

## Enhanced Light Emission by Exciton-Surface Plasmon Coupling

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### ABSTRACT

Surface plasmon coupling technique was performed to enhanced green light emissions from InGaN/GaN quantum well. We found that photoluminescence intensities were increased by fabricated nano-grating structures on the gold layers and enhancement ratios depend on the grating periods. We also simulated the localized SP modes by 3D-finite difference time domain (FDTD) calculation. The experimental results were well correlated to the calculated results, and we found that the both exciton-SP coupling and light extraction process can be controlled by the nano-structures of the interfaces. This suggests that even more efficient emission should be obtainable by optimizing the nanostructure geometries.

### INTRODUCTION

We have an earnest desire to enhance a green emission of InGaN-based single quantum well (QW) structures. Recently, high efficient blue InGaN emission has already been achieved and commercialized, but it is very difficult to get similar high efficiency at other wavelength regions. We propose exciton-SP coupling method as one solution to dramatically increase the efficiencies of light emitting materials and devices. The idea of SP enhanced light emission had been previously described [1-2], and for the first time, we directly measured significant enhancement of internal quantum efficiency of visible light emission due to spontaneous recombination rate increases for InGaN-QWs [3-4], CdSe-QDs [5], and organic light emitters [6-7]. The SP coupling technique can enhance light emission at any wavelength region by choosing a metal layer. High efficient InGaN emission with RGB colors should be applicable to a white light LED without a yellow phosphor.

In order to understand more detail mechanism of exciton-SP coupling and design even more efficient device structures, we perform both experimental approach and theoretical calculations. Recently we report the photoluminescence (PL) measurements for several nano-grating structures on the metal layers [8]. Here we compare the experimental results with the simulation of the localized SP modes by three-dimension finite difference time domain (3D-FDTD) calculation.

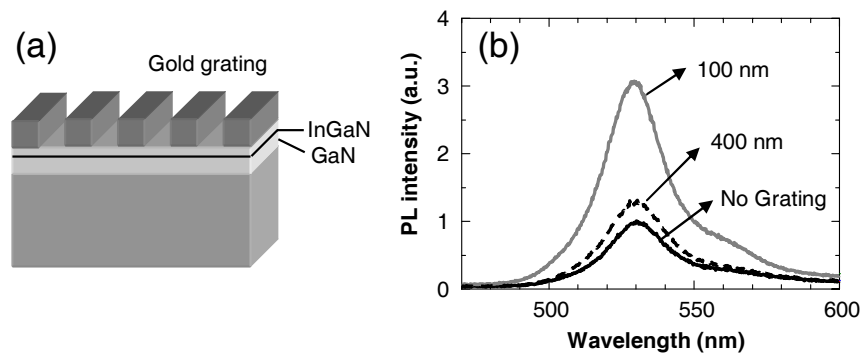
### EXPERIMENT

A GaN(10 nm)/InGaN(3nm)/GaN(4  $\mu$ m) QW was grown on a sapphire substrate by a metal-organic chemical vapour deposition (MOCVD). A 50nm thick gold film was evaporated

on top of the surface of wafers. After polishing the bottom surface of the samples, we photo-excite and detect emission from the backside of the samples through the transparent substrate. Such back side access to the QWs permit us the rapidly compare the PL from QWs with and without the influence of SPs. Photoluminescence (PL) measurements were performed by exciting the QW with a 406nm diode laser and detecting the emission with a multi-channel spectrometer. Metal grating structures (Figure 1a) were fabricated by electron beam lithography on a 50 nm thick polymethylmethacrylate (PMMA) mask coated on the metal surface. The pattern was transferred into the top metal layer by using Ar ion milling. The sample structures and the experimental condition were already described in ref. [8].

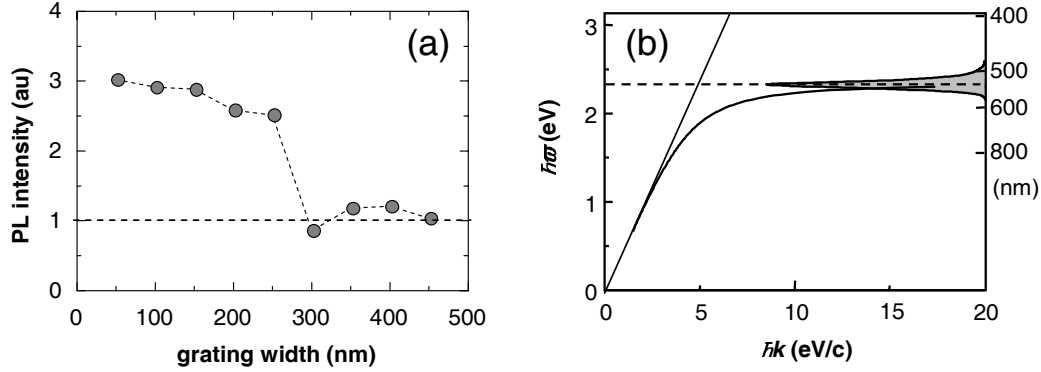
## DISCUSSION

Figure 1b shows obtained PL spectra of InGaN/GaN with gold grating with 100nm and 400nm metal widths and un-structured sample. The PL intensity was not so enhanced by coating un-structured Au layer, while the large enhancement had been observed with Ag coating even without any structures. By making nano-grating structures on the gold layer, we can improve the PL enhancements and finally obtained 3-fold enhancement.



**Figure 1.** (a) Sample structure of InGaN/GaN QW with nano gold grating. (b) PL spectra for InGaN/GaN with gold grating with 100nm and 400nm widths and un-structured sample.

Figure 2a shows the SP enhancement ratios of green light with nano-grating structured Au layers on InGaN/GaN. All metal nano-grating have 1:1 ratio for metal to window. There is a very clear correlation between the grating periods and the PL intensities. The PL peak intensity of the un-structured sample at 530 nm is normalized to 1. The PL intensities suddenly increase when the metal widths are smaller than 300 nm.

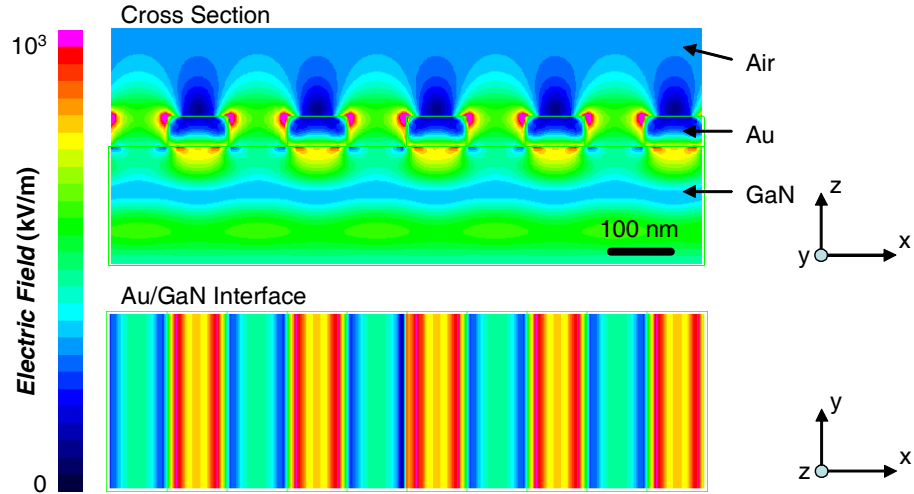


**Figure 2** (a) The grating periods dependence of the SP enhanced ratios of green InGaN/GaN with Au. (b) Dispersion diagrams of the SP at Au/GaN. Observed PL spectrum was also plotted.

Figure 2b shows the dispersion diagrams of SP on Au/GaN surfaces calculated by the dielectric functions. The SP frequencies of Au/GaN was calculated as  $\sim 2.4$  eV ( $\sim 520$ nm). This dispersion diagram shows that the density states of the SP mode become dramatically larger with approaching to the SP frequency. This large density of states increases the energy transfer from QW to SP and enhances the spontaneous emission rates, and this increases the internal quantum efficiency of emission. Though the SP frequency of Au/GaN is close to the green emission wavelength, we could not obtain a large PL enhancement for an un-structured sample. The energy coupling between SP and photon is very hard because the dispersion curve of the SP is located at outside of a light-cone (Fig. 2b). Therefore if the metal surface is perfectly flat, the SP energy would be thermally dissipated. However, the SP energy can be extracted as light by providing roughness or nano-structuring the metal layer. The fabricated nano-grating structure allows SPs of high momentum to scatter, lose momentum, and couple to radiated light. Designing of the nano-structure is very important for SP-photon coupling and light extraction, and here, we could control the PL enhancement by using nano-grating structures.

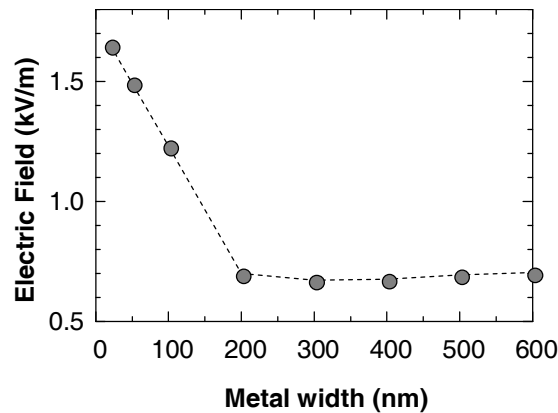
### 3D-FDTD calculations

Another very important role of a nano-grating is to localize the SP mode in the nano-structures. The localized SP mode provides a giant electromagnetic field at the metal surface and it has been used for high sensitive sensors, high density memories, efficient solar cells, and so on. In order to evaluate the spatial distribution of the electromagnetic field, the 3D-FDTD simulation [9] is one of the very powerful tools. Such simulation may bring the more understanding of the mechanism and optimization of more effective geometry. Figure 3 shows the obtained electromagnetic field distribution around gold nano-grating with 100nm width and 200nm period on GaN. X-polarized plane wave with 530 nm wavelength and 1 V/m amplitude was used as a source wave. The large electric fields were observed at Au/air and Au/GaN interface. These large E-fields should be attributed to the localized SP at the interface. Both the exciton-SP coupling and SP-photon coupling should be very active when the intensities of the localized E-fields are very large.



**Figure 3** Simulated spatial distribution of electromagnetic field around Au nano-grating on GaN.

Fig. 4 shows the grating period dependence of the highest values of the E-field intensities at the Au/GaN interface. The localized E-field becomes suddenly larger at the shorter metal width than 200 nm. This tendency is similar to the experimental results. This suggests that the controlling of the localized SP mode is also effective to the exciton-SP coupling. We believe that the localized SP frequencies may be modified in the nano-structures and it might bring a better coupling condition between the SP at Au/GaN and green emission. We should be able to control both the QW-SP coupling and the SP-photon coupling by changing the widths and periods of nano-grating structures.



**Figure 4** Metal grating width dependence of the localized E-field intensities calculated by the 3D-FDTD simulation.

The obtained results suggest that the nano-structure geometry is very important factor to decide the light extraction and tuning of SP coupling condition. Both experimental approach by fabricating nano-structures and theoretical approach by using 3D-FDTD simulation are very powerful way to elucidate the underlying physics of the SP coupling. Quite recently, several theoretical studies about surface plasmon coupled light emission with grating structures. [10-12] Even more efficient light emission efficiencies should be achievable by controlling grating

structures. Undoubtedly, the SP coupling technique would lead the new super bright semiconductor light sources, which could be very cheap to make, easy to process, and would become commonly used light source instead of fluorescent tubes in the near future.

## CONCLUSIONS

The nano-structure geometry is very important factor to decide the light extraction and tuning of SP coupling condition. Both experimental approach by fabricating nano-structures and theoretical approach by using 3D-FDTD simulation are very powerful way to elucidate the underlying physics of the SP coupling. We believe that the SP coupling technique would be able to enhance light emission with any wavelength by tuning the coupling condition.

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