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## Light Emission Properties of GaN-Based Laser Diode Structures

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Cathodoluminescence is applied for evaluation of in-depth and in-plane variations of light emission from two types of GaN-based laser diode structures. We evaluate in-depth properties of the laser diode emission and demonstrate that potential fluctuations still affect emission of laser diodes for e-beam currents above thresholds for a stimulated emission.

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### 1. Introduction

It is commonly accepted that potential fluctuations, resulting in strong localization effects in InGaN quantum wells (QWs), are responsible for efficient light emission from GaN-based light emitting diode (LED) structures ([1] and references therein). Localization restricts motion of free carriers and excitons in QWs, and, in the consequence, reduces the probability of their nonradiative recombination at dislocations. Unfortunately, these potential fluctuations are assumed to be

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screened in laser diode (LD) structures at high excitation densities. This fact was used to explain difficulties in achieving laser emission from InGaN QWs [1].

In our recent works we reported that a stimulated emission can be achieved under e-beam pumping in homo- and hetero-epitaxial structures of InGaN, GaN, and AlGaN [2, 3]. This possibility we utilize in the present work to evaluate in-plane instabilities of a stimulated emission and to relate them to details of microstructure of a given LD sample. Stimulated emission is observed only for the structures of a good structural quality and without top *p*-type doped layer. We will show that even in these cases the stimulated emission shows fairly large in-plane fluctuations of intensity, which directly correlate to details of microstructure of the sample.

## **2. Electron beam pumping of emission of homo-epitaxial LD GaN structures**

The important advantage of cathodoluminescence (CL) experiments under e-beam pumping is the possibility of evaluation of in-depth and in-plane variations of light emission [3–6]. In-depth properties of the CL can be studied by measuring emission spectra at different e-beam energies. In turn, in-plane changes of intensity of a given emission can be determined by scanning e-beam through the selected areas of the structure [3–6].

In the present study CL was excited by an incident e-beam normal to the surface of LD structures or with e-beam applied along the laser cavity of these structures. The CL was collected with a cylindrical mirror mounted over the sample. Accelerating voltage or/and e-beam current density were set at the optimal conditions for the detection of the CL emission from a given region of the structure. Then, we studied in-plane homogeneity of the CL emission, by scanning e-beam through selected areas. We also studied dependences of the CL emission on excitation density, by varying current density of the e-beam electrons.

First studies were performed for the homo-epitaxial LD structure with 300  $\mu\text{m}$  cavity formed by cleaving. The active region of this LD structure consisted of five  $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}/\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$  QWs embedded between two 0.1  $\mu\text{m}$  thick GaN wave guiding layers and two cladding layers. The lower cladding layer consisted of GaN/ $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$  superlattice (2.5 nm/2.5 nm) with 120 repetitions. The upper cladding layer was in the form of 0.36  $\mu\text{m}$  thick  $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}$ , covered with a thin GaN cap layer.

At 6 to 10 kV (Fig. 1a) accelerating voltage only the upper part of the device is excited, i.e., the CL comes from the upper GaN cap layer, underlying AlGaN upper cladding layer and from GaN wave guiding layer. Two surprisingly strong defect-related emissions (see Ref. [6] for their explanation) are also observed — the yellow and the blue CL emissions, at these excitation conditions. The origin of all these CL emissions we determined from their characteristic responses in the

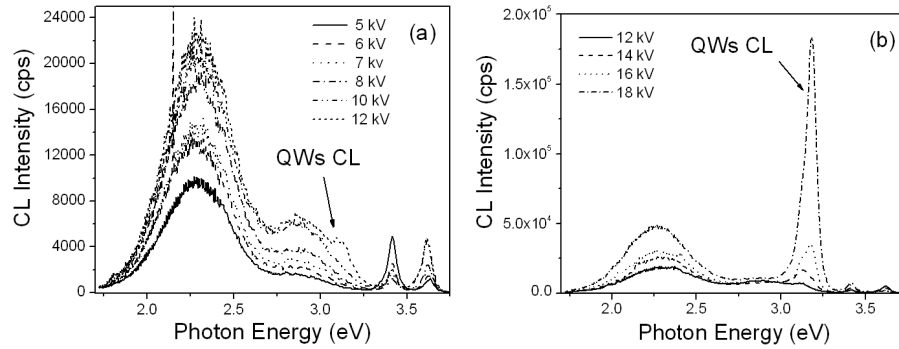


Fig. 1. (a, b) Depth profiling CL spectra of homo-epitaxial LD structure with  $300\ \mu\text{m}$  laser cavity taken at  $2000\times$  magnification at different accelerating voltages at the constant current density ( $17.6\ \text{nA}$ ).

depth-profiling CL measurement. The relevant experimental results are shown in Fig. 1a, b.

Emission from the InGaN QWs (active region of the LD structure) is not seen, when only the upper layers of the device are excited, indicating that energy transfer, photon recycling or carrier diffusion from the upper layers to the QWs region of the device are inefficient. The InGaN emission becomes dominant at high accelerating voltages (see Fig. 1b). At  $30\ \text{kV}$  voltage the QW emission is so strong that other emissions are not seen at used detection conditions.

Dependence of the QWs emission on e-beam current density was studied. A clear threshold dependence of this emission is observed for current about  $10\ \text{nA}$  (Fig. 2). For larger currents the CL is dominated by a stimulated emission. We

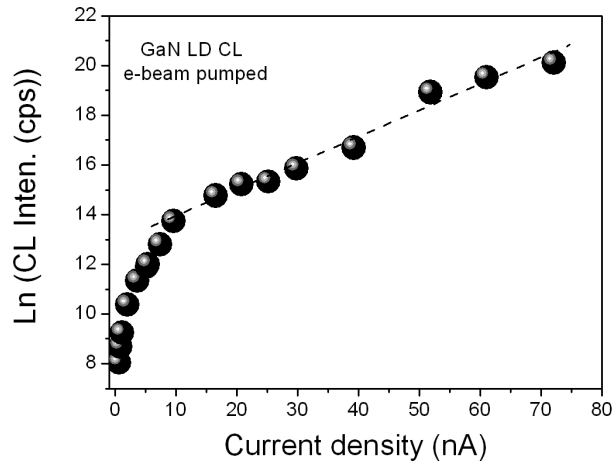


Fig. 2. Current density dependence of the InGaN QW emission. The CL data indicate that conditions for a stimulated emission are achieved for e-beam currents larger than  $10\ \text{nA}$ .

measured in-plane homogeneity of the stimulated emission by scanning e-beam through different areas of the structure at  $2000\times$  magnification. In-plane changes of the CL intensity are easily resolved. All details of microstructure of the sample are seen, including growth steps (Fig. 3a, b) and totally dark areas (Fig. 3a) from regions of dislocations. The large radius of these dark areas (only a few of them were found in homo-epitaxial structures) indicates that the diffusion length of carriers is now very much enhanced as compared to that estimated by us from CL studies performed at low excitation densities [7] (several  $\mu\text{m}$  instead of hundreds of nm).

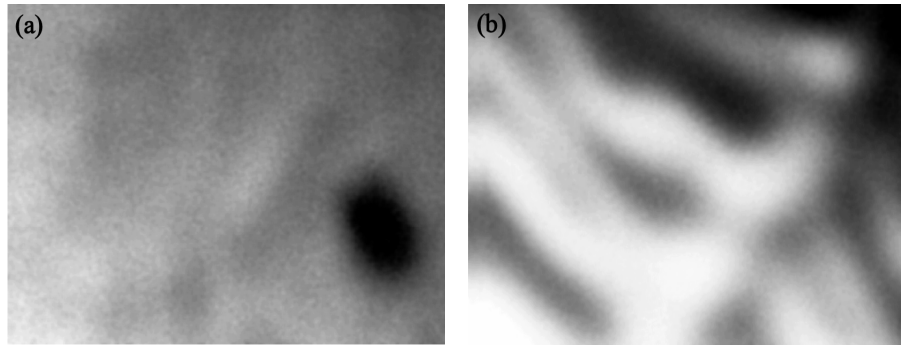


Fig. 3. (a, b): In-plane fluctuations of the QW emission observed for excitation density above the threshold value for the stimulated emission. CL maps were taken from two regions of the LD.

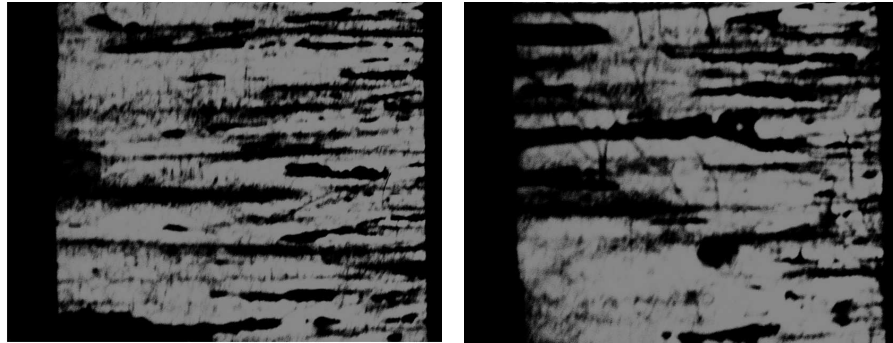


Fig. 4. CL maps taken from two areas of the LD structure grown on a free-standing HVPE GaN substrate. CL was measured with e-beam excitation along the laser cavity at  $480\times$  magnification and 10 kV with detection set at 368 nm emission.

Spot mode CL measurements confirmed large in-plane variations of the CL intensity, but also showed noticeable shifts of the spectral position of the QWs CL.

These shifts may originate from indium fluctuations, from various strain conditions, from changes of the QWs width, etc.

In Fig. 4 we show maps of light emission intensity observed for the e-beam excitation along the LD structure. We show here the CL data collected for the LD structure grown on a freestanding HVPE GaN substrate. This LD, of a similar structure as the one discussed above, had increased dislocations density as compared to the one grown on bulk GaN substrate. These dislocations are observed in Fig. 4 as dark lines in band edge CL maps. Scanning CL images shown in Fig. 4 indicate that a large number of dislocations start from the upper *p*-type doped layer of the structure. These data were taken for the structure with an upper *p*-type doped layer. As already mentioned, for this LD structure we could not excite stimulated emission by incident e-beam normal to the surface of the sample. Thus, the data shown in Fig. 4 were taken for e-beam current below the threshold for the stimulated emission.

### 3. Conclusions

Summarizing, our CL investigations indicate that potential fluctuations are still present in LD structures, at high excitation densities. The CL measurements indicate also that dislocations are formed in LD structures not only at interface to the substrate, but also many of them is formed in upper parts of the device, starting from a *p*-type doped layer. Their presence considerably reduces light emission from LD devices.

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