Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

Development of microLED

Cite as: Appl. Phys. Lett. **116**, 100502 (2020); doi: 10.1063/1.5145201
Submitted: 15 January 2020 · Accepted: 6 February 2020 ·
Published Online: 9 March 2020

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ABSTRACT

This perspective provides an overview of early developments, current status, and remaining challenges of microLED (μLED) technology, which was first reported in Applied Physics Letters in 2000 [S. X. Jin, J. Li, J. Z. Li, J. Y. Lin and H. X. Jiang, "GaN Microdisk Light Emitting Diodes," Appl. Phys. Lett. **76**, 631 (2000)]. Today, microLED is recognized as the ultimate display technology and is one of the fastest-growing technologies in the world as technology giants utilize it on a wide range of products from large flat panel displays and televisions, wearable displays, and virtual reality displays to light sources for the neural interface and optogenetics. It is anticipated that the collective R&D efforts worldwide will bring microLED products not only to the mass consumer electronic markets but also to serve the society on the broadest scale by encompassing sectors in medical/health, energy, transportation, communications, and entertainment.

It is fascinating to witness that a change in the format of light emitting diodes (LEDs) from a standard size of 300 μm × 300 μm for indicators and 1 mm × 1 mm for power LEDs for lighting[1,2] to a micro-size of ∼10–30 μm[3–7] has created a sub-field in III-nitride and display research and launched intensive efforts in the development of emerging III-nitride devices and products.[8] The huge opportunity in consumer electronics is the major driving force behind the recent developments of innovative technologies and products based on micro-size LEDs (or microLEDs). According to MarketWatch, "The global MicroLED market is valued at $170 million in 2018 and is expected to reach $17 billion by the end of 2025, growing at a compound annual growth rate (CAGR) of 78.3% during 2019–2025."[9] To further illustrate the growth of this sub-field within the III-nitride and display fields, Fig. 1 plots the number of publication items related to "microLEDs" or "micro-size LEDs" for the years from 2000 to 2019 via the Google Scholar search. The plot displays a typical growth of a fresh field, which in this case began in 2000 with a gradual growth until 2005. Beginning in 2006, the field experienced an exponential growth with a total of nearly 3000 publication items in 2019. The R&D activities most likely are not yet peaking off, and the growth is expected to continue for a while since many researchers believe that the opportunities created by the microLED technology will be too massive to miss. Currently, "almost all the big names in the tech industry see MicroLEDs as the next big thing,"[10] and researchers are racing to overcome the key technical barriers to bring microLED products to the market. Emerging microLED products include wearable displays for high speed three-dimensional/augmented reality/virtual reality (3D/AR/VR) display applications, high brightness/contrast large flat panel displays and TVs, and light sources for the neural interface and optogenetics and for visible light communications (Li-Fi).

The inception of the microLED concept was[3–7] during the period of the emergence of blue/white LED based solid-state lighting after the invention of III-nitride blue LEDs in the early 1990s.[11–13] It was well

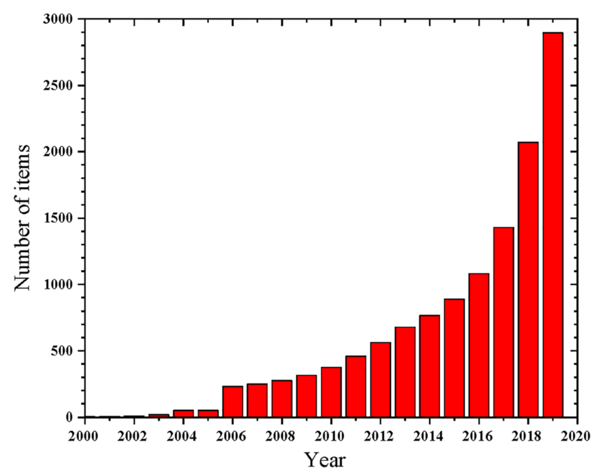

FIG. 1. Plot of publication items related to microLED or micro-size LED vs years from 2000 to 2019 via the Google Scholar search.

known from the traditional III–V semiconductors that optoelectronic devices, including emitters and detectors with micro-cavities, possess unique advantages such as low power consumption, high quantum efficiency, enhanced speed, reduced lasing threshold, ability of miniaturization and 2D array integration, and reduced cost.[14–16] Various III-nitride microstructures, including micro-disks, rings, pyramids, prisms, waveguides, and optically pumped vertical cavity surface emitting lasers (VCSELs), have been successfully fabricated by different research groups prior to 2000.[17–29] Enhanced quantum efficiencies, optical resonant modes, and optically pumped lasing actions were observed in GaN micro-disks, rings, pyramids, and GaN VCSEL structures.[17–28]

The question naturally arises: What features will a micro-sized blue/green LED and array have? Although the device architecture of microLED itself is much simpler than that of a VCSEL,[14] back then, we faced two major technical challenges for realizing blue/green μLEDs.[29] The first problem was the relatively poor p-type conductivity due to the known large Mg acceptor energy level of about 160 meV in GaN,[1,11–13] which becomes more severe as the LED size scales down to about 10 μm. The second issue was that the ratio of the etched region to the active area increases with a decrease in the μLED size, which tends to enhance the non-radiative recombination of injected electrons and holes due to plasma etching induced damage[30] to the sidewalls of μLEDs. These two issues were overcome to some extent, and we were able to inject current into μLEDs to generate intense blue emission.[3–7] The results of the first μLED and μLED array based on InGaN quantum wells (QWs) are summarized in Fig. 2,[3] which illustrates a μLED array fabricated on a single InGaN LED wafer. The SEM image shown in Fig. 2(b) reveals that this first μLED array has a pitch of 50 μm and a μLED pixel size of 12 μm in diameter with a Ni/Au p-contact of 10 μm in diameter. Figure 2(c) illustrates a blue μLED in action under current injection, whereas Fig. 2(d) shows a conventional blue LED with a size of 300 μm $\times$ 300 μm in action for comparison.

A natural subsequent step was to implement various schemes to address μLEDs within a μLED array to create practical devices. Very quickly, many potential applications started to emerge for μLEDs and arrays. One example is an interconnected μ-LED with enhanced emission efficiency over the conventional LEDs of the same device area.[4] Another example is by connecting a number of μLEDs in series so that the sum of the voltage drop across the individual μLEDs adds up to the voltage of a high voltage AC or DC supply to create a single-chip high voltage AC/DC-LED to match the infrastructure for lighting.[31–33] As of today, GaN high voltage single-chip AC/DC-LEDs have been widely commercialized for general illumination and for automobile headlights. The third example is a μLED array with independently addressed pixels or microdisplay (μdisplay), which was first introduced by the authors' group in between 2000 and 2001.[5,6] To demonstrate the concept, a 10 $\times$ 10 array (with a pixel size of 12 μm) passive driving "μdisplay" was first demonstrated, which is capable of only displaying characters.[6] Around the same time, it was shown that μLEDs have a sub-nanosecond response time.[7] Several groups were engaged early in the development of μLED technology and its applications.[34–43] For instance, the concepts of MicroLEDs for Li-Fi and medical applications were pursued early on.[34–40] A matrix-addressing scheme was developed to demonstrate a passive-matrix microdisplay with 128 $\times$ 96 pixels.[35] The concepts of flip-chip bonded microdisplays and μLEDs on Si substrates have also been developed.[41–43]

The real breakthrough in μLED displays was achieved in 2011 by the authors' group by demonstrating full-sale high-resolution (640 $\times$ 480 pixels in Video Graphics Array or VGA format) monochrome blue and green microdisplays capable of delivering video graphics images using an active matrix driving scheme.[44–46] The challenge for achieving μLED based μdisplays with active driving is that

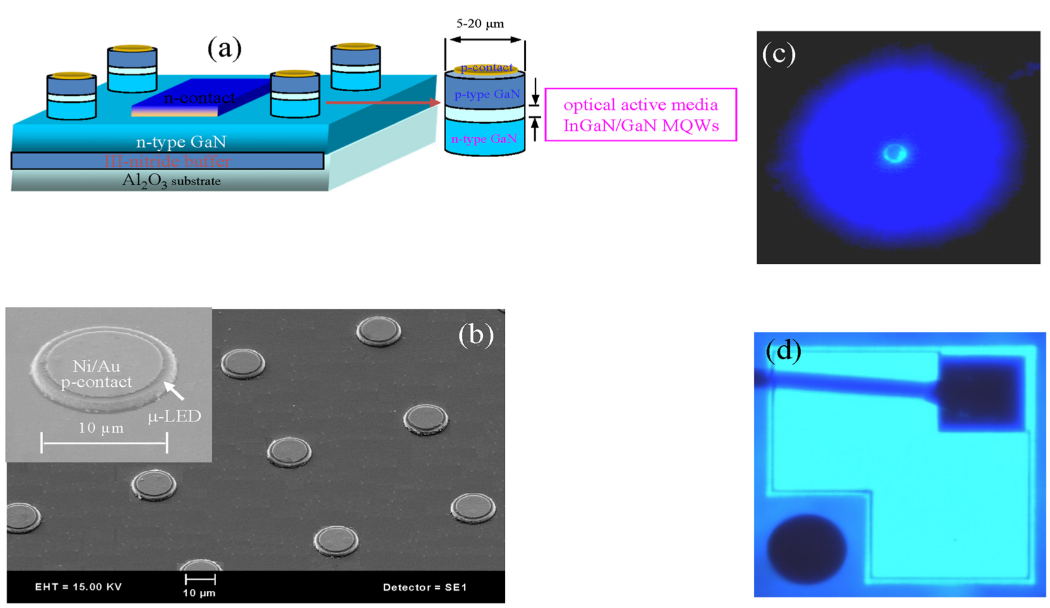

FIG. 2. The first current injection microLED based on p-GaN/InGaN/n-GaN QWs. (a) Schematic layer structure diagram of an InGaN/GaN QW microLED (μLED) array. (b) SEM image of an InGaN/GaN QW μLED array with a μLED pixel diameter of 12 μm and a p-type Ni/Au contact diameter of 10 μm. (c) Optical image of a blue μLED in action. (d) Optical image of a conventional blue LED (0.3 mm $\times$ 0.3 mm) in action for comparison. Reproduced from Jin *et al.*, Appl. Phys. Lett. **76**, 631 (2000). Copyright (2000) AIP Publishing.

III-nitride μLEDs cannot be fabricated directly over Si IC circuitry. To achieve an active driving scheme, a hybrid μdisplay concept was adopted. The microLED array was heterogeneously integrated with a CMOS active matrix driver via flip-chip bonding using indium metal bumps,[44–48] as shown schematically in Fig. 3(a). A microdisplay controller CMOS active matrix with 640×480 pixels with a controllable current from 0.5 to 10 μA per pixel has been designed and fabricated in a CMOS process.[44–48] Figure 3(b) shows an image of a packaged flip-chip bonded actively driven microdisplay. This microdisplay has 640×480 pixels in a VGA format with a μLED pixel size of 12 μm in diameter and 15 μm in pitch or 1667 pixels per inch (ppi). Figure 3(c) shows a green μdisplay in action with its size relative to a US quarter and displays a video graphic image of a leopard in Fig. 3(d). Each green μLED pixel outputs roughly 1 mcd/μA, and the luminance increases almost linearly with driving current (I) for $I < 100$ μA. For the μdisplay shown in Fig. 3 with a pitch distance of 15 μm, when every pixel within the array is lit up and operates at 1 μA, the brightness of the μdisplay is several orders of magnitude higher than those of liquid crystal displays (LCDs) and organic LEDs (OLEDs).[44–48] The μLED microdisplay also has an outstanding thermal stability. The emission intensity of the μLED emission decreased only by about 10% when the operating temperature was raised from room temperature to +100 °C and remained almost constant when the temperature was cooled down from room temperature to −100 °C, while the operating voltage at 0.1 mA decreased from 4.1 V at −100 °C to 2.9 V at +100 °C due to increased free holes and improved p-type conductivity of the p-layer with increasing temperature.[44] Moreover, μLEDs have a "turn-off" speed on the order of 0.2 ns.[7]

Though the first active matrix driving μLED microdisplay capable of video graphics image delivery is monochromatic (blue or green),[44–48] it demonstrated the validity of the μLED technology. It possesses outstanding characteristics as a display in comparison with other technologies such as LCD and OLED displays, including high brightness, efficiency, speed, high thermal stability, and contrast.[44–48] These exceptional features were quickly recognized as important advantages for next generation displays. Figure 4 summarizes potential applications of μLEDs, which currently are under intensive pursuits by almost all the big names in the tech industry for (a) smart watches, (b) smart phones, (c) i-glasses, (d) dashboard- and pico-projectors, and (e) 3D/AR/VR displays. In particular, the sub-nanosecond response of μLEDs has a huge advantage over other display technologies for 3D/AR/VR displays since these devices need more images, more pixels per image, more frames per second, and fast response.[49]

After the demonstration of the first VGA monochrome μLED microdisplay,[44–48] substantial progress has been made in the development of monochromatic μLED microdisplays with higher pixel density, smaller pixels, and larger display size.[50–53] However, the most important next step for μLED microdisplays is the realization of a full color microdisplay. Different approaches to the pursuit of full color include (a) quantum dot (QD) color conversion,[54–57] (b) nanowire microLEDs,[58–60] and (c) combination of three monochromatic red, green, and blue μdisplays based on AIGalnP (Red) and GaN (green and blue) materials.[61] However, these approaches face different challenges such as low convention efficiency and cross talk for QD color conversion, are difficult to integrate nanowire wafers with driving circuits, and are difficult to integrate μdisplays with an optical control system for the combination of three μdisplays. Therefore, it remains to be seen which method will eventually succeed. We believe that this is a remaining area that academic researchers can still make important contributions.

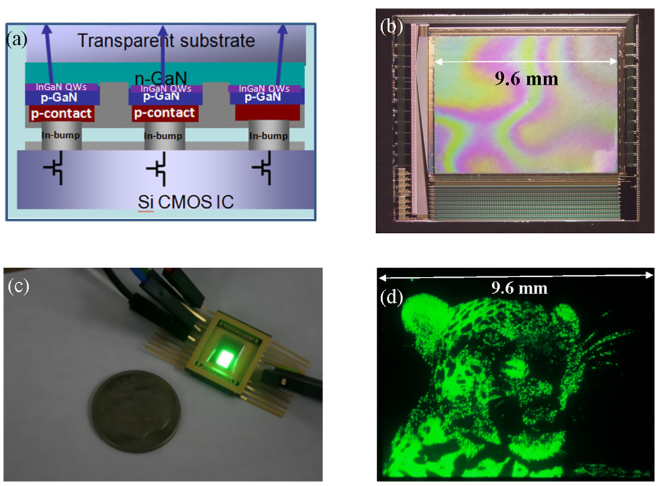

FIG. 3. The first monochromatic (blue or green) full-scale InGaN/GaN QW microLED microdisplay in the VGA format (640×480 pixels) capable of playing video graphics images. (a) Illustration of flip-chip bonding between the μLED matrix array and CMOS driver IC via indium bumps to form a highly integrated microdisplay in one package. Reproduced from Day *et al.*, Appl. Phys. Lett. **99**, 031116 (2011). Copyright (2011) AIP Publishing; (b) Optical microscopy image of a packed VGA InGaN/GaN QW microdisplay. Reproduced from Day *et al.*, Appl. Phys. Lett. **99**, 031116 (2011). Copyright (2011) AIP Publishing. (c) A fully assembled InGaN/GaN QW microdisplay (having 640×480 pixel with a pixel size of 12 μm and a pitch distance of 15 μm) operating at a driving current of 1 μA per pixel, with its size relative to a US quarter. Reproduced from Day *et al.*, Proc. SPIE **8268**, 82681X (2012). Copyright (2012) SPIE. (d) A grayscale projected image of a leopard from a green VGA InGaN/GaN QW microdisplay (having 640×480 pixels with a pixel size of 12 μm and a pitch distance of 15 μm) operating at a driving current of 1 μA per pixel. Reproduced from Day *et al.*, Proc. SPIE **8268**, 82681X (2012). Copyright (2012) SPIE.

FIG. 4. Potential applications of microLED microdisplays for (a) smart watches [credit: Apple], (b) smart phones [credit: Apple], (c) i-glasses [credit: Apple], (c) dashboard and pico-projectors [credit: Fabian Kirchbauer; BMW AG], and (e) 3D/AR/VR displays [credit: Yucel Yilmaz, Adobe Stock].

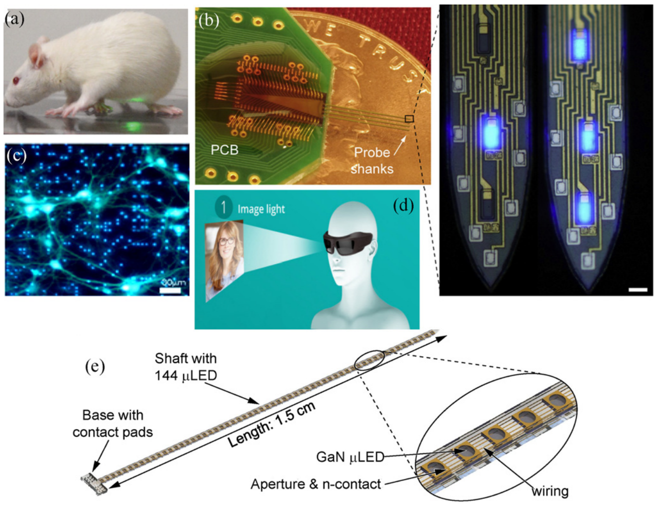

FIG. 5. MicroLED for medical applications. (a) Rat implanted with a green μ-LED for optogenetic stimulation. Reproduced from Mickle *et al.*, Nature **565**, 361 (2019). Copyright (2019) Springer Nature. (b) μLED probe drives localized spiking in freely moving mice: photograph of an implantation-ready μLED probe on a penny and high-magnification images of the illuminated μLEDs (inset, scale bar, 15 μm). Reproduced from Wu *et al.*, Neuron **88**, 1136 (2015). Copyright (2015) Elsevier, Inc. (c) Neural cells expressing ChR2 are covered by a 64 $\times$ 64 matrix of the μLED array with individual control of their intensity and timing (inset, scale bar, 30 μm). Reproduced from Grossman *et al.*, J. Neural Eng. **7**, 016004 (2010). Copyright (2010) IOP Publishing. (d) μ-LED microdisplay aiding people who are blind or have sight loss. Reproduced from V. C. Coffey; Opt. Photonics News **29**(4), 24–31 (2018). Copyright (2018) OSA. (e) Schematic of an optical cochlear implant probe comprising a probe base carrying contact pads and a 1.5-cm-long shaft comprising 144 μLEDs. Reproduced from Klein *et al.*, Front. Neurosci. **12**, 659 (2018). Copyright (2018) Klein, Gossler, Paul, and Ruther.

Another area in which μLEDs can make a large impact is in medical applications.[38–40,62–71] Figure 5 shows the illustrations of (a) a μLED array implanted inside a rat for neutron stimulation with wireless control;[68] (b) μLED based multi-shank optogenetic neural probes that can provide spatially confined optical stimulation of simultaneously monitored neurons in behaving animals;[64] (c) μ-LED for neural stimulation and optogenetics,[38–40] (d) μLED microdisplays to aid people who are blind or have sight loss;[69] and (e) μLEDs for optical cochlear implants to aid people with hearing loss.[66,70,71] The most important advantages of μLEDs for applications of neural stimulation/optogenetics are its ability of array formation, comparable size with neurons and high spatial resolution, and high speed in comparison with conventional LEDs, and they have a lower light intensity in comparison with a micro-laser, which may cause damage to neurons or cells.

FIG. 6. Evolution of MicroLED large flat panel displays and TVs: (a) first μLED TV of 55" "Crystal LED TV" produced by Sony in 2012 [credit: Sony]. (b) 146″ modular MicroLED TV "The Wall" showcased by Samsung in 2017 [credit: Samsung]. (c) An extremely large 16 K (21 m $\times$ 5.5 m) MicroLED "Crystal LED TV" showcased by Sony in 2019 [credit: Sony].

The most significant progress made in μLED displays is in fact in the large flat panel displays and TVs. Figure 6 illustrates several generations of such products demonstrated by large consumer electronics companies since 2012. The first large screen μLED TV was successfully developed by Sony in 2012, named Crystal LED display.[72] It has a total of 6.22 million μLED pixels (1920 $\times$ 1080 $\times$ 3). In comparison to LCD displays, it has 3.5 times higher picture contrast, 1.4 times better color range, a wider viewing angle of 180°, a lower power consumption of less than 70 watts, and better motion reproduction with 10 times faster response time compared to LCD models. Based on Sony's Crystal LED display, a mechanical method has been developed and used to transfer millions of μLED pixels from III-nitride blue/green and AlGaInP red wafers to a large flat surface, which provides electrical and control circuit connections to each μLED pixel of the display.

Sony's large-scale μLED TV again demonstrated the validity of μLED technology and initiated a furious race in the display industry to bring μLED large flat panel display products to the global consumer electronic markets. Though with many outstanding features, the manufacturing yield of Sony's first generation large μLED TV could be problematic because the whole TV was built from a single panel of millions of pixels. As illustrated in Fig. 6(b), when the next large μLED TV, a 146-in. μLED TV, showcased with the brand name of "The Wall" by Samsung in 2017,[73] it incorporates a method of combining an array of much smaller modules (or panels) to form a large flat panel display. This modular approach significantly improved the overall manufacturing yield since the yields for each module and for the final TV assembly are enhanced. It appears that the use of the modular approach has become an industrial standard for manufacturing large flat panel μLED displays and TVs. The most recent μLED large display showcased by Sony at the 2019 National Association of Broadcasters trade show in Las Vegas has a format of 16 K and a dimension as large as 21 m $\times$ 5.5 m, as illustrated in Fig. 6(c). It still maintains all the outstanding features of μLEDs mentioned above. This recent progress clearly demonstrates that with the method of combining many modules, there is no limit in terms of size of the flat panel displays. However, as of today, even with the modular approach, the price of these products is still beyond having a mass market appeal. With the rapid progress made recently in this field, the question is no longer if they can but rather when they will penetrate mass markets for various applications. One thing to be cautious about is how large will the market demand for μLED flat panel displays and TVs actually be. With the existing OLED and QD LCD displays with good performances on the market at relatively low prices, it still remains to be seen if μLED flat-panel displays can dominate the mass consumer electronic markets as the "ultimate display" or just suite for some niche applications.

Looking forward, μLEDs appear to be particularly suitable for medical applications for the neural interface/optogenetics[38–40,62–71] and for LiFi.[36,37,74–76] There appear no genuine barriers to use μLEDs for these applications. Various μLEDs including different sizes, form factors such as μLEDs on flexible and curved surfaces,[62–71] colors, and response speeds for different applications have already emerged. However, the efficiency of μLEDs tends to decrease with reducing size due to enhanced surface effects, and hence, one needs to take into consideration the trade-off between bandwidth, operating speed, and efficiency when designing optical systems for these applications.[77]

On the other hand, μLED based microdisplays and large flat panel displays still face significant challenges. For μdisplays, the most critical issue is to realize a true full-color format. For μLED large flat panel displays, recent demonstrations of large TV and displays certainly revealed that in particular, designed tools and facilities for μLED mass transfer and assembly have been developed by a few large companies, and hence, there are no barriers from science and engineering perspectives. It appears that overcoming the manufacturing yield is more challenging than anticipated since it has been more than 7 years since the demonstration of the first μLED large TV (Crystal LED) by Sony in 2012. The μLED and μdisplay manufacturers need to develop their own specialized infrastructures and supply chains. All of these will take time to mature. In the academic arena, in our opinion, similar to the field of polymeric OLED displays,[78] there is still a great deal of research opportunities to further develop innovative techniques for microLED transfer and assembly, such as laser-induced forward transfer or laser-based layer transfer,[79–82] microtube technology,[83] light-based debonding,[84] transfer using a magnetorheological elastomer,[85] chemical lift-off,[86] transfer printing,[87,88] and other techniques.

Despite the remarkable progress, many opportunities remain for taking advantages of improved understanding of the basic III-nitride material properties and growth/device processes to benefit the further development of the microLED technology. For instance, microLEDs are expected to operate at high current densities for many emerging applications. As such, more studies on the phenomenon of roll-over quantum efficiency (or efficiency droop effect) at high current densities, possibly due to Auger or Mg impurity band conduction effects in visible and UV LEDs,[89–95] are needed for microLEDs. It is also well known that III-nitride LED structures grown on GaN bulk substrates exhibit more desirable characteristics over those grown on sapphire substrates. However, little work has so far been done on the fabrication of microLEDs on GaN and SiC bulk substrates. The utilization of such device structures[86–109] in comparison with those of microLED wafers grown on sapphire could provide useful insights into the effects of dislocation density on the efficiency of microLEDs and approaches for further reducing the leakage current density and enhancing p-type conductivity in microLEDs. Similarly, very little comparison works have been carried out on microLEDs fabricated from polar, semi-polar, and non-polar InGaN quantum wells. As such, the properties and performances of semi-polar or non-polar microLEDs are very scarce, but they are of high interest as these structures[77,110–116] are able to provide insights into the potential effects of strain and spontaneous polarization on the efficiency, operating speed, and optical polarization properties of microLEDs.

Another important aspect of III-nitride heterostructures and QWs is the polarization-induced doping, which has been widely exploited to improve p-type doping in III-nitride LEDs, lasers, and p-type field effect transistors,[117–120] which however has yet to be explored in microLEDs for improved performance. Likewise, valuable insights can be gained from novel device architectures utilized to realize VCSELs, superluminescent LEDs, and micro-cavity lasers,[121–127] such as tunnel junction intracavity contact,[122] to further improve the characteristics of microLEDs. Furthermore, due to the lack of red InGaN wafers, realizing full color all III-nitride microLED microdisplays is exceedingly challenging, but it is highly desirable. InGaN nanowires and nanocolumn (NC) LEDs have shown promising results for full color microLED applications.[58–60,128–131] Most recently, a 16×16 array of InGaN/GaN-based NC microLEDs with different emission colors has been attained monolithically via a one-step selective area growth, pointing to the potential of integrated NC microLEDs for realizing full-color microLEDs.[131] At the same time, approaches including funnel-tube array and projection lithography patterned QDs on microLED wafers have shown to provide improved conversion efficiencies and reduced cross talk.[132,133] On the other hand, the benefits of InGaN quantum dots (QDs) that have been extensively explored recently in blue and UV III-nitride wafers[134–138] and in nanowire based micro-emitters[139,140] have yet to be investigated for microLEDs. It will be interesting to investigate the characteristics of QD embedded microLEDs, as QDs are expected to inhibit non-radiative recombination channels and hence affect the quantum efficiency and the operating speed of microLEDs.

A recent interesting development is the growth of III-nitride on a two-dimensional (2D) or layer-structured template, and the utilization of this 2D template as a release layer for mechanical transfer of III-nitride-based devices,[141–144] as a layer-structured material such as hexagonal boron nitride (h-BN), enables a natural separation of the active layer from the substrate to produce freestanding device structures.[145–147] The fabrication of microLEDs on 2D templates could potentially facilitate innovative techniques for microLED transfer and assembly and enable novel freestanding and flexible microcavity photonic devices, complementary to more established techniques for achieving flexible inorganic photonic/electronic devices.[62–71,87,88,148]

In summary, we see a very bright future for MicroLEDs. The most significant driving force is the potential huge market demand for this technology. The collective efforts from the R&D communities of III-nitrides, LEDs, lighting, displays, and optogenetics will overcome technological challenges and will ultimately enable the microLED technology to flourish to serve society at the broadest scale.

We are indebted to our former and current group members for their collective contributions to the development of microLED technology and to Dr. Jing Li in particular. We are also grateful to the AT&T Foundation for the support of Ed Whitacre and Linda Whitacre endowed chairs.

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