depth in a diffused junction sample. The $\alpha$ parameter is believed to reveal the magnitude and the distribution

<table>
<thead>
<tr>
<th>$V_f$</th>
<th>x-origin</th>
<th>Extracted $L$</th>
<th>Error (%)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-0.4</td>
<td>3.1453</td>
<td>-0.02</td>
<td>-0.4201</td>
</tr>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>3.1480</td>
<td>0.06</td>
<td>-0.4062</td>
</tr>
<tr>
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<td>3.1448</td>
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<td>-0.3186</td>
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<tr>
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<td>2.7</td>
<td>3.1461</td>
<td>0.003</td>
<td>-0.2874</td>
</tr>
<tr>
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<td>3.3</td>
<td>3.1452</td>
<td>-0.03</td>
<td>-0.2494</td>
</tr>
<tr>
<td>1.1</td>
<td>3.9</td>
<td>3.1464</td>
<td>0.01</td>
<td>-0.2158</td>
</tr>
</tbody>
</table>

$L=3.146\mu$m, $T=19\mu$m, $s=2.5\mu$m, $x_l=27.5\mu$m, $x_R=10\mu$m, and $V_s=0V$.

Figure 2. Percentage of extraction error at different x-origin measured from probe 1 for $L=3.146\mu$m, $T=19\mu$m, $s=2.5\mu$m, $x_l=27.5\mu$m, $x_R=10\mu$m, $V_f=0.1V$ and $V_s=0V$.

Figure 3. Electric field distribution at the left of probe 1 at different $V_f$ for $L=3.146\mu$m, $T=19\mu$m, $s=2.5\mu$m, $x_l=27.5\mu$m, $x_R=10\mu$m, and $V_s=0V$. 

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TABLE II. X-ORIGIN POSITION MEASURED FROM PROBE 1 TO ACHIEVE GOOD MINORITY CARRIER DIFFUSION LENGTH AND ITS CORRESPONDING $\alpha$ VALUE FOR DIFFERENT PROBE SPACING

<table>
<thead>
<tr>
<th>Probe spacing, s</th>
<th>$x$-origin</th>
<th>Extracted $L$</th>
<th>Error (%)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-1.1</td>
<td>3.1442</td>
<td>-0.06</td>
<td>-0.5172</td>
</tr>
<tr>
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<td>-0.8</td>
<td>3.1461</td>
<td>0.003</td>
<td>-0.4889</td>
</tr>
<tr>
<td>1.3</td>
<td>-0.6</td>
<td>3.1480</td>
<td>0.06</td>
<td>-0.4643</td>
</tr>
<tr>
<td>1.9</td>
<td>-0.4</td>
<td>3.1453</td>
<td>-0.02</td>
<td>-0.4349</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.4</td>
<td>3.1453</td>
<td>-0.02</td>
<td>-0.4201</td>
</tr>
</tbody>
</table>

$L=3.146\mu m, T=19\mu m, x_l=27.5\mu m, x_t=10\mu m, V_1=0.1V$ and $V_2=0V$

![Electric field distribution at the left of probe 1 at different probe spacing](image)

Figure 4. Electric field distribution at the left of probe 1 at different probe spacings with minority carrier diffusion length $L=3.146\mu m$, $V_1=0.1V$ and $V_2=0V$ of the electric field, i.e. $\alpha$ is a function of the electric field or $V_j$ bias.

Table II shows the required $x$-origin position with respect to probe 1 to achieve an accurate minority carrier diffusion length extraction and its corresponding $\alpha$ value for different probe spacings with minority carrier diffusion length $L=3.146\mu m$, $V_1$ at 0.1 V, $V_2$ is grounded and other parameters are as described in Section III. It can be seen that the $x$-origin is shifted towards the left of probe 1 when the probe spacing increases. If the probe spacing is decreased, the locus of strong fields to the left of probe 1 becomes smaller as shown in Fig. 4, the electric field profile for different probe spacings at depth $z=0.3\mu m$, that generated using the MEDICI. This is because at these locations, the field generated by probe 1 can be more easily cancelled by the field generated by probe 2 when they are closer to one another. As a result, increasing the probe spacing has similar effect as increasing the $V_j$ bias voltage. As a result, the $\alpha$ is also a function of probe spacing.

V. CONCLUSION

The accuracy of this two-point probe method depends on the location of the $x$-origin and how the location of the $x$-origin should be changed with the $V_j$ bias and probe spacing is discussed in this paper. The $\alpha$ parameter for this junction-less EBIC technique using two-point probe is found to be a function of the bias and probe spacing.

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