

Surface plasmon enhanced super bright InGaN light emitter

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We use surface plasmons to increase the light emission efficiency from InGaN/GaN quantum wells by covering these with thin metallic films. Large luminescence enhancements were measured when silver or aluminum layers are deposited 10 nm above an InGaN light emitting layer, whereas no such enhancements are obtained from gold coated samples. The internal quantum efficiencies of quantum wells before and after metallization were determined from the temperature dependence of the photoluminescence intensity. Our results indicate that the use of surface plasmons will lead to a new class of very bright light emitting diodes, and highly efficient solid-state light sources.

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1 Introduction

Since 1993, InGaN light emitting diodes (LEDs) have been improved and commercialized [1, 2], but their original promise as solid-state replacements for light bulbs has so far been delayed as their light emission efficiencies have been limited [2]. Here we describe a method to enhance this light emission efficiency through the energy transfer between surface plasmons (SPs) and quantum wells (QWs). SPs, excited by the interaction between light and metal surfaces [3–6], are known to strongly modify fluorescence lifetimes, enhance absorption of light in molecules [7] and increase Raman scattering intensities [8, 9]. Since 1990, SPs have also received much attention for use in LEDs [10–15]. Although coupling of spontaneous emission from InGaN QWs into the SP modes of thin silver films has been individually observed through increased absorption at the SP frequency [16], and time-resolved measurement confirm that the recombination rate in QWs can be increased [17], light has not yet been efficiently extracted from plasmon-enhanced emitters at visible wavelengths. Quite recently, we have reported for the first time large photoluminescence (PL) increases from InGaN/GaN QW material coated with metal layers [18]. By polishing the bottom surface of grown InGaN samples, QW emission can be photoexcited and measured through the back of the substrate, permitting the rapid comparison between PL from QWs in proximity with different metal coatings and distance to the metal film.

2 Experimental

InGaN/GaN single quantum well wafers were grown on a (0001) oriented sapphire substrate by a metal-organic chemical vapor deposition (MOCVD). The sample structures consist of a GaN (4 μm) buffer layer, an InGaN SQW (3 nm) and a GaN cap layer 10 nm, 40 nm, and 150 nm in thickness. Silver, alu-

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minum, or gold layers, 50 nm in thickness, were evaporated on top of the surfaces of these wafers. To perform the PL measurements, a cw-InGaN diode laser (406 nm) was used to excite the quantum wells from the bottom surface of wafer. PL was collected and focused into an optical fiber and subsequently detected with a multichannel spectrometer (Ocean optics). Neutral density filters were used to vary the excitation power (from 0.18 to 4.5 mW) to determine the power dependence of the PL intensities, and their temperature dependence was studied by using a by cryostat (oxford) with the ability of cooling from room temperature to 6K.

3 Results and discussions

Figure 1(a) shows typical PL spectra from an InGaN/GaN QWs separated from silver, aluminum, and gold layers by 10 nm GaN spacers. The PL peak of the uncoated wafer at 470 nm is normalized to 1, and a 14-fold enhancement in peak PL intensity is observed from the silver coated emitter. The PL intensity integrated over the emission spectrum is increased by 17 times. 8-fold peak intensity and 6-fold integrated intensity enhancements are obtained from aluminum coated InGaN QW, whereas the PL is not increased after gold coating. A small increase in the PL intensity might be expected after metallization since the metal reflects pump light back through the QW, doubling the effective path of the incident light, but differences between gold and silver reflectivities at 470 nm cannot explain the large difference in the measured enhancement alone. The PL enhancement after coating with Ag and Al can be attributed to strong interaction with SPs. Electron-hole pairs excited within the QW couple to electron vibrations at the metal/semiconductor interface when the energies of electron-hole pairs in InGaN ($\hbar\omega_{\text{InGaN}}$) and of the metal SP ($\hbar\omega_{\text{sp}}$) are similar. Then, electron-hole recombination may produce SPs instead of photons, and this new recombination path increases the spontaneous recombination rate. If the metal/semiconductor surface were perfectly flat, it would be difficult to later extract light from the SP, a non-propagating evanescent wave. However, roughness and imperfections in evaporated metal coatings can scatter SPs as light.

The plasmon energy ($\hbar\omega_{\text{p}}$) of silver is 3.76 eV [19], but this energy must be modified for a Ag/GaN surface to approximately $\hbar\omega_{\text{sp}} \sim 3$ eV (400 nm) when using the dielectric constant of silver [19] and GaN [20]. Thus, silver is suitable for SP coupling to blue emission, and we attribute the large increases in PL intensity from Ag-coated samples to such resonant SP excitation. In contrast, the estimated $\hbar\omega_{\text{sp}}$ of gold on GaN is lower than ~ 2 eV (~ 560 nm) [19], and no measurable enhancement is observed in Au-coated

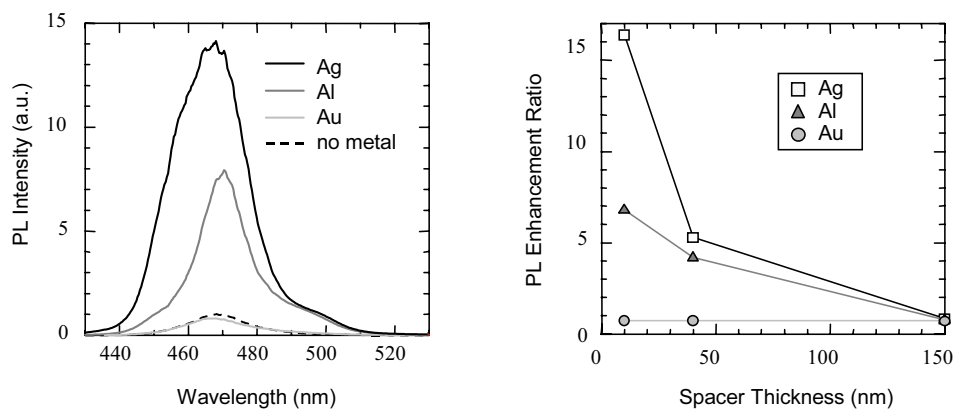


Fig. 1 (a) PL spectra of InGaN/GaN QWs coated with Ag (black line), Al (dark grey line) and Au (light grey line). The distance between the metal layers and QWs was 10 nm. The PL peak intensity of uncoated InGaN/GaN QW (dashed line) at 470 nm was normalized to 1. (b) The PL enhancement ratios were measured for samples with Ag (square), Al (triangle), and Au (circle) plotted against the thicknesses of GaN spacers.

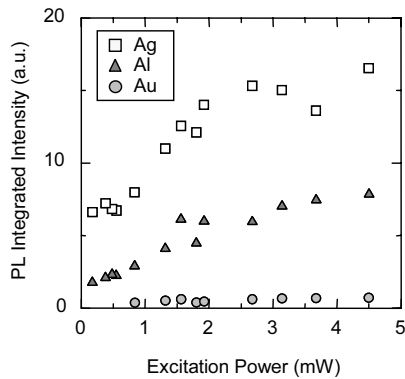


Fig. 2 Excitation power dependence of the PL enhancement ratios of InGaN/GaN QWs separated from Ag (square), Al (triangle), and Au (circle) layers by 10 nm GaN spacers.

InGaN emitters as the SP and QW energies are not matched. In the case of aluminum, the $\hbar\omega_{\text{sp}}$ is higher than ~ 5 eV (~ 250 nm) [19], and the real part of the dielectric constant is negative over a wide wavelength region for visible light. Thus, a substantial and useful PL enhancement is observed in Al-coated samples, although the energy match is not ideal at 470 nm and a better overlap is expected at shorter wavelengths.

PL intensities of Al and Ag coated samples were also found to strongly depend on the distance between QWs and the metal layers whereas Au coated sample did not. Figure 1b compares PL enhancement ratios for three different GaN spacer thicknesses (of 10, 40, and 150 nm) for Ag, Al and Au coatings. Al and Ag samples show exponential increases in PL intensity as the spacer thickness is decreased, whereas no such improvement was measured in gold coated QWs. This spacer layer dependence of the PL enhancement ratios matches our models of SP-QW coupling, as the SP is an evanescent wave that exponentially decays with distance from the metal surface. Only electron-hole pairs located within the near-field of the surface can couple to the SP mode, and this penetration depth (Z) of the SP fringing field into the semiconductor is given by $Z = \lambda/2\pi [(\epsilon'_{\text{GaN}} - \epsilon'_{\text{metal}})/\epsilon'_{\text{metal}}]^2$ where ϵ'_{GaN} and ϵ'_{metal} are the real parts of the dielectric constants of the semiconductor and metal, and Z can be calculated as $Z=47, 77$, and 33 nm for Ag, Al, and Au, respectively. Figure 1b shows a good agreement between these calculated penetration depths and measured values for Ag and Al coated samples.

We also find that PL enhancement increases with excitation power (Fig. 2). In InGaN QWs, electron-hole pairs are often localized by spatial bandgap modulations resulting from fluctuations in indium composition, QW width, or piezoelectric field. These radiative recombination centers for electron-hole pairs explain the PL insensitivity to growth defects of InGaN/GaN QW material. However, the emission efficiency is reduced at high excitation powers as these localization centers are saturated. When metal layers are deposited within the near field of the QW, electron-hole pairs can rapidly couple to surface plasmon modes, saturation can be avoided, and LEDs can achieve high emission efficiencies and brightness even under intense excitation. The coupling rate (k_{sp}) between QWs and SPs are expected to be very fast due

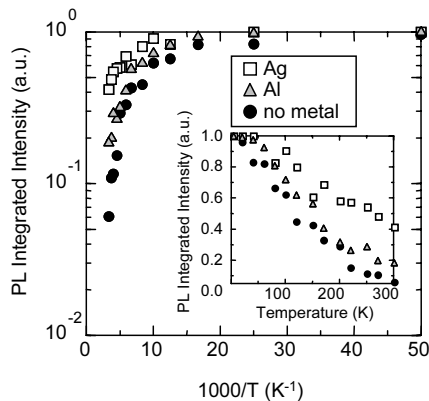


Fig. 3 Linear and Arrhenius plots of the temperature dependence of integrated PL intensities of InGaN/GaN QWs with Ag (square), Al (triangle), and uncoated sample (circle) with 10 nm GaN spacers. PL integrated intensities at 4.2 K were normalized to 1.

to the high electromagnetic fields introduced by the large density of states from the SP dispersion diagram.

As spontaneous emission rates are increased, so are the internal quantum efficiencies (η_{int}), which is given by the ratio of the radiative (k_{rad}) and nonradiative (k_{non}) recombination rates of electron-hole pairs. In order to obtain the enhanced η_{int} to separate the SP enhancement from other possible effects, we have measured the temperature dependence of the PL intensity. Figure 3 shows the Arrhenius plots of the integrated PL intensities from InGaN QWs separated from Ag and Al films by 10 nm spacers, and compares these to uncoated samples. η_{int} values from uncoated QWs were estimated as 6 % at room temperature by assuming $\eta_{\text{int}} \sim 100$ % at 4.2 K. These η_{int} values increased 6.8 times (to 41 %) after Ag coating and 3 times (to 18 %) after Al coating, explainable by spontaneous recombination rate enhancements through SP coupling. η_{int} is a fundamental property and not depend on the pumping method (photo pumping or electron pumping). The external emission efficiency of LED final device is proportional to η_{int} . Therefore, 6.8-fold increasing of η_{int} means that 6.8-fold improvement of the efficiency of LED devices should be achievable. Such improved efficiencies of LEDs are expected to be much larger than those of current fluorescent lamps or light bulbs.

4 Conclusion

We conclude that the SP enhancement of PL intensities of InGaN is a very promising method for developing solid-state light sources with high emission efficiencies. We have directly measured significant enhancements of η_{int} due to spontaneous recombination rate increases. SP coupling is one of the most interesting solutions for developing efficient photonic devices, as the metal can be used both as an electrical contact and for providing high electromagnetic fields from SPs. We believe that this work provides a foundation for the rapid development of highly efficient and high-speed solid-state light emitters.

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