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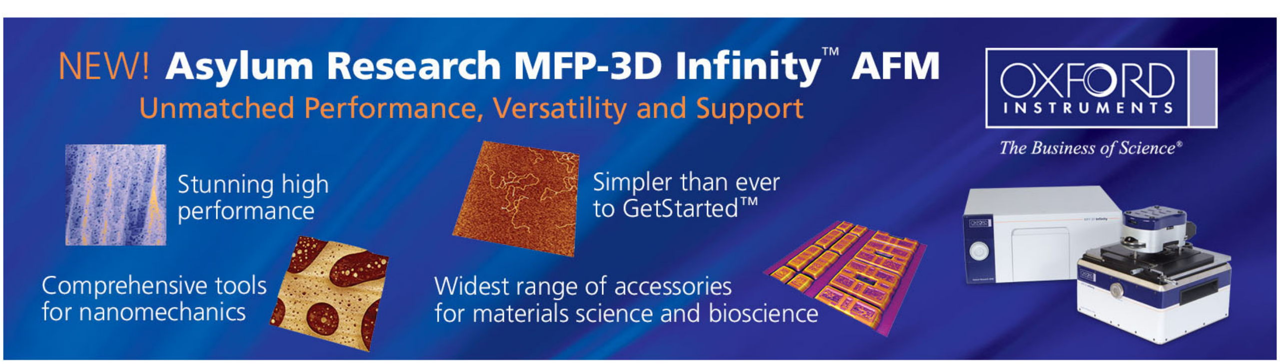

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Continuous wave operation of current injected GaN vertical cavity surface emitting lasers at room temperature

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We report the demonstration of the continuous wave laser action on GaN-based vertical cavity surface emitting lasers at room temperature. The laser structure consists of a ten-pair Ta_2O_5/SiO_2 distributed Bragg reflector (DBR), a 7λ-thick optical cavity, ten-pairs InGaN/GaN multiquantum wells with an AlGaN electron blocking layer, and a 29-pair AlN/GaN DBR. The laser has a threshold current of about 9.7 mA corresponding to the current density of about 12.4 kA/cm^2 and a turn-on voltage about 4.3 V at 300 K. The lasing wavelength was 412 nm with a linewidth of about 0.5 nm. A spontaneous emission coupling efficiency factor of about 5×10^{-3} and the degree of polarization of about 55% were measured, respectively. The laser beam has a narrow divergence angle of about 8°. © *2010 American Institute of Physics*. [doi:10.1063/1.3483133]

GaN-based materials have attracted a great attention since the early 1990s due to the wide direct band gap and the promising potential for the optoelectronic devices such as light emitting diodes and laser diodes.[1,2] So far, GaN-based edge emitting lasers have been demonstrated and applied in commercial products for high density optical storage applications. However, the vertical cavity surface emitting lasers (VCSELs), with superior characteristics such as the single longitudinal mode emission, low divergence angle, and array capability, are still under development and currently gaining much attention. Optically pumped GaN-based VCSELs have been reported by using different kinds of optical cavity structures, such as dielectric distributed Bragg reflectors (DBR) VCSELs with cavities consisting of dielectric top and bottom DBRs,[3] and hybrid DBR VCSELs with cavities consisting of epitaxially grown nitride bottom DBRs and dielectric top DBRs.[4] We have recently demonstrated the continuous wave (cw) current injection of GaN-based VCSEL with hybrid mirrors at 77 K in 2008.[5] Subsequently, the room temperature operation of GaN-based VCSEL devices was reported using optical cavities sandwiched by double dielectric DBRs.[6,7] 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.[8] In this paper, we report the achievement of cw 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 AlGaN electric blocking layer on the top of the InGaN multiple quantum well (MQW) to prevent the carrier overflow.[9] 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.

Figure 1(a) 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

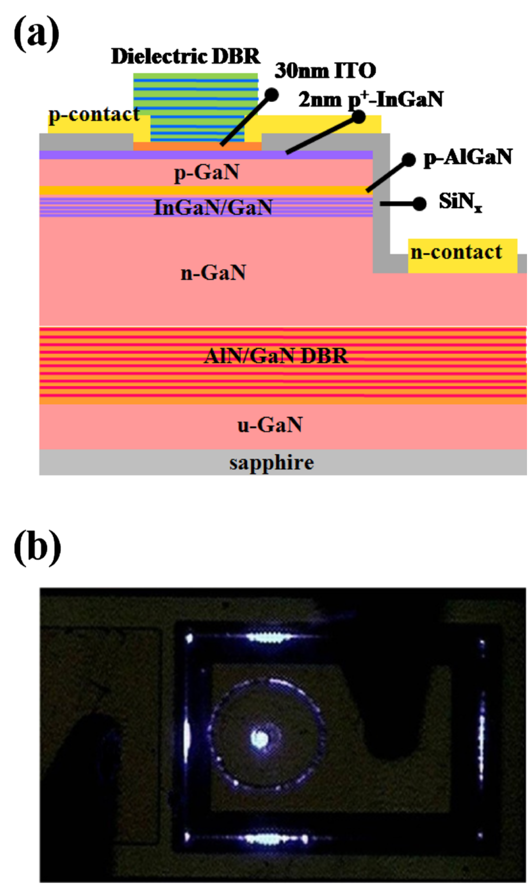

FIG. 1. (Color online) (a) The schematic diagram of the overall GaN-based VCSEL structure with hybrid mirrors. (b) The CCD image of GaN-based VCSEL devices operated under 2 mA at room temperature.

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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 (λ =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 AlGaN layer as the electron blocking layer, a 110 nm thick p-GaN layer, and a 2 nm thick p^+ InGaN layer as the contact layer. The AlGaN electron blocking layer was served to reduce the electron overflow to the p-GaN layer. In order to reduce the crack problems encountered in the AlN/GaN DBRs, we inserted one AlN/GaN superlattice into each five DBR periods at first 20 pairs of DBR. Then the superlattice was inserted into each three DBR periods for the remaining nine pairs of DBR to reduce the tensile strain.[10] 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. By this way, the current injection aperture of VCSEL devices was about 10 μm 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^+ InGaN 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 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. Both of the 29-pair AlN/GaN DBR and the ten-pair Ta_2O_5 DBR show a high reflectivity of over 99% at the peak wavelength at 410 nm in the n-k measurement system. Figure 1(b) shows the charge-coupled device (CCD) image of a VCSEL device injected at 2 mA under cw current injection at room temperature.

The GaN-based VCSEL devices with current injection apertures of about 10 μm in diameter were tested by using a Keithely 238 cw current source. The emission light was collected by a 100 μm diameter multimode fiber and fed into the spectrometer using a grating of 1800 g/mm with a spectral resolution of about 0.15 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 K. Figure 2(a) shows L-I-V curves at 300 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 mA corresponding to the current density of about 12.4 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

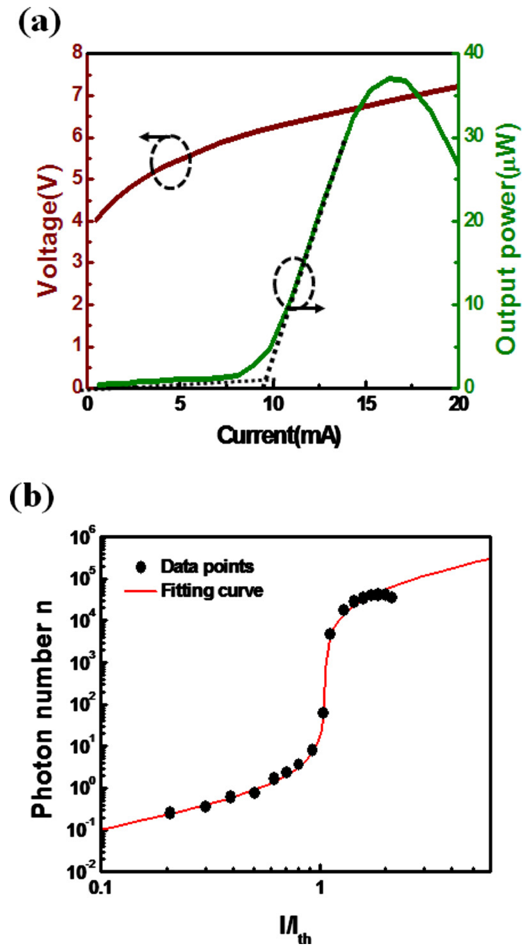

FIG. 2. (Color online) (a) The output power and the voltage as a function of injection current at 300 K. The threshold current and turn-on voltage are about 9.7 mA and 4.3 V. (b) The laser emission intensity vs injection current in logarithmic scale. The circle points and the solid curve are the measurement data and the fitting curve. The β value is about 5×10^{-3}.

turn-on voltage is about 4.3 V indicating the good electrical contact of the 30 nm ITO transparent layer and the 2 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 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. 2(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}.

Figure 3(a) shows the emission spectra of our GaN-based VCSEL devices at current injection of $0.6I_{th}$, $1I_{th}$, 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. 3(b) shows the CCD image of a lasing spot size of about 2 μm 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 μm fiber. Figure 3(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 3(c) shows the DOP of the laser beam. The solid line is the fitting curve. The DOP value was estimated to be about 55°.

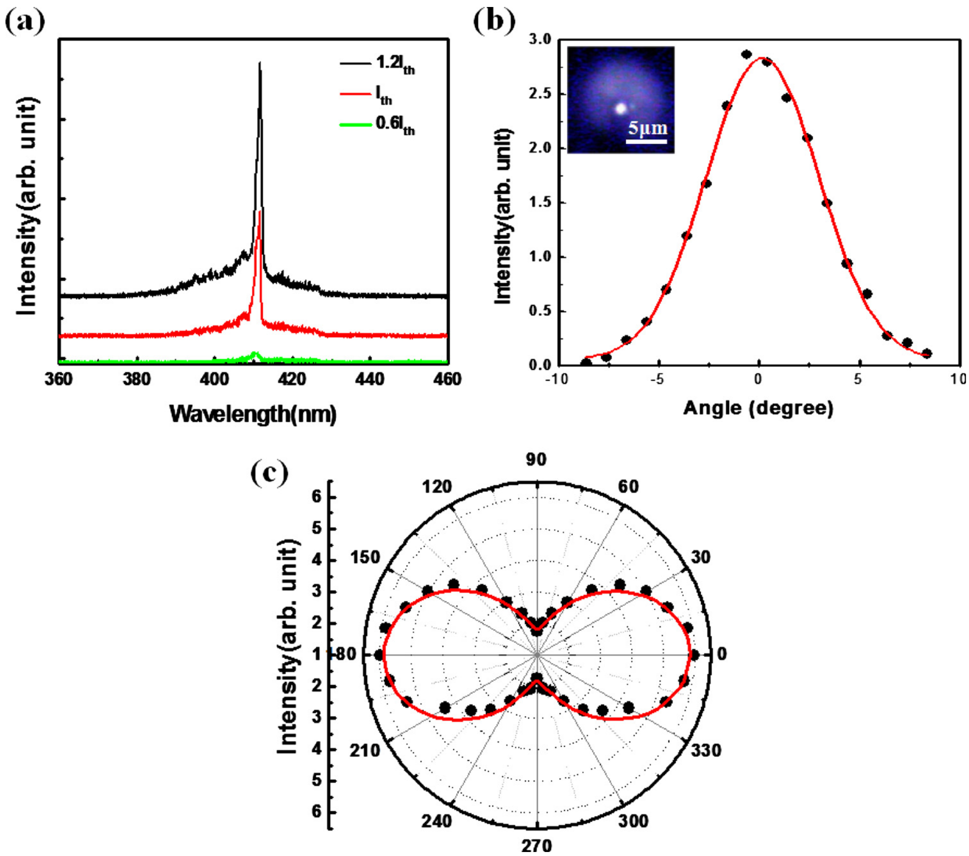

FIG. 3. (Color online) (a) The emission spectra were recorded at injection current of $0.6I_{th}$, $1I_{th}$, and $1.2I_{th}$. (b) The laser divergence angle of about 8° was measured by the angular-resolved measurement system. The inset image shows the lasing spot with the diameter of about 2 μm. (c) The DOP of VCSEL device is about 55%. The circle points are the measurement results and the solid line is the fitting curve.

In summary, we have demonstrated the cw room temperature operation of GaN-based VCSELs with hybrid mirrors. The laser has 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. An AlGaN electric blocking layer on the top of the InGaN MQWs is also inserted to prevent the carrier overflow. 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.

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