Simulation of Metallic Photonic Crystal Triangular Arrays Embedded in GaN Light Emitting Diodes

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***Abstract*—The metallic photonic crystals (MPC) in gallium nitride (GaN) light-emitting diodes (LED) can exhibit photonic crystal band gaps and surface plasmon resonance (SPR) phenomena. The simulation results are presented by using finite-different time-domain (FDTD) method. We designed the two-dimensional (2D) triangular arrays of metallic photonic crystals that are located on the p-GaN surface, ITO surface, inside the ITO layer, or inside the p-GaN layer to enhance the light extraction and thus improve the external quantum efficiency. The results included triangle array period parameter of 800 nm, fill factor (Rq) of 0.1, metallic thickness of 10 nm. It was shown that, for example, the light extraction efficiency was enhanced from 81.38% to 91.67% when the photonic crystal arrays were designed at 120 nm inside the ITO layer.**

Keywords—simulation; metallic photonic crystal; light-emitting diode; surface plasmon; efficiency

I. INTRODUCTION

The rise of green energy technology has made light-emitting diode (LED) widely accepted as lighting source. It is well known that the internal quantum efficiency of GaN LED is approaching to 98~100%. But only a small fraction of light can escape to the outside due to the total internal reflection (TIR) caused by large mismatch in refractive indices. This can result low light extraction efficiency and unnecessary LED chip heating problems [1]. Cho et al. used Au nanoparticles that were embedded in the p-GaN layer. They found multiple quantum well (MQW) localized surface plasmons (LSP) that made wavelength red-shift to 520 nm, and increased by 86% at this wavelength at driving current of 20 mA [2]. By finite-different time-domain (FDTD) method, Chen et al. used Ag layer under MQWs. The square lattice, photonic crystal cyclinder array was formed on top of the p-GaN by second Ag layer, and the filled by indium tin oxide (ITO). This study simulated the photonic crystal lattice constant (a), fill factor (Rq), Ag thickness (t_{mpc}) of the second Ag layer with p-GaN. It was demonstrated that metallic photonic crystal (MPC) produced surface Plasmon resonance (SPR) to couple incident light. The light extraction efficiency was enhanced by 4 times with a=410 nm, Rq=0.3, t_{mpc}=130 nm [3].

Photonic crystals (PCs) employ periodic dielectric constant (refractive index) materials to form photon status structure arrange. They manipulate portion of wavelength in assignable direction to form a confined effect [4,5]. It has been indicated that PCs increase light extraction efficiency by three main mechanisms. First, it is prevention of lateral propagation of light and enhancement in vertical direction from an LED by photonic crystal bandgap (PCB). Second, the PCs, like Bragg grating structure, produce multiple diffraction effect. The incident angle is modified at the device and air interface. The light (photon) has more chance to escape to device. Third, the multiple diffused scattering of light by PCs that breaks TIR to enhance light extraction efficiency [6].

Why structure of surface plasmons can increase the light extraction? Some of the photons that are released from the MQWs can couple with devices. The others may just carry out TIR inside the devices. If the materials have defects, they lead photons to convert into thermal energy and result in bad influence. If photons encounter the structure of nano-metallic at this moment, it can produce the surface plasmon with high density of energy level. Therefore, the radiation of efficiency of surface plasmon is higher than traditional electron and hole. It can be assumed that photons and surface plasmon comply with the conditions of conservation of momentum. Photons are then not absorbed and reflected, but have the opportunities to exist by the shape of surface plasmon, using the structure of periodic surface of the photonic crystals. The wave vector is produced by the structure which can match with the wave vector that photons need. The incident electromagnetic wave can obtain extra horizontal wave vector and lead surface plasmon to generate resonance. Thus, if we can convert the form of surface plasmon into photons and couple them, there will be two ways in production of photons.

II. EXPERIMENTAL DETAILS

FDTD simulation was employed to analyze triangular lattice metallic photonic crystals in p-GaN surface, ITO surface, inside the ITO layer, and inside the p-GaN layer. This method used Maxwell's equations to separate electric field and magnetic field in the x, y, z directions of the space, then time. The refractive indices of GaN, ITO and Ag at the wavelength of 460 nm were 2.4, 2 and 0.04+2.66i, respectively. The metallic photonic crystals were embedded at various locations in LED structure. The parameters included period range 200-800 nm, fill factor 0.1-0.9, Ag thickness (t_{Ag}) 0-100 nm, L_{ITO} 0-250 nm, $L_{p\text{-}GaN}$ 0-170 nm. TM wave was the simulated mode.

III. RESULTS AND DISCUSSIONS

A. P-GaN Surface

Fig.1 shows Ag MPC located on p-GaN surface. Higher Ag thickness can reduce efficiency and fill factor has a significant influence over the structure. For the 2D triangle

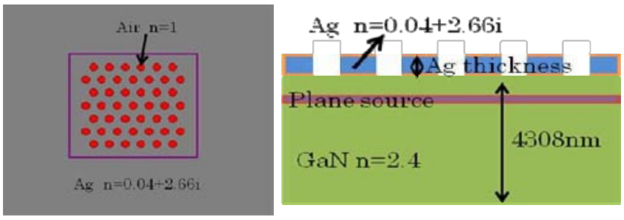

Fig. 1 Schematic of triangle array and sample cross section.

array, the control LED sample efficiency is 74.6%, and the MPC LED sample exhibits a relative efficiency of 72.9% with period 800 nm, Rq 0.9, Ag thickness 10nm.

B. *ITO Surface*

Fig. 2 is the schematic diagram with air hole triangle array located in nano-metallic films on ITO surface of LED. In a standard process, in order to increase the current diffusion, 250 nm ITO is used, which can lead variation in refraction and affect the distribution situation of electromagnetic wave and the light extraction efficiency for the whole devices. According to Snell's law, the scattering angle between ITO and air is higher than that of GaN and air, which results in variance of light path and the relatively higher device efficiency. The control LED shows a relative efficiency of 83.17%. However, the metallic photonic crystal LED sample exhibits relative efficiency of 81.03%. The structure parameters are period 800 nm, Rq 0.9, and Ag thickness 10 nm, still in reduction by 2.14%

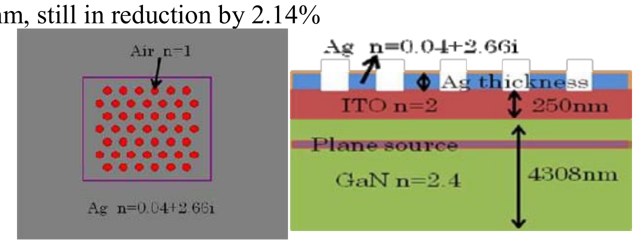

Fig. 2 Schematic illustration of the MPC on ITO surface.

C. *Inside the ITO*

MPC is localed inside ITO layer that formed holes in metallic Ag nano-films, shown in Fig. 3. Some process would mix metallic particles to increase current property. At the same time, mixed metallic nano particles may produce surface plasmons that can enhance light extraction efficiency. The parameters have been Rq 0.3, Ag thickness 20 nm, period 800 nm, L_{ITO} 220 nm. The maximum efficiency is 91.64%, while the control LED efficiency is 83.3%. The increase is 8.34%.

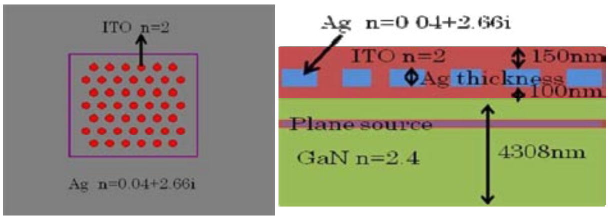

Fig. 3 Schematic illustration of the MPC inside the ITO layer.

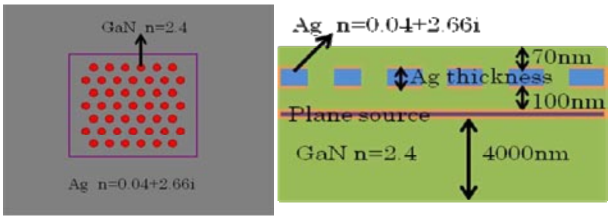

Fig. 4 Schematic illustration of the MPC inside the p-GaN.

D. *Inside the p-GaN*

MPC is located inside p-GaN layer that formed holes in the metallic nano-films. The parameters have been set at Rq 0.1, Ag thickness 10 nm, period 800 nm, $L_{p\text{-}GaN}$ 120 nm, which gives maximum efficiency of 91.67%. The control LED efficiency is 81.38%, thus increased by 10.29%.

IV. CONCLUSION

The simulation has indicated that metallic photonic crystals on the LED surface, due to the large difference in refractive index, could not result in relative efficiency improvement. On the other hand, when the metallic photonic crystals were embeded in the ITO layer and p-GaN layer, due to inclusion inside the devices, the phenomenon of surface plasmon would appear. The use of photonic crystal structure and the surface plasmon could be coupled to produce excess photons. The efficiency could be increased by 8-10%. Compared with nano-metal plates and nano-metal cylindricals, although metal nano-particles could generate surface plasmon effect, the nature of the metal material still exists. The nano-metal cylindrical surface plasmon effect was less obvious. If the different parameters are well designed and matched, there will be excited photonic crystals and surface plasmon phenomena, and enhanced LED light extraction efficiency can be expected.

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