Metal mirror assisting light extraction from patterned AlGaInP light-emitting diodes

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We demonstrate light extraction from metal reflector-based AlGaInP photonic crystal (PhC) light-emitting diodes (LEDs). The photons reflected by a high-reflectivity, small-absorption, bottom Ag mirror steadily interact with the PhC, and thus enhanced light extraction is achieved. The square lattice PhC patterns were fabricated on an upper n-doped AlGaInP surface with a depth of 500 nm. An optical power measurement using an integration sphere shows that the extraction efficiency of the PhC LED is ≈1.8 times larger than that of the nonpatterned LED. A three-dimensional finite difference time domain simulation is performed to understand the output enhancement extracted by the PhC and the effect of internal absorption. © 2009 American Institute of Physics.

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Semiconductor light-emitting diodes (LEDs) are emerging as a promising light source to surpass classical fluorescent lamps for illumination. LEDs have various advantages such as high external efficiency, long device lifetime, convenient color tuning, and environmentally friendly materials. However, the achievement of high extraction efficiency in LEDs is still a challenging issue for practical applications. Several efficient structures have been proposed to increase this efficiency. For example, sidewall beveling,1 radiation engineering,2 and photonic crystal (PhC) patterning3–5 can extract more photons initially trapped by total internal reflections (TIRs). The underlying principle for these ideas is to move the photons guided by TIRs inside a leaky light cone within a minimal traveling distance.

PhC patterning is a common and efficient method that can be incorporated into any type of LED. The additional Bloch momentum resulting from the periodic PhC pattern renders the phase-matching condition to be satisfied and thus the TIRs are minimized. In particular, the effect of PhC patterning is expected to be more significant in LEDs with bottom reflectors. The photons that do not escape at once from the device propagate a certain distance, reflect at the bottom mirror, and then obtain the subsequent escape chance through interaction with the PhC. In this case, internal absorptions such as mirror loss and material loss heavily affect output enhancement; therefore, the reduction of internal absorption is crucial.

In this study, we propose and demonstrate metal reflector-based AlGaInP PhC LEDs that minimize mirror loss. Square lattice PhC patterns were fabricated on the upper plane of an n-doped AlGaInP layer. An Ag mirror with a high reflectivity for all incident angles was employed as a bottom mirror. The output enhancement of this PhC LED was measured via a conventional integration sphere setup and compared with that of a nonpatterned reference LED. In addition, a three-dimensional (3D) finite difference time domain (FDTD) simulation was performed to quantitatively investigate the dependence of output enhancement by a PhC on internal absorption.

The AlGaInP LEDs can be classified into distributed Bragg reflector (DBR)-based,6,7 and metal reflector-based LEDs [Fig. 1(a)].8,9 The metal reflector-based LED has the following distinct advantages compared with the DBR-based LED. First, no electrical degradation is expected in a metal reflector-based LED with the PhC pattern introduced in the top n-doped layer because current spreading is less sensitive in the n-doped layer. Second, the metal mirror exhibits superior reflectance behavior to the DBR overall incident angles. In particular, the high reflectance (R > 0.9) beyond a critical angle is necessary to extract the photons trapped by TIR.

We fabricated the wide-area (1 × 1 mm2) AlGaInP PhC LEDs with a bottom metal reflector using the following procedures. First, p-GaP/p-AlGaInP/i-AlGaInP multiple quantum well (MQW)/n-AlGaInP heterostructures were grown on an n-GaAs substrate using metal-organic vapor phase epitaxy. The metal layer of Ag was evaporated on the p-GaP layer by electron beam evaporation for a reflector. Then, a Si substrate was bonded to the top metal layers of the AlGaInP heterostructure using a conventional metal eutectic bonding

FIG. 1. (Color online) (a) Schematics of the metal reflector-based AlGaInP LEDs. (b) Fabrication procedure for the metal reflector-based AlGaInP PhC LEDs (top) and SEM images of the processed PhC (bottom, left) and nonpatterned reference (bottom, right) LEDs.
process. The removal of the bottom GaAs substrate was followed using a NH₄OH-based solution.

Next, to define square lattice PhC patterns in an etch mask of SiO₂, a photolithography process (h-line) and dry etching using CHF₃/CF₄ were carried out [top, Fig. 1(b)]. Inductively coupled plasma reactive ion etching with BCl₃/Cl₂ was then performed to drill down the n-AlGaInP layer. In order to prevent any substantial increase in the operation voltage, an n-contact electrode region was protected during the AlGaInP etching process [top, middle, Fig. 1(b)]. Finally, the n-contact electrode was metallized onto the nonpatterned n-doped AlGaInP layer. Scanning electron microscopy (SEM) images of the final processed devices are shown at the bottom, left of Fig. 1(b). The PhC pattern uniformly covers the upper layer beside the n-contact electrode region. The lattice constant of the PhC pattern (a) is 1200 nm, and the radius of the air holes is about 0.35a. Although this lattice constant is away from the optimal value as discussed later due to the resolution limit of the photolithography, the difference in the output enhancement tends to decrease with the increase of etch depth. Atomic force microscopy measurements show that the etch depth of each hole is ~500 nm. We also fabricated the nonpatterned reference LED in the same wafer for a fair comparison [bottom right, Fig. 1(b)].

In order to investigate the electrical and optical properties of the fabricated LED devices, we measured operation voltage and output power as a function of applied current. In the measurement, the LEDs were mounted n-side-up on a lead frame and encapsulated with Si gel (n ~ 1.4). Figure 2(a) shows typical I-V (current-voltage) characteristics of the PhC LED (red line) and the nonpatterned reference LED (black line). Note that the threshold voltages (~1.7 V) and slopes of both LEDs are almost identical. This implies that the introduction of the PhC pattern barely increased the series resistance in spite of the effectively reduced thickness of the n-dope AlGaInP layer. In terms of wall-plug efficiency, it is meaningful to maintain the original operation voltage in the LED incorporated with the PhC pattern.

Next, the output powers from the PhC LED and the nonpatterned reference LED were measured using a conventional integration sphere as a function of injection current swept from 5 to 900 mA [Fig. 2(b)]. The integration sphere covered the entire emission spectrum of the AlGaInP LED (λ_e = 630 nm, ∆λ_e = 30 nm) [inset of Fig. 2(a)]. The relative output enhancement factor is a good criterion to quantitatively reveal the effect of the PhC structure in the LED. In our LED with the Ag bottom mirror, the output enhancement factor is ~1.8 at a standard current of 350 mA. This value is larger than that of the LED with the previously reported DBR bottom mirror (~1.25). Such an increased enhancement factor is attributed to the higher reflectance beyond a critical angle in the metal reflector-based LED. Thus, the bottom metal reflector is more suitable for higher extraction efficiency in PhC LEDs.

To better understand the output enhancement behavior in the metal reflector-based LED, we performed a 3D FDTD simulation [Fig. 3(a)]. In this simulation, the AlGaInP (n = 3.3) LED structure with a finite size (~12 μm) is surrounded by perfect mirrors, except the upper plane, so as to describe the indefinite propagation of light [see inset of Fig. 4(a)]. Since the vertical radiation through the upper plane is dominant, this assumption takes close account of a practical structure. The structural parameters of the PhC pattern introduced in the upper plane of the structure are identical to those of the fabricated one shown in Fig. 1(b). The refractive index of the ambient medium was set to be 1.4, which is identical to that of the Si gel encapsulant. Randomly polarized dipole sources with a central wavelength (λ_r) of 630 nm and a spectral width (∆λ) of 30 nm were excited in every unit grid of the whole computation structure. A detection plane is located at a distance of ~λ_e/λ_r from the upper emission surface in order to record net energy flow. Finally, the extraction efficiency was defined as the ratio of the energy accumulated via the top GaN LED surface to the total generated energy.

We compared the extraction efficiencies in the LEDs with and without the perfect bottom mirror as a function of the propagation distance that photons travel after radiation. Then, in the absence of the bottom mirror [black and red lines, Fig. 3(a)], the extraction efficiencies became saturated merely within the propagation distance of ~20 μm regard-
less of the PhC pattern. This propagation distance corresponded to one round trip in the LED. Here, the absence of the bottom mirror implies that the perfectly matched layer is located at the bottom of the structure. On the other hand, when a perfect bottom mirror was introduced, the overall extraction efficiency increased steadily during several round trips [green and blue lines, Fig. 3(a)]. Particularly, the photons reflected by the bottom mirror continuously interacted with the PhC structure and thus the extraction efficiency of the PhC LED (blue line) became much larger than that of the LED without the PhC (green line). In other words, the bottom mirror allows trapped photons to be diffracted by the PhC pattern until the generated photons are totally absorbed.

As a result, the absolute output power is not only improved, but the output enhancement factor is also larger in the PhC LED with a bottom reflector.

In addition, it is worthy to note that the measured relative enhancement is inversely proportional to the current [blue line, Fig. 2(b)]. In fact, the AlGaInP MQWs tend to be more absorptive at higher current density over the transparent condition. Thus, the relative enhancement can be more pronounced at lower current density. This discussion is supported by the 3D FDTD simulation that computes relative enhancement as a function of the absorption imposed inside MQWs, as shown in Fig. 3(b). As expected, the relative enhancement of a PhC LED versus a nonpatterned one increased as the MQW layer became more transparent. Consequently, it is important to reduce material loss as well as mirror loss by adjusting the epitaxial growth condition to ensure outstanding extraction efficiency.

Lastly, we determined the optimal lattice constant and hole depth of the PhC by an absorptive 3D FDTD simulation. Basically, the metal reflector-based AlGaInP LEDs can be regarded as a multimode waveguide structure formed by air (or Si gel) and the bottom mirror. In order to achieve the highest extraction efficiency, one should design the optimal PhC pattern to effectively perturb various guided modes. The extraction efficiencies with different hole depths (125, 500, and 1000 nm) are computed as a function of the lattice constant of the square lattice PhC pattern [Fig. 4(a)]. Here, the extraction efficiency is defined by a ratio of the energy accumulated via the top AlGaInP LED surface to the total energy. The optimal lattice constant for the highest efficiency in every hole depth was found to be ~500 nm. These simulation results can be understood by conventional diffraction theory. In fact, the PhC pattern with a small lattice constant is useful to extract fundamental and lower-order guided modes that occupy a relatively large fraction of the trapped energy.10–12 However, the lower-order modes would not be diffracted well by the PhC because the fields of these well-guided modes are minimally overlapped with the PhC pattern. On the other hand, a PhC with a large lattice constant allows the higher-order guided modes to be effectively extracted, but the energy portion of these modes is small. Thus, the optimal lattice constant shown in Fig. 4(a) is determined by compromising both the modal overlap with the PhC pattern, and the energy fraction of the modes. In addition, the extraction efficiency is evaluated as a function of hole depth for a small lattice constant of \( a = 400 \) nm and a large lattice constant of \( a = 1200 \) nm [see Fig. 4(b)]. The PhC pattern for a large lattice constant of 1200 nm extracts more photons in the higher-order guided modes with long evanescent-field tails. Thus, a large hole depth (up to \( \sim 5n/\lambda \)) causes the higher-order modes to strongly interact with the PhC pattern, and increases the extraction efficiency. One can understand that the extraction enhancement observed in the experiment originates mainly from the diffraction of the higher-order guides modes. Such a large lattice constant provides a generous fabrication tolerance required for mass production. On the other hand, the extraction efficiency for a small lattice constant of 400 nm tends to saturate with a relatively smaller hole depth (\( \sim n/\lambda \)). Therefore, it is necessary to determine proper etch depth for different lattice constants of the PhC pattern.

In summary, we demonstrated \( \sim 1.8\)-fold output enhancement by incorporating a square lattice PhC into the top surface of an \( n \)-doped layer in the AlGaInP LED with a bottom Ag reflector. The operation voltage of the PhC LED, identical to the nonpatterned reference voltage, was measured. Using 3D FDTD simulation, optimal parameters for the PhC pattern were computed for high extraction efficiency. In addition, we determined that less internal absorption led to higher output enhancement in the PhC LED. We believe that these efforts in reducing internal loss will be helpful in achieving greatly enhanced light extraction in LEDs.

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