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Electroluminescence from lattice defects of photonic crystal slabs in blue-light-emitting diodes

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Lattice defect structures embedded into perfect photonic crystal slabs have been fabricated onto the GaN surfaces of InGaN/GaN multi-quantum-well light-emitting diodes. The photonic crystal slab with a triangular lattice constant of 230 nm showed suppressed light extraction for the electroluminescence at a peak of 464 nm, but the light radiated through lattice defects. The perfect photonic crystal slab shows the cooperative phenomenon of a light scattering similar to Wood's anomaly in a metallic grating, and lattice defects result in the leaky modes of light extractions by breaking the symmetry of cooperative light scattering. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2769101]

Recently, optoelectronic devices have been extensively investigated in order to enhance light extraction by introducing two-dimensional photonic crystal (PC) slabs.[1] The PC slab is a periodic dielectric material with a finite thickness and with a photonic band gap property for the light propagation in a plane.[2] The in-plane photonic band gap can suppress spontaneous emission via Bragg scattering, while the index guiding prevents light leakage in the perpendicular direction.[3,4] Furthermore, the defect structures of PC slabs have been introduced in compound semiconductor optoelectronic devices as cavities due to their high quality factor and small modal volume for photon confinement. The low-threshold lasing was realized in PC optoelectronic devices[5–7] and, furthermore, the PC structure was incorporated into vertical-cavity surface-emitting lasers (VCSEL) which were operated in a single mode.[8,9]

The PC effect has been investigated with respect to the photoluminescence from InGaN/GaN multi-quantum-well structures for various lattice constants of two-dimensional PC slabs.[10,11] For the lattice constant of a half wavelength of the incident light in the dielectric material, dark photoluminescence has been seen. This is a cooperative phenomenon of light scattering, which is similar to Wood's anomaly in metallic gratings. In a metallic grating, the dark spectral bands have appeared for a lattice constant corresponding to an integral multiple of wavelengths of the incident light.[12] It is curious to search the grating effect for the lattice defects of the PC slab and to clarify the breaking of the cooperative symmetry of multiple photon scattering.

In this work, the broken symmetry of cooperative light scattering was investigated for the lattice defects of PC slabs fabricated onto the GaN surfaces of InGaN/GaN multi-quantum-well light-emitting diode (LED) structures. Both single lattice defect and hexagonal ring lattice defect structures of PC slabs have been fabricated, and the light emissions from the active layers passing through the PC slabs have been observed by the electroluminescence measurements. Even though there is only a point defect, it is very probable for light extraction to occur, indicating the broken symmetry of perfect PCs.

The epitaxial layers of blue LED structures have been grown on sapphire substrates using a metallorganic chemical vapor deposition. After a 30-nm-thick buffer layer was grown at 520 °C, a 3-μm-thick n-type GaN layer was deposited at 1130 °C. Next, we produced a multiple quantum well active region consisting of 2-nm-thick InGaN wells and 8-nm-thick GaN barriers emitting light at a blue wavelength of 464 nm. The multiple quantum well regions consist of six alternating layers of InGaN wells and GaN barriers, each grown at the same temperature of 790 °C. Then, a 250-nm-thick p-type GaN layer is grown and postannealed at 700 °C for 15 min.

Figure 1 shows a blue LED structure incorporated with nanoscaled triangular-lattice nanoholes with a lattice constant of 230 nm and with a diameter of 150 nm. Three samples of PC slabs were designed on polymethylmethacrylate (PMMA) photoresist films using an electron-beam nanolithography process on the p-type GaN surfaces of LEDs, as is shown with critical dimension-scanning electron microscopy (CD-SEM) images. The sample of a perfect PC slab has the periodic structure without any missing lattice points. However, the PC sample with a single lattice defect has a vacancy of lattice points and the PC sample with a hexagonal ring defect has six vacant lattice points. Each patterned area of the PC slabs of $250\times250\ \mu m^2$ and a thickness of PMMA photoresist of 200 nm has been fabricated on blue LEDs for

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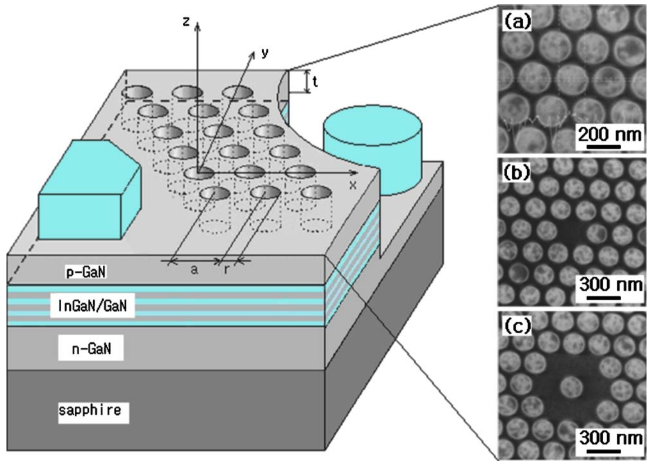

FIG. 1. (Color online) Schematic diagram of the InGaN/GaN multi-quantum-well LED structures incorporated with PC slabs. The slabs were designed to the same nanoscaled triangular-lattice nanoholes with a lattice constant of $a=230$ nm and a radius of $r=75$ nm. After the processing of electron-beam nanolithography, the CD-SEM images of 200-nm-thick PMMA patterns are shown for (a) a perfect, (b) a single lattice defect, and (c) hexagonal ring defect structures.

the same epitaxial wafer. The PMMA layer on the coated surface protects the GaN layer from etching by the plasma gas. The inductively coupled plasma (ICP) dry etching process was performed for 5 s using a high-density plasma consisting of a mixture of BCl_3 and Cl_2 ambient. Finally, the patterned PMMA layer on the GaN surface was developed in a solution of methylisobutyl ketone and isopropyl alcohol.

Figure 2 shows the atomic force microscope (AFM) and the CD-SEM images on both samples of a single lattice defect and a hexagonal ring defect. The sample of a single lattice defect of a PC slab with a lattice constant of $a=230$ nm is shown in Fig. 2(a). The LED chip has only one lattice point nanohole not patterned and, therefore, not etched out. The dimension of the nanohole diameter is 150 nm and has a depth of 8 nm. However, a perfect PC slab has the same lattice constant and diameter with a different depth of 28 nm. Figure 2(b) shows the AFM and the CD-SEM images on the sample for the hexagonal-ring defect structure of a PC slab with a lattice constant of $a=230$ nm. The nanohole has a diameter of 150 nm and a depth of 17 nm. In a LED chip, a group of nanoholes at lattice points in a hexagonal ring structure has not been patterned and not etched out.

In the sample of a single lattice defect structure, the thickness of the slab or the depth of the nanoholes is very thin and the surface is relatively rough compared to both samples of the perfect and the hexagonal ring defect structures. In spite of the same etching process on a wafer for three samples, the nanohole depths defining the thicknesses of the slabs are quite different in each sample. We should expect that since the PC slab of the sample of a single lattice defect structure is too thin to show the PC effect, it might show the same intensity to the bare sample without the PC slab. The light extraction behavior from defect structures of PC slabs has been evaluated from electroluminescence measurements.

Figure 3 shows room-temperature electroluminescence (EL) spectra from the defect structures of PC slabs on

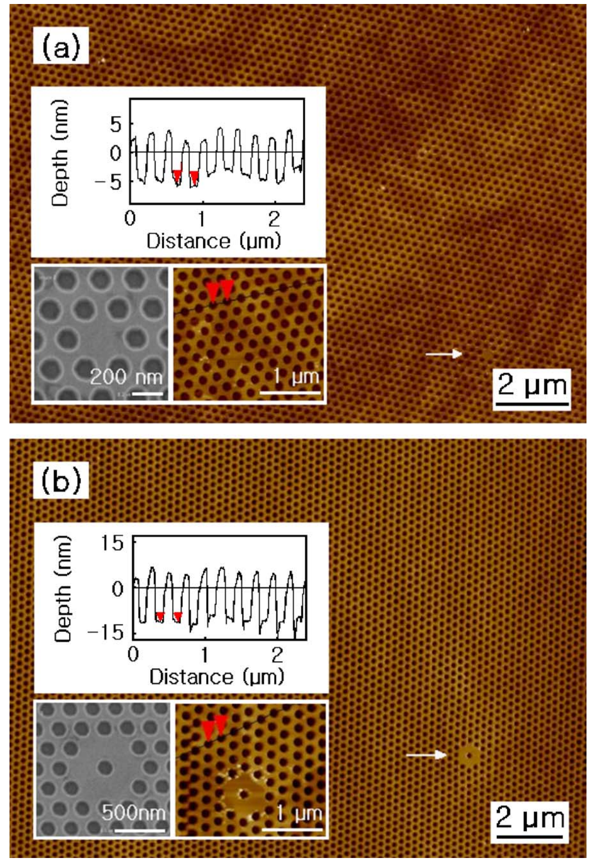

FIG. 2. (Color online) AFM and CD-SEM images of samples for (a) a single lattice defect and (b) a hexagonal ring defect structure of PC slabs. In each LED chip, there exists only one lattice defect point, as is shown by the arrow.

InGaN/GaN multi-quantum-well LEDs. The EL spectra were measured at a forward voltage of 3 V. For the bare (ref.) sample without the PC slab, the blue light emitted from the InGaN/GaN multi-quantum-well structure can vertically

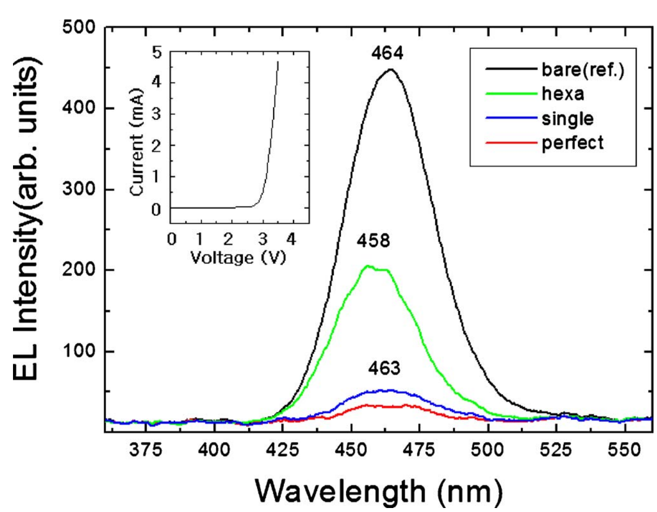

FIG. 3. (Color online) Room-temperature EL spectra from the defect structures of PC slabs on InGaN/GaN multi-quantum-well LEDs. There is no EL extraction from the perfect PC slab, a little extraction in a single lattice defect, and a further enhancement in a hexagonal ring defect structure. The largest relative intensity of the bare (ref.) sample without a PC slab is shown for comparison. The inset is the current and voltage measurement for the EL, and the EL spectra were measured at the forward voltage of 3 V.

propagate to the *p*-type GaN surface layer and shows a very high EL intensity at a peak of 464 nm with a full width at half maximum (FWHM) of 0.214 eV. However, for the sample with a perfect PC slab, the EL intensity at a peak of 464 nm, which corresponds to a normal frequency ($a/\lambda = \omega a/2\pi c$) of 0.495, was strongly suppressed and almost no light was extracted. For the sample of a single lattice defect of the ultrathin PC slab, the EL intensity at a peak of 463 nm with a FWHM of 0.249 eV for a normal frequency of 0.496 is slightly enhanced compared to the intensity extracted from the perfect PC sample. This results in a weak, leaky mode in the light extraction of luminescence, even from the shallow nanoholes. Furthermore, the sample with the hexagonal ring defect of the PC slab showed a further enhancement of the EL intensity at a peak of 458 nm with a FWHM of 0.219 eV up to a half intensity of the bare sample without the PC slab.

It is reasonable to speculate the grating effect of multiple photons from these experimental results. Multiple photons showed the cooperative phenomenon of the light scattering in perfect periodic systems of PC slabs. This optical behavior is similar to an optical interference filter. The optical interference filter defines as a very thin multicoating system where the interference pattern is constructive over a small spectral region of wavelengths so that the transmission of light occurs while, at other wavelengths, the interference pattern is destructive and prevents the transmission of light.[13]

In the perfect PC slab on the *p*-type GaN surface, the multiple photons generated from the active plane of the InGaN/GaN multi-quantum-well layer have formed the destructive interference in the specific bandwidth of the wavelength with the relationship $\lambda = 2a$ in the triangular lattice constant of a. This cooperative phenomenon is similar to Wood's anomaly in the metallic grating as a one-dimensional PC, where the very narrow band of dark interference is related to $a = n\lambda$ with the integer n.[12] This is the PC effect on the symmetry of the cooperative light-scattering mode in the array theorem of nanogratings.[10,11] At other wavelengths, the constructive interference provides the transmission of light as a leaky mode of a PC waveguide, which has been extensively utilized for light enhancement with PC slabs.[14]

For the defect structures of PC slabs, the emitted light from the quantum well layer has leaked and the light transmission partially happens, even through the sub-wavelength-scale area of lattice defect structures. The very thin PC slab with a thickness of 8 nm for the sample with a single lattice defect shows the suppression of light through the cooperative scattering at PC nanoholes and the release of light through the leaky mode at the unetched nanohole. For the sample with a hexagonal ring defect structure, the further light extraction has appeared through the leaky mode of unetched nanoholes. Even though the samples with lattice defect structures have light extractions, the very broad FWHMs of ELs have not decreased, indicating that the multiple photons could not be confined in the lattice defect structures. As the defect area is increased, the intensity of the extracted light is enhanced and limited to the intensity of the bare sample without the PC slab. Therefore, the defect structures could induce the symmetry of cooperative light scattering in the perfect PC slab to be broken and require a special geometrical condition for the nanocavity as a basic building block of the optical stimulation.[15]

In summary, the defect structures of PC slabs on InGaN/GaN multi-quantum-well light-emitting diode structures have been fabricated with unetched lattice points on both single lattice defect and hexagonal ring defect samples. The PC slab with a triangular lattice constant of 230 nm showed the suppressed light extraction for the EL at a peak of 464 nm, but the light released through the lattice defects. This indicates that the PC slab is in a grating mode of cooperative light scattering with the destructive interference of multiple photons. The lattice defects form the leaky modes of light extraction by breaking the symmetry of cooperative light scattering.

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