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What is the real value of diffusion length in GaN?

E.B. Yakimov *

Institute of Microelectronics Technology RAS, IPTM, 142432 Chernogolovka, Russia
National University of Science and Technology MISiS, Moscow, Russia

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ABSTRACT

The applicability of scanning electron microscopy methods for excess carrier diffusion length measurements in GaN is discussed. The discussion is based on author's experiments and on the available literature data. It is shown that for semiconductors with submicron diffusion length special attention should be paid to the choice of measuring method and experimental conditions. Some reasons for diffusion length overestimation and underestimation are analyzed. It is shown that a measurement of collected current dependence on electron beam energy is the most suitable method for submicron diffusion length evaluations because it is much easier to meet conditions for a proper application of this method than for other widely used methods. The analysis of data previously reported in literature and author's results have shown that the diffusion length values in the range from 70 to 400 nm are the most reliable for state-of-the-art n-GaN epilayers.

1. Introduction

Gallium nitride is an attractive wide band gap semiconductor material for ultraviolet/visible optoelectronics, as well as high-power and high-temperature electronics [1]. A key parameter to design and optimize optoelectronic devices is the excess carrier diffusion length, which has been measured by various techniques, including the cathodoluminescence (CL) and electron beam induced current (EBIC) methods. In addition, the diffusion length is widely used for the characterization of material quality therefore this parameter can be used to compare the quality of epilayers grown by different methods and by different producers. Therefore, the reliability of diffusion length measurements is of great practical importance. Diffusion length values in n-GaN have been reported to be in the range from 20 nm to a few microns. Such a wide range of diffusion length values is partly determined by variation in dopant concentration and defect density, although it seems that the method used also affects the obtained diffusion length values. Thus, the EBIC measurements in the so called planar-collector geometry [2–7] and the CL study of dislocation contrast decay [8–11] have been mostly used to obtain the diffusion length in GaN and as a rule values larger than 250 nm were obtained by the first method while values lower than 100 nm were obtained by second one. A correlation between the defect density and the diffusion length was observed in some papers [3,12,13], while the diffusion length values measured by different techniques differ significantly even for the materials with the close defect densities and dopant concentration. Moreover, a few times difference in diffusion length values obtained by different methods in one sample was demonstrated [7,14]. It should be also stressed that in the most cases the diffusion length values in GaN are much lower than those in traditional semiconductors, such as Si or GaAs, therefore the applicability of standard techniques for diffusion length measurements in GaN and other materials with submicron diffusion length is not so obvious. For these reasons a question arises about the reliability of diffusion length measurements in GaN by different methods.

In the present paper diffusion length measurements in GaN by the EBIC and CL methods are discussed. The discussion is based on experiments carried out in the author's group and on the available literature data. Possible reasons for the diffusion length underestimation or overestimation are analyzed. It is shown that in the state-of-the-art n-GaN the diffusion length hardly exceeds 500 nm.

2. EBIC measurements of diffusion length

The diffusion length is usually determined as $L = (D\tau)^{0.5}$, where D is the ambipolar diffusivity [15,16], which at a low excitation level is equal to the minority carrier diffusivity, and τ is the excess carrier lifetime. It should be taken into account that the hole mobility in GaN is 4–10 times lower than the electron mobility [1] therefore the same relation should be expected for diffusivities.

* Address: Institute of Microelectronics Technology RAS, IPTM, 142432 Chernogolovka, Russia.

E-mail address: yakimov@iptm.ru

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For this reason the diffusion length in p-GaN can be 2–3 times larger than that in n-GaN, if the same lifetime values in both types of materials are assumed. Below the diffusion length measurements in n-GaN will be considered because the most measurements were carried out on such material.

Among the many techniques available for the diffusion length measurements, EBIC has been ranked as one of the most convenient and reliable methods. It is based on the electron-hole pair generation inside a sample by an incident focused electron beam and subsequently their diffusion to a collector (a Schottky barrier or p–n junction). As shown in [15,16], the excess carrier transport in the quasi-neutral region can be described by the ambipolar diffusion. Depending on the recombination rate, a certain proportion of the excess carriers will reach the depletion region of the collector. In this region they are separated by the electric field and this produces an induced current in the external circuit. A few approaches have been proposed for diffusion length measurements by the EBIC method [17,18] and all of them are based on the measurement of collected current dependence on the distance of excess carrier generation point to the depletion region edge. Usually this distance can be varied by moving the e-beam away from the depletion region or by changing the electron penetration depth by changing the primary electron energy E_b.

Three main approaches are used to extract the diffusion length value L from the EBIC measurements. The first one is based on measurements of collected current I_c decay with a distance x from the depletion region edge of the Schottky barrier or p–n junction parallel to the beam (so called normal-collector geometry) [19–21]. When the surface recombination can be neglected, for $x > R$, where R is the electron range and is usually considered as the characteristic size of generation volume, the collected current in this geometry is simply proportional to $\exp(-x/L)$. Of course, the need for a sample cross-section preparation is an obvious disadvantage of this approach. If the surface recombination velocity s cannot be neglected, the expression describing the $I_c(x)$ dependence for arbitrary L and s values is more complex [19,21]. It should be noted that the surface recombination effect on the $I_c(x)$ dependence is determined by the relation $s{\cdot}\tau/L$ and for GaN with a small τ value the surface recombination effect often can be neglected. The more important factor for semiconductors with a small diffusion length such as GaN is the finite size of generation volume because the most of expressions describing $I_c(x)$ dependence were obtained under the point-source approximation. From a common point of view that means that they can be applied at $x \gg R$ only. But for $L < R$ this leads to very small collected current values. The effect of extended generation was analyzed in [22,23], where it was shown that this effect can be neglected for $x > R$ but it can be essential at smaller distances. Taking into account the fact that for e-beam with E_b = 10 keV, R is about 450 nm in GaN and it increases with E_b as $E_b^{1.75}$, the size of extended excess carrier source can significantly affect the submicron diffusion length measurement precision. Therefore for the reliable measurements using this approach the beam energy should be chosen very carefully.

For diffusion length measurements in semiconductor films and planar structures the measurement configuration known as the planar-collector geometry [24–27] is very popular. This technique gained popularity mainly because in the case of planar structures it does not need special sample preparation. In this method the collected current I_c decay is measured on the collector-free surface as a function of distance x from the edge of Schottky barrier or p–n junction perpendicular to the beam. The analytical solution for such geometry describing the collected current $I_c(x)$ decay for the structures with negligible depletion region width W was obtained in [28]. It should be noted that the analytical solution obtained in [28] can be easily extended for a generation volume of finite size. However, much simpler expressions are usually used for fitting the experimental dependences in this geometry because, as shown in [24,25,27], the collected current decay under the point-source approximation can be described by the asymptotic expression

$$I_c(x) = \exp(-x/L) \times x^{-n}, \qquad (1)$$

with $n = 1/2$ for small surface recombination velocity ($s \to 0$) and $n = 3/2$ for $s \to \infty$. The expression (1) was obtained under the assumptions that $L \gg W$, $x \gg W$, $x \gg L$ and $x \gg R$ [29,30]. These restrictions, especially the last one, can be rather critical in the case of GaN. Nevertheless, usually it was not taken into account and this could lead, as shown below, to large errors in diffusion length values.

The most suited approach for submicron diffusion length measurements is based on the measurement of collected current I_c dependence on E_b, when the e-beam generates the excess carriers under the collector junction located perpendicular to the beam [31,32]. The main advantage of this method is the well-defined boundary condition $\Delta p = 0$ on the depletion region edge, where Δp is the excess carrier concentration. Therefore the surface recombination does not affect the collected current and for the Schottky barrier the metal thickness t_m, W and L values should be used as variable parameters for collected current fitting. If t_m and W values are known from complementary measurements the only variable parameter is L. However, no simple asymptotic expressions were proposed to describe the $I_c(E_b)$ dependence in this geometry, therefore the diffusion length in this method can be obtained only by fitting the experimental dependence with calculated one. For a sample with thickness much larger than L and a Schottky barrier as the collector the collected current in this geometry can be calculated as [18,33]

$$I_c = e\beta\left\{\int_{t_m}^{W} h(z)dz + \int_{W}^{\infty} h(z)\exp[-(z-W)/L]dz\right\}, \qquad (2)$$

where z is the depth (the distance from the irradiated surface), $h(z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x,y,z)dxdy$ is the normalized depth-dose dependence describing the depth dependence of the electron–hole generation rate and $g(x,y,z)$ is the normalized function describing three-dimensional electron–hole generation rate. The coefficient $\beta = \frac{I_b E_b \eta}{e E_i}$ is the total number of electron–hole pairs created by the electron beam, I_b is the beam current, η is the fraction of beam energy absorbed inside the sample ($\eta = 1 - \chi E_{av}/E_b$, where χ is the backscattered electron yield and E_{av} is the average energy of backscattered electrons) and E_i is the average energy necessary for electron–hole pair creation. As seen from (2), the calculated current significantly depends on the $h(z)$ function therefore its knowledge is very important. As shown in [34], for GaN $h(z)$ calculated by the Monte-Carlo method can be approximated as

$$h(z) = \frac{3.207}{R_{Beth}}\exp\left[-A\left(\frac{z}{R_{Beth}} - 0.11\right)^2\right], \qquad (3)$$

where $R_{Beth}(\mu m) = 0.0132{\cdot}E_b(\mathrm{keV})^{1.75}$ is the electron Bethe range, i.e. the mean path length of electron trajectories and $A = \begin{cases} 42.8, & z < 0.11 \cdot R_{Beth} \\ 16.5, & z \geqslant 0.11 \cdot R_{Beth} \end{cases}$. The η/E_i value necessary for collected current calculations for GaN is $8{\cdot}10^{-2}\ \mathrm{eV}^{-1}$. This value have been obtained by fitting the numerous experimental $I_c(E_b)$ dependences [34].

Normalized $I_c(E_b)$ dependences calculated for n-GaN with the 50 nm thick Ni Schottky barrier, the dopant concentration N_d of $10^{17}\ \mathrm{cm}^{-3}$ and the diffusion length varied in the range from 50 nm to 20 μm are presented in Fig. 1. It is seen that for $L > 20$ μm this technique is practically insensitive to L. However, it suits submicron diffusion length measurements very well.