Maskless Fabrication of GaN-Based Light-Emitting Diodes

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Abstract: A versatile maskless process flow was developed to fabricate a GaN-based individually-addressable LED array. This new fabrication approach combines CMOS-controlled micro-LED writing and silver nanoparticle inkjet printing. An array filling factor of 99% was achieved.

Introduction: Standard manufacture of light-emitting diodes (LEDs) requires several etching and lift-off fabrication steps. Most of these steps require patterning of photoresist (PR) by ultraviolet (UV) exposure through a hard quartz-based photomask designed for a particular fabrication step. Consequently, each change in design requires the production of a new photomask. Fabricated by electron-beam lithography, these photomasks can cost anywhere between one and many thousands of dollars depending on the pattern resolution. Consequently maskless fabrication approaches have attracted much attention as they could achieve significant reduction in the fabrication cost and process time. Several maskless methods have been developed the past decade including laser writing, interference writing, inkjet printing and zone-plate-array lithography, and have already been used for the fabrication of photonic devices [1,2]. A maskless approach would greatly benefit the fabrication of LED array as their processing requires many lithography steps.

We present here an entirely maskless process flow for the fabrication of GaN-based individually addressable LED arrays. This new approach is based on the use of complementary metal-oxide-semiconductor (CMOS)-controlled micro-LED UV writing and silver (Ag) nanoparticle inkjet printing. The LED arrays thereby fabricated have a filling factor of 99% for an output power up to 2mW per pixel and are fully compatible with flip-chip bonding. They are fabricated in a suitable configuration for many applications including lab-on-chip sensors, micro-displays and time-resolved spectroscopy [3].

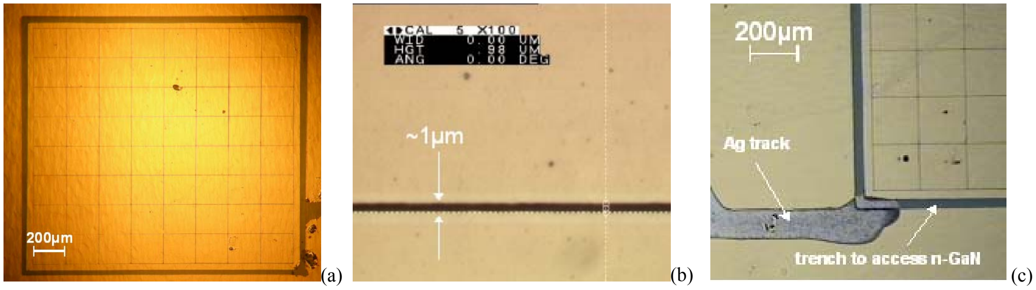

Fig. 1: Optical micrographs of the tessellated LED array. (a) before the inkjet printing step, (b) close-up view of a trench and (c) close-up view of a silver track.

Fabrication: The target being to demonstrate a fully maskless process flow, *all* the fabrication steps requiring the use of a hard photomask were replaced by alternatives. Photoresist (PR) patterning steps relied on the use of CMOS-controlled UV LED writing via a 10:1 demagnifying imaging system [4]. The UV device used for this work consists of a 370nm-emitting 8x8 micro-LED array with different pixel diameters ranging from 84µm down to 14µm. The elements of the array are controlled independently by a matched array of CMOS drivers directly bonded at the back of the micro-LEDs [5]. The sample underneath an imaging setup is moved by a computer-controlled XY stage. A Fujifilm Dimatix DMP-2800 inkjet printer was used for Ag deposition with a 10pL droplet delivery cartridge filled with commercially available Ag nanoparticles suspended in a solvent mixture.

The GaN-based LED array was fabricated from a commercial p-i-n LED wafer grown on c-plane sapphire, with its peak emission wavelength at 450nm. First, the wafer was cleaved and cleaned in successive baths of acetone, methanol, isopropanol and deionised water then dried with a nitrogen flow. The clean chip was first soaked for 3min in an 18% aqueous HCl solution to remove the native oxide, then rinsed for 3min in deionised water. Immediately afterwards, deposition with an electron beam evaporator of a bilayer of Ni/Au (6nm/6nm) was performed, followed by rapid thermal annealing at 500^{o}C for 120s in an oxygen-nitrogen ambient to form semi-transparent ohmic contacts to the p-doped GaN layer. Next, an optical mirror consisting of a 50nm/200nm Ti/Au bilayer was deposited by sputtering, followed by a plasma-enhanced chemical vapour deposition of a 500nm-thick SiO_2 layer to be used as a hard mask for the subsequent mesa etching. Finally a 500nm-thick PR (Microposit S1805) was spin-coated and soft-baked according to the vendor's datasheet in preparation for the micro-LED writing.

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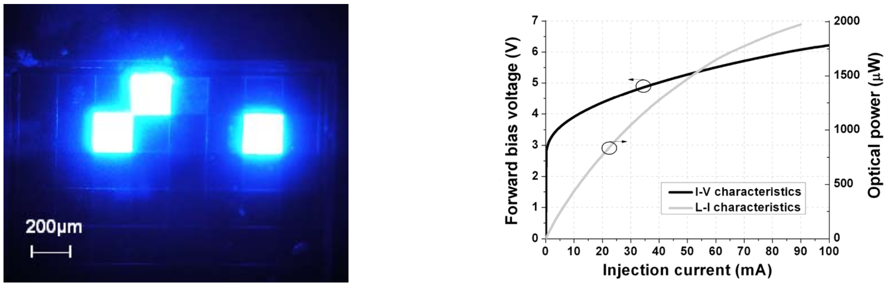
The maskless patterning to define the LED mesa was performed with the micro-LED direct writing system at a linear translation speed of 70µms^{-1}. A single 14µm-diameter pixel (demagnified to 1.4µm spot size in the imaging system) was used for all the LED writing processes giving an exposure dose of about 40mJcm^{-2}. The PR was then developed using a standard developing solution. A *tessellated-type* LED array design was chosen which consists of an array of 8x8, 200µm x 200µm LEDs with a targeted 1µm gap between adjacent pixels, resulting in a 99% filling factor array. A frame of 35µm width around the array was also added in the design to have an easy access to the n-doped GaN layer for subsequent metal contact deposition. This pattern was then transferred to the SiO_2 layer by reactive ion etching (RIE) and a multistep process combining RIE and inductively coupled plasma etching was used to etch the metal stack and the GaN-based layers down to the n-GaN, resulting in a 8x8 n-shared mesa array. Finally the residual SiO_2 layer was stripped off the sample and Ag contacts and tracks were deposited by inkjet printing. The Ag nanoparticles were printed at 23°C ambient with a cartridge temperature of 30°C and 3.3m.s^{-1} drop velocity for optimum drop formation. A 35µm drop separation was chosen to give suitable droplet coalescence on the sample to generate smooth continuous metal tracks. Heating at 200°C for 2 hours evaporated the residual solvent from the metal tracks, and also improved the tracks' conductivity through sintering. The target was to achieve a resistivity as close as possible to the value of the bulk material (1.59µΩ.cm in the case of Ag). The resistivity of the Ag tracks thereby obtained was previously measured to be 3.8µΩ.cm. The device was finally wire bonded in a flip-chip configuration on a printed circuit board for characterisation purposes.

Experimental results and discussion: An optical micrograph of the tessellated device before inkjet printing of silver tracks is shown in Fig. 1a. We see that each trench is perfectly defined with an average width close to the targeted value of 1µm, as shown in Fig. 1b. Fig. 1c shows one of the printed Ag tracks. One sees that the silver track partly covers the n-GaN-access trench but does not touch the LED mesa, ensuring electrical contact without any short-circuit of the LED junction. Fig. 2a shows an optical micrograph of the tessellated LED array with few pixels turned on, demonstrating the individually-addressable capabilities of the device. Typical injection current versus forward bias voltage (I-V) and optical output power versus injection current (L-I) characteristics per pixel are shown on Fig. 2b. The optical output was measured from the back side of the device (through the transparent sapphire substrate) using a power meter and a calibrated Si photodetector placed in close proximity. The device shows good electrical and optical performance with a maximum output optical power of 2mW per pixel at an injected current of 90mA. A higher turn-on voltage (~4V) than typical for GaN-based LEDs (~3V) is observed, probably due to the higher potential barrier at the Ag – n-GaN interface compared with a more standard n-metal contact such as Ti/Au.

Conclusion: A fully maskless process flow was developed to fabricate a GaN-based LED array. As a demonstrator, an individually-addressable GaN-based 8x8 LED array emitting at 450nm was fabricated. Micro-LED writing was used to define 200µm x 200µm mesas with a gap of only 1µm between adjacent pixels, providing an array filling factor of 99%, and Ag inkjet-printing was used to create the metal tracks and n-GaN contacts. With a maximum output optical power of 2mW per pixel at an injected current of 90mA (at ~6V), the device shows good electrical and optical performance demonstrating the feasibility of this maskless fabrication approach combining flexibility and low cost.



(a) (b)

Fig. 2: (a) Optical micrograph of 3 turned-on pixels and (b) typical I-V and L-I characteristics per pixel from the tessellated LED array.

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