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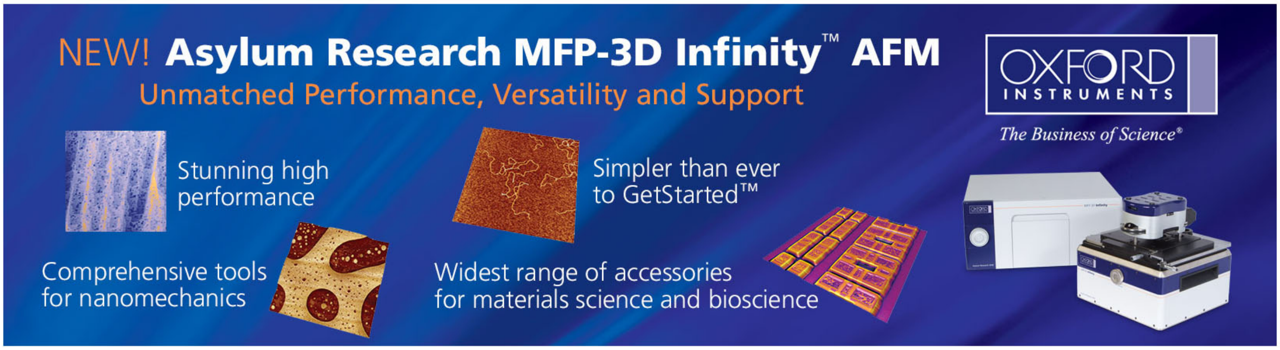

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APPLIED PHYSICS LETTERS **96**, 151115 (2010)

Ultraviolet GaN-based microdisk laser with AlN/AlGaN distributed Bragg reflector

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We demonstrated a 4.7 μm GaN-based microdisk laser with 25-pair AlN/AlGaN distributed Bragg reflector in ultraviolet range without undercut or deeply-etching procedures. The distributed Bragg reflector provides a high reflectivity of 85%, and selects lasing mode around 375 nm wavelength. Under optical pumping conditions, the lasing action was observed with a low threshold power density of 0.03 $\mathrm{kW/cm^2}$. We also characterized the whispering gallery mode profiles of the microdisk with finite-different time-domain simulation. © *2010 American Institute of Physics*. [doi:10.1063/1.3399781]

In recent years, GaN-based materials have been attracted a lot of attention for applications due to the large direct band gap and the promising potential for the optoelectronic devices, including light emitting diodes (LEDs) and laser diodes.[1–5] The high reflectivity GaN-based distributed Bragg reflector (DBR) is one of key elements for GaN optical devices such as resonant cavity light-emitting diodes[6] and vertical-cavity surface-emitting lasers.[7,8] To extend the applications of GaN-based lasers/LEDs into UV region, there are many studies related to the UV GaN-based DBR.[9–14] Blue-light microdisk lasers have also been reported in GaN-based suspended membranes formed by photoelectrochemical etching.[4,5,15] In this paper, we demonstrated a UV GaN-based microdisk laser in AlN/AlGaN DBR platform without chemical undercut process. This type GaN laser not only simplifies the fabrication procedures but also benefits electrically pumped scheme and thermal conduction of the compact lasers. To achieve a good vertical confinement, an AlN/AlGaN UV DBR structure was designed on the bottom of the microdisk cavity. It can be acted as a mirror to reflect light from the bottom area and a lower refractive index layer to control guided modes.

GaN microdisk cavities were implanted in an ultraviolet GaN-based AlN/AlGaN DBR structure. AlN/AlGaN DBR structure was grown by a low pressure metal-organic chemical vapor deposition system. A 3.4 μm thick undoped GaN was first grown on a C-plane (0001) sapphire substrate. Then 25-pair $\mathrm{AlN/Al_{0.2}Ga_{0.8}N}$ structure was grown at 900 °C, followed by a 200 nm undoped GaN gain layer on the top of epitaxial structure. The cross-section SEM image of UV DBR was shown in Fig. 1. The growth details were reported in our previous works.[16,17] A 300 nm silicon nitride layer and a 300 nm polymethylmethacrylate (PMMA) layer were deposited on the top of GaN wafer as the masks during the processes. Microdisk patterns were defined on the PMMA layer by electron beam lithography. The patterns were then transferred into the DBR layer by reactive ion etching with $\mathrm{CHF_3/O_2}$ mixture and inductive coupled plasma etching with $\mathrm{Cl_2/Ar}$ mixture.

The illustration of a microdisk on the AlN/AlGaN DBR structure is shown in Fig. 2(a). Figure 2(b) is a top-view SEM image of a microdisk array, and Fig. 2(c) is the magnified image of a microdisk from an angle-view. The size of fabricated microdisk is approximately 4.7 μm in diameter. Its etch depth was about 500 nm, which includes 200 nm undoped GaN and 300 nm DBR layers was decided by the vertical profile of whispering gallery modes. Chemical undercut or deeply etching steps are unnecessary for this GaN microdisk because of good vertical confinement from DBR structure, compare to GaN microdisk cavity without DBR.[4,5,18]

To understand optical properties of AlN/AlGaN DBR structure, the reflectivity was characterized. The UV DBR structure is designed for the UV wavelength around 370 nm. The thickness of AlN and AlGaN layers are 45 and 42 nm decided by the formula $d_{\mathrm{AlN}}=\lambda/4n_{\mathrm{AlN}}$ and $d_{\mathrm{AlGaN}}=\lambda/4n_{\mathrm{AlGaN}}$. Here n_{AlN} and n_{AlGaN} are refractive indices of AlN and AlGaN which are 2.03 and 2.19, respectively. The dashed curve in Fig. 3 is the simulated reflectivity spectrum from transmission matrix method for the UV DBR. The solid

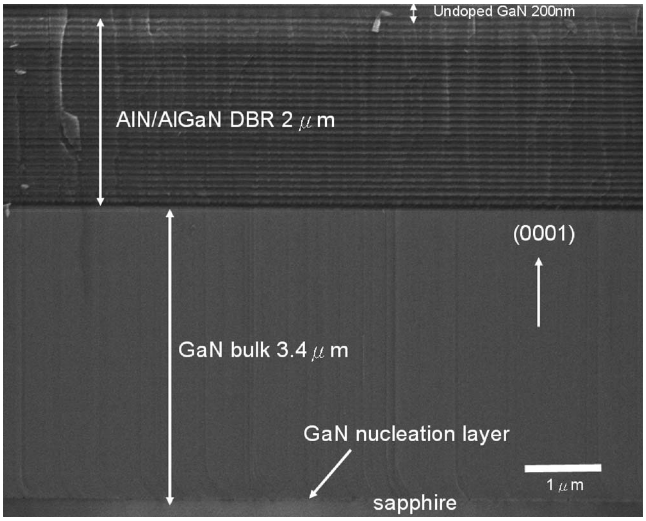

FIG. 1. A SEM image of UV DBR from cross-section view. The total thickness of 25-pairs AlN/AlGaN is about 2 μm.

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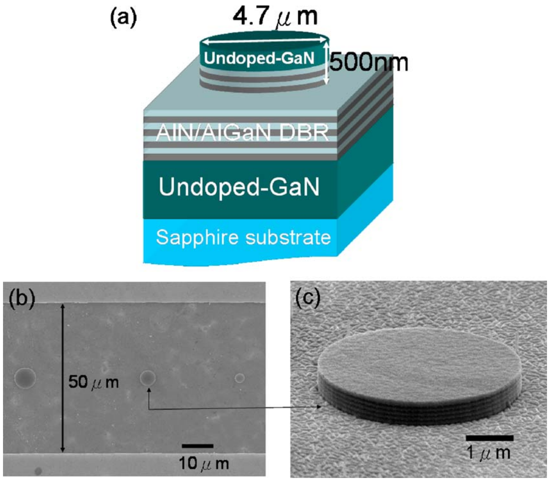

FIG. 2. (Color online) (a) Schematic structure of a GaN-based microdisk with AlN/AlGaN DBR. (b) A SEM image of a GaN microdisk array with diameters of 7, 4.7, and 3 μm. (c) A magnified SEM image of a 4.7 μm GaN microdisk from an angle-view.

curve in Fig. 3 is the measured spectrum with a normal incident light from 300 to 440 nm wavelength. The DBR has the highest reflectivity of 85% at 375 nm wavelength with 15 nm stop-band width.

The fabricated GaN-based microdisk cavities were then optically pumped by using a frequency-tripled $Nd:YVO_4$ 355 nm pulsed laser with a pulse width of 0.5 ns and a repetition rate of 1 kHz. The normal incident beam has a spot size of 50 μm which can cover the whole microdisk. The light emission from the device was collected by a 15× objective lens through a multimode fiber, and coupled into a spectrometer with the charge-coupled device detectors.

Figure 4(a) shows the measured PL spectrum from nonpattern area of the UV DBR sample. The gain peak of the undoped GaN is located around 360 nm wavelength. The lasing action of the GaN microdisk cavity on the DBR structure was observed during the characterization. Figure 4(b) shows the measured spectra from a 4.7 μm microdisk cavity below (red) and above (black) threshold. There are four resonant modes in the spectrum which are labeled with mode A, B, C, and D. Two lasing modes (mode A and mode B) were observed at 377 nm and 379 nm wavelength. Figure 4(c) shows the light-in light-out (L-L) curves of mode A (black) and mode B (red). Their threshold power densities are 0.03 kW/cm^2 and 0.043 kW/cm^2, respectively. By estimating the ratio of wavelength to linewidth $(\lambda/\Delta\lambda)$ around

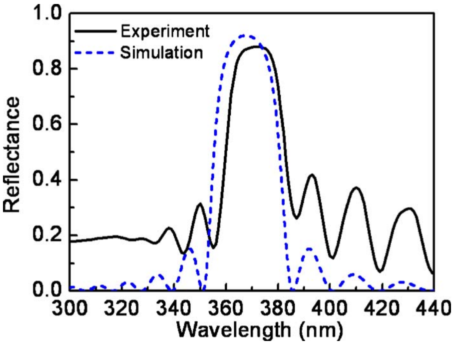

FIG. 3. (Color online) Calculated (dashed) and measured (solid) reflectivity spectra of the UV DBR with 25-pairs AlN/AlGaN.

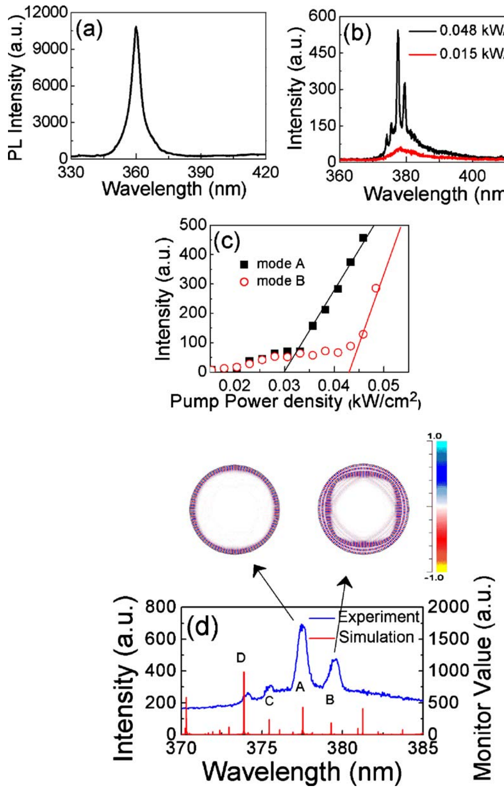

FIG. 4. (Color online) (a) PL spectrum of undoped GaN on the top layer. (b) Measured spectra from a microdisk laser below and above threshold. Lasing wavelengths of the microdisk are 377 and 379 nm. (c) The light-in light-out curve (L-L curve) from the microdisk laser. (d) Comparison of FDTD simulation (red) and measurement (blue). Top two inset figures are calculated H_z mode profiles of mode A and B.

transparency, the quality factors (Q) of mode A and B are approximately 400 and 320. The Q value could be raised by increasing the etching depth and smoothing the sidewall of the GaN microdisk cavity.

To understand more details of lasing modes, the finite-difference time-domain method (FDTD) with the effective index was used to perform the simulation for this 4.7 μm microdisk. Figure 4(d) provides the comparison between simulation and measurement. The blue curve is the measured spectrum, and the red curve is the simulated spectrum from FDTD. The four resonant modes (mode A, B, C, and D) are all match well to high response modes from the simulation. Top two figures of Fig. 4(d) are calculated H_z mode profiles of lasing modes at 377 and 379 nm wavelength. Two lasing modes, mode A and mode B were verified to be the first-order and third-order whispering-gallery modes (WGM) from FDTD calculated mode profiles. Since the higher-order whispering-gallery mode usually has a lower Q value, the mode B has a higher threshold which is observed from the L-L curves in Fig. 4(c).

In the GaN-based microdisk cavity, the UV DBR plays an important role to select the lasing wavelength region. The gain peak of the GaN without the DBR is around 360 nm wavelength, however the lasing and resonant modes are around 377 nm wavelength. This 17 nm difference in wavelength is attributed to the reflection of the UV DBR mirror. The region of resonant mode also agrees to the bandwidth of DBR reflectivity spectrum in Fig. 3. This DBR effect in the GaN expitaxial structure had been observed in our previous works.[17] We should note that the reflectivity spectrum is usually calculated by considering a single plane wave with an incident angle in transmission matrix method. However, WGM modes contain many different wavevectors. The reflectivity of the DBR should be considered comprehensively with all possible incident angles of optical mode. But the vertical incident component still dominates due to small size of WGM modes. The UV DBR also reduces number of resonant modes in a microdisk because of its bandwidth. The mode reduction decreases energy waste on nonlasing modes. Therefore a high efficient GaN laser can be expected. For future applications, the cavity with DBR structure opens a possibility to select wavelength for lasers.

In summary, we had demonstrated a compact GaN-based microdisk laser with UV AlN/AlGaN DBR structure. Two lasing modes were observed at 377 and 379 nm wavelength with low thresholds of 0.03 and 0.043 $\mathrm{kW/cm^2}$. This DBR structure has strong advantages in simplifying fabrication and tuning lasing wavelength.

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