Performance enhancement of InGaN light-emitting diodes by laser lift-off and transfer from sapphire to copper substrate

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Laser lift-off technique was employed to carry out transfer of prefabricated InGaN multiple-quantum-well light-emitting diodes (LEDs) from sapphire onto Cu substrate. Silver epoxy was used as the bonding material. Characterization results showed tremendous device improvements in terms of maximum allowable current, light output power, and reliability from the use of conductive Cu substrate. LEDs on Cu could withstand a maximum current of 530 mA before breakdown while those on sapphire could only withstand 350 mA. At 40 mA, light output power of LEDs on sapphire and Cu was 0.74 and 0.95 mW, respectively. In addition, reliability test at constant current of 300 mA showed improvement in light output power for LEDs on Cu whereas LEDs on sapphire suffered deterioration with time.
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Current gallium nitride (GaN) based device technologies include light-emitting diodes (LEDs), laser diodes (LDs), and UV detectors on the photonic side and high temperature microwave power and ultrahigh power switches on the electronic side. With the recent development of high quality GaN crystalline film, there has been rapid progress in the development of high brightness blue LEDs and cw LDs at room temperature.

One problem associated with conventional GaN-based LEDs is the use of nonconductive sapphire substrate. Sapphire is still the most common substrate for the growth of GaN due to its relatively low cost, high temperature stability, similar crystal symmetry with the III nitrides, large band gap, and epi-ready surface quality. Lots of constraints are imposed on the film quality because of the lattice and thermal-expansion coefficient mismatch between the sapphire and GaN. Most important, the poor thermal conductivity of sapphire has prevented efficient dissipation of heat generated by high-current devices, such as LDs and high-power transistors. The high thermal resistance of sapphire substrate and the relatively high current densities combine to degrade the device performance and lifetimes due to excessive heating from the active area during operation. As a result, many research groups have attempted to integrate GaN with other more conductive materials. One advantage of using an electrically conductive substrate is that backside ohmic contacts to GaN-based devices are made possible and this is not attainable with a sapphire substrate.

A more viable means of materials integration for GaN thin films with dissimilar materials is through wafer-bonding and thin-film laser lift-off (LLO) techniques. The process would allow a prefabricated device structure on sapphire to be transferred onto a new host substrate. The LLO process was first demonstrated by Kelly *et al.*[1] with the third harmonic of a *Q*-switched Nd:YAG laser beam directed through the transparent sapphire which can rapidly and effectively separate GaN thin films from its growth substrates. Wong *et al.*[2,3] have also reported pulsed UV laser processing of GaN thin films using a KrF excimer laser at 5 eV of wavelength 248 nm whereby GaN is thermally decomposed at the interface and, thus, separated from sapphire. At this wavelength, it is well above the absorption edge of GaN of 3.4 eV and sapphire is transparent. Characterization of the GaN thin film before and after LLO had shown no detectable degradation of GaN crystal structural, chemical, optical, and electrical quality.[4–6]

Since these first demonstrations, other groups soon reported the transfer of prefabricated GaN LEDs and LDs on sapphire, onto Cu[7–9] and Si[10–14] substrates to improve heat dissipation of the optoelectronic devices. Much work is focused on transferring LEDs onto Si and LDs onto Cu substrates by using Pd–In bonding process,[15] which is a stable high temperature intermetallic bond. Although Tavernier *et al.*[10] attempted transfer of GaN LEDs onto Cu, their results showed deterioration in electrical properties. Here, there was no damage on the LEDs after LLO and transfer. In addition, the highest reported current that was tested on GaN LEDs[13] on sapphire and LDs[9] on sapphire and Cu are 150 and 300 mA, respectively. To our knowledge, reliability of GaN LED has not been studied under high constant current of 300 mA. Furthermore, the maximum current that can be sustained by LEDs on sapphire and Cu after LLO was first reported here.

In this work, InGaN multiple-quantum-well (MQW) LED structures were grown by metalorganic chemical vapor deposition on *c*-face sapphire substrates. The epitaxial layers consist of a 1-μm-thick undoped GaN as buffer layer, a 2-μm-thick *n*-type Si-doped GaN cladding layer of concentration 1×10^{18} cm^{-3}, a five GaN/InGaN MQW active region, and a 0.3-μm-thick *p*-type Mg-doped GaN upper clad-

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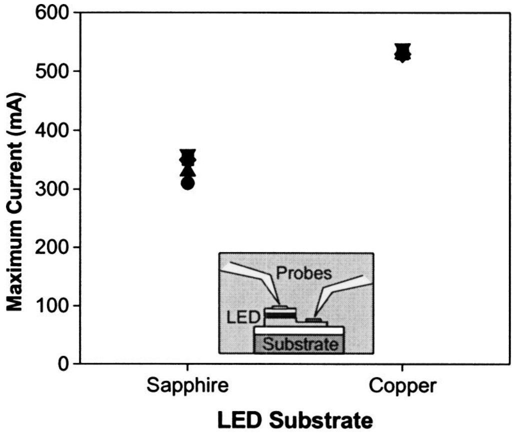

FIG. 1. Maximum allowable current of LEDs on sapphire and Cu substrate before LED breakdown. The inset illustrates probe placements on *p*- and *n*-metal pads during measurement. Five LEDs from each substrate were tested at room temperature and in cw mode. Current was applied from 1 mA and step increased by 10 mA after holding each step for 5 s. This continued until the LED burnt out. The highest current at which the LED burnt out is defined as the maximum allowable current. Results for LEDs on sapphire were more scattered while those on Cu were more consistent. LEDs on Cu were able to withstand a higher amount of current before breakdown.

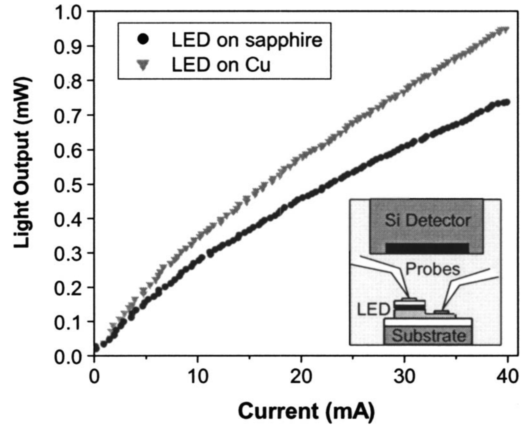

FIG. 2. $L-I$ curves for LEDs on sapphire and Cu substrate. Inset shows the measurement configuration which consists of the Si detector mounted directly above the LED so light emitted from the top surface of the LED was collected by the detector to obtain these results. At 40 mA, the light output for LED on sapphire and Cu was 0.74 and 0.95 mW, respectively.

ding layer of concentration $5\times10^{17}\ \mathrm{cm}^{-3}$. The center wavelength of the InGaN MQW LED is 463 nm. Standard InGaN MQW LEDs of $300\times300\ \mu\mathrm{m}^2$ were first fabricated on the sapphire by photolithography, inductively coupled plasma etching, and thin-film deposition. Before LLO, the sample was cleaved to dimensions of $3\times3\ \mathrm{mm}^2$. LLO was then done to separate the LED thin film from sapphire. In this work, the same LLO method used by Wong *et al.*[3] was used to separate sapphire from the epitaxial layers. A single 600 mJ/cm^2, 23 ns KrF (248 nm) excimer laser pulse was directed through the transparent sapphire substrate. The absorption of the laser at the GaN/sapphire interface induces a highly localized, rapid thermal decomposition of the GaN, producing metallic Ga and N_2 gas.[3] After LLO, heating the interface above 30 °C allows easy separation of the GaN from sapphire and the LED membrane was transferred to Cu substrates using silver epoxy as the bonding material.

Current–voltage ($I-V$) characteristics of the LED were measured before and after LLO and transfer onto Cu. There was no deterioration in the electrical properties of the LED after LLO. Therefore, LLO did not cause any damage to the LED. The LEDs were then tested at room temperature on a probe station and in cw mode. This measurement was done by applying current from 1 mA and step increased by 10 mA after holding each step for 5 s. This continued until the LED burnt out. We define the highest current at which the LED burnt out as the maximum allowable current. This was visually detected as the blue light went off immediately. The results are shown in Fig. 1. The inset illustrates the probe placements on *p*- and *n*-metal pads during measurement. Five LEDs were tested for each type of substrate. It can be seen that results for LEDs on sapphire were more scattered while those on Cu were more consistent. As expected, LEDs on Cu were able to withstand a higher amount of current before they broke down. The excellent thermal conductivity of Cu enabled the LEDs to sustain current as high as 530 mA. The maximum current of 350 mA for sapphire is still way lower than that of Cu. In fact, the Cu substrate acted as a heatsink such that the cooling of LED was much more efficient than on sapphire substrate.

Figure 2 shows the comparison of light output power versus current ($L-I$) results for LEDs on Cu and sapphire. The inset shows the measurement configuration that was employed during the light output power measurements. It consists of the Si detector mounted directly above the LED and current was applied through the probes. The detector above thus collected light emitted from the top surface of the LED. Obviously, LEDs on Cu produced stronger light output power than that of sapphire. At 40 mA, the light output for LED on sapphire and Cu was 0.74 and 0.95 mW, respectively. It was about 29% stronger. This is again attributed to the superior thermal conductivity of Cu. The results again proved the work of Wong *et al.*[7–9] that Cu is a much more promising substrate than sapphire because the thermal impedance was reduced and light output power was increased for devices on Cu rather than sapphire. Mathine *et al.*[16] also transferred GaAs vertical-cavity surface-emitting lasers (VCSELs) from their original GaAs substrates to Cu substrates and their results showed a doubling of the light output power and a 20% reduction in the thermal impedance. The external quantum efficiency at 40 mA was calculated[17] to be about 0.73% and 0.44% for LED on copper and sapphire, respectively. In comparison with the work of Wong *et al.*,[18] the values presented here are relatively lower. This may be due to the low epitaxial quality of the original wafer which was commercially purchased and also the device fabrication processes that were not yet optimized.

Light output power versus time was measured to study the reliability of the LEDs on Cu and sapphire substrates. The extreme conditions under the test were able to differentiate the distinctive performance of a conductive substrate from a nonconductive one. The applied current was high enough to cause deterioration to the LEDs in a short period of time. Constant current of 300 mA was applied to the LEDs on both sapphire and Cu substrates. The light output power was then monitored for 60 min. The results are shown in Fig. 3. First, the output power of LED on Cu is stronger than that of sapphire. At the beginning, its light output power was 36% stronger than that of sapphire (1.90 versus 1.41

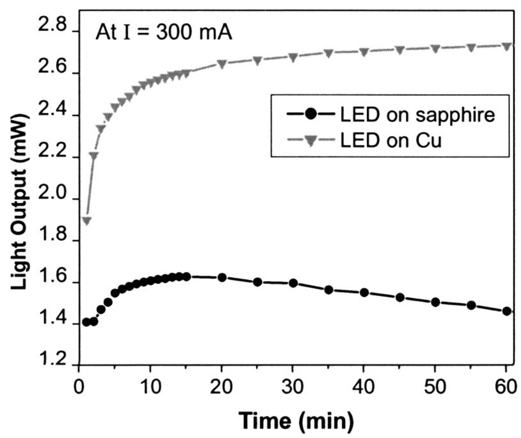

FIG. 3. Reliability testing of LEDs on sapphire and Cu substrate. Constant current of 300 mA was applied to the LED for 60 min. At the beginning, light output power of LEDs on Cu was 36% stronger than that of sapphire (1.90 vs 1.41 mW). At the end of 60 min, this value shot to 87% (2.73 vs 1.46 mW). This disparity was brought about by the steady increase in light output for LED on Cu and also the deterioration of LED on sapphire with time.

mW). However, at the end of 60 min, this value shot to 87% (2.73 versus 1.46 mW). This drastic gap was brought about by the steady increase in light output for LED on Cu and also the deterioration of LED on sapphire with time.

It was noted that the output power of LED on Cu steadily increased with time rather than deteriorated like that of sapphire. There were two possible explanations for this increase, which is an indication that the quality of the LED on Cu actually improved with time. First, the superior thermal conductivity of Cu helped in the efficient dissipation of heat such that the LED continued to withstand such high current without any degradation. As a result of this, there might be electrical annealing on the GaN LED while steady current was being applied. It was reported that the electrical annealing may cause a reduction in point-defect recombination centers in the MQW of GaInP VCSELs[19] and, thus, improve device performance.[19,20] For GaN, it is well known that thermal annealing improves its crystal quality dramatically.[21] In this case, the application of high current may actually benefit the LED with similar advantages of thermal annealing.

In the first 15 min, there seemed to be some electrical annealing effect on the LED on sapphire as its light output increased slightly. However, degradation of the LED took over for the next 45 min. Due to the poor thermal conductivity of sapphire, it is clear that the current had caused so much heating in the LED that degradation of the LED dominated for much of the 60 min. On the other hand, if current lower than 300 mA was applied, the LED on sapphire may benefit from the electrical annealing. When current as high as 300 mA was applied to the LED continuously, an intense amount of heat was generated within the LED. If this amount of heat was not dissipated quickly enough, the LED would be overheated and damaged in a short period of time. As seen from the previous results, the role of the substrate plays a vital role in ensuring efficient heat dissipation. For sapphire, since it is not a conductive material, the heat will be localized and trapped for a longer time. Excessive heating in the LED will reduce the quantum efficiency and enhance diffusion of impurities as well as migration of dislocations.[22] In addition, its lifetime will reduce at higher temperature. That is why the LED started to deteriorate with time. This indeed emphasizes the outstanding performance of Cu as a substrate for GaN LED. Cu indeed is a promising material for the substrate of applications which demand high power and high temperature capabilities. In addition, Cu offers an added degree of freedom in device configuration. The excellent heatsink property of Cu substrate has directly improved the performance of the GaN devices and the devices can be reconfigured into a vertically connected device with back side contacts.

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