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## Lasing in metal-coated GaN nanostripe at room temperature

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This study demonstrated a metal-coated GaN nanostripe laser operable at room temperature. The ultraviolet lasing mode was observed at a wavelength of approximately 370 nm with a low threshold power density of 0.042 kW/cm<sup>2</sup>. The lasing mode of the metal-coated nanostripe was characterized using finite-element method simulation. The results showed the significance of metal coatings in this nanocavity structure for lasing at room temperature. © 2011 American Institute of Physics. [doi:10.1063/1.3572023]

In recent years, the size of the semiconductor lasers has been reduced to the nanoscale, to integrate them into optical devices. Metal-coated cavities have been embraced as a promising candidate to achieve this goal, despite the lossy characteristics of the materials involved. The advantages of optical confinement and the field enhancement of surface plasmon effects enable metal-coated cavities to break the diffraction-limit constraining the size of lasers.<sup>1</sup> Moreover, to lower the absorption of metal, a thin dielectric layer was inserted between the gain material and metal, resulting in a higher quality factor and lower threshold gain, making lasing action possible.<sup>2</sup> In 2007, Hill *et al.*<sup>3</sup> demonstrated one of the smallest semiconductor nanolaser, with a nanorod size far below the lasing wavelength. To achieve lasing in metal-coated cavities at room temperature, Hill *et al.*<sup>4</sup> demonstrated a subwavelength metal-coated waveguide laser in 2009. Since that time, these devices have been widely studied from both the theoretical and experimental perspective,<sup>5,6</sup> in an attempt to understand the effects of metals on subwavelength cavities. However, recent research has focused mainly on devices operating in the region of communication and infrared wavelengths.<sup>7,8</sup> The combination of a metal-coated cavity using GaN-based materials has never been reported in previous research. Although wide-bandgap GaN-based materials have found their way into many applications including light emitting diodes,<sup>9</sup> laser diodes,<sup>10</sup> and vertical surface emitting lasers,<sup>11,12</sup> the size of these devices remain at the micrometer scale.

In this paper, we demonstrated lasing in metal-coated GaN nanostripes at room temperature under optical pumping conditions. To make lasing action in this device possible, we employed SiO<sub>2</sub> as an insertion layer between the metal and GaN to improve the quality factor, in conjunction with aluminum providing high reflectivity in the ultraviolet (UV) region and high thermal conductivity. The lasing action was observed in GaN-based metal-coated nanocavities around UV wavelengths region at room temperature.

The GaN nanostripe was fabricated on an undoped GaN layer, acting as a gain medium for the device. A schematic diagram is presented in Fig. 1. The 2 μm thick undoped GaN layer was grown on a C-plane (0001) sapphire substrate using a low pressure metal-organic chemical vapor deposi-

tion (MOCVD) system. To fabricate the device, we first deposited a 300 nm Si<sub>3</sub>N<sub>4</sub> layer as an etching mask, followed by a 300 nm thick polymethylmethacrylate (PMMA) layer. The nanostripe pattern was defined using E-beam lithography on the PMMA layer, whereupon the pattern was transferred to the Si<sub>3</sub>N<sub>4</sub> layer through reactive ion etching (RIE) with CHF<sub>3</sub>/O<sub>2</sub> mixture. The nanostripe pattern was etched down to the undoped GaN layer using inductively coupled plasma and reactive ion etching (ICP-RIE) with a Cl<sub>2</sub>/Ar mixture, and the mask layers were removed using wet etching after these processes had been completed. A scanning electron microscope (SEM) image of the GaN nanostripe prior to the deposition of SiO<sub>2</sub> and metal shielding layers is shown in Fig. 2(a). A 20 nm thick SiO<sub>2</sub> layer was deposited on the nanostripe, and this layer was used to reduce the influence of surface roughness caused by the previous dry etching process. Surface roughness increases the loss associated with the absorption of metal, thereby lowering the quality factor and increasing the lasing gain threshold. Such an increase in the lasing gain threshold could preclude the possibility of achieving lasing at room temperature. A uniform aluminum (Al) layer with a thickness of 60 nm was then deposited on the device using E-gun evaporation. Compare to metals widely applied in plasmonic devices such as Ag and Au, Al has a higher reflection in UV wavelength region (Al: 92%, Ag: 25%, Au: 38% at 370 nm), though Al also has a higher absorption (Al: 151 μm<sup>-1</sup>, Ag: 55 μm<sup>-1</sup>, Au: 65 μm<sup>-1</sup> at 370 nm). Therefore a better optical confinement

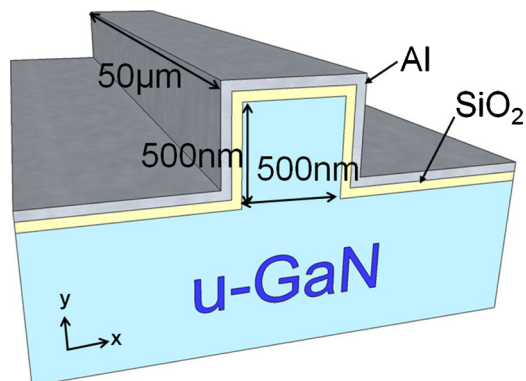


FIG. 1. (Color online) Schematic diagram of the metal-coated GaN nanostripe.

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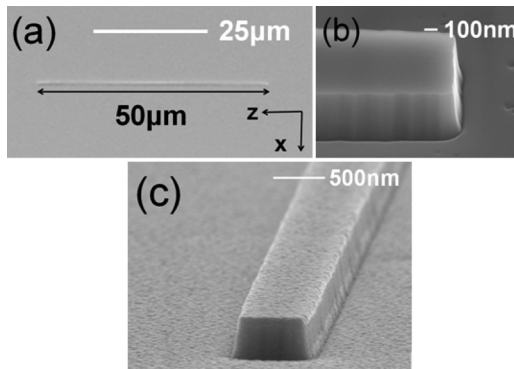


FIG. 2. (a) SEM image (top view), of a GaN nanostructure prior to the deposition of metal and SiO<sub>2</sub> layers; (b) magnified SEM image of one side of GaN nanostructure from angled view; (c) magnified SEM image of one side of GaN nanostructure from angled view following the deposition of SiO<sub>2</sub> and aluminum.

from an Al-coated GaN cavity can be expected. The size of the GaN nanostructure was approximately 500 nm in width and 50 μm in length, and the etching depth is 500 nm. Figure 2(b) shows a magnified image of one side of the GaN nanostructure. The complete structure of the device after processing is shown in Fig. 2(c).

The metal-coated GaN nanostructure was optically pumped using a frequency-tripled Nd: YVO<sub>4</sub> 355 nm pulsed laser at room temperature with a pulse width of 0.5 ns, at a rate of 1 kHz. The spot size of the normal incident beam was approximately 50 μm, covering part of the nanostructure. A 15× objective lens was used to collect the light emitted from the GaN nanostructure through a multimode fiber, which was coupled with a spectrometer employing a charge-coupled device. Despite the fact that the absorption of the metal reduces the power of lasers, we opted to pump directly from the top of the device to avoid the enormous losses that would have resulted from the undoped GaN, had we chosen to pump from the back of the wafer.

To ensure that the lasing action originated in our structure, we first used an He–Cd 325 nm continuous-wave laser to pump the undoped GaN layer, conducting this test with and without the metal and SiO<sub>2</sub> layers to observe the photoluminescence (PL) spectrum at room temperature. The peak wavelength of the undoped GaN layer without shielding layers was approximately 362 nm. However, the spectrum of the undoped GaN layer with aluminum and SiO<sub>2</sub> did not have a peak at 362 nm because the signal from approximately 350 to 380 nm had been totally absorbed by the shielding layer. The PL spectrum shown in Fig. 3(a) confirms that our design enabled lasing action. Moreover, Fig. 3(b) shows the PL spectrum of the device below (black) and above (red) the threshold under room temperature pulsed conditions. This device operated with only a single lasing mode at 370 nm. Figure 3(c) shows the light-in light-out curves of this mode, with a threshold power density of approximately 0.042 kW/cm<sup>2</sup>, and a quality factor (Q) of approximately 200, as estimated by the ratio of wavelength to linewidth ( $\lambda/\Delta\lambda$ ) around transparency. Following the soft turn-on at approximately the threshold power density, the measured light output was linear, serving as proof of the lasing action in this device. Compared to the sample without a metal or SiO<sub>2</sub> shielding layer, the high thermal conductivity and reflectivity of the aluminum made measurement easier and in-

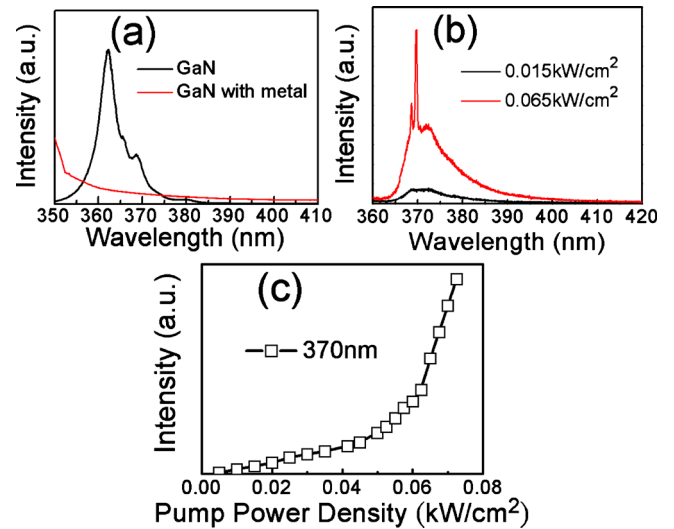


FIG. 3. (Color online) (a) PL spectrum of undoped GaN layer with and without the SiO<sub>2</sub> and aluminum shielding layers; (b) measured spectra from metal-coated GaN nanostructure laser below and above threshold. Lasing wavelength of the GaN nanostructure is 370 nm; (c) light-in light-out curve (L-L curve) of the metal-coated GaN nanostructure laser.

creased the possibility of lasing at room temperature. As expected, the nanostructure without the coating layer showed higher optical loss and lower Q value. It was for these reasons that lasing action was not observed in this experiment.

To garner a better understanding of the experimental results, we employed finite-element-method (FEM) for the simulation of optical modes using this metal-coated GaN nanocavity. The simulation model comprised a sapphire layer, an undoped GaN layer, a thin SiO<sub>2</sub> layer, and a metal shielding layer. We adopted the refractive indexes of undoped GaN and the aluminum layer established by Peng and Piprek<sup>13</sup> and Rakic *et al.*,<sup>14</sup> with the refractive index of SiO<sub>2</sub> as 1.46. This model included a perfectly matched layer surrounded the nanocavity to absorb redundant signals, which would have reflected back to the metal-coated nanostructure, thereby influencing the optical mode. Figures 4(a) and 4(b) show simulated optical mode profiles for a GaN nanostructure cavity with and without metal-coating. In Fig. 4(a), the model incorporating metal and SiO<sub>2</sub> layers had an optical mode well confined within the nanostructure, demonstrating a clear standing wave pattern with 3.5 nodes. However, using the nanostructure without a metal shielding layer, the optical mode shown in Fig. 4(b) leaked into the region of air with a standing wave that lacked uniformity, compared with the results of the metal-coated device. The wavelength of the optical mode shown in Fig. 4(a) was 367 nm, and the quality factor (Q) extracted from the eigenvalue of the mode was approximately 150, which was ten times greater than the optical mode shown in Fig. 4(b). This illustrates the difficulty of achieving GaN nanostructure lasing without shielding layers. The small difference in wavelength between the simulation and experimental results can be attributed to imprecise fabrication processes and the imprecision of material indices used in the model. From these simulation results, we confirmed that the metal shielding layer in this structure played an important role in lasing at room temperature. Vertical confinement would be the key to further increasing the quality factor of the device. The adoption of a distributed Bragg reflector (DBR) beneath the undoped GaN layer could confine the

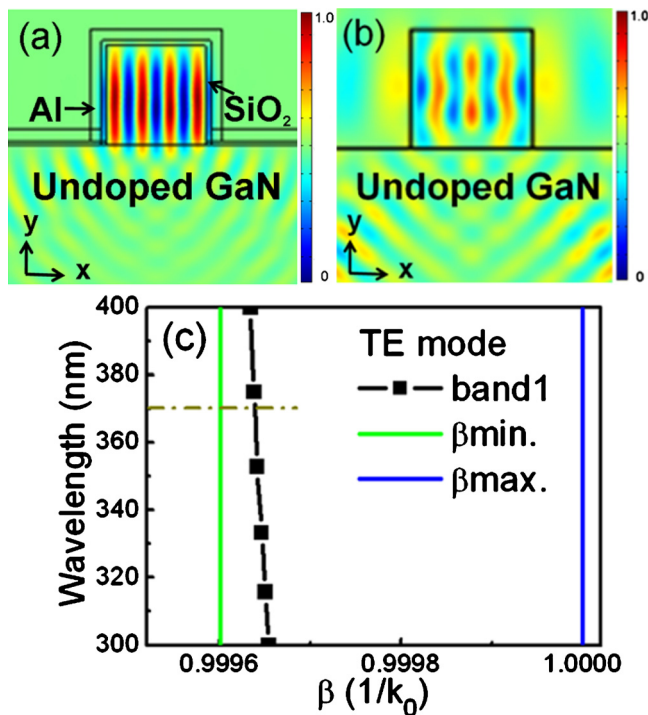


FIG. 4. (Color online) (a) Calculated  $E_z$  mode profile of metal-coated GaN nanocavity; (b) calculated  $E_z$  mode profile of the GaN nanocavity without metal and  $\text{SiO}_2$  shielding layers; (c) band diagram of the metal-coated GaN nanostripe.

optical mode and prevent scattering to the undoped GaN layer beneath the nanostripe as shown in Fig. 4(a). This would form a three-dimensional cavity with a combination of metal-coated sidewall and a distributed Bragg reflector,<sup>15</sup> representing a promising means to further improve the performance of the device or even enable operation of the device under electrically-pumped conditions. The lasing performance of the GaN metal laser could also be much improved by including GaN-based heterostructure and modulating stripe sidewall geometry.<sup>16</sup> Moreover, the band diagram of this structure shown in Fig. 4(c) helps to clarify this lasing action. The lasing mode of this metal-coated GaN stripe is a hybrid plasmonic waveguide mode which combines a TE waveguide mode of the GaN stripe and the surface plasmon modes from the Al/SiO<sub>2</sub>/GaN interfaces. The similar structure had been studied for an InGaAs/InP stripe<sup>4</sup> and a dielectric cylindrical nanowire.<sup>17</sup> A small Fabry–Perot resonant closed to the lasing mode was also observed in the spectrum of Fig. 3(b). The Fabry–Perot mode spacing can be described by the formula  $\Delta\lambda = \lambda^2/2n_gL$ , and the effective index of the lasing mode is approximately 1.5 extracted from the nearly 1 nm mode spacing in spectrum. In the wavelength range between 300 and 400 nm, there was only one waveguide band, and the lasing wavelength of our experiment was in agreement with the waveguide mode calculated in the band diagram. This provides further proof that this metal-coated GaN nanostripe could form an optical mode, with a clear standing wave pattern, thereby making lasing action possible. It is worth to note that the SiO<sub>2</sub> dielectric layer benefits quality factor and electrical injection of the cavity. However, it might reduce the overlap between lasing modes and gain medium, especially for surface plasmon waves at metal–dielectric interface.

In summary, this study demonstrated UV lasing from a metal-coated GaN nanostripe at room temperature. Using an E-beam lithography technique, we fabricated a GaN nanostripe 500 nm in width, 500 nm in height, and 50  $\mu\text{m}$  in length. We then deposited a thin SiO<sub>2</sub> and aluminum layer on the nanostripe to form a metal-coated nanocavity. We observed lasing action at 370 nm wavelength with a low threshold power density of 0.042 kW/cm<sup>2</sup>. FEM simulation results show that a metal-coated nanostripe cavity could sustain a standing wave pattern, which would not occur in a nanostripe cavity without a metal shielding layer. The wavelengths of the mode were quite close to those of the experimental results. The band diagram of this structure also supports the notion that the nanostripe structure would form an optical mode. This is a clear indication that the metal coating used on the nanocavity played an important role in lasing results at room temperature. The results presented here represent a breakthrough in the integration of metal-coated nanocavities with GaN materials. Future efforts will focus on improving the performance of the device by increasing vertical confinement of the optical mode, enabling the device to be electrically-pumped. Such developments would provide enormous potential for applications in the very near future.

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