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# Investigation of electrical properties of InGaN based micro light emitting diode (µLED) arrays achieved by direct epitaxy

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A systematic study has been carried out on a series of InGaN based micro-LED (µLED) array samples which were achieved using our direct epitaxy overgrown approach on patterned templates by metalorganic chemical vapour deposition technique, where the diameters of the µLEDs are 40 µm, 5 µm and 3.6 µm, respectively. Our selective epitaxy approach allows us to circumvent the major limitations of conventional fabrication methods of µLEDs which unavoidably introduce dry-etching induced damages. Electrical characterisations have been performed on our selective epitaxy overgrown µLEDs as well as conventional µLEDs fabricated using a standard dry-etching method. For our overgrown µLEDs, the leakage current per µLED is smaller than those of the conventionally mesa-etched µLEDs. It is worth highlighting that our single 3.6 µm µLED exhibits as low as a leakage current of 14.1 nA at a bias of -5 V. Moreover, in terms of leakage current density, our overgrown µLEDs exhibit much smaller and more consistent leakage than their mesa-etched counterparts. Operational voltage RC constants also show more favourable to our overgrown devices than the conventionally mesa-etched µLEDs.

## 1 Introduction

Micro-light emitting diodes (µLEDs), with a size of a few or tens of micrometres, are attracting extensive attention within optoelectronics research and industry, due to a wide array of applications, such as micro-displays and Augmented Reality and Visual Reality (AR & VR).[1-4] Current µLEDs are typically electrically driven by existing silicon-based CMOS electronics.[5] Likewise, they also address maximum driving current density (in kA/cm$^2$) issues faced with conventional broad-area LEDs.[6]

$$f_c = {}^{1}\!/_{2\pi RC} = {}^{1}\!/_{2\pi R(A\varepsilon_0\varepsilon_r/L)}; \quad \varepsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$$

It is expected that the usually quick response time of µLEDs (determined by the so-called RC constant of the junction capacitance of a µLED) is favourable to achieving a high modulation bandwidth for visible light communication (VLC), which in turn allows for physical end-to-end secure connection without resorting to encryption unlike RF and microwave transmissions that may be intercepted. The theoretical cut-off frequency for a microLED used as a transmitter is dependent on the RC constant of its junction capacitance, which is defined as follows:

where $\varepsilon_0$ and $\varepsilon_r$ are free space permittivity and relative permittivity of a semiconductor which is used to fabricated into a microLED, respectively; A is the area of a microLED and L the length of the junction capacitance of the LED. A smaller RC lead to a higher frequency. Regular white LEDs coated with yellow phosphors are usually limited to a dozen Mbps, while it is expected that µLED can reach a GHz level.[7 –11]

III-nitrides are excellent candidates for developing µLEDs as key components for micro-display, due to their wide direct bandgap of 3.4 eV for GaN and tunable emission wavelengths for visible light. Compared to LCDs and OLEDs, III-nitride based µLEDs benefit the display technology in many ways: better contrast ratio, wider operating temperature, higher brightness and stability, wider view angles and better colour precision. [4] Moreover, III-nitrides permit high electrical breakdown fields, which can attain high driving current densities for µLEDs.[12,13] Due to high intrinsic electron mobility of around 1000 $cm^2 V^{-1} s^{-1}$ and high electron saturation velocity of $2.5\times10^7$ $ms^{-1}$ for GaN, further enhanced by AlGaN/GaN heterostructures, III-nitride based μLEDs allow for quick response time, high maximum current, and high frequency operation, which is already a subject of interest for power devices with high electron mobility transistors (HEMTs) going up to 300 GHz. [14-16]

So far, loads of the work on GaN-based μLEDs has been reported, but their fabrication is limited to conventional dry-etching approaches using inductively coupled plasma (ICP) or reactive ion etching (RIE) tools. [17-24] However, dry-etching tends to generate severe damages on the devices, leading to a significant reduction in both optical and electrical. Furthermore, such damages become more severe with reducing the dimension of μLEDs, [17] which is why small microLED, in particular, with a size of microLED below ≤ 5 μm, exhibit extremely low performance. This can be attributed to Shockley-Read-Hall recombination, implying a drop in EQE as electron-hole pairs recombine in trapping sites and cause phonons. In turn, this can be explained by an increase in damaged zone proportion and surface states per unit. Such trapping sites enable tunnelling for recombination and leakage too, exacerbating the problems.[18,19] So far, a few methods have been attempted for removing the sidewall damage induced by the dry-etching, such as neutral beam etching and KOH chemical treatment. [25,26] Though they have demonstrated to be effective in mitigating the etching damage, the etching approach to fabrication of μLEDs still requires a sidewall passivation and isolation, which can bring about extra processing and performance issues as well. [20, 21]

Recently, we have developed a different approach to fabrication of InGaN/GaN multi-quantum wells (MQWs) μLEDs: a selective overgrowth on patterned templates instead of mesa-etching. The green μLEDs have demonstrated high external quantum efficiency and high luminescence.[3,25] We have also grown InGaN-based HEMT-μLEDs to take advantage of higher driving current densities expected of μLEDs for *VLC*.[7] In this work, current-voltage and capacitance-voltage characteristics have been investigated systematically on the overgrown μLEDs with different sizes, which have also been compared with those μLEDs fabricated by means of usinga conventionally dry-etching approach.

## 2 Experiments

### 2.1 Methods

**Figure 1a** is a schematic drawing, showing our approach to achieving InGaN/GaN MQW μLED arrays. First, a micro-hole array pattern is formed on a n-type GaN layer on a sapphire substrate with a silicon dioxide ($SiO_2$) mask, which is called an “n-GaN template”. To fabricate the n-GaN template, a 500 nm thick AlN buffer layer is first grown on a c-plane (0001) sapphire substrate via metalorganic chemical vapour deposition (MOCVD), followed by a GaN layer and n-doped GaN layer. A 500 nm $SiO_2$ film is deposited on the template using a standard plasma-enhanced chemical vapour deposition (PECVD) technique. Afterwards, a standard photolithography and subsequent dry etching techniques are used to selectively etch the dielectric layer down to the n-GaN surface, forming regularly arrayed micro-holes.

Next, a standard LED structure is grown on the n-GaN template by MOCVD, namely, a silicon doped n-GaN layer with a dopant concentration of $5\times10^{18}$ $cm^{-3}$ is initially grown, followed by an InGaN based pre-layer (5% indium content), 5 periods of InGaN/GaN MQWs with 2.5 nm InGaN quantum wells and 13.5 nm GaN barriers as an active region, then a 20 nm p-type $Al_{0.2}Ga_{0.8}N$ blocking layer and finally a 170 nm p-type doped GaN layer. Due to the dielectric masks, the LED structure can be grown only within the micro-holes, naturally forming arrays of isolated μLEDs. It means that the dimension, the inter-pitch, the individual location and the shape of μLEDs are fully controlled. It is worthy to mention that isolation of the side-walls is not necessary during the fabrication processing. This dielectric $SiO_2$ mask has two benefits, not only eliminating the aforementioned necessity of mesa etching, but also providing insulation for each μLED. **Figure 1b** is a top-view SEM image of our overgrown μLED arrays.

For this kind of μLED array sample, all the μLEDs share a common n-type contact, and all the p-type contacts are left open which can be used in the future as indium bumps bonded to driving transistors based on a silicon CMOS IC for manufacturing a micro-display. In this work, the arrayed μLEDs are fabricated into a 330μm × 330 μm device with an area of around 0.1$mm^2$. The indium-tin-oxide is deposited as a common p-type contact for all the μLED pixels in one device and rapidly thermally annealed at 600°C for 1 minute. The n-type metal Ti/Al/Ni/Au is deposited as ohmic n-contacts. Each device also has an additional Ti/Au metal layer on top of both n-contact and p-contact as their actual electrodes. Thus, the μLEDs in one device are electronically connected in parallel.

### 2.2 Measurements

Voltage-current-resistance characteristics has been performed using a Keithley 2612B source meter unit (SMU), with a PC connection for the Tektronix-endorsed KickStart remote-testing and data extraction software package, and a probe station with an optical microscope. Current-voltage (I-V) characteristics are the most intuitive and down-to-integrated-circuit way of analysing devices. The devices were measured between -5 and 6 V. These were repeated for tens of devices throughout each sample to ensure consistency in results.

Capacitance–voltage (C-V) characteristics has been conducted by using a Keysight E4980A LCR (inductance-capacitance-resistance) meter, which has been calibrated for an open-circuit prior to measurements as a correction value. These were performed at 1 MHz which is deemed to be a high enough benchmark for small-signal frequency of operation to minimalise and normalise reactance (capacitive impedance) and determine the capacitance of the device accordingly. Capacitance data included here exclusively consists of the parallel equivalent circuit model (Cp), for the clear-cut reason of the devices themselves being in parallel. It is on a tuning scale of voltage bias from -5 to 6 V. The 4 or 5 smallest-leakage arrays from each sample have been utilised as a baseline.

## 3 Results and Discussion

A set of epitaxy overgrown µLED array samples with different sizes are used in this work, namely, a 3.6 µm diameter with an inter-pitch of 2 µm, a 5µm diameter with a 3 µm inter-pitch, and a 40 µm diameter with a 10 µm inter-pitch, respectively.

**Figure 2** shows electroluminescence (EL) spectra of a 3.6 µm µLED array device at different current densities. The inset is a photo image of emitted µLEDs under 3 $A/cm^2$ current density taken with 50× magnification. It shows uniform green luminous intensities.

Electrical properties have been investigated on the µLED array devices through I-V and C-V measurements and have also been compared to single µLEDs with a diameter of 10 µm or 40 µm, which have been fabricated by a conventional dry-etching approach.

**Figure 3a** shows the typical forward I-V curves as a function of forward bias for the 3.6 µm, 5 µm and 40 µm µLED array devices fabricated by our epitaxy overgrown approach. The 5 µm µLED array sample displays the lowest turn-on voltage and a high current value of 124.5 mA at 6 V, while the 3.6 µm µLED array sample has the highest turn-on voltage with a current of 33.8 mA at 6 V.

**Figure 3b** compares the reverse I-V curves of these epitaxy overgrown µLED arrays as a function of reverse bias. It shows that the total reverse current still favours the µLED arrays with a larger diameter. It indicates that the total leakage current increases with reducing µLED size. A typical I-V curves of the 10 µm µLED sample and 40 µm µLED sample fabricated by the conventional dry-etching method have also been presented in **Figure 3c**. In order to achieve accurate data and then draw a clear conclusion, we have carried out leakage current measurements on a few tens of µLED devices for both our epitaxy overgrown µLED arrays and the µLED samples fabricated by the conventional dry-etching method.

**Table 1** is a summary of the leakage current characteristics for both our epitaxy overgrown µLEDs and the single µLEDs fabricated by the conventional dry-etching method, where the number of our epitaxy overgrown µLEDs in each device, the leakage current per LED, and the current densities have been listed. The ranges are a simple min-max analysis of the results observed.

A quick glance at the data about leakage current per µLED shows that our epitaxy overgrown µLEDs with a diameter of 3.6 µm and 5 µm performed similarly in terms of the ratio of forward to reverse current, but the 3.6 µm µLEDs show the best result in terms of leakage current per µLED under a reverse bias of 5 V. The overgrowth conditions as well as the device size may have contributed to this result. Importantly, our epitaxy overgrown µLEDs exhibit much lower leakage currents than those ones fabricated by the conventional dry-etching method. For example, the leakage current per µLED for our epitaxy overgrown 3.6 µm µLED reaches as low as 14.1 nA under a reverse bias of 5 V.

Table 1 A summary of leakage currents of our epitaxy overgrown µLEDs and the µLEDs fabricated by the conventional dry-etching method.

| Device | Nr. of µLEDs per device | Leakage current per µLED at -5V | Leakage current density ($nA/\mu m^2$) |
|---|---|---|---|
| **Overgrown 40 µm** | 36 | 159 – 850 nA | 0.13 – 0.68 |
| **Overgrown 5 µm** | 1702 | 20 – 37 nA | 1.04 – 1.88 |
| **Overgrown 3.6 µm** | 3472 | 14 – 17 nA | 1.39 – 1.67 |
| **Convetional 10 µm** | 1 | 17 nA – 38 µA | 0.22 – 484 |
| **Convetional 40 µm** | 1 | 250 nA – 400 µA | 0.20 – 318 |

Moreover, the leakage current of our epitaxy overgrown µLEDs show a smaller deviation than those ones fabricated by the conventional dry-etching method. It suggests one of two things; either the dry-etching induced damage can be non-uniform within the sample, leading to substantially different leakage current within the same device group, or that the dry-etching processes induces difference in local defect density (from the centre part of each microLED to its edge part). Furthermore, it has been found that there is a moderate correlation between a decrease in µLED size and the leakage improvement for our epitaxy overgrown µLEDs. In contrast, those devices fabricated by the conventional dry-etching method suffer more from leakage as they get smaller, indicating the etching-induced damage becomes significantly severe with reducing the size of µLEDs as expected.

When the leakage current density is scrutinised, the leakage becomes more severe with decreasing the size of µLED. Clearly, when scaling down µLED, the perimeter to area ratio of a µLED increases, which leads to large surface recombination and increased current leakage. It is also noted that both the leakage current density and their dispersions are much smaller compared to the devices fabricated by the conventional dry-etching method. Moreover, when scaling down μLED, there is a significant increase in dispersion for the devices by the conventional dry-etching method, further confirming the severe issue of dry-etching on small μLEDs.

It is worthy to mention that ideally, the sidewalls of microLEDs are supposed to seamlessly contact with the sidewalls of the $SiO_2$ masks. In this case, the leakage current is expected to be extremely small. In order to achieve this, the sidewalls of the $SiO_2$ micro masks need to be very straight, which depends on the thickness of $SiO_2$ and ICP etching conditions. If the sidewalls of the SiO2 masks are slanted, tiny irregularities between microLEDs and $SiO_2$ mask may be formed, forming a channel for current leakage. Nevertheless, the issue could be minimised by further optimizing the conditions of template fabrication.

**Figure 4** displays the capacitance characteristics of the devices. In order to compare a single epitaxy overgrown μLED with a single μLED fabricated by the conventional dry-etching method, the total capacitances measured for the epitaxy overgrown μLED arrays were divided by the number of μLEDs within each array to obtain the capacitance for a single epitaxy overgrown μLED. This will provide a baseline to compare with a single μLED fabricated by the conventional dry-etching method, though contact resistivity and alternate current paths are likely to affect the end results in practice.

**Figure 4a** shows the typical C-V characteristics of our epitaxy overgrown 5 μm μLED, which is compared with and the μLEDs with a diameter of 10 μm fabricated by the conventional dry-etching method (it is difficult to employ a conventional dry-etching method to fabricate μLEDs with a diameter of ≤ 10 μm). Purely from the perspective of the influence of size on capacitance with ignoring any other factors, the μLEDs with a diameter of 10 μm is supposed to exhibit 4 times capacitance as our epitaxy overgrown 5 μm μLED. However, the behaviour of the 10 μm μLED is completely different, and it never ends up going to the negative capacitance region with increasing bias. This is most likely be attributed to that the etching-induced damage is so significant at this μLED size that the sidewalls and/or trapping regions actively contribute to the charge-discharge cycles of the device. As a result, other factors such as surface induced damages instead of the size dominate the capacitive reactance for the μLEDs with a diameter of 10 μm fabricated by the conventional dry-etching method.

We have further compared the C-V characteristic of our epitaxy overgrown μLEDs with a diameter of 40 μm and the μLEDs with a diameter of 40 μm fabricated by the conventional dry-etching method, which is displayed in **Figure 4b**. Similar to **Figure 4a**, the 40 μm one fabricated by the conventional dry-etching method also suffers from parasitic capacitance characteristics under higher biases. Moreover, its starting positive capacitance is higher compared to the overgrown one. Rather than decreasing and flattening out in a curve, however, the μLEDs fabricated by the conventional dry-etching method keeps increasing in capacitance as the bias increases. In contrast, both the overgrown μLEDs in **Figure 4a** and **Figure 4b** demonstrate expected negative capacitance behaviours.

**Figure 5a** shows the RC constants of our epitaxy overgrown μLEDs with different sizes as a function of bias, which have been measured by using the data multiplication of the resistance and the capacitance for each sample. The RC constants of our epitaxy overgrown μLEDs with smaller sizes reach their ‘bottom values’ under high bias, indicating a quick transient response under high bias. Further increasing bias leads their RC constants to tend to be much lower across the board for all bias, down to the range of nanoseconds or even hundreds of picoseconds. For the 40 μm sample, except for its bottomed-out corresponding bias where it shows a pretty low RC, the RC constants in the main range are much higher than those of its 5 and 3.6 μm counterparts. Despite the fact that μLED arrays naturally have parasitic capacitance between devices, [6] the collective RC constant roughly equals the individual device because equal capacitances add and equal resistances divide in parallel. This means that the RC constants are mainly dominated by the size effect for our epitaxy overgrown μLEDs as expected.

**Figure 5b** shows the RC constants of the μLEDs fabricated by the conventional etching method as a function bias. The 10 μm device consistently remains in the range from 10 to 100 ns. The response time of the 40 μm one maintains above μs under all the bias range. In contrast, **Figure 5a** shows that the smaller overgrown μLED devices allows for nanosecond response times. By combining with the reduced leakage characteristics, our epitaxy overgrown μLED devices places them in a good position for high frequency switching applications.

## 4 Conclusion

The leakage and forward currents have been measured on our epitaxy overgrown μLEDs with different sizes, showing a significant improvement in comparison with those μLEDs fabricated by the conventional dry-etching method. The influence of the μLED size on the leakage current has been systematically investigated. Due to the effective elimination of etching-induced damage by an overgrowth approach which is particularly important for smaller μLEDs, it reveals that our smaller overgrown μLEDs have much smaller leakage current than those μLEDs fabricated by the conventional dry-etching method in terms of either leakage current per μLED or leakage current density. Moreover, the μLEDs fabricated by the conventional dry-etching method display a larger dispersion in leakage current, especially for those smaller μLEDs, which is attributed to a high amount of dry-etching induced damages. Furthermore, the RC constants have also been found to be more favourable to the epitaxy overgrown devices. It is expected that our epitaxy overgrown µLEDs will bring about advantages of better pixel-level resolution, high efficiency and energy efficient to applications of micro-display, augmented/virtual reality setups and visible light communication.

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**Conflict of Interest**
The authors declare no conflict of interests.

**Figure Captions**

Figure 1 (a) Scheme and structure of our overgrown µLEDs. (b) A SEM image of a 5 µm µLED array sample.

Figure 2 EL spectra of a 3.6 µm µLED array device. The inset is a photo image under 3 A/cm2 current density.

Figure 3 (a) Forward I-V curves and (b) leakage currents of one overgrown µLED array device. (c) I-V curves of mesa-etched 10 µm and 40 µm single µLEDs.

Figure 4 Capacitances gauged for a single device at 1 MHz. (a) Overgrown 5 µm µLED vs. Mesa-etched 10 µm µLED. (b) Overgrown 40 µm µLED vs. mesa-etched 40 µm µLED.

Figure 5 RC constants of (a) overgrown µLEDs, and (b) mesa-etched µLEDs.

Table 1 Summary of leakage currents of overgrown and mesa-etched µLEDs.

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## Table of Contents (ToC)

# Investigation of electrical properties of InGaN based micro light emitting diode (µLED) arrays achieved by direct epitaxy

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A series of InGaN based micro-LEDs (µLEDs) are achieved using a direct epitaxy overgrown approach on patterned templates, which show bright green emission. Compared to µLEDs fabricated by conventional dry-etching method, the overgrown µLEDs have much smaller current leakage. The RC constants also are found to be more favourable to the epitaxy overgrown devices.