Room-temperature GaN vertical-cavity surface-emitting laser operation in an extended cavity scheme

Si-Hyun Park, Jaehoon Kim, Heonsu Jeon, Tan Sakong, Sung-Nam Lee et al.

Citation: Appl. Phys. Lett. 83, 2121 (2003); doi: 10.1063/1.1611643
View online: http://dx.doi.org/10.1063/1.1611643
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v83/i11
Published by the American Institute of Physics.

Room-temperature GaN vertical-cavity surface-emitting laser operation in an extended cavity scheme

Si-Hyun Park, Jaehoon Kim, and Heonsu Jeon[a]
School of Physics and Inter-university Semiconductor Research Center Seoul National University, Seoul 151-747, Korea

Tan Sakong, Sung-Nam Lee, Suhee Chae, and Y. Park
Photonics Lab., Samsung Advanced Institute of Technology, Suwon 440-600, Korea

Chang-Hyun Jeong and Geun-Young Yeom
Department of Materials Engineering, Sung-Kyun-Kwan University, Suwaon 440-746, Korea

Yong-Hoon Cho
Department of Physics, Chungbuk National University, Chongju 361-763, Korea

(Received 12 May 2003; accepted 23 July 2003)

A GaN-based vertical-cavity surface-emitting laser (VCSEL) has been demonstrated in an extended cavity structure. A VCSEL device had a long extended cavity, which consisted of a sapphire substrate as well as a GaN epilayer and had an integrated microlens on one side. High-reflection dielectric mirrors were deposited on both sides of the laser cavity. The laser was optically pumped and operated at room temperature. The VCSEL device lased at a low threshold excitation intensity of 160 kW/cm^2. In contrast to a conventional microcavity-VCSEL structure, the VCSEL operated in multiple longitudinal modes with mode spacing consistent with its physical thickness. [DOI: 10.1063/1.1611643]

GaN-based light emitters, both light-emitting diodes (LEDs) and laser diodes, are now standard industrial products. Potentially important applications in other device structures, whose realizations are certainly more challenging, are now being actively sought. Examples of such devices include vertical-cavity surface-emitting lasers (VCSELs)[1,2] and resonant-cavity LEDs.[3] In particular, VCSELs possess properties that are advantageous for many applications. These properties include: circular beam shape, light emission in vertical direction, possibility of arrangement in two-dimensional arrays, and fully monolithic process/test.[4] Therefore, GaN-VCSELs should be quite appealing as future high-performance, GaN-based, short-wavelength light sources.

One of the most challenging problems in bringing GaN-VCSELs to practical application is the preparation *in situ* of highly reflecting semiconductor-distributed Bragg reflectors (DBRs). Although some progress has been made in the GaN-based DBRs,[5–7] only two groups have demonstrated GaN-VCSELs; both of these were in microcavity geometries.[1,2] Someya *et al.*[1] employed hybrid mirrors: a semiconductor AlGaN/GaN reflector for the lower reflector and a dielectric SiO_2/ZrO_2 reflector for the upper one. Song *et al.*[2] used dielectric DBR mirrors, SiO_2/HfO_2, for both the upper and lower mirrors. Although successfully demonstrating GaN-VCSEL operations for the first time, the methods used are very difficult to implement for commercial use. The VCSEL reported by Someya *et al.* requires an impractical number of highly strained AlGaN/GaN layers. In the case of the all-dielectric mirror scheme of Song *et al.*, the epitaxially grown InGaN multiple-quantum-well (MQW) section needs to be separated from the sapphire substrate prior to depositing the lower mirror. In this letter, we introduce another possible GaN-VCSEL structure with an extended cavity, and explain its lasing properties obtained by means of optical pumping when operated at room temperature.

Figure 1(a) schematically illustrates the structure of the extended cavity VCSEL. Dielectric DBR mirrors are deposited on both sides of an otherwise typical InGaN MQW structure, so that the whole sapphire substrate becomes part of the laser cavity. However, for such a long cavity, a parallel planar mirror arrangement would probably not provide a stable resonator condition, because of a significant anticipated diffraction loss. Thus, prior to deposition of the lower mirror, the rear of sapphire substrate was thinned, polished, and finally integrated with a microlens. For photons within the cavity, the microlens serves as a concave mirror on one side of laser cavity. The other side of laser cavity is defined by the planar GaN epilayer, so that the overall laser structure has a plano-concave cavity.

We have previously fabricated and characterized sapphire microlenses.[8] They were fabricated by etching sapphire using re-flown photoresist lenslets as a sacrificial etching mask. To successfully etch the extremely hard sapphire, a chlorine-based high-density plasma gas in an inductively coupled plasma (ICP) system was employed. Figure 1(b) shows an example of microlenses fabricated on a sapphire substrate. The details of the ICP etching of a sapphire microlens, and its optical characteristics, can be found in Ref. 8. The radius of curvature and the diameter of the microlens used in the present experiment are 400 and 120 μm, respectively. On the basis of Gaussian beam optics,[9] the diameter

[a]Electronic mail: hsjeon@snu.ac.kr

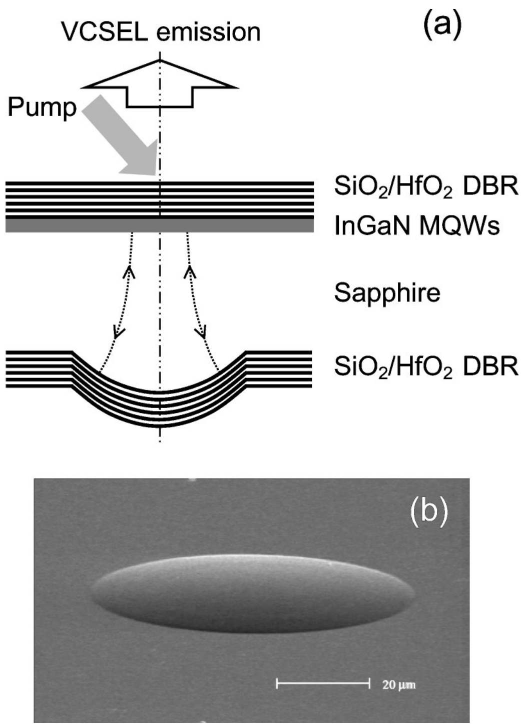

FIG. 1. (a) Schematic diagram of the extended cavity GaN-VCSEL structure. (b) Scanning electron microscope image of a sapphire microlens.

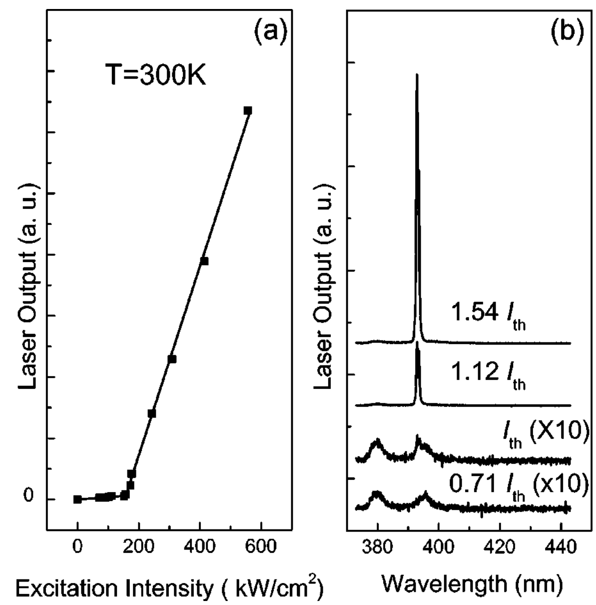

FIG. 2. Room-temperature lasing properties of a typical extended cavity GaN-VCSEL. (a) Relationship between excitation intensity and laser output and (b) laser emission spectra at different excitation levels. The laser spectra in (b) are successively shifted in vertical direction for display purpose.

of the beam waist at the MQW position in the present laser cavity has been calculated to be approximately 6.0 μm. However, its correlation with the size of the actual lasing aperture is a subject for further experimental studies.

An InGaN/GaN/AlGaN separate confinement heterostructure was grown on a (0001) sapphire substrate using a technique involving low-pressure metalorganic chemical-vapor deposition. The MQW section, composed of 10 periods of 3-nm $In_{0.1}Ga_{0.9}N$ quantum wells, and 10-nm GaN barriers, was embedded between two 86-nm $Al_{0.07}Ga_{0.93}N$ cladding layers. The whole structure was grown on a 2-μm-thick GaN buffer layer to ensure a good epilayer quality. Each dielectric DBR, prepared using an electron-beam evaporator with a quartz crystal thickness monitor, is composed of 11.5 pairs of SiO_2/HfO_2 layers. The corresponding reflectance is expected to be greater than 99.5%.

In order to determine its optical properties, a fabricated sample was simply taped to a glass plate with no extra heat sink. It was then optically pumped from the epilayer side, using a frequency-tripled, Q-switched, pulsed Nd:YAG laser. Emission spectra were taken in a backscattering geometry by a CCD camera attached to a spectrometer. The pulse width of the pump was approximately 5 ns, and the repetition rate was fixed at 10 Hz. The pumping laser beam was focused down to a size slightly larger than that of an individual microlens. All experiments were performed in ambient conditions at room temperature.

Figure 2(a) shows the relationship between the excitation intensity and the laser output of a microlensed VCSEL device, while Fig. 2(b) displays the emission spectra at a few different excitation levels. A sharp laser threshold appears at an input excitation intensity of 160 kW/cm^2. Considering that the reflectivity of the dielectric DBR at the excitation wavelength of 355 nm was measured to be about 55%, and that only a fraction of the incident photons is absorbed by MQWs, the actual threshold intensity would be much less. In contrast to a microcavity-VCSEL,[1,2] our VCSEL device is expected to operate in multiple longitudinal modes due to its long cavity length (much like an edge-emitting laser). In order to elucidate this point, high-resolution emission spectra from another VCSEL device are shown in Fig. 3. It is very clear that the spectra are periodically modulated, and that lasing occurs at a couple of those peaks. Assuming that the modulation is the result of Fabry–Perot oscillations, we estimate that the cavity length is about 50 μm, which is very close to the physical thickness of our sample as determined by an independent measurement.

Concern has been expressed that cavities formed in GaN-VCSELs by random accidental cracks could initiate in-

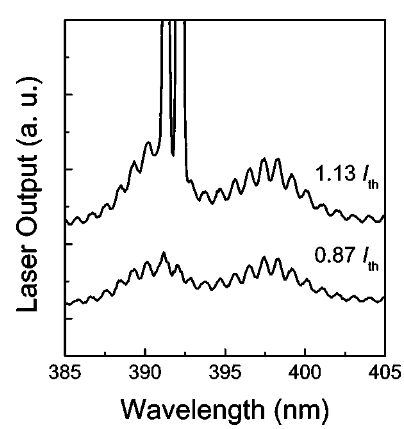

FIG. 3. High-resolution emission spectra of an extended cavity GaN-VCSEL near laser threshold. Individual longitudinal modes are clearly resolved.

plane lasing first, so that the resultant laser light could leak out through vertical cavity modes.[10] Although true VCSEL operation could be unambiguously confirmed by a well-defined far-field pattern, the low duty-cycle ($\sim 5\times 10^{-8}$) under our experimental conditions made a direct far-field observation impossible. Instead, we argue that the spectral modulation in a single periodicity (as seen in Fig. 3) provides a strong indication that the lasing originates from vertical oscillation. If the laser oscillation came from in-plane random cavities, there should exist multiple spectral modulations caused by multiple cavity lengths (or more likely in practice, no modulation, due to the randomness of the cavity lengths). Further, it is very unlikely that of the many densely spaced resonant frequencies that exist in such a long vertical cavity, in-plane lasing light would be filtered out only at one well-defined wavelength.

In conclusion, we have demonstrated room-temperature optically pumped GaN-VCSEL operation in an extended cavity structure. Emission spectra, input/output characteristics, and modal behavior confirm that lasing truly occurs along the vertical direction. Due to its long cavity length, our VCSEL device lased in multiple longitudinal modes.

This work was supported by the Korea Ministry of Industry, Commerce, and Energy, through the Basic Engineering Technologies Development Program.

[1] T. Someya, R. Werner, A. Forchel, M. Catalano, R. Cingolani, and Y. Arakawa, Science **285**, 1905 (1999).
[2] Y.-K. Song, H. Zhou, M. Diagne, A. V. Nurmikko, R. P. Schneider, Jr., C. P. Kuo, M. R. Krames, R. S. Kern, C. Carter-Coman, and F. A. Kish, Appl. Phys. Lett. **76**, 1662 (2000).
[3] M. Diagne, Y. He, H. Zhou, E. Makarona, A. V. Nurmikko, J. Han, K. E. Waldrip, J. J. Figiel, T. Takeuchi, and M. Krames, Appl. Phys. Lett. **79**, 3720 (2001).
[4] See, for example, K. Iga and F. Koyama, in *Surface Emitting Semiconductor Lasers and Arrays*, edited by G. A. Evans and J. M. Hammer (Academic, San Diego, 1993), Chap. 3.
[5] T. Someya and Y. Arakawa, Appl. Phys. Lett. **73**, 3653 (1998).
[6] H. M. Ng, T. D. Moustakas, and S. N. G. Chu, Appl. Phys. Lett. **76**, 2818 (2000).
[7] K. E. Waldrip, J. Han, J. J. Figiel, H. Zhou, E. Makarona, and A. V. Nurmikko, Appl. Phys. Lett. **78**, 3205 (2001).
[8] S.-H. Park, H. Jeon, Y.-J. Sung, and G.-Y. Yeom, Appl. Opt. **40**, 3698 (2001).
[9] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991) Chap. 9.
[10] D. M. Bagnall and K. P. O'Donnell, Appl. Phys. Lett. **68**, 3197 (1996).