

Recent advances on CW current injection blue VCSELs

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ABSTRACT

The current injection GaN-based vertical cavity surface emitting lasers with hybrid mirrors have demonstrated the CW operation at room temperature. The laser hybrid cavity composes of a 29-pair high-reflectivity AlN/GaN bottom DBR, a 7-lambda cavity region, and a 10-pair SiO₂/Ta₂O₅ 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. The laser has typical emission wavelength around 412 nm with a threshold current of about 9.7 mA at room temperature. Further details of the laser design and performance characteristics are described.

Keywords: vertical cavity surface emitting lasers (VCSEL), GaN, Distributed Bragg Reflectors

1. INTRODUCTION

GaN-based vertical cavity surface emitting lasers (VCSELs) have attracted great interest for various optical applications.¹ Highly reflective epitaxial distributed Bragg reflectors (DBRs), such as quarter-wave GaN/AlGaIn multi-layers, have played an important role in the operation of VCSELs.^{2,3} Because of the relatively high contrast of the refractive index between GaN and AlN in comparison to the GaN/AlGaIn DBRs, a small number of GaN/AlN DBR pairs is required to achieve a high reflectivity with a broad stop band width. However, the large lattice mismatch between GaN and AlN induces a lot of cracks in the DBR when the number of the epitaxial pairs increases. These cracks tend to grow into V-shaped grooves, which seriously affect the reflectivity of the DBR due to scattering, diffraction and absorption. Therefore, it is necessary to suppress crack generation to achieve a smooth surface and a high reflectivity. Shirasawa and our group have studied and reported a metal organic chemical vapor deposition(MOCVD) grown GaN/AlN DBRs.^{4,5} Ng, Moustakas, and Chu reported a molecular beam epitaxy grown GaN/AlN DBR with a reflectivity of 99%.³ However, these samples exhibited extensive cracking surfaces. Many research groups have studied and reported the approaches of using GaN/AlGaIn or AlN/AlGaIn super lattice (SL) insertion layers to reduce the biaxial tensile strain and successfully suppress crack generation while growing high Al-contained structures.⁶⁻¹⁰ Nakada et al. have reported a MOCVD grown 30-pair GaN/Al_{0.41}Ga_{0.59}N DBR with a reflectivity of 98%. They employed 100 periods of GaN/AlGaIn SL insertion layers prior to the growth of the GaN/AlGaIn DBRs to decrease the tensile strain in the DBRs.⁶ Optically pumped GaN-based VCSELs have been reported by using different kinds of optical cavity structures, such as dielectric DBR VCSELs with cavities consisting of dielectric top and bottom DBRs,¹¹ and hybrid DBR VCSELs with cavities consisting of epitaxially grown nitride bottom DBRs and dielectric top DBRs.¹² We have recently demonstrated the continuous wave (cw) current injection of GaN-based VCSEL with hybrid mirrors at 77 K in 2008.¹³ Subsequently, the room temperature operation of GaN-based VCSEL devices was reported using optical cavities sandwiched by double dielectric DBRs.^{14,15} The major improvements of their devices to achieve room temperature operation are by using a thinner transparent conducting layer of about 50 nm to reduce the internal optical loss and by using the GaN substrate to ensure the good crystal quality of active layers. However, to form VCSELs with double dielectric DBRs required complex fabrication process, such as laser lift-off or elaborated polishing and bonding process.¹⁶

In this paper, we report the growth of the high quality crack-free 20-pair GaN/AlN DBRs with insertion of three sets of 5.5 periods of GaN/AlN SL during the growth and the achievement of high reflectivity with wide stop band width. We also report the achievement of cw current injection room temperature lasing with hybrid DBR cavity and a thin indium-tin-oxide (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. Moreover, we inserted an AlGaIn electric blocking layer on the top of the InGaN multiple quantum well (MQW) to prevent the carrier

overflow.¹⁷ The lasing characteristics such as laser output power and device voltage versus injected current characteristics, degree of polarization (DOP), divergence angle, and spontaneous emission coupling factor have been measured and investigated.

2. EXPERIMENT

The GaN/AlN DBRs were grown in a low pressure EMCORE D75 MOCVD system. (0001)-oriented, 2-in.-diam sapphire substrates were used for the growth of samples. Trimethylgallium and trimethylaluminum were used as group III source materials and ammonia as the group V source material. The growth pressure was kept at 100 Torr. The surface morphology of the DBRs was studied by the optical microscope. The thicknesses of the individual layers in the DBRs were investigated by transmission electronic microscopy (TEM). Measurements on the reciprocal space maps (RSMs) of x-ray diffraction intensity were performed on the Philips X'Pert material research diffraction system around an asymmetrical GaN () Bragg peak. The reflectivity spectrum of the GaN/AlN DBRs was measured by the n & k ultraviolet-visible spectrometer with normal incidence at room temperature. Figure 1(a) shows two DBR layer structures grown and examined in this research. The normal DBR structure without the SL layers referred to as the non-SL sample was grown for comparisons. The non-SL DBR sample has the following layers: a 30-nm-thick GaN nucleation layer grown at 500 °C, a 2-μm-thick GaN bulk layer grown at 1100 °C, and 20 pairs of quarter-wave GaN/AlN layers grown at 1100 °C. The ambient gas was changed from hydrogen into nitrogen before the DBR layers were grown. For the DBR structure with SL layers, referred to as the SL sample, three sets of a half-wave layer consisting of 5.5 periods of GaN/AlN SL and GaN layer were inserted in every five pairs of the 20-pair GaN/AlN DBR structure, while keeping the other growth conditions the same as the non-SL sample. The center wavelength of these DBRs was designed to be around 400 nm.

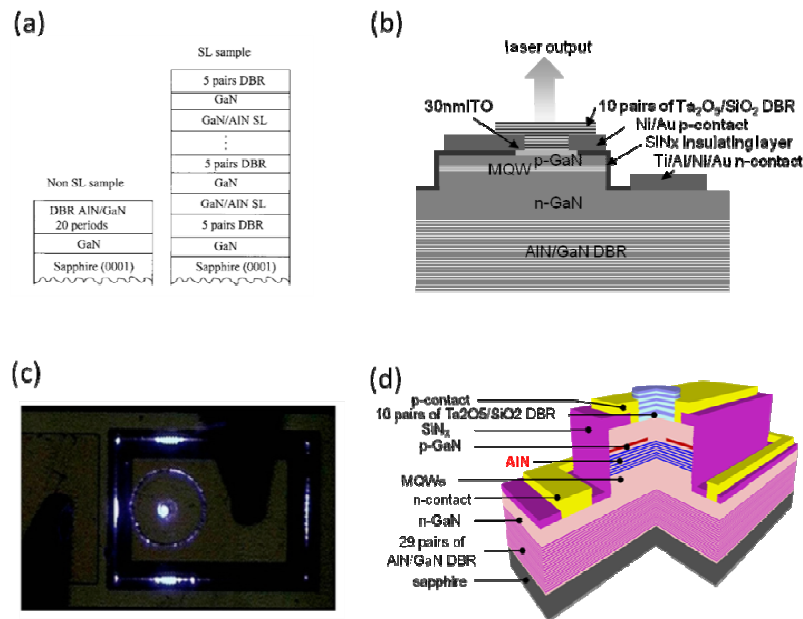


FIG. 1. (a) Structures of the non-SL and SL samples grown and examined in this study. Non-SL sample is the normal 20-pair GaN/AlN DBR and the SL sample has been inserted with three sets of 5.5 periods of GaN/AlN SL in the 20-pair GaN/AlN DBR. (b) The schematic diagram of the overall GaN-based VCSEL structure with hybrid mirrors. (c) The CCD image of GaN-based VCSEL devices operated under 2 mA at room temperature. (d) The buried AlN forms a current aperture in the structure.

Figure 1(b) shows the schematic diagram of the whole GaN-based VCSEL structure. In the structure, the positions of the ITO layer and MQWs region are located at the node and antinode positions of the electric field, respectively, to reduce the absorption from the ITO layer and to further increase the coupling between the electric field and MQWs region. The VCSEL structure was grown on a 2 in. sapphire substrate by the metal-organic chemical vapor deposition system. 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 thick

GaN buffer layer. The subsequent epitaxial structure consisted of a 29-pair AlN/GaN DBR, a 7λ cavity ($\lambda=410$ nm) including a 860 nm thick n-GaN layer, ten-pairs InGaN/GaN (2.5 nm/12.5 nm) MQWs, a 24 nm thick AlGaIn layer as the electron blocking layer, a 110 nm thick p-GaN layer, and a 2 nm thick p⁺ InGaIn layer as the contact layer. The AlGaIn electron blocking layer was served to reduce the electron overflow to the p-GaN layer. In the fabrication process, a 200 nm thick SiN_x layer was deposited by the plasma enhanced chemical vapor deposition (PECVD) as a current confined layer. By this way, the current injection aperture of VCSEL devices was about 10 μ m in diameter. Then, a 30 nm thick ITO layer was deposited as the current spreading layer due to the poor conductivity of the p-GaN layer and annealed at 600 °C for 10 min by rapid thermal annealing. The 2 nm thick p⁺ InGaIn layer on the p-GaN surface can further reduce the series resistance between the thin ITO layer and the p-GaN layer with a slight increase of absorption. Then, the p-contact and n-contact were deposited with Ni/Au of about 20 nm/150 nm and Ti/Al/Ni/Au of about 20 nm/150 nm/20 nm/150 nm by the e-gun system, respectively. Finally, ten-pairs Ta₂O₅/SiO₂ of the top dielectric DBR were deposited by the ion-assisted e-gun system to complete the whole GaN-based VCSEL devices. Figure 1(c) shows the charge-coupled device (CCD) image of a VCSEL device injected at 2 mA under cw current injection at room temperature.

We also insert the AlN in the previous structure to improve the optical confinement as shown in Fig. 1(d). First, the epi-structure was grown on a c-plane sapphire substrate and the growth stopped at the 20 nm-thick p-GaN layer just right above the AlGaIn electron blocking layer. Then, the SiO₂ hard mask used to define the current aperture was grown on that epi structure by PECVD with the effective current apertures. The 30 nm-thick AlN layer was re-grown on the patterned sample surface by MOCVD system with the epitaxial environment at 1020 °C and 100 torr. Then, the SiO₂ mask was lifted off by using buffered oxide etch (BOE) wet etching. The 130 nm p-type GaN and 2 nm InGaIn layer were regrown on the sample. The 2 nm InGaIn layer is used for reduction of the Schottky barrier height and improving the current spreading in p-type GaN. The buried AlN forms a current aperture in the structure shown as Fig. 1(d).

3. RESULTS AND DISCUSSION

Figure 2 shows the optical microscopy image of these two samples. For the non-SL sample, cracks were always observed when the number of DBR pairs is greater than 10 [Fig. 2(a)]. However, the cracks were not observed in our case when the number of DBR pairs is less than 5. As a result, we chose to insert three sets of a half-wave layer consisting of a quarter-wave GaN/AlN SL and a GaN layer in every five pairs of GaN/AlN DBRs in the SL sample. No cracks were observed for the SL sample as shown in Fig. 2(b). Figure 3 shows cross-sectional TEM images of the SL sample. The lighter layers represent AlN layers while the darker layers represent GaN layers.

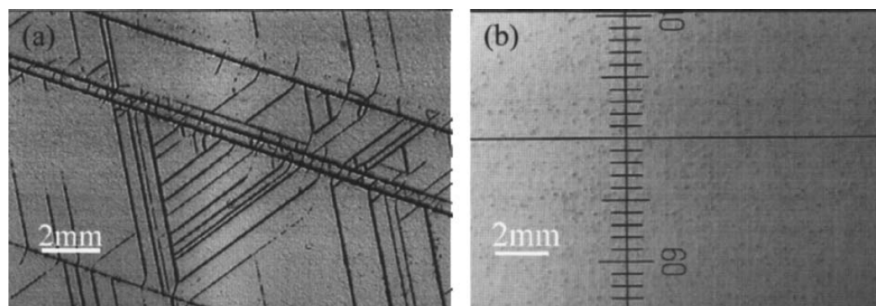


FIG. 2. Plane-view optical microscope images of the 20 periods of GaN/AlN DBRs for (a) non-SL sample and (b) SL sample.

In Fig. 3(a), no cracks can be observed in the TEM image. However, some V-shaped defects dark spots were still observed on the interfaces of GaN or AlN layers in Fig. 3(a). These V-shaped defects have been reported earlier to be due to various origins such as stacking mismatch boundaries and surface undulation.¹¹ Figure 3(b) shows the cross section of one set of 5.5 pairs of GaN/AlN SL insertion layers. The interface between GaN and AlN is sharp and abrupt. The GaN/AlN SL insertion layers were ended by one more AlN layer to identify the interface changing from the AlN layer to the GaN layer. Figure 3(c) shows reflectivity spectra of two samples. They exhibit flattop stop bands, indicating high crystal quality of the samples. The peak reflectivity of the SL sample at 399 nm is 97%, and the stop band width is 14 nm. However, the peak reflectivity of the non-SL sample at 400 nm is only 92%, and the stop band width is 13 nm. The reduction of the cracks should be an important factor in obtaining a high reflectivity of SL sample.

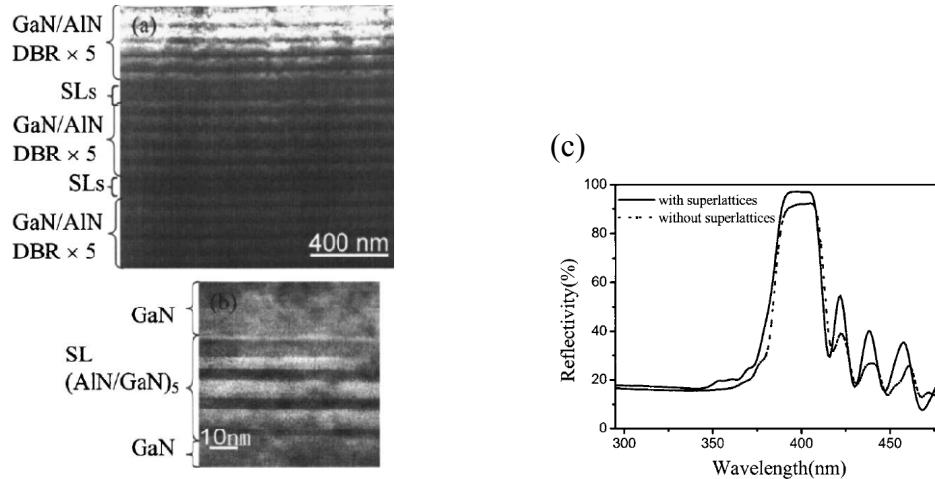


FIG. 3. TEM cross-sectional image of the SL sample for (a) top 17 pairs of DBR structure, and (b) one set of AlN/GaN SL. (c) Reflectivity spectra of 20-pair DBRs of non-SL and SL samples.

The GaN-based VCSEL devices with current injection apertures of about $10\ \mu\text{m}$ in diameter were tested by using a Keithely 238 cw current source. The emission light was collected by a $100\ \mu\text{m}$ diameter multimode fiber and fed into the spectrometer using a grating of $1800\ \text{g/mm}$ with a spectral resolution of about $0.15\ \text{nm}$. The output from the spectrometer was detected by a CCD to record the emission spectrum. The VCSEL devices were then measured at environment temperature at $300\ \text{K}$. Figure 4(a) shows L-I-V curves at $300\ \text{K}$. The dashed line is the linear fitting curve of the laser output power versus injection current. A clear lasing transition from spontaneous emission to stimulated emission can be observed at room temperature. From the linear fitting curve, the laser threshold current is around $9.7\ \text{mA}$ corresponding to the current density of about $12.4\ \text{kA/cm}^2$. The relative low threshold at room temperature operation could be due in part to the prevention of carrier overflow by using the electron blocking layer on top of the MQWs and the lower internal absorption loss of the thinner ITO layer. The turn-on voltage is about $4.3\ \text{V}$ indicating the good electrical contact of the $30\ \text{nm}$ ITO transparent layer and the $2\ \text{nm}$ thick InGaN layers. The output laser intensity from the sample increased linearly with current injection beyond the threshold current. However, the laser intensity started to roll over at higher injection current beyond $15\ \text{mA}$ due to the thermal effect. We estimated the spontaneous emission coupling factor from the log-log plot of L-I curve as shown in Fig. 4(b). The data points are matched well to the solid fitting line calculated from microcavity laser rate equations.¹¹ From the curve, we obtained an estimated β value of about 5×10^{-3} .

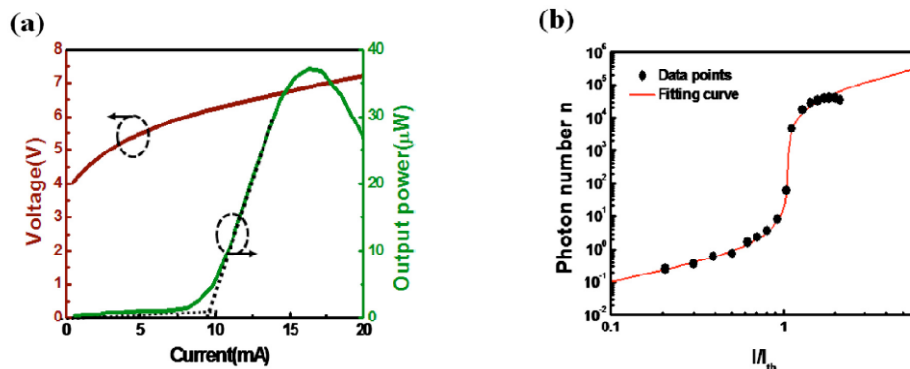


FIG. 4.(a) The output power and the voltage as a function of injection current at $300\ \text{K}$. The threshold current and turn-on voltage are about $9.7\ \text{mA}$ and $4.3\ \text{V}$. (b) The laser emission intensity vs. injection current in logarithmic scale. The circle points and the solid curve are the measurement data and the fitting curve. The β value is about 5×10^{-3} .

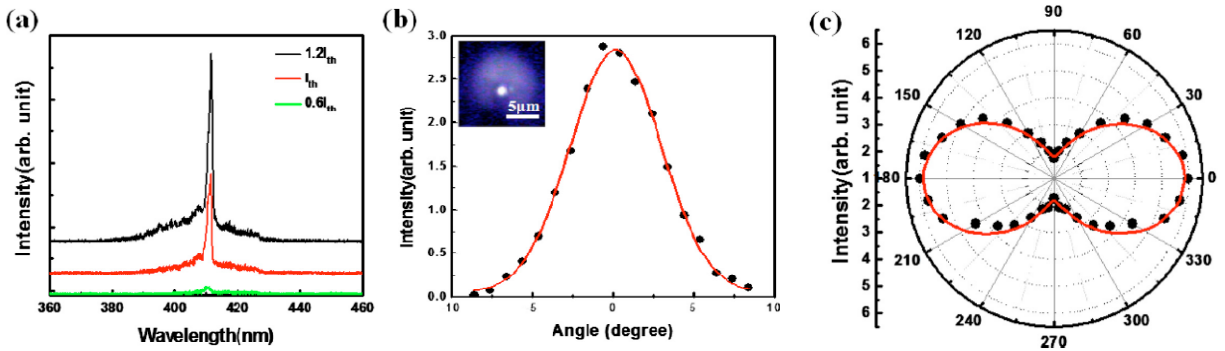


FIG. 5. (a) The emission spectra were recorded at injection current of $0.6I_{th}$, $1I_{th}$, and $1.2I_{th}$. (b) The laser divergence angle of about 8° was measured by the angular-resolved measurement system. The inset image shows the lasing spot with the diameter of about $2\text{ }\mu\text{m}$. (c) The DOP of VCSEL device is about 55%. The circle points are the measurement results and the solid line is the fitting curve.

Figure 5(a) shows the emission spectra of our GaN-based VCSEL devices at current injection of $0.6I_{th}$, $1.0I_{th}$, and $1.2I_{th}$, respectively. The laser emission wavelength was measured to be 412 nm with a linewidth of about 0.5 nm. The inset of Fig. 5(b) shows the CCD image of a lasing spot size of about $2\text{ }\mu\text{m}$ in diameter. Finally, using the angular-resolved measurement system, the laser intensity at different angles emitted from the GaN-based VCSELs was collected by using a $600\text{ }\mu\text{m}$ fiber. Figure 5(b) shows the measurement data at different angles and the solid curve is the fitting curve. We obtained a laser beam divergence angle of about 8° . Figure 5(c) shows the DOP of the laser beam. The solid line is the fitting curve. The DOP value was estimated to be about 55%.

4. CONCLUSION

In summary, we have fabricated and characterized a crack-free 20-pair GaN/AlN DBRs with the SL insertion layers. The DBR showed no observable cracks and high reflectivity of 97% compared to the 92% reflectivity of non-SL DBR samples. The stop band width was also increased from 13 to 14 nm. Then, the cw room temperature operation of GaN-based VCSELs with the high reflectivity and broad stop band AlN/GaN DBR fabrication was achievement. The laser has a thin ITO layer of 30 nm as the transparent conducting layer combining with a thin heavily doped p-type InGaIn contact layer to reduce the optical loss while maintaining good current spreading capability. At 300 K, the laser has a threshold current at 9.7 mA corresponding to 12.4 kA/cm^2 . The laser emission wavelength is 412 nm with a linewidth of about 0.5 nm. The laser has an estimated spontaneous emission coupling factor of about 5×10^{-3} . The DOP and divergence angle of the laser are measured to be 55% and 8° , respectively. The GaN-based VCSEL should have potential applications in such area as 2D/3D display, high density optical storage, and laser printing, etc.

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