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Determination of Diffusion Lengths With the Use of EBIC From a Diffused Junction With Any Values of Junction Depths

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Abstract—Minority carrier diffusion lengths determine the performance of bipolar and photodiode devices. An electron-beam-induced-current (EBIC) method has been widely used to extract this parameter. The extraction of the diffusion lengths involves a p-n junction to collect the minority carriers. The most used configuration, which is called the normal collector, assumes that the junction has an infinitely large junction depth. However, in planar devices, the junction depth is comparable to the diffusion lengths of the material. This paper presents a simple and yet accurate method to determine the diffusion lengths of the material from a diffused junction with any values of junction depths. The diffusion length of the material is extracted from the negative reciprocal of the slope of the EBIC profile in semi-logarithmic plot. It was found that the proposed method is able to extract the diffusion lengths accurately for any values of the junction depths and surface recombination velocities. The maximum error in using this method is about 6%.

Index Terms—Electron-beam applications, electron microscopy, semiconductor material measurements, simulation.

I. INTRODUCTION

THE MINORITY CARRIER diffusion lengths can be extracted accurately from a diffused junction with any values of junction depths. This paper describes a technique in extracting the diffusion lengths of a material with the use of the electron-beam-induced current (EBIC) technique.

The transport properties of carriers determine the performance and functionalities of a device. For the case of bipolar and photodiode devices, the minority carrier transport properties have a significant effect on the performance. One of the minority carrier transport parameters that are important for these devices is the minority carrier diffusion lengths [1], [2].

The EBIC technique of the scanning electron microscopy (SEM) has been widely used in determining the minority carrier diffusion lengths of many materials [3], [4]. The electron beam bombards the semiconductor surface and creates electron-hole pairs. These electron-hole pairs will diffuse away from the generation volume. If these electron-hole pairs reach a built-in electric field, the minority carriers will be separated (or collected) and will contribute to the current in the external circuit.

Fig. 1. Normal collector configuration.

One of the most often used configurations for diffusion-length measurement is shown in Fig. 1. This is normally called the normal-collector configuration. In this case, the beam is scanned in the direction normal to the collecting p-n junction. The induced current was derived in [5] and [6] for the case of zero surface recombination velocity

$$I = k \exp(-x/L) \quad (1)$$

where x is the beam distance from the depletion region edge, L is the minority carrier diffusion length, and k is a constant.

Taking the logarithm of (1) gives

$$\ln(I) = \ln k - \frac{x}{L}. \quad (2)$$

It is shown in (2) that the minority carrier diffusion length can be determined from the negative reciprocal of the slope. This equation, however, is only valid for zero surface recombination velocity. For an infinite surface recombination velocity, Berz and Kuiken gave the induced current as follows [6]

$$I = kx^{-0.5} \exp(-x/L). \quad (3)$$

Taking the logarithm of (3) gives

$$\ln \left(\frac{I}{x^{-0.5}} \right) = \ln k - \frac{x}{L}. \quad (4)$$

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Fig. 2. EBIC measurement in a diffused junction.

This equation is only valid for very large surface recombination velocity. Some sample preparation must be done to make the recombination at the surface very large. Ong *et al.* [7] generalized (1) and (3) to make the method applicable for any values of surface recombination velocities by introducing the following empirical equation

$$I = kx^\alpha \exp(-x/L). \quad (5)$$

Taking the logarithm of (5) gives

$$\ln \left(\frac{I}{x^\alpha} \right) = \ln k - \frac{x}{L} \quad (6)$$

where α (alpha) is a fitting parameter. The range of values for the fitting-parameter alpha is from 0 to -0.5 depending on the actual value of the surface recombination velocity. This method was found to be applicable to the planar-collector configuration as well, but with a different range of values for the alpha parameter [8].

In practice, however, a p-n junction is normally fabricated as a diffused junction. This is especially so for planar devices. This configuration is shown in Fig. 2. In this configuration, the junction has a finite depth, and therefore, another boundary condition must be introduced to take into account the collection of carriers at the bottom of the junction.

Some works have been done to study the induced-current profile on a structure of finite junction depth. Dimitriadis [9] used a Schottky barrier in a thin semiconductor layer where the bottom part of the device behaves just like a collecting junction. Few years later, Holloway [10] studied the profile of the induced current when a spot of light impinges onto a semiconductor surface near a diffused junction.

A thorough study was done by Soukup and Ekstrand [11] on the EBIC profile for the case when the beam is scanned on both the inside and outside of the diffused junction. In the work of Soukup and Ekstrand [11], an analytical equation was derived for the EBIC current for the configuration shown in Fig. 2. The equation, however, is only valid for the case of a very high surface recombination velocity. The diffusion lengths were extracted by comparing the experimental results with the analytical model developed. Thus, this method involves fitting the data into a complex equation. Furthermore, only

the case for very high surface recombination velocity can be extracted.

Most experimentalists prefer a simpler method to extract the diffusion lengths. Boudjani [12], for example, extracted the diffusion lengths in the base region of a transistor from the negative reciprocal slope of (2).

By using this equation, several assumptions were made implicitly. It was assumed that the junction depth of the collecting junction was large enough, and that the generation volume, where the electron-hole pairs were created, was located near the top surface of the sample. With these assumptions, the configuration is simplified to the normal-collector one, as shown in Fig. 1. However, the trend in device scaling prevents the use of this method. This is because, as the device is scaled down, the depth of the collecting junction can no longer be assumed to be infinitely large.

Another assumption in [12] was that the surface recombination velocity was negligible. For the case where the surface recombination velocity is not negligible, (2) would give a large error. In this case, (6) should be used instead [7].

This paper proposes a method of extracting the diffusion lengths accurately from any values of the junction depths and surface recombination velocities. It will be shown later that (5) can be modified slightly to take into account the junction depths of the collector. Thus, a simple and accurate method of extracting the diffusion lengths can be obtained for a diffused junction that can be used with any values of the junction depths and surface recombination velocities.

II. THEORY

It was shown in [7] that the diffusion lengths can be extracted accurately from a normal-collector configuration for any values of surface recombination velocities. The diffusion lengths are obtained from the negative reciprocal slope of (6). Comparing Fig. 1 with Fig. 2, the normal-collector configuration can be thought of as a diffused junction with an infinite junction depth.

For this infinite junction depth, the steady-state diffusion equation must satisfy at least two boundary conditions [13]

$$q = 0 \text{ at } x = 0 \quad (7)$$

$$\frac{dq}{dz} = sq \text{ at } z = 0 \quad (8)$$

where q is the minority carrier concentration, and $s = v_s/D$ is the surface recombination velocity. The x axis is taken from the junction, and the z axis is taken from the top surface.

The first boundary condition comes from the fact that the built-in electric field at the collecting junction sweeps away all the minority carriers reaching the junction. The second boundary condition is simply from the definition of the surface recombination velocity. The minority carriers recombine at the surface. In this case, the flux going to the surface is proportional to the surface recombination velocity as well as the minority carrier concentration at the surface.

Fig. 3. Planar-collector configuration.

For the case of finite junction depth, another boundary condition must be introduced to take into account the collection at the bottom of the junction. This is given by

$$q = 0 \text{ at } z = h \text{ and } x < 0 \quad (9)$$

where h is the depth of the junction, and $x < 0$ is used to indicate the location of the diffused junction in Fig. 2.

Before we can modify (5) to take into account the finite junction depth, it is useful to study the case when the junction depth is very small and close to the surface. In this case, the boundary condition can be written as

$$q = 0 \text{ at } z \approx 0 \text{ and } x < 0. \quad (10)$$

The above condition is the same as the boundary condition of a planar-collector configuration (Fig. 3) where the Schottky barrier is located at the surface ($z = 0$ and $x < 0$) [14], [15].

Therefore, it can be concluded at this point in time that the infinite junction depth has the same boundary condition as the normal-collector configuration, while the shallow junction depth has the same boundary condition as the planar-collector configuration.

It is important to note that (5) holds true for both configurations, that is, for the normal-collector [7] as well as the planar-collector configuration [8]. In the case of the normal collector, the alpha parameter ranges from 0 to -0.5 . On the other hand, the alpha parameter ranges from -0.5 to -1.5 for the case of the planar-collector configuration. In both configurations, the alpha parameter is a function of the surface recombination velocity, the normalized beam distance from the collector, and the normalized depth of the generation volume. The dependence of the alpha parameter on these three factors has been given in [16].

The finite junction depth can be taken into account in (5) by rewriting it as

$$I = k_1 x^\gamma \exp(-x/L) \quad (11)$$

where γ (gamma) and k_1 are the new fitting parameters replacing the alpha parameter and the constant k in (5). The change of symbol is intended to indicate that the new parameters are

also affected by the depth of the junction. In other words, the parameter gamma is a function of the alpha parameter as well as the depth of the junction, i.e., $\gamma = f(\alpha, h)$.

The values of the gamma parameter can be estimated easily for the case of zero surface recombination velocity. Comparing with the normal-collector configuration, it can be expected that the value is close to zero for the infinite junction depth. On the other hand, comparing with the planar-collector configuration, the value can be expected to be around -0.5 for the case of a very shallow junction depth. By comparing the gamma parameter with the alpha parameter in (5), it is expected that the effect of the surface recombination velocity is to make the gamma values more negative [17]. Therefore, the diffusion lengths can be extracted as in the previous case by fitting the EBIC data into the following equation

$$\ln \left(\frac{I}{x^\gamma} \right) = \ln k_1 - \frac{x}{L}. \quad (12)$$

The physics behind (11) can be explained as follows. For simplicity, the case of zero surface recombination velocity will be considered first. The case for finite surface recombination velocity can be easily explained after that.

When the junction depth is very large, the configuration simplifies to that of the normal collector, and the gamma value is close to zero. Substituting gamma equals to zero into (12) results in (2). The logarithmic plot of the induced current is a straight line with a slope of $-1/L$.

The induced current given in (2) will be reduced due to either recombination at the surface or, for the case of the finite junction depth, to a more recombination of carriers as they diffuse further to the bottom part of the junction. As the junction depth reduces, more carriers diffuse to the bottom part of the junction instead of being collected at the vertical part. Since the distance to reach the bottom part of the junction is longer than the vertical junction, more recombination takes place. Thus, the induced current is reduced.

This reduction in the induced current causes the profile to be no longer exponential. The logarithmic plot is no longer a straight line but rather concave upward and is below the straight line given by (2). It will be shown later that (12) fits well with this concaved curve. In this equation, the parameter gamma determines how concave the curve is. This is the same as the case for the alpha parameter [17].

In summary, as the junction depth reduces, more recombination takes place before being collected at the bottom part of the junction. Thus, the induced current decreases, and the logarithmic plot is concave upward. This results in the gamma parameter being more negative. The effect of finite surface recombination velocity is to reduce the induced current even further, and therefore, the gamma parameter is expected to be more negative when recombination at the surface is present.

The assumption used in developing the model follows [10] and [11]. First, it is assumed that the diffused junction has a sharp corner. In other words, the diffused junction has an L shape. Second, the diffused junction is assumed to be isolated. This means that there are no competing junctions near the beam positions. The last assumption also implies that the ohmic

contact locations are far enough from the beam positions so as not to affect the induced-current profile.

III. VERIFICATION

The verification of theories of this nature has traditionally been done by experimental means. However, there are some drawbacks with this method. The first is that there is a question of how accurate the fabrication process is able to control the parameters of the material. The second is the magnitude of errors, which might be introduced into the experiment. The third and the most significant drawback is that there is a limit to which the material parameters can be varied.

To overcome these drawbacks, a two-dimensional (2-D) computer simulation was chosen to verify the proposed method. MEDICI semiconductor device simulator was used for this purpose.

The device structure was created according to the configuration shown in Fig. 2. An abrupt junction with a sharp edge was used in the simulation. A fine grid of $0.1 \mu\text{m}$ was used along the surface as well as at the junction. This is to accommodate an accurate computation for minority carriers recombining at the surface and collected at the junction.

The generation volume used a Gaussian model according to Ong and Wu [18], [19]. The beam energy was set to 8 keV. This value results in a $0.75\text{-}\mu\text{m}$ electron penetration range (R) with a center of mass (z) at $0.31 \mu\text{m}$ from the surface. The minority carrier diffusion lengths were set to $3 \mu\text{m}$ for both the p and n regions. The minority carrier diffusion lengths were set by specifying the carrier lifetimes. The values of the lifetime was calculated from

$$\tau = L^2/D \quad (13)$$

where L is the minority carrier diffusion length in centimeters, and D is the diffusivity in square centimeters per second. The diffusivity in the simulation depends on the doping concentration. A uniform doping concentration of $1 \times 10^{18} \text{ cm}^{-3}$ for both p and n regions were specified.

Specifying the lifetimes affects the Shockley–Read–Hall recombination, which in turn affects the carrier-concentration distributions inside of the device. Once the carrier concentration is known, the device simulator will compute the corresponding current density. The details of the implementation of the generation volume, the setting of the minority carrier diffusion-length value as well as the EBIC simulation using MEDICI can be found in [18] and [20].

The first set of the simulations dealt with zero surface recombination velocity. The variable that was varied is the depth of the junction. The values of the junction depth (h) were chosen to be the same as the one in [11]. The h/z ratios are 200, 100, 25, 20, 15, 10, 5, 2, 1, and 0. For the last ratio, the simulation used $h/z = 0.3$ to approximate zero ratio.

The line scans were done at the region outside the diffused junction. This means that the extracted diffusion length is for the minority carrier electron. The scanning range started from $x/L = 2$ and ended at $x/L = 11$ to satisfy the requirement given in [7]. The data from each line scan were fitted into (12), and a linear regression was done. The fitting-parameter

Fig. 4. EBIC profile for the case of $h/z = 10$ and zero surface recombination velocity.

TABLE I
EXTRACTED DIFFUSION LENGTHS FOR ANY VALUES OF JUNCTION DEPTHS FOR ZERO SURFACE RECOMBINATION VELOCITY

h/z	Extracted L (μm)	Error (%)	γ
200	3.005	0.17	-0.0118
100	3.055	1.83	-0.0501
25	2.909	-3.03	-0.0567
20	2.917	-2.77	-0.1251
15	2.934	-2.20	-0.2148
10	2.952	-1.60	-0.2958
5	2.969	-1.03	-0.3655
2	2.975	-0.83	-0.3876
1	2.976	-0.80	-0.3883
≈ 0	2.975	-0.83	-0.3850

gamma was varied until the correlation coefficient r^2 reached a maximum value [7].

The second set of simulations used the same structures and varied the surface recombination velocity from 1×10 to $1 \times 10^7 \text{ cm}^2/\text{s}$. There were eight different surface recombination values used in the simulations. The same procedure was applied to obtain the diffusion lengths for the data in the second set.

IV. RESULTS

An example of the semi-logarithmic plot of the induced current is shown in Fig. 4. The maximum peak indicates the location of the vertical junction. The sudden changes at the two ends of the profile are caused by the ohmic contacts. The minority carrier diffusion length for the p region is obtained by fitting the profile at the right of the junction into (12).

Table I shows the extracted diffusion lengths for different junction depths for the case of zero surface recombination velocity. The extracted diffusion lengths have a maximum error of about 3%. For very large junction depth, the gamma value is close to zero. The values become more negative as the junction depth decreases.

The errors are slightly increased when the surface recombination velocity is taken into account. For any surface recombination velocities, the maximum error for the extracted diffusion lengths is about 6%. The gamma values become more negative as the surface recombination velocity increases for a fixed value of junction depth. This is shown in Fig. 5.

Fig. 5. Gamma-parameter variation with the surface recombination velocity for $h/z = 10$.

V. DISCUSSIONS

The EBIC profile shown in Fig. 4 agrees well with the experimental results in [21] and the theoretical calculation in [11]. Inside the diffused junction, the EBIC profile is limited by the current collected at the horizontal junction, which is a near horizontal line in Fig. 4. The peak at $45 \mu\text{m}$ shows the maximum collection at the vertical junction. Outside the diffused junction, the profile behaves as described in the theory and in [11].

The results show that the minority carrier diffusion lengths can be extracted for any values of junction depths and surface recombination velocities. The accuracy of the method was proven to be reasonably high for the given diffusion-length value.

The results in Table I suggest that the fitting-parameter gamma depends on the depth of the junction. The values of the gamma parameter become more negative as the junction depth decreases. This result agrees with the theory. This is because more recombination occurs before reaching the bottom part of the junction. Thus, the induced current reduces, and the semi-logarithmic plot of the profile becomes more concave. A more concave plot results in a more negative gamma values.

The value of the gamma parameter for a very large h/z ratio is close to zero. In this case, the configuration is similar to a normal-collector configuration. On the other hand, the gamma value is around -0.4 for the case of a very small h/z ratio. In this case, the configuration is more similar to the planar-collector configuration. Thus, the gamma values can be used to approximate the depth of the junction.

Besides being a function of the junction depth, the gamma parameter is also a function of the alpha parameter, which depends on the surface recombination velocity. For a given junction depth, the variation in the gamma values with respect to the surface recombination velocities follows that of the alpha parameter in [7], [16], [17].

VI. CONCLUSION

This paper provides a method of extracting the minority carrier diffusion lengths from a diffused junction. It has been

shown that the proposed method is able to extract the diffusion lengths accurately for any values of junction depths and surface recombination velocities.

A fitting parameter called the gamma parameter was used to take into account the depth of the junction. The gamma parameter is a function of both alpha parameters, which depend on the surface recombination velocity as well as the depth of the junction.

The gamma values become more negative as the junction depth decreases. At a fixed junction depth, the gamma values decrease as the surface recombination velocity increases. The physical explanation for the variation in the gamma values due to the junction depth and the surface recombination velocity was discussed in this paper. A more detailed study of how the alpha parameter and the junction depth affect the gamma values is underway.

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