Cathodoluminescence Profiling of InGaN-Based Quantum Well Structures and Laser Diodes — In-Plane Instabilities of Light Emission

M. Godlewski[a,b], V.Yu. Ivanov[a], E.M. Goldys[c],

M. Phillips[d], T. Böttcher[e], S. Figge[e], D. Hommel[e],

R. Czernecki[f], P. Prystawko[f], M. Leszczynski[f],

P. Perlin[f], I. Grzegory[f] and S. Porowski[f]

[a]Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warsaw, Poland
[b]College of Science, Cardinal S. Wyszyński University, Warsaw, Poland
[c]Division of Information and Communication Sciences
Macquarie University, Sydney, Australia
[d]Microstructural Analysis Unit, UTS, Sydney, Australia
[e]Institute of Solid State Physics, University of Bremen, 28334 Bremen, Germany
[f]High Pressure Res. Center (Unipress), Polish Academy of Sciences
Warsaw, Poland

Instabilities of light emission and also of stimulated emission in series of GaN epilayers and InGaN quantum well structures, including laser diode structures, are studied. A stimulated emission is observed under electron beam pumping. This enabled us to study light emission properties from laser structures and their relation to microstructure details. We demonstrate large in-plane fluctuations of light emission and that these fluctuations are also present for excitation densities larger than the threshold densities for the stimulated emission.

1. Introduction

Basov et al. first demonstrated (for liquid xenon) the possibility of generating laser radiation by excitation with an electron beam [1]. Several groups reported then electron beam pumped laser action in gas and liquid media. The concept became practical with an introduction of low voltage field emission microtips and by using semiconductor-based heterostructures. For example, blue laser light emission from ZnCdSe/ZnSe heterostructures was demonstrated [2]. It was demonstrated that microgun pumped lasers avoid limitations of p-type doping of ZnSe [2]. Doping of the active layer of laser reduces the threshold pump current only in the case of short nonradiative lifetimes in the device [3]. Otherwise, we can use undoped structures.

Another advantageous property is that the laser action can often be achieved at record low threshold currents [4]. Threshold currents as low as 5 A/cm^2 (for ZnSe), 12 A/cm^2 (for ZnSe/ZnSSe superlattice) [5] and 3 A/cm^2 [6] were reported. Lowering of a threshold current helps to eliminate some of degradation processes accounted in semiconductor-based laser devices [7].

Laser action under electron beam pumping was achieved in very different media and structures: for example for advanced laser structures, such as VCSEL structures [8], but for single quantum well (QW) and double QW GRINSCH structures with 0.5–1 mm long microcavities [2], as well. Importantly, laser action was also reported in very simple structures, such as in samples covered with metal mirrors [9] or even from large area single crystals [10]. Laser modes were reported only in the former case [2]. In all cases the method turned out to be very useful also in studying degradation mechanisms in semiconductor based structures [11, 12].

In this paper we report observation of a stimulated emission in QW structures of GaN/InGaN. This observation allows us to evaluate in-plane instabilities of stimulated emission and to relate them to microstructure details of the samples studied.

2. Samples and experimental techniques

The samples have been grown by metalorganic vapor phase epitaxy (MOVPE) on sapphire (heterostructures) or bulk GaN substrate (homoepitaxial samples). Two series (each of four samples) of heteroepitaxial GaN epilayers were studied. These samples were grown on sapphire/GaN templates with dislocation density of 1×10^{10} cm^{-2} (g411 series) or 2×10^{9} cm^{-2} (g457 series). Each series consisted of template and of three epilayers with 1500 nm thickness. One of them was undoped, two other were n-type doped with Si to the level 10^{18} cm^{-3} and 10^{19} cm^{-3}.

Homoepitaxial samples have the highest structural quality achievable at present, with densities of dislocations typically below 10^4 cm^{-2}. Two series (511 and 534) of homoepitaxial QW structures were studied. Each of them contained

an active region consisting of 20 InGaN QWs with GaN barriers. Indium fraction was about 2% in 511 series and 2.8–3% in series 534. The structures had a different width of QW and barrier regions — 2.8 nm (QW)/5.3 nm (barrier) for 511 series and 4 nm (QW)/8 nm (barrier) in series 534. Growth temperature was 790°C for the 511 series and 785°C for the 534 series. Structures were grown on GaN bulk substrate covered with GaN buffer layer (1 μm thick in 534 series, 0.55 μm thick in 511 series). Samples varying in structural quality were selected to get better insight into origin of the observed emission instabilities.

Scanning electron microscopy (SEM) and cathodoluminescence (CL) measurements were performed at room temperature using a JEOL JSM-6300F scanning microscope with a field emission gun (for SEM) and JEOL 35C electron microscope, equipped with MonoCL2 setup of Oxford Instruments for CL studies.

3. Results and discussion

It was reported that photoluminescence of GaN and InGaN epilayers and QW structures is significantly enhanced upon n-type doping [13–15]. The effect was tentatively explained by screening of piezoelectric fields, improvement of morphology (smoother interfaces) or by saturation of deep dislocation-related centers, expected in heavily doped samples. The latter limits role of dislocations as centers of nonradiative recombination. To verify such possibility we performed CL studies of a series of GaN epilayers of a different dislocation density and doping level. CL intensity upon varying excitation density was measured. The results are shown in Fig. 1. To the relatively large current (10 nA) CL intensity increases nonlinearly, but relatively slowly. Such observation was in line with previous data and could suggest that in fact we compensate/saturate centers of nonradiative recombination.

A rapid jump in the CL intensity was observed for current above 9–10 nA (Fig. 1). This suggested that we reached threshold current to excite a stimulated emission, but the explanation was only tentative, since we observed the effect only
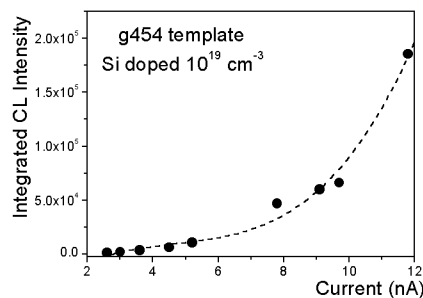

Fig. 1. Dependence of the CL intensity on excitation current in CL study of Si doped GaN epilayer grown by MOVPE on GaN/sapphire template with 2×10^9 cm^{-2} dislocations.

for heavily *n*-type doped epilayer grown on template with a lower (but still relatively high) dislocation density. To verify such possibility, and also to use it for studying CL instabilities, we employed CL for a series of homoepitaxial samples with a high structural quality. We used similar structures to the one for which we reported record low threshold power for optical pumping of a stimulated emission [16].

The results of CL studies of homoepitaxial samples are shown in Fig. 2. Three of five samples studied showed a threshold-like dependence on beam current density, which we explain by a stimulated emission from the films. The most intensive (with the smallest threshold) CL emission was observed for the sample 534 A. For this sample we also observed a large homogeneity of CL emission, i.e., electron beam density dependence is similar, when measured at different areas of the film.
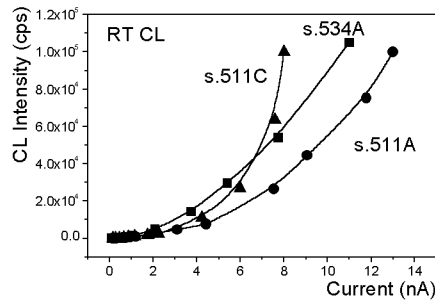
Fig. 2. Threshold density dependences measured for three InGaN/GaN homoepitaxial structures at 2000 magnification, 10 kV accelerating voltage and at room temperature.

As mentioned in the introduction, structures pumped with electron beam often show record low threshold densities. We can evaluate the threshold density in our system by taking as an excitation radius, radius of a cloud of primary and secondary electrons. This radius is fairly small, of about 50 nm, since diffusion of carriers and excitons is limited by strong localization effects. The estimated threshold density is then in the range of 100 A/cm^2, i.e., is fairly low. Problems with *p*-type doping and with contacts technology lead to much larger threshold densities in laser structures operating under current injection conditions.

After selecting structures showing a stimulated emission we studied their morphology and relation between morphology and in-plane fluctuations of the QW emission. The relevant results are shown in Figs. 3 and 4. We found a clear correlation between CL properties and structural quality of the structures. The samples showing the lowest threshold densities show the best structural quality. Density of pinholes and dislocations is low. Atomic size growth steps are observed.

Figure 4 shows in-plane fluctuations of the QW stimulated emission on the example of the 511 C structure. The observed CL fluctuations directly reflect
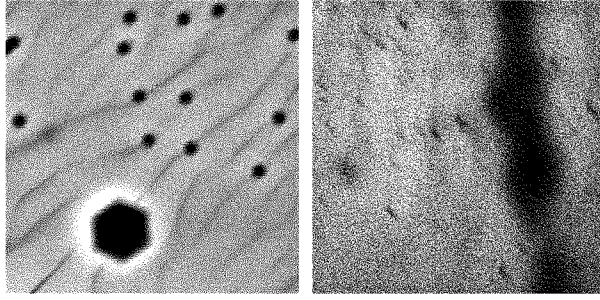
Fig. 3. SEM images taken at 10 kV accelerating voltage and at 20000 magnification (from 5 × 5 μm region) for 534 A (left) and 511 C (right) GaN/InGaN homoepitaxial QW structures.
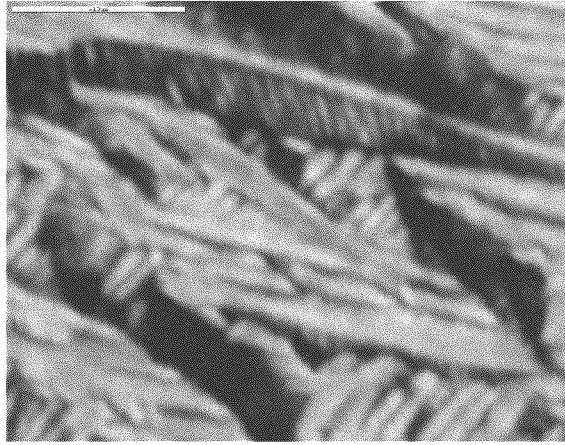

Fig. 4. Scanning CL images taken with detection set at the edge CL, at 10 kV accelerating voltage and at 6000 magnification, using 1.8 nA excitation current (threshold density).

growth details. Atomic size growth steps, as observed in the SEM, are even more pronounced in the scanning CL study. We can thus claim that there is a direct correlation between structural quality of the films and light emission properties. CL fluctuates in the intensity for excitation below and above threshold density. The observed fluctuations reflect microstructure of the sample and not e.g. indium fraction fluctuations, which typically are of a much smaller scale.

4. Conclusions

We report observation of a stimulated emission from homoepitaxial GaN/InGaN QW structures. Stimulated emission is observed only for the structures of a good structural quality and shows in-plane fluctuations of intensity, which directly correlate to microstructure of the structures.

Acknowledgments

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