Enhanced Internal Quantum Efficiency and Light Extraction Efficiency of Light-emitting Diodes with Air-gap Photonic Crystal Structure Formed by Tungsten Nano-mask

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Received July 15, 2013, Accepted August 13, 2013

We demonstrate the blue InGaN/GaN multiple quantum wells light-emitting diodes (LEDs) with an embedded air-gap photonic crystal (PC) which was fabricated by the lateral epitaxial overgrowth of GaN layer on the tungsten (W) nano-masks. The periodic air-gap PC was formed by the chemical reaction of hydrogen with GaN on the W nano-mask. The optical output power of LEDs with an air-gap PC was increased by 26% compared to LEDs without an air-gap PC. The enhanced optical output power was attributed to the improvement in internal quantum efficiency and light extraction efficiency by the air-gap PC embedded in GaN layer.

Key Words: InGaN/GaN light-emitting diode, Air-gap photonic crystal, Tungsten nano-mask, Internal quantum efficiency, Light extraction efficiency

Introduction

Among the many recent approaches leading to improved light extraction efficiency (LEE) in GaN-based light-emitting diodes (LEDs), photonic crystal (PC) structure has been extensively investigated to realize the high efficiency LEDs. A PC is a periodic structure comprising two materials with different refractive indices. Multiple scattering of photons by lattices of periodically varying refractive indices act to form a photonic band gap (PBG) in which propagation of certain wavelengths of the electromagnetic waves are prohibited, resulting in an enhanced light extraction in a vertical direction from LEDs. Usually, the PC structure in GaN-based LEDs has been formed directly in the p-GaN layer because the high refractive index contrast between GaN and air in these air-gap structures yields an enhanced PC diffraction strength. However, the incorporation of a PC structure in the p-GaN layer requires the use of a plasma etching process, resulting in plasma damage to the p-GaN layer. Furthermore, the observed enhancement in light extraction is usually significantly lower than the theoretical limit, due to the limited interaction of the surface PC with some of the guided modes, notably the low order modes. To solve these problems, several groups have reported epitaxially grown PC structures which were fabricated by lateral epitaxial overgrowth (LEO) or selective area epitaxy of GaN layer using dielectric mask or air void structure.

In this letter, we report on the electrical and optical properties of blue LEDs with an air-gap PC formed in GaN layer. Square-lattice air-gap PC embedded in GaN layer was realized through the LEO method using tungsten (W) nano-mask array without an additional etching process. The periodic air-gap structure inserted into GaN layer reduced threading dislocations and improved the internal quantum efficiency. Furthermore, the LEE of LEDs was significantly enhanced by the PC effect and showed the improvement of optical output power of LEDs without showing any degradation of electrical properties.

Experimental

Figure 1(a) shows a schematic of an LED with an embedded air-gap PC. The LED was grown on a c-plane (0001) sapphire substrate by metalorganic chemical vapor deposition. After the growth of a 25 nm-thick GaN nucleation layer at 550 °C, a 2 μm-thick undoped GaN layer was grown at 1020 °C. To fabricate the PC structure, circular hole patterns with a diameter of 200 nm and a spacing of 100 nm between patterns were generated in a photoresist (PR) layer on the undoped GaN layer. Furthermore, the observed enhancement in light extraction is usually significantly lower than the theoretical limit, due to the limited interaction of the surface PC with some of the guided modes, notably the low order modes. To solve these problems, several groups have reported epitaxially grown PC structures which were fabricated by lateral epitaxial overgrowth (LEO) or selective area epitaxy of GaN layer using dielectric mask or air void structure.

Figure 1(b)
shows the atomic force microscopy (AFM) image of the GaN capping layer grown at a temperature of 1030 °C for 5 min, where W nano-masks are embedded in a GaN layer. After the regrowth of 1 μm-thick undoped GaN layer, a 1 μm-thick n-GaN layer was grown on the GaN epilayer covered with the W nano-mask. Figures 1(c) and (d) show the tilted plan-view and cross-sectional scanning electron microscopy (SEM) images of a coalesced LEO GaN epilayer that was grown by using a W nano-mask. As shown in Figures 1(c) and (d), the full coalescence of LEO GaN was achieved, and the W nano-masks were fully covered by the GaN epilayer. In particular, it is noticed that periodic air-gap structures are created under the W nano-mask without an additional etching process. The period, radius, and height of the air-gap structure are 300 ± 20, 100 ± 10, and 100 nm, respectively. The formation of an air-gap structure is attributed to the decomposition of GaN by the chemical reaction of hydrogen with GaN and W during the LEO growth of GaN layer. It was reported that the W mask is not dense and the hydrogen molecules and their radicals pass through the W mask, resulting in the decomposition of the GaN epilayer under the W mask.12,13 Next, five periods of InGaN/GaN multiple quantum wells (MQWs) were grown at 750 °C, followed by the growth of a 200 nm-thick p-GaN layer at 1000 °C. Finally, LEDs with an embedded air-gap PC were fabricated and the detailed procedure for the fabrication of the LEDs with a size of 300 × 300 μm² was reported elsewhere.13

Results and Discussion

The air-gap PC structure embedded in GaN epilayer was designed using a simulation program based on the preconditioned conjugate-gradient plane-wave expansion method.1 This study is mainly focused on transverse-electric (TE) mode bands that are characterized by light propagating in parallel to the slab of LED. The optimal period and radius of air-gap region are estimated to be 300 and 100 nm for the blue wavelength of 470 nm. Furthermore, we predict the LEE and the propagation of light emitted from the MQWs via the PC structure using a 3-dimensional finite difference time domain (3-D FDTD) simulation based on a genetic algorithm with periodic boundary condition introduced by a square array of the air-gap structure. The total amount of light emitted from the LED was detected by receivers covering all directions. Figure 2 shows the FDTD simulation results of a blue LED with and without an embedded air-gap PC in the GaN epilayer. The time-dependent integrated light output of the LED with an embedded air-gap PC is higher than that of the LED without an embedded air-gap PC. Particularly, Figure 2 clearly shows that the light emitted from the MQWs with an embedded air-gap PC propagates more vertically in the bottom side direction of the LED, compared to the LED without a PC structure because a PC structure inhibits the emission of the guided modes or redirect trapped light into radiated modes, resulting in increasing LEE of LEDs.1-3

In order to characterize the structural property of the embedded air-gap PC structure and the LEO GaN epilayer grown by using the W nano-mask, transmission electron microscope (TEM) analysis was performed on the LED samples. Figure 3 shows a cross-sectional TEM image of the LEO GaN layer with an embedded air-gap PC structure. As shown in Figure 3, the periodic air-gap structures are well created and clearly embedded in the GaN epilayer. The residual W masks are also slightly remained in the air-gap structure. Especially, the air-gap structures effectively prevent the propagation of TDs in GaN layer from the nucleation layer on the substrate to the top GaN surface. These results indicate that the surface morphology and crystal quality of
the LEO GaN layer is significantly improved because the TDs are terminated when they encounter the air-gap structure, resulting in a decrease in the dislocation density of LEO GaN layer.\textsuperscript{13,14}

Figure 4 shows the room temperature and temperature-dependent photoluminescence (PL) spectra of InGaN/GaN MQWs with and without an embedded air-gap PC. The PL spectra were measured from the bottom side of the LEDs at room temperature using a He–Cd laser ($\lambda = 325$ nm) with an excitation laser power of 50 mW. As shown in Figure 4, the PL intensity of MQWs with an embedded air-gap PC is higher than that of MQWs without an embedded air-gap PC. The integrated PL intensity of MQWs with an embedded air-gap PC is increased by 35% compared to that of MQWs without an embedded air-gap PC. The enhancement of PL intensity can be attributed to the increased IQE of MQWs due to the reduction of dislocation density and the increased LEE by PC effect. To clearly confirm that the improvement of IQE is due to the reduction of dislocation density by the air-gap structure, the temperature-dependent PL was measured at temperatures ranging from 10 to 300 K. The inset of Figure 4 shows an Arrhenius plot of the integrated PL intensities of MQWs with and without an embedded air-gap PC structure. The integrated PL intensity of MQWs can be fitted by the equation:\textsuperscript{15,16}

$$I(T) \propto \frac{1}{1 + \sum C \exp(-E/k_B T)}$$

where $I(T)$ is the integrated PL intensity of MQWs, $C$ is the constant related to the density of non-radiative recombination centers, $E$ is the activation energy of the corresponding non-radiative recombination centers, and $k_B$ is Boltzmann’s constant. The calculated $E$ is 105 meV for MQWs with an embedded air-gap PC and 90 meV for MQWs without an embedded air-gap PC and the calculated constant $C$ is 15 for LEDs with an embedded air-gap PC and 23 for conventional LEDs, respectively. The large value of $E$ for MQWs with an embedded air-gap PC indicates that the energy barrier for carrier capture by non-radiative centers such as TDs is high in the regrown GaN epilayer.\textsuperscript{13,16} The small constant $C$ for an LED with an embedded air-gap PC also means that LEDs with an embedded air-gap PC have a lower density of non-radiative recombination centers than LEDs without an embedded air-gap PC. In the case of IQE, the IQE of MQWs with an embedded air-gap PC is estimated to be 64%, and this is higher than the IQE of 56% of MQWs without an embedded air-gap PC. These results indicate that the increased PL intensity is attributed to the increased LEE by the embedded air-gap PC and the increased IQE of MQWs by decreased density of defects such as screw and edge-type TDs in the GaN epilayer by the air-gap structure.

Figure 5 shows the current-voltage ($I$-$V$) characteristics of LEDs with and without an embedded air-gap PC. Both measurements show nearly identical $I$-$V$ curves. As shown in Figure 5, the forward voltage of the LED with an embedded air-gap PC is 3.7 V, which is same as that of LED without an embedded air-gap PC. The series resistance of 13.9 of LED with an embedded air-gap PC is also very close to 13.8 of LED without an embedded air-gap PC. To examine the reverse current characteristics of LEDs, the $I$-$V$ curves are plotted on a semi-logarithmic scale as shown in the inset of Figure 5. The LED with an embedded air-gap PC shows a reverse-bias leakage current of $1 \times 10^{-6}$ A at $-4$ V, which is lower than $5 \times 10^{-6}$ A of the conventional LED without an embedded air-gap PC. This reduction of reverse-bias leakage current is believed to be due to the decrease in dislocation density in LED because the LEO of GaN on W nano-mask decrease the defects in GaN epilayer.\textsuperscript{17}

To investigate the optical properties of blue LEDs with an embedded air-gap PC, the electroluminescence (EL) was measured from the LEDs. As shown in Figure 6(a), the EL intensities of the blue LEDs with an embedded air-gap PC are larger than that of the LED without an embedded air-gap PC. This result is attributed to the improved crystal quality and the enhanced LEE through the PC effect. Figure 6(b)
shows the optical output power of LEDs with and without an embedded air-gap PC as a function of injection current. The optical output power of LEDs was measured from the bottom side of the LEDs using a Si photodiode with a diameter of 2 cm connected to an optical power meter. As shown in Figure 6(b), the optical output power of LEDs with an embedded air-gap PC structure is increased by 26% at 20 mA of injection current compared with that of conventional LEDs without an embedded air-gap PC. This improvement in optical output power is a result of an improvement in IQE of the MQWs due to the reduction of TDs and the increase in LEE owing to the PC effect which inhibits the emission of guided modes and redirects trapped light into the radiated modes.13

**Conclusion**

In conclusion, we demonstrate the blue LEDs with an air-gap PC embedded in a LEO GaN epilayer using W nanomasks. The periodic air-gap structure was formed by the chemical reaction of hydrogen with GaN on the W nanomask. The electrical characteristics of blue LEDs with an embedded air-gap PC are not degraded and the optical output power of LEDs with an embedded air-gap PC is increased by 26% at 20 mA compared with that of conventional LEDs without an embedded air-gap PC. The increase in optical output power was attributed to an improvement in the IQE and LEE of the LEDs by the air-gap PC in GaN layer.

**Acknowledgments.** This work was supported by the World-Class University Program funded by the Ministry of Education, Science, and Technology (MEST) through the National Research Foundation of Korea (R31-10026), and by a Korea Science and Engineering Foundation (KOSEF) NCRC grant funded by the Korea government (MEST) (project no. R15-2008-006-02001-0).

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