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Comparison of InGaN/GaN light emitting diodes grown on *m*-plane and *a*-plane bulk GaN substrates

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InGaN/GaN-based light emitting diodes (LEDs) grown on *m*-plane, *a*-plane and off-axis between *m*- and *a*-plane GaN bulk substrates were investigated. A smooth surface was obtained when *a*-plane substrate was applied; however, large amounts of defects were observed. Photoluminescence measurements of the LEDs with a well thickness of 2.5 nm revealed that all the LEDs showed the peak emission wavelength at 389 nm. The PL intensity of the *a*-plane LED is one order of magnitude lower than that of the *m*-plane LED. The *a*-plane LEDs showed significant lower electroluminescence output powers than *m*-plane LEDs, suggesting that excitons are trapped by the defects, which act as non-radiative recombination centers.

1 Introduction Nonpolar and semipolar III-nitride-based optoelectronic devices are attractive compared to the polar *c*-plane devices. This is because the *c*-plane devices suffer from the quantum-confined Stark effect (QCSE) [1, 2] due to the large internal electric fields, which result from discontinuities in spontaneous and piezoelectric polarization at hetero-interfaces [3]. These polarization-related internal electric fields along the *c*-axis cause the spatial separation of electrons and holes, which result in a reduction of carrier recombination efficiency [4]. The advantage of using nonpolar planes over *c*-plane nitrides is that polarization-related internal electric fields will be eliminated. Two possible nonpolar planes in GaN are considered; *m*-plane [5–9], and *a*-plane [10–14]. Recently, *m*-plane light emitting diodes (LEDs) and laser diodes (LDs) on *m*-plane bulk GaN substrates have been reported [6–9]. The output power and external quantum efficiency (EQE) of the LED [6] under pulsed operation at 20 mA were as high as 28 mW and 45.4%, respectively.

However, there have been no reports for the fabrication of LEDs grown on *a*-plane bulk GaN substrates. Growth of *a*-plane LEDs hetero-epitaxially grown on *r*-plane Al_2O_3 contains stacking faults (SFs) and threading dislocations (TDs). The densities of SFs and TDs are on the order of 10^5 cm^{-1} and 10^{10} cm^{-2}, respectively [15]. The lateral epitaxially overgrown (LEO) technique makes it possible to reduce SFs and TDs to lower than 3×10^3 cm^{-1} and 5×10^6 cm^{-2}, respectively [16]. These defect densities are relatively low, although, the DC output power of the LED on *a*-plane LEO GaN template was 240 µW [14] at 20 mA, which is significantly lower than for conventional *c*-plane LEDs [17]. In this study, we investigated InGaN/GaN LEDs grown on *m*-plane, *a*-plane and off-axis between *m*- and *a*-plane GaN bulk substrates. We have found that *a*-plane LEDs show a significantly lower emission efficiency than *m*-plane LEDs at 390–405 nm.

2 Experimental procedure The *m*-plane, *a*-plane, and off-axis substrates were prepared by slicing from *c*-plane free-standing GaN crystals which were grown by hydride vapor phase epitaxy (HVPE) at Mitsubishi Chemical Co., Ltd. The off-axis angles of the substrates from *m*- toward *a*-direction were 0.01° (*m*-plane), 1.0°, 5°, 10°, and 30° (*a*-plane) measured by X-ray diffraction (XRD).

The off-axis angles of the substrates toward the c^+- or c^--direction were within 0.05°. The surfaces were polished by chemical and mechanical treatments. The substrates have atomically flat surfaces (RMS value of 0.1 nm) and TD densities less than 5×10^6 cm^{-2}. The free electron concentrations were around 7×10^{17} cm^{-3}.

All samples were grown by metal organic chemical vapor deposition (MOCVD) at atmospheric pressure. The InGaN/GaN LED structures were similar to the previous report [18]. The InGaN well thickness in the MQWs was varied from 2.5 nm to 8.0 nm and the GaN barrier thickness was kept at 20 nm. The LEDs (300×300 μm^2 mesa size) were fabricated using standard photolithography and dry etching processes. Evaporated indium tin oxide (ITO) and Ti/Al/Ni/Au were employed as a p- and n-contact, respectively. After wafer processing, wafers were diced into discrete dices. Conventional die bonding and wire-bonding techniques were applied, and individual LED chips were formed into silicone-resin encapsulated lamps. The EL emission spectra and output power measurements of the packaged LEDs were performed in an integrating sphere at room temperature (RT). Photoluminescence measurement was performed at RT excited by He–Cd laser at 325 nm.

3 Results and discussion Figure 1(a)–(d) are Nomarski optical micrographs of the LED surfaces grown on GaN substrates with off-axis angles from *m*- toward *a*-direction of (a) 0.01° (*m*-plane); (b) 1.0°; (c) 10°; and (d) 30° (*a*-plane). The surface on the *m*-plane consisted of four-faceted pyramids as shown in Fig. 1(a). These pyramid facets are inclined to the *a*-axis, c^+-axis (Ga-polar), and c^--axis (N-polar) directions. The pyramid features disappeared when an off-axis angle of 1.0° was applied; however, the samples on off-axis angles of 5° (not shown) and 10° showed rough surfaces (Fig. 1(c)), indicating that island growth is dominant. A smooth surface was obtained when an on-axis *a*-plane substrate was applied (Fig. 1(d)); however, large amounts of pits (~10^5 cm^{-2}) were confirmed by

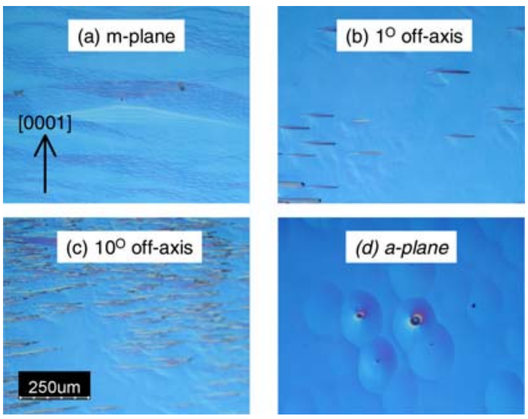

Figure 1 (online colour at: www.pss-rapid.com) Nomarski optical micrographs of LED surfaces grown on GaN substrates with an off-axis angle from *m*- toward *a*-direction of (a) 0.01° (*m*-plane), (b) 1.0°, (c) 10°, and (d) 30° (*a*-plane).

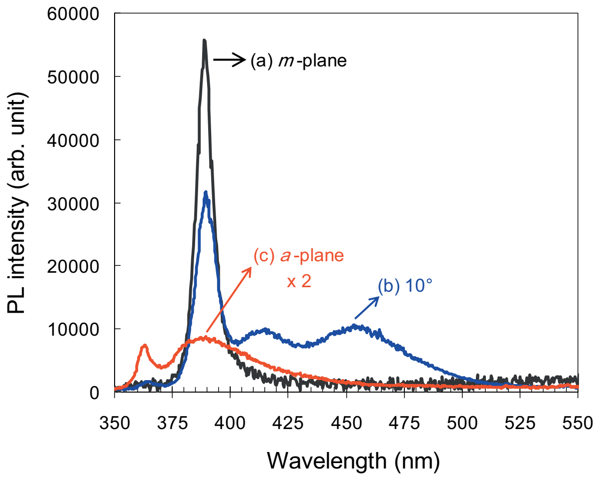

Figure 2 (online colour at: www.pss-rapid.com) PL spectra of the LEDs grown on GaN substrates with an off-axis angle from *m*- toward *a*-direction of (a) 0.01° (*m*-plane), (b) 1.0°, (c) 10°, and (d) 30° (*a*-plane).

scanning electron microscopy (SEM). These defects were formed from the n-GaN layer. We thus applied various growth conditions for the n-GaN layer, including growth temperature (1050–1185 °C), V/III ratio (1500–3000) and growth rate (6–12 μm/h). All the samples, however, showed the same defects. We reported that a flat surface was obtained on the off-axis substrate toward the *c*-direction [18]. These results thus suggest that off-axis toward *c*-direction is essential to obtain a step flow growth mode [19].

PL spectra of the LEDs with an InGaN well thickness of 2.5 nm grown on *m*-plane, 10° off-axis, and *a*-plane substrates are shown in Fig. 2. All the LEDs showed the same peak emission wavelength at 389 nm, which is attributed to the InGaN QWs. For the 10° off-axis, in addition to the main peak (389 nm), two other peaks (415 nm, 455 nm) were observed. The 455 nm peak is probably due to facet-related emissions since the surface of the 10° LED is rough and the peak wavelength of the co-loaded 5° off LED from *m*-plane toward the c^--plane (N-face) was 454 nm [18]. These results indicate that the indium incorporation ratio on the nonpolar planes is almost the same between *m*- and *a*-plane. The *a*-plane LED showed two peaks of 364 nm and 389 nm, corresponding to the n-GaN and InGaN QW emission, respectively. The full width at half maximum (FWHM) of the InGaN emission is 4 times broader. Moreover, the PL intensity is one order of magnitude lower than that of the *m*-plane LED, suggesting that excitons in the MQWs are trapped by the defects, which act as non-radiative recombination centers.

The dependence of the EL output power and the EQE on the drive current for the *m*- and *a*-plane LEDs (InGaN well thickness of 8 nm) is shown in Fig. 3. The emission spectra were measured at drive currents from 1 mA to 30 mA. The output power and the EQE for the *m*-plane LED at DC current of 20 mA were 11.2 mW and 18.2%. The output power and EQE for the *m*-plane LED with a

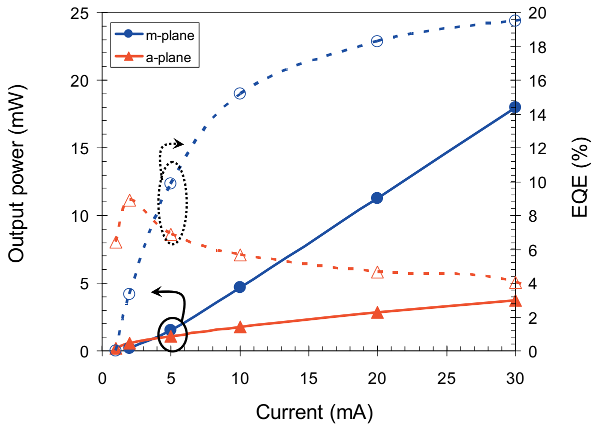

Figure 3 (online colour at: www.pss-rapid.com) EL output power (closed symbols) and EQE (open symbols) for the LED grown on *m*-plane (circles) and *a*-plane (triangles) substrate.

well thickness of 5 nm (not shown) were 16.5 mW and 26.5%, respectively. These values are comparable to the previous report [20]. For the *a*-plane LED, the output power and EQE (well thickness of 8 nm) were 2.9 mW and 4.6%, respectively. It should be noted that the devices showed the same level of reverse leakage current (less than 1 μA) at a –10 V. The forward voltage (V_f) of the *a*-plane LED at 20 mA is 7.3 V, which is larger than that of the *m*-plane LED (6.5 V). We investigated the effects of carrier concentrations for n-/p-GaN layers or the Al composition for AlGaN electron blocking layer on *a*-plane LEDs. The results revealed that all the LEDs showed output powers in the range of 1–2 mW. These values are 3–20 times lower than those of the *m*-plane LEDs. We thus attribute the lower output power for the *a*-plane LEDs to defects in the MQWs, which act as non-radiative recombination centers. Another possible explanation is that localized radiative centers [1] exist in the InGaN QW. Further investigation is required to make clear the origin of the low emission efficiency for the *a*-plane LEDs.

4 Conclusion A comparison of InGaN/GaN light emitting diodes grown on *m*-plane and *a*-plane bulk GaN substrates was performed. A smooth surface was obtained when an *a*-plane substrate was applied; however, large amounts of defects were observed. PL measurements revealed that all LEDs showed peak emission wavelength at 389 nm. The *a*-plane LEDs showed 3–20 times lower output powers than *m*-plane LEDs. We thus attribute the lower output powers for the *a*-plane LEDs to defects in the MQWs, which act as non-radiative recombination centers.

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