Sub-micron lithography using InGaN micro-LEDs: mask-free fabrication of high-fill factor LED arrays

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Abstract—The fabrication of gallium-nitride based (GaN) light emitting diode (LED) arrays by a direct writing technique, itself using micron-sized LEDs (micro-LEDs), is reported. CMOS-driven ultraviolet GaN-based micro-LED arrays were used to pattern photoresist layers with feature sizes as small as 500nm. Chequerboard-type square LED array devices were then fabricated using such photoresist patterns based on either single pixel or multi-pixel direct writing, and implemented as part of a completely mask-less process flow. These exemplar arrays comprised either 450nm-emitting $199 \times 199 \mu m^2$ pixels on a $200 \mu m$ pitch or 520nm-emitting $21 \times 18 \mu m^2$ pixels on a $23 \mu m$ pitch. Fill-factors of 99% and 71.5% were achieved with optical output power densities per pixel of $5W/cm^2$ and $20W/cm^2$ at 90mA and 6mA dc injected currents, respectively.

Index Terms—Gallium nitride, micro light-emitting diodes (micro-LEDs), nanolithography, semiconductor device manufacture

I. INTRODUCTION

Standard manufacture of semiconductor devices requires multiple fabrication steps which involve patterning of photoresist (PR) by ultraviolet (UV) light exposure through a series of customized quartz-based photomasks. Consequently, each change in design requires the production of one or more new and expensive photomasks. As an alternative, maskless fabrication approaches have attracted much attention as they offer flexibility and significant reduction of fabrication cost. Several maskless methods have been developed including laser direct writing, 2-photon writing, interference lithography and inkjet printing, and these techniques have already been used for the fabrication of optoelectronic devices.[1-3] III-nitride semiconductor technology can already provide efficient LEDs with peak emission wavelengths around 365nm and 405nm, corresponding respectively to the i-line and h-line emissions from mercury discharge lamps used in mature photolithography. However, related III-nitride LEDs are also being developed offering emission into the deep UV, compatible with the majority of photo-acid generators and more advanced optical lithography.[4] In addition, III-nitride LEDs offer many advantages compared to mercury lamps,

including compactness, low power consumption and no content of toxic material. Furthermore, the output power of these LEDs and their emission mode (pulsed and dc) can be easily changed via an integrated electronic driver circuit. Several proof-of-concept demonstrations of micro-patterning by LED direct writing have already been made using either conventional broad-area devices or micro-LEDs (we consider an LED as "micro" when one of its dimensions is below $100 \mu m$).[5-7] Feature sizes as small as $20 \mu m$ were obtained by using proximity exposure with micro-LEDs, while similar feature sizes have also been obtained using a broad-area LED source coupled to a microscope objective.[5,6] The use of micro-LEDs brings the primary advantages of offering a large density of emitters on a small-scale chip, and a higher power density per pixel than broad-area LEDs.[8]

We report here on the use of 8x8 micro-LED arrays with pixel sizes as small as $14 \mu m$-diameter in an imaging optical setup (similar to the setup in ref. [10] but with a 10:1 demagnification) to pattern PR with features down to 500nm-width in order to process GaN-based LED hetero-structures.[9,10] First, a single pixel was used to pattern a sacrificial PR mask for a "chequerboard-type" array with individually addressable LEDs emitting at 450nm.[11] The chequerboard device was designed with a targeted $1 \mu m$ gap between adjacent pixels, resulting in a 99% filling factor arrays in a suitable configuration for subsequent flip-chip bonding to custom complementary metal-oxide-semiconductor (CMOS).[9,13] Typical measured optical output powers here were 2mW ($5W/cm^2$) per pixel at a driving current of 90mA. Parallel direct writing is then implemented using 2 micro-pixels each of $24 \mu m$ diameter to create a 32x32 chequerboard design emitting at 520nm. This had $21 \times 18 \mu m^2$ pixels on a $23 \mu m$ pitch, each delivering $77 \mu W$ ($20W/cm^2$) at 6mA injection current. These arrays were fabricated in a suitable configuration for applications including lab-on-chip sensors, micro-displays, time-resolved spectroscopy and optoelectronic tweezing,[12,13] and provide demanding demonstrations of the capabilities of micro-LED direct writing in the rapid and accurate fabrication of active optoelectronic devices.

II. MICRO-LED MASK-FREE LITHOGRAPHY

This work used micro-LED arrays emitting at a wavelength of 370nm, flip-chip bonded onto a CMOS silicon backplane.[9,13] The micro-LED device is an 8x8 array of micro-disk pixels on a $200 \mu m$ pitch with diameters progressing from $84 \mu m$ to $14 \mu m$ in $10 \mu m$ steps. The pixels are arranged in rows with fixed pixel diameters. All the pixels share a common negative electrode (n-contact) and are individually addressed through their respective positive contact (p-contact). Each pixel is provided with a $92 \times 92 \mu m^2$ separate bonding pad, connected to the pixel with a metal track

to complete the positive connection (inset Fig. 1.). This method of off-pixel bonding facilitates contacting of small-sized pixels to enable the highest direct writing resolution. CMOS driving offers the capability of individual dc and pulsed operation of the micro-LEDs down to few hundreds of picoseconds through a computer-controlled interface as well as projection of programmable patterns.[9] The forward bias voltage versus current of representative CMOS-bonded 14µm and 24µm-diameter pixels is shown in Fig. 1. Turn-on voltages estimated with the tangent method are about 6V and 5.5V respectively, and currents of 20mA are reached for bias voltages of 7.6V and 7.1V, respectively. The CMOS chip design allows a maximum forward bias of 8V. Typical optical output powers were measured with a large-area Si photodetector placed in near contact above the device, so as to collect all of the front-emitted optical power. Typical optical output powers as a function of injected current are plotted in Fig. 1. At 20mA, optical power of 210µW (14µm device) and 275µW (24µm device) were measured.
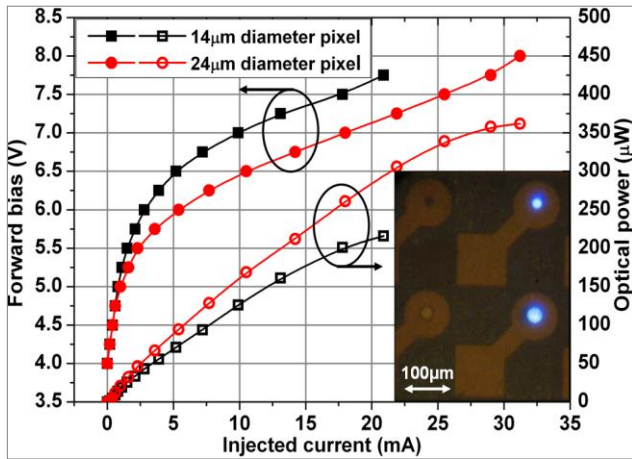

*Fi*g. 1. : Voltage and optical output power versus injected current of two representative pixels of 14µm and 24µm in diameter emitting at 370nm. Inset, an optical micrograph of representative pixels of 14µm and 24µm diameters individually addressed from the 8x8 micro-LED arrays.

In the following direct writing experiments, micro-LEDs are imaged using an optical setup as in [10], using a 4x and 40x microscope objectives for collection and projection, respectively, and demagnifying the pixels by a factor 10. The sample covered with PR is placed on an X-Y translation stage and positioned at the focus using the high-resolution z-stage supporting the 40x projection microscope objective.[10] The writing process itself is entirely automated through a computer interface. For the first demonstration, single micro-LEDs were used to evaluate the writing performance of the setup. The CMOS was configured to drive in dc mode at a voltage of 5V and the power densities were measured at focus in this configuration for all the pixels of diameters 14µm and 24µm (Fig. 2(a)). Average optical power densities of 1.7W/cm^2 and 1.2W/cm^2 with variances of 0.3W/cm^2 and 0.2W/cm^2 are calculated from these sets of results. The velocities of the X-Y stages are controlled to deliver the appropriate exposure dose and to adjust the feature size written into the PR. Typical writing speeds range from 20µm/s to 140µm/s leading to

average exposure doses at focus of 280mJ/cm^2 down to 40mJ/cm^2 for the 14µm-diameter pixel and from 360mJ/cm^2 to 51mJ/cm^2 for the 24µm-diameter.[10] Feature sizes written at different velocities by both pixels were investigated by atomic force microscopy (AFM) over an area of 5x5µm^2 of the patterned region. Trenches were written in resist S1805 (600nm thick) which requires an exposure dose at 370nm of 40mJ/cm^2 (value from manufacturer's datasheet). Fig. 2 (b) summarizes the measured trench bottom widths for these writing experiments ranging from 9µm down to 2µm and 6µm down to 0.5µm for the 24µm and 14µm-diameter pixels, respectively. The inset of Fig.2 shows a 500nm base-width trench realized with the 14µm-diameter pixel at a writing speed of 140µm/s. The profile shows a significant non-verticality of the trench sidewalls, resulting from the intrinsic exposure profile of the PR film, but not posing limitations for the microfabrication applications envisaged.
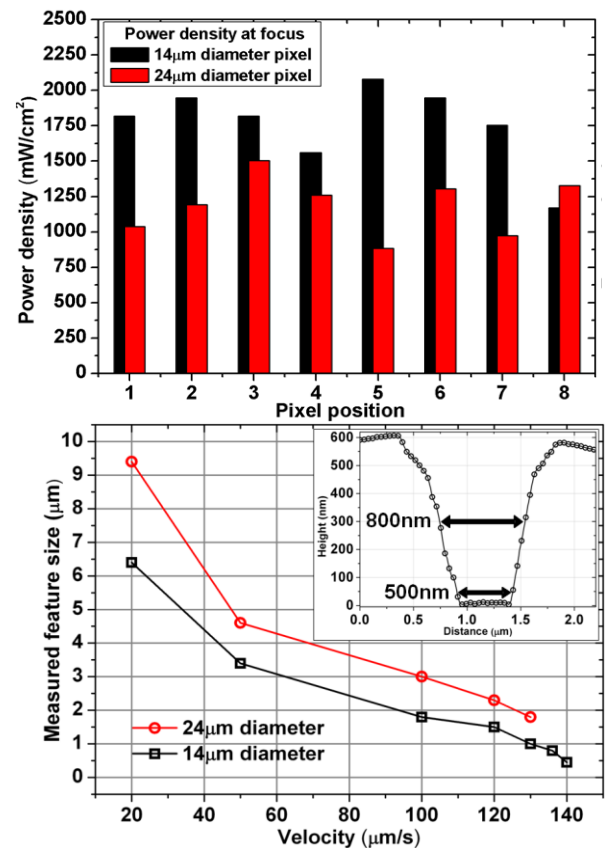

Fig. 2. : a) Optical power densities evaluated at focus for pixels diameter of 14µm and 24µm (1.4 and 2.4µm diameter at focus, respectively) for a drive voltage of 5V. b) S1805 PR feature sizes (trench bottom) exposed by representative pixels of each diameter upon increased stages velocity. Inset: AFM scan profile of a S1805 trench written at 140µm.s^{-1}.

III. DEVICE FABRICATION AND CHARACTERIZATION

First, a chequerboard-type LED design with an 8x8 array of 200µm-pitch, 199x199µm^2 LEDs was chosen as a demonstrator device, as each pixel can be easily individually wire bonded. Also it is directly compatible with the CMOS-backplane technology which has been developed to bond and drive our custom LED array devices.[9] The chequerboard GaN-based LED array was fabricated from a commercial p-i-n

LED wafer grown on c-plane sapphire, with a peak emission wavelength of 450nm. After a de-oxidation step in HCl, the deposition of a bilayer of Ni/Au (10nm/20nm) was performed by electron beam evaporation, followed by rapid thermal annealing at 500ºC for 120s in purified air ambient to form semi-transparent ohmic contacts to the p-doped GaN layer. Next, a 50nm/200nm Ti/Au bilayer (used both as high reflectance mirror and high conductance electrode) 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 subsequent etching. A 600nm-thick PR film was spin-coated and soft-baked according to the vendor's datasheet in preparation for the micro-LED pattern writing. The maskless patterning to define the LED mesa was performed at a linear translation speed of 140μm/s using a single 14μm pixel. The velocity was then reduced to 10μm/s in order to write a large frame around the emission area for access to the n-doped GaN (see Fig. 3(a)). The PR was then developed using a standard solution providing minimum features of about 560nm in width on average forming the 8x8 array and a surrounding frame of about 35μm width around the array. This pattern was then transferred to the SiO_2 layer by reactive ion etching and a multi-step process combining wet and inductively coupled plasma etching was used to etch the metal stack and the GaN-based layers down to the n-GaN layer, resulting in an 8x8 n-shared mesa array. Finally the residual SiO_2 layer was stripped off the sample by wet etching. An optical micrograph of the chequerboard device's p-contact side after processing is shown in Fig. 3(a), left. Each trench is well defined with an average width close to the targeted value

of 1μm (Fig .3(a), right). The final gaps between pixels are larger than the PR feature defined by the mask-less lithography (560nm) owing to the finite isotropic component of the various dry etch steps acting on the sidewalls.

An inkjet printing step of silver (Ag) nanoparticles defined metal tracks to connect the shared n-GaN in order to avoid a metal lift-off step and thus to demonstrate a full maskless fabrication process. The Ag nanoparticles (Silverjet DGP, 40% w/w) were printed with a Dimatix DMP-2800 system with a 35μm drop separation to give suitable droplet coalescence on the sample to generate continuous metal tracks.[14] Heating at 200ºC for 2 hours evaporated the residual solvent from the metal tracks and improved the tracks' conductivity through sintering. The resistivity of the printed tracks was measured using a 2-point probe method knowing the cross-section (measured by profilometry) and the length between probes (measured on a test sample with SiO_2 as substrate). After sintering, the resistivity of the Ag tracks thereby obtained is 15.4μΩ.cm (versus 1.59μΩ.cm for bulk Ag). Each pixel was finally individually wire bonded to a printed circuit board for characterization purposes. The inset of Fig. 3(b) shows an optical micrograph of the chequerboard-LED array with representative pixels turned on, demonstrating the individually-addressable capabilities of the device. The electrical and optical performance of the array was assessed. Typical injection current versus forward bias voltage (I-V) and optical output power versus injection current (L-I) characteristics of a representative pixel are shown in Fig. 3(b). The directed 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 ($5W/cm^2$) at an injected current of 90mA ($750μW$ - $2W/cm^2$ at 20mA injected current). A typical voltage of 4.3V at 20mA is measured which is somewhat higher than a typical GaN-based LED (usually around 3V). This is likely due to the lower conductivity of the nanoparticle Ag ink and the higher potential barrier at the Ag/n-GaN interface compared with a more standard n-metal contact such as Ti/Au, but is illustrative of the potential for a fully maskless LED fabrication process flow.

The parallel writing capability of our setup was then demonstrated with 2 adjacent 24μm-diameter pixels (namely pixels 7 and 8 from Fig. 2(a)) driven at the same forward bias voltage, 7.5V (25.5mA typical dc injected current). The pixels were both placed within the field of view of the collection microscope objective so that their emission is collected altogether. In this configuration and driven individually, each pixel delivers a different optical power at focus of 0.163μW ($3.6W/cm^2$) and 0.17μW ($3.75W/cm^2$), respectively, due to variation in pixel-to-pixel performances as shown in Fig. 2(a). However, due to the characteristics of the CMOS design, the current flowing through the chip when several LEDs are driven simultaneously induces a voltage drop at the LED electrodes due to the ground bounce effect.[15] Consequently, when driven
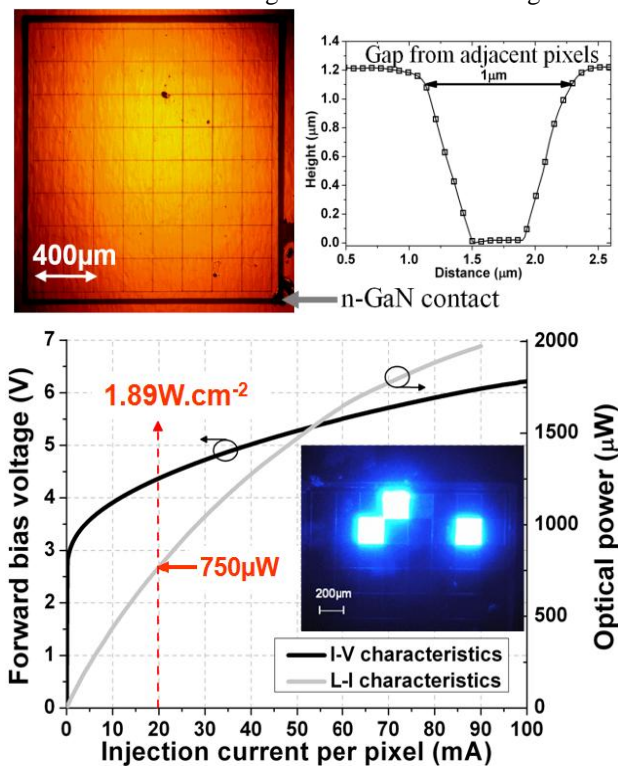

Fig. 3. : a) Optical micrograph of the entire 450-nm emitting 8x8 array (left) and AFM scan profile of a representative gap between adjacent pixels of the array (right). b) I-V and L-I characteristics of a typical pixel of the 8x8 array with, inset, an optical micrograph of several pixels individually addressed.

simultaneously, the optical power projected is not the sum of the individual optical powers, instead a total optical power at focus of 0.131µW (2.9W/cm^2) is estimated per driven pixel. The chequerboard-design was again chosen to illustrate the lithographic capability in this case for high density micro-LED arrays emitting at 520nm. An array of 32 x 32 elements with a 23-µm pitch was thus coded for a 2 pixel writing experiment. In the vertical direction (direction according to inset of Fig. 4.) each trench is exposed using a single pixel while, in the horizontal direction, both pixels are used consecutively. The writing speed was fixed to 100µm/s in vertical giving a typical exposure dose of 69mJ/cm^2, and 200µm/s in the horizontal direction to take into account the overlapping exposure path from the two pixels. After PR patterning, the same etching process was applied as described previously resulting in an array of individually-addressable rectangular pixels. In this case the resulting fill-factor is reduced to 71.5% with 21x18µm^2 pixels as shown in the optical micrograph inset of Fig. 4. Probes were used here to electrically and optically characterize the device. Fig. 4 summarizes the typical I-V and L-I curves for a pixel of the array. The pixel delivers an optical power of 77µW at an injection current of 6mA, giving an optical power density of 20W/cm^2 with current density of 1.6kA/cm^2.
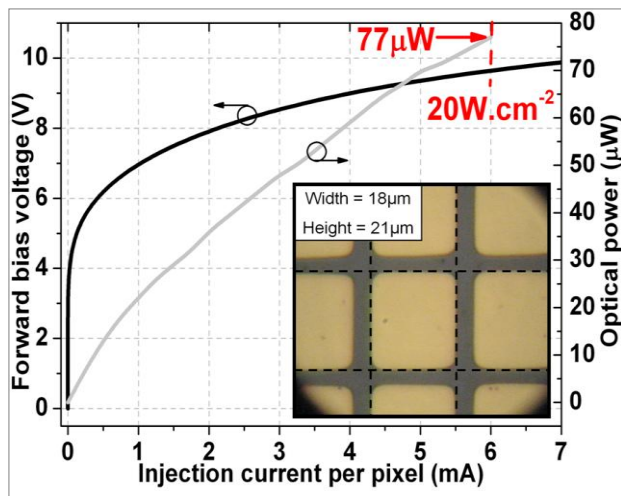

Fig. 4. : I-V and L-I characteristics of a typical pixel of the 520-nm emitting 32x32 elements array with, inset, an optical micrograph centered on a pixel from the array.

IV. CONCLUSION

A custom-made 370-nm emitting micro-LED array bonded on CMOS backplane was used as a maskless photolithography tool to fabricate complex and tailored optoelectronic devices through the use of an optical demagnifying setup and computer control. This direct writing technique was first used to pattern PR layers giving features as narrow as 500nm at 140µm/s writing velocities. In combination with wet and dry etching and inkjet printing, custom designed 450nm emitting, 99% fill-factor, 8x8 broad-LED array and 520nm-emitting 32x32 micro-LED array were fabricated by single and two-pixels parallel writing respectively. Typical optical output powers

emitted by a single element were measured to be up to 5W/cm^2 and 20mW/cm^2, respectively, at injected current of 90mA and 6mA. These results demonstrate the advantages of micro-LED maskless lithography, including re-configurable written patterns with sub-micron feature sizes and multi-beam parallel writing and implementation as part of a mask-less process flow, to address the easy fabrication of complex optoelectronic and photonic devices such as, but not limited to, GaN-based LED arrays.

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