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Enhancement of photoluminescence efficiency from semi-polar InGaN/GaN multiple quantum wells with silver metal

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ABSTRACT

We have studied the effect of surface plasmon polariton (SPP) and localized surface plasmon (LSP) on the emission of semi-polar InGaN/GaN light emitting diode (LED) with multi-quantum wells structure. From the photoluminescence (PL) measurement at room temperature, spectrally-integrated enhancements of semi-polar SPP LEDs with 15 and 40-nm-thick Ag films were 1.7 and 2.9, respectively. The absorbance peak of Ag nanoparticles was red-shifted as diameter of Ag nanoparticles increases. However, the absorbance peak of Au nanoparticles was not related with their diameters. Spectrally-integrated enhancement of semi-polar LSP LED with 250-nm-diameter Ag nanoparticles was shown to 1.3. These results showed that the blue emission of semi-polar InGaN/GaN LED can be improved by SPP and LSP.

1. Introduction

An InGaN/GaN Multiple-quantum well (MQW)-based light emitting diode (LED) with high emission efficiency is vital to develop high-brightness solid state lighting devices. To achieve the high efficiency of LEDs, it is necessary to increase internal quantum efficiency (IQE) and extraction quantum efficiency (EQE). Among many approaches for the improvement of IQE and EQE such as semi-polar LED, photonic crystal LED, LED with patterned sapphire substrate, and surface plasmon LED, have been investigated for many years [1–4]. Most of all, surface plasmons (SPs) have been actively studied to enhance the luminescence efficiency of light emitting diode. SPs are the collective oscillation of electrons at the metal/dielectric interface. SPs can be sorted by surface plasmon polariton (SPP) and localized surface plasmon (LSP) according to their propagation characteristics. SPP is surface electromagnetic wave propagating in a direction parallel to the metal film/dielectric interface, whereas LSP is local oscillation among the isolated metal nanoparticles with a resonance frequency that is determined by morphology of the nanoparticles.

Although many research about SPP and LSP for enhancing luminescence efficiency of *c*-plane LED have actively and widely been studied for years, SPP and LSP which are applied to InGaN/GaN semi-polar LEDs have not been investigated. The semi-polar LED has been proposed to reduce quantum-confined stark effect, which is result of a spontaneous and piezoelectric polarization field parallel to the [0 0 0 1] direction [5,6]. To make further improvement of luminescence of semi-polar LED, we try to enhance of photoluminescence (PL) intensity of the semi-polar LED by using the effect of SSPs and LSPs.

In this paper, we studied the effect of SPP and LSP resonance on blue emission from InGaN/GaN semi-polar LEDs with Ag films and nanoparticles. Morphology of Ag nanoparticles was formed by thermal annealing and measured by atomic force spectroscopy (AFM). To analyze the enhancement of light emission intensity from semi-polar LEDs with Ag film and nanoparticles, PL measurements were conducted at room temperature. By using effect of SPP and LSP modes, we studied increase of luminescence in the semi-polar LED with Ag metal films and nanoparticles

2. Experiments

The semi-polar InGaN/GaN LED was grown on [1 1 -2 2] *m*-plane sapphire substrate using a metal organic vapor chemical deposition method. A 2.0-μm-thick Si doped n-GaN layer was deposited on *m*-plane sapphire substrate, and then three periods of InGaN/GaN MQWs were grown on n-type GaN. Finally, a 10-nm-thick Mg-doped p-GaN layer was grown to complete a typical LED structure. Semi-polar SPP LED was fabricated by depositing Ag film with thickness of 10 and 40 nm on semi-polar InGaN/GaN LED. PL measurements were carried out to study the optical properties of semi-polar LED structures before and after depositing metal film. Here, the samples were excited by monochromatic light of

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390-nm-wavelength from 450 W Xenon lamp passing through a monochromator, and then PL emission was collected from the back-side of semi-polar LEDs.

Ag and Au nanoparticles were fabricated by thermal annealing of thin Ag and Au film. The thin Ag and Au film were deposited on semi-polar LED structure by thermal evaporation. Both 5 and 10-nm thick Ag films and 3 and 5-nm-thick Au films were annealed at 350 °C for 15 min. The LED with 10-nm-thick Au and 15-nm-thick Ag film were annealed at 500 °C for 10 min, respectively. The LSP modes of Ag and Au nanoparticles were measured by UV–visible absorption spectroscopy.

Semi-polar LSP LED with periodic line array patterns was formed by a photolithography process. The width and period of line arrayed patterns were 10 and 20 μm, respectively. Next, Ag film with thickness of 15 nm deposited on the line-patterned LED by thermal evaporation. The lift-off process to remove the photoresist was performed by aceton. Finally, then, Ag nanoparticles were formed by the Ostwald ripening mechanism by rapid thermal annealing in N_2 ambient at 350 °C for 10 min [7]. PL measurements were carried out using He–Cd laser (325 nm). The PL measurements were conducted with top excitation and top PL collection at room temperature.

3. Results and discussion

Fig. 1 shows a cross sectional TEM image of semi-polar InGaN/GaN LED structure. Here, it appears 15-nm-thick Mg-doped p-GaN top layer, three MQWs with 25-nm-thick, and 2-μm-thick Si doped n-GaN bottom layer deposited on *m*-plane sapphire substrate. The SPs as an evanescent wave exponentially decays with distance from metal surface, and then the exciton located only within the near field of the surface can couple to SPs mode. Therefore, top GaN layer thickness is critical for generating coupling between MQWs and SPs [8,9]. The penetration depth (Z) of the SPs fringing field into semiconductor is given by below equation

$$Z = \lambda/2\pi\left[\frac{\varepsilon'_{GaN}-\varepsilon'_{metal}}{\varepsilon'^{2}_{metal}}\right]^{1/2} \quad (1)$$

ε'_{GaN} and ε'_{metal} are the real parts of the dielectric constants of semiconductor and metal. So, Z is calculated as 47 and 33 nm for Ag and Au, respectively [10,11]. Thickness of Mg-doped p-GaN layer was 15 nm is suitable to generate SP coupling between metal and MQWs of semi-polar InGaN/GaN LED.

Fig. 2(a) shows PL spectra from semi-polar SPP LED with 15 and 40-nm-thick Ag film, respectively. As-grown semi-polar LED was used as the reference. Peak wavelength of reference LED was 453 nm. PL intensities of the SPP LED with by 15 and 40-nm-thick Ag films were more enhanced in wavelength regions from 400 to 700 nm than that of reference sample. Furthermore, PL intensity of the SPP LED with 40-nm-thick Ag film was more increased than that of SPP LED with 15-nm-thick Ag film. When the luminescence intensity of the reference LED integrated over the emission spectrum from 412 to 500 nm was normalized to 1, the spectrally-integrated enhancement of the SPP LEDs with 15 and 40-nm-thick Ag film were 1.7 and 2.9, respectively. By this result, it can be found that strength of SPs–MQWs coupling was increasing with thickness of Ag film, which leads SPs energy to a value close to the exciton energy of MQWs [12,13]. Increase of PL intensity of the semi-polar LED with 40-nm-thick Ag film may be looked upon as enhancement by reflection. However, in Ref. [14], enhanced PL intensity of the LED by SPPs with Ag film is not attributed to reflection of Ag film but SP-MQWs coupling.

Fig. 2(b) shows the enhancement of PL intensities in the SPP LEDs with 15 and 40-nm-thick Ag films as a function of wavelength. In Ref. [9], the enhancement ratio of *c*-plane InGaN/GaN LED with 40-nm-thik Ag showed similar result from our semi-polar InGaN/GaN LED with 40-nm-thick Ag film, although it increased at shorter wavelength with difference of our result. The surface plasmon energy ($\hbar\omega_p$) of silver is 3.76 eV, but this energy must be modified for Ag/GaN surface coating to $\hbar\omega_p \approx 3$ eV ($\approx$410 nm) when using the dielectric constant of Ag and GaN [15,16]. The energies of SPs and MQWs of semi-polar LED were matched, so that enhancement ratio of semi-polar LED with 15 and 40-nm-thick Ag layer indicated 3.4 and 3.8 at wavelength of 431 nm, respectively.

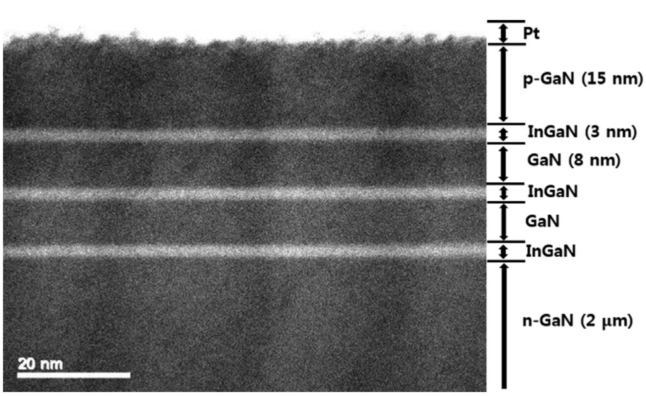

Fig. 1. (a) A cross sectional TEM image of semi-polar InGaN/GaN LED structure as the reference sample.

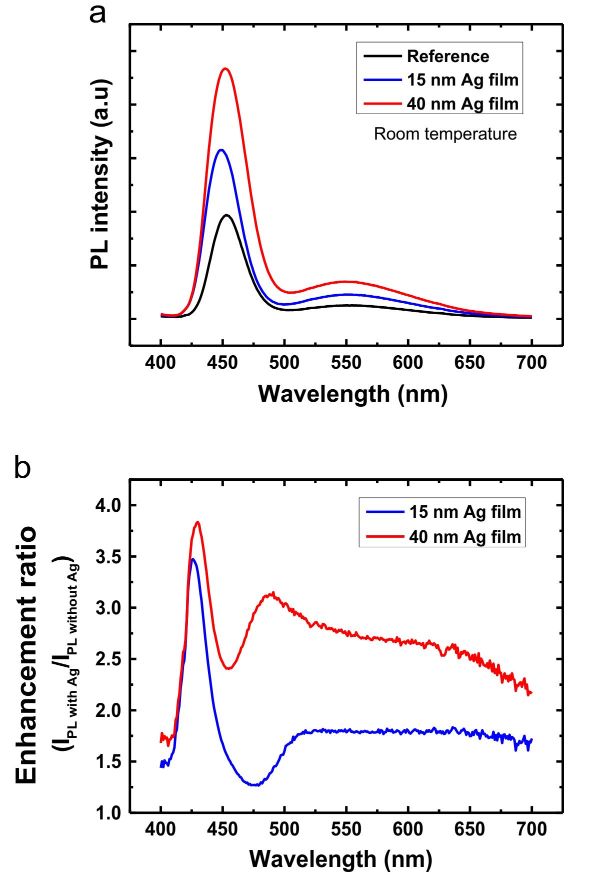

Fig. 2. (a) Room temperature PL spectra of *m*-plane LED with 15 and 40-nm-thick Ag film and (b) enhancement ratio of *m*-plane LED with 15 and 40-nm thick Ag film as a function of wavelength.