Performance improvement of GaN-based light-emitting diodes grown on patterned Si substrate transferred to copper

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Abstract: LEDs on Si offer excellent potential of low cost manufacturing for solid state lighting and display, taking advantage of the well-developed IC technologies of silicon. In this paper, we report how the performance of LEDs grown on Si can be improved. Multiple quantum well InGaN LED structure was grown on patterned silicon substrates and circular LEDs 160 µm in radius were processed. Fabricated LEDs were then transferred to an electroplated copper substrate with a reflective mirror inserted by a double-flip transfer process, to improve the light extraction efficiency and heat dissipation. The light output power of LEDs on copper increased by ~80% after the transfer. The operating current before the onset of light output power saturation also increased by 25% because of the good thermal conductivity of copper. The light output power of packaged LEDs on copper was 6.5 mW under 20 mA current injection and as high as 14 mW driven at 55 mA.

OCIS codes: (230.3670) Light-emitting diodes; (230.0250) Optoelectronics.

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1. Introduction

Compared with sapphire substrates that are widely used for GaN-based LED growth, Si substrates allow for much lower manufacturing cost, especially if large-area (6- to 12-inch) substrates are adopted, and advantage of IC-like processing are taken for the low- and mid-end blue, green and white LED markets. III-nitride based light-emitting diodes (LEDs) grown on silicon (111) substrates have been investigated in the past [1–3]. However, the large mismatches in lattice and thermal expansion coefficient causing cracks on GaN film remain a major issue. Patterned Si substrates have been used to facilitate small area growth and hence relieving the stress in the discontinuous GaN film [4]. Another major drawback of using Si as substrate is that the light extraction efficiency of LEDs suffers from the light-absorbing property of Si. Almost half of the light emitted downward from the active region is absorbed by the substrate [5], resulting in low external quantum efficiency. To minimize the absorption of light in the substrate, a reflector can be placed between the substrate and the LEDs. Light emitting from the active region towards the substrate will then be reflected and can escape from the top surface. Insertion of an AlN/AlGaN Distributed Bragg Reflector (DBR) between the substrate and the LED structure is one of the common methods [6]. However, it is even more challenging to grow a crack-free LED and DBR with high reflectivity due to the stringent requirements on the epitaxial growth imposed by the relatively large lattice and thermal mismatch. Furthermore, such long growth time would be highly uneconomical for commercialization even achievable technologically. Another method is to transfer the grown LEDs from the absorptive substrate to a light-reflecting substrate or a substrate with mirror structures on top. For LEDs grown on sapphire, Laser Lift-Off (LLO) technique is commonly used to remove the sapphire substrate [7,8], at the expense of higher manufacturing cost, lower yield, and possible damage to the LED film. In contrast, separation of nitride films from silicon substrate could be easily implemented by chemical wet etching. GaN-based LEDs grown on Si (111) substrate have been transferred onto copper substrate by a selective lift-off process combined with mechanical polishing of the original Si substrate [9]. Copper substrate can significantly improve the heat dissipation of the LEDs, enabling large-area and high power applications of LEDs.

In this work, a double-flip approach was utilized to transfer LEDs from its original silicon substrate to a copper substrate. Fabricated LEDs grown on patterned Si substrate were bonded to a temporary sapphire substrate as the first flip. After the silicon removal by chemical etching, the back side of the devices was covered with an evaporated mirror followed by an electroplated copper substrate, serving 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 processing 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.

2. Experiments

Multiple quantum well (MQW) blue LED structures were grown on 2-inch silicon (111) substrates by metal-organic chemical vapor deposition (MOCVD) in an Aixtron 2000HT system. Prior to the growth, the Si substrates were patterned with circular islands 250 μm in radius, separated by 3.5-μm deep trenches using an STS ICP-RIE Si deep etch system.

The substrates were heated up to 1130 °C for 5 minutes under an H_2 ambient to remove the native oxide. An HT-AlN (HT for "High-Temperature") nucleation layer was grown on the Si substrate at the same temperature, followed by the deposition of a SiN_x in situ mask for 110 seconds. 1 µm undoped-GaN buffer layer was then grown using an ammonia flow modulation method [10]. An 8-pair superlattice consisted of 6 nm HT-AlN/25nm HT-AlGaN was inserted to reduce the tensile stress. The LED structure which consists of 2 µm n-GaN, 5 periods of InGaN/GaN blue MQWs, 30 nm p-AlGaN electron blocking layer and 200 nm p-GaN was grown on top of the buffer. The entire GaN epitaxial layer structure is schematically shown in Fig. 1(a). The deep trench as shown in Fig. 1(b) shows isolated GaN growth on the silicon island, to avoid accumulation of tensile stress on the entire wafer, resulting in crack-free GaN epi-layer. This patterned growth method is also favorable for scaling to large size silicon wafers in terms of strain management.

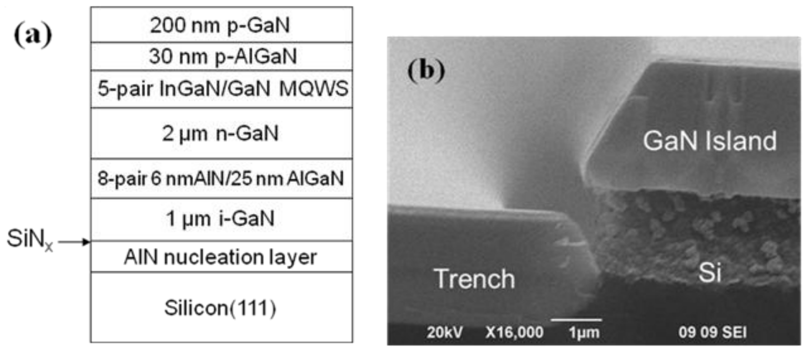

Fig. 1. Schematic diagram of LEDs structure grown on Si substrate (a) and SEM image of GaN island on patterned Si substrate (b).

LEDs were fabricated on the circular GaN islands correspondingly. During the processing, a SiO_2 mask grown by plasma-enhanced CVD was used for inductively coupled plasma (ICP) etching. 160 µm in radius circular mesas were patterned by standard photolithography and etched down to the n-GaN by ICP etching. Ni (5 nm)/Au (5 nm) current spreading layer was deposited on the p-GaN surface using electron-beam evaporation, followed by annealing in an atmospheric ambient at 570°C for 5 minutes. Then, Ti (30 nm)/Al (70 nm)/Ti (10 nm)/Au (50 nm) multi-metal layers were evaporated to form the p- and n- electrodes. The finished device cross-section is shown in Fig. 2(a). The p-electrode is at the center of the LED with a ring-shape n-electrode surrounding the mesa as shown in Fig. 2(b).

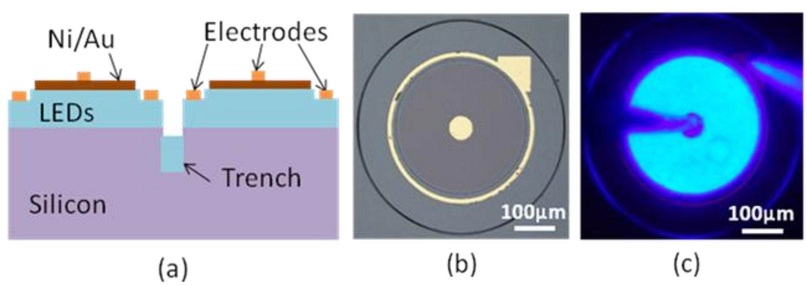

Fig. 2. (a) Schematic diagram of fabricated LEDs on Si. (b) Microscope picture of a circular LED with 160 µm in radius mesa on Si. (c) Emission image of a circular LED on Si at 5 mA.

After the standard LED device fabrication, a double-flip process was used to transfer the fabricated LEDs onto a copper substrate with the device orientation unchanged (p-side up). On the front surface of the fabricated devices, a polyimide layer SDR-PI-5 was spin-coated and baked up to 210°C for 4 hours, to protect the LEDs during Si wet etching. The trenches between the LEDs were also filled with polyimide, which prevented the etching solution permeating into front side of the LEDs through the trenches during Si 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:

#145863 - $15.00 USD
Received 13 Apr 2011; accepted 2 Jun 2011; published 1 Jul 2011

3) for 40 minutes 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 e-beam evaporation. The aluminum serves as a reflective mirror and the gold serves as a seed layer for subsequent copper electroplating. The thin titanium layer improves adhesion between the epi-layer and copper substrate. A 100-µm thick copper was electroplated as the new substrate for the LEDs, and the wax residue was removed by trichloroethylene (TCE) afterward. The protective polyimide was removed in an organic resist stripper (MS2001) at 70°C. Thus, with the second flip step, the LEDs were transferred from the temporary sapphire to the plated copper as substrate and the final structure of LEDs on copper is shown in Fig. 3(a). The color of the LEDs changed from gray on silicon substrate to more silvery on copper substrate as shown in Fig. 3(b), this was because the light absorptive silicon was removed and a reflective metal mirror was inserted between the LEDs and copper substrate.

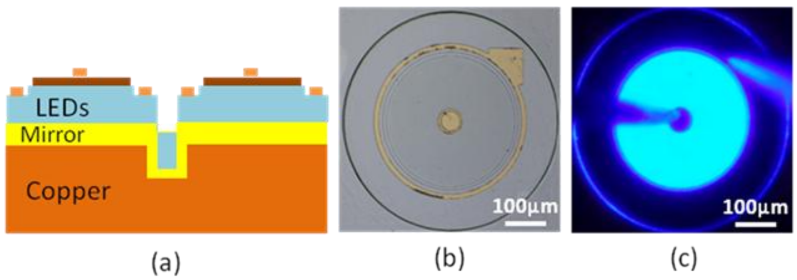

Fig. 3. (a) Schematic diagram of fabricated LEDs on Cu. (b) Microscope picture of a circular LED with 160 µm in radius mesa on Cu. (c) Emission image of a circular LED on Cu at 5 mA.

Current-voltage characteristics of LEDs were measured using an HP 4155A semiconductor parameter analyzer. A spectrometer (Ocean Optics USB2000) and an integrating sphere were utilized to compare LED characteristics before and after transfer. The LED samples were diced and wire-bonded on transistor-outline (TO) cans for output power measurements. All the device characterization was conducted with more than ten LED devices throughout the entire sample (typically 1.5 cm × 1.5 cm). It was observed that both the silicon and copper substrates had good uniformity over most area of the sample and the data presented below are representative values.

3. Results and discussion

The light emission images of LEDs on silicon and on copper with low current drive are shown in Fig. 2(c) and Fig. 3(c), respectively. Both samples exhibited good uniformity of light emission, while the one on copper had higher brightness at the same injection current of 5 mA. Figure 4 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 3.7 V and 4.0 V, respectively. It is believed that the increase of forward voltage was caused by degradation of the metal contacts during the polyimide solidification process at 210°C. This is confirmed by another experiment that increased forward voltage of LEDs on silicon substrates was observed when they were baked with the same condition as used in the polyimide solidification process. Similar thermal degradation of Ni/Au/p-GaN ohmic contact was reported [11], in which the deterioration of contacts was related to the reduced conductivity of NiO component of the contact metallization [11,12]. The increase of forward voltage can be eliminated by replacing the polyimide with other protection materials and further experimentation. The reverse leakage current of LEDs at −5 V on silicon and copper was in the same order of magnitude, this implies that no damage on the LED was caused by the transfer process.

Received 13 Apr 2011; accepted 2 Jun 2011; published 1 Jul 2011

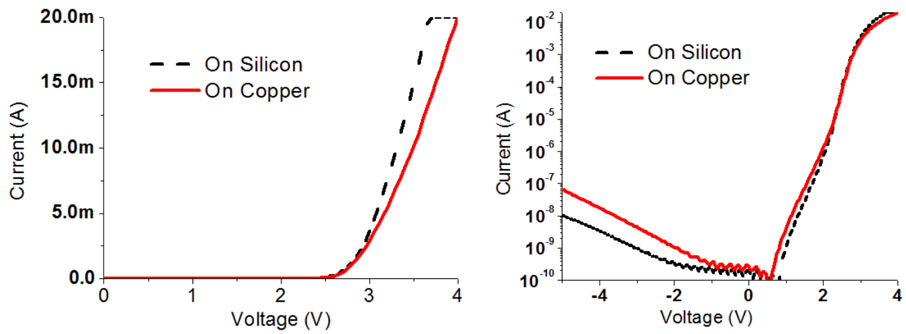

Fig. 4. Current-voltage characteristics of LEDs on Si and on copper substrate.

The electroluminescence (EL) spectra of LEDs on silicon and on copper substrates at 20 mA are shown in Fig. 5(a). It is obvious that the emission wavelength at 460 nm is unchanged after the double-flip transfer process, indicating no extra stress was introduced to the LEDs. The light output power of the LED on silicon before substrate removal was 1.4 mW, which increased by ~80% to 2.5 mW for the copper sample. The reflectivity of Al metal layer was reported to be higher than 90% at 460 nm [13], while the reflectivity of an untreated silicon surface was reported to be ~45% at 460 nm [14]. 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 the high-temperature LED structure growth. However, the 80% 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 output power at higher injection currents where the heating issue is more serious.

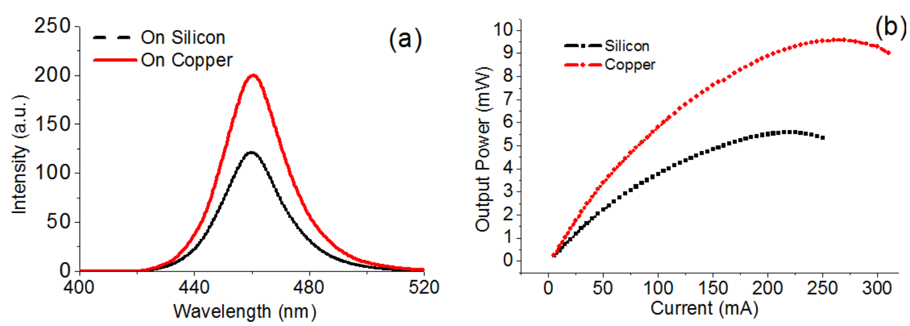

Fig. 5. (a) EL spectra of LEDs on Si and on copper substrate at 20 mA. (b) Light output power versus injection current (L-I) characteristics of LEDs on Si and on copper substrate.

For high-brightness and high-power applications, LEDs are required to operate at high injection currents. Consequently, a significant amount of heat is generated that seriously degrades the performance of LEDs when the heat cannot be dissipated efficiently. Furthermore, excessive heating in the LEDs reduces the quantum efficiency and enhance the diffusion of impurities as well as migration of dislocations. The thermal conductivity of silicon is 148 $W{\cdot}m^{-1}{\cdot}K^{-1}$ while it is 400 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for copper [15]. By transferring LEDs from Si to copper substrate, improved device performance and longer life-time can be expected.

Figure 5(b) shows the light output power versus injection current (L-I) characteristics of the LEDs on silicon and on copper. The LEDs were mounted on a heat sink to avoid heat accumulated inside the packages. LEDs on copper showed distinct improvement on the output power over a wide range of injection current as compared with those on silicon. The LEDs on

Received 13 Apr 2011; accepted 2 Jun 2011; published 1 Jul 2011

copper could be driven with > 250 mA injection current without light output power saturation, while the LEDs on silicon saturated at around 200 mA. It should be pointed out that the thickness of the final copper substrate can be easily adjusted for different applications by varying the electroplating time. The thickness of the copper can be changed from 20 µm for flexible applications to a few hundred micrometers for good thermal dissipation.

Finally, the LEDs on silicon and on copper were packaged as shown in Fig. 6(a). The light extraction efficiency of GaN LEDs is low because the reflective index of GaN differs greatly from that of the air. The emitted light is trapped inside the GaN due to the total internal reflection. The light extraction efficiency could be improved significantly by LED packages and/or surface roughening. The LEDs were mounted and wire-bonded to commercial high power LED packages with a reflector cup. Silicone OE-6550 from Dow Corning was used to encapsulate and serve as a hemispherical lens of the LED. The light output power of the LED on copper increased from 2.5 mW on TO cans to 6.5 mW under 20 mA current injection after packaging. The large improvement was attributed to the silicone lens and the reflector cup. Silicone has a high refractive index and high optical transparency, such that more light can be escaped from the GaN to the air. The hemispherical lens as shown in Fig. 6(b) makes the angle of incidence of light at the silicone-air interface is always normal, as a result, total internal reflection does not occur at the silicone-air interface. Up to 14 mW of output power was measured when driven with 55 mA.

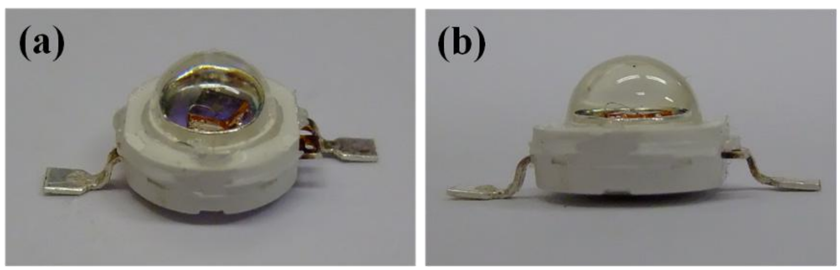

Fig. 6. (a) Packaged LEDs on copper substrate. (b) Lateral view of packaged LEDs with hemispherical lens.

4. Conclusion

In summary, GaN-based blue LEDs grown on patterned silicon substrate were transferred onto a copper substrate, using a double-flip process. In chip form, the light output power of LEDs on copper increased by about 80% as compared with that of LEDs on Si over a wide range of injection current. The light output power of the LEDs grown on silicon increased almost 5 times from 1.4 mW to 6.5 mW with 20 mA injection after the transfer process and packaging. With Si used as the growth substrate, and copper as the final substrate, the demonstrated LED transfer process shows advantages of low cost, high yield, high reliability, and flexibility of LEDs grown on Si.

Acknowledgment

This work was supported in part by the Research Grants Council under Grant 615705 and in part by the Innovation and Technology Commission of the Hong Kong Special Administrative Government under Grant GHP/034/07GD. The authors would also like to acknowledge the Advanced Photoelectronic Technology Ltd. (APT) for the supporting of packaging materials.