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Demonstration of an InGaN-based light-emitting diode on an AlN/sapphire template by metalorganic chemical vapor deposition

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Structural, electrical, and optical properties of an InGaN-based light-emitting diode (LED) on an AlN/sapphire template have been studied and compared with the conventional LED properties on a sapphire substrate. In comparison to the LED on sapphire, the LED on AlN/sapphire template has shown better electrical and optical characteristics, which are due to a low threading dislocation density, high resistive, and thermal conductive AlN layer. An additional advantage is to grow a high-quality LED structure on an AlN/sapphire template without using low-temperature-grown GaN or an AlN buffer layer. [DOI: 10.1063/1.1492857]

Recently, major developments in wide band gap III–V nitride compound semiconductors have led to the commercially available high brightness light-emitting diodes (LEDs) and realization of laser diodes.[1,2] These devices mainly have been grown on sapphire substrates using a two-step growth technique, in which a low-temperature-grown AlN or GaN layer is used as a buffer layer.[1–3] However, conventional LEDs grown on sapphire substrates using a low-temperature buffer layer contain a high density of threading dislocations.[4] Reliability of the laser diode and the quantum efficiency of the ultraviolet LED are very sensitive to the threading dislocation density.[2,5,6] Very recently, we have shown that a high-quality GaN layer can be grown using the AlN/sapphire template as a substrate.[7] The AlN layer has been grown on a (0001) sapphire substrate at high temperature by metalorganic chemical vapor deposition (MOCVD). Therefore, if the LED structure will be grown directly on the AlN/sapphire template, many advantages come from the growth of a LED on the AlN/sapphire. The first advantage is that the low-temperature-grown buffer layer is not necessary, which is quite different from the conventional commercially available LEDs on sapphire. The second one is the threading dislocation density in the active layer can be reduced. This results in the improvement of characteristics of the ultraviolet LED and the laser diode. The third one is that the self-heating effects can be suppressed because the thermal conductivity of the AlN layer (2 W/cm K) is larger than that of the GaN layer (1.3 W/cm K) beneath the active layer in the conventional LED. In this letter, we report the first characteristics of the LEDs grown on the AlN/sapphire template and demonstrate good performances. These results come from high-quality multiple-quantum-well (MQW) structure, excellent thermal conductivity, and high resistivity of the AlN layer.

The InGaN MQW LED structures were grown on both the commercially available sapphire substrates with (0001) orientation (*c* face) and the AlN/sapphire templates using the Nippon Sanso MOCVD system (SR-2000) under atmospheric pressure. The AlN/sapphire template supplied from NGK Insulators consists of a 1-μm-thick AlN on a (0001) sapphire substrate.[7] Trimethylgallium (TMG), trimethylaluminum (TMA), trimethylindium, monosilane, biscyclopentadienyl magnesium, and ammonia (NH_3) were used as Ga, Al, In, Si, Mg, and N sources, respectively. The LED on sapphire consists of a 30-nm-thick GaN buffer layer at 500 °C, a 3-μm-thick n^+-GaN layer at 1180 °C, the MQW structure, a 20-nm-thick p-$Al_{0.08}Ga_{0.92}N$ layer at 760 °C, and a 200-nm-thick p-GaN layer at 1180 °C. The MQW structure consists of an 800-nm-thick n-GaN layer, an undoped three period of MQW consisting of 3-nm-thick InGaN wells and 5-nm-thick InGaN barrier layers. The LED on an AlN/sapphire template starts from the growth of a 2.8-μm-thick n^+-GaN layer at 1180 °C and has the MQW structure the same as that of the sapphire substrate. Note that no low-temperature-grown buffer layer was used in the growth of a LED on an AlN/sapphire template. For the growth of n^+-GaN layer, the flow rates of NH_3 and TMG were 5 l/min and 69 μmol/min, respectively. The flow rates of NH_3, TMG, and TMA were 5 l/min, 29.5, and 5.2 μmol/min for the growth of the $Al_{0.08}Ga_{0.92}N$ layer, respectively.

The fabrication process was accomplished as follows. The surface of the p-GaN layer was partially etched to the n-GaN using BCl_3 plasma reactive ion etching (RIE). To active the Mg in the p-GaN layer and also recover the RIE damage in the n-GaN layer, the thermal annealing was performed at 750 °C for 25 min in a N_2 ambient. Next, a Ti/Al/Ni/Au (16/80/12/60 nm) metal was deposited onto the

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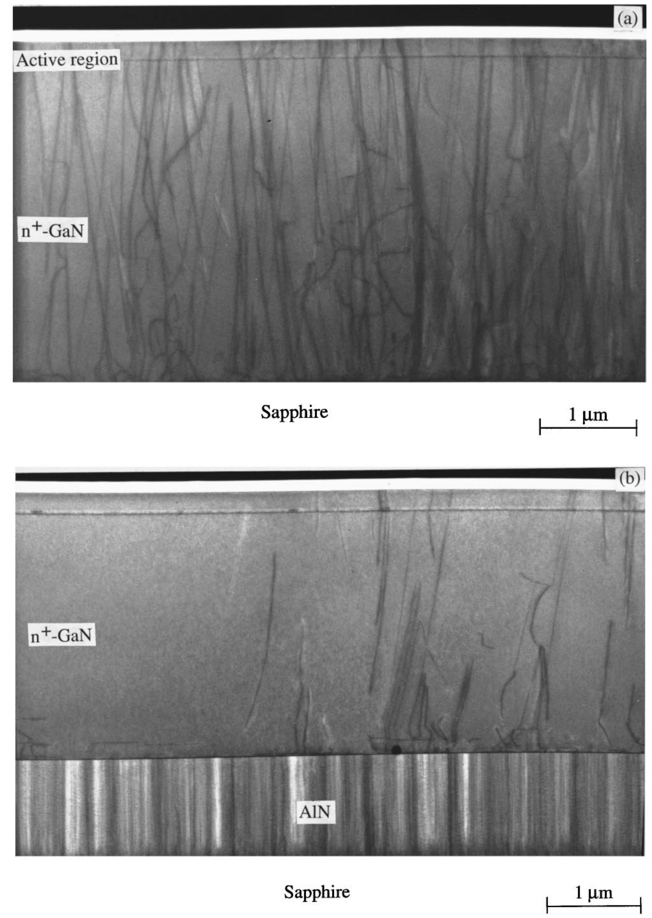

FIG. 1. Bright-field cross sectional TEM images of LEDs grown on (a) a sapphire substrate and (b) an AlN/sapphire template.

n-GaN layer and annealed at 700 °C for 30 s. A transparent Ni/Au (6/12 nm) and a Ni/Au (12/60 nm) metals were deposited onto the p-GaN and annealed at 600 °C for 3 min. $I-V$ measurements were carried out using a semiconductor parameter analyzer (HP 4145B). Light output power and electroluminescence spectra were measured at room temperature using an optical power meter (Anritsu ML910B) and an optical spectrum analyzer (Anritsu MS9702B/MS9030A), respectively. In the case of light output power measurements, the detector was set 1 cm above the surface of a bare LED chip. The LEDs were tested using an on-wafer testing configuration. The active area of the LEDs as 1.99×10^{-3} cm^2.

Figures 1(a) and 1(b) show the cross-sectional transmission electron microscopy (TEM) images of the LEDs grown on the sapphire substrate and the AlN/sapphire template, respectively. In the conventional LED on sapphire, many dislocations were seen as dark lines generating at the GaN/sapphire interface and propagating in a direction normal to the substrate. Most of dislocations were intruded into the active region and some were seen to bend in the n^+-GaN layer. These behaviors are similar to the previously reported result.[4] On the other hand, it is clear that the threading dislocation density can be reduced in the LED grown on the AlN/sapphire template as shown in Fig. 1(b). Although a large number of dislocations were observed in the AlN layer on sapphire, very few dislocations were penetrated into the upper layers. No dislocations were observed in some active regions. Another feature is that some dislocations were moving for a short distance along the AlN/n^+-GaN interface. The dislocation density in the active region is calculated by counting along a plane normal to the growth direction and using the thickness of the TEM sample of 0.4 μm. We conclude that the dislocation densities are $2-5\times10^9$ cm^{-2} for the LED on sapphire and $5\times10^7-3\times10^8$ cm^{-2} for the AlN/sapphire template. Additional studies are required to clarify the mechanism of threading dislocation reduction in the AlN/sapphire template.

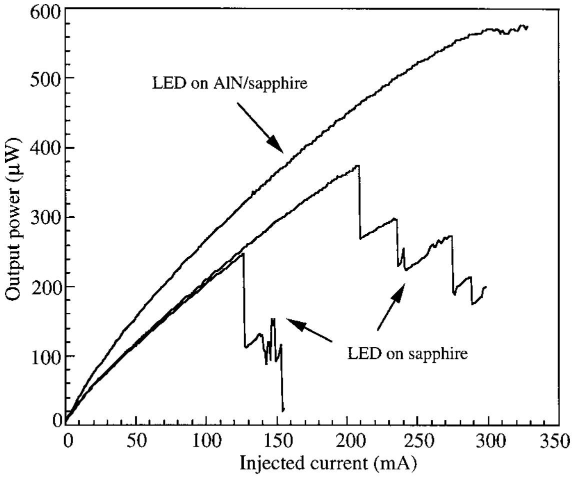

FIG. 2. Comparison of typical $L-I$ characteristics of blue LEDs on sapphire and an AlN/sapphire template. The LEDs have the peak emission wavelength of ~470 nm. The detector was set 1 cm above the surface of a bare LED chip.

The operating voltage and the differential series resistance of both LEDs were about 3.6 V and 30 Ω, respectively, at the forward current of 20 mA. However, the reverse voltages of the LEDs on the sapphire and the AlN/sapphire template were -15 and -28 V for, respectively, at -0.1 mA. Thus, the reverse $I-V$ characteristic was improved using the AlN/sapphire template. This significant improvement comes from the suppression of leakage current due to the low threading dislocation density LED structure as shown in Fig. 1. The comparison of typical light output power–injected current ($L-I$) characteristics of the blue LEDs on sapphire and AlN/sapphire is shown in Fig. 2. The output power at 20 mA was 60 and 79 μW for the LEDs on the sapphire and the AlN/sapphire template, respectively. The output power from the LED on sapphire increased up to 210 mA and dropped suddenly with the increase of injected current. On the other hand, the output power from the LED on the AlN/sapphire template increased sublinearly up to 300 mA and saturated due to the thermal effect. Due to the same value of specific contact resistance of both LEDs, equivalent heat generation will take place at the p and n contacts. Therefore, the reason for the increase of the output power in the LED on AlN/sapphire template at higher injected current is due to the low density of threading dislocations in the active region, which act as the nonradiative recombination centers. Another reason is probably due to the spreading of heat through the high thermal conductive AlN layer, compared to the GaN layer in the conventional LED.

Figure 3 shows the external quantum efficiency as a function of the emission wavelength of the LEDs grown on

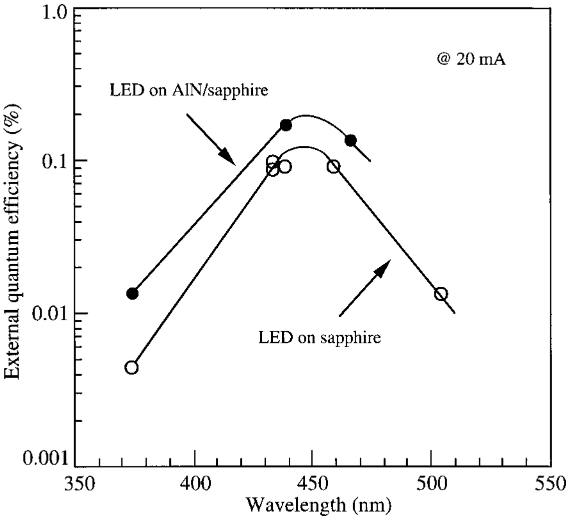

FIG. 3. External quantum efficiency as a function of emission wavelength for the LEDs on sapphire and an AlN/sapphire template. The injected current was 20 mA. The detector was set 1 cm above the surface of a bare LED chip.

the sapphire substrate and AlN/sapphire template at the forward current of 20 mA. The LED on sapphire shows the highest efficiency around at 450 nm and the lower efficiency at the shorter and longer wavelength regions. The low efficiency at the longer wavelength region is thought to be due to the quantum-confined Stark effect. The decrease of efficiency at the shorter wavelength attributes to the lack of localized energy states caused by the fluctuation of In composition.[8] Although the LED on the AlN/sapphire template exhibited the similar tendency to that of the LED on sapphire, the external quantum efficiency of the LED on AlN/sapphire was higher than that of sapphire. In particular, the efficiency at the shorter wavelength was improved by use of the AlN/sapphire template. For instance, the external quantum efficiency was improved from 0.004% to 0.013% using the AlN/sapphire template. The efficiency at a shorter wavelength strongly depends on the nonradiative recombination centers formed by a large number of dislocations because the localization of the energy state is weak at the shorter wavelength region.[8] Therefore, the improved efficiency observed at the shorter wavelength is probably due to the low threading dislocation density as shown in Fig. 1(b).

In summary, we have characterized the InGaN-based LEDs on the AlN/sapphire templates grown by MOCVD. The LED on the AlN/sapphire template exhibited better electrical and optical characteristics than the conventional LED on sapphire. These improvements are attributed to a lower threading dislocation density in the active layer, and also the high resistive and high thermal conductive AlN layer. The low-temperature-grown buffer layer is not necessary for the growth of high-quality LED structure using the AlN/sapphire template. The AlN/sapphire templates are also suitable substrates for the growth of ultraviolet LED and laser diode.

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