Improved Surface Plasmon Coupling with an InGaN/GaN Quantum Well for More Effective Emission Enhancement

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Abstract
With a dielectric layer between metal and semiconductor for generating surface plasmon, the dissipation rate of metal is reduced and the evanescent-field range is increased such that surface plasmon coupling leads to stronger emission enhancement.

Introduction
Although it has been shown that surface plasmon (SP) coupling with the quantum wells (QWs) in an InGaN/GaN QW light-emitting diode (LED) can enhance LED emission efficiency [1-3], its practical application is still hindered by two major concerns, including metal dissipation loss and the proximity of the metal nanostructure for generating SPs to the QWs [4-6]. In such a coupling process, carrier energy in the QWs is transferred into SPs through the amplification of the evanescent fields of the SPs. The effective emission of SPs leads to the overall emission efficiency enhancement. In this situation, part of SP energy is dissipated by the metal nanostructure supporting the SP that creates another energy loss channel. Also, for effective coupling, the distance between the metal surface and QW must be in the order of a few tens nm. Such a thin p-type GaN layer over QWs makes current spreading ineffectively. In this paper, we demonstrate a novel method for solving these two problems simultaneously. By inserting a thin dielectric layer with its refractive index lower than that of GaN, the induced SP field can be redistributed such that the major part of SP energy is in the dielectric medium. Therefore, metal dissipation can be tremendously reduced. Meanwhile, the evanescent field coverage range can be significantly increased. In other words, the dissipation loss is reduced and the p-type GaN layer between metal and QW can be increased to reach a value of a conventional LED.

Enhanced LED Emission through SP-QW Coupling
Several demonstrations of LED emission enhancement have been reported by this research group. One of them is briefly described here [2]. Here, the output enhancement of a green InGaN/GaN QW LED through the coupling of QW with localized SPs (LSPs), which are generated on Ag nanostructures on the top of the device, is demonstrated. The suitable Ag nanostructures for generating LSPs of resonance energies around the LED wavelength are formed by controlling the Ag deposition thickness and the post-thermal-annealing condition. With a 20 mA current injected onto the LED, enhancements of up to 150 % in electroluminescence peak intensity and of 120 % in integrated intensity are observed. By comparing this with a similar result of blue LED previously published, it is confirmed that surface plasmon coupling for emission enhancement can be more effective for an InGaN/GaN QW of lower crystal quality, which normally corresponds to the emission of a longer wavelength. Fig. 1 shows a plan-view SEM image of the thermally annealed nanostructure of a 12-nm Ag film (NS (12nm)) on LED sample C. Fig. 2 shows the transmission spectra of various Ag structures showing LSP resonance energies. The curves of NS (12nm) and TF (12nm) correspond to LED samples C and B, respectively. Fig. 3 shows the EL intensity variations of the three LED samples with injection current. LED sample A corresponds to a conventional LED. Here, 120-150 % increase of LED output intensity can be observed through SP-QW coupling.

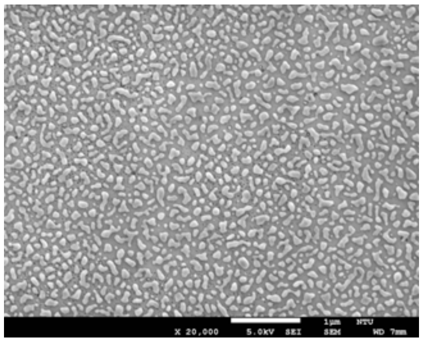

Fig. 1 Plan-view SEM image of the thermally annealed nanostructure of a 12-nm Ag film on the LED epitaxial wafer.

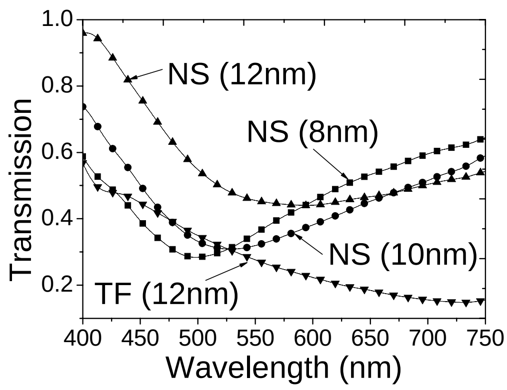

Fig. 2 Transmission spectra of various Ag structures showing LSP resonance energies. The curves of TF and NS correspond to thin film and nanostructure, respectively.

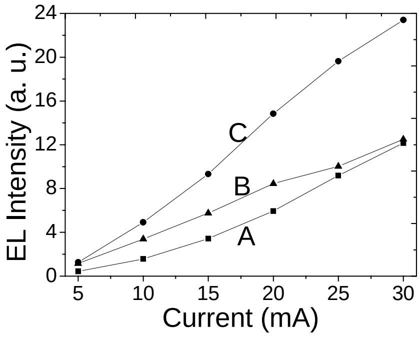

Fig. 3 EL intensity variations of the three LED samples with injection current.

Effect of the Inserted Dielectric Layer

To reduce the SP dissipation rate and elongate the coverage of evanescent field of SP, we insert a SiO_2 layer between the 20-nm GaN cap layer (on a green-emitting InGaN/GaN QW) and the Ag nanostructures. Fig. 4 shows the comparison of photoluminescence (PL) intensity between the samples of bare QW (QW), Ag nanostructures on GaN (QW-Ag), and Ag nanostructures on 10-nm SiO_2, which is deposited on the QW sample. One can see that the sample with the SiO_2 layer has much stronger PL intensity, when compared with the other two samples. Fig. 5 shows the time-resolved PL (TRPL) profiles of the three samples. Here, the faster decays of the samples with Ag indicate the significant SP-QW coupling.

To confirm the observed enhancement through the insertion of the SiO_2 layer, we use the model of flat interface for theoretical calculation. Fig. 6 shows the theoretical results of surface plasmon polariton (SPP) lifetime (inverse of dissipation rate) under various conditions, including a 50-nm Ag thin film on SiO_2 of various thicknesses. The label of Ag/SiO_2 represents a sample of Ag on a thick SiO_2 layer. Here, one can see that on GaN, the SPP lifetime increases with increasing SiO_2 thickness until certain thickness is reached. Fig. 7 shows the evanescent electric field profiles of various cases. The positive side stands for the metal. Here, one can see that although the field decays fast in the SiO_2 layer, beyond which it decays quite slowly in the GaN layer. Therefore, beyond -80 nm, the evanescent field is strongest in the case of 20-nm SiO_2 layer. Such theoretical results can explain well the experimental observations in Figs. 4 and 5.

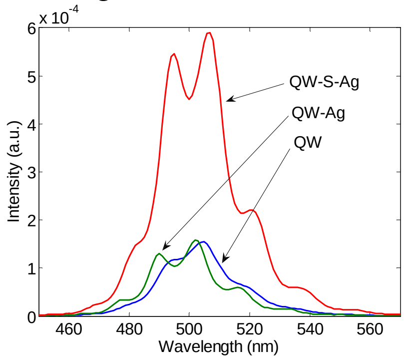

Fig. 4 Comparison of PL intensity.

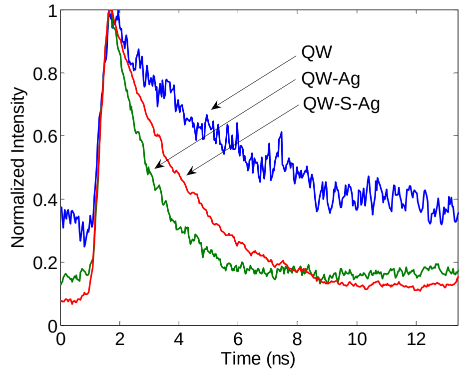

Fig. 5 Comparison of TRPL profiles.

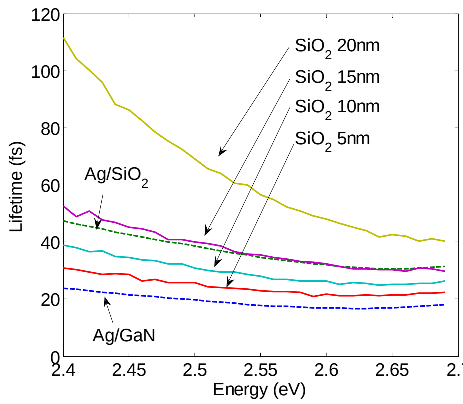

Fig. 6 SPP lifetimes under various conditions.

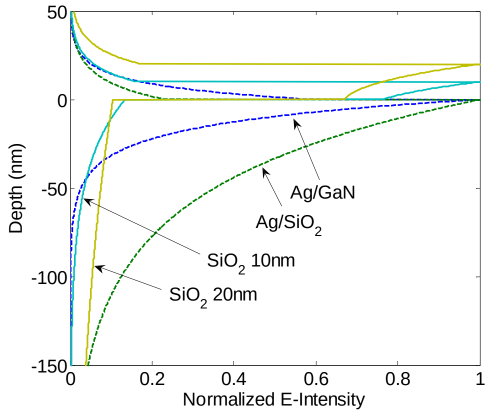

Fig. 7 Evanescent field distributions under various conditions.

Conclusions

In summary, we have demonstrated that by inserting a dielectric layer of a lower refractive index between metal and semiconductor, emission enhancement can be further improved through SP-QW coupling. Theoretical calculations for SPP confirmed the trend of experimental data.

References

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