Novel blue continuous-wave current-injected light source

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An electrically pumped gallium nitride vertical-cavity surface-emitting laser exhibits promising performance at a wavelength of 462nm, achieved with excellent electrical properties.

Vertical-cavity surface-emitting lasers (VCSELs) contain two high-reflectivity distributed-Bragg reflectors (DBRs) as well as a short cavity characterized by a small optical-mode volume. They emit a single longitudinal mode in a circularly symmetric beam with little beam divergence. Both characteristics are superior to those achieved with edge-emitting lasers and desirable for many practical applications in, for example, high-density optical storage and laser printing. In addition, the strong field in the micro-cavity facilitates exploration of cavity quantum-electrodynamics effects, such as single-photon and polariton emission, controlled spontaneous emission, and low threshold (or thresholdless) lasing.

Over the past decade, two developments have affected the realization of electrically pumped gallium nitride (GaN)-based VCSELs. First, high-reflectivity, high-quality DBRs composed of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN exhibit a large lattice mismatch that forms cracks in the epitaxially grown DBR structure. These cracks could result in a reduction in optical reflectivity and become a leakage-current path. The second is the fabrication of novel, high-transparency, high-conductivity contacts for current injection, which was triggered by the difficulties encountered in constructing low-resistance p-type GaN layers.

In 1996, GaN-based edge-emitting laser diodes were first realized at room temperature by Nakamura's team.¹ Arakawa and co-workers subsequently fabricated an $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ VCSEL and observed lasing at 77K for the first time in 1998.² We recently fabricated a crack-free high-reflectivity DBR by incorporating AlN/GaN superlattice layers between the DBR structures to reduce V-shaped defects and act as strain buffers.³

Figure 1 shows the device structure employing hybrid mirrors. It consists of 29 pairs of AlN/GaN DBRs and a 5λ (where λ refers to the operating wavelength) active region with a

Figure 1. Schematic diagram of an electrically pumped vertical-cavity surface-emitting laser. DBR: Distributed-Bragg reflector. GaN, AlN: Gallium, aluminum nitride. MQW: Multi-quantum well.

790nm-thick n-type GaN layer, 10 pairs of InGa_x/GaN multiple quantum wells, and a 120nm-thick p-type GaN layer. The DBR showed a high peak reflectivity of 99.4% ($\lambda = 450\text{nm}$). A 0.2 μm -thick SiN_x layer was used as current block to limit the current-injection area to 10 μm in diameter. We used indium tin oxide (ITO) as our transparent contact layer on top of the p-type GaN film to reduce device resistance. ITO offers excellent properties (such as high transmission and great conductivity) to realize the first continuous-wave (CW) current-injected blue GaN VCSEL. We also deposited p and n contacts as current-injection layers. Finally, an eight-pair Ta₂O₅/SiO₂ dielectric DBR (with a measured reflectivity of about 99% at $\lambda = 450\text{nm}$) was deposited as the top DBR mirror to complete the full hybrid microcavity-VCSEL device.⁴

Continued on next page

Figure 2. Injection current as a function of voltage and emission intensity. I-V: Current-voltage (left-hand y axis). L-I: Current-intensity (right-hand y axis).

Figure 3. Electroluminescence (EL) spectrum for different injection currents. FWHM: Full width at half maximum. I_{th} : Threshold current.

We measured the VCSELs under CW current injection at 77K. Figure 2 shows the light output intensity as a function of injection current and current-voltage characteristics of the VCSEL sample. The turn-on voltage was about 4.1V, thus showing the laser's good electrical properties. The laser was characterized by a clear threshold current at 1.4mA, which we increased linearly beyond the threshold.

Figure 3 shows the electroluminescence spectrum for various injection currents (above the threshold) and a dominant

laser wavelength of 462.8nm. The inset image shows the 10 μ m emission aperture at 1mA, where we observe the nonuniform emission intensity in the form of several bright emission spots (caused by indium fluctuations in the multiquantum wells).

In conclusion, we fabricated and demonstrated an electrically pumped GaN-based VCSEL at 77K. The crack-free, high-reflectivity DBR and high-quality ITO layer facilitated lasing at a threshold current of 1.4mA for a dominant wavelength of 462.8nm at 77K. The turn-on voltage was 4.1V, with great electrical characteristics. As our next steps we still need to resolve a few technical issues, such as improvement of the epitaxial quality, better current and optical confinement, and advanced structure design, before a CW GaN-based VCSEL can be realized at room temperature.

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Continued on next page

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