Vertical LEDs on Rigid and Flexible Substrates Using GaN-on-Si Epilayers and Au-Free Bonding

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***Abstract*— Vertical-injection light-emitting diodes (VLEDs) were fabricated and demonstrated on mechanically rigid and flexible substrates using GaN-on-Si epilayers and a cost-effective Au-free Cu/Sn bonding method. With a mirror layer between the VLEDs and the receptor Si(100) carrier, 500 μm × 500 μm VLEDs emit up to 134-mW optical power at a drive current of 300 mA. The peak wall-plug efficiency was 23% at 1-A/cm^2 current injection density. Due to excellent heat dissipation of the metal and Si carrier, the VLED junction temperature was measured to be only 47.5 °C at a working current density of 350 mA/mm^2 and increased by 0.27 °C per 1-mA current increment. After release from the rigid substrate, the 40-μm-thick Cu/Sn/Cu bonding layer can also work as a handling substrate to paste LED thin films onto flexible substrates, including plastic and paper. The self-contained VLED structure exhibited the original I–V characteristics and high brightness on various substrates. The results attest to the feasibility of using GaN-on-Si epilayers and Cu/Sn/Cu bonding for a wide range of applications, including low-cost solid-state lighting and flexible illuminations.**

***Index Terms*— Au-free bonding, GaN LEDs grown on Si, rigid and flexible substrates, vertical LEDs.**

I. Introduction

GaN/InGaN light-emitting diodes (LEDs), with their high internal quantum efficiency, low-power consumption, and long lifetime, are widely used in applications, such as indication lights, display, general illumination, and so on [1]–[4]. In the last decade, to lower the cost of LED manufacturing, the growth technology of GaN on inexpensive and large area Si substrates has been developed [5]–[8]. In spite of the large lattice constant and thermal expansion mismatch between GaN and Si, great advances have been achieved in growing high-quality GaN-based LEDs on Si substrates [6], [9]. Considering the light-absorptive properties of a Si substrate, it is preferred to fabricate vertical-injection LEDs (VLEDs) with light-reflective mirrors and/or a roughened surface to significantly increase light extraction [10]–[13]. To fabricate VLEDs, a key step is to bond LEDs onto a carrier substrate using a metal-based soldering layer. Au-based metal combinations, such as Au/In [11], Ti/Au [14], and Au/Sn [15], are commonly used as the bonding layers for transferring the LED thin film onto a Si carrier.

Despite the attractive performance demonstrated by VLEDs using Au-based bonding layers, the high cost of depositing micrometer-thick Au is an important obstacle for the development of cost-effective solid-state lighting. Furthermore, the use of Au is not compatible in a Si production line. Thus, in recent years, there has been a trend to develop Au-free metallization schemes to allow the fabrication of GaN-on-Si devices, e.g., the development of a high electron mobility transistor [16]–[18] in standard CMOS lines to make full use of production facilities and to further lower production cost.

Flexible LEDs (FLEDs) made of III-N materials [19]–[22] can be an alternative to organic LEDs in applications, such as deformable displays, wearable electronics, and biomedicine (e.g., optical-stimulation cochlear implants) [22], with a longer lifetime, a wider operating temperature range, and better reliability. There have been a number of reports about the fabrication of FLEDs using GaN-on-sapphire epilayers. Chun *et al.* [23], [24] reported transferring LEDs grown on sapphire to a polyimide flexible substrate. However, a few studies have been devoted to the fabrication of FLEDs using GaN-on-Si epilayers [25], in particular, the fabrication of vertical-injection FLEDs using LEDs grown on large area and inexpensive Si substrates. The fabrication of FLEDs using LEDs-on-sapphire typically involves a laser liftoff process, which needs a laser blocking layer to prevent unwanted damage to the flexible substrate [24]. The use of LEDs-on-Si epilayers not only benefits from mature Si removal processes, such as grinding and wet/dry etching, but also mitigates device damage by the laser and makes the large area fabrication possible.

Cu/Sn-based metal bonding, as a type of Au-free bonding, has been widely used in metallic bonding for various purposes, e.g., 3-D chip stacking [26], device fabrication [27], [28], and thin-film transfer [29]. However, the Cu/Sn-based bonding method has not been applied in the fabrication of the VLED using GaN-on-Si epilayers. In this paper, we report the fabrication and device results of VLEDs on mechanically rigid Si substrates using GaN-on-Si epilayers and a gold-free Cu/Sn/Cu soldering layer. Applying the same technique, VLEDs on flexible substrates (plastic and paper) using GaN-on-Si are also reported for the first time. The superior characteristics of VLED on various substrates, including low leakage current, high wall-plug efficiency (WPE), high saturation current, and low junction temperature, show that the VLEDs reported

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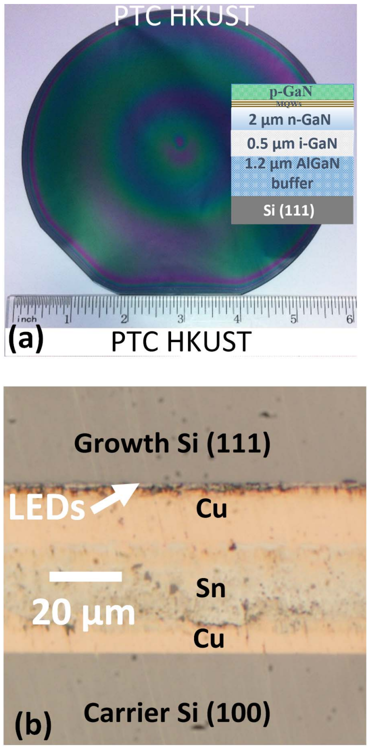

Fig. 1. (a) GaN LEDs grown on a 6-in Si substrate. (b) Cross-sectional image showing LED growth substrate bonded with a Si(100) carrier using a Cu/Sn/Cu metal bonding layer.

here have great potential in fabricating low-cost yet high-performance lighting fixtures for various applications.

II. Material and Fabrication Details

The GaN LEDs used in this paper were grown on a 6-in Si(111) substrate by AIXTRON Flip Top 1 × 6-in closed couple showerhead metal organic chemical vapor deposition (MOCVD) reactor, equipped with LayTec's EpiCurve-TT *in situ* monitor. The epilayers included a 1.2-μm-thick graded AlGaN buffer, a 500-nm-thick undoped GaN layer, a 2-μm-thick Si-doped n-type GaN layer, ten pairs of InGaN/GaN multiple quantum wells, and a 120-nm Mg-doped p-type GaN [Fig. 1(a)].

The process steps of VLEDs on a Si(100) carrier are briefly described as follows: a square mesa of LEDs was isolated by etching GaN epilayers in trenches down to the Si(111) growth substrate. Then, the sidewalls of the LED mesas were passivated by depositing a layer of SiO_2 using plasma-enhanced chemical vapor deposition. Next, a layer of Indium tin oxide (ITO) was deposited by an e-beam evaporator and annealed to form transparent ohmic contact with p-GaN. Subsequently, a layer of Al-based metal layer was deposited on top of ITO as a mirror layer and a seed layer, on which selective electroplating of Cu and Sn was carried out on individual LED mesas. Then, the wafer was flipped upside down and bonded to a Si(100) carrier which has been preelectroplated with Cu and Sn. The thermocompression bonding process was conducted by heating the samples to 280 °C and applying a pressure of 15 N/cm^2. After metal bonding, the original Si(111) growth substrate was grinded down to 150-μm thick and eventually eliminated by inductively coupled plasma (ICP) etching using SF_6-based gas. After further removal of the AlN/AlGaN buffer layer by dry etching, the n-GaN layer was exposed and roughened by dipping the sample into 60 °C 6-M KOH for 2 min. The whole process was finished by depositing a layer of Ti/Al-based metal as n-electrode. For the fabrication of VLEDs on flexible substrates, the Si(100) carrier was replaced by a SiO_2/Si(100) carrier, in which the SiO_2 layer acts as a sacrificial layer for lifting VLEDs-on-metal off the rigid Si(100) substrate. Then, the VLEDs on the metal foil could be pasted onto flexible substrates, such as plastic and paper substrates through an adhesive layer.

III. Results and Discussion

After MOCVD growth, the epitaxy quality and the surface morphology of the LED-on-Si(111) epitaxial structure were examined by high-resolution X-ray diffraction (XRD) and atomic force microscopy, respectively. The full-width at half-maximum of the XRD rocking curves were 440 and 553 arcsec for (002) and (102) orientations, respectively, showing a good crystalline quality for optoelectronic devices. The LED also showed a very smooth surface with a root mean square roughness of only 1.4 nm for a 10 × 10 μm^2 scan area.

A. VLEDs on Rigid Si(100) Carrier

Fig. 1(b) shows a cross-sectional image of a Cu/Sn/Cu bonding layer, through which an LED sample grown on Si(111) was bonded onto a Si(100) carrier. The total bonding metal thickness is ~40 μm, which could be obtained within 1 h by electroplating simultaneously on both the LED surface and the Si carrier surface. At a current density of 20 mA/cm^2, the electroplating rate of Cu and Sn is 20 and 48 μm/h, respectively, which is much faster than the deposition rate of an e-beam evaporator. As shown in Fig. 1(b), no voids were observed for the bonding interface, which provided firm support for the LED thin-film process and LED operations.

Fig. 2(a) schematically shows the fabricated VLED devices on a rigid Si(100) carrier using a Cu/Sn/Cu soldering layer or VLEDs on bonding metal foil pasted onto flexible substrates. As shown in Fig. 2(b) and (c), the VLED surface (n-GaN) was covered by high-density 1-μm high domes after the process steps, including Si grinding and elimination, AlN/AlGaN buffer removal by BCl_3/Cl_2 etching, and KOH roughening. The textured surface would help reduce total internal reflection (TIR) at the GaN/air interface, which is one main limiting factor of light extraction efficiency.

To make comparisons between VLEDs on the Si(100) carrier and planar LEDs on the growth Si(111) substrate, LEDs with a dimension of 320 μm × 320 μm were used. As shown in Fig. 3, at 20 mA, the operating voltages of the VLED and the planar LED on Si was 3.50 and 3.73 V, respectively. The I–V curves also show that the VLED structure has a series resistance of 17.7 Ω, which is much smaller than 31.3 Ω in the planar LED structure. The lower forward voltage and the series resistance in the VLED were attributed to better current spreading in the p-GaN layer, because the whole p-GaN was in contact with thick electroplated bonding metals as

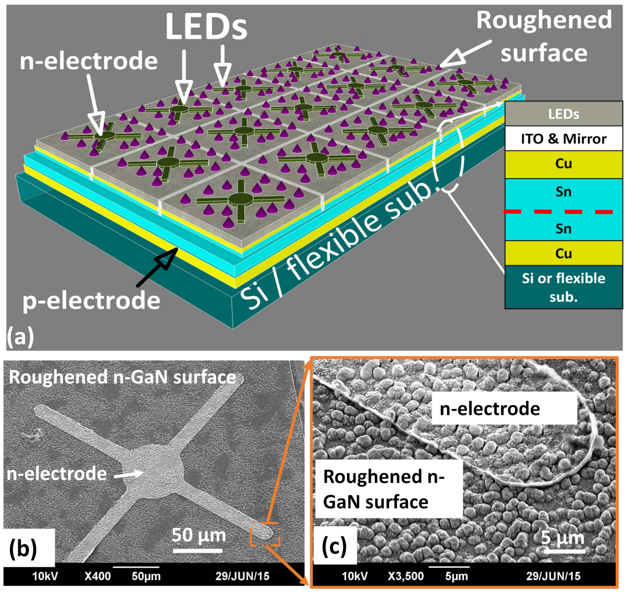

Fig. 2. (a) Schematic of VLEDs on a Si carrier or flexible substrates with roughened surface and top n-electrode. (b) Plan view SEM image of fabricated VLED surface. (c) Zoomed-in view of roughed LED surface and n-electrode.

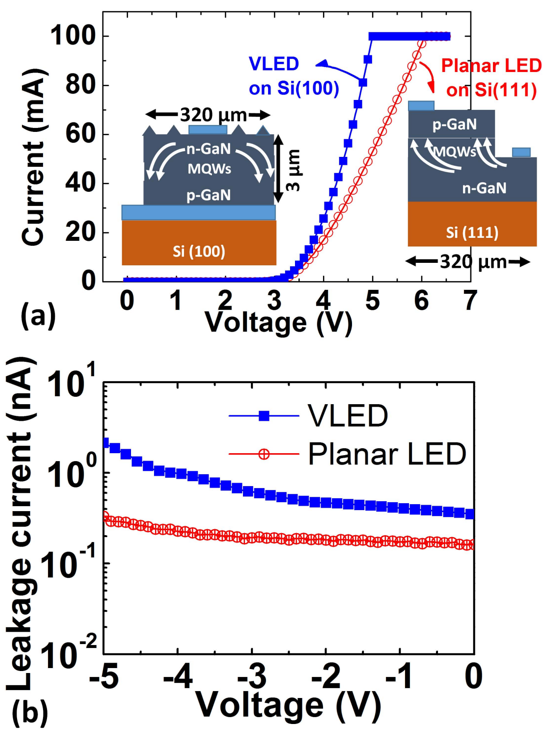

Fig. 3. Current–voltage characteristics for VLED and planar LED on Si in (a) forward voltage range and (b) reverse voltage range. The schematics of two kinds of LEDs are also included.

a p-electrode to improve the innate high resistivity of the p-GaN layer. In addition, the much smaller transverse resistance in the VLED structure also facilitated the reduction in the total series resistance. When reversed-biased, both LEDs showed very low leakage currents, which were measured as −2.2 and −0.3 nA at −5 V. The slightly increased leakage current in VLED was attributed to damage during the ICP etching process.

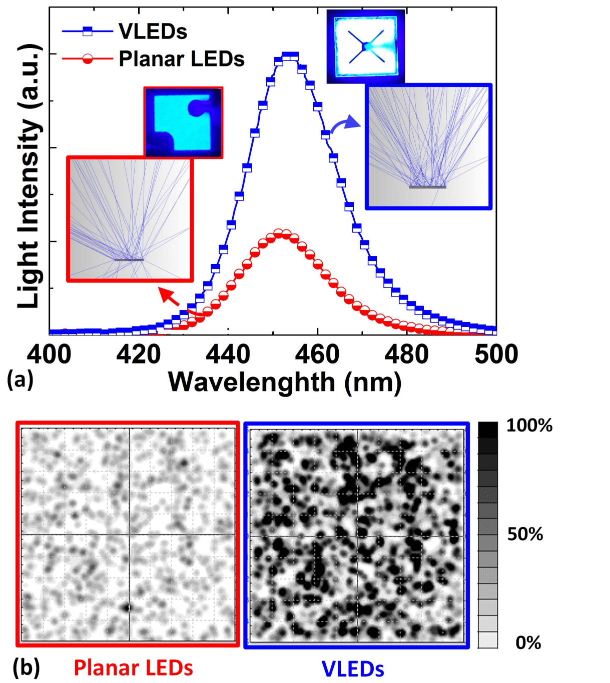

Fig. 4. (a) Emission spectra of VLED and planar LED on Si at 20 mA. Insets: comparison of radiant flux for two LEDs. (b) Irradiation maps from two LED surfaces using a ray-tracing simulation software.

Fig. 4(a) shows the measured emission spectra of a 320 μm × 320 μm VLED on the Si carrier, and a planar LED on the original growth Si substrate. At 20 mA, the light output power (LOP) of the VLED was 2.9 times of that from the planar LED. This optical power improvement can be attributed to light reflection and the textured n-GaN surface. As the downward-emitting light could be effectively reflected by the Al-based mirror layer instead of being absorbed by the Si, and photons could easily escape from the textured GaN surface rather than being reflected back due to TIR, the light extraction efficiency was significantly enhanced. A more detailed device comparison indicated that a VLED with a textured surface emitted ∼40% more blue light than a VLED with a smooth surface [30]. In summary, the Si substrate removal and mirror insertion could roughly double the LOP while a textured surface further enhanced the optical power by ∼40%. Fig. 4(b) shows the irradiance distribution from two LED surfaces by ray-tracing simulation. The total light flux ratio out of the devices for planar LEDs and VLEDs is 1.2:4.2, which matches well with the optical power improvement for fabricated VLEDs on Si(100).

Fig. 5 shows the measured optical power density–current density–voltage characteristics of 500 μm × 500 μm VLEDs after silicone encapsulation to make comparisons with recent results in the literature. Using an integrating sphere, the LOP of a VLED at 20 mA was 13.4 mW, which can be translated to a WPE of 19%. The peak WPE of ∼23% was observed at a relatively small current density of 10 mA/mm^2. The L–I curve is linear up to 300 mA (1200 mA/mm^2). At 300 mA, a 500 μm × 500 μm VLED emitted 134.4 mW of optical power. The device in this paper is among the state-of-the-art VLEDs reported in the literature using

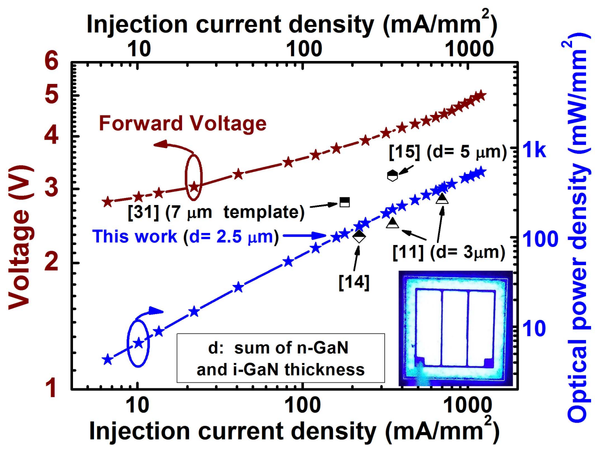

Fig. 5. Optical power density versus injection current density of VLEDs demonstrated in this paper and in previous reports.

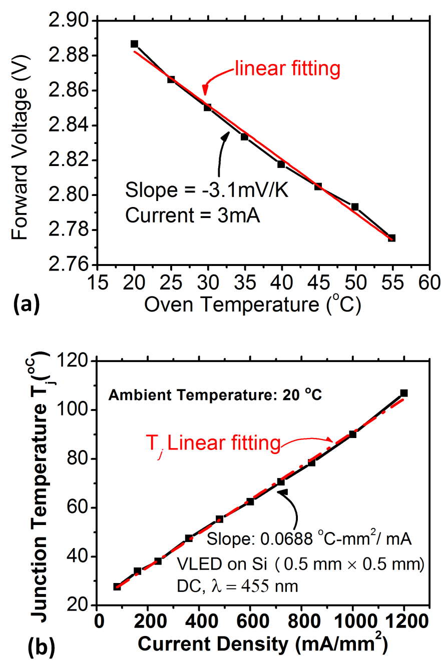

Fig. 6. (a) Dependence of forward voltage of VLEDs on temperatures. (b) Junction temperature as a function of dc forward current.

LED-on-Si epilayers. The total GaN thickness was chosen to be 2.5 μm for good enough GaN crystalline quality and a thin strain-engineered buffer layer (a 1.2-μm graded AlGaN layer). Keeping the whole structure simple, the epilayers growth time could be greatly shortened compared with those with the much thicker GaN layer [15], [31]. Furthermore, during the buffer removal process, etching damage could be minimized as only a thin buffer needs to be eliminated to expose n-GaN for electrode. As a result, higher process yield could be achieved. Further enhancement in the WPE is expected with improved starting epimaterials grown on silicon.

The junction temperature [32] of the VLED on the Si carrier was measured in a thermal transient tester (MicReD T3ster) [33]. Fig. 6(a) shows the dependence of VLED forward voltage on the ambient temperatures from 20 °C to 55 °C. The injection current was set to be as low as 3 mA, so that no obvious self-heating occurred. A linear curve was found, and the slope (temperature coefficient) was determined to be −3.1 mV/K. Fig. 6(b) shows the junction temperature versus the dc forward current density up to 1200 mA/mm^2. A nearly linear relation between junction temperature and current was observed. According to the slope, for a 500 μm × 500 μm VLED, the junction temperature increased by only 0.27 °C when the injection current was increased by 1 mA. At a typical working current density of 350 mA/mm^2, the junction temperature was measured to be 47.5 °C. The low junction temperature was attributed to good thermal conductivity of both the Cu–Sn–Cu metal layer and the Si carrier.

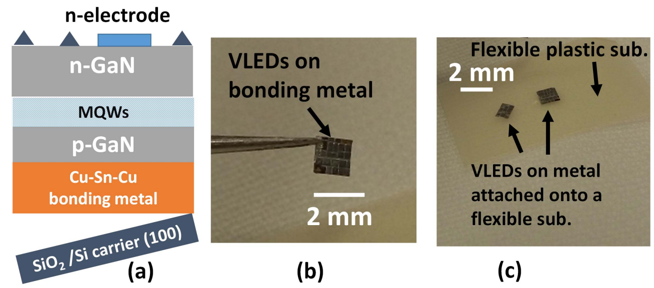

Fig. 7. (a) Schematic of separating VLEDs on bonding metal from a SiO_2/Si substrate. (b) and (c) Photographs of transplantable VLEDs on a 40-μm bonding metal layer and attached onto a flexible plastic substrate.

The low leakage current, high optical power, high saturation current, and low junction temperature indicated that VLEDs on a rigid Si receptor fabricated using the Cu/Sn–Sn/Cu bonding method have promising potential in producing low-cost yet high-performance lighting fixtures.

B. VLEDs on Flexible Substrates

When the LED epitaxial layers were bonded and transferred onto a SiO_2/Si(100) carrier, the fabricated VLED structure, together with the 40-μm-thick metal layer, could be lifted off by etching away the sacrificial intermediate SiO_2 layer in solution-based oxide etchant, as shown in Fig. 7(a). Fig. 7(b) shows an image of an LED sample (1.8 mm × 1.8 mm) that is separated from the rigid Si(100) substrate and can be handled by tweezers. Considering the self-contained properties of VLEDs on metal foil that both n- and p-electrodes are well formed on the top and bottom of the LED thin film after release from the SiO_2/Si template, the VLEDs on metal foil can be attached onto various substrates, either conductive or nonconductive, without sacrificing its I–V properties and light emission capability.

Fig. 7(c) shows the VLEDs on the metal foil attached onto a flexible plastic substrate. The flexible VLEDs showed similar forward voltages compared with those on rigid Si substrates: the forward voltage was ∼4.15 V at 50 mA for a 320 μm × 320 μm VLED, as shown in Fig. 8(g). When the plastic substrate was bent to a radius of 5 mm [Fig. 8(a)–(f)] and 3 mm, the VLEDs showed unchanged I–V curves–nearly identical forward voltage and leakage current. The leakage current stayed as low as around −2 nA at −5V under all

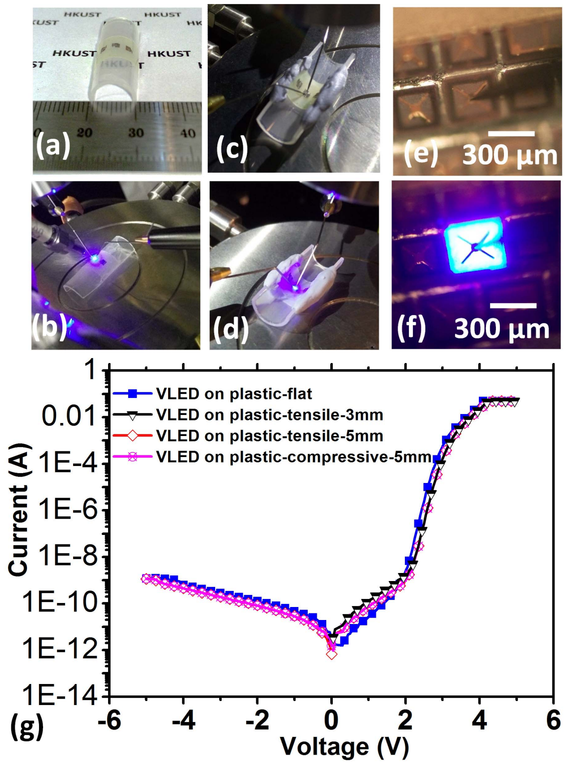

Fig. 8. Photographs of VLEDs on a flexible plastic substrate in (a) and (b) tensile stress mode and (c)–(e) compressive stress mode. (f) Slightly distorted lighting image was due to bending. (g) I–V characteristics of VLEDs on flexible substrates at different bending conditions.

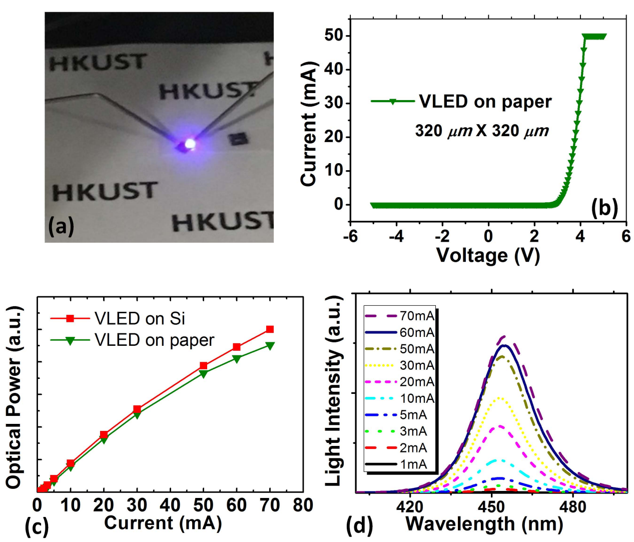

Fig. 9. (a) Light-emitting image of VLED on a paper substrate (image taken at 0.5 mA). (b) I–V characteristics. (c) Optical power comparison between VLEDs on Si and on paper. (d) Emission spectrum for a VLED on paper from 1 to 70 mA.

bending conditions, indicating that the lifted-off VLEDs on the metal foil maintain their LED properties, and flexible VLEDs have good robustness in applications where bending is necessary.

Fig. 9(a) and (b) shows the I–V characteristic and a light-emitting image of a VLED attached onto a regular printing paper, which is probably the most cost-effective and environment-friendly flexible substrate [34]. Fig. 9(c) showed the optical power (measured using an integrating sphere) comparison between VLED on a SiO_2/Si carrier (before release) and VLED on the paper (after release). It can be observed that the LOP of the VLED on the paper linearly increases for currents up to 40 mA, and the optical power was almost the same to that of VLED on the SiO_2/Si carrier, indicating undegraded brightness after substrate transfer. The VLED on the paper started to get saturated at 50 mA ($\sim$555 mA/mm^2), which represents one of the largest saturation current densities for LEDs on flexible substrates [35]–[37]. It is believed that the 40-μm-thick bonding metal layer helps dissipate heat and prevent the early onset of LOP saturation, but the saturation current is still limited by the poor heat dissipation capability of the paper, glue layer, and possible interfacial defects [34], [38]. Fig. 9(d) displays the emission spectra of a 320 μm $\times$ 320 μm VLED-on-paper for currents from 1 up to 70 mA. At a relatively low current injection (0–20 mA), the peak wavelength slightly blue shifts from 456.3 to 455 nm due to the filling of band-tail states [39]. As the injection current further increases, the wavelength starts to red shift from 455 nm (20 mA) to 457 nm (70 mA) due to bandgap reduction induced by self-heating [40] and the low thermal conductivity of the paper substrate. The unaffected I–V characteristics and high brightness of the VLEDs on various flexible substrates indicate the potential of our approach for the next generation flexible electronics and wearable electronics.

IV. Conclusion

The GaN LEDs grown on 6-in Si(111) were fabricated into a vertical structure using a cost-effective Cu/Sn/Cu bonding technique. With a mirror layer between the VLEDs and the receptor Si(100) carrier, and a textured surface, the LOP of a VLED at 20 mA was 13.4 mW, which translates to a WPE of 19%. Due to the excellent heat dissipation of metal and Si, the junction temperature of the VLED on Si was measured to be only 47.5 °C at a working current density of 350 mA/mm^2. Using a SiO_2 sacrificial layer, the VLEDs together with the bonding metal were able to be lifted off and attached onto flexible substrates, including plastic and paper. With sufficient support from the bonding metal, VLEDs on various flexible substrates and under different bending conditions showed undegraded I–V characteristics and high brightness. These results indicate that VLEDs on rigid and flexible substrates by the Cu/Sn/Cu bonding method with the use of high-quality GaN-on-Si epilayers are a promising solution to providing low-cost, high-performance light emitters for a variety of practical illumination applications.

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REFERENCES

[1] M. H. Crawford, "LEDs for solid-state lighting: Performance challenges and recent advances," *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 4, pp. 1028–1040, Jul./Aug. 2009.

[2] S. Nakamura and M. R. Krames, "History of gallium–nitride-based light-emitting diodes for illuminationn," *Proc. IEEE*, vol. 101, no. 10, pp. 2211–2220, Oct. 2013.

[3] C. J. Humphreys, "Solid-state lighting," *MRS Bull.*, vol. 33, no. 4, pp. 459–470, 2008.

[4] J. Y. Tsao, "Solid-state lighting: Lamps, chips, and materials for tomorrow," *IEEE Circuits Devices Mag.*, vol. 20, no. 3, pp. 28–37, May/Jun. 2004.

[5] A. Krost and A. Dadgar, "GaN-based optoelectronics on silicon substrates," *Mater. Sci. Eng. B, Solid-State Mater. Adv. Technol.*, vol. 93, pp. 77–84, May 2002.

[6] A. Dadgar, "Sixteen years GaN on Si," *Phys. Status Solidi B*, vol. 252, no. 5, pp. 1063–1068, 2015.

[7] X. Zou, K. M. Wong, W. C. Chong, J. Ma, and K. M. Lau, "High-efficiency blue and green LEDs grown on Si with 5 micrometer thick GaN buffer," *Phys. Status Solidi C*, vol. 11, pp. 730–733, Apr. 2014.

[8] B. Zhang, H. Liang, Y. Wang, Z. Feng, K. W. Ng, and K. M. Lau, "High-performance III-nitride blue LEDs grown and fabricated on patterned Si substrates," *J. Cryst. Growth*, vol. 298, pp. 725–730, Jan. 2007.

[9] X. Zou, K. M. Wong, X. Zhu, W. C. Chong, J. Ma, and K. M. Lau, "High-performance green and yellow LEDs grown on SiO_2 nanorod patterned GaN/Si templates," *IEEE Electron Device Lett.*, vol. 34, no. 7, pp. 903–905, Jul. 2013.

[10] H. Kim *et al.*, "Design of high-efficiency GaN-based light emitting diodes with vertical injection geometry," *Appl. Phys. Lett.*, vol. 91, no. 2, p. 023510, 2007.

[11] R.-H. Horng *et al.*, "Performance of GaN-based light-emitting diodes fabricated using GaN epilayers grown on silicon substrates," *Opt. Exp.*, vol. 22, no. S1, pp. A179–A187, 2014.

[12] K. M. Wong, X. Zou, P. Chen, and K. M. Lau, "Transfer of GaN-based light-emitting diodes from silicon growth substrate to copper," *IEEE Electron Device Lett.*, vol. 31, no. 2, pp. 132–134, Feb. 2010.

[13] K. M. Lau, K. M. Wong, X. Zou, and P. Chen, "Performance improvement of GaN-based light-emitting diodes grown on patterned Si substrate transferred to copper," *Opt. Exp.*, vol. 19, no. S4, pp. A956–A961, 2011.

[14] S.-J. Lee, K. H. Kim, J.-W. Ju, T. Jeong, C.-R. Lee, and J. H. Baek, "High-brightness GaN-based light-emitting diodes on Si using wafer bonding technology," *Appl. Phys. Exp.*, vol. 4, no. 6, p. 066501, 2011.

[15] Z.-Y. Li *et al.*, "High-efficiency and crack-free InGaN-based LEDs on a 6-inch Si (111) substrate with a composite buffer layer structure and quaternary superlattices electron-blocking layers," *IEEE J. Quantum Electron.*, vol. 50, no. 5, pp. 354–363, May 2014.

[16] Z. Liu, M. Sun, H.-S. Lee, M. Heuken, and T. Palacios, "AlGaN/AlN/GaN high-electron-mobility transistors fabricated with Au-free technology," *Appl. Phys. Exp.*, vol. 6, no. 9, p. 096502, 2013.

[17] H.-S. Lee, D. S. Lee, and T. Palacios, "AlGaN/GaN high-electron-mobility transistors fabricated through a Au-free technology," *IEEE Electron Device Lett.*, vol. 32, no. 5, pp. 623–625, May 2011.

[18] M. Van Hove *et al.*, "CMOS process-compatible high-power low-leakage AlGaN/GaN MISHEMT on silicon," *IEEE Electron Device Lett.*, vol. 33, no. 5, pp. 667–669, May 2012.

[19] C.-W. Sher *et al.*, "Large-area, uniform white light LED source on a flexible substrate," *Opt. Exp.*, vol. 23, no. 19, pp. A1167–A1178, 2015.

[20] T.-I. Kim, R.-H. Kim, and J. A. Rogers, "Microscale inorganic light-emitting diodes on flexible and stretchable substrates," *IEEE Photon. J.*, vol. 4, no. 2, pp. 607–612, Apr. 2012.

[21] J.-H. Seo *et al.*, "A simplified method of making flexible blue LEDs on a plastic substrate," *IEEE Photon. J.*, vol. 7, no. 2, Apr. 2015, Art. ID 8200207.

[22] C. Goßler *et al.*, "GaN-based micro-LED arrays on flexible substrates for optical cochlear implants," *J. Phys. D, Appl. Phys.*, vol. 47, no. 20, p. 205401, 2014.

[23] J. Chun *et al.*, "Transfer of GaN LEDs from sapphire to flexible substrates by laser lift-off and contact printing," *IEEE Photon. Technol. Lett.*, vol. 24, no. 3, pp. 2115–2118, Dec. 1, 2012.

[24] J. Chun *et al.*, "Laser lift-off transfer printing of patterned GaN light-emitting diodes from sapphire to flexible substrates using a Cr/Au laser blocking layer," *Scripta Mater.*, vol. 77, pp. 13–16, Apr. 2014.

[25] H.-S. Kim *et al.*, "Unusual strategies for using indium gallium nitride grown on silicon (111) for solid-state lighting," *Proc. Nat. Acad. Sci. USA*, vol. 108, no. 25, pp. 10072–10077, 2011.

[26] R. Agarwal *et al.*, "Cu/Sn microbumps interconnect for 3D TSV chip stacking," in *Proc. Electron. Compon. Technol. Conf.*, 2010, pp. 858–863.

[27] W.-J. Liu *et al.*, "Low-temperature bonding technique for fabrication of high-power GaN-based blue vertical light-emitting diodes," *Opt. Mater.*, vol. 34, no. 8, pp. 1327–1329, 2012.

[28] H.-Y. Kuo, S.-J. Wang, P.-R. Wang, K.-M. Uang, T.-M. Chen, and H. Kuan, "A Sn-based metal substrate technology for the fabrication of vertical-structured GaN-based light-emitting diodes," *Appl. Phys. Lett.*, vol. 92, no. 2, p. 021105, 2008.

[29] N. P. Pham, M. Rosmeulen, C. Demeulemeester, V. Motsnyi, D. S. Tezcan, and H. Osman, "Substrate transfer for GaN based LEDs grown on silicon," in *Proc. 44th Int. Symp. Microelectron. (IMAPS)*, 2011, pp. 130–135.

[30] L. Zhang *et al.*, "High brightness GaN-on-Si based blue LEDs grown on 150 mm Si substrates using thin buffer layer technology," *IEEE J. Electron Devices Soc.*, vol. 3, no. 6, pp. 457–462, Nov. 2015.

[31] J.-Y. Kim *et al.*, "Highly efficient InGaN/GaN blue LED on 8-inch Si (111) substrate," *Proc. SPIE*, vol. 8262, p. 82621D, Feb. 2012.

[32] Y. Xi and E. F. Schubert, "Junction–temperature measurement in GaN ultraviolet light-emitting diodes using diode forward voltage method," *Appl. Phys. Lett.*, vol. 85, no. 12, pp. 2163–2165, 2004.

[33] *Thermal Characterization of IC Packages, LEDs and Systems*. [Online]. Available: https://www.mentor.com/products/mechanical/micred/t3ster/, accessed Oct. 23, 2015.

[34] D. Tobjörk and R. Österbacka, "Paper electronics," *Adv. Mater.*, vol. 23, no. 17, pp. 1935–1961, 2011.

[35] W.-S. Choi, H. J. Park, S.-H. Park, and T. Jeong, "Flexible InGaN LEDs on a polyimide substrate fabricated using a simple direct-transfer method," *IEEE Photon. Technol. Lett.*, vol. 26, no. 21, pp. 2115–2117, Nov. 1, 2014.

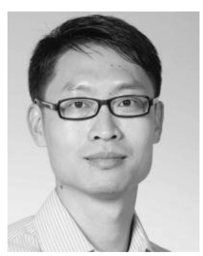
[36] P. Tian *et al.*, "Flexible vertical structure GaN-based light emitting diodes on an AuSn substrate," in *Proc. IEEE Photon. Conf. (PHO)*, Oct. 2011, pp. 551–552.

[37] R.-H. Horng, C.-H. Tien, S.-H. Chuang, K.-C. Liu, and D.-S. Wuu, "External stress effects on the optical and electrical properties of flexible InGaN-based green light-emitting diodes," *Opt. Exp.*, vol. 23, no. 24, pp. 31334–31341, 2015.

[38] T. Olli, O. Jyrki, J. Eveliina, and K. Kimmo, "Thermal management in flexible substrates for LEDs," in *Proc. IMAPS Nordic Annu. Conf.*, 2014, pp. 1–6.

[39] L. W. Wu *et al.*, "Influence of Si-doping on the characteristics of InGaN–GaN multiple quantum-well blue light emitting diodes," *IEEE J. Quantum Electron.*, vol. 38, no. 5, pp. 446–450, May 2002.

[40] D. S. Wuu *et al.*, "Enhanced output power of near-ultraviolet InGaN–GaN LEDs grown on patterned sapphire substrates," *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 288–290, Feb. 2005.



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