The Lasing Characteristics of GaN-Based Vertical-Cavity Surface-Emitting Laser With AlN–GaN and Ta_2O_5–SiO_2 Distributed Bragg Reflectors

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***Abstract*—The characteristics of a GaN-based vertical-cavity surface-emitting laser (VCSEL) with 25 pairs AlN–GaN distributed Bragg reflector (DBR) and eight pairs Ta_2O_5–SiO_2 DBR was investigated and analyzed under the optical pumping at room temperature. The GaN-based VCSEL emits a blue wavelength at 448 nm with a linewidth of 0.17 nm with a near-field emission spot diameter of about 3 μm. The laser beam has a near linear polarization with a degree of polarization of about 84%. The laser shows a high spontaneous emission coupling efficiency of about 5×10^{-2} and a high characteristic temperature of about 244 K.**

***Index Terms*—AlN, distributed Bragg reflector (DBR), GaN, vertical-cavity surface-emitting laser (VCSEL).**

I. Introduction

WIDE bandgap nitride-based materials have been widely used to realize ultraviolet and blue light-emitting diodes and laser diodes [1]–[4]. The GaN-based blue/violet laser diodes, including vertical-cavity surface-emitting laser (VCSEL) and edge-emitting laser, have many potential applications such as high-density storage and high-resolution laser printing. In particular, the VCSEL possesses many advantageous properties over the edge emitting laser. These include circular beam shape, light emission in vertical direction, and formation of two-dimensional arrays. Over the past five years, GaN-based VCSELs with various cavity structures have been reported to achieve laser operation under optical pumping at room temperature [5]–[9]. Someya *et al.* [5] and Zhou *et al.* [8] employed 43 pairs of $Al_{0.34}Ga_{0.66}N$–GaN and 60 pairs of $Al_{0.25}Ga_{0.75}N$–GaN as the bottom dielectric Bragg reflectors (DBRs), respectively, and achieved lasing action. Song *et al.* [7] and Tawara *et al.* [6] reported lasing action of nitride VCSEL with two dielectric DBRs. Our group recently reported the lasing action of GaN-VCSEL using hybrid DBR cavity consisting of AlN–GaN bottom DBR and dielectric top DBR under optical pumping at room temperature [9]. Meanwhile the investigation of the characteristics of the GaN-based VCSELs has gradually attracted more attentions. Kako *et al.* [10] investigated the coupling efficiency of spontaneous emission (β) and the polarization property of the nitride VCSEL and obtained a high β value of 1.6×10^{-2} and a strong linear polarization of 98%. Tawara *et al.* [6] also found a high β value of 10^{-2} in the nitride VCSEL with two dielectric mirrors. Honda *et al.* reported the estimation of high characteristics temperature of GaN-based VCSEL [11]. However, so far no experimental result of the characteristic temperature of the GaN-based VCSEL has ever been reported. The characteristic temperature of lasers is one of the important parameters for applications such as optical storage. In this letter, we report the investigation of the lasing characteristics of the GaN-based VCSEL and show the high spontaneous emission coupling efficiency and high characteristic temperature of this laser with a nearly linear polarization laser beam.

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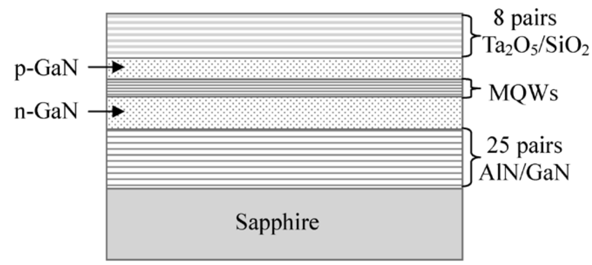

Fig. 1. Structure of the VCSEL structure analyzed in the experiment.

II. Experiment

The GaN-based VCSEL investigated in this study has a similar structure as reported earlier [9]. It was grown on a sapphire substrate in a vertical-type metal–organic chemical vapor deposition system (EMCORE D-75). The full epitaxial structure consists of a 25-pair AlN–GaN bottom DBR, a 380-nm-thick n-type GaN cladding layer, a ten-pair $In_{0.2}Ga_{0.8}N$–GaN multiquantum well (MQW), and a 100-nm-thick p-type GaN cladding layer. Then, an eight-pair Ta_2O_5–SiO_2 dielectric mirror served as top DBR was deposited by the E-gun as the top DBR. The schematic diagram of the overall VCSEL structure is shown in Fig. 1. The

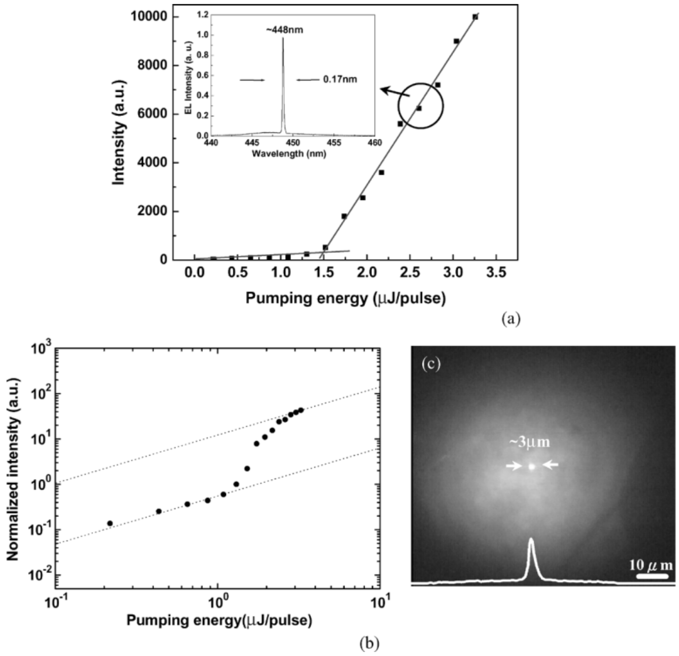

Fig. 2. (a) Light output intensity as a function of the pumping energy at room temperature. The inset is the spectrum of laser emission at the pumping energy of $1.71E_{\mathrm{th}}$. (b) Figure replotted (a) in a semilogarithm scale. (c) Surface emission image of GaN-based VCSEL at the pumping energy of $1.71E_{\mathrm{th}}$.

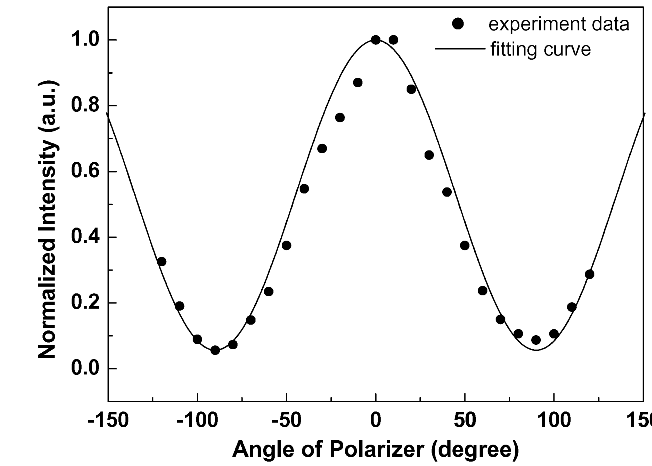

Fig. 3. Polarization characteristic of the laser emission at the pumping energy of $1.71E_{\mathrm{th}}$. The solid dot shows the experiment data and the solid line is the fitting curve.

detail of device fabrication process was published elsewhere [9]. During these processes, the reflectivity spectra of the AlN–GaN DBR structure and the Ta_2O_5–SiO_2 dielectric mirror were measured by the n&k ultraviolet-visible spectrometer with normal incidence at room temperature. The peak reflectance of the top and bottom DBR were 97.5% and 94% at 450 nm, respectively.

The emission spectrum of the GaN-based VCSEL structure was measured using a microscopy system (WITec, alpha snom) at room temperature. The optical pumping of the sample was performed using a frequency-tripled Nd:YVO_4 355-nm pulsed laser with a pulsewidth of ~0.5 ns at a repetition rate of 1 kHz. The pumping laser beam with a spot size of 60 μm was incident normal to the VCSEL sample surface. The light emission from the VCSEL sample was collected using an imaging optic into a spectrometer/charged coupled device (Jobin-Yvon Triax 320 Spectrometer) with a spectral resolution of ~0.1 nm for spectral output measurement.

The characteristic temperature of GaN-based VCSEL sample was measured using the same microscopic optical pumping system with the sample placed in a cryogenics controlled chamber. The temperature of the chamber can be controlled from room temperature of 300 K down to 120 K using liquid nitrogen. The chamber has a window for laser pumping and output monitoring during the experiment.

III. Results

The light emission intensity from GaN-based VCSEL as a function of the pumping energy is shown in Fig. 2(a). A distinct threshold characteristic was observed at the threshold pumping energy (E_{th}) of about 1.5 μJ corresponding to an energy density of 53 mJ/cm^2. Then the laser output increased linearly with the pumping energy beyond the threshold. A dominant laser emission line at 448 nm appearing above the threshold pumping energy is shown in the inset. The laser emission spectral linewidth reduces as the pumping energy above the threshold energy and approaches 0.17 nm at the pumping energy of $1.71E_{\mathrm{th}}$. In order to understand the β of this cavity, we normalized the vertical scale of Fig. 2(a) and replotted it in a semilogarithm scale, as shown in Fig. 2(b). According to [12], the difference between the heights of the emission intensities before and after the threshold corresponds roughly to the value of β. The β value of our VCSEL estimated from Fig. 2(b) is about 5×10^{-2}. We also estimated the β value based on the approximation equation used in [10]

$$F_p = \frac{3}{4\pi^2}\frac{Q}{\frac{V_c}{\left(\frac{\lambda}{n}\right)^3}}$$

$$\beta = \frac{F_p}{1+F_p}$$

where F_p is the Purcell factor, Q is the cavity quality factor, λ is the laser wavelength, Vc is the optical volume of laser emission, and n is the refractive index. As we have reported earlier [9], the photoluminescence (PL) spectrum of our GaN-based VCSEL showed a narrow emission peak with full-width at half-maximum of 1.4 nm, which corresponds to a cavity quality factor of 320. The refractive index is 2.45 for the GaN cavity. For the estimation of the optical volume, we used the spot size of the laser emission image shown in Fig. 2(c) which is about 3 μm and the cavity length of about 7.3λ with considering the penetration depth of the DBRs and estimated the V_c to be about 7.6×10^{-12} cm^3. By using these parameters, the Purcell factor of about 2×10^{-2} was obtained and we estimated the β value to be about 2×10^{-2}, which has the same order of magnitude as the above β value estimated from Fig. 2(b). This β value is three orders of magnitude higher than that of the typical edge-emitting semiconductor lasers (normally about 10^{-5}) [5], [6] indicating the enhancement of the spontaneous emission into a lasing mode by the high quality factor microcavity effect in the VCSEL structure.

Fig. 3 shows the laser emission intensity as a function of the angle of the polarizer at the pumping energy of $1.71E_{\mathrm{th}}$. The

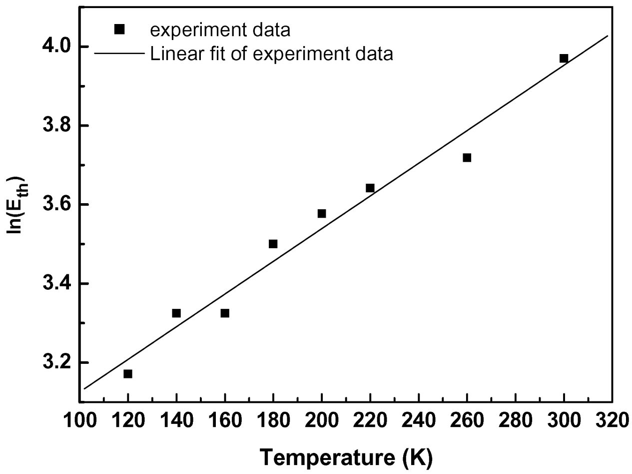

Fig. 4. Seminatural-logarithm threshold energy as a function of the operation temperature. The solid dot shows the experiment data and the solid line is the linear fit of the experiment data.

variation of the laser emission intensity with the angle of the polarizer shows nearly a cosine square variation. The degree of polarization (P) is defined as $P = (I_{\max} - I_{\min}/I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensity of the nearly cosine square variation, respectively. The result shows that the laser beam has a degree of polarization of about 84%, suggesting a near linear polarization property of the laser emission.

Fig. 4 shows the seminatural-logarithm plots of the dependence of the threshold pumping energy $(\ln E_{\text{th}})$ on the operation temperature (T). The threshold energy gradually increased as the operation temperature rose from 120 K to 300 K. The relationship between the threshold energy and the operation temperature could be characterized by the equation $E_{\text{th}} = E_0 \times e^{T/T_0}$, where T_0 is the characteristic temperature and E_0 is a constant. Therefore, we obtain a high characteristic temperature of about 244 K by linear fitting the experiment data. The high T_o of our sample within the temperature range could be due to various factors. We measured the lasing wavelength variation with the temperature. The result showed a slight red shift of about 1.6 nm as the temperature rose from 120 K to 300 K. The PL emission of the MQW was also measured and the result showed a red shift of about 2.9 nm over the same temperature range. These results suggest that the gain peak almost align with the cavity mode within this temperature variation range. Therefore, the high characteristic temperature obtained from our GaN-based VCSEL sample could be partly attributed to the good alignment of the gain peak and cavity mode. Furthermore, the ten-pair $In_{0.2}Ga_{0.8}N$–GaN MQW structure which could suppress the carrier leakage from the MQW active layers to the cladding layers and the thick GaN cavity (480 nm in thickness) provides a good heat dissipation path during the high carrier injection and high temperature conditions [13].

IV. Conclusion

We have investigated the performance of the GaN-based VCSEL with emission wavelength at 448 nm under the optical pumping at room temperature. The laser beam has a nearly linear polarization property with a degree of polarization of about 84%. The laser has a high β value of about 5×10^{-2} indicating the coupling coefficient enhancement due to the laser microcavity, and a high characteristic temperature of 244 K suggesting potential for high temperature applications.

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