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EBIC measurements of small diffusion length in semiconductor structures

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The problems arising under submicron diffusion length measurements by the EBIC are discussed. As an example the results of diffusion length measurements in GaN are presented. It is shown that fitting the collection efficiency dependence on beam energy is the most reliable method for this purpose. The depth–dose dependence for GaN is calculated by the Monte-Carlo method and its analytical approximation is presented. This expression was verified experimentally by simultaneous fitting the collected current dependence on beam energy for a few applied bias values.

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1. Introduction

Scanning electron microscopy in the Electron Beam Induced Current (EBIC) mode is now widely used for the local measurements of excess carrier diffusion length L in semiconductor structures [1–3]. The application of the EBIC for L measurements is the most effective in the structures with submicron size and in semiconductors with L in the submicron range. The methods for extracting the diffusion length value from the EBIC measurements are well developed [1,3] but under their applications for semiconductors with submicron diffusion length some problems arises. In particular, the method of measurements should be chosen very carefully.

In the present paper the submicron diffusion length measurements are discussed. As an example, the results of diffusion length measurements in GaN are presented. It is shown that fitting the collection efficiency dependence on beam energy is the most reliable method for this purpose. The distribution of electron-hole pair generation necessary for such approach is calculated by the Monte-Carlo method and verified experimentally.

2. EBIC measurement of diffusion length

Typical semiconductor material, the diffusion length in which usually does not exceed $1\,\mu$m, is GaN. It is widely used for light emitting diodes, lasers and photodetectors. The diffusion length is very important parameter for this material and its measurement attracts an attention of many researches. The results of L measurements in this material rather well illustrate some problems arising under such measurements, when L is in the submicron range. In the overwhelming majority of diffusion length measurements in GaN the so-called planar geometry was used [4–7]. In this method a decay of collected current I_c is measured as a function of distance x from the edge of Schottky barrier perpendicular to the beam (Fig. 1). The simple asymptotic expression describing this decay as $I_c \propto \exp(-x/L)\cdot x^{-n}$, where $n = 1/2$ for the small surface recombination velocity $(S \to 0)$ and $n = 3/2$ for $S \to \infty$, were proposed [8–11] that made this technique very popular especially when the generation function is unknown. However, usually it was not taken into account that this expression was obtained under assumptions that $L \gg W$, $x \gg W$, $x \gg L$ and $x \gg R$ [9], where W is the depletion region width and R is the electron range. Taking into account that for common GaN structures $W \approx 100$ nm and $L \approx 100$ nm, while R is varied from 150 nm to about $5\,\mu$m for the beam energy E_b range from 5 to 35 keV, it is not evident that the above asymptotic expression could be applied to the data obtained on GaN. Moreover, as shown in [8], for the applicability of above-mentioned equation the repeated measurements at different E_b and currents should give the same diffusion length values. To check this measurements of I_c decay on GaN epilayers at different E_b have been carried out and the results obtained are presented in Fig. 2. It is seen that the decay depends essentially on E_b, i. e. the applicability test is not fulfilled and a question arises about the reliability of such measurements.

Other well-known method to extract the diffusion length from the EBIC data for the junction perpendicular to e-beam is based on the measurements of collection ef-

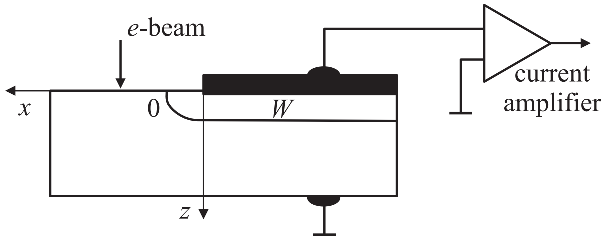

Figure 1. Electron beam — sample configuration of planar geometry measurements.

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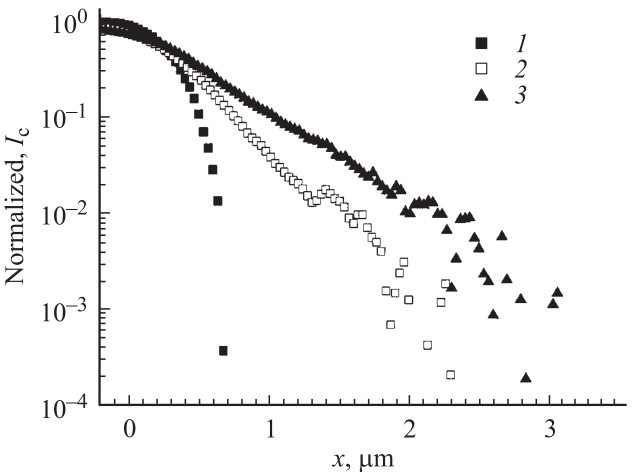

Figure 2. I_c decay measured in GaN with $L \approx 100\,\text{nm}$ at $E_b = 5$ (*1*), 15 (*2*) and 25 keV (*3*).

ficiency dependence on E_b [12,13]. The collection efficiency β is usually determined as $\beta = \frac{I_c E_i}{I_b E_b \eta}$, where I_b is the beam current, η is the beam energy absorption coefficient and E_i is the average energy necessary for electron–hole pair creation. As shown in [14,15] this method for GaN films gives the diffusions length values, which well correlate with the defect structure and the lateral resolution obtained in the EBIC mode. But for its application the depth–dose dependence describing the depth dependence of electron–hole generation rate should be known. The precision of depth–dose dependence description is especially important for materials with submicron L because diffusion spreading of excess carrier distribution in such materials is small.

Usually for a simulation of $\beta(E_b)$ dependences the diffusion equation was solved under assumption that inside the depletion region the collection probability is equal to 1. In the structures with a small L the collection probability could not be assumed to be equal to 1 inside the depletion region therefore in the present work the drift-diffusion equation was solved numerically for the simulation of $\beta(E_b)$ dependences.

The depth–dose dependence for GaN was calculated by the Monte-Carlo method. In the model used the scattering cross-sections were considered separately, and computational step was chosen to be equal to the (random) free path, in contradiction to the continuous slowing down approximation, in which the energy losses evaluation was based on the continuous nature of losses usually described by the Bethe formula. The elastic cross-section was described under simulations using the Mott formula. Ionization of inner-shell atomic electrons was taken into consideration using the semi-empirical Gryzinsky formula [16]. This formula is not accurate enough for the electrons with low binding energy, therefore, for the electrons from outer-shells the Meller expression [17] was used. Plasmon generation and decay are also taken into account using the formalism developed in [18]. It is shown that the calculated depth–dose dependence can be approximated as

$$h(z) = \frac{3.207}{R_{\text{Beth}}} \exp\left[-A\left(\frac{z}{R_{\text{Beth}}} - 0.11\right)^2\right],$$

where $R_{\text{Beth}}\,(\mu\text{m}) = 0.0132 \cdot E_b\,(\text{keV})^{1.75}$,

$$A = \begin{cases} 42.8, & z < 0.11\,R_{\text{Beth}} \\ 16.5, & z \geq 0.11\,R_{\text{Beth}} \end{cases}.$$

This distribution slightly differs from those calculated using other available Monte-Carlo programs. Although the difference is not large it could lead to a noticeable difference in diffusion length obtained. In principal, the generation function approximation could be verified by fitting the experimental $\beta(E_b)$ dependences. But in this case a number of fitting parameters increases that leads to a decrease of fitting precision. To improve this precision in the present work simultaneous fitting of a few collection efficiency dependences on E_b obtained at different bias was carried out. In this case the only fitting parameter, which is changed with bias is the depletion region width, which was obtained independently from the $C{-}V$ measurements.

The $\beta(E_b)$ dependences were measured at different bias on the Schottky barrier made on GaN layer with $L = 250\,\mu\text{m}$, to which a larger bias could be applied without essential increase in dark current. The results obtained are presented in Fig. 3. It is seen that the measured $\beta(E_b)$ dependences for three values of applied bias could be well fitted by calculated ones, when the obtained depth–dose dependence is used. The L value obtained from fitting also well correlate with the lateral resolution obtained on this structure. Thus, it was verified that the obtained depth–dose dependence can be used for the simulation

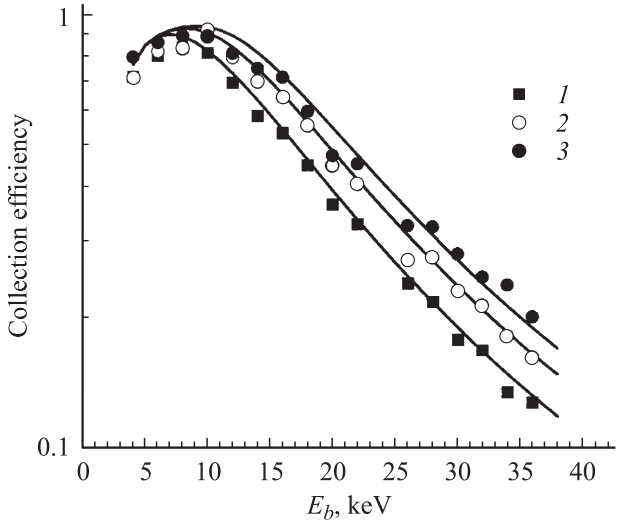

Figure 3. Collection efficiency dependence on E_b measured at applied bias 0 (*1*), 1 (*2*) and 2 V (*3*). Simulated curves are shown by solid lines, $L = 250\,\text{nm}$.

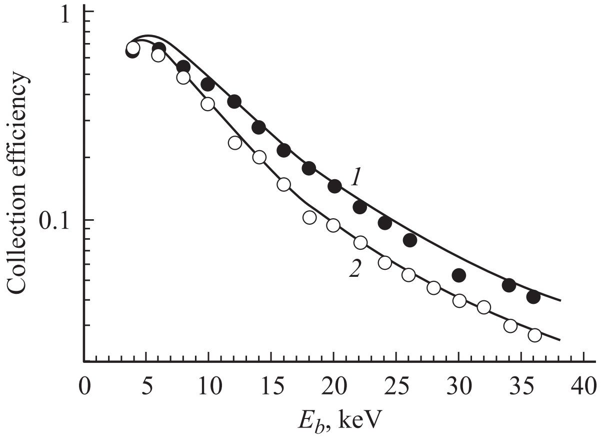

Figure 4. Collection efficiency dependence on E_b measured on two Schottky diodes on the same sample as that presented in Fig. 2. Simulated curves are shown by solid lines, $L = 100$ and 60 nm for dependences *1* and *2*, respectively.

of $\beta(E_b)$ dependences in GaN. It should be noted that fitting the $\beta(E_b)$ on structures with different L allows also to obtain a value of η/E_i as of about $8 \cdot 10^{-2}$, which is also important for the for quantitative description of $\beta(E_b)$ for different GaN based structures.

The results of measurements on the same structure, which was studied in the planar geometry (Fig. 2), were presented in Fig. 4 together with calculated curves. The experimental dependences were obtained on two different Schottky diodes to illustrate the diffusion length distribution over the sample. Fitting allows to estimate the diffusion length values on these diodes as 60 and 100 nm, i. e. smaller than that on the structure, which was used for the measurements with different applied bias. The obtained scattering in L values measured in different places of the same structure is typical for the structures studied. It should be noted that the close value was obtained by fitting the curve for 5 keV from Fig. 2, but in this case the scattering of resilts was larger even for the same diode.

3. Conclusion

Thus, it is shown that the applicability relations for the planar geometry widely used for diffusion length measurements are not fulfilled for the GaN structures with a small diffusion length. The measurements of collection efficiency dependence on beam energy give more reliable diffusion length values for such structures. The depth–dose dependence for GaN has been calculated and its analytical approximation is presented. The expression obtained was verified experimentally.

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