

Optically pumped $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$ multiple quantum well vertical cavity surface emitting laser operating at room temperature.

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Abstract — Room temperature vertical cavity lasing at the wavelength of 433nm has been successfully realized in $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$ multiple quantum well without Bragg mirrors under photo-excitation. At high excitation intensity, one of the modes of the Fabry-Perot cavity formed by the GaN/sapphire and the GaN/air interfaces, shows a strong superlinear increase in intensity with excitation intensity rise. The vertical cavity surface emitting laser (VCSELs) structure is grown by metal-organic chemical vapor phase deposition and the threshold is as low as $200\text{kW}/\text{cm}^2$. The lasing in the sample probably results from the ultrahigh material gain due to the spontaneous formation of dense array of nanoscale InGaN quantum dots (QDs) having an exceptional high area density.

Index Terms— Laser excitation, Optoelectronic devices Quantum well lasers.

I. INTRODUCTION

GaN-based semiconductors have attracted much attention for its use in high brightness light emitting diodes (LED) [1] and continuous wave (CW) blue laser diodes (LD) [2]. GaN-based lasing was realized mainly in edge-emitting laser diode. An ideal laser source is one which is tunable, easy to focus, stable, insensitive to feedback and with a narrow emission linewidth. Traditional edge-emitting diode lasers only partially achieve these requirements. Such lasers have elliptical, divergent beams that are a result of diffraction at the rectangular emission area of a conventional diode laser resonator. The divergence varies inversely with the size of this emission area. Thus the beam divergence perpendicular to the junction is significantly greater than that parallel to it. This can be avoided in vertical cavity surface emitting laser (VCSELs). The vertical structure has further significant advantages: the laser may also be easily tested before bonding, can be easily incorporated into ICs

and is also highly suitable for use in 2-dimensional arrays. Until now, the surface lasing has been demonstrated in the InGaN/GaN MQW structure at low temperatures [3-5], or even at room temperature with AlGaIn/GaN distributed Bragg reflectors (DBRs)[6]. To our knowledge, no vertical lasing from a structure without DBRs at room temperature has been reported so far. In this paper we report the growth and optical properties of the structure composed of $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$ multiple quantum well (MQW) structure. We demonstrate the possibility of achieve surface lasing under optical pumping even without the use of high-reflectivity Bragg mirrors.

II. EXPERIMENTS

$\text{In}_x\text{Ga}_{1-x}\text{N} / \text{In}_y\text{Ga}_{1-y}\text{N}$ MQWs were grown on (0001) sapphire substrates using low-pressure MOCVD. Prior to the growth of the epitaxial layer of GaN films, a thin GaN buffer layer with a thickness of about 25 nm was grown at 520 °C on the sapphire substrates. The substrate temperature was elevated to 1020 °C to grow a GaN film with the thickness about 2 μm . Then, a four period $\text{In}_x\text{Ga}_{1-x}\text{N} / \text{In}_y\text{Ga}_{1-y}\text{N}$ MQWs were grown on the GaN epitaxial layer. The MQWs was grown at 740 °C. Trimethylgallium (TMGa), Trimethylindium (TMIIn) and ammonia (NH_3) were used as Ga, In and N sources, respectively. During the growth of the InGaIn well layer, the flow rates of TMG, TMI, NH_3 , H_2 and N_2 were 20 and 85 $\mu\text{mol} / \text{min}$ and 18, 1, and 8 slm, respectively. The well width and the barrier width were about 3nm and 10nm, respectively. The In composition in the barrier is about 1%. After growth of the InGaIn MQW, the growth temperature was raised to 1030°C for deposition of a 10-nm-thick GaN cap layer. The sample is marked as sample B. The total thickness of the sample is about 2 μm .

The structure was characterized using a Philip Double Crystal high-resolution X-Ray Diffraction (HRXRD) system using Cu $K\alpha_1$ radiation. The $\omega - 2\theta$ scan curve shows higher-order satellite peaks indicating a good $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$ interface. PL spectrum was measured at room temperature (RT) by a micro-PL system. A KIMMON He-Cd laser (325 nm) was used as the laser

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source. The laser beam was focused on the sample surface to a spot with the diameter of $\sim 10 \mu\text{m}$. Only the emission vertical to the surface is collected. Laser power density was varied from 30 kW/cm^2 to 300 kW/cm^2 . The excitation intensity was adjusted using neutral density filters.

III. RESULTS AND THE DISCUSSION.

The optical cavity was formed by the GaN/air and GaN/sapphire interfaces playing the role of mirrors. In Fig. 1, we show the PL spectra of the sample at room temperature with the excitation intensity of 30 kW/cm^2 to 300 kW/cm^2 , respectively. (below and beyond the lasing threshold.) As shown in Fig. 1, a very narrow luminescence emission peak is observed at 433 nm after the excitation intensity exceeded than the threshold. The top part of the higher excitation intensity spectrum is cut off because of signal saturation. The full width of half maximum (FWHM) of the 433 nm peak is decreased from 20 nm to 2.5 nm when the excitation intensity increased from 30 kW/cm^2 to 300 kW/cm^2 . This remarkable FWHM narrowing is accompanied by a clear superlinear growth of the corresponding PL peak intensities as shown in Fig.2. PL spectra of the emission and the peak intensities of the emission are plotted as a function of the pump intensity in Fig.2. Results are shown for pump intensities ranging from 30 kW/cm^2 to 240 kW/cm^2 . The peak intensity increases slowly with pump intensity rising up to about 200 kW/cm^2 , above which the intensity increases much more rapidly. This superlinear increase behavior clearly points to stimulated emission in the vertical direction. The threshold excitation density is about 200 kW/cm^2 for our sample, which is lower than that of the reported results [3-6]. To our knowledge this is the first clear demonstration of laser action at room temperature in InGaN VCSELs without a DBRs structure enveloping the active layer.

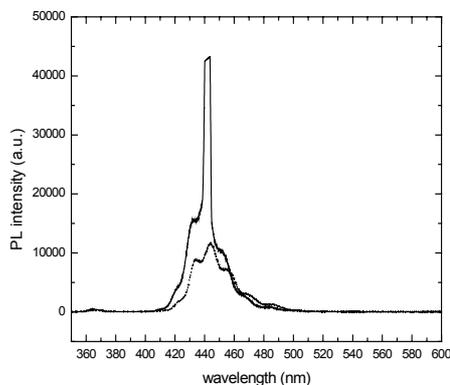


Fig. 1 The room temperature PL spectra of the InGaN MQWs below the threshold (dot line) and beyond the threshold (solid line)

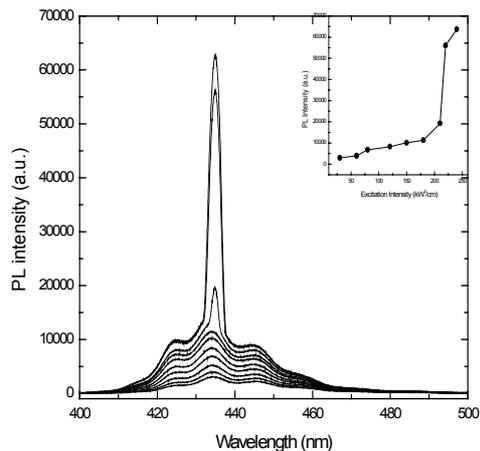


Fig. 2. The PL spectra of surface emission with different excitation intensity. The inset spectrum is the PL intensity as a function of the excitation intensity.

A number of previous studies, has reported the evidence of surface stimulated emission in GaN-based structures. Several groups have presented the stimulated emissions that are sharper than the spontaneous emission spectrum observed at lower excitation levels [7-8]. However, the results reported here present the unambiguous observation of laser action in an InGaN MQWs vertical structure. The stimulation emission and lasing have the same physical mechanism but different in some aspects. First, previous reports on stimulated emission did not show the observation of cavity modes. In our results, we clearly see spectral features sufficiently sharp to indicate multipass amplification in a Fabry-Perot cavity. Stimulated emission usually originates on the high-energy side of the low-power spontaneous emission spectrum, that is, there is a peak shift between the two emissions [9]. Comparing the emission peak of the spontaneous emission and that of the stimulated

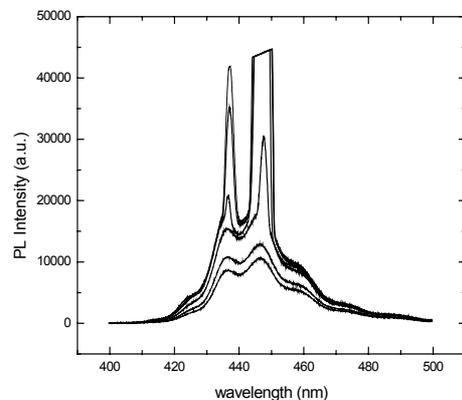


Fig. 3 The PL spectra of the sample with different location shown the two stimulated emission.

emission in our sample, there only has a slight shift. In our sample, the peaks in the spontaneous emission come from the interference. After the excitation intensity is higher than the threshold (the gain is greater than or equal to the loss at a photon energy), the spontaneous emission induces stimulated emission, and a significant photon density arises in a supported cavity mode. Then, the emitted photons stimulate even further recombination in a chain reaction. The peak position where the interference is enhanced determines the mode cavity supported. Thus the peak of the stimulated emission fall in with the spontaneous emission.

From Fig. 3, we also observed another stimulation emission at higher energy. The observed mode spacing of 11nm is consistent with expectations for our VCSEL structure.

The observation of lasing implies the high quantum efficiency of the sample. To investigate the origin of this high gain, we grew two other samples with the same MQWs structures but at the different temperature. Sample A was grown at 760°C and the sample C at 730°C. The $\omega - 2\theta$ scan XRD curve of the both samples show high order of satellite peak. The micro-PL spectra of the three samples at low excitation intensity (30 kW/cm²) were shown in Fig. 4. Sample A has the highest emission energy and the highest emission intensity. For sample B and sample C with the decreasing in value. The energy and the intensity of the PL emission peak are proportional to the growth temperature because the InGaN crystal quality is expected to be better at higher growth temperatures. However, lasing is only observed in sample B that was grown at the lower temperature than that of the sample A. This result probably results from another element affecting the emission, that is, the formation of the InGaN QDs in the InGaN quantum well. The evidence was found for In phase segregation in InGaN MQWs. [9,10] The radiative recombination of the InGaN MQWs LEDs and LDs was attributed to excitons localized in deep traps which originated from the In-rich region in the InGaN MQWs acting as QDs. [10,11] The In phase segregation is affected by the growth temperature.[12] Usually, the lower the growth temperature, the more In will be incorporated into the InGaN, and the more serious In phase segregation will occur. At the same time, the InGaN crystal quality will degrade at the lower growth temperature. Therefore, at a suitable growth temperature, the quantum efficiency of the MQWs is highest, as the case of the sample B. We would like to attribute the lasing of the sample B to the ultrahigh material gain due to the spontaneous formation of dense array of nanoscale InGaN QDs having an exceptional high area density. The further investigation for the origin of the high gain in sample B is needed.

Finally, we would like to discuss the future study and some problems in our samples. In a laser, the confinement factor Γ is the percentage of light guided into the active layer. A modal gain equals to the threshold gain (g_{th}) multiplied by the confinement factor can be defined. This

gain is a measure of the power transferred from the active region into the propagating mode. The modal gain is

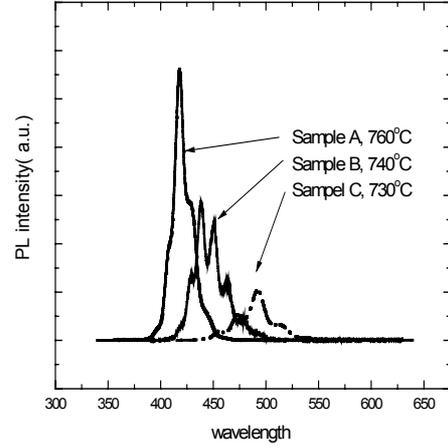


Fig. 4 The PL spectra of the samples grown at different temperatures at low excitation intensity.

necessary to overcome internal loss in the medium (α_i) and the external loss (α_{ext}) and achieve surface lasing. Given by

$$g_{mo} = \Gamma \cdot g_{th} = \Gamma(\alpha_i + \alpha_{ext}) = \Gamma \cdot [\alpha_i + \frac{1}{2L} \ln(\frac{1}{R_1 R_2})] \quad (1)$$

R_1 and R_2 are the reflectivity coefficient for the both interfaces forming the cavity, and L is the cavity length. where the threshold carrier concentration n_{th} can be written as,

$$n_{th} = \frac{d_m}{d} \left(\frac{8 \cdot \pi \cdot \nu^2 g_{mo} \cdot \tau_r \cdot \Delta \nu \cdot n_r^2}{c^2} \right) \quad (2)$$

where τ_r is the lifetime of the carriers in the conduction band before spontaneous mission takes place, ν is the frequency of the photon, d_m is the thickness of the mode volume, and d is the thickness of the active layer. From the Equ. (1) and (2), we can estimate the effect of the confinement layer and DBRs mirrors on the threshold. First, supposing the refractive index are the unity to the air, 2.33 and 1.75 for GaN and sapphire, respectively, then, the reflectivity coefficients is about 2.0% for GaN/sapphire and 15.9% for GaN/air interfaces. On the other hand the DBRs mirror increases the reflectivity of the both cavity interfaces to 30% and 50%, respectively. According to the Equ. (1) and (2), the threshold could be decreased 3 times if the DBRs mirror were used. Secondly, without lateral confinement, the confinement factor could be as low as

0.1, thus, the threshold could be decreased several times with the suitable lateral cladding layer. DBRs mirrors and the lateral structures have not been used in our sample, which imply there is still large room to decrease the threshold in our structure. Moreover, the systematically investigation for the relationship between lasing mechanism and MQW structure is necessary and underway. Furthermore, the laser has the characteristics of a narrow far-field intensity distribution while stimulated emission has the same angle behavior as spontaneous emission, as it stimulated by the photon of the spontaneous emission (that is, it has a single-pass nature.) To investigate this aspect, the further measurement in a system with a detector equipped with a goniometer is in progress. We also should consider the lines widths of the laser modes. Measured FWHM for the laser modes ranged from 2-4 nm, which are somewhat broadened for typical edge-emitting semiconductor lasers. They are reasonable for VCSELS structure without DBRs structures and partly come from our measurement equipment, which has no enough high wavelength resolution, and the detector is saturated at high excitation intensity.

IV. CONCLUSION

In conclusion, the vertical cavity surface emission laser is realized for the first time in InGaN MQWs structure without any DBRs at room temperature. No DBRs mirrors and lateral confinement in this structure also imply that the threshold could be further decrease.

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