Efficient GaN slab vertical light-emitting diode covered with a patterned high-index layer

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(Received 21 April 2008; accepted 28 May 2008; published online 19 June 2008)

We demonstrate the enhancement of light extraction from a wide-area (500 × 500 μm²) GaN slab light-emitting diode (LED) that results from covering it with a TiO₂-patterned layer. To fabricate this device, a Cu supporter is electroplated onto the p-GaN face followed by detaching the sapphire substrate with a laser lift-off process. At the standard current of 60 mA, the wall-plug efficiency of the TiO₂-patterned LED is ∼ 14.8%, i.e., the efficiency is enhanced by a factor of ∼ 1.8 over that of nonpatterned LEDs. Our three-dimensional finite-difference time-domain computations confirm that this output increases with the index of the patterned layer. © 2008 American Institute of Physics. [DOI: 10.1063/1.2945892]

Highly efficient solid-state white lighting devices are emerging as powerful illumination building blocks that can be used as replacements for incandescent or fluorescent lamps. Blue light-emitting diodes (LEDs) consisting of InGaN/GaN multiple quantum wells (MQWs) are core elements of such white light emission sources. Up to date, in most GaN LED devices, because of the insulating sapphire substrate, an intracavity structure is typically fabricated for the injection of carriers, and thus the path of current is partially horizontal [Fig. 1(a), left]. However, in such a structure, the injected current is inclined to be locally concentrated around sideways of the device and this is responsible for the generation of parasitic leakage current. Even worse, the overall efficiency drastically declines with increases in the current because of the poor thermal conductivity of the sapphire substrate.1–3 To overcome these problems, metal-based GaN slab vertical LEDs have recently been proposed, in which an n-i-p GaN slab is located on a thick conductive metal layer instead of a sapphire substrate [Fig. 1(a), right].4,5

However, improvements in the extraction efficiency of vertical LEDs are still required because the principal light escape route through the side facets of the sapphire substrate is lost, compared to the conventional intracavity structure.4 Thus, vertical LEDs require efficient outcoupling structures that convert trapped photons into leaky modes before they are lost. Periodic photonic crystals (PhCs) have recently been aggressively employed to minimize the total internal reflection. The additional Bloch momentum that results from the periodic pattern improves the level of satisfaction of the phase-matching conditions.7–10 However, plasma etching process of the doped GaN layer used to fabricate PhC patterns may degrade the electrical characteristics of such device.10 Further, the index contrast of the PhC affecting the diffraction strength is limited.

In this study, we deposit a high-refractive index TiO₂-patterned layer onto the top emitting surface of a GaN slab vertical LED. An integration sphere setup is used to compare the wall-plug efficiencies of the TiO₂-patterned device and a nonpatterned device. The dependences of the extraction efficiency and the optimum lattice constant (a) on the index contrast of the PhC are investigated theoretically with absorptive three-dimensional finite-difference time-domain (3D-FDTD) computations.

A GaN slab LED can be understood as a multimode waveguide structure. Each guided mode in the GaN LED structure can be represented by a wavevector. Of these modes, the lower-order guided modes are mainly composed of light with a glancing angle. As can be seen in the momentum-space diagram [Fig. 1(b)], a PhC with a small lattice constant favors the extraction of the low-order guided modes, which make up a relatively large fraction of the trapped energy. One problem is then that the low-order slab modes are generally not well diffracted because these short-range evanescent field limits their spatial overlap with the PhC.6 However, when the refractive index of the patterned layer is larger than that of GaN, the guided mode profile penetrates deeper into the higher-index layer and many more photons flow into this higher-index layer from the light emitting low-index GaN layer. In this case, photons will interact more strongly with closer periodic PhC structures and the intrinsic absorption losses of the active GaN medium will also be reduced accordingly.

Absorptive 3D-FDTD computations are performed as a quantitative investigation of the approach [Fig. 2(a)]. The extinction coefficient of the MQWs is taken into account in order to establish a realistic model of a GaN slab LED.11 The structure is surrounded by perfect mirrors (except the upper emitting surface) so that light propagates indefinitely. Randomly polarized dipole sources with a central wavelength (λc) of 450 nm and a spectral width (Δλ) of 25 nm are excited in every unit grid inside squares with sides the length of the lattice constant to prevent the unwanted resonant cavity effect from arising. Note that the dipole sources are suffi-
According to the refractive index of the dielectric layer, we compute the upper emission surface in order to record net energy flow. **Fig. 2(a)** demonstrates the device structure, with the light extraction efficiency depending on the lattice constant [Fig. 2(b)]. The filling factor is fixed at 0.50. It is expected, as discussed above, that a higher-index patterned layer results in better light extraction efficiency. The incorporation of a PhC into a material (such as InGaN or Si3N4) with a lower index than a GaN core is expected to be less effective in diffraction of the guided modes regardless of its lattice constant. On the other hand, the cases of higher index, the output enhancement more strongly depends on the lattice constant. It is also noteworthy that the optimal lattice constant that maximizes the extraction efficiency gradually becomes smaller as the index contrast of the PhC increases. This shift can be understood by considering the momentum-space diagram in Fig. 1(b). The PhC with a larger index contrast interacts more strongly for a smaller lattice constant with the low-order guided modes that satisfy the phase-matching conditions. Lastly, there is a possibility of achieving further improvement with the higher-index patterning when the GaN slab is much thinner to <1 μm. In such a structure, the modification of the guided mode profile by the higher-index layer becomes more dominant.

In order to fabricate the GaN slab vertical LED, we prepare a conventional sapphire-based GaN epitaxial wafer. The characteristics of the GaN wafer are described in Ref. 10. First, mesa structures with an area of $500 \times 500 \mu m^2$ are isolated by carrying out an inductively coupled plasma reactive ion etching (ICP-RIE) with Ar2 and BCl3/Cl2. The reflective electrode is then metallized onto the p-GaN layer. After the 100-μm-thick Cu supporter is electroplated, the initial substrate of sapphire is detached with a laser lift-off process using a pulsed ArF laser ($λ = 194$ nm). After the laser lift-off process, we remove Ga residue by chemical cleaning using HCl and BOE, respectively. Then, the surface roughness measured by an atomic force microscopy is just a few nanometers. For the PhC patterning process, a 230-nm-thick TiO2 film is deposited onto the top GaN surface with a low-temperature (40 °C) rf sputtering process [Fig. 3(a)]. The optical constant of the TiO2 film is measured separately by using an ellipsometry apparatus [Fig. 3(b)]. The refractive index of the TiO2 film is found to be higher than that of GaN ($n = 2.46$) in the visible spectrum range. In particular, at blue-emitting wavelengths near 450 nm, the refractive index is up to 2.7 and the absorption loss is negligible. Square-lattice periodic holes (a=1200 nm) are defined in the thin TiO2 layer with conventional photolithography (h-line) and then etched by performing ICP-RIE with Ar2 and C2F6. Note that the plasma etching for the TiO2 layer is not very reactive to the GaN material. Besides, the upper GaN layer is lightly doped so that it hardly influences current spreading. Prior to the deposition of the n-electrode, an n-GaN layer is partially exposed matching its shape to serve as an effective current spreading layer. A scanning electron microscopy (SEM) image of the final processed device is shown in Fig. 3(c). Note that the patterned TiO2 layer is positioned above the n-electrode geometrically. The fraction of the n-electrode over the total light-emitting region is merely 10%. For fair comparison, a device with a nonpatterned surface is also fabricated on the same wafer. The only difference is that we protect a half of the wafer from TiO2 plasma etching to make the nonpatterned device. Thus, all characteristics such as emission wavelength, contact resistance should be identical each other.

First, we compare electrical properties of the TiO2-patterned and reference devices by measuring their I-V (current-voltage) characteristics with a contact prober [Fig. 4(a)]. The threshold voltages of the two devices are almost identical whereas the slope of the patterned device is obviously steeper. The resistance of the p-contact is sufficiently low ($\sim 10^4 \Omega/cm^2$) so that it does not affect the operation voltage. Thus, one can understand that the slope of the I-V curve is mainly influenced by the series resistance. As seen in the lower inset of Fig. 3(c), the TiO2-patterned device has bumpy n-GaN surface below the n-electrode due to the pat-

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**Fig. 1.** (Color online) (a) Schematic diagrams of lateral and vertical GaN-based LEDs. The arrows indicate the direction of electron flow. (b) Momentum-space diagram showing the diffraction of guided modes according to the phase-matching conditions.

**Fig. 2.** (Color online) (a) 3D-FDTD computation model of a GaN slab LED. The thickness and filling factor of the patterned layers are fixed at 225 nm and 0.30, respectively. (b) Light output enhancement as a function of the lattice constant (a) for various patterned layer refractive indexes. The optimal lattice constant tends to smaller values as the refractive index increases.

**Fig. 3.** (Color online) (a) The fabrication procedure for integrating a TiO2-patterned layer with n-electrode metallization. (b) Refractive indexes (unfilled circles) and absorption coefficients (filled squares) of the TiO2 film measured with ellipsometry. (c) SEM image of the processed TiO2-patterned GaN slab LED.
terned TiO$_2$ etch mask. We believe that this surface corrugation enlarges the effective area of contact between the $n$ electrode and the $n$-GaN layer, which reduces the operation voltage ($V_{op}$). The $V_{op}$ of the TiO$_2$-patterned device is normal, which indicates that the doped GaN layers are not affected by plasma-induced damage during the TiO$_2$ etching process. Electroluminescence images of the two devices are captured with a coupled charge detector at a low current of 15 $\mu$A [see the insets in Fig. 4(a)]. It can clearly be seen that the TiO$_2$-patterned device is brighter than the reference device, which confirms that there is better light extraction from the PhC structure.

In order to quantitatively compare their output power comparison, all the fabricated LED devices are mounted $n$-side-up on a lead frame and then encapsulated with transparent Si gel ($n=1.42$). The whole emission spectra of the GaN LEDs ($\lambda_c=450$ nm, $\Delta\lambda=25$ nm) are recorded by using an integration sphere as the injection current is swept up to 400 mA [Fig. 4(b)]. At a standard current of 60 mA, the integrated output power of the TiO$_2$-patterned device is found to be greater by a factor of $\sim$1.5 than that of the reference device. Note that the output power of the reference device becomes saturated once the injected current is above 200 mA, which is attributed to the high contact resistance of the reference device. The excessive joule heating arising from high operation voltage degrades the internal quantum efficiency of InGaN/GaN MQWs.\(^1\) The combined effects of the reduction in $V_{op}$ and the output enhancement mean that the wall-plug efficiency of the TiO$_2$-patterned LEDs ($\sim$14.8\%) is better by a factor of $\sim$1.8 than that of the reference device ($\sim$8.3\%). In addition, the inset in Fig. 4(b) shows the light output measured at the standard current before and after encapsulation (averaged over ten devices). The average output enhancement for the PhC devices is higher before encapsulation than after encapsulation. The improved enhancement that arises for an ambient medium with a lower index is due to the stronger diffraction strength that results from the higher index contrast of the PhC.

In summary, we report the fabrication of high-efficiency TiO$_2$-patterned metal-supported GaN slab LEDs. The output of the TiO$_2$-patterned LEDs is found to be enhanced by a factor of $\sim$1.5 over that of nonpatterned LEDs, with superior I-V characteristics ($\Delta V_{op}$ $>$ 0.5 V). According to our 3D-FDTD results, the use of the TiO$_2$ patterns with smaller lattice constants promises greater output power. Furthermore, the TiO$_2$ patterns fabricated by a lift-off process provide the greatly improved reliability of GaN LEDs. We believe that the fabrication and design of this highly efficient, thermally stabilized, and reliable GaN slab vertical LED covered with an external higher-index PhC layer is a significant advance toward future high-current, high-power illumination applications.


