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CW lasing of current injection blue GaN-based vertical cavity surface emitting laser

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Here, we report the cw laser operation of electrically pumped GaN-based vertical cavity surface emitting laser (VCSEL). The GaN-based VCSEL has a ten-pair InGaN/GaN multiple quantum well active layer embedded in a GaN hybrid microcavity of 5λ optical thickness with two high reflectivity mirrors provided by an epitaxially grown AlN/GaN distributed Bragg reflector (DBR) and a Ta_2O_5/SiO_2 dielectric DBR. cw laser action was achieved at a threshold injection current of 1.4 mA at 77 K. The laser emitted a blue wavelength at 462 nm with a narrow linewidth of about 0.15 nm. The laser beam has a divergence angle of about 11.7° with a polarization ratio of 80%. A very strong spontaneous coupling efficiency of 7.5×10^{-2} was measured. *© 2008 American Institute of Physics*. [DOI: 10.1063/1.2908034]

Wide band gap GaN-based optoelectronic devices, light emitting devices and lasers in particular, have become important devices for practical applications. The electrically pumped GaN-based lasers are so far based on the edge emitting structure that has a long Fabry–Pérot-type optical cavity (approximately several hundreds of microns), multiple emission modes, and an asymmetric laser beam profile with a large beam divergence. On the contrary, the vertical cavity surface emitting laser (VCSEL) structure, in particular, with a small optical mode volume having a microcavity of only a few λ optical thickness, can emit a single mode with a circular symmetry beam and a small beam divergence that are more superior than the edge emitting lasers and are desirable for many practical applications in high density optical storage, laser printing, etc. Although optically pumped GaN-based VCSELs were reported[1–4] earlier, so far there has been no electrically pumped GaN-based VCSEL reported.

The difficulty in the realization of an electrically pumped GaN-based VCSEL mainly comes from two factors. First is the requirement of high reflectivity and high quality distributed Bragg reflectors (DBRs). The reported DBR structure that is composed of $Al_xGa_{1-x}N$ and GaN has a large lattice mismatch and a difference in the thermal expansion coefficients between these two materials that tend to form cracks in the epitaxially grown DBR structure. These cracks in the DBR could result in the reduction in optical reflectivity and increase in the scattering loss. Moreover, the cracks could also become a current leakage path, making the realization of an effective current injection into GaN VCSEL very difficult. The second factor is the need for a high transparency yet good conductivity contact for injection of the carriers into the multiple quantum well (MQW) active region. Since the *p* doping of GaN is very difficult, the carrier injection path with low resistance and optical loss is required for efficient current injection. In this paper, we report the cw laser action of current injection GaN-based VCSEL at 77 K. The laser has an InGaN MQW active layer embedded in a high quality hybrid microcavity structure with two high reflectivity mirrors which consist of an epitaxially grown crack-free AlN/GaN DBR and a Ta_2O_5/SiO_2 dielectric DBR. This hybrid microcavity structure allows the incorporation of an intracavity current injection structure that has a highly transparent and conductive indium tin oxide (ITO) current injection layer as the *p* contact and a coplanar *n* contact. The laser action was achieved under cw current injection at 77 K with single mode emission at 462.8 nm at a low threshold current of 1.4 mA and a high degree of polarization.

Figure 1(a) shows the schematic of the hybrid microcavity GaN VCSEL structure. The device fabrication steps are as follows: first, the MOCVD reactor was used to grow the device epitaxial structure. The epitaxial structure mainly consists of a 29-pair AlN/GaN DBR and a 5λ (our target wavelength is $\lambda=460$ nm) optical thickness microcavity composed of a 790-nm-thick Si-doped *n*-type GaN, ten pairs of $In_{0.2}Ga_{0.8}N$ (2.5 nm)/GaN (7.5 nm) MQWs, and a 120-nm-thick Mg-doped *p*-type GaN layer. The MQWs were located at the antinode of light field in the microcavity for enhancing the coupling of photons and the cavity mode. To obtain a crack-free and high reflectivity AlN/GaN DBR, we insert the AlN/GaN superlattices into the AlN/GaN DBR structure during the epitaxial growth to reduce the biaxial tensile strain in AlN/GaN DBR.[5] The superlattice has 5.5 pairs of AlN/GaN corresponding to a half-wavelength stack and was inserted in every four pairs of AlN/GaN quarter-wavelength stacks to form a 29-pair AlN/GaN bottom DBR. The grown DBR showed a high peak reflectivity of $R=99.4\%$ with a spectral bandwidth of ~25 nm. The epitaxially grown structure was then processed to form the intracavity coplanar *p* and *n* contacts for current injection, as shown in Fig. 1(a). A 0.2-μm-thick SiN_x layer was used to form a current injection and a light emitting aperture of 10 μm in diameter. An ITO was deposited on top of the aperture to serve as the transparent contact layer. Since the ITO locates within the VCSEL microcavity, the thickness of ITO is set to 240 nm, corresponding to 1λ optical length ($\lambda=460$ nm) in order to match the resonance phase condition of the microcavity. We annealed the ITO layer at 525 °C

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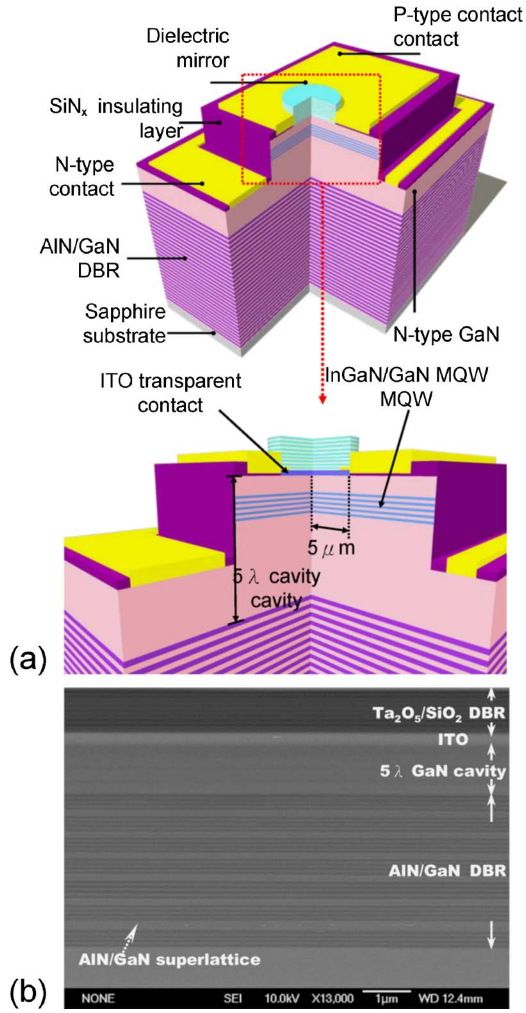

FIG. 1. (Color online) (a) The schematic diagram of the GaN VCSEL. (b) The cross section image of the VCSEL microcavity with hybrid DBRs observed by SEM.

under the nitrogen ambient to reduce the contact resistance as well as to increase transparency, thus reducing the internal cavity loss. The deposited ITO has a measured transmittance of about 98.6% at $\lambda = 460$ nm. Finally, an eight-pair Ta_2O_5/SiO_2 dielectric DBR (measured reflectivity of about 99% at $\lambda = 460$ nm) was deposited as the top DBR mirror to complete the full hybrid microcavity VCSEL device. Figure 1(b) shows the scanning electron microscopy image of the completed VCSEL devices.

For VCSEL performance characterization, we diced the fabricated VCSEL devices into an individual device size of $120 \times 150\ \mu m^2$ and packaged them into the TO can. The packaged VCSEL device was mounted inside a cryogenic chamber for testing under cw current injection condition using a cw current source at 77 K. The emission light was collected by a 25 μm diameter multimode fiber using a microscope with a 40× objective (numerical aperture=0.6) and fed into the spectrometer. The system has a focal distance of 320 mm and a grating of 1800 g/mm with a spectral resolution of 0.15 nm. The output from the spectrometer was detected by a charge-coupled device (CCD) to record the emission spectrum. The spatial resolution of the imaging system was about 1 μm as estimated by the diffraction limit of the objective lens. The near and far field patterns were measured using a confocal microscopy system with two symmet-

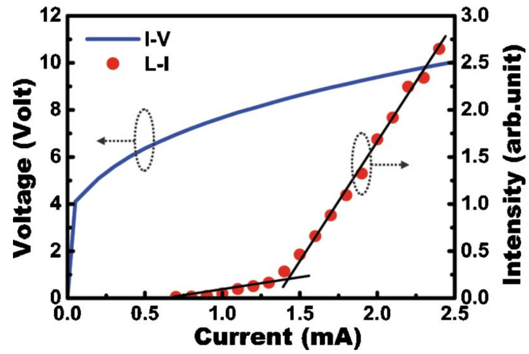

FIG. 2. (Color online) The light output intensity vs injection current and current–voltage characteristics of GaN VCSEL measured under the cw condition at 77 K. The solid line in light output intensity vs current characteristic is a guide for the eye.

ric lenses having a magnification of 40× and a fiber with a 25 μm diameter located at the focal plane for collection of the light emission from the VCSEL sample.

Figure 2 shows the light output power versus cw injection current and current-voltage characteristics of the VCSEL sample at 77 K. The turn on voltage is about 4.1 V, indicating the good electrical contact of the ITO transparent contact layer and the intracavity current injection scheme. The laser light output power showed a distinct threshold characteristic at the threshold current (I_{th}) of about 1.4 mA and then was linearly increased with the injection current beyond the threshold. The threshold current density is estimated to be about 1.8 KA/cm^2 for a current injection aperture of 10 μm in diameter, assuming the current is uniformly injected within the aperture.

Figure 3(a) shows the laser emission spectrum at various injection current levels. A dominant single laser emission line at 462.8 nm appears above the threshold current. Figure

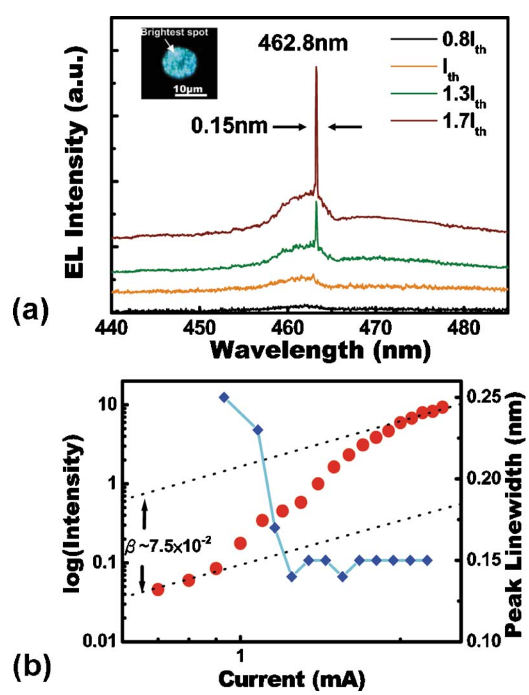

FIG. 3. (Color online) (a) The laser emission spectrum at different injection current levels measured at 77 K. (Inset) CCD image of the emission from the aperture. (b) The logarithm light output intensity and the laser emission linewidth vs the injection current. The dash lines are guides for the eye.

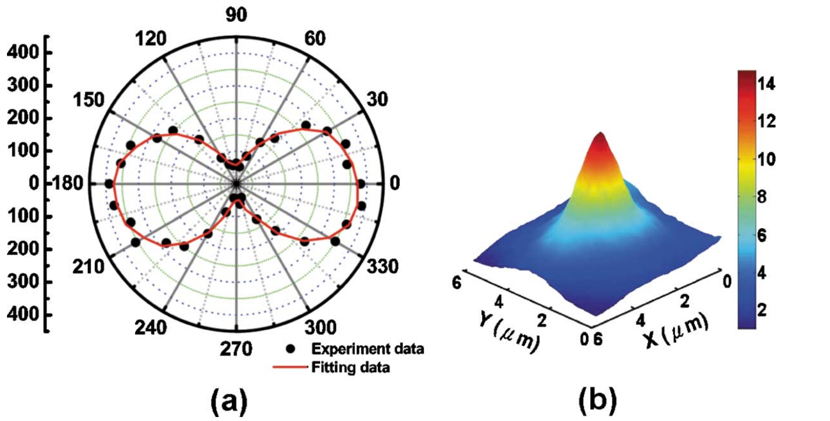

FIG. 4. (Color online) (a) The polarization characteristics of the laser emission from the GaN VCSEL at the threshold. The experiment data is symbolized by dots and the red line is the fitting result. (b) Near field image of the laser spot at the threshold.

3(b) shows the light emission linewidth at various injection current levels. The laser emission spectral linewidth drastically reduces with the injection current above the threshold current and approaches the spectral resolution limit of 0.15 nm at the injection current of $1.7I_{\mathrm{th}}$. The inset of Fig. 3(a) shows the CCD image of the spatial laser emission pattern across the 10 μm emission aperture at an injection current of 1 mA slightly below the threshold. We observed a nonuniform emission intensity across the emission aperture with several bright emission spots. We believe the nonuniformity in the emission intensity across the aperture could be due to the In nonuniformity that creates a nonuniform spatial gain distribution in the emitting aperture as reported earlier.[6] In fact, the lasing action we observed was mainly from those spots with the brightest intensities as indicated in the inset of Fig. 3(a). The spatial dimension of these bright spot clusters is only about a few microns in diameter. As shown in Fig. 4(b), the diameter of the near field intensity of the laser spot at the threshold is around 3 μm. A similar result was also observed and reported recently for the optically pumped GaN VCSELs.[7]

We estimated the spontaneous emission coupling factor β of our VCSEL sample from Fig. 3(b), which is the logarithm plot of Fig. 2. According to Horowicz *et al.*,[8] the difference between the heights of the emission intensities before and after the threshold corresponds roughly to the value of β. We obtained a β value of about 7.5×10^{-2} for our VCSEL. We also estimated the β value from the Purcell factor F_p using the approximation equations:[9] $F_p=(3/4\pi^2)\times\{Q/[V_c/(\lambda/n)^3]\}$ and $\beta=F_p/(1+F_p)$, where Q is the cavity quality factor, λ is the laser wavelength, V_c is the optical volume of laser emission, and n is the refractive index. The refractive index is 2.45 for the GaN cavity. The optical volume V_c is estimated to be about 1.2×10^{-11} cm^3 for a measured emission spot size of about 3 μm, as shown in Fig. 4(c), and the cavity length of about 10.5λ, considering the thickness of the ITO and the penetration depth of the DBRs. The cavity Q is about 1.8×10^3 based on the emission linewidth of 0.25 nm near the threshold. By using these parameters, we obtained an estimated Purcell factor of about 7.9×10^{-2} and an estimated β value of about 7.4×10^{-2}, which is close to the value we obtained above from Fig. 3(b). This β value is nearly three orders of magnitude higher than that of the typical edge emitting laser which is generally in the order of 10^{-4}–10^{-5}.[10] Figure 4 shows the polarization characteristics and near field beam patterns of the laser. The laser emission has a degree of polarization of about 80%. A near diffraction-limited far-field pattern with a small divergence angle of about 11.7° in both horizontal and vertical directions was measured.

In conclusion, we fabricated and demonstrated the cw operation of an electrically pumped GaN-based VCSEL at 77 K. The VCSEL has a hybrid DBR microcavity consisting of high reflectivity AlN/GaN DBR and Ta_2O_5/SiO_2 DBRs and a ten-pair InGaN/GaN MQW active layer. cw laser action occurred at a threshold current of 1.4 mA with an emission wavelength at 462.8 nm in blue wavelength at 77 K. The laser beam has a low divergence angle of about 11.7° and a degree of polarization of about 80%. The laser shows a strong spontaneous emission coupling with an estimated coupling efficiency of about 7.5×10^{-2}.

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