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

Yow-Gwo Wang, Shu-Wei Chang, Cheng-Chang Chen, Ching-Hsueh Chiu, Ming-Yen Kuo, M. H. Shih, and Hao-Chung Kuo

Citation: Applied Physics Letters **99**, 251111 (2011); doi: 10.1063/1.3671648
View online: http://dx.doi.org/10.1063/1.3671648
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/99/25?ver=pdfcov
Published by the AIP Publishing

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

Yow-Gwo Wang,[1] Shu-Wei Chang,[1,2] Cheng-Chang Chen,[1,3] Ching-Hsueh Chiu,[1] Ming-Yen Kuo,[2] M. H. Shih,[1,2,a)] and Hao-Chung Kuo[1]
[1]*Department of Photonics, Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan*
[2]*Research Center for Applied Sciences (RCAS), Academia Sinica, Taipei 11529, Taiwan*
[3]*Energy and Environment Research Laboratories, Industrial Technology Research Institute (ITRI), 195, Sec. 4, Chung-Hsin Road, Chutung 310, Taiwan*

(Received 29 August 2011; accepted 1 December 2011; published online 22 December 2011)

The room temperature lasing action from a metal-coated GaN nanoring cavity was observed by optical pumping. The GaN nanoring is 7 μm in diameter and 400 nm in width. The quality factor of the cavity is approximately 860 with a threshold power density of 37.5 mJ/cm^2. Such a device performance was attributed to the combination of metal-coated nanocavity with whispering-gallery modes. Moreover, the group index extracted from the experiment was 5.99 and was verified with calculations and analyses of the lasing modes as well as their characteristics. The study showed a promising way to further improve the performance of metal-coated nanolasers. © *2011 American Institute of Physics*. [doi:10.1063/1.3671648]

Metal-coated nanocavities have been intensely studied in recent years, attempting to shrink the sizes of semiconductor lasers into the subwavelength regime and improve the device performance. Different structures have been reported to utilize the advantages of metal-coated nanocavities: Nanorod with heterostructure was reported in 2007,[1] and nanorod with different distributed Bragg reflectors (DBRs) was also demonstrated in 2010 and 2011, respectively.[2,3] The bowtie structure was proposed in 2008 theoretically.[4] Furthermore, in 2009, the combination of waveguide structure and metal shielding layers was demonstrated by Hill *et al.*, utilizing the bulk semiconductor gain medium and waveguide modes of the coupled surface plasmon due to the two interfaces between the metal and active regions.[5] In 2010, Yu *et al.* demonstrated nanopatch lasers.[6] Even though many structures have been proposed to utilize the advantages of metal-coated nanocavities, the quality factors of these devices were not high, and most of them were operated in cryogenic conditions. The advantages of whispering gallery modes (WGMs), including the good output coupling efficiency to other optical devices and absence of extra feedback structures to form the standing wave, make nanoring structures suitable for the development of photonic integrated circuits. In 2011, the metal-clad ring structure was studied theoretically,[7] and the quality factor and other scaling properties were discussed. It is suggested that metal-coated nanoring structures could be an attractive candidate of metal-coated nanolasers. Later, Kim and Ku demonstrated metal-clad nanoring laser experimentally, and the smallest ring was about 1.2 μm in diameter and 300 nm in width.[8,9] However, the device only operated at cryogenic temperatures with a quality factor of about 160.[8] The advantages of ring structures have not been fully utilized.

In this paper, we demonstrate lasing in metal-coated GaN nanoring at room temperature. The diameter of the ring was about 7 μm, and the width of was 400 nm, which was only 1.09 times of the lasing wavelength. An aluminum layer was uniformly coated on the GaN nanoring to form the cavity. From the experimental result, the quality factor was approximately 860, and the threshold power density was 37.5 mJ/cm^2. The lasing action at room temperature in metal-coated nanoring with a high quality factor was observed in the ultraviolet regime.

Compared to our previous work (Ref. 10), the device size of the ring structure can be shrunk more while the quality factor, an important parameter for laser operation, could be still higher. On the other hand, the group index estimated from the experimental data was about 5.99. Such a high group index could be attributed to the influences of metal coating and frequency dispersion of GaN at high carrier densities on the optical modes.

The device was fabricated on an undoped GaN layer which acted as the gain medium and was 2 μm in thickness. The GaN layer was grown on a C-plane (0001) sapphire substrate by a low pressure metal-organic chemical vapor deposition (MOCVD) system. Figure 1 shows the schematic diagrams of metal-coated GaN nanorings. First, a 300 nm thick Si_3N_4 layer was deposited on the wafer as an etching mask, and then a 300 nm thick polymethylmethacrylate

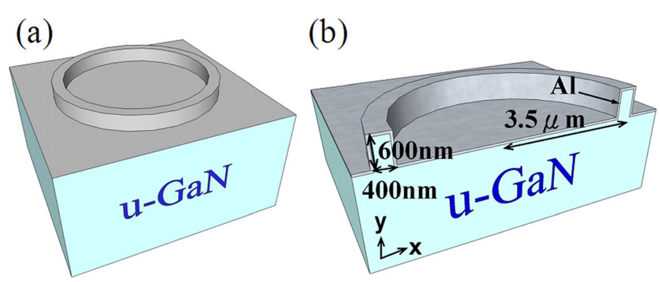

FIG. 1. (Color online) (a) Schematic diagram of the metal-coated GaN nanoring laser. (b) Cross-sectional schematic diagram of the 7 μm-diamter metal-coated GaN nanoring laser.

a)Electronic mail: mhshih@gate.sinica.edu.tw.

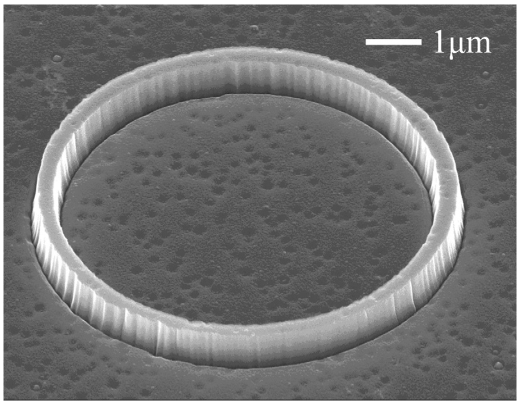

FIG. 2. The SEM image of the metal-coated GaN nanoring laser after the deposition of aluminum.

(PMMA) layer was coated on it for the following processes. The e-beam lithography was used to define the nanoring pattern on the PMMA layer. The pattern was then transferred to the Si_3N_4 layer by the reactive ion etching (RIE) with CHF_3/O_2 mixture. After that, the nanoring pattern was fabricated by etching down to the undoped GaN layer using the inductively coupled plasma reactive ion etching (ICP-RIE) with Cl_2/Ar mixture. All the remaining mask layers were removed by wet etching. After the processes mentioned above, a uniform aluminum layer with a thickness of 50 nm was deposited on the device by e-gun evaporation to form the metal-coated nanoring cavity. The scanning electron microscope (SEM) image of the metal-coated GaN nanoring was shown in Fig. 2. In the fabrication, aluminum was adopted because its reflectivity was higher than that of silver or gold in the ultra-violet range,[11] and lasing actions in Al-coated nanocavities have been reported in previous works.[10,12] Therefore, a good optical confinement in Al-coated GaN cavity is expected. In addition, to fully utilize the advantages of surface plasmon effect, we did not insert a thin dielectric layer between GaN and metal layer in our experiment. The device performance was not significantly altered by this thin dielectric layer even though it might reduce the optical loss from metal,[13] and we still observed lasing actions at room temperature.

To obtain the characteristics of metal-coated GaN nanoring, we use a frequency-tripled Nd: YVO_4 355 nm pulsed laser with a pulse width of 0.5 ns and repetition rate of 1 kHz to optically pump the device. The spot size of the normally incident beam was approximately 50 μm. A 15$\times$ objective lens was used to collect the light emitted from the GaN nanoring through a multimode fiber and coupled into a spectrometer equipped with charge-coupled device detectors. We directly pumped the sample from the device top to avoid the huge absorption from undoped GaN beneath the nanoring structure, even though the metal layer might also reflect and absorb the pumping power.

The peak lasing wavelength of the 7 μm-diameter GaN nanoring was 363 nm with a quality factor of around 860, and the threshold power density was approximately 37.5 mJ/cm^2. Figure 3(a) shows the photoluminescence (PL) spectra of the 7 μm-diameter metal-coated GaN nanoring above and below threshold pump power density. Figure 3(b) shows the light-in and light-out curve (L-L curve) and also the linewidth of the lasing peak. The turn-on behavior on the L-L

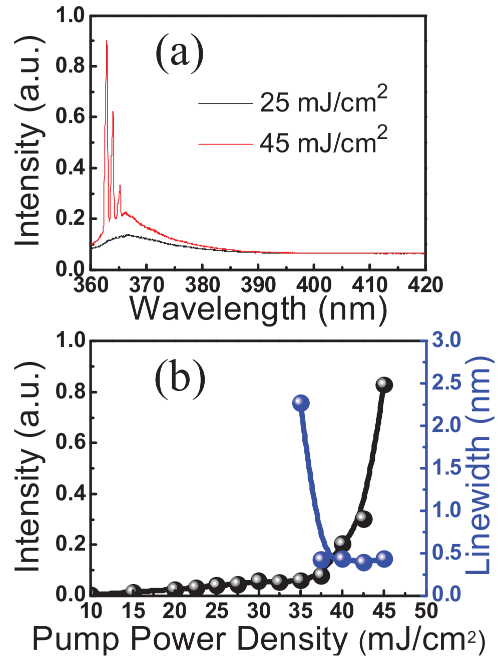

FIG. 3. (Color online) (a) The PL spectra of metal-coated GaN nanoring laser below and above threshold. (b) The light-in light-out curve of the metal-coated GaN nanoring laser and linewidth of the lasing peak.

curve indicates the lasing action of the metal-coated nanoring laser. The threshold power density would have been lower if photons of the pumping beam were injected into device more efficiently rather than being reflected or absorbed by the adjacent area. The linewidth narrowing behavior of the lasing peak in Fig. 3(b) could also be the proof of the lasing action. From the ratio of wavelength to linewidth ($\lambda/\Delta\lambda$) around transparency, the quality factor of the device is about 860, which is the highest reported data for metal-coated nanoring laser at room temperature. It is worth to noting that the Al layer coated on the ring not only improves the optical confinement for the GaN nanoring but also reduces the influence of surface roughness caused by the dry etching process. Therefore, a high quality factor and a low lasing threshold can be observed in the metal-coated nanocavity.

To further analyze the data obtained from micro PL measurements, we calculate the group index from the spacing of WGMs [$n_g = \lambda^2/(2\pi R\Delta\lambda)$],[14] where R ($=3.5\,\mu$m) is the radius of the ring, and λ is the lasing wavelength. The spacing of WGMs can be extracted from the experiment data. For the 7 μm-diameter nanoring, the wavelength spacing is approximately 1 nm, and we obtained a group index of about 5.99, which is higher than the refractive index of bulk GaN in this wavelength range.[15] We believe that the large group index is due to the effects of metal coating and dispersive gain medium on the optical mode, which was also reported in previous works.[5,16] To confirm this picture, we adopt a frequency-domain model which takes the frequency dispersions of metal (Al) and GaN in the presence of gain into account. The model is equivalent to a generalized eigenvalue problem to be solved at each frequency and is implemented with the finite-element method. The frequency-dependent eigenvalues provide spectral characteristics of cavity modes, and eigenvectors obtained at resonance are the corresponding mode profiles. The details of the approach can

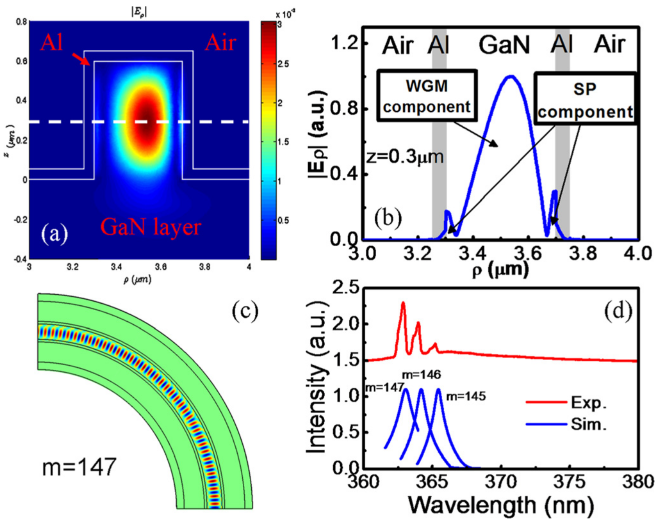

FIG. 4. (Color online) (a) The cross-sectional view of E_ρ mode profile of the metal-coated GaN nanoring. (b) The E_ρ mode profile at $z = 300$ nm (along the white-dash line in (a)). (c) The top view of E_ρ mode profile of the metal-coated GaN nanoring. (d) The comparison between the experimental and theoretical resonance spectra of metal-coated GaN nanoring.

be found in Ref. 17. The permittivity of Al is calculated with the Lorentz-Drude model[18] while that of the gain medium is obtained based on the band structure of bulk GaN (using the **k**·**p** method) and density-matrix formalism in the presence of excessive electrons and holes, which explicitly takes the Kramers-Kronig relation, and therefore the frequency dispersion of the gain medium, into account. These frequency-dependent permittivities are then input into the model. The theoretical group indices are estimated from the spectral spacing of resonance peaks from calculations.

The cross sectional and the top views of the E_ρ profile of WGM with the azimuthal number $m = 147$ are shown in Figs. 4(a)–4(c), respectively. Fig. 4(b) shows the E_ρ mode profile at $z = 300$ nm (along the white-dash line in Fig. 4(a)). The field is well-confined in the metal-coated GaN nanoring, which confirms that the lasing mode of our device is basically a hybrid mode, exhibiting both the characteristics of whispering gallery mode in the GaN ridge and surface plasmon mode around the interface of Al metal layer and GaN.[8] Taking the frequency dispersion of metal and gain medium (GaN) into account, we calculate the resonance spectra around the threshold to estimate the group index. In addition to the dispersions from metal and ring structure, the gain in GaN (at a carrier density$\sim 10^{19}$ cm^{-3}) induces another dispersion component (positive slope with respect to frequency) and also enhances the group index. As shown in Fig. 4(d), the lasing wavelengths on the experimental spectrum agree well with those on the theoretical resonance spectrum, and the theoretical group indices are 5.2 when calculated from the spacing of modes 145 and 146 and 5.7 from the spacing between modes 146 and 147. The theoretical group indices match well with the experimental value of about 5.99. This confirms that under high carrier density ($10^{18} \sim 10^{19}$/cm^3), we could observe slow light effect in the metal-coated GaN nanoring cavity. Compared to reported ultraviolet microdisk or microring lasers,[19,20] the metal-coated GaN nanoring laser has a slightly larger diameter; however, this laser also exhibits a smaller mode profile ($\sim$500 nm × 350 nm) due to the improved radial optical confinement from the Al metal layer.

In summary, room-temperature lasing with a high group index in metal-coated GaN nanoring was demonstrated. The quality factor and the threshold power density of the device were approximately 860 and 37.5 mJ/cm^2, respectively. We observed high group index in our structure, which is attributed to the effects of metal and gain medium under high carrier density and is confirmed by our calculations. In addition, from the theoretical mode profile, the lasing modes are hybrid modes exhibiting the characteristics of both the whispering gallery mode and surface plasmon mode. This result shows a promising way to further shrink the size of the metal-coated nanocavities and improve the device performance simultaneously.

The authors thank Professor S. L. Chuang from University of Illinois at Urbana-Champaign and Professor T. C. Lu from National Chiao Tung University for insightful suggestions. We are also grateful to the Center for Nano Science and Technology at National Chiao Tung University, Tyn-tek Corporation and the 2011 Lam Research Award. The study is supported by the National Science Council of the Republic of China, Taiwan under Contract Nos. NSC 99-217-2112-M-001-003-MY3 and NSC 100-3113-E009-001-CC2.

[1]M. T. Hill, Y. S. Oei, B. Smallbrugge, Y. Zhu, T. de Vries, P. J. van Veldhoven, F. W. M. van Otten, T. J. Eljkemans, J. P. Turkiewicz, H. de Waardt, E. J. Geluk, S. H. Kwon, Y. H. Lee, R. Notzel, and M. K. Smit, Nat. Photonics **1**, 589 (2007).
[2]C. Y. Lu, S. W. Chang, S. L. Chuang, T. D. Germann, and D. Bimberg, Appl. Phys. Lett. **96**, 251101 (2010).
[3]C. Y. Lu, S. L. Chuang, A. Mutig, and D. Bimberg, Opt. Lett. **36**, 2447 (2011).
[4]S. W. Chang, C. Y. A. Ni, and S. L. Chuang, Opt. Express **16**, 10580 (2008).
[5]M. T. Hill, M. Marell, E. S. P. Leong, B. Smallbrugge, Y. Zhu, M. Sun, P. J. van Veldhoven, E. J. Geluk, F. Karouta, Y. S. Oei, R. Notzel, C. Z. Ning, and M. K. Smit, Opt. Express **17**, 11107 (2009).
[6]K. Yu, A. Lakhani, and M. C. Wu, Opt. Express **18**, 8790 (2010).
[7]M. W. Kim and P. C. Ku, Opt. Express **19**, 3218 (2011).
[8]M. W. Kim and P. C. Ku, Appl. Phys. Lett. **98**, 131107 (2011).
[9]M. W. Kim and P. C. Ku, Appl. Phys. Lett. **98**, 201105 (2011).
[10]Y. G. Wang, C. C. Chen, C. H. Chiu, M. Y. Kuo, M. H. Shih, and H. C. Kuo, Appl. Phys. Lett. **98**, 131110 (2011).
[11]*Handbook of Optics*, 2nd ed., edited by M. Bass and E. W. Van Stryland (McGraw-Hill, New York, USA, 1994), Vol. 2.
[12]M. P. Nezhad, A. Simic, O. Bondarenko, B. Slutsky, A. Mizrahi, L. Feng, V. Lomakin, and Y. Fainman, Nat. Photonics **4**, 395 (2010).
[13]S. H. Kwon, J. H. Kang, C. Seassal, S. K. Kim, P. Regreny, Y. H. Lee, C. M. Lieber, and H. G. Park, Nano Lett. **10**, 3679 (2010).
[14]H. W. Choi, C. W. Jeon, M. D. Martin, P. R. Edwards, R. W. Martin, and S. Tripathy, J. Appl. Phys. **93**, 5978 (2003).
[15]T. Peng and J. Piprek, Electron. Lett. **32**, 2285 (1996).
[16]C. Y. Lu, S. W. Chang, S. H. Yang, and S. L. Chuang, Appl. Phys. Lett. **95**, 233507 (2009).
[17]S. W. Chang, Opt. Express **19**, 21116 (2011).
[18]A. D. Rakic, A. B. Djurisic, J. M. Elazar, and M. L. Majewski, Appl. Opt. **37**, 5271 (1998).
[19]C. C. Chen, M. H. Shih, Y. C. Yang, and H. C. Kuo, Appl. Phys. Lett. **96**, 151115 (2010).
[20]X. Liu, W. Fang, Y. Huang, X. H. Wu, S. T. Ho, H. Cao, and R. P. H. Chang, Appl. Phys. Lett. **84**, 2488 (2004).