Transfer of GaN-Based Light-Emitting Diodes From Silicon Growth Substrate to Copper

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***Abstract*—III-nitride light-emitting diodes (LEDs) grown on Si (111) substrates have the potential of low-cost manufacturing for solid-state lighting and display, by taking advantage of the well-developed IC technologies of silicon. In this letter, LEDs grown on silicon substrates were transferred onto copper substrates, to maximize light extraction and heat dissipation. On Si substrates, 300 × 300 μm^2 multiple quantum well InGaN LEDs were first grown and processed. The top surface of the fabricated devices was then temporarily bonded to a sapphire wafer and the Si substrate was chemically etched. Ti/Al/Ti/Au layers were deposited on the backside of LEDs. An 80-μm-thick copper layer was electroplated and the temporary bonding was removed, resulting in LEDs on copper substrate. The optical output power of LEDs on copper increased by ∼70% as compared to that of the LEDs on silicon. The improved performance was attributed to the removal of the light-absorbing Si substrate and the good thermal conductivity of copper.**

***Index Terms*—Copper, GaN, light-emitting diode (LED).**

I. INTRODUCTION

NITRIDE-BASED light-emitting diodes (LEDs) grown on silicon (111) substrates have been studied extensively [1]–[4]. Compared with sapphire substrate that has been widely used for GaN-based LED growth, the Si substrate allows much lower manufacturing cost particularly for large-area (6- to 12-in) applications, and processing simplicity for the low- and mid-end LED markets. However, the light extraction efficiency of LEDs grown on Si usually suffers from the light-absorbing property of Si substrates. Nearly half of the light emitted downwards from the active region is absorbed by the substrate [5], resulting in low efficiency, serious energy loss, and heating issues. To minimize the absorption of light in the substrate, inserting a distributed Bragg reflector (DBR) between the substrate and the LED structure is one of the methods [6]. However, it is usually difficult to achieve a crack-free DBR with high reflectivity, due to the strict requirements on the epitaxial growth imposed by the relatively large lattice and thermal mismatch. Another option is to transfer grown LEDs from the absorptive substrate to a light-reflecting substrate or a substrate with mirror structures on top. The transfer of nitride films from original sapphire substrates to copper substrates has been demonstrated [7]–[9]. Due to the lack of a well-developed chemical etchant for sapphire, the laser liftoff technique is commonly used to remove the sapphire substrate, at the expense of high manufacturing cost, poor uniformity, and damage to LED films. In contrast, the separations of nitrides films from silicon substrate could be implemented by wet chemical etch. GaN-based LEDs grown on Si (111) substrate have been transferred onto copper substrate by a selective liftoff process combined with mechanical polishing of the original Si substrate [10].

In this letter, a double-flip approach was utilized to transfer LEDs from a silicon substrate to a copper substrate. Fabricated LEDs on Si substrate were bonded to a temporary substrate as the first flip. After the silicon removal by chemical etching, the devices were transferred to a copper substrate by electroplating, as the second flip. Therefore, after the double-flip process, the LEDs maintained the same orientation (p-side up) as those before transfer. Furthermore, all the device fabrications are made on the Si substrate right after growth, and no further device fabrication processes are required after the transfer. This could significantly improve the process yield and reliability. The transferred LEDs showed significant improvement on the light output power and thermal dissipation.

II. EXPERIMENT

Multiple quantum well (MQW) blue LED structures were grown on silicon (111) substrates by metal–organic chemical vapor deposition [1]. From the Si substrate to the top surface, the LED structure consisted of a thin nucleation layer, a 0.8-μm-thick undoped GaN layer, an AlN/AlGaN interlayer, a 1-μm-thick Si-doped n-GaN layer, five periods of InGaN/GaN MQWs, and a 200-nm-thick Mg-doped p-GaN layer. A SiO_2 mask grown by plasma-enhanced CVD was used for inductively coupled plasma etching. 300 × 300 μm^2 mesas were patterned by standard photolithography and etched down to the n-type GaN. Ni (5 nm)/Au (5 nm) current spreading layer was deposited on the p-GaN surface by electron-beam evaporation, followed by annealing in an atmospheric ambient at 570 °C for 5 min. Then, Ti (30 nm)/Al (70 nm)/Ti (10 nm)/Au (50 nm) multimetal layers were evaporated to form the p- and n- electrodes. The finished device structure is shown in Fig. 1(a).

After the standard LEDs fabrication process, the double-flip process was used to transfer the fabricated LEDs onto a copper substrate with the device orientation unchanged. On the entire front device surface, a polyimide layer was spin coated and baked up to 180 °C for 4 h, to protect the LEDs

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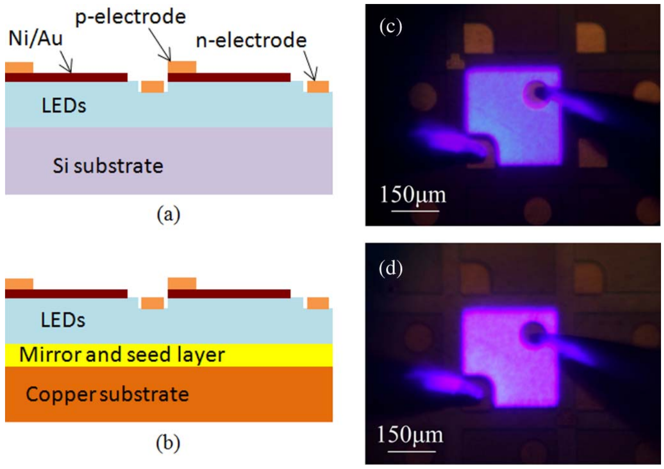

Fig. 1. Schematic of (a) standard LEDs on silicon and (b) standard LEDs transferred to copper substrate. Emission image of 300 × 300 μm^2 LED (c) on silicon and (d) on copper substrate at 5 mA.

during Si wet etching. Subsequently, the device side of the wafer was temporarily bonded to a sapphire wafer using wax (Apiezon Wax W). The bonded structure was put into an HNA solution ($HF : HNO_3 : CH_3COOH = 1 : 2 : 3$) for 40 min to completely remove the Si substrate. After etching, Ti (5 nm)/Al (150 nm)/Ti (10 nm)/Au (100 nm) metal layers were deposited on the exposed back side of the LEDs using electron-beam evaporation. Aluminum served as a reflective mirror and Au acted as a seed layer for subsequent copper electroplating. An 80-μm-thick copper was electrodeposited as the new substrate for the LEDs. The temporarily sapphire wafer was debonded from the LEDs on a hot plate, and the wax residue was removed by trichloroethylene. The protective polyimide was removed in an organic resist stripper (MS2001) at 70 °C. Thus, as the second flip step, the LEDs were flipped from the temporary sapphire to a copper substrate and the final structure of LEDs on copper is shown in Fig. 1(b).

Current–voltage (I–V) characteristics of LEDs were measured using an HP 4155A semiconductor parameter analyzer. To measure the light output power before and after transfer, a spectrometer (Ocean Optics USB2000) and an integrating sphere were utilized, and the LED samples were diced and wire bonded on transistor-outline cans. All the device characterizations were conducted on more than ten LED devices throughout the entire sample (typically 1 cm × 1 cm). It was observed that both the silicon sample and copper sample had good uniformity over most area of the sample and the data presented below are all representative values.

III. RESULTS AND DISCUSSION

The light emission images of LEDs on silicon and on copper are shown in Fig. 1(c) and (d), respectively. Both samples exhibited relatively good uniformity of light emission, while the one on copper had higher brightness at the same injection current of 5 mA.

Fig. 2 shows the I–V characteristics of the LEDs on silicon substrate and on copper substrate with reflective mirror. The forward voltages of LEDs driven at 20 mA on silicon and on copper substrate were 4.30 and 4.78 V, respectively. It is believed that the increase of forward voltage was caused by the degradation of metal contact resistivity during the 180 °C polyimide solidification process. This is confirmed by the fact that the forward voltage of LEDs on silicon substrate also increased by ~0.50 V when they were baked with the same condition as used in the polyimide solidification process. The similar thermal degradation of Ni/Au/p-GaN ohmic contact was reported [11], in which the degradation of contacts was related to the reduced conductivity of NiO component of the contact metallization [11], [12]. The optimization of the solidification conditions of polyimide could further suppress the contact degradation.

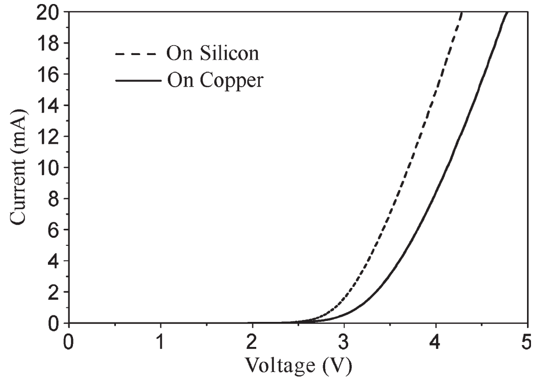

Fig. 2. Current–voltage characteristics of LEDs on Si and on copper substrate.

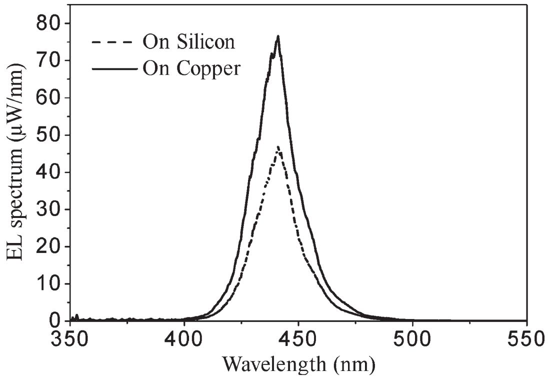

Fig. 3. EL spectra of LEDs on Si and on copper substrate at 20 mA.

The electroluminescence (EL) spectra of the LEDs on silicon and on copper substrate at 20 mA are shown in Fig. 3. It is obvious that the wavelength of the emitted light remained at ~442 nm, almost unchanged after the double-flip transfer process. This indicates that the transfer process used in this letter did not introduce extra stress in the LED films. The light output power of the LED on silicon before substrate removal was 1.18 mW, which increased by 70% to 2.00 mW for the copper sample. In this letter, the reflectivity of the Ti/Al/Ti/Au mirror layers was measured to be 73% at the wavelength of 440 nm. As a reference, the reflectivity of an untreated single crystalline silicon (111) surface was measured to be 43% at 440 nm, which is consistent with previously reported number [5]. The reflectivity of the silicon substrate in the LED samples is likely to be different from bulk silicon due to the change of silicon surface morphology during high-temperature

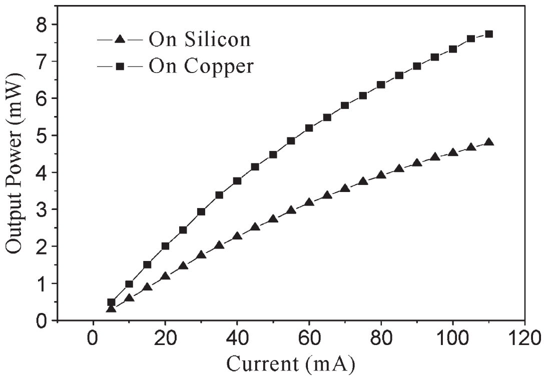

Fig. 4. Light output power versus injection current (L–I) characteristics of LEDs on Si and on copper substrate.

LED structure growth. However, the 70% improvement on the optical output power at relatively low-level injection current (20 mA) should be mainly attributed to the removal of the silicon substrate and the use of a mirror structure containing highly reflective aluminum. The improved thermal conductivity of copper is believed to play a more significant role on the light output power at higher injection currents where the heating issue is more serious.

For high-brightness and high-power applications, the LEDs are required to operate at high injection currents. Consequently, lots of heat will be generated that will seriously degrade the performance of LEDs when the heat cannot be dissipated efficiently. Furthermore, the excessive heating in the LEDs will reduce the quantum efficiency and enhance the diffusion of impurities as well as migration of dislocations. Therefore, thermal conductivity of the substrate is crucial to the lifetime and performance of LEDs. The thermal conductivity of silicon is $148\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ while it is $400\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ for copper [13].

Fig. 4 shows the light output power versus injection current (L–I) characteristics of the LEDs on silicon and copper. LEDs on copper substrate showed distinct improvement on the light output power over a wide range of injection currents as compared with those on silicon. The thickness of the copper substrate in this letter was 80 μm only and a thicker copper substrate could further improve the heat dissipation of LEDs. In fact, by varying the electroplating time, the thickness of the final copper substrate can be easily adjusted for different applications. In this letter, the thickness of the copper has been changed from 20 μm for flexible applications to a few hundred micrometers for good thermal dissipation.

IV. CONCLUSION

In summary, III-nitride-based blue LEDs grown on silicon (111) substrate were transferred onto a copper substrate, using a double-flip process. The light output power of LEDs on copper increased by about 70% as compared with that of LEDs on Si over a wide range of injection currents. With Si being used as the growth substrate, and copper as the final substrate, the demonstrated LED transfer process provides the advantages of low cost, high yield, high reliability, and flexibility.

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