Characteristics of Current-Injected GaN-Based Vertical-Cavity Surface-Emitting Lasers

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***Abstract*—This paper reviews the fabrication technology and performance characteristics of current-injected GaN-based vertical-cavity surface-emitting lasers (VCSELs) with hybrid distributed Bragg reflectors (DBRs). The GaN-based VCSEL consists of a ten-pair Ta_2O_5/SiO_2 top DBR, a 7λ-thick optical cavity embedded with 10 InGaN/GaN multiquantum wells, and a 29-pair AlN/GaN bottom DBR. Lasing action is observed under continuous-wave operation at room temperature. The laser characteristics, such as temperature-dependent laser threshold current, emission wavelength, and spontaneous emission coupling factors, have been measured and discussed.**

***Index Terms*—Distributed Bragg reflectors (DBRs), GaN, vertical-cavity surface-emitting laser (VCSEL).**

I. INTRODUCTION

GaN-BASED wide bandgap materials have been widely used in the fabrication of light-emitting devices, such as LEDs, and laser diodes (LDs) [1], [2]. The edge-emitting-type GaN-based LDs were reported under continuous-wave (CW) operation at room temperature (RT) by Nakamura *et al.* in 1996 [2]. Since then, the edge-emitting-type GaN-based LDs have become prevalent as dominant light sources in the high-density optical storage system. On the other hand, the GaN-based vertical-cavity surface-emitting lasers (VCSELs) have attracted much attention because of their superior characteristics, such as low threshold current, single-longitudinal-mode operation, symmetric and low divergence angle, and 2-D array capability [3]–[5]. These superior characteristics inherited in GaN-based VCSELs have many applications, such as high-density optical storage system, laser printing, laser mouse, and micro- or picoprojectors. However, there are still many challenges to realize a GaN-based VCSEL.

The key issues limiting the development of GaN-based VCSELs are the lattice mismatch between GaN and sapphire substrates, the difficulty in growing high-quality and high-reflectivity GaN-based distributed Bragg reflectors (DBRs), and low optical gain exhibited in InGaN multiple quantum wells (MQWs) due to the complicated issues, such as built-in polarization field in the quantum well, seriously broadening linewidth due to the phase separation with In-rich clusters, and the carrier leakage out of the active regions.

There have been many research groups focused on the growth and fabrication of GaN-based VCSEL. In 1996, Redwing *et al.* reported the optical pumping results of GaN-based VCSEL structure at RT for the first time [6]. Their VCSEL structure consisted of all epitaxially grown layers, including a 10-μm GaN active region and 30-period $Al_{0.40}Ga_{0.60}N/Al_{0.12}Ga_{0.88}N$-based top and bottom mirrors. The threshold pumping energy was as high as 2.0 MW/cm^2 due to the low mirror reflectivity of about 84%–93% and the thick GaN active layer. Subsequently, the $In_{0.1}Ga_{0.9}N$ VCSEL was fabricated and observed lasing action at 77 K by Arakawa *et al.* [7]. The structure was constructed by a hybrid-type cavity consisting of an $In_{0.1}Ga_{0.9}N$ active layer grown on a 35-pair $Al_{0.34}Ga_{0.66}N$/GaN-based bottom DBR with the reflectivity of 97%, and a 6-pair TiO_2/SiO_2 dielectric top DBR with the reflectivity of 98%. In addition, Song *et al*. using laser lift-off (LLO) technology demonstrated the dielectric-type VCSEL structure consisting of ten-pair SiO_2/HfO_2 top and bottom dielectric DBRs and InGaN MQWs [8]. The cavity quality factor was as large as 600 due to the high reflectivity of the top and bottom DBRs exceeding 99.5% and 99.9%, respectively. Moreover, the RT lasing at blue wavelength in the hybrid-type GaN-based VCSEL under optical pumping has been reported by Someya *et al.* [9]. The structure was formed by an InGaN MQW sandwiched between nitride-based and oxide-based DBRs. Thereafter, Carlin *et al.* reported the crack-free fully epitaxial nitride microcavity in 2005 [10]. The cavity was formed by lattice-matched AlInN/GaN-based DBR with reflectivity up to 99%. In the following years, several groups reported the optically pumped GaN-based VCSELs [11]–[14]. We

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also reported optically pumped GaN-based VCSEL structures in dielectric- [15], [16] and hybrid-type cavity structures [17]–[19].

The electrically pumped GaN-based VCSEL has not been reported until 2008. Lu *et al.* first demonstrated electrically pumped GaN-based VCSEL with hybrid DBRs at 77 K [20]. The GaN-based VCSEL structure consisted of a ten-pair InGaN/GaN MQW active layer embedded in a GaN hybrid microcavity of 5 λ optical thickness, and sandwiched between an epitaxial AlN/GaN DBR and a Ta2O5/SiO2 dielectric DBR with reflectivity 99.4% and 99%, respectively. A 240-nm indium-tin-oxide (ITO) was deposited on top of the aperture to serve as the transparent contact layer. CW laser action was achieved at a threshold injection current of 1.4 mA in a 10-μm aperture at 77 K. The laser emitted a blue wavelength at 462 nm with a narrow linewidth of about 0.15 nm. In the same year, Higuchi *et al.* demonstrated CW lasing GaN-based VCSEL at RT [21]. The structure of the VCSEL consisted of top and bottom dielectric SiO_2/Nb_2O_5 DBRs and a two-pair InGaN/GaN quantum-well active layer. The optical cavity consisted of a 7λ-thick GaN semiconductor layer. A 50-nm ITO layer was deposited as a p-type ohmic contact and current spreading layer. The LLO technique was used to remove the sapphire substrate, and GaN-based VCSEL was mounted on a Si substrate by wafer bonding. The threshold current was 7.0 mA for an 8-μm aperture device and the emission wavelength was approximately 414 nm. In 2009, the same group further improved the lasing characteristics of GaN-based VCSEL fabricated by using GaN substrates. The results showed a higher maximum output power and a longer lifetime than that fabricated using a sapphire substrate due to the reduction of dislocation density [22]. In 2010, we demonstrated the GaN-based VCSEL with a hybrid cavity under current injection operating at RT with the lasing wavelength of 412 nm [23]. In the following sections, the method to grow and fabricate the hybrid type GaN-based microcavity will be described in Section II. In Section III, the design of ITO thickness will be discussed. The characteristics of current-injected GaN-based VCSEL will be presented in Section IV. Section V will briefly describe the perspectives and Section VI will summarize this paper.

II. GROWTH AND FABRICATION OF HYBRID MICROCAVITY

Due to the difficulty of growing high-quality and high-reflectivity nitride-based DBRs, the possible structural designs for nitride-based VCSELs can be classified into three major types. First type is the fully epitaxial VCSEL consisting of epitaxially grown III-nitride top and bottom DBRs. Despite that the fully epitaxial microcavity is easy to control the cavity thickness, it is difficult for a fully epitaxial VCSEL to avoid the crack problem due to the accumulation of the strain and to achieve high-reflectivity DBRs [10], [24]. The second type is double dielectric DBR VCSEL. This structure can exhibit high cavity quality factor due to the high-reflectivity DBRs. But the fabrication techniques, such as LLO, are extremely complicated [15]. The third type is the hybrid-type VCSEL, consisting of bottom epitaxial and top dielectric DBRs, which can compromise the advantages and disadvantages of the aforementioned two VCSEL structures [17], [18]. The hybrid DBR VCSEL can avoid the complex process for the electrically pumped VCSEL applications.

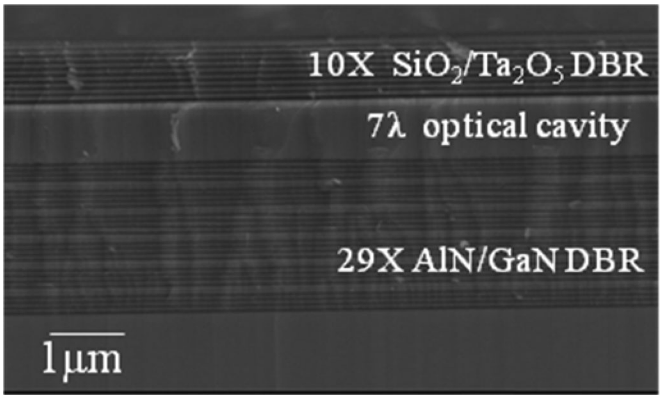


Fig. 1. Cross-sectional SEM image of the whole hybrid GaN-based microcavity structure.

One of the important ingredients in VCSEL is the microcavity. Our hybrid microcavity was grown on a 2-in sapphire substrate in a low-pressure high-speed rotating-disk metal-organic chemical vapor deposition system (EMCORE D75). In the growing process, trimethylgallium, trimethylindium, trimethylaluminum, and ammonia were used as the Ga, In, Al, and N sources. The substrate was thermally cleaned in the hydrogen ambient for 5 min at 1100 °C, and then a 30-nm-thick GaN nucleation layer was grown at 500 °C. The growth temperature was raised up to 1100 °C for the growth of a 2-μm GaN buffer layer. Then, the 29 pairs of AlN/GaN DBR with 5 AlN/GaN superlattice insertion layers were grown under the fixed chamber pressure of 100 torr. In order to reduce the strain problem between the AlN and GaN of the bottom DBR, we inserted one superlattice into each of the five DBR periods of DBR [25]. The overall DBR had 29 AlN/GaN pairs with superlattice insertion layers. On top of this 29-pair AlN/GaN DBR was a 860-nm-thick Si-doped n-type GaN cladding layer, followed by the MQW active region consisting of ten 2.5-nm-thick $In_{0.2}Ga_{0.8}N$ QWs and 12.5-nm-thick GaN barrier layers. Then, a 24-nm-thick AlGaN layer as the electron-blocking layer, a 115-nm-thick p-GaN layer, and a 2-nm-thick p^+ InGaN layer as the contact layer were grown. The AlGaN electron-blocking layer was served to reduce the electron overflow to the p-GaN layer. The *p-i-n* layer formed a 7λ cavity in optical thickness. The MQWs were located at the antinode of light field in the microcavity for enhancing the coupling of photons and the MQWs. A thin heavily doped p-type InGaN contact layer plays a role to reduce the optical loss while maintaining good current spreading capability. Fig. 1 shows the scanning electron microscopy (SEM) image of the whole hybrid microcavity structure with the bottom 29-pair AlN/GaN DBR, the 7λ optical cavity, and the top 10-pair Ta_2O_5 DBR deposited by ion-assisted e-gun system.

To testify the cavity quality in our structure, a hybrid microcavity structure without the ITO layer was fabricated for reflectivity and photoluminescence (PL) measurement. In Fig. 2, both of the 29-pair AlN/GaN DBR and the 10-pair Ta_2O_5 DBR

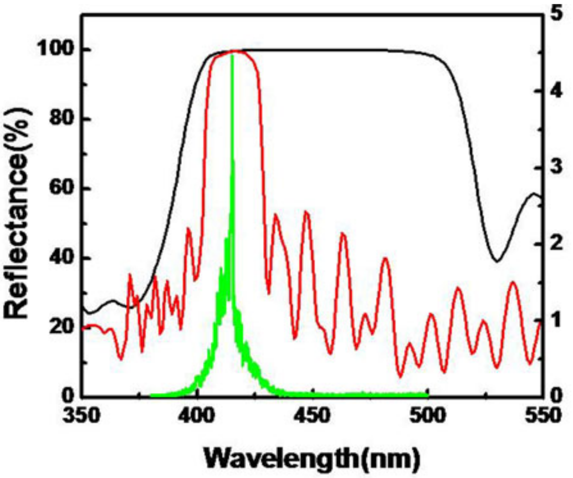


Fig. 2. Reflectivity spectra of top DBR (black line), and bottom DBR (red line), and the corresponding PL (green line) spectrum of the hybrid microcavity.

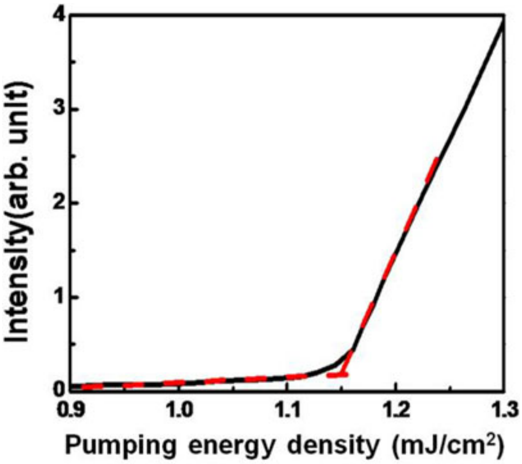


Fig. 3. Light-emission intensity of the GaN-based hybrid microcavity as a function of the pumping energy density.

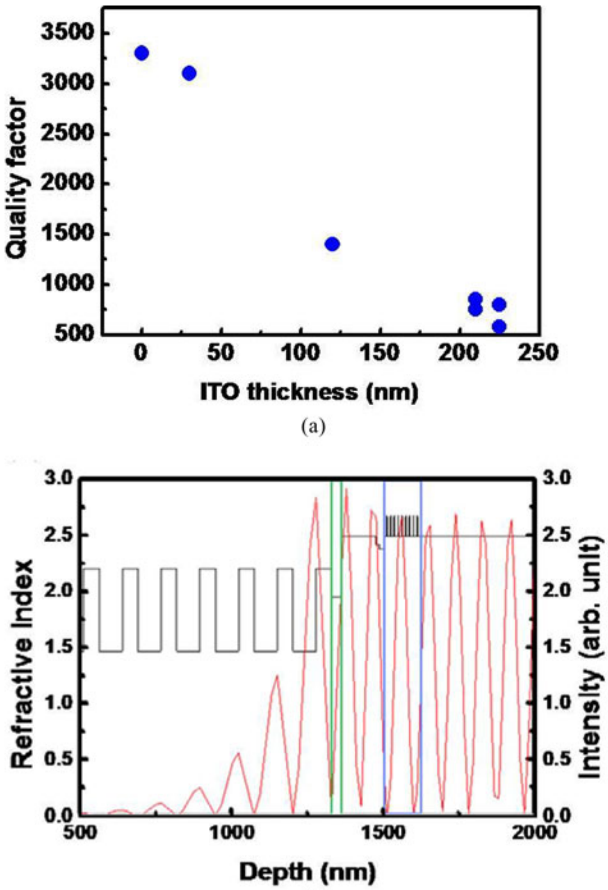
showed high reflectivity of over 99% at the peak wavelength at 410 nm in the *n–k* reflectivity measurement system. The PL emission peak from the hybrid DBR VCSEL structure located exactly within the stopband of two DBRs at 415 nm, and the cavity quality factor (*Q* value) was estimated to be about 1600, demonstrating relatively good cavity quality. We further examined the lasing threshold of this hybrid microcavity structure without the ITO layer by optical pumping. A frequency-tripled Nd:YVO_4 355-nm pulsed laser with a pulsewidth of ~0.5 ns at a repetition rate of 1 kHz was used as the pumping source. The pumping laser beam with a spot size of 60 μm was incident normal to the cavity sample surface. The light emission from the cavity sample was collected using an imaging optic into a spectrometer/charge-coupled device (CCD) (Jobin-Yvon Triax 320 Spectrometer) with a spectral resolution of ~0.15 nm for spectral output measurement. Fig. 3 shows the output light-emission intensity of the GaN-based cavity with hybrid DBRs as a function of the pumping energy density under RT. A threshold energy density of 1.15 mJ/cm^2 was obtained. The relatively low-threshold pumping energy compared to our previous results [19] could be due to the crystal quality improvement of DBR grown with inserted superlattice layers and the effect of the AlGaN electron-blocking layer, which can efficiently confine the carriers in the MQWs.

III. DESIGN OF ITO LAYER THICKNESS

For the electrically pumped VCSEL structure, the ITO layer plays an important role as a current spreading layer inserted between the top dielectric DBR and p-GaN layer. However, the insertion of an ITO layer would increase the internal cavity optical loss due to the absorption loss inherited in the ITO layer. In order to properly estimate the impact of the ITO layer in the hybrid DBR VCSEL structure, we have applied transfer matrix method to calculate the cavity quality factor by estimating the transmission linewidth of the calculated resonant mode. The absorption coefficient of the ITO layer was set to be about 4.58×10^3 cm^{-1} at 420 nm [26], while the other layers remained transparent for the resonant wavelength at around 420 nm. Different ITO layer thickness from 0, 30, 120, 210, to 225 nm were simulated. In Fig. 4(a), the quality factor reduces drastically from 3300 to about 700 when the thickness of the ITO layer varies from 0 to 225 nm. For a 30-nm-thick ITO layer, the simulated value of the Q value of the cavity is about 3100, which is a little smaller than that with a 0-nm-thick ITO layer. Therefore, we consider this thickness to be useful for the electrically pumped VCSEL structure without sacrificing too much cavity Q value. Furthermore, to reduce the absorption loss of the ITO layer, the position of the ITO layer was placed at the node of the optical field, as shown in Fig. 4(b). However, to ensure good electrical contact characteristics, an additional heavily doped p$^+$ InGaN was introduced between the thin ITO layer and the p-GaN layer. This heavily doped InGaN layer is also placed at the node of the optical field inside the VCSEL cavity to minimize any additional absorption loss introduced by this heavily doped layer.

IV. CHARACTERISTICS OF GAN-BASED VCSEL

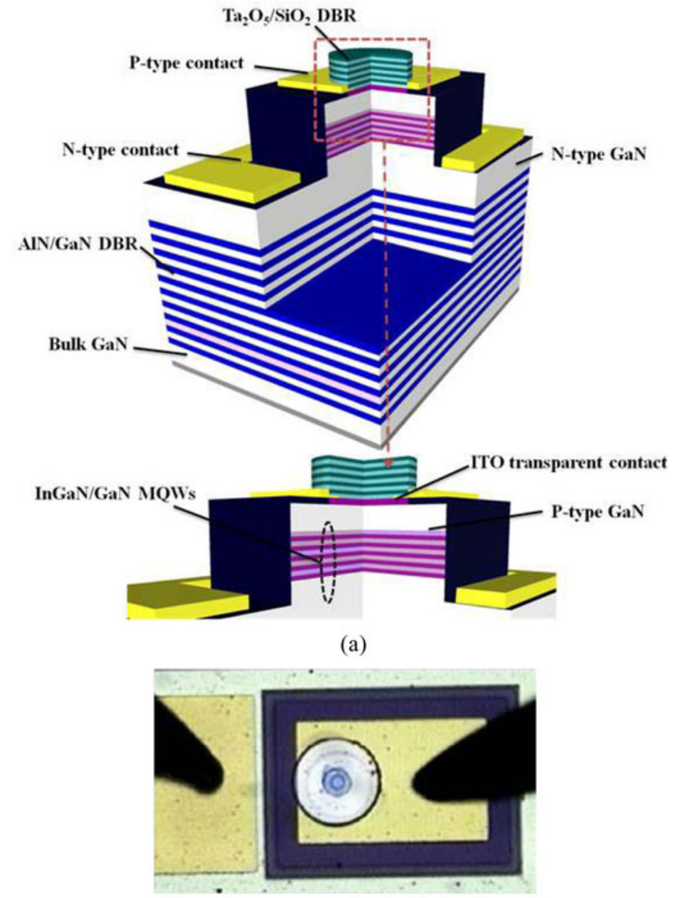
In order to fabricate the VCSEL structure for current injection, more processes are required. Since the as-grown bottom AlN/GaN DBR was undoped and nonconductive, we then processed the as-grown wafer to form the intracavity coplanar *p* and *n* contacts for current injection. In the fabrication process, a 200-nm-thick SiN_x layer was deposited by the plasma-enhanced chemical vapor deposition as a current confined layer. A 10-μm-diameter current injection aperture for VCSEL devices was defined by optical lithography. Next, a 30-nm-thick ITO layer was deposited as the current spreading layer and annealed at 600 °C for 10 min by rapid thermal annealing. Then, the p- and n-contacts were deposited with Ni/Au of about 20/150 nm and Ti/Al/Ni/Au of about 20/150/20/150 nm by the e-gun system, respectively. Finally, ten pairs of Ta_2O_5/SiO_2 of the top dielectric DBR were deposited by the ion-assisted e-gun system to complete the whole GaN-based VCSEL devices. Fig. 5(a)



(a)

(b)

Fig. 4. (a) Simulated quality factors with different thickness of ITO. (b) Optical field intensity (red line) and refractive index (black line) as a function of the distance from top layer. Green square and blue square represent the ITO and MQW region, respectively.



(a)

(b)

Fig. 5. (a) Schematic diagram of the overall GaN-based VCSEL structure with hybrid DBRs. (b) OM image of GaN-based VCSEL when no current injection was applied.

shows the schematic diagram of the overall GaN-based VCSEL structure with hybrid DBRs.

Fig. 5(b) is the optical microscopy (OM) image of the GaN-based VCSEL when no current injection was applied. The VCSEL device was mounted inside a cryogenic chamber for testing under different temperature conditions. The sample was driven by a Keithley 238 current source with the CW operation mode. The emission light was then collected by a 25-μm-diameter multimode fiber using a microscope with a 40× objective and fed into the spectrometer/CCD (Jobin-Yvon Triax 320 Spectrometer) with a spectral resolution of $\sim$0.15 nm for spectral output measurement.

The emitted laser power and the operation voltage from the GaN-based VCSEL as a function of the injection current were measured at 200, 240, 270, and 300 K, as shown in Fig. 6(a). The distinct threshold characteristics were observed with the threshold injection current ($I_{\rm th}$) of about 7.5, 8.2, 9.2, and 9.7 mA at the temperature of 200, 240, 270, and 300 K, respectively. The linewidth of electrically pumped VCSEL was about 0.5 nm, and the threshold current density was 12.4 kA/cm^2 at 300 K. In comparison with the previous report [22], the relative low threshold current density at RT operation could be in part due to the prevention of carrier overflow by using the AlGaN electron-blocking layer on top of the MQWs, and the lower internal loss of the thin ITO layer. The output power from the sample increased linearly with current injection beyond the threshold current. However, at the RT, the laser power started to roll over at higher injection current beyond 15 mA due to the thermal effect, as shown in Fig. 6(b). The roll-over current and the maximum laser output power were increased as the ambient temperature was decreased.

As for the electrical characteristics of the GaN-based VCSEL, when the measurement temperature increased from 200 to 300 K, both of the series resistance and the turn-on voltage of the laser device were decreased from 220 to 180 Ω and 4.55 to 4.3 V, respectively. This could be caused by the worse hole conductivity in p-GaN material at lower temperature (200 K) compared with the RT (300 K) since the activation energy of hole in GaN is relatively high. It should be noted that the turn-on voltage at RT was about 4.3 V, indicating the good electrical contact of the 30-nm ITO transparent layer and the 2-nm-thick heavily doped p$^+$ InGaN layers.

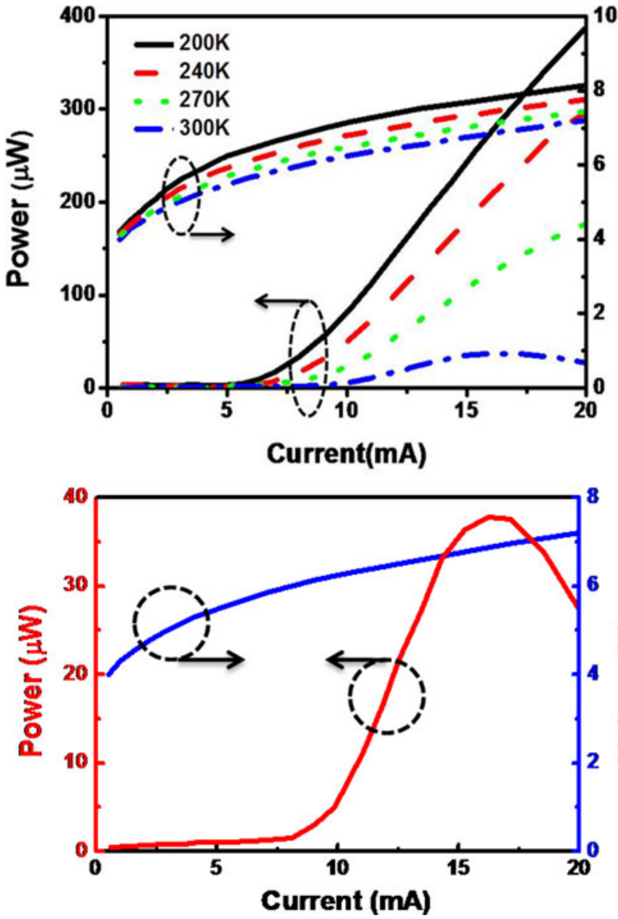


Fig. 6. (a) *LIV* curves under different measurement temperatures of 200 (solid line), 240 (dashed line), 270 (dotted line), and 300 K (dotted dashed line). (b) The *LIV* curve at 300 K; red line and blue line are the *LI* and *IV* curves, respectively.

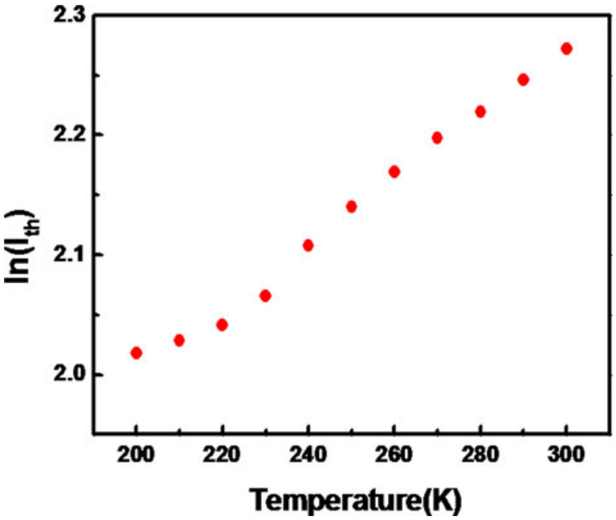


Fig. 7. Seminatural logarithm plot of the dependence of the threshold current [$\ln(I_{\rm th})$] on the ambient temperature.

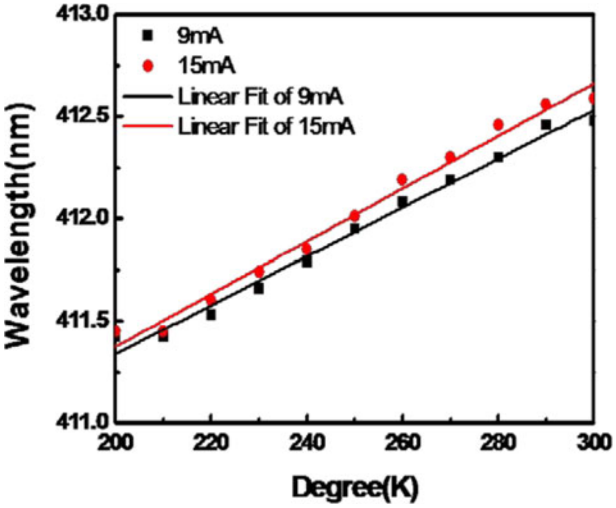


Fig. 8. Lasing wavelength of GaN-based VCSEL as a function of temperature at 9 and 15 mA.

Fig. 7 shows the seminatural logarithm plot of the dependence of the threshold current [$\ln(I_{\rm th})$] on the ambient temperature (*T*). The threshold current gradually increased as the operation temperature rose from 200 to 300 K. In general, the relation between the threshold current and the operation temperature could be characterized by the equation $I_{\rm th} = I_0 \times e^{T/T_0}$, where T_0 is the characteristic temperature and I_0 is a constant. The natural logarithm of the threshold current should show the linear relationship with the ambient temperature empirically for the edge-emitting lasers. For our VCSEL device, the linear fitted characteristic temperature T_0 was calculated to be about 313 K from 220 to 300 K. However, due to the short cavity and single-longitudinal-mode characteristics inherited in the VCSEL cavity, the laser threshold strongly depends on the relative wavelength separation between the cavity resonant mode peak and the gain peak of InGaN MQWs.

The relationship between the natural logarithm of the threshold current and the ambient temperature in VCSEL devices usually appears as a nonlinear curve [27]. Since the redshift speed for the gain peak of InGaN MQWs is faster than that for the cavity resonant mode peak as the temperature increases, an optimum operation temperature can be expected when the gain peak and cavity mode peak are aligned. As can be seen in Fig. 7, a better gain-mode alignment in our GaN-based VCSEL device could be achieved at lower temperature, which is around the lowest point of the curve of characteristic temperature. In addition, the lower T_0 near the RT could be due to the higher leakage current and/or the nonradiative recombination rate.

Fig. 8 shows the lasing wavelength of the GaN-based VCSEL as a function of the ambient temperature operated at 9 and 15 mA, respectively. The lasing wavelength of the VCSEL is mainly determined by the average refractive index throughout the laser cavity. Since the optical field localized mostly in the 7λ GaN cavity layer, as shown in Fig. 4(a), the increase of the refractive index in the GaN cavity layer as the temperature increases will result in the redshift of the lasing wavelength.

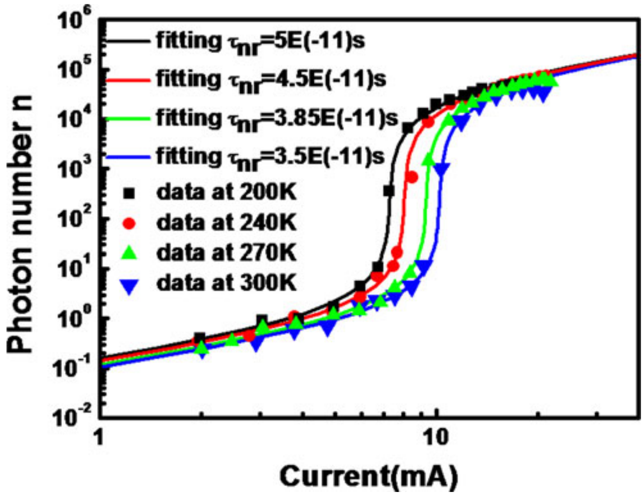


Fig. 9. Laser-emission intensity versed injection current in logarithmic scale. The solid curve is the fitting curve. The β value is about 5×10^{-3} at 300 K.

As a result, the lasing wavelength shows a redshift of about 1 nm as the temperature rose from 200 to 300 K. This lasing wavelength shift per Kevin degree is calculated to be about 10^{-2} nm/K. This value is close to the previous report about the GaN material [28]. Therefore, the longer emission wavelength of the VCSEL operated at 15 mA in comparison to that operated at 9 mA is due to the heating effect. The thermal resistance thus can be deduced to be about 380 K/W at RT.

Due to the short cavity nature of our GaN-based VCSEL, spontaneous emission will easily couple to the laser cavity mode, which can help to reduce the threshold condition. The spontaneous emission coupling factor β*,* defined as the ratio of the spontaneous emission rate coupled to the specific laser mode to the overall spontaneous emission rate, can be extracted by fitting the rate equation expressed as follows [29]:

$$I = \frac{q\gamma}{\beta}\left[\frac{p}{1+p}(1+\xi)\left(1+\beta p+\frac{\tau_{\rm sp}}{\tau_{\rm nr}}\right)-\xi\beta p\right] \qquad (1)$$

where I is the injection current, q is the electron charge, β is the spontaneous emission coupling factor, p is the total photon number in the cavity, V is the volume of the active material, $\tau_{\rm nr}$ is the nonradiative recombination lifetime, $\tau_{\rm sp}$ is the spontaneous emission lifetime, ξ is a dimensionless parameter defined by $\xi = N_0\beta V/\gamma\tau_{\rm sp}$, where γ is the cavity decay rate in per second, which is inversely proportional to the cavity photon lifetime, and N_0 is the transparency carrier density. We estimated the cavity photon number from the laser output power under different ambient temperatures shown in Fig. 6, and replotted the photon number and the injection current in logarithm scales shown as dots in Fig. 9. Then, applying the rate equation with the fitting parameters, such as $\tau_{\rm sp} = 10^{-9}$ s, $V = 1.96 \times 10^{-12}$ cm^3, $N_0 = 10^{19}$ cm^{-3}, and $\gamma = 10^{12}$ s^{-1} [29]. In here, although the $\tau_{\rm sp}$ depends on temperature, the variation of $\tau_{\rm sp}$ would be small under this temperature range [30]. The fitted solid lines shown in Fig. 9 are well matched to the experimental data with the spontaneous emission coupling factor $\beta = 5 \times 10^{-3}$. The value is two order of magnitude higher than that of the typical edge-emitting semiconductor lasers (normally about 10^{-5}) [31], indicating the enhancement of the spontaneous emission into a lasing mode by the high quality factor microcavity effect in the VCSEL structure. It should be noted that the β values were calculated to be 7×10^{-3}, 6.2×10^{-3}, 5.6×10^{-3}, and 5×10^{-3} at temperatures of 200, 240, 270, and 300K, respectively. These values are quite closed under different temperature; therefore, the nonradiative recombination lifetime shall vary to account for the different threshold currents. From these fitting parameters, $\tau_{\rm nr}$ were fitted to be 5×10^{-11} s, 4.5×10^{-11} s, 3.85×10^{-11} s, and 3.5×10^{-11} s at temperatures of 200, 240, 270, and 300 K, respectively. The decrease of the nonradiative recombination lifetime suggests the degraded internal quantum efficiency as the temperature increases. In addition, the relatively small nonradiative recombination lifetime in the active region could be one of the reasons of high threshold current density and low output efficiency in our current devices.

V. PERSPECTIVES

We have demonstrated the lasing action of GaN-based hybrid DBR VCSEL under electrical pumping at RT. However, there are still many issues of VCSEL structure to be further improved. The crystal quality of the active layer has to be refined to reduce the nonradiative recombination channels. By using freestanding GaN substrate [22] or applying superlattice layers before the growth of InGaN MQWs [32] could effectively reduce the defect density to enhance the GaN VCSEL performance. On the other hand, the effective current injection is required for the low threshold current operation since the current leakage paths can be vertically passing through the InGaN MQW and/or horizontally extending out of the current aperture. Although we have applied AlGaN electron-blocking layer in the GaN-based VCSEL structure, the strain-induced polarization field could adversely lower the barrier height, which the leakage current could still occur in the vertical current path. As a result, the introduction of polarization-matched InGaN/AlInGaN MQWs could independently control the interface polarization charges and bandgap, which can help to design a preferable electron-blocking layer [33]. As for the effective current injection in the horizontal direction, the current aperture should get close to the InGaN MQW as much as better. In addition, the present GaN-based VCSEL structure requires transverse optical confinement to further reduce the threshold current and properly control the laser beam quality. This could be rather challenging because oxidation of the GaN-based material remains difficult. Nonetheless, a properly designed transverse optical confinement layer can combine the function of the current aperture to realize a low-threshold high-efficiency GaN-based VCSEL.

VI. SUMMARY

The GaN-based VCSELs with hybrid mirrors have demonstrated the CW operation at RT. The laser structure is composed of a 29-pair high-reflectivity AlN/GaN bottom DBR, a 7λ

cavity region, and a 10-pair SiO_2/Ta_2O_5 dielectric DBR. The laser structure has utilized a thin ITO layer of 30 nm as the transparent conducting layer, combining with a thin heavily doped p-type InGaN contact layer, to reduce the optical loss while maintaining good current spreading capability. On the top of the InGaN MQW, an inserted AlGaN electric blocking layer plays a role to prevent the carrier overflow. At RT, the laser has a threshold current at 9.7 mA and current density corresponding to 12.4 kA/cm^2. The spontaneous emission coupling factor of the GaN-based VCSEL was estimated to be about 5×10^{-3}. Furthermore, the laser device has good electrical characterisitics with a low turn-on voltage and the series resistance of 4.3 V and 180 Ω, respectivly. The successful operation of electrically pumped GaN-based VCSELs at RT shall lead to novel applications requiring low operation current and power in the near future.

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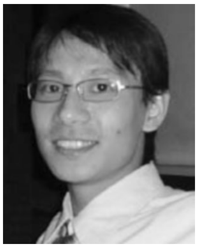

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