Fabrication, characterization and applications of flexible vertical InGaN micro-light emitting diode arrays

Pengfei Tian,[1,2,*] Jonathan J. D. McKendry,[2] Erdan Gu,[2,*] Zhizhong Chen,[3] Yongjian Sun,[3] Guoyi Zhang,[3] Martin D. Dawson,[2] Ran Liu[1]

[1]*Institute for Electric Light Sources, Fudan University, Engineering Research Center of Advanced Lighting Technology, Ministry of Education, Shanghai, China.*
[2]*Institute of Photonics, Department of Physics, University of Strathclyde, Glasgow, United Kingdom*
[3]*School of Physics, Peking University, Beijing, China.*
[*]*pftian@fudan.edu.cn;erdan.gu@strath.ac.uk*

Abstract: Flexible vertical InGaN micro-light emitting diode (LED) arrays have been fabricated and characterized for potential applications in flexible micro-displays and visible light communication. The LED epitaxial layers were transferred from initial sapphire substrates to flexible AuSn substrates by metal bonding and laser lift off techniques. The electrical characteristics of flexible micro-LEDs degraded after bending the devices, but the electroluminescence spectra show high stability even under a very small bending radius 3 mm. The high thermal conductivity of flexible metal substrates enables high thermal saturation current density and high light output power of the flexible micro-LEDs, benefiting the potential applications of flexible high-brightness micro-displays and high-speed visible light communication. We have achieved ~40 MHz modulation bandwidth and 120 Mbit/s data transmission speed for a typical flexible micro-LED.

1. Introduction

Flexible InGaN light emitting diodes (LEDs) have been demonstrated recently [1], which combine the flexibility of soft substrates and the high efficiency of InGaN LEDs, and therefore have found many potential applications in areas including deformable displays [2], solid state lighting [3], and optogenetics [4]. The most commonly used commercial InGaN LEDs are grown on sapphire substrates with low thermal dissipation ability, which motivates the development of vertical LEDs by transferring the LED epitaxial layers onto substrates with higher thermal conductivity [5,6]. The vertical LEDs have special characteristics of improved current spreading and roughened *n*-GaN surface to achieve higher LED efficiency at high injection currents. The vertical LED techniques have been employed to develop flexible LEDs on polymeric substrates for optical cochlear implants [7]. The polymeric substrates provide advantages of high flexibility to bend the flexible devices to small bending radii, but its low thermal conductivity can lead to a fast thermal saturation with increasing current. For applications in solid state lighting and visible light communications (VLC) [8], high driving current densities are required to achieve high light output power and high-speed data transmission, so substrates with high thermal conductivity are favored for these applications. VLC can be a fast, safe and convenient way to transmit signals through wearable and flexible implant devices without potential radio frequency radiation hazard. In addition, micro-light emitting diodes (micro-LEDs) instead of conventional broad-area LEDs have been widely used in flexible devices [1-4]. Comparatively, the micro-LEDs can sustain very high current densities, deliver high density of light output power, achieve very high optical modulation bandwidth, and localize the light emission area [8,9,10]. However, flexible vertical micro-LEDs on substrates with high thermal conductivity have not been developed, and the application of flexible devices in VLC has not been reported.

In this work, flexible vertical micro-LED arrays on metal substrates were developed through metal bonding and laser lift-off (LLO) techniques. Different from conventional structure of flexible LEDs with both *p*-contact and *n*-contact on the same side for each micro-LED pixel [1-4], the flexible vertical micro-LEDs share one *p*-contact on the bottom side and we address each flexible micro-LED pixel from the top side. With higher thermal conductivity than the flexible polymeric substrates, such as polyethylene terephthalate (PET), the metal substrates enable high operation current density of flexible micro-LEDs to achieve high light output power and high optical modulation bandwidth [11], leading to the potential applications in high-brightness micro-displays and high-speed VLC. Metal substrates also offer other advantages over polymers in terms of scope for permanent deformation. The electrical and optical characteristics of these flexible micro-LEDs were studied before and after bending. The electroluminescence (EL) spectra were measured under different substrate bending radii to investigate the effect of bending-induced strain on their optical characteristics. Under a bending radius 6 mm, the flexible micro-LEDs can sustain a current density 375 A/cm^2 before thermal roll-off. Based on these characteristics, we demonstrated the potential applications of flexible micro-LEDs in flexible micro-displays and VLC, and the related limitations are also analyzed.

2. Experiment

We used commercial blue-emitting InGaN LED wafers grown by metal organic chemical vapor deposition on (0001) sapphire substrates. The LED epitaxial structure consists of a typical p-i-n structure with an *n*-GaN layer, InGaN/GaN multiple quantum wells (MQWs) and a *p*-GaN layer. We started from large-area mesas of 1 mm×1 mm down to sapphire substrates defined by photolithography and dry etch processes. Indium-tin-oxide (ITO) and Ti/Ag/Ti/Au layers were deposited in sequence on the mesas to form *p*-type ohmic contacts and reflective mirrors, respectively. To allow metal-to-metal bonding, Pd/Ti/Au layers were deposited on a Si wafer to make a transfer substrate. By controlling the heating and cooling down processes, the LED wafer was bonded onto the Si transfer substrate by a 50-μm-thick flexible AuSn (80:20 wt.%) layer within a vacuum furnace. Then, a frequency-tripled, nanosecond-pulse Nd:YAG laser with an energy density of about 600 mJ/cm^2 was used to irradiate from the sapphire backside to lift off the sapphire substrate. While the sapphire substrate was lifted off, due to the very different coefficients of thermal expansion of AuSn (15.9×10^{-6}/ºC) and Si (2.6×10^{-6}/ºC), the Si substrate was also separated simultaneously from the other side, leaving LED dies on the AuSn layer retained as a flexible substrate. To achieve this simultaneous separation, the dwell times of 3 mins at 280 ºC and 4 mins at 340 ºC were used for bonding , followed by rapid cooling from 340 ºC under nitrogen flow (versus vacuum). A large residual stress at the AuSn/Si bonding interface can be induced through rapid cooling [12], which will enable the Si substrate simultaneous separation during the LLO process.

After transferring the epitaxial layers onto a flexible AuSn substrate, flexible micro-LEDs can be fabricated based on the large-area mesa pattern, as illustrated in Fig. 1. Note that developing micro-LED arrays from large-area mesas instead of a piece of LED wafer benefits the latter performance of the micro-LED arrays. The intrinsic stress between the epitaxial layers and the sapphire substrates was partly relaxed after defining large-area mesas, which helps improve the integrity of LED epitaxial layers and reduce the probability of more dislocation generation during the metal bonding and sapphire removal processes [13]. To facilitate the further photolithograph processes, the flexible LED/AuSn wafer was bonded onto a temporary Si substrate by dissolvable adhesive as shown in Fig. 1. Dry etching was used to etch a 4×4 flexible micro-LED array down to the AuSn substrate with a pixel size of 140×140 μm. Then a SU8-2002 isolation layer for the *p*-pad and *n*-pad was spun and apertures on each micro-LED mesa were then created by photolithography. After surface treatment of the nitrogen-face GaN, Ti/Al/Ti/Au layers were deposited on the mesas to interconnect micro-LED pixels. In Fig. 1, we show the interconnection electrodes of a 4×4 micro-LED array, and more designs, e.g. individually addressable micro-LED arrays, can be achieved depending on future applications. The thermal annealing process was not used to achieve good *n*-type ohmic contact as high temperature annealing may cause irreversible damage to the flexible metal substrate and SU8 layer. The *n*-GaN layer has much higher conductivity than *p*-GaN, so a current spreading layer is not necessary, and due to such high conductivity of the *n*-GaN layer we can even use the probes to test each flexible micro-LED pixel individually before depositing the interconnection metal. Finally, the temporary Si substrate was removed through dissolving the adhesive to complete the flexible micro-LED device fabrication.

The current versus voltage (*I-V*) characteristics of the devices were measured by a probe station connected to a source measure unit. The EL spectra were obtained by using an Ocean Optics USB4000 Spectrometer. The light output power versus current (*L-I*) characteristics were measured by placing a Si detector on top of the flexible micro-LEDs. The optical -3dB modulation bandwidth was measured by combining a small-signal modulation from an HP8753ES network analyzer with a direct current (DC) bias using a high-speed probe. Then, a photo detector was employed to collect the light output power from the LED pixel and the network analyzer was used to record the frequency response. For data transmission tests, we used pseudo-random binary sequences with a standard pattern length of 2^7-1 bits and a peak-to-peak voltage swing of 0 to 2V.

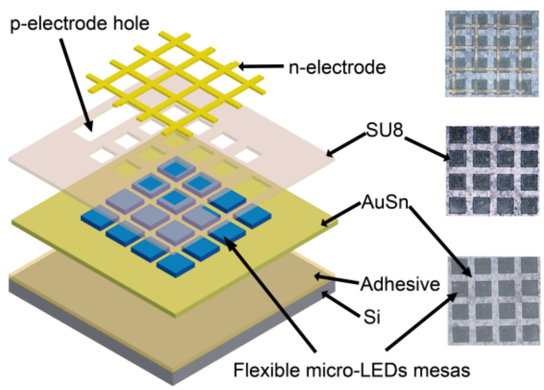

Fig. 1. In the left frame are illustrations of processing steps for fabricating flexible micro-LEDs. In the right frame are the microphotographs of flexible micro-LEDs during fabrication. Bottom: etched flexible micro-LED mesas. Middle: patterned SU8 as the isolation layer for *p*-pad and *n*-pad. Top: deposited Ti/Al/Ti/Au to form interconnected electrodes of flexible micro-LEDs array. The flexible micro-LED pixel size is 140 µm.

3. Characteristics

Fig. 2 shows the typical *I-V* characteristics of one pixel in a 4×4 flexible micro-LED array. The series resistance R_{series} calculated from R_{series}=dV/dI is 40 Ω, which is similar to the reported value of a micro-LED on sapphire substrate with a comparable size [7]. To test the pixel-to-pixel uniformity of these flexible micro-LED pixels, we test the *I-V* characteristics of 6 randomly picked pixels. The currents of these LED pixels at 5 V are summarized in the inset of Fig. 2, showing a fluctuation of ±10%. The good uniformity is attributed the excellent electrical conductivity of the bottom AuSn substrate. Then, the *I-V* characteristics of a flexible micro-LED pixel after ten bending cycles were measured as shown in Fig. 3. The R_{series} increases to 80 Ω after bending the device. We have not found obvious damages of the flexible AuSn substrates and the micro-LEDs, so the bending-induced damages may come from the bonding interface of micro-LEDs and AuSn substrates.

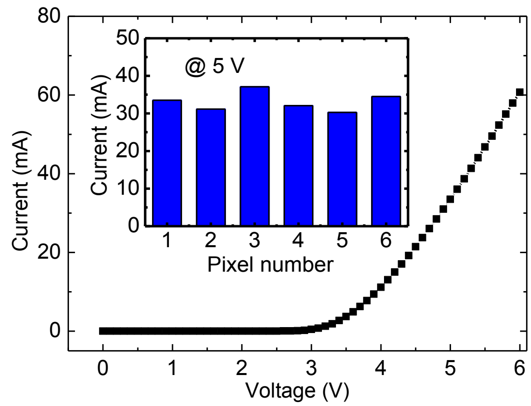

Fig. 2. The typical *I-V* characteristics of flexible micro-LEDs. Inset: current at 5 V for 6 randomly picked pixels.

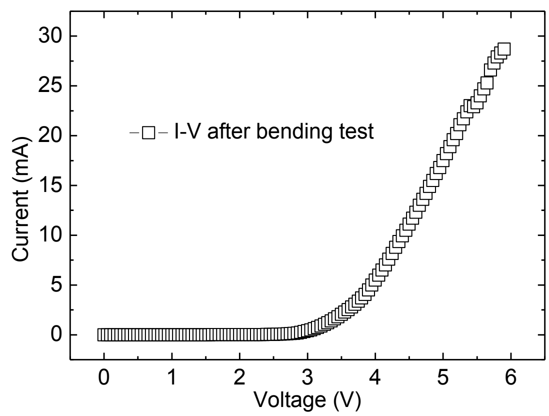

Fig. 3. *I-V* characteristics of one flexible micro-LED after ten bending cycles.

To further investigate the device bending effect on the characteristics of flexible micro-LEDs, the EL spectra at 1 mA under bending radii of infinity, 6 mm, and 3mm were measured as shown in Fig. 4. The inset demonstrates probing a flexible micro-LED on a column with 3 mm radius. A Lorenz fitting was employed to estimate the emission peak position. We measured the EL spectra of 5 flexible micro-LEDs under each bending radius and averaged the fitted values to minimize the fitting errors. The flexible micro-LED shows blue shift ~0.2 nm under a bending radius 6 mm and ~0.5 nm under a bending radius 3 mm from the EL peak wavelength ~463.6 nm at flat state. Actually, the fluctuation of these peak values is ±1 nm, and the slight peak shift mentioned is identified by the averaged values. Comparatively, in our previous work [14], the flexible broad-area LED with a size of 1 mm×1 mm shows a much larger blue shift of peak wavelength of several nms under a bending radius of 3.5 mm. Our theoretical work by using an advanced device simulation programme *APSYS*^{TM} has demonstrated that the device bending caused the compressive strain relaxation inside the MQWs and thereby the reduced quantum-confined Stark effect (QCSE) which leads to the blue shift of LED wavelength (not shown here) [15,16]. The very small blue shift of the flexible micro-LEDs in this work indicates the bending-induced strain effect is negligible inside the MQWs. We also noticed that, under a very small bending radius of 3 mm, the flexible micro-LEDs show uniform light emission inside the micro-LED die, different from the non-uniform light emission from flexible 1 mm×1 mm broad-area LEDs under a small bending radius 3.5 mm in our previous work [14]. The mechanical performance of the flexible micro-LEDs has been significantly improved, suggesting that smaller LEDs are more suitable for flexible LED design.

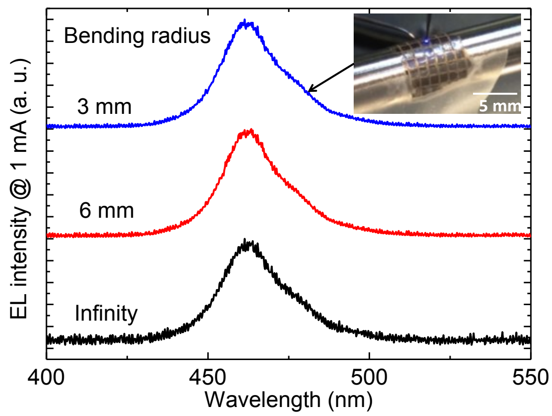

Fig. 4. Experimentally measured EL spectra of flexible micro-LEDs at 1 mA with substrate bending radii of infinity, 6 mm, and 3 mm, respectively. Inset: optical image of probing a flexible micro-LED pixel under a bending radius 3 mm.

The *L-I* characteristics of a typical flexible micro-LED on a column with a bending radius of 6 mm were shown in Fig. 5. It can be seen that the flexible micro-LED can sustain a current 70 mA (~357 A/cm^2) before thermal rollover. The high sustainable current density was largely attributed to the high thermal conductivity of the AuSn substrate, which helps develop high-brightness micro-display and high-speed VLC systems. The thermal saturation current is similar to a micro-LED on sapphire susbstrate with a comparable size [9], demonstrating excellent thermal dissipation abilities of the flexible vertical micro-LEDs even under bending state. We consider that, the bonding interface damages after bending the devices can partly limit the thermal dissipation of flexible micro-LEDs, which means the flexible micro-LED performance can be further improved through reducing the bending-induced damages [17]. From the inset of Fig. 5, it is found the uniformity of the light output power at 5 mA is ±5% for 6 randomly picked pixels. The good uniformity of the electrical and optical characteristics of the flexible micro-LED array enables their potential application in flexible micro-display.

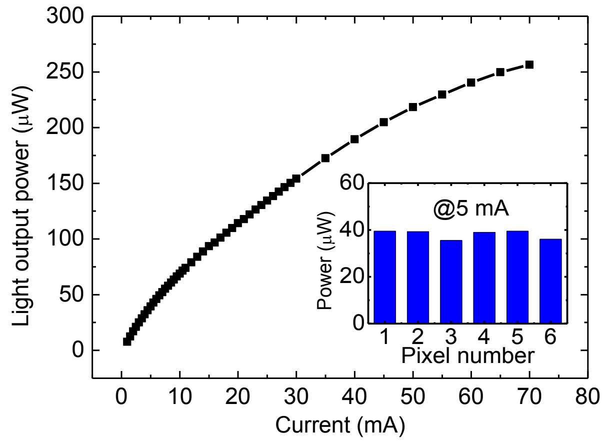

Fig. 5. *L-I* characteristics of a typical flexible micro-LED on a column with a bending radius 6 mm. Inset: light out put power at 5 mA for 6 randomly picked pixels.

4. Applications

To demonstrate the potential application of flexible micro-LEDs in micro-displays, Fig. 6(a) shows an optical image of probing interconnected flexible micro-LEDs under a bending radius of 12 mm. In Figs. 6(b) and (c), a line and an array of flexible micro-LED pixels are shown. The light emission around the micro-LED mesas is caused by the waveguide effect of the SU8 layer and LED epitaxial layers. It is found that the pixel-to-pixel light emission is non-uniform and some pixels cannot be switched on for a 4×4 array of flexible micro-LEDs. To explain the possible reasons for such non-uniformity, the enlarged microscopic image of one flexible micro-LED is shown in Fig. 6(d). On the one hand, the mesa depth of etched micro-LED pixel is around 6 μm including both epitaxial GaN layers and metal layers, leading to a sharp edge for electrode interconnection. On the other hand, the GaN surface after LLO is pretty rough, which is beneficial to increase the light extraction efficiency but may deteriorate deposited interconnection electrodes. The sharp edges and rough metal electrode may induce additional resistance of the interconnected electrodes and even the electrode disconnection especially under bending state. Through adjusting the shape of the mesa edge by an optimized dry etching recipe and depositing thicker metal layers as interconnection electrodes in our future work, it is expected the uniformity of the interconnected micro-LEDs will be greatly improved.

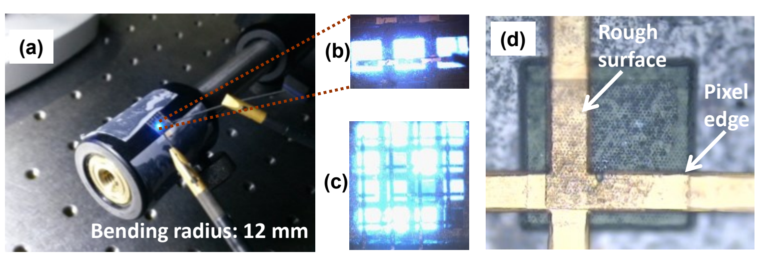

Fig. 6. (a) Typical optical image of probing interconnected flexible micro-LED pixels on a column with a bending radius 12 mm. Light emission of (b) a row and (c) a 4×4 array of flexible micro-LEDs. (d) Enlarged image of the interconnected metal track on a flexible micro-LED. The flexible micro-LED pixel size is 140 μm.

In previous studies, it has been demonstrated that the micro-LEDs have performance advantages over broad-area LEDs in VLC due to the low capacitance and high operation current density [9]. Here, we report the the application of flexible micro-LEDs in VLC for the first time. Using the as-fabricated flexible micro-LEDs in this work, the optical modulation bandwidth and eye diagrams were obtained. Fig. 7(a) shows the setup for these measurements, in which one flexible micro-LED was probed on a column with a bending radius 12 mm and the emission light was collected by a photodetector through optical lenses. Fig. 7(b) shows the measured modulation bandwidth of the micro-LED pixel gradually increases with the injection current when current is less than ~20 mA, and saturates at ~40 MHz from ~20 mA to 52 mA. Furthermore, to show the device can be actually used for data transmission, the eye diagrams of flexible micro-LEDs at a data transmission rate of 75 Mbit/s were taken at an injection current of 28 mA as shown in Fig. 7(c). Although the bandwidths at injection currents larger than ~20 mA are almost constant in Fig. 7(b), a higher data transmission rate, such as 120 Mbit/s (Fig. 7(d)), can be only achieved at a higher injection current, e.g. 60 mA. These results demonstrate the potential application of flexible micro-LEDs in VLC, but also show both the high modulation bandwidth and high light output power are important for high-speed data transmission. We noticed that, compared with micro-LEDs on sapphire substrates, the highest modulation bandwidth and data transmission speed of flexible micro-LEDs are low [8]. The modulation bandwidth may be limited by the product of the device capacitance and the series resistance due to the lack of high-quality *n*-contact [10]. Moreover, the series resistance increased after bending the device. For data transmission, due to the device flexibility as shown in Fig. 7(a), only a part of the light emission from flexible micro-LEDs was collected by the optical lenses and the photo detector. The combined effects of low modulation bandwidth and part light collection of the photo detector cause the relatively low data transmission speed.

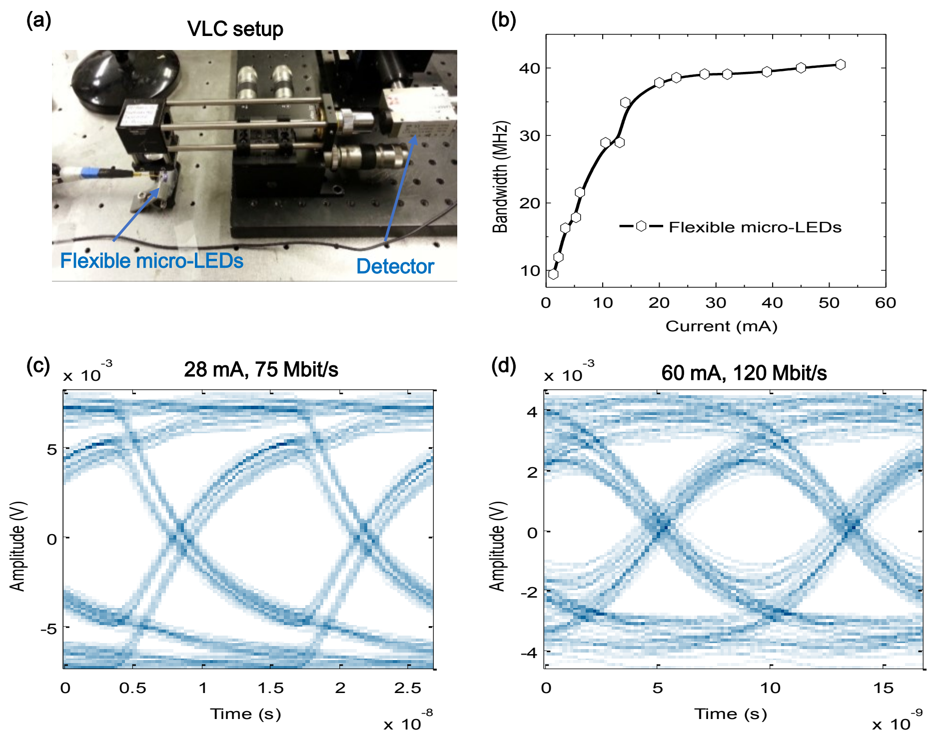

Fig. 7. (a)The VLC setup for flexible micro-LEDs under a bending radius 12 mm. (b) Measured modulation bandwidth of one typical flexible micro-LED pixel. The eye diagrams for data transmission speeds (c) 75 Mbit/s at 28 mA and (d) 120 Mbit/s at 60 mA.

5. Summary

Using a novel combination of metal bonding/debonding and LLO techniques, InGaN LED epitaxial layers were transferred onto a flexible AuSn metal substrate. Then, flexible InGaN micro-LED arrays were fabricated and characterized. The electrical performance degradation after bending the device suggests the bonding interface damage may appear. However, the negligible EL spectra shift under a small bending radius 3 mm shows the bending-induced strain effect on LED epitaxial layers is pretty small. The *L-I* characteristics suggest that the flexible micro-LEDs can sustain ~357 A/cm^2 before thermal saturation due to the high thermal conductivity of the AuSn substrate, enabling the following applications in flexible micro-displays and VLC. Light emission of interconnected flexible micro-LED arrays demonstrates their potential application in micro-displays. Also, the flexible micro-LEDs can achieve a maximum bandwidth ~40 MHz and data transmission speed 120 Mbits/s at 60 mA for VLC application.

References:

[1] T. Kim, Y. H. Jung , J. Song, D. Kim, Y. Li, H. Kim, I. Song, J. J. Wierer, H. A. Pao, Y. Huang, and J. A. Rogers, "High-efficiency, microscale GaN light-emitting diodes and their thermal properties on unusual substrates," Small **8**(11), 1643-1649 (2012).

[2] S. Park, Y. Xiong, R. Kim, P. Elvikis, M. Meitl, D. Kim, J. Wu, J. Yoon, C. Yu, Z. Liu, Y. Huang, K. Hwang, P. Ferreira, X. Li, K. Choquette and J. A. Rogers, "Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays," Science **325**(5943), 977-981 (2009).

[3] H. Kim, E. Brueckner, J. Song, Y. Li, S. Kim, C. Lu, J. Sulkin, K. Choquette, Y. Huang, R. G. Nuzzo, and J. A. Rogers, "Unusual strategies for using indium gallium nitride grown on silicon (111) for solid-state lighting," Proc. Natl. Acad. Sci. **108**(25), 10072-10077 (2011).

[4] J.-W. Jeong, J. G. McCall, G. Shin, Y. Zhang, R. Al-Hasani, M. Kim, S. Li, J.Y. Sim, K.-I. Jang, Y. Shi, D.Y. Hong, Y. Liu, G.P. Schmitz, L. Xia, Z. He, P. Gamble, W.Z. Ray, Y. Huang, M.R. Bruchas and J.A. Rogers, "Wireless optofluidic systems for programmable in vivo pharmacology and optogenetics," Cell **162**(3), 1-13 (2015).

[5] Y. C. Chiang, C. C. Lin, and H. C. Kuo. "Novel thin-GaN LED structure adopted micro abraded surface to compare with conventional vertical LEDs in ultraviolet light," Nanoscale Res. Lett. **10**(182), 1-8 (2015).

[6] B. Hahn, B. Galler, and K. Engl, "Development of high-efficiency and high-power vertical light emitting diodes," Jpn. J. Appl. Phys. **53**(10), 100208 (2014).

[7] C. Goßler, C. Bierbrauer, R. Moser, M. Kunzer, K. Holc, W. Pletschen, K. Köhler, J. Wagner, M. Schwaerzle, P. Ruther, O. Paul, J. Neef, D. Keppeler, G. Hoch, T. Moser and U. T. Schwarz. "GaN-based micro-LED arrays on flexible substrates for optical cochlear implants", J. Phys. D: Appl. Phys. **47**(20), 205401 (2014).

[8] J. J. D. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, "Visible light communications using a CMOS-controlled micro-light-emitting diode array," J. Lightwave Technol. **30**(1), 61–67 (2012).

[9] Z. Gong, S. Jin, Y. Chen, J. McKendry, D. Massoubre, I. M. Watson, E. Gu, and M. D. Dawson, "Size-dependent light output, spectral shift, and self-heating of 400 nm InGaN light-emitting diodes," J. Appl. Phys. **107**(1), 013103 (2010).

[10] P. Tian, J. J. D. McKendry, Z. Gong, S. Zhang, S. Watson, D. Zhu, I. M. Watson, E. Gu, A. E. Kelly, C. J. Humphreys, and Martin D. Dawson, "Characteristics and applications of micro-pixelated GaN-based light emitting diodes on Si substrates," J. Appl. Phys. **115**(3), 033112 (2014).

[11] A. J. Trindade, B. Guilhabert, E. Y. Xie, R. Ferreira, J. J. D. McKendry, D. Zhu, N. Laurand, E. Gu, D. J. Wallis, I. M. Watson, C. J. Humphreys, and M. D. Dawson, "Heterogeneous integration of gallium nitride light-emitting diodes on diamond and silica by transfer printing," Opt. express **23**(7), 9329-9338 (2015).

[12] P. Tian, Z. Chen, Y. Sun, S. Qi, H. Zhang, J. Deng, F. Yu, T. Yu, X. Kang, Z. Qin, G. Zhang, "Phase distribution in eutectic AuSn layer changed by temperature ramping rate and its effect on the performance of GaN-based vertical structure LEDs", Mater. Sci. Eng. B **175**(3), 213–216 (2010).

[13] Y. Sun, T. Yu, H. Zhao, X. Shan, X. Zhang, Z. Chen, X. Kang, D. Yu, and G. Zhang, "Microanalyses of the reverse-bias leakage current increase in the laser lift off GaN-based light emitting diodes," J. Appl. Phys. **106**(1), 013101 (2009).

[14] P. Tian, E. Xie, Z. Gong, Z. Chen, T. Yu, Y. Sun, S. Qi, Y. Chen, Y. Zhang, S. Calvez, E. Gu, G. Zhang, and M. D. Dawson, "Flexible vertical structure GaN-based light emitting diodes on an AuSn substrate", IEEE Photonics 2011 Conference, 551 (2012).

[15] J.-R. Chen, Y.-C. Wu, S.-C. Ling, T.-S. Ko, T.-C. Lu, H.-C. Kuo, Y.-K. Kuo, and S.-C. Wang. "Investigation of wavelength-dependent efficiency droop in InGaN light-emitting diodes," Appl. Phys. B, 98(4):779-789 (2010).

[16] J. Piprek and S. Nakamura. "Physics of high-power InGaN/GaN lasers," IEEE Proceedings-Optoelectronics, **149**(4):145-151 (2002).

[17] S.-I. Park, A.-P. Le, J.Wu, Y. Huang, X. Li, and J. A. Rogers. "Light emission characteristics and mechanics of foldable inorganic light-emitting diodes," Adv. Mater. **22(**28), 3062-3066 (2010).