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Room temperature lasing in metal-coated GaN by grating structure

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1. Introduction

In recent years, the metal-coated nanocavities have become the hot topic due to the advantages of the surface plasmonic effect and stronger optical confinement of the metal-coated cavities. Therefore, the plasmon laser will sustain the light well below it's the diffraction-limit and the subwavelengh laser was demonstrated [1-3]. Furthermore, the absorption problem of metal would lower the performance of the laser, so we insert a thin dielectric layer between the gain material and metal to reduce this kind of problem, resulting in making a higher quality factor and lowering threshold gain laser possible [3]. Up to date, there are some different structures in metal-coated nanolaser have been reported as below. In 2007, Hill *et al.* [4] demonstrated the nanorod laser with the size far below its lasing wavelength. And the nanodisk and nanopatch structure was proposed in 2010 [5-6]. Furthermore, the nanostripe GaN laser was demonstrated in lasing at the room temperature [7]. However, even though many metal-coated nanolasers have been proposed, the quality factors of these structures were not high enough, and most of them were operated in cryogenic conditions.

Here, photonic crystals are regarded much attention owing to their photonic band structure recently [8]. Light at the band edge of one dimensional photonic band gap has nearly zero group velocity and forms a standing wave which makes the laser action possible. By combining the advantages of the metal-coated cavities and the structure of one dimensional photonic crystal, we can obtain single-mode output and high quality factor laser possible. Therefore, in this study, we demonstrated lasing in metal-coated GaN by grating structure at room temperature under optical pumping conditions.

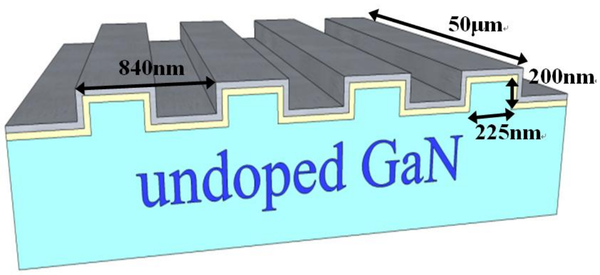

Fig. 1 Schematic diagram of the metal-coated GaN by grating structure.

2. Experimental

The schematic diagram is shown in figure 1. The gain medium of the GaN grating structure laser was a 2 μm thick undoped GaN layer, which is grown on a c-plane (0001) sapphire substrate by metal-organic chemical vapor deposition (MOCVD) technique. Then, the 200 nm thick Si_3N_4 was deposited on the planed GaN as an etching mask by plasma-enhanced chemical vapor deposition (PECVD). After that, we coated the 250nm polymethylmethacrylate (PMMA) on Si_3N_4 by spin-coating method. We define the grating pattern on the PMMA layer by E-beam lithography, then using reactive ion etching (RIE) with CHF_3 /O_2 mixture to etch down to the Si_3N_4 layer. Next, we transfer the grating pattern from Si_3N_4 layer to the undoped GaN layer with about 200nm depth by inductively coupled plasma reactive ion etching (ICP-RIE) with Cl_2 /Ar mixture. The Si_3N_4 mask layers were removed by wet etching after all above processes. To improve the quality factor of the device, we deposit 30nm Si_3N_4 layer on the patterned GaN layer. After that, a 50 nm aluminum layer was coated on the device by E-gun evaporation to form the grating structure of metal-coated GaN laser. Figure 2 showed the SEM image of the GaN grating structure after the deposition of metal. The period of the grating is 840 nm with the 225 nm width of the stripes and the 200 nm height of grating.

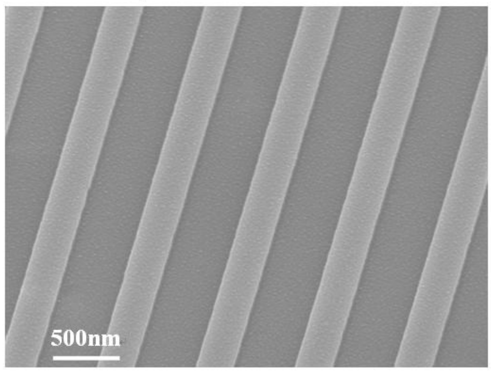

Fig. 2 The SEM image of the GaN grating structure after the deposition of metal.

The grating structure of metal-coated GaN was optically pumped by a frequency-tripled Nd: YVO_4 355 nm pulsed laser at room temperature with a pulsed width of 0.5 ns and a repetition rate of 1 kHz. A 15× objective lens was used to collect the lasing signal from the grating structure laser through a multimode fiber, and coupled into a spectrometer with the charge-coupled device detectors. The diameter of laser spot size is approximately 50 μm, which could cover the device completely. We optically pumped our device from the metal-coated surface, because the bulk GaN layer beneath the device was too thick to pump from the backside. It would absorb part of the energy from the pumping source.

3. Results and discussions

Figure 3(a) shows the measured spectra from a metal-coated GaN by grating structure above (red) and below (black) threshold under room temperature. A band edge mode lasing around 368 nm wavelength is observed in the experiment. The light-in and light-out curve of the lasing mode and the linewidth of the grating laser was shown in Figure 3(b). The linear behavior after the threshold confirmed its lasing behavior, and the threshold power density was about 0.019 kW/cm^2. Moreover, the narrowing linewidth also proved the lasing action in the metal-coated GaN nanoring laser. By estimating the ratio of wavelength to linewidth ($\lambda/\Delta\lambda$) around transparency, the quality factor of this device was about 570. The higher quality factor represented the longer average lifetime of resonant phonons in the cavity lowering the threshold power density needed to make lasing action happen. The high quality factor of our device could be attributed to the band edge mode and the surface plasmon mode at the interface of aluminum and GaN layer [7].

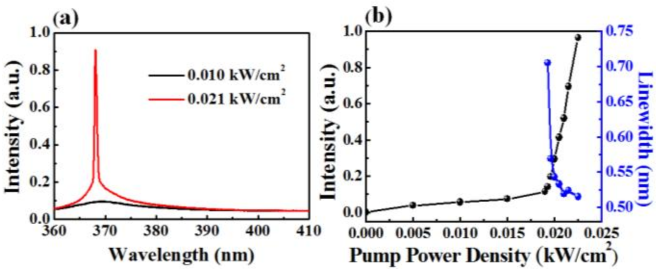

Fig. 3 (a) Measured spectra from a metal-coated GaN laser by grating structure below (black) and above (red) threshold, lasing wavelength of the grating laser is 368nm; (b) The Light-in and Light-out curve (L-L curve) from metal-coated GaN grating laser.

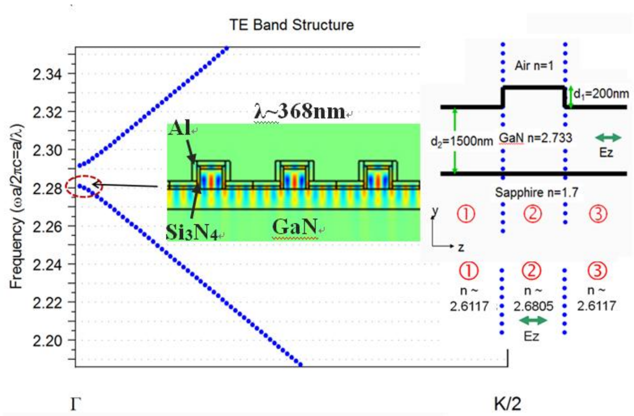

Fig. 4 The band structure of the metal-coated GaN grating laser and the band edge mode profile by FDTD simulation. (a = 840 nm)

To make sure the lasing signal is truly from the grating structure, we measure the PL spectrum of the plane surface of undoped GaN with and without the Si_3N_4 and aluminum shielding layers and confirms that there are no lasing signals of these two samples. Moreover, by finite element method and effective index method, we prove that the single mode lasing is from the band edge mode by the band diagram of the grating structure in figure 4, and all these simulation results fit to experimental result pretty well with only a small difference between them.

4. Conclusions

In the conclusion, lasing action from a metal-coated GaN by grating structure at room temperature with a high quality factor of 570 and the threshold power density of 0.019 kW/cm^2 was demonstrated. And a band edge mode is observed with a lasing peak around 368 nm. Moreover, the metal-coated structure improved the optical confinement of the device and reduced the size of GaN laser. This result provided promising information to improve the device performance.

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