Emission characteristics of high-gain GaN-based Vertical-Cavity Surface-Emitting Lasers

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Abstract: GaN-based vertical-cavity surface-emitting lasers (VCSELs) with high optical gain and short cavity lifetime are favorable for the generation of ultra-short pulses in the blue and green regions. In our previous works, 6 and 2 picosecond short-pulses have been generated from gain-switched InGaN VCSELs with 3- and 10-period InGaN/GaN quantum wells (QWs) in the active layers by using an up-conversion measurement system. To further increase the gain of the VCSEL for the generation of even shorter pulses, 20-period InGaN/GaN QWs samples were fabricated. The emission characteristics of these high-gain VCSELs were investigated and analyzed under the optical pumping at room temperature.

1. Introduction

Low-cost, compact and pulsed semiconductor lasers with ultra-short output pulses are on demand in many applications such as high-density optical storage, high-speed optical communications, optical signal processing, and time-resolved spectroscopy [1, 2]. Vertical-cavity surface-emitting laser (VCSEL), as a novel semiconductor laser, has many particular advantages over conventional edge-emitting lasers including single-longitudinal-mode operation, low laser threshold, circular output beam with low divergence, and densely-packed two-dimensional arrays. Moreover, the high optical gain and short cavity lifetime in the VCSELs due to their short cavity lengths make them favorable for the generation of ultra-short pulses via gain-switching. Actually, picosecond pulses have been widely reported in both optically and electrically pumped gain-switched GaAs-based VCSELs over the past few decades [3, 4]. However, the increasing requirements for next-generation of optical storages with higher storage density and capacity, and laser printers with higher graphical resolution have promoted the shortening of the laser wavelengths, which makes nitride-based VCSELs with the laser emission in blue and green regions into very promising devices. In recent years, enormous efforts have been devoted to obtain ultra-short blue pulses using the InGaN VCSELs via a simple gain-switching technique. Optical pulses as short as 6 and 2 ps have been generated from gain-switched InGaN VCSELs with 3- and 10-period InGaN/GaNquantum wells (QWs) in the active regions in our previous works[5, 6] by using an up-conversion measurement system. Nevertheless, the gain-switched blue pulses should be further shortened, on the basis of our rate-equation analysis [7], by increasing optical gain in the active regions of InGaN VCSELs; for example, by increasing the QW numbers in the cavity.

In this paper, high-gain InGaN VCSELs with 20-period InGaN/GaN QWs were fabricated. Distributed Bragg reflectors (DBRs) with high reflectivity of 97.5% centered at about 420 nm and lower reflectivity below 400 nm were designed and fabricated for optical pumping. To avoid the effect of dopants, undoped GaN layers were grown in the active region. Optical properties of the 20-period InGaN/GaN QW VCSELs were studied with femtosecond pulse laser excitation. The results show that the InGaN VCSELs demonstrate single-longitudinal-mode lasing at 411.6 nm with a linewidth of 0.3 nm under impulsive optical pumping with a threshold pumping energy of about 271 nJ. The success in the fabrication of the high-gain InGaN QW VCSELs should be useful for further gain-switching investigation towards ultrashort pulse generations.

2. Experimental methods

The VCSEL epitaxial structure grown on a (0001)-oriented sapphire substrate by metal-organic chemical vapor deposition includes a 30-nm GaN nucleation layer, a 3-µm GaN bulk layer, 20 period quantum wells consisting of 15-nm GaN barriers and 2-nm InGaN wells, and a 100-nm GaN cap layer. 12.5 pairs of Ta_2O_5 and SiO_2 were evaporated on the top of the grown VCSEL structure to form the bottom distributed Bragg reflector (DBR). Then, the structure was bonded onto a quartz substrate, followed by a laser lift-off (LLO) process using a KrF excimer laser to remove the sapphire substrate. Next, the GaN surface after LLO was thinned and polished through inductively coupled plasma (ICP) etching and chemical mechanical polishing (CMP) techniques. Finally, a second dielectric DBR consisting of 8 pairs of Ta_2O_5 and SiO_2 was deposited. The Ta_2O_5/SiO_2 dielectric DBRs exhibit a broad stopband width of about 85 nm, with peak reflectivities of 97.5% and 99.8% centered at about 420 nm for the top and bottom sides, respectively. The schematic diagram of the fabricated GaN-based VCSEL is shown in Fig. 1(a). The root mean square (RMS) roughness of the GaN surface measured by atomic force microscopy (AFM) was 0.7 nm in a scan area of 2 µm × 2 µm after CMP. The sub-nanometer roughness smooth surface provide favorable condition for high reflectivity DBRs evaporation [8]. Figure 1(b) shows the experimental apparatus for the optical measurements of the VCSEL. The GaN-based VCSEL was optically pumped at room temperature by a fs impulsive optical excitation at 370 nm, with a repetition rate of 1 kHz and a pulse width of 150 fs.

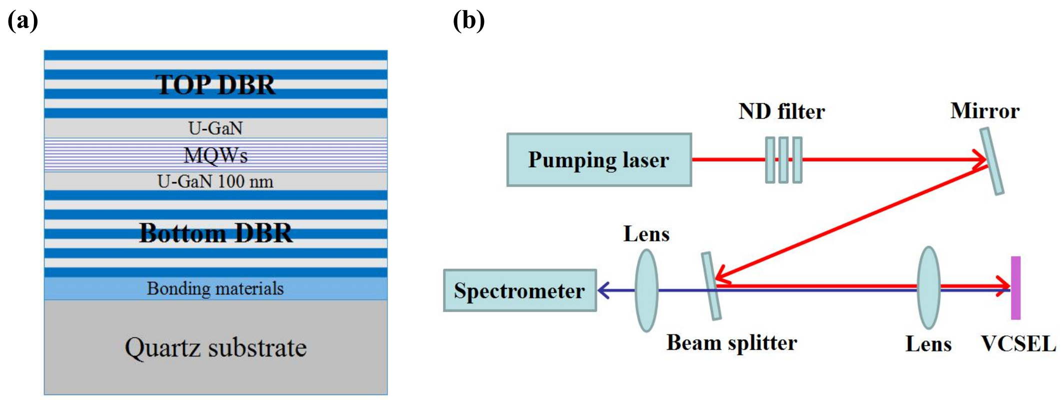

Figure 1. (a) Schematic structure of the InGaN VCSEL. (b) Diagrams of the experimental setup for optical pumping measurements.

3. Results

Figure 2(a) shows the variation of emission spectrum with increasing the pumping energy. As shown in the figure, these spectra obviously show the transition from spontaneous emission to stimulated emission with a single dominant peak. Above the threshold pumping energy, a sharp emission peak appears at 411.6 nm with a linewidth of 0.3 nm (resolution limit). The inset shows the laser emission intensity versus the pumping time at the pumping energy of 1.8 E_{th}, indicating highly stable and reliable performance of the VCSEL device. Figure 2(b) shows the light emission intensity from the VCSEL as a function of the pumping energy. A distinct threshold characteristic was observed at the threshold pumping energy of about 271 nJ corresponding to an energy density of 13.8 mJ/cm^2. Note that the reflectivity of the top DBR is 88% at the pumping wavelength of 370 nm, it is respected that the threshold pumping energy should be much more lower since only 12% of the pumping energy can be absorbed by the active region of the VCSEL.

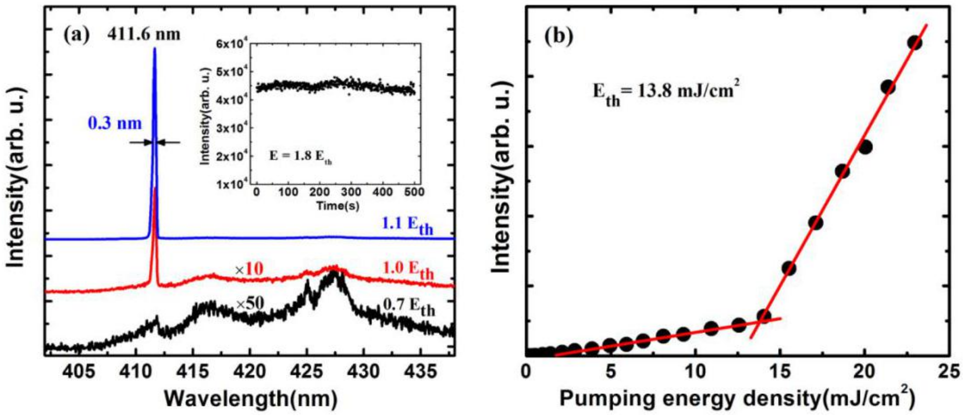

Figure 2. (a) The variation of emission spectrum with increase of the pumping energy. The inset is the laser emission intensity vs the pumping time at the pumping energy of 1.8 E_{th}. (b) Emission intensity as a function of the pumping energy at room temperature.

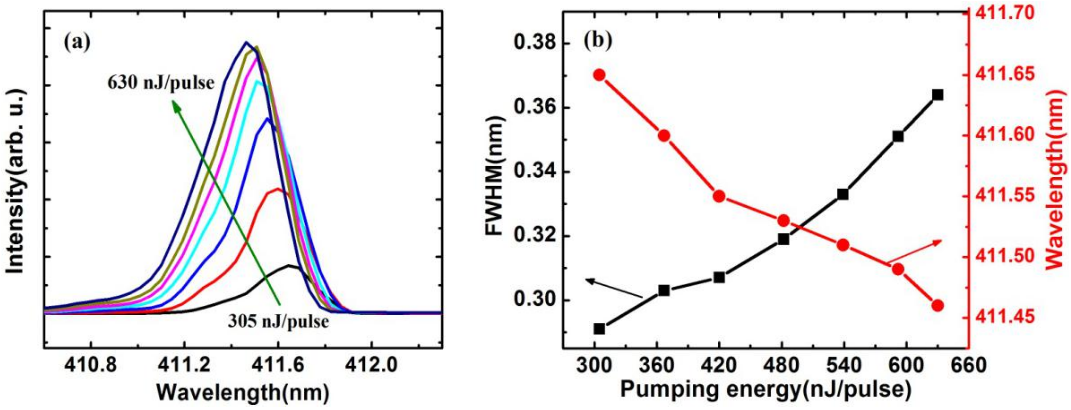

Figure 3. Lasing spectra (a) and lasing wavelengths and FWHM of the lasing spectra (b) as a function of pumping energy from 305 nJ/pulse to 630 nJ/pulse.

The variation of the laser emission spectra with increasing pumping energy from 305 nJ/pulse (1.1 E_{th}) to 630 nJ/pulse (2.3 E_{th}) were shown in Fig. 3(a). The pumping-energy dependence of the FWHM and peak wavelength of the lasing emission were shown in Fig.

3(b). The blue shift of the lasing wavelength and the increase of the linewidth with increasing pump energy are typical behaviors of gain-switched semiconductor lasers during pulse lasing, which can be explained by the initial transient spectral broadening (or wavelength chirping) on the short-wavelength side of the gain-switched pulses at elevated pumping energy [9].

Figure 4(a) is a replot of the laser emission intensity as a function of pumping energy in a logarithmic scale. The spontaneous emission coupling factor β, estimated from the difference between the heights of the emission intensities before and after lasing, was ~0.16, which is nearly one order of magnitude higher than those of previous reported [10], indicating a higher quality resonant cavity of the fabricated VCSEL in present study. Figure 4(b) depicts the polarization characteristics of the VCSEL. The degree of the polarization, given by $(L_{max}-L_{min})/(L_{max}+L_{min})$, where L_{max} and L_{min} are respectively the maximum and minimum relative light intensities, was measured to be about 65% at the pumping energy of 1.8 E_{th}.

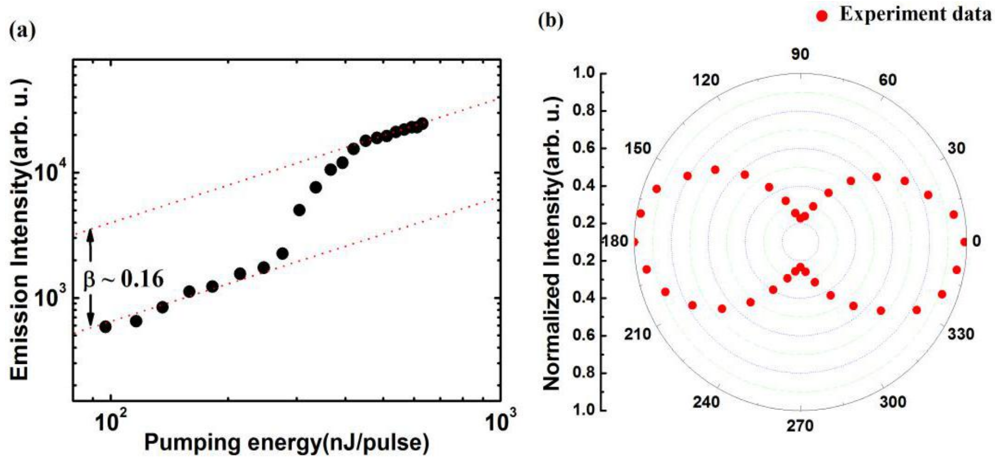

Figure 4. (a) Emission intensity vs pumping energy in a logarithmic cale. The dash lines are guides for the eye. (b) The polarization characteristics of the laser emission from the InGaN VCSEL at the pumping energy of 1.8 E_{th}.

4. Conclusion

High-gain GaN-based VCSEL with 20-period InGaN/GaN QWs were design and fabricated. The laser emission characteristics of the VCSEL were investigated under optical pumping at room temperature. The laser emitted at a wavelength of 411.6 nm with a linewidth of 0.3 nm and a threshold pumping energy of about 271 nJ. Further investigations on the gain-switching dynamics of this high-gain VCSEL are in preparation.

References

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