EBIC investigation of InGaN/GaN multiple quantum well structures irradiated with low energy electrons

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Abstract. Light emitting structures with InGaN/GaN multiple quantum wells have been studied in the Electron Beam Induced Current (EBIC) mode of a scanning electron microscope (SEM). Special attention is paid to the channels of enhanced carrier transport across the active region demonstrating bright EBIC contrast. Defects with the smallest bright contrast are associated with threading dislocations while the large defects present in lower density could be associated with dislocation bunches. Low energy (10 keV) electron beam irradiation in the SEM was found to suppress the bright EBIC contrast of these defects. A comparison with the cathodoluminescence spectra changes due to similar exposure allows us to assume that recombination enhanced diffusion is responsible for the effects observed.

1. Introduction
Despite intensive industry development of blue light emitting diodes (LED) based on the Multiple Quantum Well (MQW) InGaN/GaN system, aimed at the production of effective solid-state lighting, some fundamental properties of this system are still not completely understood. One such problem is the effect of extended defects on LED parameters. In spite of very high dislocation density ($10^8-10^{10}$ cm$^{-2}$) the quantum efficiency of LEDs based on GaN is rather high. It was believed that the high quantum efficiency was associated with the carrier localization inside the InGaN quantum wells. It was shown that dislocations could play a significant role in such localization [1]. Extended defects in semiconductor structures usually produce dark contrast in the Electron Beam Induced Current (EBIC) mode due to the enhancement of excess carrier recombination. However, in the MQW InGaN/GaN structures two types of defects demonstrating bright EBIC contrast were observed in [2-5]. It was shown that bright EBIC contrast of 1-2% could be associated with threading dislocations. The nature of other defects with a density of about $10^5$ cm$^{-2}$ demonstrating bright contrast up to 50% was not clarified up to now. As shown in [4,5], these large defects enhance carrier transport across the active layer that determines the bright EBIC contrast formation. A further problem is associated with the effect of extended defects on LED degradation. A study of low energy electron beam irradiation (LEEBI) effect on the EBIC signal could provide the useful information concerning this problem and could also help to clarify the pronounced LEEBI effect on the cathodoluminescence in the InGaN/GaN MQW structures [6,7].

In the present paper the LEEBI effect on the electrical properties of defects with bright EBIC contrast in the MQW InGaN/GaN LED structures has been studied in the EBIC mode. The profile
width of EBIC contrast was studied for two types of threading defects with bright contrast. The kinetics of collected current changes both near the defects and far from them due to e-beam exposure have been investigated.

2. Experimental

The LED structures were grown by metal-organic chemical vapor deposition on (0001) sapphire substrates. They consist of a 3 µm thick n-GaN lower layer doped with Si (N_d ~ 3·10^{18} cm^{-3}), a buffer superlattice InGaN/GaN with low In content (<10%), a MQW InGaN/GaN layer with three and five periods of 3 nm InGaN (In 20%) and 12 nm GaN layers and 0.1 µm thick p-GaN cap layer with Mg concentration of about 10^{20} cm^{-3}.

For the EBIC measurements mesa structures with a diameter of 0.45 mm were etched by Ar ion sputtering and metal contacts with a diameter of 0.35 mm were evaporated in the middle of them. The EBIC measurements were carried out on uncovered parts of the mesa structures using a JEOL JSM 840A scanning electron microscope in the normal geometry, with e-beam perpendicular to the p-n junction plane. Irradiation by the focused e-beam was carried out at room temperature in the same microscope at beam energy of 10 keV and beam current smaller than 10^{-3} A.

As usual the collection efficiency \( \beta \) was obtained from the current collected in the EBIC mode \( I_c \), as

\[
\beta = \frac{I_c E_i}{I_b E_b \eta},
\]

where \( E_i \) is the average energy necessary for the electron-hole pair creation, \( I_b \) and \( E_b \) are the beam current and energy respectively, and \( \eta \) is the average beam energy absorption coefficient. For GaN the \( \eta / E_i \) ratio was found to be close to \( 8 \times 10^{-2} \) [8]. The following expression was used to simulate the \( \beta(E_b) \) dependence [9]

\[
\beta = \int_0^\infty \psi(z) b(z) dz,
\]

where \( \psi(z) \) is the collection probability (the probability for a minority carrier created at a depth \( z \) to be collected in the EBIC mode) and \( b(z) \) is the depth-dose dependence, which was assumed to be the same as for GaN [8]. For the LED structures studied \( \psi(z) \) was calculated as \( \psi(z) = \psi_1(z, W, z_0) \cdot \psi_{DR} \), where \( \psi_1(z, W, z_0) \) is the probability for carriers to reach the depletion region, (obtained by a numerical solution of the diffusion equation for p- and n-regions), \( W \) is the depletion region width, \( z_0 \) is the p-n junction depth and \( \psi_{DR} \) is the probability for excess carriers to permeate through the depletion region, which was assumed to be independent of \( z \). Usually this probability is close to 1 and the excess carrier recombination inside the depletion region could be neglected. It needs to be taken into account only for low-doped materials or for structures with very high recombination rates (very small diffusion lengths). However, in the MQW structures the excess carriers are captured by quantum wells inside the depletion region and could be collected only if they overcome the barriers between the wells by the thermal activation or by tunneling. As shown in [2,5] in this case the measured \( \beta(E_b) \) dependence could be fitted by multiplying \( \psi_1(z, W, z_0) \) by a coefficient \( \psi_{DR} \), which depends on the position of quantum wells inside the depletion region and on the dopant concentration. This coefficient for the MQW structures could be rather small. For the structures in which at least a few quantum wells are located close to the depletion region edge, \( \psi_{DR} \) could be as low as 0.25, i.e. 75% of excess carriers reaching the depletion region recombine in the quantum wells. The \( \psi_{DR} \) value together with the diffusion length \( L \) in the lower n-GaN layer, the effective diffusion length in p-region and \( W \) could be estimated by fitting the \( \beta(E_b) \) dependence obtained from the experimental data. That could be done because different parts of the \( \beta(E_b) \) dependence are determined mainly by one of these parameters and \( \psi_{DR} \) determines the absolute collection efficient value only. Thus, at small \( E_b \) the \( \beta(E_b) \) dependence is mainly determined by the effective diffusion length in the p-region, while the position of the
maximum essentially depends on $W$. The $\beta(E_b)$ dependence decay at large $E_b$ is mainly determined by the diffusion length $L$ in the lower n-GaN layer.

3. Results and discussion

The dependences of collection efficiency $\beta$ on beam energy $E_b$ measured on the MQW structure with 3 quantum wells (curve 1) and on two structures with 5 quantum wells are presented in figure 1. The calculated dependences are shown in the same figure by solid lines. The collection efficiency decay at large $E_b$ could be fitted rather well with the excess carrier diffusion length $L$ in the n-GaN layer of 130 (1), 110 (2) and 180 nm (3). Thus, the difference in diffusion length values for the structures studied is not large and the observed difference in the collection efficiency for these three structures is mainly determined by the different recombination rate inside the depletion region characterized by the $\psi_{\text{DR}}$ value. For the structure with 3 quantum wells (curve 1) $\psi_{\text{DR}}$ value obtained from fitting is practically equal to 1, i.e. the $\beta(E_b)$ dependence is close to that calculated neglecting recombination inside the depletion region. But the collected efficiency measured in the LED structures with 5 quantum wells (curves 2 and 3) is significantly lower than that calculated under such an assumption ($\psi_{\text{DR}} = 0.5$ and 0.28, respectively). Thus for these structures recombination inside the depletion region is essential and should be taken into account.

![Figure 1](image1.png)

**Figure 1.** Measured (symbols) and simulated (lines) $\beta(E_b)$ dependence for the LED structures with three (1) and 5 quantum wells (2,3). $\psi_{\text{DR}} = 0.97$ for (1), 0.5 for (2) and 0.28 for (3).

![Figure 2](image2.png)

**Figure 2.** Images of region with a bright contrast defect in the secondary electron (left) and in the EBIC modes (right).

As shown in [4,5] by fitting the $\beta(E_b)$ dependence, near the defects with the large bright contrast the $\psi_{\text{DR}}$ value increased. Thus, these defects provide channels of enhanced excess carrier transport across the InGaN/GaN MQW active layer by suppressing the recombination inside the InGaN wells or by increasing the probability to overcome the barriers between the wells. But the microscopic nature of these defects is not clear up to now. They could be micropipes, dislocation bunches or V-defects [10, 11]. As could be seen in figure 2, where the EBIC image of bright defect and the image of the
same region in the secondary electron mode are presented, no pits or hillocks are revealed on the surface at the defect position. Thus, if the bright contrast is associated with V-defects or micropipes, it should be assumed that under the upper p-GaN layer growth the defects were filled and the surface was totally planerized, which seems unlikely.

The size of these defects could be estimated from the EBIC investigations. Indeed, the bright contrast is formed inside the active layer containing quantum wells, i.e. at a depth smaller than 200 nm. At such depth the lateral resolution in the EBIC mode for the structures with the small diffusion length is rather high, especially at large \(E_b\) [12]. This could be seen in figure 3 (curve 1), where the profile of the EBIC bright contrast normalized for its maximum value for an individual threading dislocation is presented. The contrast is calculated as \(C = I_{\text{def}}/I_0 - 1\), where \(I_{\text{def}}\) and \(I_0\) are the collected current values with e-beam located at the defect and far from it. In the same figure the normalized contrast profile for a large bright defect is shown by the curve 2. It is seen that while the Full Width at Half Maximum (FWHM) for the individual dislocation is about 70 nm, the FWHM for the large defect is 900 nm. The FWHM for the individual dislocation confirms that the generation region size in the active region is indeed small. Thus the larger FWHM for the large bright defect shows that the FWHM is determined by its size. The size of the large bright defect could be estimated as several hundred nm, which is significantly larger than the size of commonly observed V-defects. Thus, we believe that the defects with the large bright EBIC contrast could be associated with dislocation bunches, although we cannot totally exclude V-defects or micropipes as the origin for such contrast.

![Figure 3. Profiles of normalized bright EBIC contrast for a threading dislocation (1) and for a large bright defect (2). \(E_b = 35\) keV.](image)

To study the effect of low-energy e-beam exposure on electrical behaviour, a 19 \(\mu m^2\) area containing the defects with large bright EBIC contrast was irradiated with a beam current of about 10\(^{10}\) A. In EBIC mode (figures 4b-4c) the irradiation region can be seen as a rectangular region in the center of images surrounded by bright boundaries. In figure 4 two defects with bright contrast are located inside the irradiated region and one is outside it. The evolution of EBIC signal \(I_{\text{cir}}\) normalized on the signal from the non-irradiated region \(I_{\text{cir}}\) for two bright defects in the irradiated region and for the irradiated region far from them with exposure time is shown in figure 5. As can be seen in figures 4 and 5, the bright contrast monotonically decreases with irradiation time and at irradiation doses larger than 1.5 C/cm\(^2\) these defects could not be revealed in the EBIC image of the irradiated region. Thus, the difference between the EBIC signals from the defect region and far from it monotonically decreases under the LEEDI. This suggests that such treatment leads to healing of the defective regions. The EBIC signal from the irradiated region also changes due to irradiation. However, it increases for a small exposure time and then started to decrease. At doses larger than 1.3 C/cm\(^2\) it becomes smaller than that from the non-irradiated region. This small decrease could be explained qualitatively by the build-up of hydrocarbons on the surface after a long e-beam exposure, which is revealed in the secondary electron mode.
Our recent cathodoluminescence (CL) investigations have shown [7] that irradiation of the same structures by low energy electrons leads to the formation of a new InGaN related emission band blue shifted in comparison with the initial one. The total InGaN related luminescence intensity increases at the first stage of irradiation and then starts to decrease. Such behaviour of InGaN quantum well related luminescence was very similar to that shown for the EBIC signal in figure 5 for the irradiated region. In both cases the maximum was observed at similar e-beam exposure doses. That allows us to assume that the LEEBI effect on the EBIC signal and on the InGaN related emission was determined by similar mechanisms.

The analyses carried out in [7] showed that the LEEBI effect on the CL could be explained under the assumption that e-beam irradiation led to a local change of In content due to In or Ga recombination enhanced diffusion. As a result, some new quantum dot like regions could be formed due to the e-beam exposure and the new emission bands arise in addition to existing ones. The inhomogeneous potential distribution formed under this process could lead both to a suppression of excess carrier recombination inside the quantum wells and to a change of tunneling probability, that in turn could increase the EBIC signal. It is seen in figure 4 that the boundary of the irradiated region gives the bright contrast in the EBIC mode. If indeed irradiation changes the In content, the electric field arising at the boundary between irradiated and non-irradiated regions could suppress the excess carrier recombination and produce the bright contrast. Besides, it is well known [13] that LEEBI
destroys Mg-H pairs in p-GaN. If such pairs are present in the structures studied, the released hydrogen could passivate the recombination centers and thus increasing the EBIC signal. The observed healing of defect regions could mean that the enhanced diffusion processes and/or their effect on the local well structure and composition near the bright contrast defects are more effective than in the defect-free region.

![Figure 5. Dependence of $I_{cirr}/I_{cnir}$ ratio on irradiation time for two bright defects shown in figure 4 (squares) and for the irradiated region (filled circles) (Image)](image)

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**References**

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