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A Direct Epitaxial Approach To Achieving Ultrasmall and Ultrabright InGaN Micro Light-Emitting Diodes (μ LEDs)

Jie Bai, Yuefei Cai, Peng Feng, Peter Fletcher, Xuanming Zhao, Chenqi Zhu, and Tao Wang*

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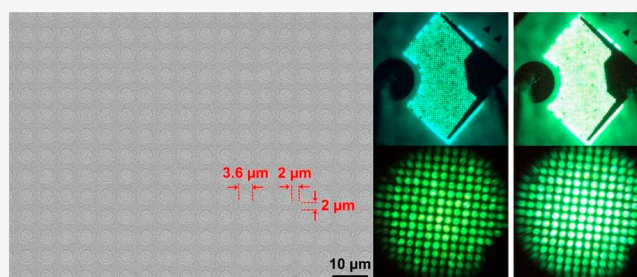
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ABSTRACT: A direct epitaxial approach to achieving ultrasmall and ultrabright InGaN micro light-emitting diodes (μ LEDs) has been developed, leading to the demonstration of *ultrasmall, ultraefficient, and ultracompact green μ LEDs with a dimension of 3.6 μ m and an interpitch of 2 μ m*. The approach does not involve any dry-etching processes which are exclusively used by any current μ LED fabrication approaches. As a result, our approach has entirely eliminated any damage induced during the dry-etching processes. Our green μ LED array chips exhibit a record external quantum efficiency (EQE) of 6% at \sim 515 nm in the green spectral region, although our measurements have been performed on bare chips which do not have any coating, passivation, epoxy, or reflector, which are generally used for standard LED packaging in order to enhance extraction efficiency. A high luminance of $>10^7$ cd/m² has been obtained on the μ LED array bare chips. Temperature-dependent measurements show that our μ LED array structure exhibits an internal quantum efficiency (IQE) of 28%. It is worth highlighting that our epitaxial approach is fully compatible with any existing microdisplay fabrication techniques.

KEYWORDS: μ LEDs, selective overgrowth, InGaN/GaN, external quantum efficiency, internal quantum efficiency, dry-etching



There is a significantly increasing demand for developing III-nitride micro light-emitting diodes (μ LEDs) for a wide range of applications, such as autodisplay, next generation TV, microdisplays for smartphones and smart-watches, and Augmented Reality and Virtual Reality (AR and VR) applications.^{1–3} III-nitride μ LEDs exhibit a number of unique features compared with organic LEDs (OLEDs) and liquid crystal displays (LCDs). Unlike LCDs, III-nitride microdisplays, where μ LEDs are the key components and are self-emissive, exhibit high resolution, high efficiency, and high contrast ratio.^{1–4} III-nitride μ LEDs exhibit long operation lifetime and chemical robustness in comparison with OLEDs. OLEDs are typically operated at an injection current density which is several orders of magnitude lower than that of semiconductor LEDs in order to maintain a reasonable lifetime.^{1–4}

In terms of the dimension requirements of μ LEDs for the applications listed above, autodisplay and next-generation TV require μ LEDs with a dimension of <100 μ m (although smaller is better), while the μ LEDs with a dimension of <50 μ m (although smaller is better; ideally ≤ 10 μ m) are essential for the other applications, in particular, AR/VR devices which require μ LEDs with a dimension of <5 μ m. Furthermore, μ LEDs can be used for high-speed data transmission with a GHz modulation bandwidth for visible light communication (VLC) applications^{5,6} due to significantly reduced junction

capacitance as a result of reduced dimension compared with current standard LEDs.

III-nitride μ LEDs are exclusively fabricated by means of combining a standard photolithography technique and subsequent dry-etching processes on a standard III-nitride LED wafer.^{7–12} Generally speaking, surface damage will be unavoidably introduced by dry-etching processes, which enhances nonradiative recombination leading to reduction in optical performance.^{13–18} This issue is minor and can be safely ignored for broad area LEDs with a dimension of >100 μ m. However, this issue becomes increasingly severe with decreasing μ LED dimension, eventually becoming a major factor and thus leading to severe degradation in optical performance.^{14,15,19} Although sidewall passivation using dielectric materials can to some degree reduce plasma induced damage to μ LEDs during dry-etching processes, the improvement is marginal even if an advanced *atomic layer deposition* (ALD) technique instead of a standard plasma-enhanced chemical vapor deposition (PECVD) technique is used for surface passivation.¹⁴ In this case, an extra issue has been

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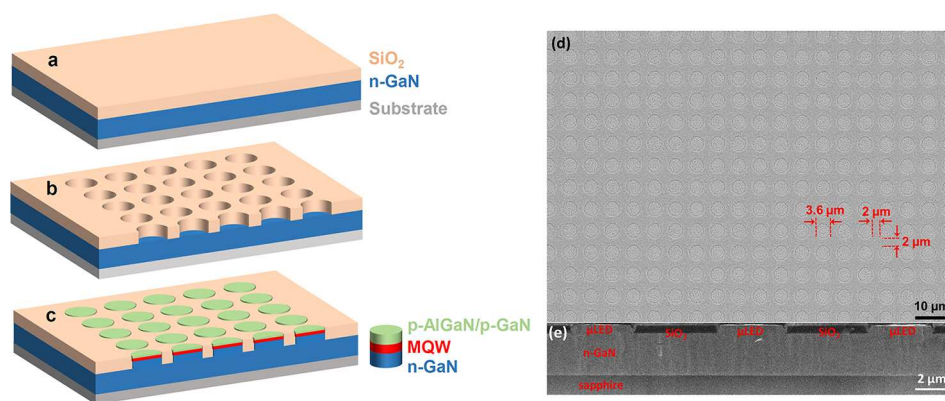


Figure 1. Schematic of our invention (a) SiO₂ mask deposition; (b) SiO₂ mask patterning; (c) μLED array overgrowth; (d) plane-view and (e) cross-sectional SEM images of our regularly arrayed μLED wafer showing a diameter of 3.6 μm and an interpitch of 2 μm.

generated due to the passivation process, namely, the etching-back of the dielectric layer on top of the p-contact/p-GaN that also degrades electrical injection in the p-GaN region, leading to an additional challenge.¹³

Therefore, there has been a nearly complete absence of reports on μLEDs with a dimension of <5 μm so far, while μLEDs with a dimension of <5 μm are the key components for AR/VR devices. The external quantum efficiency (EQE) of the μLED with a dimension of <5 μm is very low and is limited to 1 to 5%, meaning that such μLEDs cannot offer a better efficiency than OLEDs. Very recently, blue μLEDs with a dimension of <5 μm in a square shape have been reported and have shown severe damage on the sidewalls of the μLEDs clearly observed by scanning electron microscope (SEM) measurements.²⁰ This also implies that the conventional fabrication approach which combines a standard photolithography technique and subsequent dry-etching processes may not work for the fabrication of ultrasmall μLEDs (with a dimension of <5 μm) with reasonably good performance.

In order to overcome the great challenge, a fundamental change in terms of epitaxial growth and fabrication is required, meaning that the conventional fabrication approach needs to be abandoned. In this work, we have reported a fundamentally different approach to any conventional fabrication methods, demonstrating ultrasmall, ultraefficient, and ultracompact green μLEDs with a dimension of 3.6 μm and an interpitch of 2 μm by developing a selective overgrowth method, namely, the selective overgrowth only takes place within prepatterned SiO₂ microhole arrays with a hole diameter of 3.6 μm and an interpitch of 2 μm. The dry-etching processes for the formation of μLED mesas, which are the unavoidable steps in the conventional fabrication approaches have been completely eliminated. Furthermore, the SiO₂ microhole masks also naturally serve as a kind of surface passivation without requiring any additional processes or etching-back processes, which further simplifies subsequent device fabrication. Consequently, ultrahigh brightness of above 10⁷ cd/m² and an ultrahigh peak EQE of 6% at ~515 nm in the green spectral region have been achieved.

Figure 1 shows the schematics of our invention. A standard silicon doped n-GaN layer with a thickness of 1.5 μm was initially grown on *c-plane* sapphire by means of any standard GaN growth approach such as the classic two-step growth method using a metal–organic vapor phase epitaxy (MOVPE) technique. This is labeled as an “as-grown n-GaN template”. Subsequently, a SiO₂ dielectric film with a thickness of 500 nm

was deposited on the n-GaN layer by using a standard PECVD as shown in Figure 1a. Afterward, by means of employing a photolithography technique and then etching processes, the dielectric layer was selectively etched down to the n-GaN surface by means of a standard inductively coupled plasma (ICP) technique, where the etching processes were carried out using a mixture of Cl₂ with a flow rate of 20 sccm and Ar with a flow-rate of 30 sccm under 35 mTorr pressure at an etching power of 250 W. With this simple procedure, regularly arrayed microholes with a diameter of 3.6 μm and an interpitch of 2 μm have been formed, as depicted in Figure 1b.

Subsequently, a standard III-nitride LED structure was grown on the SiO₂ mask patterned GaN template by MOVPE; namely, a silicon doped n-GaN layer is initially grown, followed by an InGaIn based prelayer (5% indium content), 5 periods of InGaIn/GaN multiple quantum wells (MQWs) with 2.5 nm InGaIn quantum wells and 13.5 nm GaN barriers as an active region, then a 20 nm p-type Al_{0.2}Ga_{0.8}N as a blocking layer and finally a 200 nm p-doped GaN layer. The total thickness of the overgrown structures is ~500 nm, which is similar to the thickness of the SiO₂ masks. Because of the dielectric masks, the LED structure can be grown within the microholes, naturally forming μLED arrays as shown in Figure 1c, where the diameter, the individual location, the shape, and the interpitch are fully determined by the SiO₂ microhole masks without involving any μLED mesa etching processes. It means that the dimension, the individual location, the shape, and the interpitch of μLEDs are fully controlled.

Figure 1d,e shows typical plane-view and cross-sectional SEM images of our regularly arrayed μLEDs wafer, respectively, which demonstrate a nice circular shape with an excellent uniformity in terms of shape, diameter, and interpitch. The diameter of each μLED is 3.6 μm and the interpitch is only 2 μm. Such a small diameter and an interpitch are extremely important for manufacturing a microdisplay with a high resolution in a compact manner. Furthermore, Figure 1d also demonstrates a very high filling factor of our μLED wafer. The μLEDs are embedded in the SiO₂ masks and have flat top faces which are nearly level with the SiO₂ mask surface. It is worth highlighting that the μLED arrays are designed in such a smart manner, in which each μLED pixel shares a common n-contact and all the p-contacts are left open (which can be used in the future for indium bumps bonded to drive transistors on a silicon CMOS IC for manufacturing a microdisplay).¹ Therefore, our regularly arrayed μLED structure is fully compatible with any existing

microdisplay fabrication techniques, such as the widely used pick-and-place technology¹ or a direct integration of μ LED arrays with arrays of transistors that provide active-matrix switching for individually addressable μ LED microdisplays.¹

Temperature-dependent photoluminescence (PL) measurements have been carried out on the μ LED sample in order to estimate its internal quantum efficiency (IQE). A 375 nm diode laser was used as an excitation source, and the emission was dispersed by a monochromator (Horiba SPEX 500M) and then detected by an air-cooled charge-coupled device (CCD). The samples were placed in a closed-cycle helium cryostat, where the temperature range can be controlled from 10 to 300 K. Figure 2a displays the PL spectra which have been measured

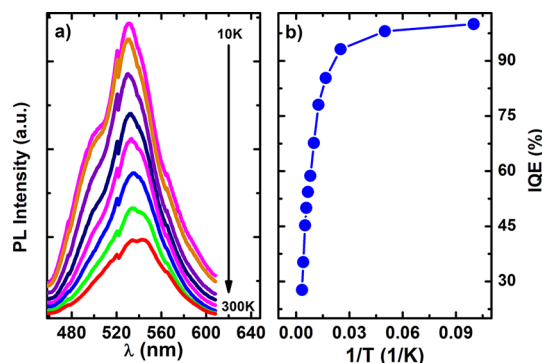


Figure 2. Temperature-dependent PL spectra (a) and estimated IQE (b) of our regularly arrayed μ LED wafer with an emission in the green spectral regions.

as a function of temperature from 10 to 300 K, showing strong emissions at \sim 520 nm in the green spectral region. Figure 2b shows the integrated PL intensity as a function of temperature measured under an excitation power density of 3 W/cm², from which an IQE of 28% has been estimated.

Here in this paper, we would like to demonstrate that our invention can be used for the fabrication of regularly arrayed μ LEDs featuring ultrasmall dimensions, ultrahigh efficiency, ultrahigh brightness, and ultracompactness. Therefore, we have simply fabricated such a regularly arrayed μ LED wafer into a LED device with an area of 0.1 mm², which contains a few thousand 3.6 μ m μ LEDs, as schematically shown in Figure 3a. Transparent p-type contact was formed by depositing a layer of indium–tin-oxide (ITO) which was annealed in air at 600 °C for 1 min. Ti/Al/Ni/Au alloys were deposited as n-type contact. Ti/Au alloys were deposited as p-type and n-type electrodes. All the characteristics of our μ LED chips have been measured on bare chips, meaning that no coating, no passivation, no epoxy, and no reflector are used for improving extraction efficiency.

In order to clearly display emitting μ LED pixels, microscopy images have been taken under a low driving current density using a micro electro-luminescence (EL) measurement system, which is equipped with two objective lenses (one with 10 \times magnification and NA = 0.28 and another one with 50 \times magnification and NA = 0.43). Figure 3b,c display the typical emission images of one μ LED array chip at an injection current of 1 and 3 mA, corresponding to a current density of 3 A/cm² and 9 A/cm², respectively. Figure 3b,c also provide the typical emission images taken under a low and a high magnification in order to demonstrate μ LED pixels clearly, showing that all individual 3.6 μ m μ LED pixels exhibit strong green emission

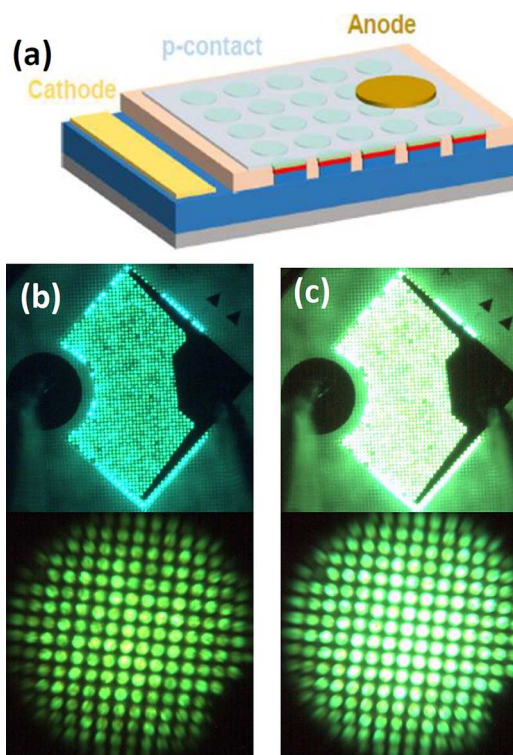


Figure 3. (a) Schematic drawing of our green μ LED array. (b) Emission microscopy images of our μ LED arrays at an injection current density of 3 A/cm² (upper: under a low magnification; bottom: under a high magnification). (c) Emission microscopy images of our μ LED arrays at an injection current density of 9 A/cm² (upper: under a low magnification; bottom: under a high magnification).

under a low current density of 3 A/cm². Taking into account the area of each μ LED with a diameter of 3.6 μ m, each 3.6 μ m μ LED can be lit up at an ultralow driving current of 0.3 μ A under 2.5 V bias. It also means that the power consumption for a microdisplay, for example, with 640 \times 480 pixels, is only about 0.23 W. When the injection current density is increased to 9 A/cm², the emission is very bright. It is worth highlighting that the injection current density used for our μ LEDs under operation is less than half of a typical current density (22 A/cm²) used for conventional broad area LEDs (such as 330 μ m \times 330 μ m). This implies that the lifetime of a microdisplay, if fabricated using our μ LEDs, should be at least as long as those of broad area LEDs which have an expected operation lifetime exceeding 100 000 h under normal operation conditions.³

Current–voltage (I – V) characteristic and electroluminescence (EL) measurements were performed on bare-chip devices at room temperature in a continuous wave (CW) mode with a Keithley 2400 sourcemeter using our microscope station.

Figure 4a shows the EL spectra of the μ LED array bare chip measured as a function of injection current ranging from 10 to 120 mA, corresponding to the current density from 30 to 360 A/cm². All the spectra exhibit single emission peaks at around 505–520 nm in the green spectral region, and the EL intensity increases with increasing injection current density. The inset is a typical emission image of our μ LED array chip which was taken at 20 mA current, demonstrating very bright green light. Figure 4b displays a typical I – V characteristic of our μ LED array chips as a function of forward bias, showing 20 mA injection current at 3.4 V, which is comparable to a standard

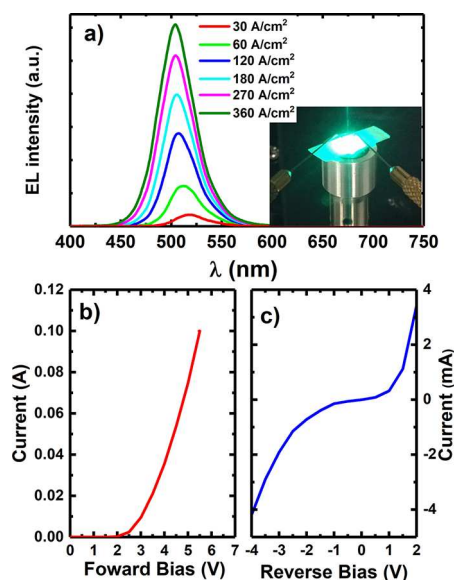


Figure 4. (a) EL spectra of a μ LED chip measured as a function of injection current at room temperature. Inset: Emission photo of a μ LED array chip taken at 20 mA. (b) I - V characteristics of a μ LED array chip as a function of forward bias. (c) I - V characteristics of a μ LED array chip as a function of reverse bias.

broad-area InGaN LED. This also demonstrates that our μ LED array chip exhibits good electrical properties. Figure 4c shows a typical I - V characteristic of our μ LED array chip as a function of reverse bias, which examines a leakage current of the μ LED array chip, demonstrating that the leakage current is as low as 4.1 μ A at -4 V, corresponding to a reverse current density of 0.013 A/cm². This leakage current density of our 3.6 μ m μ LED array chips is lower than that of the 10 μ m blue μ LEDs (not green μ LEDs, and it is much more difficult to fabricate green μ LEDs than blue μ LEDs) fabricated by the conventional μ LED fabrication approach along with an extra passivation process using advanced ALD technique,¹⁴ although the diameter of our μ LEDs is much smaller. This further confirms the major advantages of our invention in terms of electrical performance.

Light output powers and luminous flux were measured in a CW mode on TOS-header bonded bare-chip LEDs (namely, without any surface coating, passivation, epoxy, or reflector involved) using a LCS-100 characterization system equipped with an integrating sphere and a CCD APRAR spectrometer. Figure 5a shows the luminance of our μ LED array chip as a function of injection current density, demonstrating that high luminance of above 1×10^7 cd/m² has been achieved, which is 2–3 orders of magnitude higher in comparison with current OLEDs or LCDs.⁴ Figure 5b exhibits a typical EQE of our μ LED array bare chip as a function of injection current density of up to 400 A/cm², demonstrating a peak EQE of $\sim 6\%$, which is a record EQE compared with any existing report on μ LEDs in the green spectral region.^{2–4,13} Furthermore, Figure 5 also indicates that our ultrasmall μ LEDs without any heat-sink components involved can sustain a high current density of above 400 A/cm², further confirming the material quality of our grown μ LEDs obtained using our invention. Please note that the measurements were performed on a bare chip without any package or coating. Based on our experience, it is expected that the EQE can be further increased if a proper package

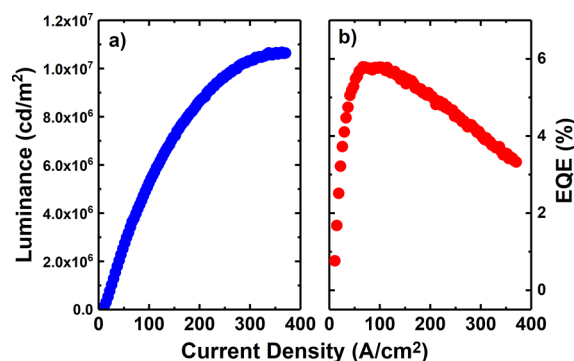


Figure 5. (a) Brightness of our μ LED array chip as a function of injection current density; (b) EQE of our μ LED array chip as a function of injection current density. Please note that the measurements are performed on a bare chip without any package or coating.

which can significantly improve extraction efficiency is made (extraction efficiency could be enhanced by a factor of 2).

In summary, we have demonstrated a completely different approach which allows us to achieve ultrasmall, ultraefficient, and ultracompact μ LEDs with a dimension of down to 3.6 μ m and an interpitch of down to 2 μ m. Our invention is based on an overgrowth on prepatterned templates with SiO₂ microhole arrays, thus eliminating all the drawbacks of the conventional μ LED fabrication approaches. As a result, a record peak EQE of 6% at ~ 515 nm in the green spectral regions has been achieved on our μ LED array bare chips. A high luminance of $>10^7$ cd/m² has been obtained. Temperature-dependent measurements show an internal quantum efficiency of 28% for our μ LED array structure.

■ AUTHOR INFORMATION

Corresponding Author

Tao Wang – University of Sheffield, Sheffield, United Kingdom; orcid.org/0000-0001-5976-4994; Email: t.wang@sheffield.ac.uk

Other Authors

Jie Bai – University of Sheffield, Sheffield, United Kingdom; orcid.org/0000-0002-6953-4698

Yuefei Cai – University of Sheffield, Sheffield, United Kingdom

Peng Feng – University of Sheffield, Sheffield, United Kingdom

Peter Fletcher – University of Sheffield, Sheffield, United Kingdom

Xuanming Zhao – University of Sheffield, Sheffield, United Kingdom

Chenqi Zhu – University of Sheffield, Sheffield, United Kingdom

Complete contact information is available at: <https://pubs.acs.org/10.1021/acsp Photonics.9b01351>

Notes

The authors declare no competing financial interest.

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