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Ultra-compact Circular Polarized Metal/GaN Double-Spiral Cavity Lasers

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Abstract

The compact size, room temperature operated circular polarization laser was demonstrated with the metal/GaN double-spiral cavity. The lasing action was observed at 363 nm ultraviolet wavelength, and the highest circular polarization was found to be +1.6 of the dissymmetry factor.

1. Introduction

Recently, increasing attentions are paid to various applications of circular polarized light, such as optical communication [1], quantum-based optical information processing [2], and bio-medical diagnosis [3]. As a result, researches of circularly polarized light source become an important issue investigated by various groups.

The control of circular polarized light has been realized by spiral structure. For example, circular polarized laser with dissymmetry factor +1.4 was achieved by metal/GaN single-spiral nanowire cavity from our previous study [4]. In order to further take advantage of the field enhancement of the chiral structures which made it possible to shrink the device, we tried to utilize the double-spiral structure to fabricate an ultra-compact circular polarized laser, and then analyzed the relation between polarization characteristic and footprint of our cavity to see how small can the laser size reach but remain certain degree of circular polarization.

2. Experiments

Fig. 1 (a) shows the period, width, and height of the metal/GaN double-spiral cavity, which were designed to be 1000 nm, 300 nm, and 500 nm respectively. The SEM images of 4, 6, and 8 periods of spirals are demonstrated in Fig. 1 (b) to 1 (d), with the radius being nearly 4 μm, 6 μm and 8 μm respectively. The gain medium of the metal/GaN cavity laser was a 2 μm thick undoped GaN layer, and it was grown on a c-plane (0001) sapphire substrate by metal organic chemical vapor deposition (MOCVD). After that, we used plasma-enhanced chemical vapor deposition (PECVD) to deposit 300 nm thick of Si_3N_4 on the planed GaN as an etching mask. Then, 250 nm of polymethylmethacrylate (PMMA) was spin-coated on Si_3N_4. We define the spiral pattern on the PMMA layer by E-beam lithography, and then applied reactive ion etching (RIE) with CHF_3/O_2 mixture to etch down to the Si_3N_4 layer. Afterwards, we transfer the spiral pattern from Si_3N_4 layer to the undoped GaN layer with about 500 nm 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 of the above processes. Before adding the metal, we deposited 30 nm of Si_3N_4 on GaN layer to improve the quality factor. Last, a 50 nm aluminum layer was coated on the device by E-gun evaporation to form the double-spiral metal cavity.

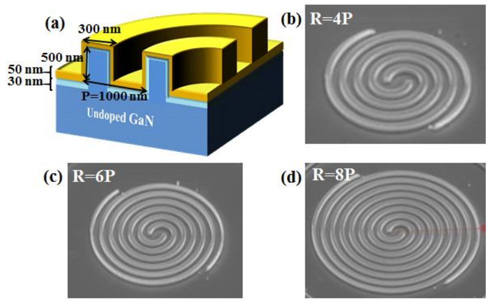

Fig. 1 (a) Schematic diagram of the metal/GaN double-spiral cavity. (b)(c)(d) The SEM image of the left-handed metal/GaN double-spiral cavity with different radius(R=4P, 6P, 8P).

3. Results and Discussions

The metal/GaN double-spiral cavity was optically pumped by a frequency-tripled Nd:YVO_4 355 nm pulsed laser whose pulsed width was 0.5 ns and the repetition rate was 1 kHz, at room temperature. A 100× objective lens was used to collect the lasing signal from the planar chiral nanolaser through a multimode fiber and coupled into a spectrometer with a charge-coupled device (CCD) detector. The devices were normally pumped from the top side to prevent the huge absorption of the thick bulk GaN layer beneath the surface of devices.

Fig. 2 (a) shows the photoluminescence spectra of the 10 periods of metal/GaN double-spiral cavity at room temperature. A lasing peak wavelength of approximately 363 nm was observed. Fig. 2 (b) depicts both the light-in and light-out curves of the lasing mode and the linewidth in relation to incident pump power density. The incident threshold pump power density of left-handed double-spiral metal cavity was about 25 W/cm^2. The lasing characteristic of our metal cavity was confirmed by the linear behavior above the threshold pump power density and the narrowing linewidth which verified emission photons in the GaN were converted from spontaneous emission to stimulated emission.

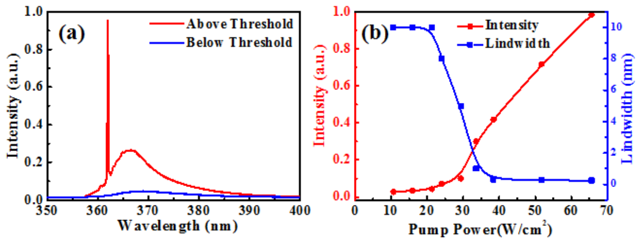

Fig. 2 (a) PL spectrum of the left-handed metal/GaN double-spiral cavity below (blue) and above (red) threshold (b) The Light-in and Light-out curve (L-L curve) and the linewidth variation from left-handed metal/GaN double-spiral cavity.

For investigating the polarization characteristics of the metal/GaN laser, we modified the μ-PL measurement setup by adding a circularly polarized analyzer. In this study, we combined a tunable quarter-wave plate, in which the λ/4 phase retardation can be tuned to various wavelength (from 150 nm to 6 μm), and a linear polarizer within the UV region to construct a circularly polarized analyzer for distinguishing the polarization state of our double-spiral lasers. Fig. 3 (a) shows the tunable quarter-wave plate setting for the 363 nm region in which the c-axis is at +45° with respect to the vertical direction (z-axis) that separates the RCP from LCP through polarization conversion. After passing through the circular polarized filter, the measured horizontal component (x-axis) of the linear polarization represents the intensity of RCP light, denoted as I_R, whereas the perpendicular component (y-axis) of the linear polarization indicates the intensity of LCP light, denoted as I_L. Therefore, by comparing the intensity difference of these two linear polarization components, we can assess whether the polarization state of the emission laser is RCP- or LCP-like. Once we measure the I_R and I_L of the emission light, the dissymmetry factor g_e is shown below as eq. (1)

$$g_e = 2\frac{I_L - I_R}{I_L + I_R} \quad (1)$$

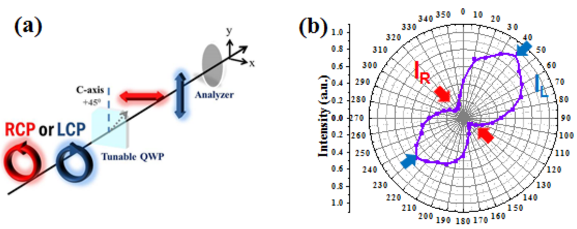

Fig. 3 (a) Schematic diagram of circularly polarized analyzer which can separate the LCP and RCP light by checking the direction of the linear polarization converted by the tunable quarter-wave plate. Degree of polarization of perpendicular and horizontal linear polarization light converted from the (b) L chirality laser (10 periods)

Fig. 3 (b) shows the polarization curve of the lasing signal after the quarter-wave plate and linear polarizer. It confirmed that the double-spiral metal cavity could produce LCP laser signal with circular polarized state. The highest value of the g_e factor (+1.6) happened at 10 periods of spiral cavity, which agreed highly with the theoretical pure left-handed circular polarized light (+2).

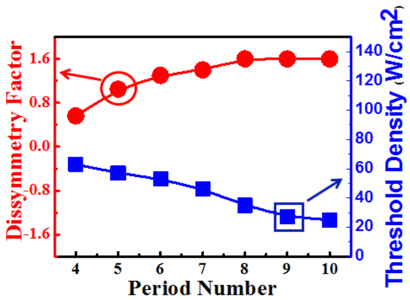

Fig. 4 Threshold density and the g_e factor against the periods of the left-handed metal/GaN double-spiral cavity.

To find out the influence caused by the device's footprint, we fabricated various size of cavities and compared their dissymmetry factor and threshold density with period number of spiral structure. As shown in Fig. 4, the g_e factor decreased from 1.6 to 0.56 when we made spiral cavity diminished from 10 periods (radius= 10 μm) to 4 periods (radius= 4 μm), while the threshold density increased from 25 W/cm^2 to 63 W/cm^2. It was mainly due to the fact that less number of spirals has poorer confinement of light, which raise the optical loss to form the result we got.

3. Conclusion

In short, we had demonstrated metal/GaN double-spiral cavity lasers with circularly polarized and ultraviolet lasing action at room temperature. Though the dissymmetry factor would go down as we decreased the period of double-spiral cavity, the laser was able to show circular polarization even better than some spiral structures developed by other groups, which meant our ultra-compact lasers have potential for applying at optical information technologies, chip-scale integrated circuit and biological applications.

Acknowledgements

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