Thermal stability of InGaN multiple-quantum-well light-emitting diodes on an AlN/sapphire template

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InGaN multiple-quantum-well light-emitting diodes (LEDs) were grown on an AlN/sapphire template by metalorganic chemical vapor deposition. The crystalline quality was investigated by x-ray diffraction and electron-beam-induced current. The thermal stability of the LED was demonstrated by measurements of current–voltage, light output power–current, and electroluminescence (EL) spectra at different temperatures. The output power at 200 mA decreased by 7.3% for the LED on the template upon increasing temperature from 25 to 95 °C, while that for the LED on sapphire decreased by 23.9%. The peak external quantum efficiency decreased from 0.23% to 0.22% and from 0.15% to 0.10% for the LEDs on the template and on sapphire, respectively. The EL spectrum peak at 20 mA shifted to lower energy by 17.2 meV for the LED on the template upon increasing temperature, while that for the LED on sapphire shifted by 32.7 meV. The LED on the template exhibited a higher output power and a better thermal stability with respect to the conventional LED on sapphire using a low-temperature GaN buffer layer, which is due to the low threading dislocation density in the active layer and the high thermal conductivity of AlN layer.
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I. INTRODUCTION

GaN-based light-emitting diodes (LEDs) and laser diodes have been introduced to the commercial marketplace. The application of LED technology to fields such as large-screen video display and traffic control is continuously increasing. Because the technology is used outdoors, it must be able to operate under various environmental conditions. Thus, the stability of the LED is very important. Commonly, sapphire is the most used substrate for the GaN-based device growth, and the popular method of growth is to use GaN or AlN films deposited at low temperature (LT) on sapphire substrate as a buffer layer.[1,2] However, the performance of GaN-based electronic and optoelectronic devices is limited by the poor thermal conductivity of sapphire substrate and by the high density of threading dislocations induced by the large mismatch in the lattice constant and the thermal expansion coefficient between the epilayer and substrate.[3] Recently, high-quality GaN-based epilayers were obtained using an AlN/sapphire template instead of sapphire substrate.[4] The performance of the GaN-based devices grown on the AlN/sapphire template was improved.[5,6] In this study, the crystalline quality and the thermal stability of the LEDs grown on the AlN/sapphire template, which consists of 1-μm-thick AlN film grown on sapphire substrate, was studied. In comparison with the conventional LED on sapphire using a LT-GaN buffer layer, the LED on the template exhibited a higher output power and a better thermal stability due to the low threading dislocation density in the active layer and the high thermal conductivity of AlN layer.

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II. EXPERIMENTAL PROCEDURE

An epitaxial 1-μm-thick AlN film was grown on 2-in. *c*-face sapphire substrate at a high temperature using low-pressure metalorganic chemical vapor deposition (MOCVD), which is called AlN/sapphire template.[7] InGaN multiple-quantum-well (MQW) LED structures were grown on the AlN/sapphire template using the Nippon Sanso MOCVD system (SR-2000) under atmospheric pressure. The source materials of Ga, Al, In, and N were trimethylgallium, trimethyaluminum, trimeylindium, and ammonia (NH_3), respectively. Hydrogen was used as a carried gas. Monosilane (SiH_4) diluted in hydrogen was used as an *n*-type dopant, and the *p*-type dopant is bis-cyclopentadienyl magnesium (Cp_2Mg). Prior to the growth of the LED structure, a 2.0-μm-thick n^+-GaN was grown directly on the template at 1180 °C. An 800-nm-thick *n*-GaN layer, an undoped three periods of MQW consisting of 3-nm-thick $In_{0.2}Ga_{0.8}N$ wells and 5-nm-thick $In_{0.01}Ga_{0.99}N$ barrier layers, a 20-nm-thick p-$Al_{0.08}Ga_{0.92}N$ layer at 760 °C, and a 0.2-μm-thick *p*-GaN cap layer at 1180 °C were then grown successively. For a comparison, the same LED structure was grown on sapphire substrate following a 30-nm-thick LT GaN buffer layer and a 3.0-μm-thick n^+-GaN layer. The LEDs on sapphire and on the template were fabricated as follows. The Ti/Al/Ni/Au (16/80/12/60 nm) *n*-type ohmic contact was formed and annealed at 700 °C for 30 s after the surface of *p*-GaN layer was partially etched to the *n*-GaN using reactive ion etching and the thermal annealing was performed at 750 °C for 25 min in an N_2 ambient. A transparent metal Ni/Au (6/12 nm) and a Ni/Au *p*-type contact was deposited and annealed at 600 °C for 3 min. The active area of the LED is about 1.99×10^{-3} cm^2. The characteristics of LEDs were tested

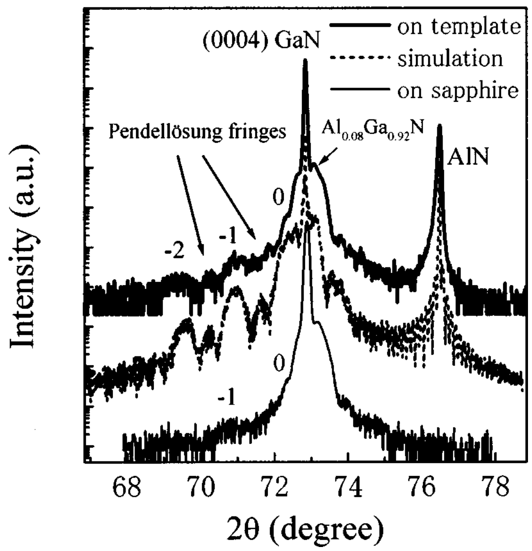

FIG. 1. A comparison of XRD rocking curves in GaN (0004) ω–2θ scan mode between the LED on sapphire and on AlN/sapphire template.

using an on-wafer testing configuration. $I-V$ measurements were carried out using a semiconductor parameter analyzer (Agilent 4155C). Light output power (L) was measured using an optical power meter (Anritsu ML910B). The electroluminescence (EL) spectrum was measured by the optical spectrum analyzer (Anritsu MS9030A and MS9702B). The ambient temperature was controlled by a laser diode controller (ILX Lightwave LDC-3722). Since the air will mist the bare LED chip surface when the temperature is lower than room temperature, the ambient temperature range from 25 to 95 °C was adopted in our experiments. In the case of light output power measurements, the optical detector was set 1.0 cm above the LED surface.

III. RESULTS AND DISCUSSION

A. Crystalline quality

Figure 1 shows a comparison of x-ray diffraction (XRD) rocking curves in GaN (0004) ω–2θ scan mode between the LED on sapphire and on the template. Only the zeroth- and first-order satellite peaks of InGaN MQW can be seen in the experimental curve for the LED on sapphire. On the other hand, the zeroth-, first-, and second-order satellite peaks and the Pendellösung fringes can be seen clearly for the LED on the template, which indicate the high quality of the MQW structures with perfect interfaces. The simulated curve of the LED structure grown on the template fits the experimental one well. The full widths at half-maximum (FWHM) of GaN (0004) ω scan were about 82.8 and 231.6 arcsec for the LED on the template and on sapphire, respectively. The crystalline quality was further demonstrated by the electron-beam-induced current (EBIC) measurement. The EBIC images of the two kinds of LEDs are shown in Fig. 2, for the LED on sapphire [Fig. 2(a)], and for the LED on the template [Fig. 2(b)]. The accelerating voltage of 10 kV and the magnification of 10 k were used. The dark regions in the EBIC images reveal the nonradiative recombination and trapping probably associated with a high dislocation density, resulting in fully depleted minority carrier. The dark grain densities are about 3×10^8 and 5×10^7 cm^{-2} for the LEDs on sapphire and on the template, respectively. Egawa *et al.* reported that the dislocation densities measured by transmission electron microscopy (TEM) were $2-5\times10^9$ and $5\times10^7-3\times10^8$ cm^{-2} for the LEDs on sapphire and on the template, respectively.[5] The dark grain density measured by EBIC is less than the TEM result. This is because the dark grain in EBIC corresponds to a high dislocation density region. The XRD and EBIC results indicated that the LED structure on the template shown a better crystalline quality and more perfect interfaces than the one on sapphire using a LT-GaN buffer layer, which was due to the small mismatch in the lattice constant and the thermal expansion coefficient between the template and the GaN-based epilayers.

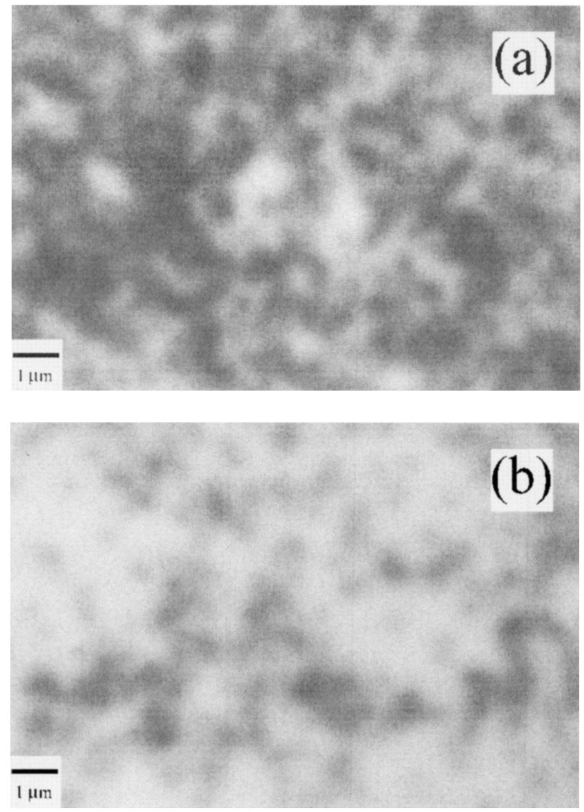

FIG. 2. EBIC images of InGaN MQW LED (a) on sapphire substrate and (b) on AlN/sapphire template.

B. *I–V* characteristics

1. Forward

Figure 3 shows the typical semilogarithmic forward $I-V$ characteristics dependent on ambient temperature, for the LED grown on sapphire [Fig. 3(a)], and for the LED on the template [Fig. 3(b)]. Both LEDs show almost the same operating voltage of 3.6 V at a forward current of 20 mA and the series resistance of 30 Ω at RT. As shown in Fig. 3(a), the LED on sapphire shows three segments in the forward $I-V$ curves. Segment I is the effect of series resistance. Segment II is the diffusion current region. Segment III is the tunneling current region, which is related to the dislocations.[8] The

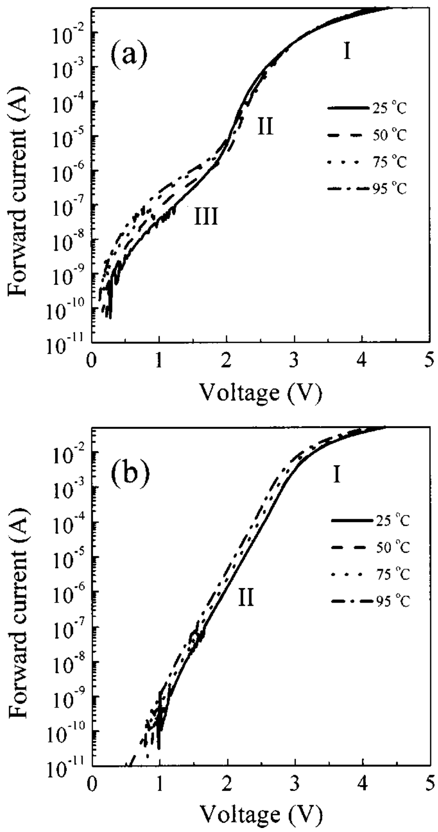

FIG. 3. Forward log(I)–V characteristics of the LED dependent on ambient temperature (a) on sapphire substrate and (b) on AlN/sapphire template.

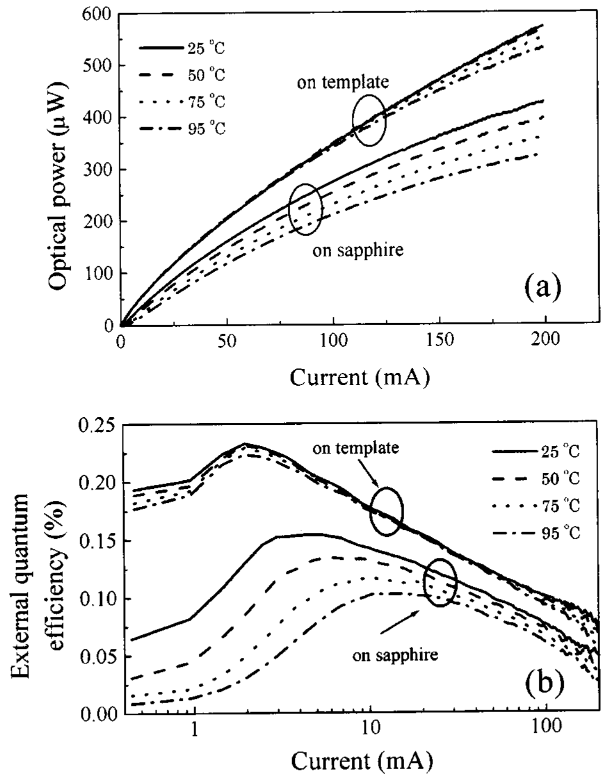

FIG. 5. Temperature dependence of light output power (a) and external quantum efficiency (b) versus current of LEDs on sapphire and on the template.

slopes of segment II and III were changed with increasing temperature. In contrast to the LED on the template, the forward $I-V$ curve exhibits only two segments. The tunneling current region cannot be observed in Fig. 3(b) due to its low dislocation density. Segment II shows a stable slope with increasing temperature.

2. Reverse

The typical semilogarithmic reverse $I-V$ characteristics dependent on ambient temperature are shown in Fig. 4. The leakage current of the LED on the template was an approximate order of magnitude lower than the one on sapphire. This significant improvement originated from the suppression of leakage current due to the low threading dislocation density, as shown in Fig. 2. The leakage current increases with temperature for the LED on sapphire due to its high dislocation density, while for the LED on the template, almost no change can be observed with increasing temperature.

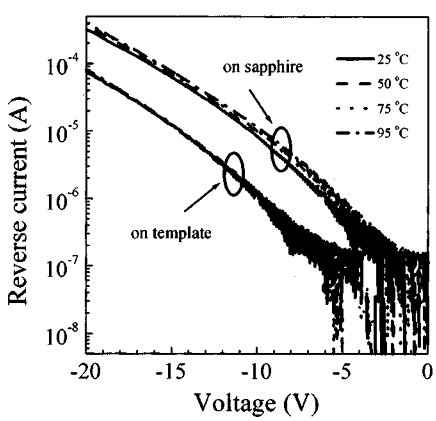

FIG. 4. Reverse log(I)–V characteristics of the LED dependent on ambient temperature (a) on sapphire substrate and (b) on AlN/sapphire template.

C. *L–I* characteristics

The temperature dependence of $L-I$ characteristics of the LED on sapphire and on the template under a dc operation are shown in Fig. 5(a). At 200 mA driving current, the output power decreased by 23.9% for the LED on sapphire upon increasing temperature from 25 to 95 °C. In contrast, there was only a 7.3% decrease for the LED on the template. No optical power decrease can be observed when the driving current is lower than 100 mA for the LED on the template.

The external quantum efficiency (EQE) versus dc driving current at different temperatures are shown in Fig. 5(b). The peak EQE decreased from 0.23% to 0.22% for the LED on the template with increasing temperature, while that of the LED on sapphire decreased from 0.15% to 0.1%. The peak position of the EQE, which is related to the nonradiactive recombination centers, was shifted from 4.45 to 11.45 mA for the LED on sapphire due to the increased nonradiactive recombination at high temperature. In contrast to the LED on the template, the peak position of the EQE was at 1.97 mA, and no shift was observed with increasing temperature. At the same temperature, the output power and the EQE

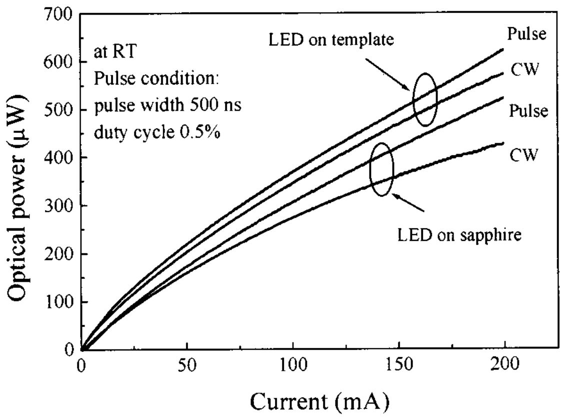

FIG. 6. A comparison of the typical $L-I$ characteristics of the LEDs under pulsed and dc operation.

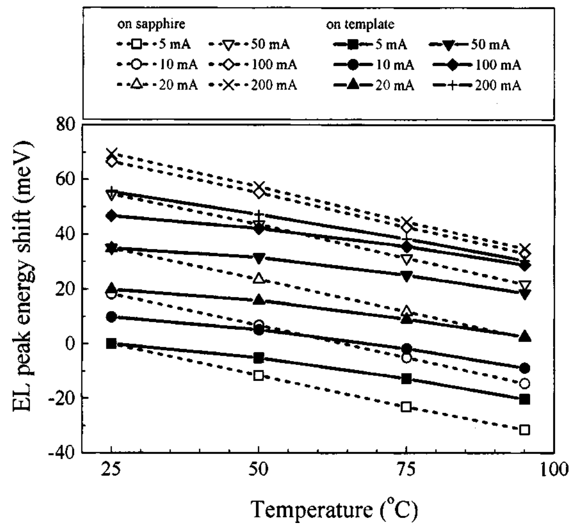

FIG. 7. EL peak energy shift versus ambient temperature at various driving currents. For a clear comparison, the relative shifts were calculated with respect to the peak energy at 5 mA and at an ambient temperature of 25 °C.

of the LED on the template were larger than that of the LED on sapphire. This is due to the low threading dislocation density in the active layer, which acts as a nonradiactive recombination center. A better thermal stability of LED on the template compared to the one on sapphire is due to the presence of high thermal conductivity of the AlN layer.

In Fig. 6, the heat spreading effect of the AlN layer was demonstrated by a comparison of the typical $L-I$ characteristics of the LEDs under a pulsed and a dc operation at RT. The pulse width of 500 ns and the duty cycle of 0.5% were adopted. The effect of heat generation can be ignored under the pulsed operation. The output power under a dc operation is lower than that under a pulsed operation due to the heat effect. In comparison with the pulsed operation, the output power under a dc operation decreased by 18.2% for the LED on sapphire at 200 mA driving current. On the other hand, that for the LED on the template decreased by less than 8%, which is because of the high thermal conductivity of AlN layer, which is of capable spreading the generated heat at the junction quickly.

D. Electroluminescence (EL) spectrum

The relative EL peak energy shift versus ambient temperature at various dc driving currents is shown in Fig. 7. The growth condition and indium composition of the QWs and barriers were same for the two samples. The wavelengths and the FWHMs of the EL spectra at 20 mA and at RT were about 463 and 28 nm, and 467 and 32 nm for the LEDs on sapphire and on the template, respectively. The wavelength of the LED on sapphire is somewhat shorter than that on the template probably due to a growth fluctuation. For a clear comparison, the relative shifts were calculated with respect to the peak energy at 5 mA and at ambient temperature of 25 °C. At the same driving current, the EL peaks of both LEDs show a redshift with increasing temperature due to bandgap narrowing caused by heat generation. However, the degree of the redshift was different for the two samples. At 20 mA, the EL peak shifts to lower energy by about 32.7 meV for the LED on sapphire upon increasing temperature from 25 to 95 °C. In contrast, only a 17.2 meV redshift was observed for the LED on the template. This is due to the heat generated at the junction, which can be quickly spread through the high thermal conductivity of the AlN layer. At the same ambient temperature, the EL peak exhibits a blueshift with increasing the driving current for both LEDs. The blueshift in both LEDs was significant at low driving current, and the speed of the blueshift slowed down at a high driving current due to the compensation of the redshift induced by heat generation. As can also be seen, the degree of blueshift in the LED on the template is smaller than that in the LED on sapphire. At 25 °C, the EL peak blueshifts were about 69.5 and 55.5 meV upon increasing current from 5 to 200 mA for the LEDs on sapphire and on the template, respectively.

There are two kinds of explanations for the blueshift upon increasing the current. One is the band-filling effect of the localized energy states formed by the indium compositional fluctuation.[9–12] Another is the quantum-confined Stark effect (QCSE), which resulted from the piezoelectric fields induced by the lattice mismatch.[13–15] However, the density of localized states in the two samples was almost same since the indium composition of the QWs and barriers was similar in the two samples.[12] The blueshift induced by the band-filling effect will be similar in both samples. Thus, the large difference in the blueshift between the two samples cannot be explained by the band-filling effect. On the other hand, the LED on the template exhibits a smaller strain in the epilayer with respect to the LED on sapphire due to the small mismatch in the lattice constant and the thermal expansion coefficients between the epilayer and AlN layer. It is well known that a larger strain induces a stronger QCSE. As a result, a large blueshift will be seen in the EL spectrum. Therefore, the large difference in the blueshift between the two samples was dominated by QCSE.

IV. CONCLUSIONS

InGaN MQW LEDs were grown on an AlN/sapphire template by MOCVD. High crystalline quality of the LED on the template has been proved by XRD and EBIC measurements. The thermal stability of the LED on the template was demonstrated by the temperature dependence of $I-V$, $L-I$, and EL peak shift measurements. Upon increasing temperature from 25 to 95 °C, the output power at 200 mA from the LED on the template decreased by only 7.3%, the peak EQE decreased from 0.23% to 0.22%, the position of the peak EQE was at 1.97 mA, and no shift was observed with increasing temperature. At 20 mA, the EL peak shifted to lower energy by only 17.2 meV with increasing temperature. In comparison to the LED on sapphire, the LED on the template showed a higher output power and a superior thermal stability due to the presence of high thermal conductivity of the AlN layer and low dislocation density.

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