Toward a high-performance, low-power microprojector with a surface-emitting blue laser

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A hybrid vertical-cavity surface-emitting laser with bottom epitaxial and top dielectric distributed Bragg reflectors can lead to novel applications.

Wide-band-gap materials based on gallium nitride (GaN) have been widely used to make light-emitting devices such as light-emitting diodes (LEDs) and laser diodes (LDs). Continuous-wave, room-temperature, edge-emitting GaN-based LDs were first reported by Nakamura et al. in 1996. Since then, edge-emitting GaN-based LDs have become the light sources of choice for high-density optical storage systems. In contrast, GaN-based vertical-cavity surface-emitting lasers (VCSELs) have not yet been successfully realized, although they offer superior characteristics. These include low threshold current; single longitudinal mode operation; a low-divergence, symmetric, output beam; and easy formation of 2D arrays. These properties make GaN-based VCSELs suitable for many applications such as high-density optical storage systems, laser printing, laser mice and ‘picoprojectors’ that are small enough to be held in the hand.

The key issues limiting the development of GaN-based VCSELs are the lattice mismatch between GaN and sapphire substrates, the difficulty of growing high-reflectivity GaN-based distributed Bragg reflectors (DBRs), and low optical gain in indium gallium nitride (InGaN) multiple quantum wells (MQWs). This is due to inherent polarization and indium (In) segregation issues, where local variations in the balance of indium and gallium cause fluctuations in the band gap.

Possible structural designs for nitride-based VCSELs can be classified into three major types. First is the fully epitaxial VCSEL, consisting of epitaxially grown III-nitride (i.e., the nitride of a group III metal) top and bottom DBRs. This is the standard design for III-V VCSELs (i.e., those based on compounds of elements from groups III and V of the periodic table). However, a serious lattice mismatch between GaN/aluminum nitride (AlN) alloys prevent the material from growing crack-free. The second type is the double dielectric DBR VCSEL. This can exhibit a high cavity quality factor (Q) due to the high-reflectivity DBRs, but it requires extremely complicated fabrication techniques, such as laser lift-off. The third type is a hybrid VCSEL, consisting of bottom epitaxial and top dielectric DBRs. It avoids the complex fabrication process of the double dielectric DBR type while maintaining a high-finesse cavity (that is, an optical cavity with a high ratio of free spectral range to bandwidth of its resonances).

We designed and made a current-injected GaN-based VCSEL with hybrid DBRs, the third type. We used a 10-pair tantalum oxide/silicon oxide (Ta$_2$O$_5$/SiO$_2$) top DBR deposited by an...
ion-assisted e-gun system and a $7\lambda$-thick optical cavity (where $\lambda$ is the wavelength) embedded with 10 InGaN/GaN multi-quantum wells. We used a metal organic chemical vapor deposition (MOCVD) system (EMCORE D75) to make the crack-free 29-pair AlN/GaN bottom DBR (see Figure 1). We also incorporated a p-AlGaN electron blocking layer, a p+ InGaN heavily doped layer for better contact, and a 30nm sputtered thin indium tin oxide (ITO) layer. We measured the top and bottom mirror reflectivity and checked the control of the cavity mode of the device by overlapping the reflectivity and photoluminescence (PL) spectra. In Figure 2, both the 29-pair AlN/GaN DBR and the 10-pair Ta$_2$O$_5$ DBR showed high reflectivity of over 99% at the peak wavelength of 410nm. The PL emission peak from the hybrid DBR VCSEL structure is located at 415nm, within the stop band of the DBRs, and we estimated the cavity Q value to be relatively high at about 1600.

Figure 3(a) shows the schematic diagram of the overall GaN-based VCSEL structure with hybrid DBRs. Figure 3(b) is a magnified photograph of the GaN-based VCSEL. We mounted the VCSEL device inside a cryogenic chamber for testing under different temperature conditions. We used a Keithley 238 current source to drive it under continuous wave (CW) operation. We then collected the emission light with a 25\(\mu\)m-diameter multimode fiber using a microscope with a 40X objective and fed it into a spectrometer/CCD (Jobin-Yvon Triax 320 spectrometer) with a spectral resolution of \(\sim0.15\)nm for output spectral measurement.

![Figure 2](image2.png)  
**Figure 2.** The reflectivity spectra of the top DBR (black line) and bottom DBR (red line), and the corresponding PL spectrum of the hybrid microcavity (green line).

![Figure 3](image3.png)  
**Figure 3.** (a) The schematic diagram of the overall GaN-based VCSEL structure with hybrid DBRs. (b) Optical microscope of GaN-based VCSEL when no current injection was applied. ITO: Indium tin oxide. MQWs: Multiple quantum wells.

We measured the emitted laser power and the operation voltage from the GaN-based VCSEL as a function of the injection current at 200K, 240K, 270K, and 300K: see Figure 4(a). We observed distinct threshold characteristics for threshold injection current $I_{th}$ of about 7.5mA, 8.2mA, 9.2mA, and 9.7mA at 200K, 240K, 270K, and 300K, respectively. The linewidth of our electrically-pumped VCSEL was about 0.5nm and the threshold current density was 12.4kA/cm$^2$ at 300K. 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 could be partly responsible for the relatively low threshold current density at room temperature we obtained, compared with a previously reported GaN VCSEL.\(^{5}\) The sample

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output power increased linearly with current injection beyond the threshold current. However, at room temperature, the laser power started to roll over at higher injection current (beyond 15mA) due to the thermal effect: see Figure 4(b). The rollover current and the maximum laser output power increased as the ambient temperature was decreased.

In summary, we demonstrated CW operation of GaN-based VCSELs with hybrid mirrors at room temperature. This should lead to novel applications with low power consumption and high optical performance requirements in the near future, such as micro/picoprojectors for laser displays. In the future, we will develop a low power consumption VCSEL by inserting a current confinement layer and improving the crystal quality for high power.

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Hao-Chung Kuo received a BS in physics from National Taiwan University (Taiwan) and an MS in electrical and computer engineering from Rutgers University in 1995. He received a PhD from the University of Illinois at Urbana Champaign in 1999. He has had an extensive professional career in both research and industrial research institutions. Kuo was a research assistant at Bell Laboratories (1993–1995), and a senior R&D engineer at Agilent Technologies (1999–2001) and LuxNet Corporation (2001–2002). Since October 2002, he has been with the National Chiao Tung University as a faculty member. His research interests include semiconductor lasers, VCSELs, blue and UV LED lasers, quantum-confined optoelectronic structures, optoelectronic materials, and solar cells. He has authored and coauthored 140 internal journal papers, and two invited book chapters. He holds six patents and has a further 10 pending. In addition, he is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), associate editor of the IEEE/Optical Society of America (OSA) Journal of Lightwave Technology, and in 2009 was associate editor of the Journal of Selected Topics in Quantum Electronics special issue on solid-state lighting (2009). In 2007, he received the Ta-You Wu Young Scholar Award from the National Science Council of Taiwan in 2007 as well as the Young Photonics researcher award from the OSA/SPIE Taipei chapter.

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References