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Light extraction enhancement from GaN-based thin-film LEDs grown on silicon after substrate removal using HNA solution

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One of the promising methods to obtain high optical output power from LEDs grown on Si is to eliminate the absorptive Si substrate. In this paper, we report how GaN-based thin-film LEDs grown on silicon (111) substrates by MOCVD were successfully transferred to a copper substrate by room-temperature electroplating and how the original Si substrate was removed by HNA solution. After fabrication, the III-nitride LED thin films showed no cracks or degradation. And the light output power of LEDs after Si removal increased by ~ 30% compared with conventional ones before the Si removal.

1 Introduction

GaN based light-emitting diodes (LEDs), grown on silicon (111) substrates have been investigated because Si substrates have many advantages such as low manufacturing cost, large size, and better thermal conductivity over sapphire substrates [1-3]. However, there are two main problems to be overcome for improving the performance of LEDs directly grown on Si: (1) large mismatch in the lattice constant and thermal expansion coefficients between GaN and Si often causes GaN thin films to crack [4]; (2) with a smaller bandgap, Si substrates absorb the light emitting downward by the multiple quantum wells, resulting in serious optical loss. It was estimated that nearly half of the light from the active region is absorbed by the Si substrate [5].

The first problem was widely investigated and crack-free GaN films grown on Si have been achieved by various growth techniques. Patterned Si substrates have been used to facilitate small area growth by relieving the stress in the discontinuous GaN films [6, 7]. To overcome the second problem, one of the techniques is to insert an AlN/AlGaN Distributed Bragg Reflector (DBR) between the substrate and the active layer [8, 9]. Highly reflective GaN-based DBR requires many pairs of AlN/AlGaN layers because of small refractive index difference between AlN and GaN. However, this is limited by the total critical thickness of the III-N film on Si in practice because cracking becomes a serious issue with increasing layer thickness. Furthermore, the additional MOCVD growth time defeats the original motivation of low-cost manufacturing. Another option is to remove the original substrate and transfer the GaN-based LEDs onto other reflective and more conductive substrates. For LEDs grown on sapphire, Laser Lift-Off (LLO) technique is the most commonly used method to remove the sapphire substrate, leading to higher manufacturing cost and lower device yield [10].

In this work, we describe a new and cost-effective method of removing the Si substrate completely by wet-chemical etching and adaptation of a room-temperature electroplated Cu as a new substrate. The process began with the deposition of a thin current spreading layer (Ni/Au), and then polyimide passivation. After defining a metal contact hole in the center of each die, a thick copper layer was electroplated to connect all the p-GaN together, forming a common p-electrode. Protecting the copper substrate with wax, the sample was put into a HNA solution to remove the Si substrate completely. After Si removal, the buffer layers were selectively etched by an ICP system with a SiO_2 mask to expose the n-GaN and to deposit metal contact. The LEDs fabricated on Cu show excellent features of crack-free, enhanced and uniform light-emitting characteristics.

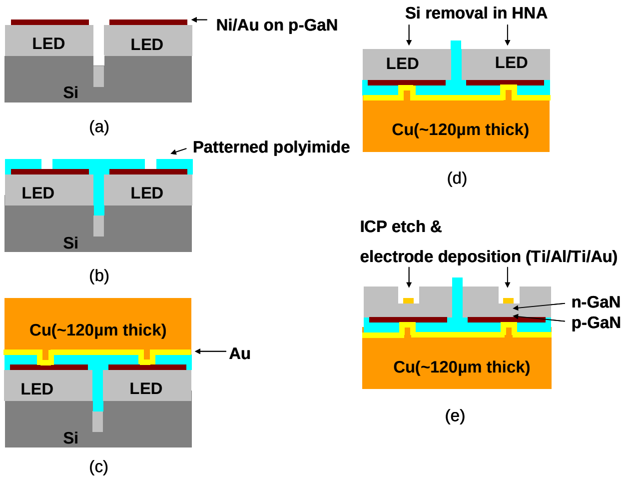

Figure 1 Schematic diagram of LEDs on Cu substrate process: (a) current spreading layer deposition; (b) polyimide passivation; (c) Cu layer electroplating; (d) Si removal in HNA; (e) undoped GaN etching & n-type contact deposition

2 Experiment

Before growth, 2-in (111)Si substrates were patterned with square islands 500 x 500 μm^2 in size, separated by 3-µm deep and 20 µm wide trenches using an STS ICP-RIE Si deep etch system. Conventional GaN-based multiple quantum well blue LED structures were grown on the patterned silicon substrates by metalorganic chemical vapor deposition (MOCVD) [7]. From the Si substrate to the top surface, the 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, 5 periods of InGaN/GaN MQWs and a 200-nm-thick Mg-doped p-GaN layer. Activation of the p-GaN contact layer was done at 800°C for 5minutes. After growth, the LEDs were transferred from the original Si (111) substrate onto plated-Cu used as a new substrate as described below. Firstly, a thin Ni/Au (5nm/5nm) current spreading layer was deposited onto the p-GaN layer by e-beam evaporation, followed by annealing in an atmospheric ambient at 570 °C for 5 minutes. Then a layer of polyimide was coated using a spin-coater to cover the surface and fill the trenches between LED dies. Small square openings (80 µm×80 µm) were defined for electrical connection by photolithography. The rest of the polyimide was hardened by gradually ramping the temperature from 150 °C to 250 °C in 4 hours. Afterwards, a 3000 Å-thick Au as electroplating seed layer was sputtered, and Cu electroplating was carried out immediately for 6 hours, achieving a 120 µm thick Cu layer on top of the LEDs. Then, the Cu was protected by Apiezon wax, and the sample was put into an HNA (HF: HNO_3: CH_3COOH=1:2:3 in volume ratio) solution for about 40min to remove the Si substrate completely. The LEDs were still firmly attached to the copper through the relatively soft polyimide layer. After the Si removal and with the p-GaN facing downward, a layer of SiO_2 was deposited on top of the GaN buffer layers by Plasma-enhanced chemical vapour deposition (PECVD) as mask for contact opening. The undoped GaN buffer layer was selectively removed by Inductively Coupled Plasma (ICP) etching using $BCl_3/Cl_2/He$ plasma to expose the n-GaN with patterned SiO_2 as etching mask. Finally, a Ti/Al/Ti/Au (30/70/10/50nm) multi-metal layer was evaporated to form the n-electrodes. A Schematic of the complete process is shown in Fig. 1.

Conventional LEDs grown on Si substrates were also fabricated as a baseline comparison without substrate removal. To measure the light output power, LED samples were diced and wire-bonded on TO cans. Measurements of output power were carried out using a spectrometer (Ocean Optics USB2000) and an integrating sphere at room temperature.

3 Results and discussion

Figure 2 are micrographs of a fabricated LED. Both the optical and SEM photos indicated that the LED film was completely transferred from the Si substrate to the new Cu substrate without introducing any cracks. The solidified polyimide can prevent the LEDs from being electrically shorted during metal sputtering and Cu electroplating, as well as protecting the thin current spreading layer from the attack of the HNA solution.

Figure 3(a) compares the light emission of an LED on silicon (left) and on copper substrate (right) under a microscope at 10 mA current injection. The LED on Cu showed good luminance uniformity and higher light output power.

Room temperature electroluminescence (EL) measurements show that the optical power of LEDs on Cu is around 30% higher at the same injection current compared with conventional LEDs on Si without substrate removal. The output power improvement is attributed to removal of the absorptive Si substrate, and light reflection to the top from the gold layer underneath the LED. Furthermore, as

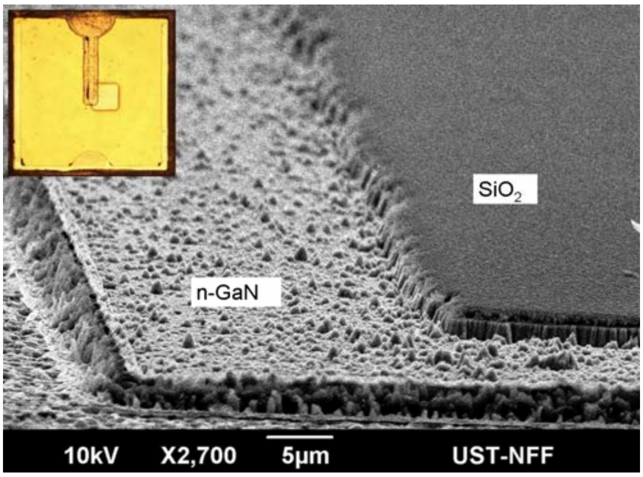

Figure 2 SEM picture of a corner of LED on Cu and ICP selective etching using SiO_2 as mask. The inset is a bird view of a fabricated LED on Cu.

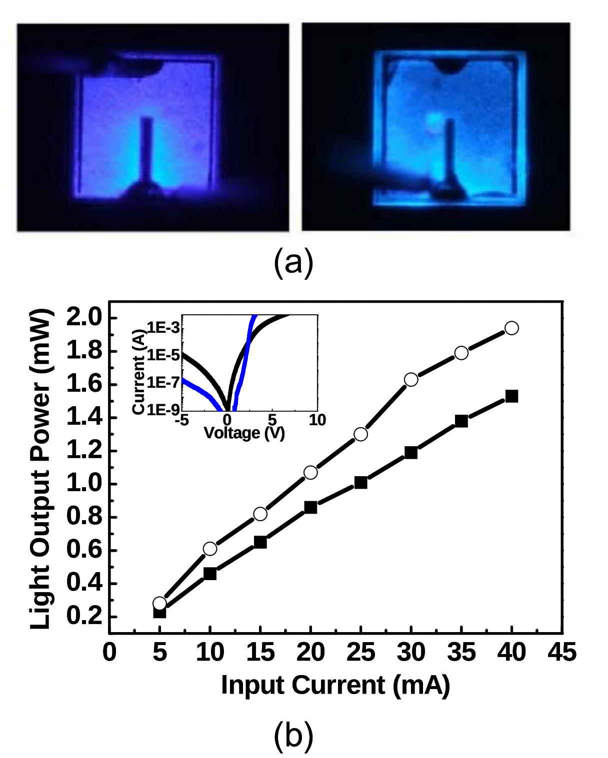

Figure 3 (a) Emission image comparison between LED on Si (left) and LED on Cu (right), under the same current of 10 mA and device dimension of 500 x500 μm^2; (b) L-I characteristics of LEDs on Si (dots) and on Cu (circles); the inset is the I-V characteristics of the LED on Si (blue) and LED on Cu(black).

	Peak Wavelength (nm)	FWHM (nm)
LED on Si	474 nm	26.44
LED on Copper	482 nm	30.53

Table 1 Comparison of peak wavelength and FWHM of lighted LEDs at 20 mA.

SiO_2 was kept on top of the device after serving as dry etch mask, which could result in less total internal reflection (TIR) inside the GaN and extract more light out of the LED because the refractive index of SiO_2 (~1.5) lies between that of GaN (~2.4) and air(~1.0). Uniform light-emitting should also benefit from the vertical LED configuration.

After the transfer from Si substrate onto Copper, it is noticed that the wavelength of the LED red-shifted by 8 nm (Table 1). And the amount of red shift was independent of current injection conditions. This shift may be caused by tensile stress introduced during the polyimide baking step and following the copper layer electroplating process. This phenomenon will be further investigated. And the increased FWHM might be related to some minor damage on the GaN layer during the ICP etch step.

4 Conclusion

In conclusion, GaN-based thin-film LEDs grown on silicon (111) substrates were successfully transferred to a copper substrate by room-temperature electroplating and HNA wet etching. After Si removal, vertical LEDs with the p-side down configuration were fabricated. LEDs on Cu show excellent physical features (crack-free), with improved and uniform light emission. The optical output power of LEDs on Cu substrate increased by ~ 30% compared with conventional ones on Si without substrate removal. This enhancement can be attributed to elimination of the absorptive Si substrate, light reflection from the Au layer and the use of SiO_2 intermediate layer between GaN and air.

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References

[1] S. Guha and N.A. Bojarczuk, Appl. Phys. Lett. **72,** 415-417 (1998).
[2] A. Dadgar, M. Poschenrieder, and O. Contreras, Phys. Status Solidi A **192**, 308-313 (2002).
[3] B. Zhang, T. Egawa, H. Ishikawa, Y. Liu, and T. Jimbo, Jpn. J. Appl. Phys. **42**, 226-228 (2003).
[4] S. J. Lee, G. H. Bak, S. R. Jeon, S. H. Lee, and S. M. Kim, Jpn. J. Appl. Phys. **47**, 3070–3073 (2008).
[5] W. Zhou, M. Tao, L. Chen, and H. Yang, J. Appl. Phys. **102,** 103105 (2007).
[6] A. Dadgar, M. Poschenrieder, J. Blasing, K. Fehse, A. Diez, and A. Krost, Appl. Phys. Lett. **80**, 3670-3672 (2002).
[7] B. Zhang, H. Liang, Y. Wang, Z. Feng, K. W. Ng, and K. M. Lau, J. Cryst. Growth **298,** 725-730 (2007).
[8] R. Butte, E. Feltin, J. Dorsaz, G. Christmann, J. F. Carlin, N.Grandjean, and M. Ilegems, Jpn. J. Appl. Phys. **44**, 7207–7216 (2005).
[9] H. Ishikawa, K. Asano, B. Zhang, T. Egawa, and T. Jimbo, Phys. Status. Solidi A **201**, 2653-2657 (2004).
[10] Y. Sun, T. Yu, Z. Chen, X. Kang, S. Qi, Semicond. Sci. Technol. **23,** 125022 (2008).