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Surface 210 nm light emission from an AlN p–n junction light-emitting diode enhanced by A-plane growth orientation

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$(11\bar{2}0)$ A-plane AlN p–n junction light-emitting diode (LED) with a wavelength of 210 nm is demonstrated. The electroluminescence from the A-plane LED is inherently polarized for the electric field parallel to the [0001] c-axis due to a negative crystal-field splitting energy. The polarization ratio (electric-field component ratio of parallel and perpendicular to c-axis) is as high as 0.9. The radiation pattern of the A-plane LED shows higher emission intensity along the surface normal, while that of a conventional (0001) C-plane LED shows lower emission intensity along the surface normal. The different radiation patterns can be explained by the polarization property. © *2010 American Institute of Physics*. [doi:10.1063/1.3446834]

Aluminum nitride (AlN) is a direct-band gap semiconductor with a band gap energy of 6 eV, the largest among semiconductors.[1] Therefore, AlN is a promising material for light-emitting devices with ultrashort wavelengths. Previously, we achieved both n-type and p-type doping in AlN (Refs. 2–5) and fabricated an AlN p–n junction light-emitting diode (LED) with near-band-edge electroluminescence (EL) at a wavelength of 210 nm, the shortest ever reported for any kind of LED.[5,6] The AlN LEDs were grown with (0001) C-plane orientation, the same as AlGaN-based ultraviolet LEDs.[7,8]

Recently, we reported that the near-band-edge emission from AlN, which is attributed to a free-exciton transition, strongly polarizes for the electric field parallel to the [0001] c-axis ($E \parallel c$) and determined the polarization ratio to be as high as 0.995 by analyzing angle-dependent photoluminescence of a C-plane AlN layer.[9] The strong $E \parallel c$ polarization is attributed to the negative large crystal-field splitting energy of AlN.[1,9–11] Due to the strong $E \parallel c$ polarization, the near-band-edge emission is intrinsically weak parallel to the c-axis direction but strong normal to it (parallel to the $[11\bar{2}0]$ a-axis or $[10\bar{1}0]$ m-axis directions). Therefore, for the conventional C-plane LED structure, the $E \parallel c$ polarization results in low light extraction. In addition, the radiation pattern shows weak intensity along the surface normal but strong intensity along an inclined direction from the surface normal. Such a complicated radiation pattern is not suitable for producing directional light for applications. On the other hand, a non-C-plane, like $(11\bar{2}0)$ A-plane or $(10\bar{1}0)$ M-plane, LED structure is expected to enhance the light extraction and show strong emission intensity along the surface normal.

In this letter, we demonstrate A-plane AlN LEDs and characterize the polarization property of the near-band-edge EL. Then, we compare the radiation pattern of the A-plane LED with that of the conventional C-plane LED. The observed different radiation patterns are discussed in terms of the polarization.

The AlN LED structures were grown by metalorganic vapor phase epitaxy (MOVPE). To fabricate an A-plane AlN LED, we used an A-plane 6H–SiC $(11\bar{2}0)$ substrate as shown in Fig. 1. The LED consists of a 300-nm-thick AlN buffer layer, n-type Si-doped AlN/AlGaN superlattices (SLs), a 60-nm-thick n-type Si-doped AlN layer, a 120-nm-thick undoped AlN emission layer, a 15-nm-thick p-type Mg-doped AlN layer, and a 5-nm-thick p-type Mg-doped AlGaN contact layer. The Si doping concentration was 1×10^{19} cm^{-3} for the n-type SLs and 2×10^{18} cm^{-3} for the n-type AlN. The Mg doping concentration was 2×10^{19} cm^{-3} for the p-type AlN and AlGaN. Following the MOVPE growth, a mesa structure was formed by dry etching down to the n-type SLs. The mesa size was 200×200 μm^2. A Ti/Al/Ti/Au (25/100/50/100 nm) electrode was formed on the n-type SLs, and a semitransparent Pd/Au (2/2 nm) electrode was formed on the p-type contact layer. For comparison, we also fabricated

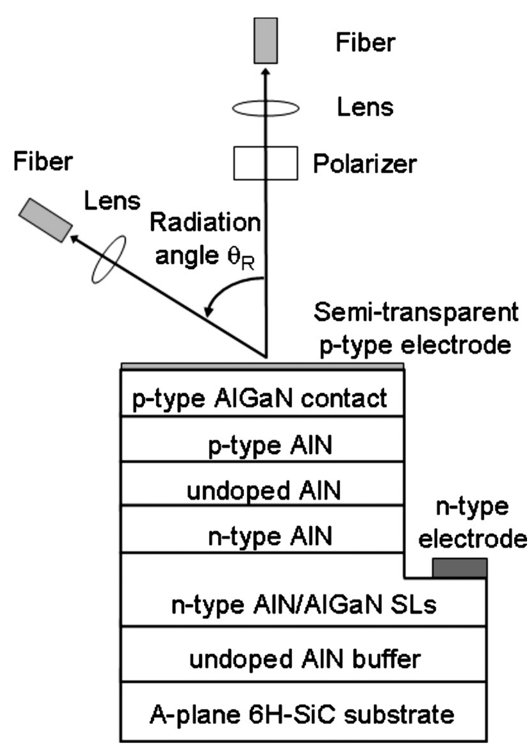

FIG. 1. Schematic of the A-plane AlN p–n junction LED structure and experimental setup for EL measurement.

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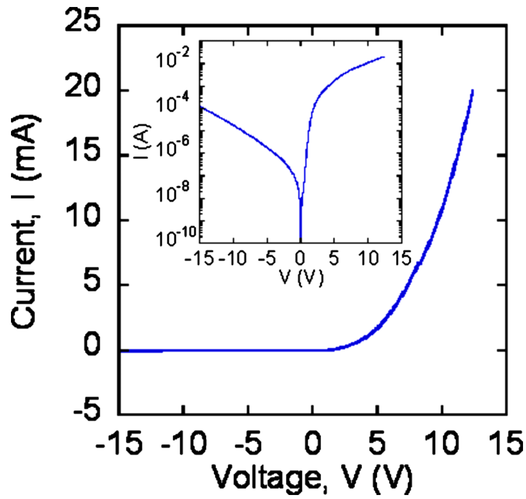

FIG. 2. (Color online) I-V characteristics of the A-plane AlN p–n junction LED.

a C-plane AlN LED using a C-plane SiC (0001) substrate.

The device characterization was performed on-wafer under direct current (dc) bias at room temperature. As shown in Fig. 1, the EL from the AlN LED surface was collected with a fused silica lens with a numerical aperture of 0.25 and focused into an optical fiber. Then, the EL was dispersed by a monochromator and detected with charged coupled device arrays. For the polarization measurement, a polarizer was inserted between the LED and the lens, and the EL was collected along the surface normal as a function of the polarizer orientation Φp. At Φp=0°, the electric field E of light was set to be parallel (perpendicular) to the c-axis (m-axis). To characterize the radiation property of the LED, we measured the EL intensity without the polarizer as a function of radiation angle θ_R, which is defined as the angle from the surface normal to the optical axis of the lens.

Current-voltage (I-V) characteristics of the A-plane LED exhibited a rectifying property with a rectification ratio of 6×10^2 at ±10 V as shown in Fig. 2. At a forward current of 20 mA, the forward voltage was 13 V, which is larger than expected from the band gap energy of AlN. The series resistance was estimated to be about 250 Ω, which mainly originates from the resistance of the lateral conduction part in n-type region. The high resistance limits the forward current.

Figure 3(a) shows the EL spectra of the A-plane LED at different polarizer orientations Φp. The EL spectra were measured at 20 mA. The EL peak was observed at a wavelength of approximately 210 nm, which is the same as that of the near-band-edge EL from C-plane LED.[5,6] As the polarizer orientation increased from 0° and 90°, the EL intensity drastically decreased by a factor of 19. Figure 2(b) shows the EL intensity as a function of polarizer orientation Φp. The periodic variation in the EL intensity was observed as the polarizer was rotated. The EL intensity became maximum at Φp=0° and 180°, which corresponds to the electric field parallel to the c-axis (E∥c), while it became minimum at Φp=90° and 270°, which corresponds to the electric field perpendicular to the c-axis (E⊥c), confirming that the polarized EL. The polarization ratio ρ, which is defined as $\rho=(I_\parallel-I_\perp)/(I_\parallel+I_\perp)$, where $I_\parallel$ and $I_\perp$ are the EL intensities for **E**∥c and **E**⊥c, was estimated to be 0.9. This is close to our reported value of 0.995, which was estimated by angle-dependent PL measurement of the C-plane AlN layer.[9] For the C-plane LED, the EL intensity does not change with polarizer orientation.

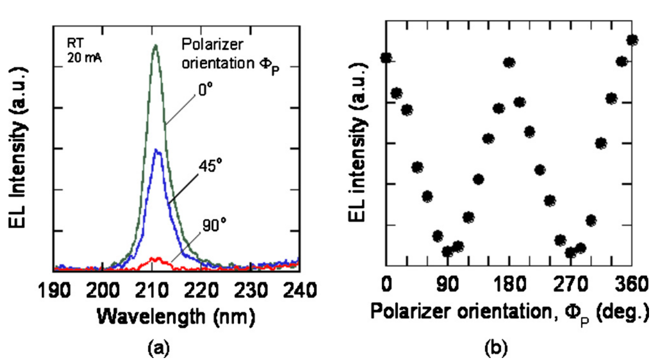

FIG. 3. (Color online) (a) EL spectra of the A-plane AlN p–n junction LED at polarizer orientation Φp=0°, 45°, and 90°. (b) EL intensity as a function of the polarizer orientation.

Because of the strong E∥c polarization, the A-plane LED is expected to show high emission intensity compared with the C-plane LED. Using the polarization ratio, we calculated the light extraction efficiency to be only 0.4% for the C-plane but 10% for the A- or M-planes. The extracted light intensity from the A- or M-planes is thereby estimated to be 25 times higher than that from the C-plane. However, the EL intensity of the A-plane LED was about 70 times lower than that of the C-plane LED. The output power (external quantum efficiency) at 20 mA was 125 nW (1×10^{-4}%) for the C-plane LED and 1.8 nW (1.5×10^{-6}%) for the A-plane LED, respectively. The lower EL intensity indicates that the internal quantum efficiency of the A-plane LED is still lower than that of the C-plane LED. The dislocation density of the A-plane AlN (3×10^9 cm^{-2}) was higher than of the C-plane AlN (5×10^8 cm^{-2}). In addition, the intensity ratio of vacancy/impurity-related emission[12] around 400 nm to the near-band-edge emission for the A-plane LED was 18 times higher than that for C-plane LED. Therefore, for the A-plane LED, the lower near-band-edge EL intensity probably results from the higher defect density. Further improvement of the A-plane growth will increase the efficiency.

Next, we investigate the influence of the surface orientation on the radiation property. The radiation patterns of the A-plane and C-plane LEDs are shown on the left in Figs. 4(a)–4(c). For the A-plane LED, because the polarization along the m-axis and c-axis is different, the EL intensity was measured along the m-axis and c-axis as shown in Figs. 4(a) and 4(b), respectively. However, similar radiation patterns were observed in both directions. They exhibited maximum EL intensities along the surface normal (θ_R=0°). As the radiation angle increased from 0° to 50°, the EL intensity decreased, confirming that the A-plane LED enhances the surface emission. On the contrary, as shown in Fig. 4(c), for C-plane LED, the EL intensity was weak along the surface normal. As the radiation angle increased from 0° to 50°, the EL intensity drastically increased.

To explain the observed radiation properties, we calculated the radiation patterns by considering the polarization. Schematics of radiation from A-plane and C-plane AlN are shown on the right in Figs. 4(a)–4(c). Because of the high polarization ratio, by using dipole radiation, the emission intensity profile inside AlN, $I(\theta_E)$, becomes proportional to $\cos^2\theta_E+\sin^2\theta_E$ along the m-axis of A-plane AlN [Fig. 4(a)],

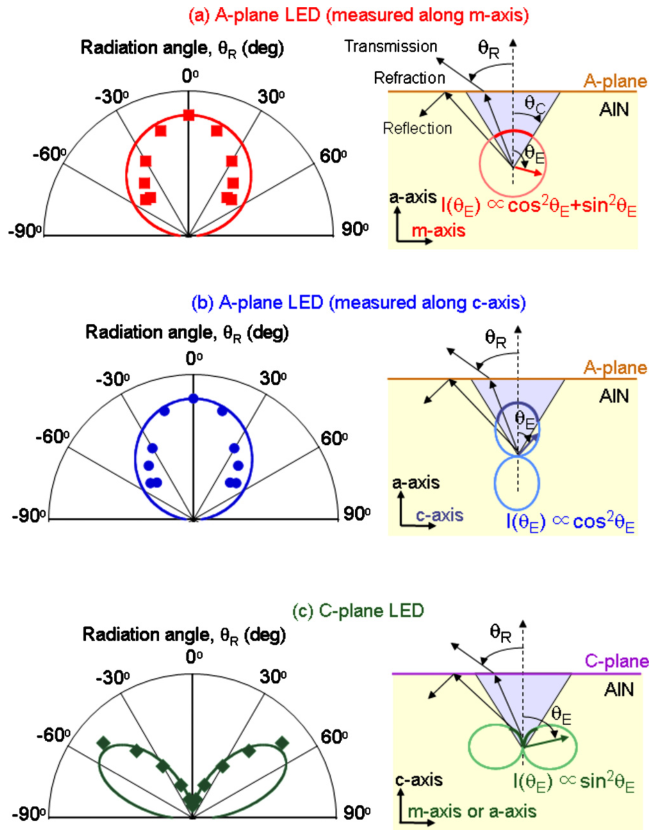

FIG. 4. (Color online) Radiation patterns and schematics of radiation along (a) the m-axis of the A-plane AlN LED, (b) the c-axis of the A-plane AlN LED, and (c) for the C-plane AlN LED. In [(a)–(c)] on the left, symbols are the experimental data and solid lines are calculated radiation patterns.

$\cos^2\theta_E$ along the c-axis of A-plane AlN [Fig. 4(b)], and $\sin^2\theta_E$ for C-plane AlN [Fig. 4(c)], where θ_E is the emission angle with respect to the surface normal. The emitted light can be extracted from the surface when the emission angle is smaller than a critical angle θ_C. By considering the emission intensity profile and light refraction/transmission at the AlN surface, the radiation pattern can be obtained. In the calculation, we took into account the numerical aperture of the lens used in our measurement and used a refractive index of 2.7 for AlN (Ref. 13) but ignored the polarization dependence of the transmission because it is small at small radiation angles. In Figs. 4(a)–4(c), the solid lines indicate the calculated radiation patterns. For the A-plane LED, because the emission intensity profile is proportional to $\cos^2\theta_E+\sin^2\theta_E$ along the m-axis and $\cos^2\theta_E$ along the c-axis, the calculated radiation patterns have the maximum intensity at the surface normal $(\theta_R, \theta_E=0°)$. Furthermore, because the critical angle θ_C is as small as 22°, at $\theta_E<22°$ the difference in the emission intensity profiles between the m-axis and c-axis, $\sin^2\theta_E$, is small. Consequently, the radiation patterns are similar. On the other hand, because the emission intensity profiles do not change much at $\theta_E<22°$, the calculated radiation patterns have an approximately Lambertian shape, i.e., cosine dependence, which is normally obtained for an isotropic emission from a planar surface.[14] In Fig. 4(c), for the C-plane AlN, because the emission intensity profile is proportional to $\sin^2\theta_E$, the radiation intensity increases with increasing radiation angle. For both LEDs, the calculated results well explain the measured ones. Due to the strong $\mathbf{E}\parallel c$ polarization, the surface orientation greatly affects the radiation properties.

In summary, an A-plane AlN LED was fabricated by using A-plane SiC substrate. We demonstrated near-band-edge EL from the A-plane LED at a wavelength of 210 nm. The polarization ratio of the EL was estimated to be as high as 0.9. Due to the strong polarization, the A-plane LED showed strong emission along the surface normal, while the conventional C-plane LED showed weak emission along the surface normal.

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