Grating-patterned Hyperbolic Metamaterials for InGaN/GaN Nanowire Quantum Dots Single Photon Source

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***Abstract*-Due to the wide adjustable range of bandgap and large exciton binding energy, InGaN/GaN nanowire quantum dots (NQDs) has been one of the most promising candidates for site-controlled single photon source (SPS) in a wide range from visible to near-infrared. Here the annular-grating-patterned hyperbolic metamaterials was proposed to enhance the performance of InGaN/GaN NQDs SPS. By combining the broadband enhancement of spontaneous emission from hyperbolic metamaterials and directional light output from annular grating, both the spontaneous emission rate and photon extraction efficiency can be enhanced. Our research provides a novel idea for high-frequency, high-brightness and directional InGaN/GaN NQDs SPS, which has good prospect for many applications such as quantum information processing.**

***Keywords*-Single photon source, Nanowire quantum dots, Hyperbolic metamaterials, Spontaneous emission rate**

I. INTRODUCTION

Due to the wide adjustable range of bandgap and large exciton binding energy, InGaN quantum dots (QDs) can emit single photon in a wide range from visible to near-infrared and work above liquid nitrogen temperature and even room temperature. It has been one of the most promising candidates for single photon source (SPS) [1-3]. Nanowire quantum dots (NQDs) fabricated by top-down method or selective area grown can obtain site-controlled SPS, which is promising for integrated chip-scale SPS [4, 5]. However, the undesirable quantum confined Stark effect (QCSE) caused by the intrinsic strong polarization field separates the electron and hole wavefunctions and significantly inhibits the spontaneous emission rate and thereby decreases the quantum efficiency [6, 7].

For the quantum information processing, high-frequency (above GHz) SPS is necessary [8, 9]. Purcell effect is a good way to enhance the spontaneous emission rate and repetition rate of quantum emitter. DBR micro-cavities, photonic crystals and plasmonics have been designed to manipulate the density of states of the electromagnetic field around the quantum emitter and thereby the spontaneous emission rate and photon collection efficiency can be increased [10, 11]. But all those methods are based upon resonance that is bandwidth limited. It is difficult to match the resonance wavelength of coupled structure with the emission wavelength of quantum emitter accurately. What's worse, the temperature dependence of the emission wavelength and resonance wavelength is usually different.

Hyperbolic metamaterials (HMM) shows hyperbolic dispersion and corresponds to infinite local photonic density of states (LPDOS), which can be used for broadband Purcell effect radiative decay engineering [12, 13]. However, most of the emission photon will dissipate inside the metamaterial due to ohmic losses in planar HMM [14]. Here, we proposed a grating-patterned hyperbolic metamaterials for InGaN/GaN NQDs SPS. Broadband enhancement of the spontaneous emission rate and photon extraction efficiency was realized.

II. SIMULATION STRUCTURE AND MODELS

The schematic of the InGaN/GaN NQDs SPS coupled with grating-patterned HMM is shown in Fig. 1. InGaN quantum dot is placed inside GaN nanowire and nearby the surface of HMM constructed by Ag/TiO_2 multilayer. The HMM was patterned with a sub-wavelength annular grating around the nanowire. Considering the quantum confinement effect, the diameter of the nanowire is set as 20 nm and the length 100 nm. The distance of the InGaN quantum dot and HMM surface is 10 nm. Both the layer thicknesses of Ag and TiO_2 are 10 nm. Period and duty ratio of the annular grating is 200 nm and 0.5 respectively.

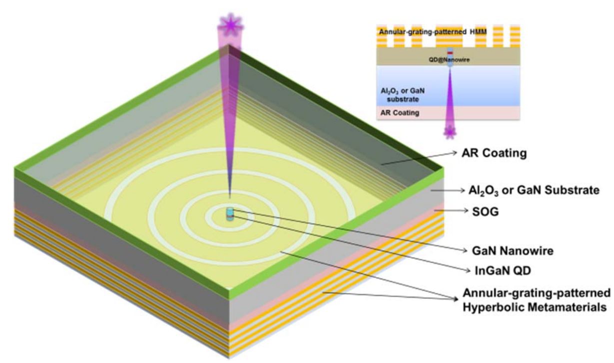

Fig. 1. Schematic of the InGaN/GaN NQDs SPS coupled with grating-patterned HMM.

In our simulation, numerical simulations by 3D finite-difference time-domain (FDTD) method are performed to explore the spontaneous emission and collection properties of the structrue. The InGaN quantum dot is simulated as an electric dipole. 5 pair of Ag/TiO_2 multilayer and 5 period concentric annular gratings were used in our simulation.

III. Result And Discussion

The Purcell factor as a function of wavelength is calculated with horizontal dipoles for the InGaN/GaN NQDs, InGaN/GaN NQDs coupled with HMM and InGaN/GaN NQDs SPS coupled with grating-patterned HMM respectively. The results are compared as shown in Fig. 2. The InGaN/GaN NQDs shows a Purcell factor of only 0.045 at 450 nm since the diameter of the nanowire is far smaller than the wavelength and the photon confinement is very weak. When the InGaN/GaN NQDs is coupled with HMM and grating-patterned HMM, the Purcell factor can be increased in all the visible range and the maximum reach 25 at 450 nm, which corresponds to the emission wavelength of InGaN QDs. The Purcell factor can be improved further by increasing the number of HMM layers.

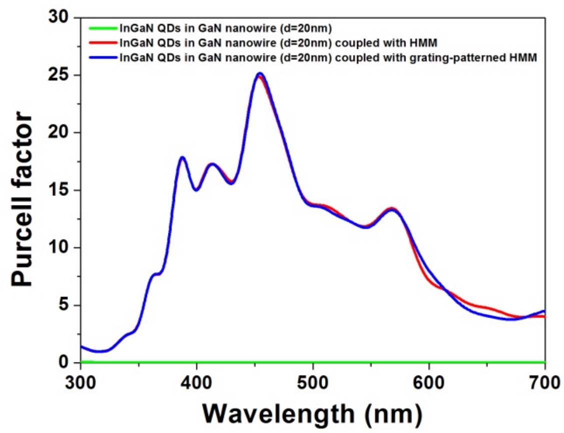

Fig. 2. Purcell factor as a function of wavelength for the InGaN/GaN NQDs, InGaN/GaN NQDs coupled with HMM and InGaN/GaN NQDs SPS coupled with grating-patterned HMM.

The electric field emitted by a horizontal dipole embedded in the GaN nanowire, GaN nanowire coupled with HMM and GaN nanowire coupled with grating-patterned HMM is also calculated to investigate the photon extraction efficiency, as shown in Fig. 3. It shows that the grating-patterned HMM can improve the photon extraction efficiency compared with no-patterned HMM or nanowire. The far field also give the same conclusion. The photon extraction efficiency can be improved further by increasing the period of the concentric annular grating and add Ag slab on the bottom of the HMM.

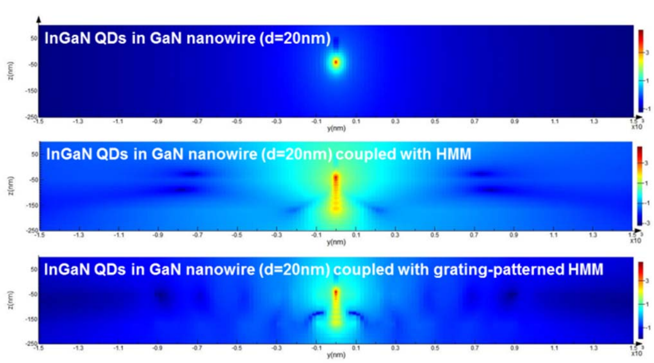

Fig. 3. The electric field emitted by a horizontal dipole embedded in the GaN nanowire, GaN nanowire coupled with HMM and GaN nanowire coupled with grating-patterned HMM.

III. Conclusion

In this paper, we proposed and numerical simulated a grating-patterned hyperbolic metamaterials for InGaN/GaN NQDs SPS. Broadband enhancement of the spontaneous emission rate and photon extraction efficiency was demonstrated. The highest Purcell factor of this device structure is 25 at wavelength of 450 nm, which is about 560 times that nanowire. The grating-patterned HMM can improve the photon extraction efficiency compared with no-patterned HMM and maintain the same Purcell factor. The structure was promised for high-frequency, high-brightness and directional InGaN/GaN NQDs SPS.

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