Lasing in metal-coated GaN nanostripe at room temperature
Yow-Gwo Wang, Cheng-Chang Chen, Ching-Hsueh Chiu, Ming-Yen Kuo, M. H. Shih, and Hao-Chung Kuo

Citation: Applied Physics Letters 98, 131110 (2011); doi: 10.1063/1.3572023
View online: http://dx.doi.org/10.1063/1.3572023
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/98/13?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Room temperature continuous wave lasing of electrically injected GaN-based vertical cavity surface emitting lasers

Room temperature ultraviolet GaN metal-coated nanorod laser

Room temperature lasing with high group index in metal-coated GaN nanoring

Laser action in Eu-doped GaN thin-film cavity at room temperature

Room-temperature optically pumped laser emission from a-plane GaN with high optical gain characteristics
Appl. Phys. Lett. 84, 2998 (2004); 10.1063/1.1711169
Lasing in metal-coated GaN nanostripe at room temperature

Yow-Gwo Wang,1 Cheng-Chang Chen,1 Ching-Hsueh Chiu,1 Ming-Yen Kuo,2 M. H. Shih,1,2,3* and Hao-Chung Kuo1

1Department of Photonics and Institute of Electro-optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan
2Research Center for Applied Sciences (RCAS), Academia Sinica, Taipei 11529, Taiwan

(Received 17 January 2011; accepted 9 March 2011; published online 30 March 2011)

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/cm². 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.1 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.2 In 2007, Hill et al.3 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.4 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,5,6 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.7,8 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,9 laser diodes,10 and vertical surface emitting lasers,11,12 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 SiO₂ 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 deposition (MOCVD) system. To fabricate the device, we first deposited a 300 nm Si₃N₄ 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 Si₃N₄ layer through reactive ion etching (RIE) with CHF₃/O₂ mixture. The nanostripe pattern was etched down to the undoped GaN layer using inductively coupled plasma and reactive ion etching (ICP-RIE) with a Cl₂/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 shown in Fig. 2(a). A 20 nm thick SiO₂ 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⁻¹, Ag: 55 µm⁻¹, Au: 65 µm⁻¹ at 370 nm). Therefore a better optical confinement

FIG. 1. (Color online) Schematic diagram of the metal-coated GaN nanostripe.
FIG. 2. (a) SEM image (top view), of a GaN nanostripe prior to the deposition of metal and SiO\textsubscript{2} layers; (b) magnified SEM image of one side of GaN nanostripe from angled view; (c) magnified SEM image of one side of GaN nanostripe from angled view following the deposition of SiO\textsubscript{2} and aluminum.

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

The metal-coated GaN nanostripe was optically pumped using a frequency-tripled Nd: YVO\textsubscript{4} 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 \(\mu\text{m}\), covering part of the nanostripe. A 15\times objective lens was used to collect the light emitted from the GaN nanostripe 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\textsubscript{2} 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\textsubscript{2} 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.

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

creased the possibility of lasing at room temperature. As expected, the nanostripe 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\textsubscript{2} layer, and a metal shielding layer. We adopted the refractive indexes of undoped GaN and the aluminum layer established by Peng and Piprek\textsuperscript{13} and Rakic \textit{et al.}\textsuperscript{14} with the refractive index of SiO\textsubscript{2} 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 nanostripe, thereby influencing the optical mode. Figures 4(a) and 4(b) show simulated optical mode profiles for a GaN nanostripe cavity with and without metal-coating. In Fig. 4(a), the model incorporating metal and SiO\textsubscript{2} layers had an optical mode well confined within the nanostripe, demonstrating a clear standing wave pattern with 3.5 nodes. However, using the nanostripe 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 nanostripe 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 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

clear standing wave pattern with 3.5 nodes. However, using the nanostripe 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 nanostripe 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 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
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 300 nm in width, 500 nm in height, and 50 µm in length. We then deposited a thin SiO2 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/cm². 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.

The authors would like to thank Professor S. L. Chuang and Dr. S. W. Chang from University of Illinois at Urbana-Champaign, and Professor T. C. Lu from National Chiao Tung University for insightful suggestions. We also are grateful to the Center for Nano Science and Technology at National Chiao Tung University, National Nano device Laboratory (NDL), and the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract Nos. NSC 99-2112-M-001-033-MY3 and NSC 100-3113-E-009-001-CC2.