Integrated dual-color InGaN light-emitting diode array through transfer printing

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***Abstract*— We demonstrate an integrated dual-color InGaN light-emitting diode (LED) array by transfer printing blue LED structures from their silicon growth substrate in between the pixels of a pre-processed green LED array on a sapphire substrate.**

I. Introduction

The transfer printing (TP) technique is enabling the heterogeneous integration of micro- and nano-structures onto non-native receiver substrates for the fabrication of multi-functional photonic devices. TP has already impacted on various fields such as flexible photonics, displays, bio-electronics and plasmonics [1-3]. Recently, we have developed a novel TP process with printing resolution below 200 nm [4], using a modified nanolithography system with elastomeric stamps. Based on this technique, we have successfully transfer-printed ultra-thin InGaN light-emitting diodes (LEDs) on different substrates and investigated their electrical, optical and modulation performance. In this work, we further apply this TP technique for hybridizing blue-emitting ultra-thin InGaN LEDs with green micro-LEDs (μLEDs) fabricated on a sapphire substrate. These hybridized devices offer wide applications in areas including multi-color displays and fast optical data transmission.

II. Fabrication and Characterization of the Blue and Green LED Components of the Hybrid Array

The first steps for the demonstration of the dual-color LED array on a single chip are the separate fabrication of green μLEDs on their sapphire substrate and of suspended ultra-thin blue LEDs on their silicon substrate. The fabrication process and performance of LEDs from each is described in this section.

A. Green-emitting InGaN micro-LEDs

A green-emitting flip-chip μLED is fabricated from a commercial 520nm InGaN epistructure grown on a sapphire substrate. In order to achieve high injection current density and therefore high modulation bandwidth [5], the disk-shaped μLED is designed with a small diameter of 20 μm. The μLED is fabricated following the conventional process for InGaN-based LED [5] with an additional deep etch step down to the sapphire substrate. This additional step is to compensate for height differences between the blue and green LEDs in further TP processing. Fig.1 shows the measured electrical, optical, and modulation performance of this green μLED. The ability to drive the μLED to a high current density means an electrical to optical (E-O) bandwidth over 400 MHz can be achieved at a current density of 10000 A/cm^2 [Fig. 1(c)].

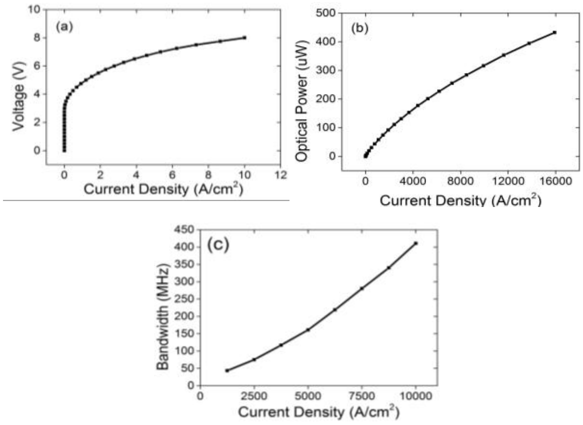

Figure 1: a) current density-voltage, b) current density-optical power, and c) current density-modulation bandwidth of a 20μm green InGaN-on-sapphire micro-LED.

B. Blue-emitting ultra-thin InGaN LEDs

Suspended, 100μm x 100μm ultra-thin InGaN-based LEDs emitting around 460 nm are fabricated from a LED epistructure grown on silicon. The detailed structure can be found in [6]. Here, we emphasize the design of sacrificial anchors to suspend the LED as highlighted in Fig. 2(a). These GaN-based anchors are defined by plasma etching and used to support the ultra-thin LED epilayers (thickness of 2 μm) during KOH under-etching to remove the silicon substrate. These anchors are vital to keep the thin LED structure from detaching from the wafer before the TP process. During TP, these ultra-thin LEDs are picked up from the silicon wafer by breaking the sacrificial anchors and transferred to the receiver substrate - in this case the sapphire substrate on which the green-emitting μLEDs have been fabricated.

The performances of these ultra-thin LEDs when printed onto different receiver substrates are shown in Fig. 2(b) to Fig. 2(d). When transfer printed onto a silica glass substrate they demonstrate an optical power up to 200 μW, Fig. 2(b), and an E-O modulation bandwidth up to 50 MHz, Fig. 2(d). When printed onto diamond these devices achieve an optical power of over 700 μW and an E-O

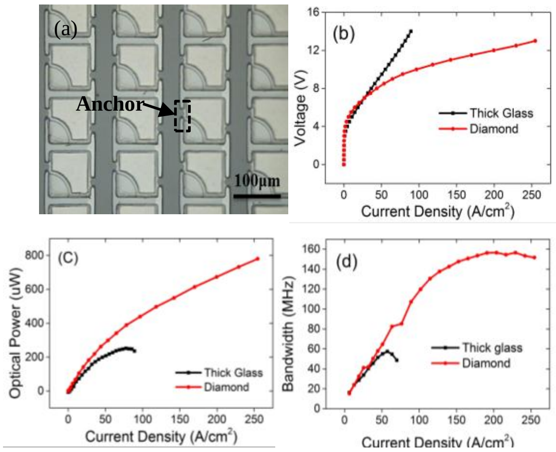

Figure 2: a) section of array of ultra-thin InGaN LEDs for TP, and b) current density-voltage, c) current density-optical power, and d) current density-modulation bandwidth for comparison between TP LED on glass and diamond substrates.

modulation bandwidth of 156 MHz. Through these comparisons, we can conclude that the achievable performance from these ultra-thin LEDs is strongly dependent on how efficiently heat can be removed from them through the receiver substrate. Therefore transfer printing onto a material with high thermal conductivity is preferable for further applications. We therefore anticipate for two-color integration that the ultra-thin LEDs printed onto sapphire, which has a thermal conductivity (23 $Wm^{-1}K$) between that of silica (1.4 $Wm^{-1}K$) and diamond (2000 $Wm^{-1}K$), will achieve relatively high optical power and modulation bandwidth.

III. BLUE-GREEN HYBRIDIZED DEVICE

As a first demonstration of dual color integration, an ultra-thin blue LED is printed next to a green one through our novel TP technique as shown in Fig. 3. In the TP process, a modified nanolithography system(NLP) is used to pick up the ultra-thin blue LED from the growth wafer with an elastomeric stamp. The stamp is fabricated with a pyramidal protrusion on each corner such that it fractures the LED supporting anchors and picks up the LED. Then the ultra-thin blue LED is bonded to the sapphire substrate of the green μLED via a combination of van der Waals forces and capillary bonding from wetting of the LED backside. The NLP used for TP allows for accurate placement of LEDs and high precision printing. The ultra-thin blue LED can therefore be accurately placed next to the green μLED and there is little limitation on the spacing between pixels (100 μm in this design), which is advantageous for color-mixing and dual color data transmission.

Further steps in this process include electrical insulation and metallization for ultra-thin blue LED printed on the sapphire substrate. Removal of the silicon substrate during the underetch step allows compressive strain engineered into the AlGaN buffer layers in the epistructure to induce curvature in the LED, which we address by deposition

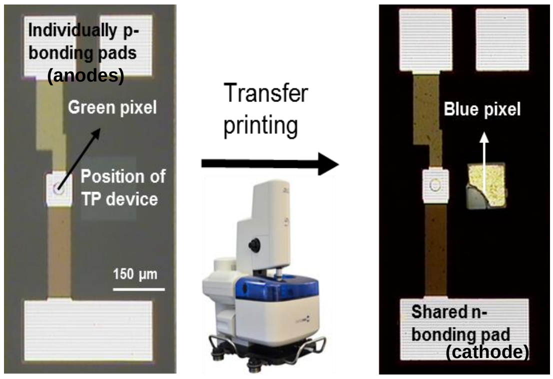

Figure 3: The design of the dual-color array before, and after transfer printing of the ultra-thin blue LED. The NLP used for transfer printing is shown in the middle of the figure.

of a thick insulation layer before metal track deposition. Once this insulation layer is deposited and patterned, Ti/Au metal tracks are deposited, after which the pixels in the dual-color array are individually addressable via their own anode and a common cathode, Fig. 3. This means that each LED can be individually controlled and therefore different color-mixings and modulation bandwidths from the array can be achieved. Our early test results on the two-color device are currently being expanded into full characterization, the results of which will be presented.

IV. CONCLUSION

In this work, we have proposed a novel approach to achieve a dual-color integrated InGaN LED array on a single chip through a TP process with high precision. The separate green and blue components of this array have been successfully fabricated and their performance has been fully studied. First results of the integration have been achieved using our ultra-precision printing capability and full characterisation is underway. Color mixing and dual-wavelength optical data measurements are being studied.

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