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Effects of Inhomogeneous Gain and Loss on Nitride-Based Vertical-Cavity Surface Emitting Lasers

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Nitride-based vertical cavity surface emitting lasers (VCSEL) with hybrid mirror has been investigated. We further measured the as-grown samples (without top dielectric distributed Bragg reflector) by μ-photoluminescence, scanning near-field optical microscopy, and cathodoluminescence (CL). By different excitation power density, the experimental results indicated that the VCSEL devices have different lasing modes and spot sizes, represented inhomogeneous gain and loss distribution in the whole structure. The non-uniform emission intensity distribution including several bright spots of about 1 to 2 µm was observed for both VCSEL devices and as-grown samples, which was obtained from CL measurement, due to the effect of indium clusters and non-uniform micro-cavity resonant in InGaN multi-quantum wells (MQWs). The results show the significant influence on commercial applications such as light emitting diodes, lasers devices and so on.

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1. Introduction

Over the past few years, nitride-based light emitting devices have attracted much attention and widely used in lighting, display, and storage applications. Especially for nitride-based vertical cavity surface emitting lasers (VCSELs), their excellent properties including circular beam shape, light emission in the vertical direction and two dimensional arrays also show great potential in these commercial products. There are some reports about the lasing action of GaN-based VCSEL which usually happens in a region of few micrometers under optical and electrical pumping.[1–3] The lasing behavior can be attributed to the inhomogeneous gain or lose distribution in the fully structure, causing different threshold energy density for each laser mode. Two possible bases are therefore plausible to be responsible for inhomogeneous phenomenon. One possible mechanism is the indium clusters dispersed in the multiple quantum wells (MQWs) confined in a range of sub-micrometers.[4–6] The other is the non-uniform micro-cavity resonant effect which plays the important role in controlling gain distribution due to the growth process.[7,8] However, not much detail information is investigated in these devices, especially on as-grown samples (without top dielectric distributed Bragg reflector). In this paper, we demonstrated the mapping results of VCSEL devices and as-grown samples including wavelength distribution, intensity distribution, and emission spectrum. Besides, we further investigated the relation between the reflection of the as-grown samples and the corresponding emission spectrum.

2. Experimental Procedure

In this experiment, the GaN-based VCSEL devices with hybrid mirror and as-grown samples were grown on *c*-plane sapphire substrate by low-pressure metal–organic chemical vapor deposition (MOCVD; Veeco D75). The detail fabrication process was described in ref. 9. The optical properties measurement was performed using a frequency-tripled Nd:YVO_4 355 nm pulsed laser with a pulse width of about 0.5 ns at a repetition rate of 1 kHz and a He–Cd 325 nm continuous wave (CW) laser. A 15× objective lens with a numerical aperture of 0.32 was placed normally to the sample to collect the light emission and to couple into a spectrometer with a charge coupled device (CCD). The spectral resolution is about 0.1 nm for spectral output measurement. In the scanning near-field optical microscopy (SNOM) system, the spot size of pumping laser is about 1 µm by beam expander. Besides, the samples can move by the piezoelectric (PZT) actuator with a resolution of about 20 nm. The cathodoluminescence (CL) measurement was carried out at 300 K by using a mono-CL3 system of Gatan installed on a field emission scanning electron microscope with beam energies of 5–20 keV.

3. Results and Discussion

The schematic diagram of GaN-based VCSEL devices is shown in Fig. 1(a) which is consisted of a 29 pairs AlN/GaN distributed Bragg reflector (DBR), a n-type GaN, a 10 pairs MQWs, a p-type GaN, and a 8 pairs Ta_2O_5/SiO_2 dielectric DBR. The emission images under different pumping energy including spontaneous and stimulated emission are also observed in Fig. 1(b). Above threshold, we can observe the fundamental or high-order lasing modes appeared under different threshold energy, represented different gain or loss distribution in the whole structure. By increasing the excitation power density, the fundamental lasing mode keeps brightening and then the second one appears near the fundamental mode with the energy value of about $1.3E_{th}$ (E_{th} is the threshold excitation power density of the fundamental lasing mode of our GaN-based VCSEL devices in optical pumping). Finally, the third laser spot is found at the pumping energy at $1.4E_{th}$.

The emission spectrums under different excitation power density are clearly showed in Fig. 2 corresponding to the emission images in Fig 1(b). The fundamental mode of the GaN-based VCSEL devices has a dominated wavelength centered at 445.28 nm with a linewidth of about 0.18 nm. By increased the excitation power density, the second and third laser emission emerged at 446.61 nm with a linewidth of about 0.15 and 447.28 nm with a linewidth of about 0.15 nm,

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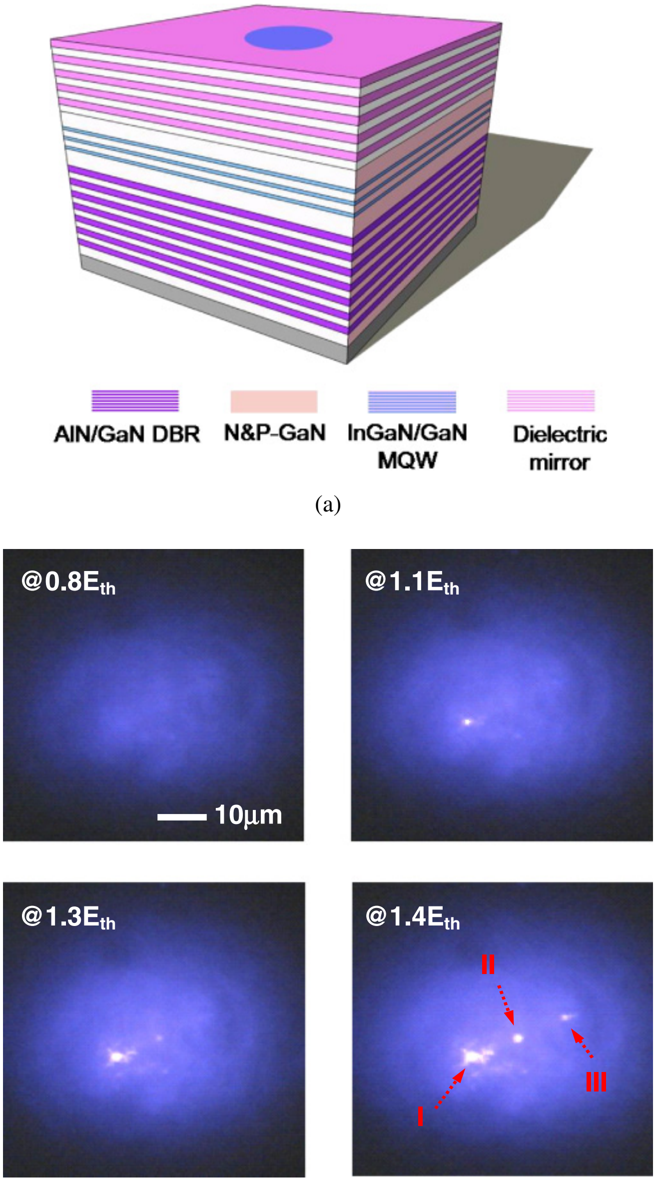


(a)

(b)

Fig. 1. (Color online) (a) Schematic diagram of GaN-based VCSEL with hybrid mirrors. (b) Emission images of the GaN-based VCSEL under different pumping energy.

respectively. In general, the lasing action tends to happen when the gain is larger than the loss by increasing carrier injection. However, the laser actions always happened at random positions and caused the different lasing threshold energies, represented the strong relation with the disorder gain distribution. These results also show the high-gain regions which could be contributed to the inhomogeneous active medium of the indium cluster and the non-uniform micro-cavity effect.

In order to investigate the gain distribution caused by indium clusters in MQWs and the micro-cavity effect, we measured the as-grown samples, eliminated the influence by top distributed Bragg reflector (DBR). Figure 3(a) shows the spontaneous emission intensity distribution of the as-grown samples excited and scanned by the He–Cd laser of the SNOM system. From this figure, we could observe the scanning area of $20 \times 20\,\mu m^2$ including several micrometers bright spots of about 1 to $2\,\mu m$. Figure 3(b) shows the wavelength distribution corresponding to Fig. 3(a). The emission wavelength distribution was also non-uniform, and the largest difference of emission wavelength at different areas in the figure was as larger as around 4 nm due to the inhomogeneous of the indium cluster in MQWs. Besides, the wavelength emitted from as-grown sample is determined by cavity mode. It could be seen from the emission spectrum of the dotted circle marked in Fig. 3(b). The emission was centered at around 440.16 nm with a linewidth of around

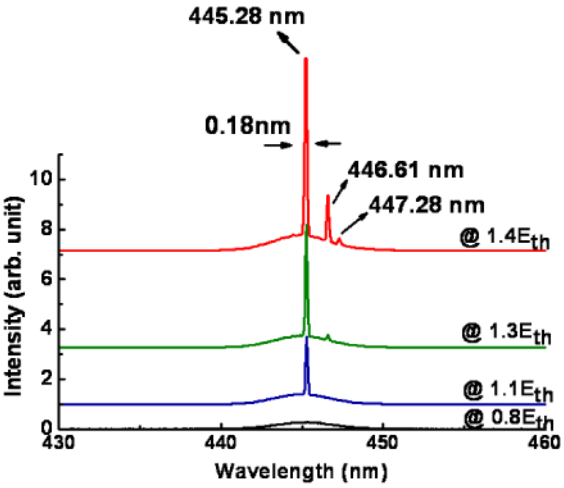
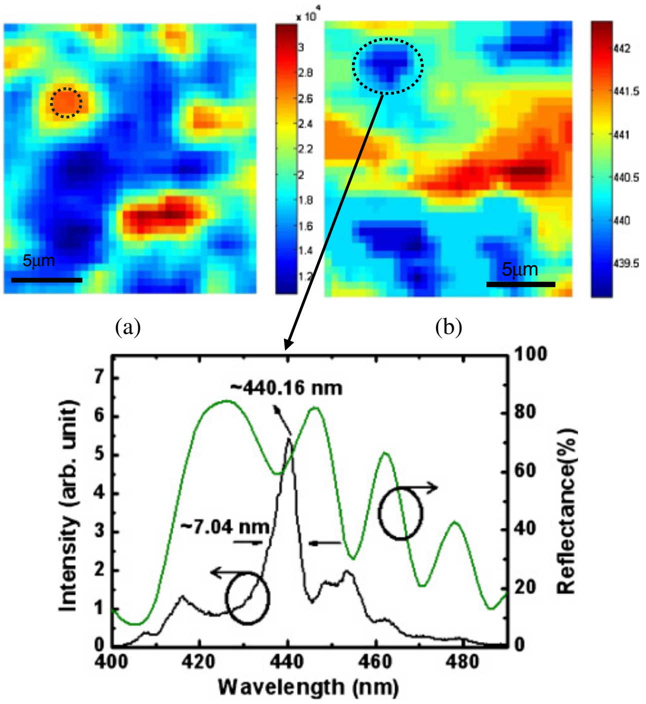


Fig. 2. (Color online) Emission spectra of the GaN-based VCSEL under four different pumping energies.



(a)

(b)

(c)

Fig. 3. (Color online) (a) Spontaneous emission intensity distribution of the as-grown sample (without top DBR). (b) Wavelength intensity distribution of the as-grown sample corresponding to (a). (c) Emission spectrum of the dashed circle marked in (b).

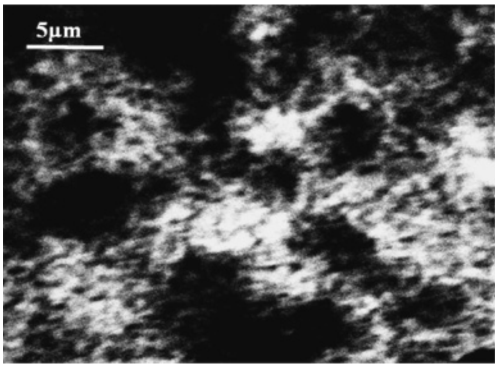


Fig. 4. CL image of as-grown sample at 446 nm.

7.04 nm, which is smaller than that of typical blue light emitting diodes (~20 nm). This means the micro-cavity resonant effect has affected the emission spectrum emitted from our sample. The measured reflectivity spectrum shown in Fig. 3(c) also shows the same result. These indicate we could understand the cavity uniformity from the wavelength distribution. From Figs. 3(a) and 3(b), we are sure that the cavity and active medium are both inhomogeneous in the epitaxial grown VCSEL structure. Non-uniform cavity modes could be seen from the inhomogeneous emission peak position. Furthermore, the inhomogeneous gain was confirmed from those regions emitting the same wavelength but having the different luminescence intensity. The high gain region should only existed at where light emission generated from MQWs matches the cavity mode. In fact, these regions are small and scattered on VCSEL samples as seen from above figures. This explains the formation of spot lasing. With this understanding, it also becomes reasonable the multiple lasing spots happen as the high gain region is close to each other.

Furthermore, we measured the plane-view mapping image of as-grown sample at 446 nm according to the higher resolution of CL system. As shown in the Fig. 4, some regions have larger intensity distribution including several bright spots of the range from 0.5 to 1 μm, corresponding to the gain distribution, showing similar characteristic of the measurement results of SNOM but having smaller bright spots due to the worse resolution of our SNOM system. The result also represents the inhomogeneous indium clusters in our InGaN MQWs.[10)]

4. Conclusions

The multiple laser spots behavior of GaN-based VCSEL was observed and has been investigated in this study. The different lasing threshold and wavelength at the same pumping region implies the gain distribution is inhomogeneous. We have also studied the wavelength and intensity distribution of as-grown sample to realize the factors causing the non-uniform gain distribution. The result shows the cavity mode and MQWs both contribute to the non-uniformity. The scattered high gain region has the well-aligned emission peak from MQWs and the cavity mode is restricted in few micro-meters. This explains the lasing action of GaN-based VCSEL is usually in a form of bright spot and scatters within the pumping region. This understanding is very crucial for developing electron-injected GaN-based VCSEL. Improving uniformity of active medium and cavity shall be the next step toward the realization of GaN-based VCSELs.

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