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EBIC characterization of light emitting structures based on GaN

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The EBIC investigations of light emitting structures based on InGaN/GaN MQW with different number of wells have been carried out. The pronounced dependence of collection efficiency on quantum well number is observed. A comparison with apparent carrier profiles calculated from the $C-V$ curves reveals the correlation between the collection efficiency and location of quantum well inside the depletion region. The defects producing bright EBIC contrast are revealed in the structure with 5 quantum wells. This contrast is associated with defects locally decreasing the excess carrier recombination inside quantum wells.

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1. Introduction

The increasing application of GaN-based structures in light emitting diodes, lasers and high power transistors generates the interest in the study of electrical and optical properties of extended defects in these materials [1]. Probably, the most important extended defects in these structures attracting essential attention are threading dislocations, the density of which in the recent GaN epitaxial layers varies typically in the range from 10^8 to $10^{10}\,\text{cm}^{-2}$. Nevertheless, high-performance light emitting diodes and lasers have been fabricated in the structures based on GaN in spite of such very high dislocation density, which in other III$-$V materials totally degrades the device performance. For this reason the properties of dislocations in GaN and GaN-based strucrures are particularly intriguing. Now it is well documented that screw threading dislocations in GaN act as effective nonradiative recombination centers [2–7], although it seems that other recombination defects determine the minority carrier diffusion length [6]. To explain the small dislocation effect on the efficiency of light emitting structures (LES) it is usually assumed that the dislocation recombination activity essentially decreases due to carrier localization. However, the detail mechanisms of such decreasing are not totally clear. Therefore, studying the characteristics of individual threading dislocations in LES based on GaN is very important for the reliable prediction of their effect on the device performance, for understanding the mechanisms of suppressing their effect on radiative recombination efficiency in LES and for development of approaches to control the dislocation properties. As shown in [7,8], the Electron Beam Induced Current (EBIC) method is very suitable for the study of dislocation recombination properties in the semiconductors with the small diffusion length, such as GaN. Due to the extremely small diffusion length the EBIC lateral resolution in GaN can achieve a value smaller than 100 nm, that allows to study the recombination activity of individual dislocations even in the structures with a dislocation density exceeding $10^9\,\text{cm}^{-2}$. However, up to now practically all EBIC investigations were carried out on GaN layers and the behaviour of threading dislocations in the LES and their effect on the LES quantum efficiency and degradation did not practically understand yet.

In the present paper the behaviour of dislocations in LES with different number of quantum wells were studied in the EBIC mode, together with measurements of LES quantum efficiency and capacitance–voltage ($C-V$) curves.

2. Experimentals

The investigated LES were grown by the metal-organic chemical vapour deposition on c-plane (0001) sapphire substrates. The LES consisted of $3\,\mu$m thick n-GaN lower layer doped with Si ($N_d \approx 3 \cdot 10^{18}\,\text{cm}^{-3}$), buffer superlattice GaN/InGaN with low In content ($< 10\%$), MQW InGaN/GaN layer with $1-5$ periods of 3 nm InGaN (In 20%) and 12 nm GaN layers and $0.1\,\mu$m thick p-GaN cap layer with Mg concentration of about $10^{20}\,\text{cm}^{-3}$.

For the EBIC and $C-V$ investigations mesa structures with a diameter of 450 nm were prepared by Ar ion sputtering and $p-n$-junctions were used for the induced current collection. The $C-V$ measurements were done at room temperature using a PAR-410 capacitance meter at a frequency of 1 MHz. The EBIC measurements were carried out in the scanning electron microscope JSM-840A (Jeol). All EBIC measurements were done in the normal geometry with e-beam perpendicular to the $p-n$-junction plane. To extract the quantitative information about the structures under study the dependence of current collected in the EBIC mode I_c on electron beam energy E_b was compared with simulated ones. Measurements of $I_c(E_b)$ dependence were carried out with e-beam scanning the $70 \times 70\,\mu$m region that allowed to average the signal over this region. The measured I_c values were then normalized dividing it by a total number of excess carriers as $I_{cn} = \frac{I_c E_i}{I_b E_b \eta}$, where I_b is the beam current, η is the beam energy absorption coefficient and E_i is the average energy necessary

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for electron–hole pair creation. This value is called the collection efficiency and presents a relative number of excess carries created by *e*-beam, which is collected in the EBIC mode for the structure under study.

3. Results and discussion

Typical $I_{cn}(E_b)$ dependences measured on the structures with 3 (circles) and 5 quantum wells (squares) are presented in Fig. 1 together with simulated ones. The dependences measured on the structures with 1 and 2 quantum wells are very similar to that measured on the structure with 3 quantum wells. As follows from fitting the $I_{cn}(E_b)$ dependence, for the structures with a number of quantum wells smaller than 3 the MQWs practically do not affect the excess carrier collection. In such structures the dependence measured is determined by excess carrier (hole) diffusion in *n*-type GaN layers to the depletion region of $p-n$-junction and is similar to that observed on GaN layers with the Schottky barrier [8]. The diffusion length obtained by fitting this cirve was of about 130 nm. Contrary, in the structure with 5 wells the $I_{cn}(E_b)$ dependence can be fitted with practically the same diffusion length but only under an assumption that about 50% of excess carriers, which reach the depletion region, recombine inside it. Such process does not change qualitatively the $I_{cn}(E_b)$ dependence but is equivalent to multiplication it by some correction factor smaller than 1 (in our case of 0.5). The similar effect was also observed in [9], where it was found that for different LES this correction factor varied from 0.3 to 0.5. A value of this factor reflects the efficiency of carrier localization inside the quantum wells (the smaller is this factor the more effective is the localization). It should be noted that these results well correlate with the value of external quantum efficiency of LES. Indeed, the highest quantum efficiency of 16–18% measured without lens was obtained for LES with 5 wells, in which the collection efficiency was lower (localization is more effective), and only 5–7% was measured at the same current 5 mA for LES with 2–3 wells, in which the correction factor is close to 1.

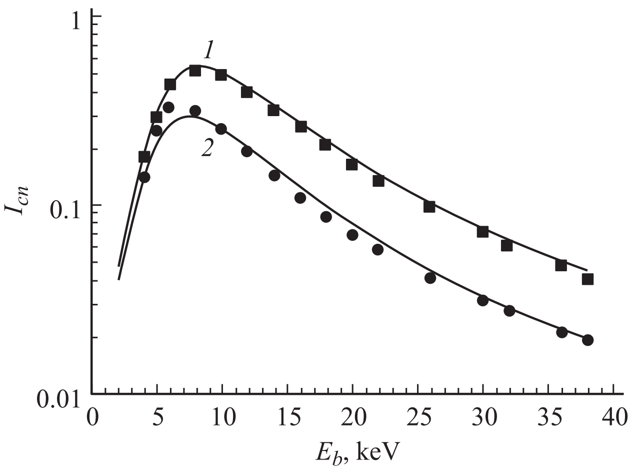

Figure 1. Collection efficiency dependence on E_b for LES with 1–3 (*1*) and 5 quantum wells (*2*). Calculated dependences are shown by solid lines.

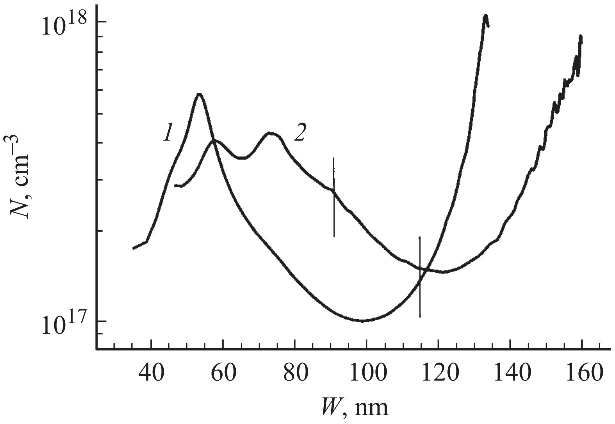

Figure 2. Apparent carrier concentration profiles calculated from the $C-V$ curves for the structures with 3 (*1*) and 5 quantum wells (*2*). The W values at $U = 0$ are shown by vertical lines.

To understand the reason for a difference between structures studied the $C-V$ measurements were carried out. Apparent carrier concentration profiles calculated from the $C-V$ curves for the structures with 3 and 5 quantum wells are presented in Fig. 2. The depletion region width W corresponding to bias $U = 0$ is shown by vertical lines on the both profiles. It is seen that in both structures at $U = 0$ (the EBIC measurement conditions) all wells are located inside the depletion region and effective filling of quantum wells with electrons can be observed at forward bias only. However, in the structure with 3 quantum wells they are located far from the depletion region boundary in the region with rather high electric field while in the structure with 5 quantum wells the deepest quantum well is located close to the depletion region boundary, i. e. in the region with low electric field. Thus, it seems that the difference between the collection efficiencies in the structures studied is mainly determined by the location of quantum wells inside the depletion region. If they are located deep inside the depletion region, where high electric field presents, this field suppresses the minority carrier recombination inside the wells, by enhancing tunneling through the barrier and due to empting the wells. In the structure with 5 quantum wells the deepest well is located in the region with rather low electric field and at zero bias it is partly filled with electrons. In this case the minority carrier capture and recombination inside this well is rather efficient that leads to a decrease of collection efficiency seen in Fig. 1 (curve *2*). It should be noted that such decrease could be even larger for the structures, in which the deepest well is outside the depletion region [9]. The difference in defect structure between the LES studied could also affect the tunneling probability but the investigations carried out up to now could not confirm or refuse such probable effect.

For revealing extended recombination defects the plan-view EBIC micrographs were analyzed. One of such micrographs is shown in Fig. 3, *a*, where the typical EBIC image obtained on the structures with the higher collected current (small quantum well number) is presented. The characteristic feature in these images is a presence of dark dots with a density of about $10^8-10^9\,\mathrm{cm}^{-2}$. This density is close to the threading dislocation density observed in GaN layers grown in the similar conditions [7,8]. As shown above, in the structures with a small number of quantum wells the wells do not practically affect the collected current therefore the black dots in the EBIC micrographs for these structures could be associated with threading dislocation effect on the excess carrier recombination in the lowest GaN layer. The width of dark dots in Fig. 3, *a* was larger than that observed in GaN epi-layers that well correlates with the deeper depletion region boundary location in the structures under study (about 200 nm at $U = 0$) as compared with about 100 nm depletion region width in GaN Schottky barriers. At a larger depth the generation region size increases that leads to widening the extended defect EBIC images. Thus, the wider contrast seems to confirm the assumption that the black dots revealed are associated with threading dislocations.

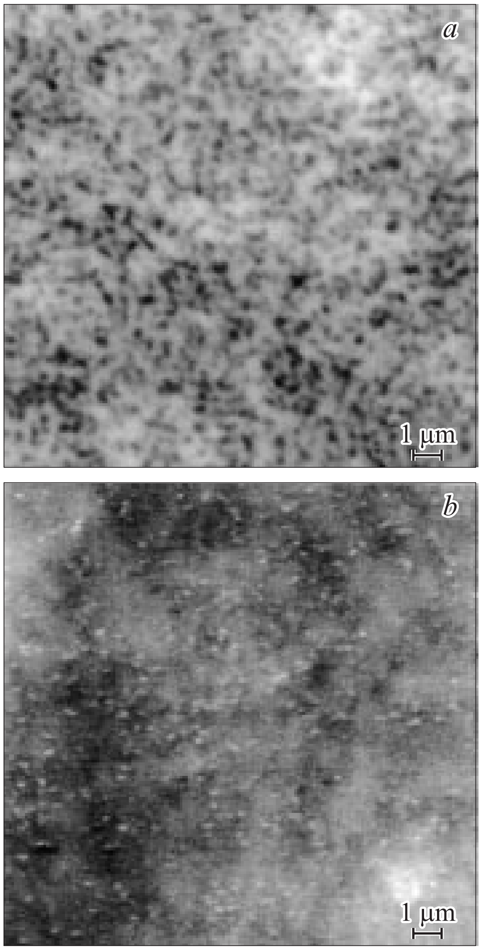

Figure 3. EBIC images of LES with 3 (*a*) and 5 quantum wells (*b*) obtained at $E_b = 35\,\mathrm{keV}$.

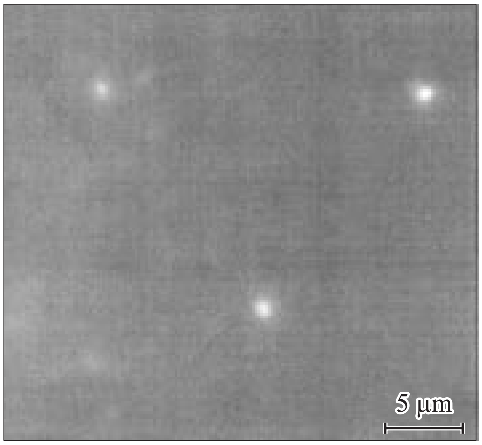

Figure 4. EBIC image of LES with5 quantum wells obtained at $E_b = 15\,\mathrm{keV}$. A few defects with a strong bright contrast could be seen.

Contrary, in the structure with 5 quantum wells bright dots with a density comparable with that of dark ones in Fig. 3, *a* are observed (Fig. 3, *b*). Besides, in this structure some large bright defects with a lower density (about $10^3\,\mathrm{cm}^{-2}$) were revealed (Fig. 4). These large defects can be seen at beam energies varied from 10 to 35 keV and the bright contrast associated with them could achieve 50%.

The width of small bright dots is smaller than that of dark ones that allows to associate them with defects located in the depletion region or close to it. The well-known mechanism for the bright contrast in the EBIC mode is associated with an enhancement of excess carrier collection near the charged extended defects outside the depletion region [10]. The observed dependence of bright contrast on E_b allows to exclude such mechanism and to assume that the bright contrast revealed in the present work is associated with the defects, which decrease the minority carrier capture and recombination inside the quantum wells. Such suppression could occur due to a change of barrier thickness and/or height near these defects, for example by their effect on barrier growth or by a formation of conductivity channels if these defects are charged. The small bright dots could be associated with threading dislocations while larger ones with dislocation bunches or with micropipes.

4. Conclusion

Thus, a correlation between the quantum well location and the collection efficiency dependence in the EBIC mode on beam energy for InGaN/GaN MQW LES is revealed. The bright EBIC contrast is revealed in LES, in which the quantum well effect on the collection current is observed. It is shown that such contrast could be associated with threading dislocations and some larger defects, probably, the dislocation bunches or micropipes, locally decreasing the excess carrier recombination inside the quantum wells.

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