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Comparison of the Performance of InGaN/AlGaN MQW LEDs Grown on c-Plane and a-Plane Sapphire Substrates

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We report a comparative study on the performance of InGaN/AlGaN multiple quantum well (MQW) light emitting diodes (LEDs) fabricated on c- and a-plane sapphire substrates, respectively. It was found that the LEDs grown on a-plane sapphire substrates exhibited enhanced electroluminescence intensity, decreased double crystal X-ray diffraction linewidth, reduced etching pit density, and smaller ideality factor compared to those deposited on c-plane sapphire substrates. The improved LED characteristics are attributed to threading dislocation density decrement inside the LEDs due to the reduced mismatch between LED structure and a-plane sapphire substrate.
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Group III-nitrides have become the most promising compound semiconductors for green color ultraviolet (UV) photonics and high power electronics over the past decade.[1] In particular, GaN-based light emitting diodes (LEDs) have received great attention owing to their applications in traffic signals, full color displays, backlightings of liquid crystal displays, and white-color solid-state light sources.[2] GaN-based blue, green, and UV LEDs have typically been grown on c-plane sapphire substrates due to the lack of suitable substrate. The GaN films were found to deposit on c-plane sapphire substrates with $[11\bar{2}0]_{GaN}$ being parallel to $[10\bar{1}0]_{sapphire}$ so that the misfit strain energy between film and substrate is minimized. Nevertheless, the lattice mismatch between GaN film and c-plane sapphire substrate remains as high as ~16% and a large number of threading dislocations (TDs) are usually generated to accommodate such a large mismatch.[3] TDs were previously reported to originate from stacking faults in the buffer layer of a GaN film grown on the c-plane sapphire substrate.[4] The presence of TDs in GaN-related films was found to deteriorate optical properties of films.[5] Thus, a reduction of TD density in the active region of a III-nitride LED is an issue of great concern for achieving high-power performance.[6] Recently, there have been reports in literatures using a-plane sapphire substrates as the replacement of c-plane sapphire substrates for preparation of InGaN-based LDs because a-plane [for instance $(11\bar{2}0)$] sapphire substrates can be cleaved along r-plane [for example $(1\bar{1}02)$].[7] For GaN films grown on a-plane sapphire substrates, it was also found that $[11\bar{2}0]_{GaN}$ and $[1\bar{1}00]_{GaN}$ were parallel to $[0001]_{sapphire}$ and $[1\bar{1}00]_{sapphire}$ with corresponding lattice mismatches being 1.8 and −0.62%, respectively.[8] Preliminary experimental results showed that, compared to the films on c-plane sapphire substrates, better quality GaN films were achieved on a-plane sapphire substrates.[9] Thus, it is of great interest to explore the dependence of substrate orientation on the characteristics of the overgrown LED structure. In this paper, we report a comparative study on the performance of InGaN/AlGaN multiple quantum wells (MQW) LED structures grown on c- and a-plane sapphire substrates.

Experimental

$In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ multiple quantum well (MQW) LED structures were prepared on c- and a-plane sapphire substrates by atmospheric pressure organometallic vapor phase epitaxy (APOM-VPE). In this case, trimethylgallium (TMG), trimethylaluminum (TMA), trimethylindium (TMI), and ammonia (NH_3) were carried by purified H_2 gas into a deposition chamber for the growth of LED structures. A typical LED structure consists of a 1 μm thick undoped GaN which is deposited first followed by the subsequent deposition of a 4 μm thick Si-doped n-GaN ($n_0 = 4 \times 10^{18}$ cm^{-3} at 300 K), 10-period $In_{0.1}Ga_{0.9}N$ (3 nm)/$Al_{0.03}Ga_{0.97}N$ (12 nm) MQWs, and a 50 nm thick Mg-doped p-GaN ($p_0 = 6 \times 10^{17}$ cm^{-3} at 300 K). Undoped GaN, n-GaN, and p-GaN layers were all grown at 1150°C while growth of MQW structure was conducted at 720°C under a V/III ratio of 7000. Conventional LED chips, 365 × 365 μm in size, were fabricated using standard photolithography and dry etch techniques. An e-gun evaporator was employed to deposit Cr/Au alloys which serve as n-type and p-type contacts of the LEDs.

To evaluate dislocation density in the LED structure, molten potassium hydroxide (KOH) was employed to etch LED surface. Typical etching procedure was conducted at 360°C for 10 min. The etch pits on etched LED structure were observed using a Hitachi S-4800 field emission scanning electron microscope (FESEM). A Bede QC 200 double-crystal X-ray diffractometer was used for the structural characterization of LEDs. A Keithley 236 source measurement unit was utilized for the current-voltage (I-V) and electroluminescence (EL) measurements of LEDs. A JEOL 1200 EX II transmission electron microscope (TEM) was employed to reveal LED microstructures. TEM samples were prepared by using a Gatan 619-PIPS argon ion milling equipment.

Results and Discussion

Figure 1 shows typical (0002) double-crystal X-ray diffraction (DCXRD) curves of $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED structures grown on c- and a-plane sapphire substrates, respectively. The insets represent the cross-sectional TEM (XTEM) images near the MQW area of the corresponding $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED structures. One can clearly observe the same satellite peaks in these structures in which high crystalline quality, sharp interface abruptness and uniform $In_{0.1}Ga_{0.9}N$ well width and $Al_{0.03}Ga_{0.97}N$ barrier thickness are achieved. Note that TEM observations agree quite well with the (0002) DCXRD results. However, a detailed inspection of Fig. 1 reveals that the full width at half-maximum (fwhm) of the (0002) GaN DCXRD signal of the LED structure grown on a-plane sapphire substrate is 173 arcsec which is narrower than 193 arcsec of the identical LED structure grown on c-plane sapphire substrate. Based on the (0002) GaN DCXRD results, it is believed that the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on a-plane sapphire substrates exhibit better structural quality than those grown on c-plane sapphire substrates.

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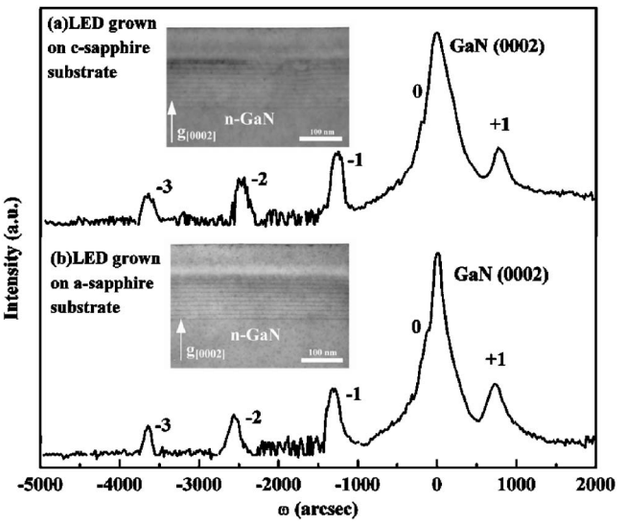

Figure 1. Typical (0002) DCXRD curves of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED structures grown on c- and a-plane sapphire substrates. Insets: the corresponding XTEM micrographs of the LEDs near MQW area, respectively.

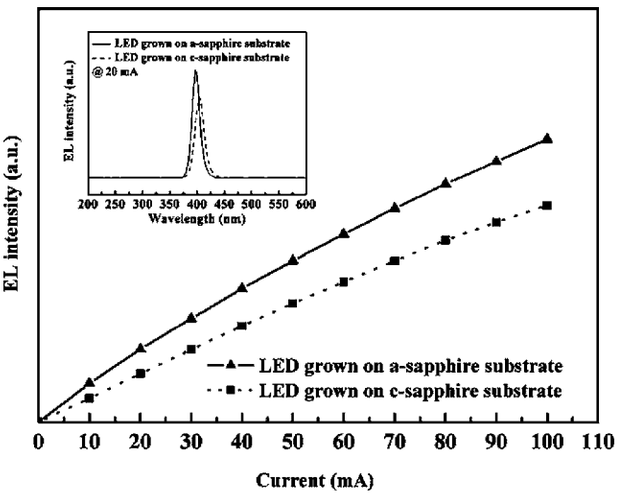

Figure 3. Plots of EL intensity vs forward current of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c- and a-plane sapphire substrates. Inset: a typical room-temperature EL spectra measured at 20 mA for the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c- and a-plane sapphire substrates.

For a forward-biased p-n junction under low level injection, it is known that the I-V relationship can be approximated as[10]

$$I \approx I_s \exp(qV_a/n_f k_B T) \quad [1]$$

where I, I_s, V_a, and n_f are forward current, reverse saturation current, applied forward bias, and ideality factor, respectively.

One can further express the I-V relationship as $\log I \approx \log I_s + 0.434(qV_a/n_f k_B T)$, and the ideality factor of p-n junction can be estimated by fitting $\log I$ vs V_a plot. In this case, five LED chips were chosen in a quarter part of a 2 in. LED wafer to obtain the average value of ideality factor which was determined being 3.0 and 2.8 in the diffusion current dominant I-V region for $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c- and a-plane sapphire substrates, respectively. Figure 2 exhibits typical plots of $\log I$ vs V_a of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c-plane and a-plane sapphire substrates. It appears that the ideality factor of the LED grown on a-plane sapphire substrate is slightly smaller than that of the one deposited on c-plane sapphire substrate. The ideality factors of GaN-based LEDs were reportedly larger than those observed in conventional semiconductor p-n junctions because of the signature of tunneling current in the forward-biased LEDs due to the presence of TDs.[11] Thus, the increment of n_f value in an $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED implies a high density of localized states near the midgap of the LED junction.[12] Such an effect was also observed in leakage currents (I_R) of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs. As shown in Fig. 2, for an $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED grown on c-plane sapphire substrate, its I_R value rises with reverse bias and reaches 34 nA at a reverse bias of −5 V while for the same LED structure grown on a-plane sapphire substrate, the corresponding I_R value reaches 13 nA at a reverse bias of −5 V. The leakage current of a GaN-based LED was reportedly larger than that of a Si-based diode due to enhanced probability of tunneling through the deep-level states created by TDs.[13,14] Thus, it is reasonable to consider that the decrement of I_R values in the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on a-plane sapphire substrates is a consequence of reduced TD densities in the LEDs. This result is in good agreement with the reduced (0002) GaN DCXRD line width of LED structure grown on a-plane sapphire substrate shown in Fig. 1.

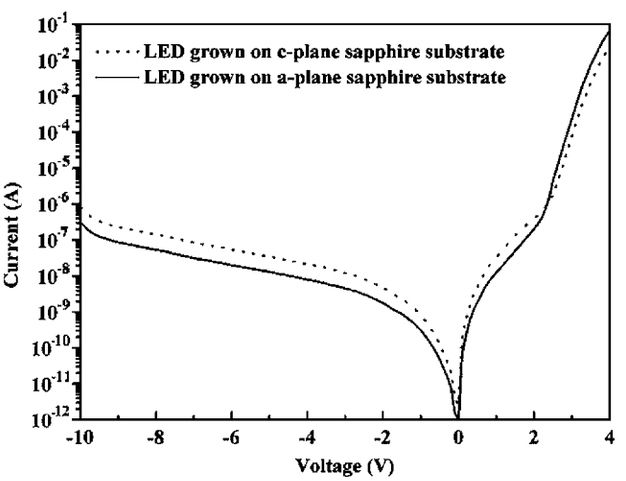

Figure 2. I–V characteristics of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c- and a-plane sapphire substrates.

Figure 3 shows EL intensity vs injection current of the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on c- and a-plane sapphire substrates. The inset shows typical EL spectra of the LEDs at 20 mA. Both EL intensity curves exhibit almost linear increment with respect to injection current up to 100 mA with the EL intensity of the LED grown on a-plane sapphire substrate being about 25% higher than that of the LED deposited on c-plane sapphire substrate. This is a good indication that the emission efficiency of an $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED grown on a-plane sapphire substrate is superior to that of the LED deposited on c-plane sapphire substrate.[15] A reduced EL fwhm of ~16 nm was found for the $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED structure grown on a-plane sapphire substrate compared to the EL linewidth of ~20 nm for the same LED structure grown on c-plane sapphire substrate under the same conditions. A blueshift of the EL of $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LED grown on a-plane sapphire substrate implies a lower In content of the InGaN wells.

Figures 4a and b are FESEM images of the etched LED structures grown on c- and a-plane sapphire substrates. Typical EPD values are 5.6×10^8 and 3.2×10^8 cm^{-2}, respectively, for LEDs grown on c- and a-plane sapphire substrates. Reduced EPD counts in the LED grown on a-plane sapphire substrate agree well with

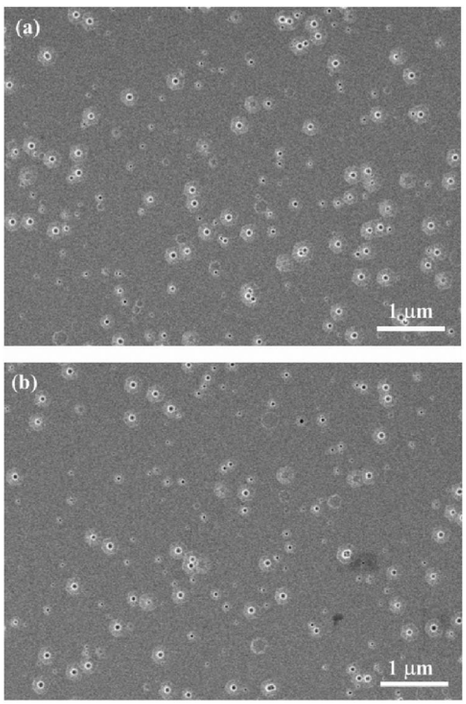

Figure 4. Typical FESEM surface morphologies of the etched $In_{0.1}Ga_{0.9}N/Al_{0.03}Ga_{0.97}N$ MQW LEDs grown on (a) c- and (b) a-plane sapphire substrates.

improved DCXRD, I-V, and EL characteristics of the LED. Thus it is believed that decrement in lattice mismatch between LED structure and a-plane sapphire substrate enables the improved LED performance.

Conclusions

We present a comparative study on characteristics of InGaN/AlGaN MQW LEDs grown on c- and a-plane sapphire substrates. It was found that FWHM of (0002) GaN DCXRD, EPD counts, EL intensity, linewidth of EL emission, and I-V characteristics of the LED structures grown on a-plane sapphire substrates were superior to those of the identical ones grown on c-plane sapphire substrates. It is believed that reduced mismatch between InGaN/AlGaN MQW LED structure and a-plane sapphire substrate enhances both material and device characteristics of the LEDs grown on a-plane sapphire substrates.

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