Surface-plasmon coupling enhances light emission

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Blue-green light-emitting diodes improve efficiencies by 25–120%.

Although tremendous progress has been made in the development of InGaN/GaN quantum-well (QW) LEDs in the past decade, the light-emitting efficiency, particularly in the green–red wavelength range, must still improve for display and solid-state-lighting applications. The use of surface-plasmon (SP) coupling to a QW to enhance emission has recently attracted much attention. In essence, SPs, including surface-plasmon polaritons (SPPs) and localized surface plasmons (LSPs), represent behavioral traits of collective electron oscillations at a metal/dielectric interface. An SPP can propagate along the interface, whereas an LSP describes local oscillations. Either type of SP can effectively produce photons when their momentum is matched.

An SP extends an evanescent field into the dielectric. When a light emitter or absorber is located near the interface and covered by the evanescent field, it can exchange energy with an SP via this field. Through this coupling mechanism, the transfer of energy from the carriers in a QW into SPs creates an effective light-emission channel. This channel is particularly effective when the defect density in the QW is high. Therefore, SP coupling to a QW has great potential for enhancing the emission efficiency of InGaN/GaN QW LEDs, particularly in the green–red range.

Recently, our team successfully fabricated InGaN/GaN QW blue and green LEDs characterized by enhanced emission efficiencies, using the SP-QW coupling mechanism. Figure 1 shows the structure of an SP-coupled blue LED (referred to as ‘LED III’), in which a periodic strip pattern of Ni/Au is coated onto the mesa surface, except in the region of the p-contact pad, with a strip width and spacing of 10µm. Below the p-contact tier, a SiO₂ dielectric layer is deposited to enhance lateral current spreading. After addition of the coating for the n-type ohmic contact, the standard LED sample (‘LED I’) is completed. In the flip-chip LED (‘LED II’), a 50nm-thin Ag film is deposited on the current-spreading strip structure such that top emission is suppressed.

This Ag film serves to generate SPPs at the Ag/GaN interface for QW-SP coupling. As shown in Figure 1 for LED III, to reduce SP leakage through the direct metal/semiconductor contact in the SP-coupled LED, a 10nm Si₃N₄ dielectric layer is deposited to cover the Ni/Au current-spreading strip structure before the final coating of a 50nm-thin Ag film is applied on the top. Therefore, the SPP-generating Ag film is isolated from both the Ni/Au current-spreading strip structure and the p-contact pad. Figure 2 shows the variation of the top and bottom-emitting electroluminescence intensities in each sample as a function of injection current. The enhancement and reduction of the output intensities

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Figure 2. Output electroluminescence (EL) intensities (in arbitrary units) of LED samples I–III around a wavelength of 460nm, as a function of injection current. Sample III uses structure shown in Figure 1.

Figure 3. Scanning-electron-microscopy image of the surface of LED sample C shows nano-sized silver islands, which generate localized surface plasmons.

from LEDs III and II, respectively, are shown, compared with that of LED I. The intensity reduction of LED II is due to the inefficient SPP radiation, because the coupled energy is lost through metal dissipation and SPP leakage into the semiconductor. By comparing the performance of LEDs I and III, one can see that the QW-SP coupling leads to a 25–50% output enhancement.

However, our simulation study\(^3\) found that the coupling of radiative LSP (the ‘bright mode’) to a QW is more effective in producing emission enhancements than SPP coupling, because the latter has a higher dissipation rate. It is also predicted numerically that SP coupling for emission enhancement can be more effective and more practical for an InGaN/GaN QW of lower crystal quality, which normally corresponds to emission at longer wavelengths. To demonstrate the reality of these predictions, we constructed three LEDs in the green range (at a wavelength of about 550nm) for comparison. To create metal nanostructures on an LED for LSP-coupling generation, we thermally anneal a thin Ag film to form nano-island structures.

The three green LED samples include the standard LED (sample A), which has the same structure as LED I. In sample B, a 10nm-thin Ag film is deposited on the top for SSP generation. To prepare sample C, the LED is thermally annealed at 200°C for 40min in ambient \(N_2\), to change the top Ag thin film into nanostructures in the window regions between the current-spreading strips. LSPs, instead of SPPs, are most common in such isolated Ag nano-island structures. Figure 3 displays a scanning-electron-microscopy image showing the Ag nano-island structures. Figure 4 shows the integrated LED-output intensities of samples A–C as a function of injection current. One can clearly see the intensity enhancements of both samples B and C. With LSP coupling, sample C shows up to 120% output-intensity enhancement compared with the conventional LED (sample A). The results in Figure 4 confirm the higher emission enhancement through LSP coupling in a green LED.

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The improved efficiency facilitated by the SP-QW coupling can be further optimized either by increasing the hole concentration in the p-type GaN layer, or by using the vertical SP-QW-coupling configuration on the n-type side. The increased hole or electron concentration allows for a further reduction of the distance between the QW and the metal/semiconductor interface, thus enhancing the coupling effect without sacrificing the current-spreading function.

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