Active Matrix Monolithic LED Micro-Display Using GaN-on-Si Epilayers

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***Abstract*—An active matrix light emitting diode (LED) micro-display system was demonstrated with GaN-on-Si epilayers and a custom-designed CMOS backplane using an Au-free Cu/Sn-based metal bonding method. The blue micro-LED array consists of 64 × 36 pixels with a pitch size of 40 μm × 40 μm and a pixel density of 635 pixels/in (ppi). The Si substrate for the LED growth was removed by reactive ion etching (RIE) using SF_6-based gas after flip-chip bonding. Crack-free and smooth GaN layers in the display area were exposed. Images and videos with 4-bit grayscale could be clearly rendered, and light crosstalk was significantly suppressed compared to its counterpart using the GaN-on-sapphire epilayers. The demonstration suggests the tremendous potential of the low-cost and large-scale GaN-on-Si epilayers and cost-effective Au-free Cu/Sn-based bonding scheme for micro-display applications.**

***Index Terms*—Active matrix, micro-display, micro-LEDs array, GaN-on-Si, Cu/Sn bonding, flip-chip.**

I. Introduction

MICRO-DISPLAYS have emerged as a promising technology to establish user interface for wearable/portable electronic devices such as augmented reality (AR) and virtual reality (VR) displays, portable projectors, and smart phones [1], [2]. Micro-displays can be classified into two broad categories. Micro-displays based on modulating light illumination, e.g. liquid crystal on silicon (LCoS) [3] require power-hungry backlights and suffer from low efficiency due to the severe light loss in the component layers. The other type is self-emissive micro-display, which can generate and emit light itself. Organic light emitting diodes (OLEDs) [4], although have been rapidly adopted, still face several challenges including lifetime, brightness and efficiency, especially for blue OLEDs. In comparison, inorganic InGaN/GaN-based micro-LEDs are emerging as an attractive candidate for micro-display technologies, as they exhibit the superior properties of high brightness, high efficiency and long lifetime.

To date, both active matrix (AM) [5]–[7] and passive matrix (PM) [8] driving schemes have been demonstrated for LED micro-displays integrated with a CMOS driver backplane. In the PM driving scheme, the anodes of each row in an LED array are connected to the data lines, while the cathodes in each column are connected to the scan lines. Pixels will be lit up when they are scanned with positive data signals. The overlapping data and scan lines, however, introduce parasitic resistance and capacitance then lower the driving efficiency and speed. In contrast, the AM driving scheme provides an independent driver for each pixel, greatly enhancing the driving capacity, which is more preferable for micro-displays with high resolution. Correspondingly, the AM scheme demands high-yield point to point bonding between individual pixel and its driver, especially for high pixel density.

To get high-quality flip-chip bonding, Au-based metallic bonding schemes have been applied to LED micro-display technology, such as Au/In [5], Au/Sn [9] and Au/Au [10], but the high cost of the thick Au layer may seriously hindered the cost-effectiveness of LED micro-displays. Thus Au-free metal bonding is highly desirable. One type of Au-free bonding scheme, Cu/Sn-based metal bonding, has been proved to have comparable bonding reliability to Au-based bonding for various purposes, such as 3-D chip stacking [11], vertical device fabrication [12], [13] and thin-film transfer [14]. Nevertheless, it has not yet been utilized for LED micro-displays.

Furthermore, almost all reported demonstrations of AM LED micro-displays are based on GaN-on-sapphire epilayers [5]–[8]. One major reason is that sapphire has remained the predominant and inexpensive substrate for commercial InGaN/GaN LED epitaxial growth. More importantly, for AM LED micro-displays, the transparent sapphire substrate facilitates the backside-display of the LED array in the flip-chip configuration. However, there are two major issues when using LEDs on sapphire for flip-chip micro displays. One is that severe light crosstalk will be induced unless the sapphire substrate is completely detached via a high-cost laser lift off (LLO) process [15]. The other is that the flip-chip bonding of LEDs on sapphire and Si-based CMOS backplane is challenging due to the thermal mismatch between sapphire and Si. Compared with sapphire, Si growth substrate can be totally removed using a standard and low-cost SF_6-based reactive ion etching (RIE) process. Moreover, due to the steady

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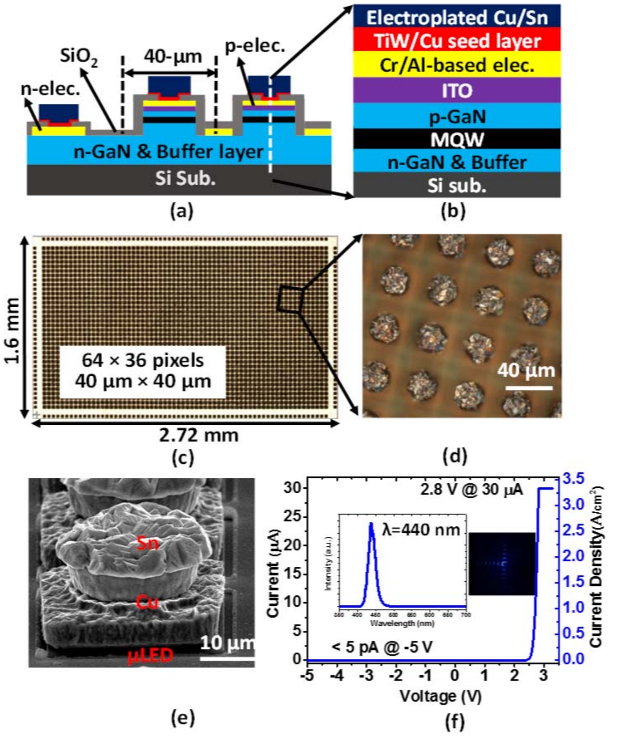

Fig. 1. (a) Schematic of GaN blue micro-LED array. (b) Detailed cross-section of the layers along the white dashed line in (a). (c) Optical image of the micro-LED array after fabrication. (d) Zoomed-in view of the Cu/Sn bumps on micro-LEDs. (e) SEM image of electroplated Cu/Sn bumps. (f) *I-V* curve of single micro-LED; insets are the emission spectra and emitting image.

progress of growing GaN LEDs on low-cost and large scale Si substrate in the recent years [16], [17], the LED-on-Si epilayers showed sufficiently high crystalline quality and good luminance uniformity for display purpose.

In this work, for the first time we demonstrate an AM LED micro-display using GaN-on-Si epilayers via an Au-free Cu/Sn-based metal bonding scheme, paving a new path for cost-effective LED micro-display applications with negligible light cross talk.

II. Material and Fabrication Details

InGaN/GaN blue LED epilayers were grown on a 6-inch Si(111) substrate by metal organic chemical vapor deposition (MOCVD). The growth started from a 1.2-μm-thick graded AlGaN buffer layer and a 0.5-μm-thick undoped GaN layer, followed by a 2-μm-thick Si-doped n-type GaN layer, ten pairs of InGaN/GaN multiple quantum wells (MQWs), and a 0.2-μm-thick Mg-doped p-type GaN layer in sequence [12].

Fig. 1 (a, b) show the schematic of the blue micro-LED array and its detailed layer structure. The fabrication of the micro-LED array is described as follows: a layer of indium tin oxide (ITO, 115 nm) was deposited on the p-GaN layer by e-beam evaporation and patterned by wet etching in diluted aqua regia using photoresist as etching mask. Then the photoresist was remained as masks to define individual micro-LEDs by dry etching GaN, making the ITO layer self-aligned to the micro-LED areas. After annealing, the ITO layer formed an ohmic contact to the p-GaN. Then Cr/Al-based metal stacks

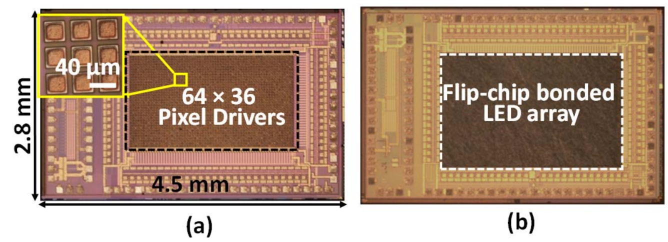

Fig. 2. (a) CMOS backplane after an additional Ti/Cu bilayer deposition. (b) Integrated chip with micro-LED array flip-chip bonded on CMOS backplane.

(Cr/Al/Ti/Au, 2/240/50/50 nm) were deposited on top of the ITO and n-GaN layer as p- and n-type electrodes, respectively. Next, the sample was passivated by depositing a layer of SiO_2 using plasma enhanced chemical vapor deposition (PECVD), with opened holes on top of both the p- and n-type electrodes. A bilayer of TiW/Cu (50/500 nm) was then deposited as a seed layer for the following Cu/Sn selective electroplating powered by a direct current (DC) supply. The seed layer was then patterned by wet etching with electroplated Cu/Sn bumps as a mask. The isolated micro-LEDs are located in the center while common n-electrodes are located at the peripheral area. The micro-LED array became ready for flip-chip bonding with the CMOS backplane after thinning the Si growth substrate down to 150 μm to shorten the Si etching time after bonding.

Fig. 1 (c) demonstrates the top-down view of the micro-LED array, which consists of 64 $\times$ 36 pixels with uniform Cu/Sn bumps on top. The chip size is 1.60 mm $\times$ 2.72 mm, with a pitch size of 40 μm $\times$ 40 μm and pixel density of 635 pixels per inch (ppi). A zoomed-in view of the Cu/Sn bumps on the micro-LEDs is shown in Fig. 1 (d). A two-step Cu/Sn electroplating process was developed to ensure good adhesion quality without short connection issues, as shown in Fig. 1 (e) and described as follows. Firstly, 5-μm-thick Cu square bumps, of 30 μm $\times$ 30 μm, were electroplated on top of the micro-LEDs, followed by smaller circular Cu/Sn (4 μm/5 μm-thick) bumps, with a diameter of 20 μm. *I-V*characteristics of a single pixel were measured after the fabrication, showing a forward voltage of 3.2 V at 30 μA and reverse leakage current less than 5 pA at -5 V (Fig. 1 (f)). The light emission peak of blue micro-LEDs was measured as 440 nm, which is determined by the starting epi.

The driving backplane was fabricated in a 0.18-μm bulk CMOS process, integrating 64 $\times$ 36 pixel drivers and an on-chip hybrid voltage regulator, featuring an input range from 2.7 V to 4.2 V and maximum output power of 216 mW. The design details could be found from our previous publication [6]. The pads of the as-fabricated CMOS backplane are covered by Al, inherently cannot be bonded with Sn. Accordingly, as shown in Fig. 2 (a), an additional bilayer of Ti/Cu (100 nm/1 μm) was deposited on top of the pixel drivers and the peripheral common n-type pads. Then the backplane was flip-chip bonded with the micro-LED array (Fig. 2 (b)) under a force of 5 N at 280° for 30 s. After the flip-chip bonding, the Si growth substrate was removed by RIE to expose the emitting LED display area.

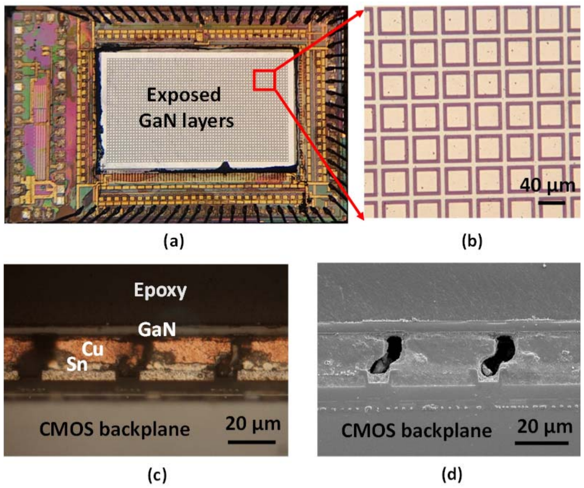

Fig. 3. (a) Integrated chip after Si growth substrate removal. (b) Zoomed-in image of exposed GaN layers. (c) Optical and (d) SEM cross-sectional images of the integrated chip.

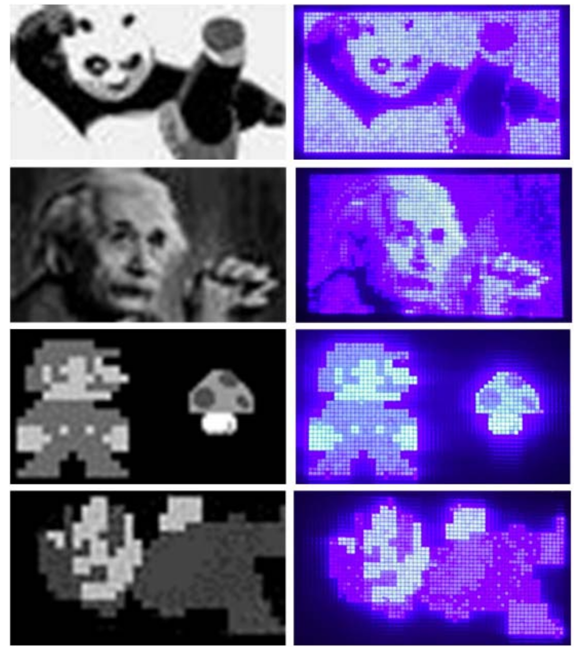

Fig. 4. Source (left) and displayed (right) images on AM LED micro-display.

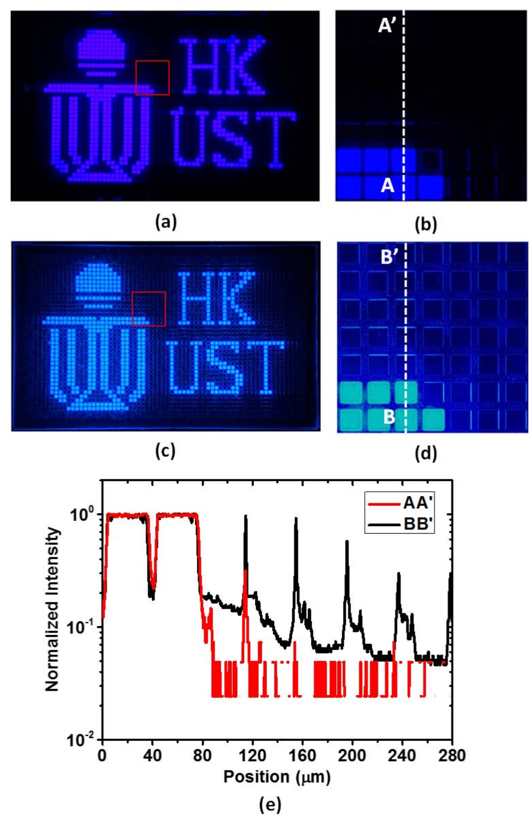

Fig. 5. (a) Displayed pattern based on micro-LED array with Si growth substrate removed. (b) Zoomed-in image of the labeled area in (a). (c) Displayed pattern based on micro-LED array with a 200-μm-thick sapphire growth substrate left. (d) Zoomed-in image of the labeled area in (c). (e) Normalized intensity profiles along the dashed lines AA' and BB'.

III. Results and Discussion

Fig. 3 (a-b) display the top-down view images of the bonded chip after removal of the Si growth substrate. The Si etching automatically stopped when the AlN buffer layer is exposed as the SF_6-based etching process can hardly etch AlN. Fig. 3(b) shows smooth and crack-free micro-LED display regions with an AlN layer as the top layer.

Fig. 3 (c) and (d) present cross-sectional optical and SEM images of the integrated chip shown in Fig. 3 (a). The free-standing GaN layers are well supported by the CMOS backplane via Cu/Sn soldering bumps. The thick Cu and Sn layers on the micro-LED array can be easily distinguished, while the Ti/Cu bilayer on the CMOS backplane is too thin to be identified. Despite the minor misalignment, one-to-one correspondence is well-established between each micro-LED and pixel-driver without any short connection between neighboring pixels. The space between the soldering bumps could be filled using an underfill flow technology to further improve the joint reliability [18].

To demonstrate the display capability, the integrated chip was wire-bonded onto a printed circuit board (PCB) and then connected to an Arduino DUE control board through a flexible printed circuit cable. Images and video of the same resolution as the micro-LED array (64 $\times$ 36) could be clearly rendered under a 4-bit grayscale control. Fig. 4 shows source (left) and displayed (right) images on this AM LED micro-display system. A high bonding yield of nearly 100% was obtained, demonstrating the bonding quality of the Cu/Sn soldering bumps.

Fig. 5 illustrates a comparison of two micro-displays starting from LED-on-Si and LED-on-Sapphire epi-wafers. Micro-LED array fabricated using GaN-on-Si epilayers with the Si growth substrate completely removed is shown in Fig. 5 (a). Micro-LED array fabricated using GaN-on-sapphire epilayers, but with a remaining 200-μm-thick sapphire growth substrate on top of it, is shown in Fig. 5 (c). Zoomed-in images of the display pattern are shown in Fig. 5 (b and d). The driving current was adjusted to have the two micro-displays render a similar light output power of around 200 μW when displaying one pattern. All four pictures were taken using the same capturing conditions (Aperture-f/2.0, Exposure time-20ms, ISO-50). As shown in Fig. 5 (c) and (d), with the 200-μm-thick sapphire growth substrate left on the display

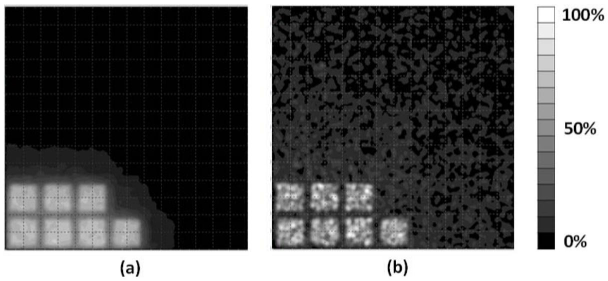

Fig. 6. Simulated light intensity distribution maps at display surface, using a ray-tracing simulation software, based on micro-LED array (a) with Si growth substrate removed and (b) with a 200-μm-thick sapphire growth substrate left, respectively.

area, the blue light emitted from the MQWs was reflected and propagated within the sapphire before escaping into free space or getting absorbed, which results in a blue background throughout the whole display panel [19]. In contrast, as shown in Fig. 5 (a) and (b), with the Si growth substrate being completely removed with only a 4-μm-thick GaN layers on top, a dark background was observed in the display panel, leading to a much better display contrast. As plotted in Fig. 5 (e), the light intensities along the dashed lines of AA' and BB' shown in Fig. 5 (b) and (d), are extracted and normalized to the maximum intensity of illuminated pixels. Light crosstalk was restricted to a lower level for micro-LEDs array using GaN-on-Si epilayes. The intensity peaks observed for positions beyond 100 μm are induced by the light reflection at the metal layers deposited on n-GaN layer.

Fig. 6 illustrates the light intensity distribution at display surfaces of these two micro-displays, simulated in a ray-tracing simulation software with light intensities normalized to their peak value. For the micro-display based on the micro-LEDs array with Si growth substrate removed, only insignificant light crosstalk occurred at the area adjacent to the illuminated pixels. In the micro-display based on the micro-LEDs array with 200-μm-thick growth substrate left, light intensity was distributed in a much wider panel area. It should be pointed out that the light emission peak wavelengths of these two micro-displays are slightly different from each other, which, however, does not compromise the conclusion made in the study.

IV. Conclusion

For the first time, an active matrix LED micro-display system is demonstrated using GaN-on-Si epilayers via Cu/Sn-based metal bonding method. A micro-LED array, consisting of 64 $\times$ 36 pixels with a pitch size of 40 μm $\times$ 40 μm, was fabricated. A two-layer Cu/Sn soldering bump technique was developed to ensure good adhesion quality without short connection. A custom-designed CMOS backplane with 64 $\times$ 36 pixel drivers and an on-chip hybrid voltage regulator was fabricated using a 0.18-μm bulk CMOS foundry process. The flip-chip bonding between the micro-LED array and the CMOS backplane was conducted under a pressure of 5 N at 280° for 30 s. The Si growth substrate was removed exposing the crack-free GaN layers in the display area. With 4-bit grayscale control by an Arduino DUE board and a 100% bonding yield, this AM LED micro-display system is capable of displaying images and videos with a resolution of 64 $\times$ 36. Moreover, the light crosstalk in this system is significantly suppressed compared to micro-display using GaN-on-sapphire. Taking advantages of low-cost, large-scale GaN-on-Si epilayers and an Au-free Cu/Sn-based metal bonding scheme, this work demonstrates the manufacturability of cost-effective monolithic AM LED micro-displays.

References

[1] K. Hayashi, S. Nomura, and Y. Sakai, "*Distinguished paper*: Glass substrate for micro display devices," *SID's Dig. Tech. Papers*, vol. 48, no. 1, pp. 1197–1200, May 2017.

[2] Z. J. Liu, W. C. Chong, K. M. Wong, K. H. Tam, and K. M. Lau, "A novel BLU-free full-color LED projector using LED on silicon micro-displays," *IEEE Photon. Technol. Lett.*, vol. 25, no. 23, pp. 2267–2270, Dec. 1, 2013.

[3] S. Martin, "Milestone in the history of field-effect liquid crystal displays and materials," *Jpn. J. Appl. Phys.*, vol. 48, no. 3S2, Mar. 2009, Art. no. 03B001.

[4] B. Geffroy, P. l. Roy, and C. Prat, "Organic light-emitting diode (OLED) technology: Materials, devices and display technologies," *Polym. Int.*, vol. 55, no. 6, pp. 572–582, Jun. 2006.

[5] X. Li, L. Wu, Z. Liu, B. Hussain, W. C. Chong, K. M. Lau, and C. P. Yue, "Design and characterization of active matrix LED microdisplays with embedded visible light communication transmitter," *J. Lightw. Technol.*, vol. 34, no. 14, pp. 3449–3457, Jul. 15, 2016. doi: 10.1109/JLT.2016.2562667.

[6] J. Jiang *et al.*, "Fully-integrated AMLED micro display system with a hybrid voltage regulator," in *Proc. IEEE Asian Solid-State Circuits Conf.*, Nov. 2017, pp. 277–280.

[7] L. Dupré *et al.*, "Processing and characterization of high resolution GaN/InGaN LED arrays at 10 micron pitch for micro display applications," *Gallium Nitride Mater. Devices XII*, vol. 10104, 2017, Art. no. 1010422.

[8] W. C. Chong, W. K. Cho, Z. J. Liu, C. H. Wang, and K. M. Lau, "1700 pixels per inch (PPI) passive-matrix micro-LED display powered by ASIC," in *Proc. IEEE Compound Semiconductor Integr. Circuit Symp.*, Oct. 2014, pp. 1–4.

[9] C. Choi *et al.*, "Localizing seizure activity in the brain using implantable micro-LEDs with quantum dot downconversion," *Adv. Mater. Technol.*, vol. 3, no. 6, Jun. 2018, Art. no. 1700366.

[10] C.-C. An, M.-H. Wu, Y.-W. Huang, T.-H. Chen, C.-H. Chao, and W.-Y. Yeh, "Study on flip chip assembly of high density micro-LED array," in *Proc. 6th Int. Microsyst., Packag., Assem. Circuits Technol. Conf.*, Oct. 2011, pp. 336–338.

[11] R. Agarwal *et al.*, "Cu/Sn microbumps interconnect for 3D TSV chip stacking," in *Proc. 60th Electron. Compon. Technol. Conf.*, Jun. 2010, pp. 858–863.

[12] X. Zou, X. Zhang, W. C. Chong, C. W. Tang, and K. M. Lau, "Vertical LEDs on rigid and flexible substrates using GaN-on-Si Epilayers and Au-free bonding," *IEEE Trans. Electron Devices*, vol. 63, no. 4, pp. 1587–1593, Apr. 2016.

[13] X. Zhang, X. Zou, X. Lu, C. W. Tang, and K. M. Lau, "Fully- and quasi-vertical GaN-on-Si p-i-n diodes: High performance and comprehensive comparison," *IEEE Trans. Electron Devices*, vol. 64, no. 3, pp. 809–815, Mar. 2017. doi: 10.1109/TED.2017.2647990.

[14] N. Pham, M. Rosmeulen, C. Demeulemeester, V. Motsnyi, D. S. Tezcan, and H. S. Osman, "Substrate transfer for GaN based LEDs grown on silicon," *Int. Microelectron. Assem. Packag. Soc.*, vol. 2011, no. 1, pp. 000130–000135, Jan. 2011.

[15] 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.

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

[17] C. Xiong *et al.*, "Integrated GaN photonic circuits on silicon (100) for second harmonic generation," *Opt. Express*, vol. 19, no. 11, pp. 10462–10470, May 2011.

[18] Y. He, B. E. Moreira, A. Overson, S. H. Nakamura, C. Bider, and J. F. Briscoe, "Thermal characterization of an epoxy-based underfill material for flip chip packaging," *Thermochim. Acta*, vols. 357–358, pp. 1–8, Aug. 2000.

[19] K. H. Li, Y. F. Cheung, C. W. Tang, C. Zhao, K. M. Lau, and H. W. Choi, "Optical crosstalk analysis of micro-pixelated GaN-based light-emitting diodes on sapphire and Si substrates," *Phys. Status Solidi A, Appl. Mater. Sci.*, vol. 213, no. 5, pp. 1193–1198, May 2016.