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Lifetime Tests and Junction-Temperature Measurement of InGaN Light-Emitting Diodes Using Patterned Sapphire Substrates

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It is well-known that the large differences in the lattice mismatch (~13.5%) and thermal expansion coefficient between GaN epilayer and sapphire substrate would eventually result in a large number of threading dislocations being induced in the GaN epilayer. The threading dislocation densities on the order of 10^9-10^{10} are typically reported. To date, several techniques including epitaxially lateral overgrowth (ELOG), air-bridges lateral epitaxial growth (ABLEG), and pendeoepitaxy (PE) have been proposed to reduce the threading dislocations. In particular, the ELOG, ABLEG, and PE require a growth of 1~2-μm-thick GaN seed layer on the sapphire substrate using metal-organic vapor phase epitaxy (MOVPE), followed by the generation of a regularly spaced recessed pattern via a standard photolithography and etching process, before attempting a regrowth using MOVPE. In other words, the foregoing techniques demand twice repeating the MOVPE growth compared to the patterned sapphire substrate (PSS), which requires only one growth run. Therefore, the PSS method is adopted to improve the crystalline quality of GaN epilayers by effectively reducing the dislocation density.

Once the quality of epilayers is enhanced, the next major issue to consider is the junction temperature of a light-emitting diode (LED), since this important parameter is closely related to the internal quantum efficiency, output power, emission wavelength, and reliability of any light-emitting devices. Since commercial LEDs are typically encapsulated in an epoxy resin, and choosing an appropriate epoxy resin requires the consideration of its glass-transition temperature (T_g). Generally speaking, the epoxy resin is able to transform from hard and brittle to soft and pliable. A distinct change in the coefficient of thermal expansion (CTE) is generally associated with T_g. A higher CTE causes the epoxy resin to expand and contract with much ease during temperature change, eventually resulting in a breakage of the wire. To avoid permanent damage to the LEDs, the heat induced by junction temperature should always be kept below T_g of the epoxy resin. Therefore, to gain a better understanding on the aforementioned heat-related issues, both the lifetime and junction temperature properties of LEDs grown on PSS and non-patterned sapphire substrate (NSS) were characterized and compared in details.

To fabricate patterned sapphire substrates, a 400-nm-thick nickel (Ni) layer was deposited by E-beam evaporation on top of the sapphire substrate. The PSS containing a periodically spaced hexagon structure has a width of 6 μm, and these hexagons are separated from each other in an interval of 3 μm using standard photolithography. Next, the PSS was etched by inductively-coupled plasma etcher, from which Cl_2/BCl_3 gases were used. The depth of the groove was 1 μm. The Ni mask was finally removed using Ni etching solution to complete the PSS structure. Both LEDs with and without the PSS structure were utilized in the experiments to carry out the growth on c-face (0001) 2-inch sapphire substrates using MOVPE at atmospheric pressure. In order to evaluate the junction temperature of these two LEDs, the forward voltage was used a parameter to assess the junction temperature of these devices. The change of forward voltage drop versus the temperature change of the junction exhibits a linear relationship. During a junction-voltage measurement, a 99% duty cycle of the driving current was injected into the LED to heat it up, while during the remaining 1% of the time a small sensing current was applied to the LED to measure the resultant forward voltage drop. The sensing current was deliberately kept at a minimum value to avoid self-heating.

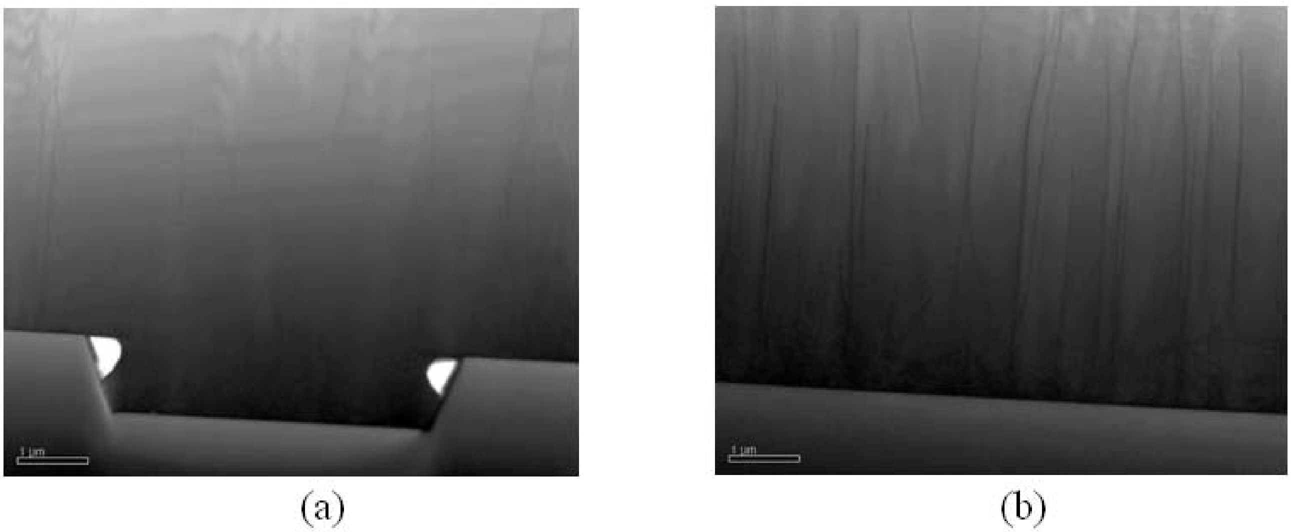

Fig. 1. Cross-sectional TEM micrographs of GaN epilayers grown on (a) PSS and (b) NSS, respectively.

Figures 1(a) and 1(b) depicts the cross-sectional transmission emission microscopy (TEM) micrographs of GaN layers on the PSS and NSS, respectively. As shown in Fig. 1(a), numerous threading dislocations originating from the interface between the GaN buffer layer and sapphire substrate due to a large lattice mismatch were spotted for NSS. On the other hand, for the PSS case depicted in Fig. 1(b), notice that an air gap is formed on the upper sidewall of the ridges. The threading dislocations extend vertically into the GaN epilayer from the top of the ridge and partially from the groove, but virtually no dislocations propagate into the top region directly above the air gap. In fact, these air gaps effectively suppress the threading dislocations from propagating into the GaN epilayer. The dislocation densities of the GaN epilayer grown on the PSS and NSS are estimated to be 5.6×10^7 cm^{-2} and 1.3×10^8 cm^{-2}, respectively.

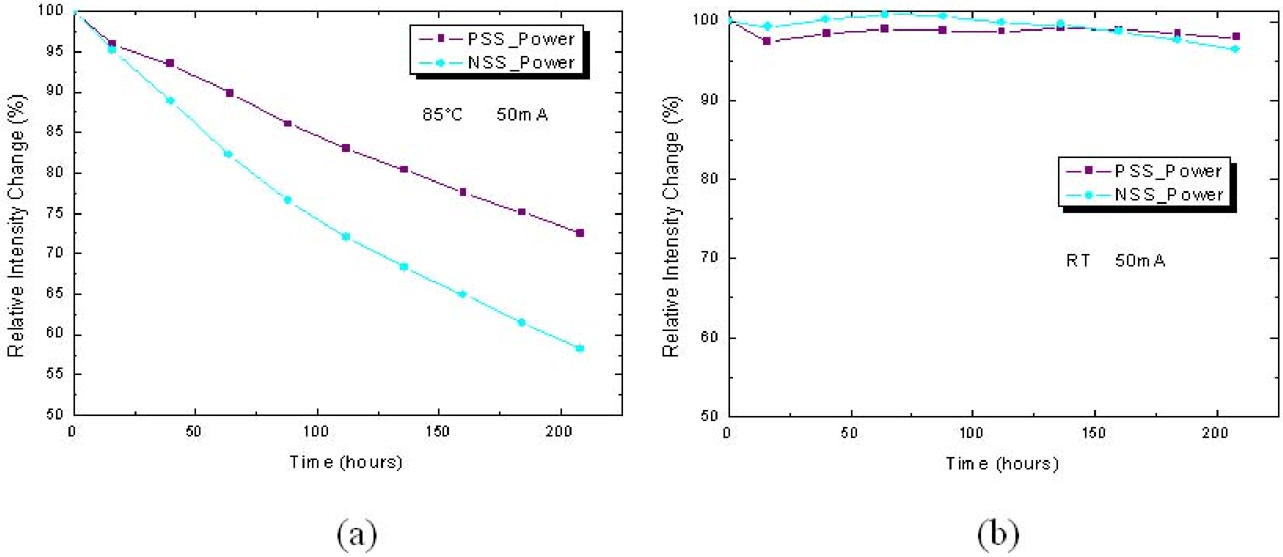

Fig. 2. Relative change in the intensity of PSS and NSS at (a) 85 ˚ C and also at (b) room temperature, for the final 208 hours.

To investigate device degradation, accelerated aging tests were executed using 2.5 times the normal operation current of the LED at high temperature (85 ˚ C) and room temperature (RT). Figure 2(a) presents the life test performed at 85 ˚ C and with 50 mA driving current involving the measurements of relative output powers of LEDs on either PSS or NSS, which are obtained by normalizing with respect to their initial readings. The initial output powers were estimated to be 11.24 and 8.89 mA for PSS and NSS at a forward current of 20 mA under a room temperature condition. As a result of the test, the output intensities were found to decay by 27.5% (8.15 mW) and 41.8% (5.17 mW) after 208 hours of aging for PSS and NSS, respectively. More than 50% loss in output intensities after 590 and 305 hours for the PSS and NSS were respectively estimated. It is well-known that the carrier recombination associated with defects and dislocations is nonradiative in nature, which contributes to thermal dissipation. Therefore, the maximum output intensity of PSS tends to be larger and more tolerable to higher injection current when compared to that of NSS. Consequently, the lifetime of NSS is much shorter. Figures 2(b) depicts the life test conducted at RT for the foregoing two LEDs. The driving current was also set at 50 mA. Similar trends in the reduction of the output intensity as obtained from the aforementioned two LEDs were also detected. Specifically, a gradual decrease in output intensity of the NSS after 112 hours of aging was noted. However, the rate of decrease was almost invariant for the PSS. The output intensities were found to decay by 2.1% and 3.6% after 208 hours of aging, and more than 50% intensity loss were estimated after 3424 and 1984 hours of tests for PSS and NSS, respectively.

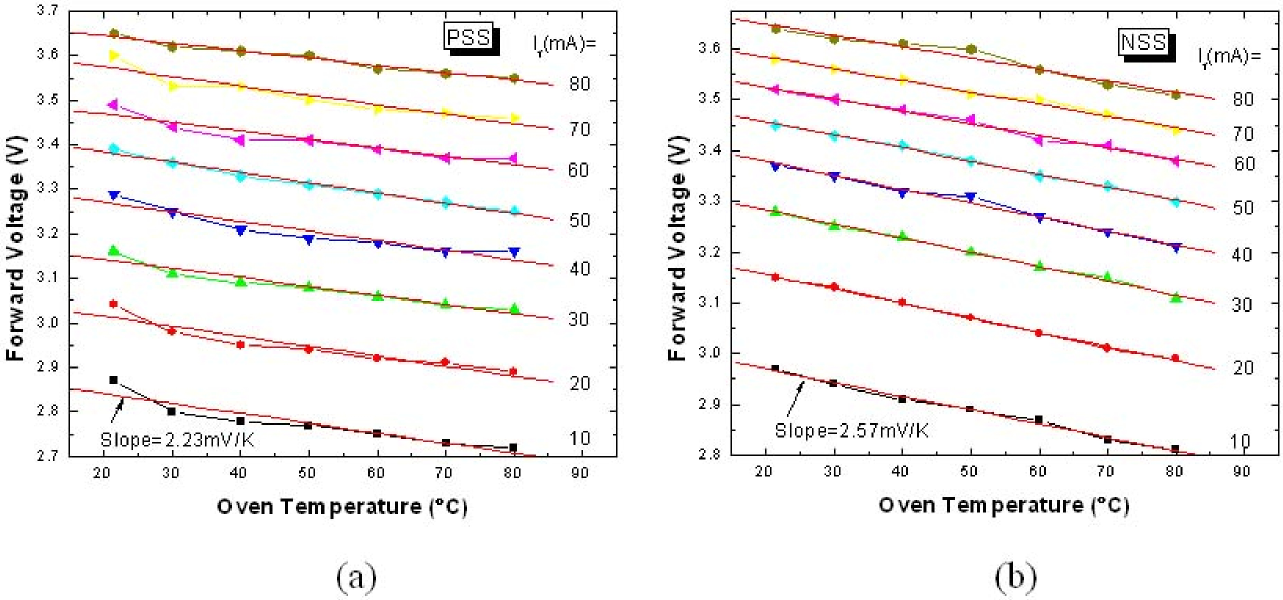

Fig. 3. Experimental forward voltage versus oven temperature for different pulse currents. A linear fit to the experimental data is also shown in (a) & (b).

The measured forward voltage as a function of junction temperature is shown in Fig. 3. To execute this measurement, both LEDs were placed in a temperature-controlled oven, and a small current was injected to bring the device in thermal equilibrium with the oven temperature. During the calibration, the pulsed current was increased in an increment of 10 mA with a current range set between 10 and 80 mA. A linear relationship was clearly observed between the junction voltage and the ambient temperature. As depicted in Fig. 3, the temperature coefficients of the PSS and NSS LEDs were estimated to be approximately -2.23 and -2.57 mV/K, respectively. The foregoing linear relationship can be expressed as $T_j = (V_f - A)/B$, where A and B are the fitting parameters, and T_j is the junction temperature.

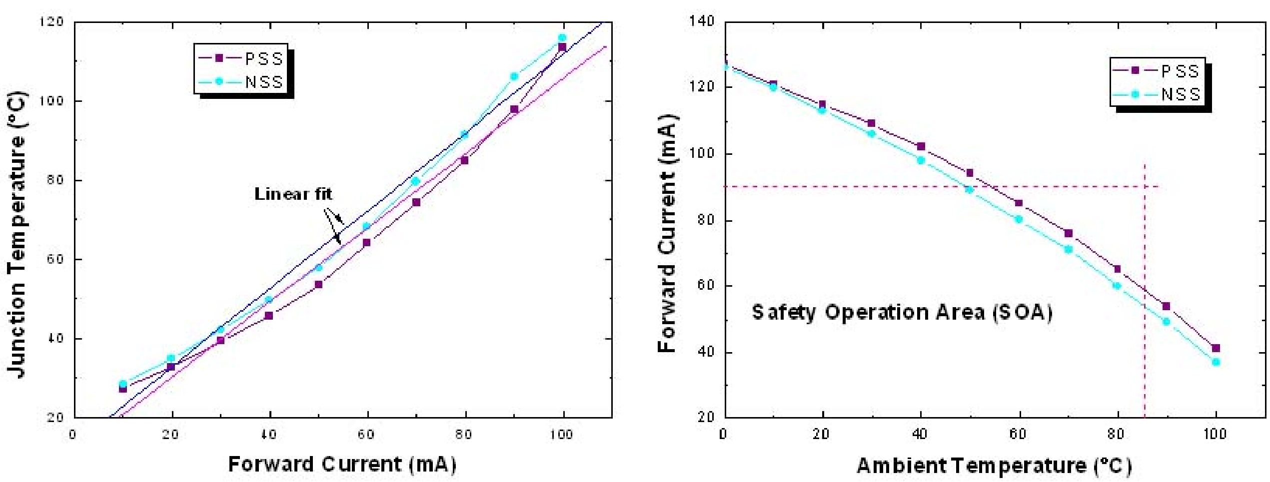

Fig. 4. (a) Junction temperature as a function of forward current for the PSS and NSS, and (b) the corresponding derating curves of the PSS and NSS LEDs.

Figure 4(a) shows the profiles of junction temperature versus the forward current for the PSS and NSS. Both curves for the PSS and NSS are approximately linear. The junction temperature of the NSS is larger than that of the PSS. Using the linear-fitting parameters from $T_j = (V_f - A)/B$, the derating curve can be easily calculated with the data obtained from the junction temperature. The calculation results are shown in Fig. 4(b). It depicts that the PSS LEDs have larger safety-operation area (SOA) than that of the NSS LEDs, indicating the PSS has larger tolerances in the operation current and ambient temperature. In other words, the PSS LEDs is capable to operate in a relatively harsher environment such as outdoor display. Moreover, an obvious change in CTE is generally associated with T_g. The epoxy resin may be changed from hard to soft as a result of higher junction temperature. A higher CTE causes the epoxy resin to expand, resulting in a premature breakage of the wire. Therefore, to avoid permanent damage to the LEDs, the heat induced by junction temperature should always be kept below the T_g of the epoxy resin.

In summary, our experimental results conclude that the ultimate crystalline quality of GaN epilayers is intimately related to the lifetime and junction temperature of light-emitting devices. Since the nonradiative carrier recombination normally occurs in regions associated with defects and dislocations, the resulting recombination mechanism will inevitably result in heat generation. Consequently, much-reduced dislocations offered by PSS is expected to render devices with better optical and electrical characteristics.