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Enhanced and partially polarized output of a light-emitting diode with its InGaN/GaN quantum well coupled with surface plasmons on a metal grating

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The enhanced and partially polarized output of a green light-emitting diode (LED), in which its InGaN/GaN quantum well (QW) couples with surface plasmons (SPs) on a surface Ag grating structure, is demonstrated. Compared with a LED sample without (flat) Ag coating, the total output intensity of an LED of SP-QW coupling can be enhanced by ~59% (~200)% when the grating period and groove depth are 500 and 30 nm, respectively. Also, a bottom-emission polarization ratio of 1.7 can be obtained under the condition of 15 nm in groove depth. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3046099]

Surface plasmon (SP) coupling with a quantum well (QW) was proven useful for enhancing the emission efficiency of a light-emitting diode (LED).[1–7] The SP features for QW coupling may include SP polariton (SPP) and localized SP (LSP), depending on the metal nanostructures formed on the LED. For SPP coupling, normally a metal grating structure is needed for effective coupling and radiation.[4,5,8] For LSP coupling, the metal geometry is crucial for matching the LSP resonant energy with the QW emission spectrum.[7,9] To develop polarized LED, a one-dimensional (1D) metal grating structure is useful not only for creating anisotropic SP features such that polarized LED output can be obtained[10] but also for enhancing emission through a large-area SPP or LSP coupling with QW. It is noted that with polarized SP coupling, the major parts of the carriers in the QW are directed to emit light in the designated polarization. This process is different from a mechanism (such as grating diffraction) for redistributing the angle dependence of unpolarized light emission. In this letter, the enhanced and partially polarized outputs of green-emitting InGaN/GaN QW LEDs with their QWs coupled with SPs on 1D Ag gratings are demonstrated. The emission enhancement can be as large as ~59% (~200)% under certain conditions, and the bottom-emission polarization ratio can reach 1.7 under another set of conditions when compared with a sample of no (flat) metal coating.

The LED epitaxial structures were prepared with metal-organic chemical vapor deposition on *c*-plane sapphire substrate. In the structure for demonstrating the SP coupling effects (structure I), after a 30 nm GaN nucleation layer (grown at 530 °C) and a 3 μm *n*-GaN (grown at 1050 °C), a single InGaN/GaN QW structure 3 nm in well thickness and 5 nm in barrier thickness (grown at 700 and 900 °C, respectively) was deposited, leading to an emission wavelength around 515 nm. Next, a 10 nm p-Al$_{0.2}$Ga$_{0.8}$N layer and then a 55 nm *p*-GaN layer (both grown at 900 °C) were deposited. Therefore, the distance between the QW and the top surface (for metal coating) is 70 nm, which is about double the e^{-1} decay length of the SP evanescent field in GaN. To show the difference in a LED without the SP-coupling effect, we prepared another epitaxial structure (structure II). The major differences between structures II and I include the increases in the p-Al$_{0.2}$Ga$_{0.8}$N thickness from 10 to 30 nm and the *p*-GaN thickness from 55 to 120 nm. Therefore, in structure II, the distance between the QW and the top surface is increased to 155 nm, which is more than four times the e^{-1} decay length of the SP evanescent field. Hence, a significant SP coupling effect in structure I and a negligible SP coupling effect in structure II are expected.

A set of LED samples (A, B, and C series of different grating periods) was fabricated based on structure I. In each sample, the LED mesa size is 300×300 μm^2. A ring pattern of Ni/Au metal layers around the mesa boundary with the ring width of 45 μm for current spreading was deposited. On the mesa top surface of sample A, there is no metal coating except the aforementioned current spreading region and ohmic contacts. In sample B, a flat Ag film of 200×200 μm^2 in dimension and 45 nm in thickness was deposited at the center of the LED mesa for possibly generating SPP coupling with the QW. Therefore, the lateral gap between the ring pattern for current spreading and the square Ag film for SP generation is 5 μm. In sample C, instead of the flat Ag thin film, a 200×200 μm^2 1D grating pattern was defined at the center of the mesa with electron-beam lithography. The grating grooves were formed to produce a depth of 15 nm on the *p*-GaN layer. Then, a Ag film of about 45 nm in thickness (counted from the grating groove bottom) was deposited. The period of the grating was varied from 400 to 550 nm with a step size of 50 nm. The duty cycle was fixed at 50%.

Then, another set of LEDs (sample A′, B′, and D series) similar to sample A, B, and C series, respectively, was fabricated also based on structure I. The device structure and fabrication conditions of samples A′ (B′) and A (B) are the same. Those of sample D and C series are the same, except that the etching depth of the GaN groove in sample D is

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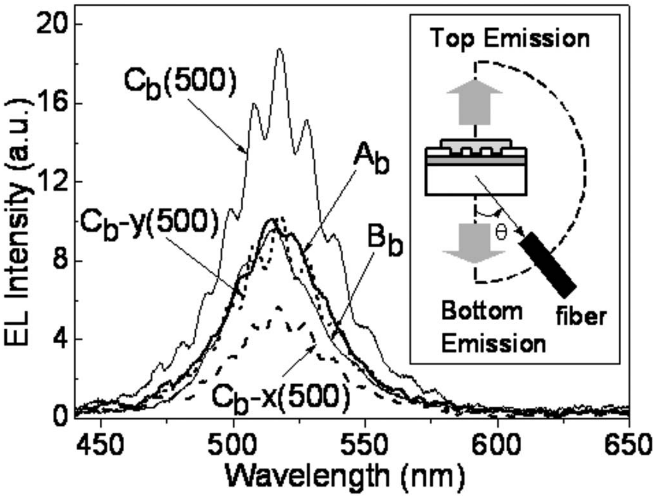

FIG. 1. LED bottom-emission spectra of samples A, B, and C(500), including its two polarization components, at 40 mA injection current. The subscript *b* in a sample notation represents bottom emission. In the inset, the setup for angle-dependent LED output intensity measurement is schematically shown.

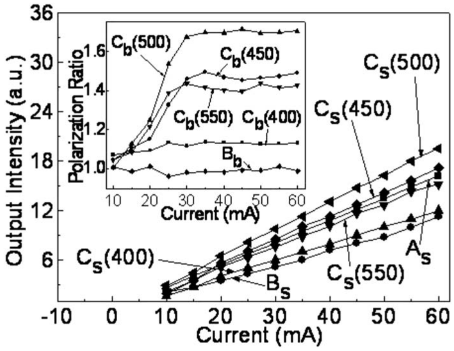

FIG. 2. Total LED output intensities (the summation of top and bottom emissions) as functions of injection current of sample A, B, and C series. In the inset, the polarization ratios of bottom emission in various samples as functions of injection current are demonstrated. The subscript *s* in a sample notation represents total intensity.

increased to 30 nm while the Ag thickness from the groove bottom to the surface is kept at 45 nm. Next, samples E, F, and G series were fabricated based on structure II with the device structure and process conditions the same as those of sample A′, B′, and D series, respectively. Therefore, although the outputs of all the grating LED samples (C, D, and G series) may be affected by grating diffraction (if at all), only those of sample C and D series are significantly influenced by grating-related SP coupling. Because the metal layer of the grating structure is thick, the SP-coupling effects can be observed only in the bottom-emission outputs of sample C and D series. Therefore, in demonstrating the polarization behaviors below, only bottom-emission outputs (with a subscript *b* for a sample notation) are used. However, to show the emission enhancement, the total outputs (the summation of top and bottom emissions, with a subscript *s* for a sample notation) are considered. In LED output intensity measurement, we monitored angle-dependent intensity with a fiber bundle of ∼1 mm in aperture diameter along the polar angle θ, as demonstrated in the inset of Fig. 1. The normal direction on the bottom (top) side corresponds to $\theta=0^\circ$ (180°). In the following, the top (bottom) emission intensity represents the angle-integrated and spectrum-integrated intensity on the top (bottom) side.

Figure 1 shows the LED bottom-emission spectra of samples A, B, and C(500), including the two polarization components of sample C(500), i.e., C_b-*x* and C_b-*y*, at 40 mA injection current. The symbol C(500) indicates sample C with the grating period at 500 nm. The *x*- and *y*-axes are defined to be parallel with and perpendicular to the grating groove direction, respectively. Here, one can see the significantly stronger emission of the *y*-polarization when compared with the *x*-polarization. The polarization ratio of the integrated intensity is about 1.7. Figure 2 shows the total LED output intensities as functions of injection current of sample A, B, and C series. All the grating LED samples of different grating periods have stronger output intensities (except at 10 mA) when compared with sample B. However, only in samples C(500) and C(450) are the total outputs stronger than that of sample A. In sample B, SPP coupling may occur. However, this coupling process, if existent, does not lead to overall emission enhancement when compared with sample A of no metal coating in the central region of mesa. In the inset of Fig. 2, the polarization ratios of bottom emission in sample B and C series as functions of injection current are demonstrated. Here, sample C(500) shows the largest polarization ratio. In all grating LED samples here, the polarization ratios become significant when injection current is larger than 20 mA and are saturated beyond 30 mA. This behavior is attributed to the variation in lateral carrier distribution in the QW. When the injection current level is low, the carriers are mainly localized beneath the current spreading region such that SP coupling is weak. When the injection current becomes large, more carriers in the QW can diffuse into the region under the Ag grating such that the SP coupling effect becomes significant. However, as the injection current increases up to 30 mA, the majority of carriers can couple with SPs for dominating LED emission, leading to a fixed polarization ratio. In Fig. 3, we show the total LED output intensities as functions of injection current of samples A′, B′, and D(500). In the inset, the polarization ratios of bottom emission in samples B′ and D(500) versus injection current are demonstrated. Here, an even more significant enhancement in sample D(500) can be seen. The total intensity is increased by about 59% (200%) when compared with that in sample A′ (B′). However, the polarization ratio of bottom-emission intensity is reduced to 1.51. The deeper

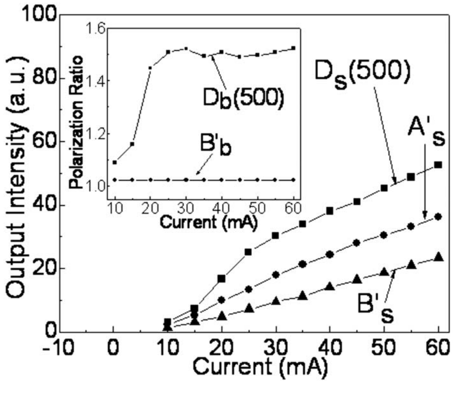

FIG. 3. Total LED output intensities as functions of injection current of samples A′, B′, and D(500). In the inset, the polarization ratios of bottom emission in samples B′ and D(500) as functions of injection current are demonstrated.

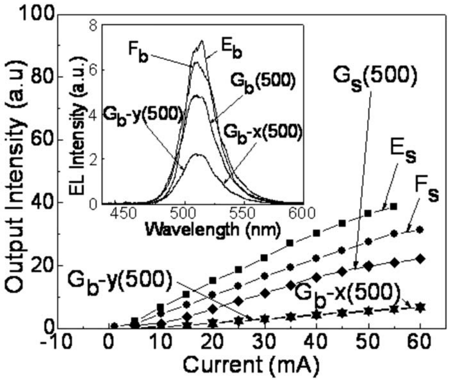

FIG. 4. Total LED output intensities as functions of injection current of samples E, F, and G(500), including its two polarization components of bottom emission. The spectra of the corresponding LED outputs of bottom emission at 40 mA are shown in the inset.

grating grooves in sample D(500) result in a higher emission enhancement but a smaller polarization ratio when compared with that in sample C(500).

To demonstrate that the major cause for the enhanced and polarized outputs in samples C and D is SP coupling, instead of grating diffraction, we compare the total output intensities as functions of injection current of samples E, F, and G(500), including the two polarization components of bottom emission in sample G(500), in Fig. 4. The spectra of the corresponding LED bottom-emission outputs at 40 mA are shown in the inset. Here, one can see that the output intensities of samples E and F are stronger than those of G(500). Also, the output of sample G(500) is unpolarized, implying that grating diffraction does not significantly influence the output of sample G(500) and hence that of sample D(500) since diffraction is a far-field phenomenon. No diffraction behavior was observed from the measured radiation patterns of all the grating samples based on the aforementioned angle-dependent measurement. This result implies the dominating effect of SP coupling in samples C and D. The relatively weaker outputs of samples F and G(500) when compared with sample E can be due to the loss caused by the reabsorption of light after it is reflected or scattered by the top-surface metal.

In summary, we have demonstrated the enhanced and partially polarized LED outputs by coupling the green-emitting QW with SPs in 1D Ag grating structures on the surface. Compared with a LED sample of no (flat) Ag coating, the total output intensity of a LED of SP-QW coupling could be enhanced by ~59% (~200%) when the grating period and groove depth were 500 and 30 nm, respectively. Also, a bottom-emission polarization ratio of 1.7 could be obtained under the condition of 15 nm in groove depth.

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