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Micro-pixel flip-chip AlInGaN LED arrays with high CW and nanosecond output power

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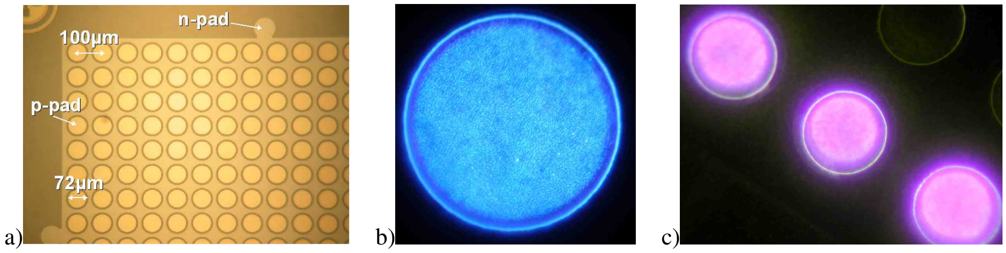
Abstract: Flip-chip AlInGaN micro-LED arrays with different wavelengths and pixel diameters have been fabricated, giving, per pixel, CW output power densities up to 32.5W/cm^2 at 20mA and pulsed output of up to 150pJ in 36ns pulses.

1. Introduction

Micro-pixellated GaN-based light-emitting diodes (‘micro-LED’s) at visible and ultraviolet wavelengths are emerging as an attractive technology for a wide range of scientific and instrumentation uses. These include mask-free lithography [1], chemical and biological detection [2], micro-projection displays and even integrated polymer and optofluidic laser pumping. Embodying such devices in flip-chip format offers the benefits of improved performance, control via a silicon backplane and the use of the sapphire upper surface of the devices as a planar substrate for further stages of integration. Here, we report the fabrication and characterization of different formats of flip-chip micro-LED devices at both 370nm and 470nm. We show that these devices can operate with high CW output power densities *per pixel* of several 10’s of Watts per square cm. Furthermore, with the objective of integrated laser pumping in mind, we investigate the high-power pulsed performance of these devices in the nanosecond regime, and demonstrate that output optical pulse energies of up to 150pJ in 36ns can be achieved.

2. Design and fabrication of the devices

The flip-chip micro-LED devices consist of an array of either 16x16 pixels (device type A) or 32x32 pixels (device type B). The former devices have a pixel diameter of 72µm on a 100µm pitch; the latter have a pixel diameter of 30µm on a 60µm pitch. The epitaxial structures for 370nm and 470nm, together with the overall device fabrication sequence, are similar to our earlier reports for ‘epi-up’ devices [3, 4]. The mesa structure of each individual micro-LED was first defined by standard photolithographic patterning and inductively coupled plasma (ICP) etching. Then, a pre-metallization HCl acid treatment was applied and Ni–Au transparent contacts were evaporated on the p-contact area. The contacts were alloyed by rapid thermal annealing (RTA) in air. An Al metal layer was then deposited and patterned onto the transparent p-contact to serve as a light reflector. The n-type metallization was formed by Ti-Au deposition to fill the area between each of the LED elements. Finally, a SiO_2 protective layer was deposited and patterned by plasma enhanced chemical vapour deposition and reactive ion etching. To facilitate the future integration of micro-optical elements, the sapphire substrate of each device was thinned down to 80µm and polished. The flip-chip LED devices were then wire bonded onto a printed circuit board for testing. Figs. 1(a,b,c) show representative optical micrographs of the devices, all imaged through the polished sapphire substrate. Fig. 1(a) shows a substantial portion of a 16 x 16 array chip with the n- and p-contact pads indicated. Fig. 1(b) shows a representative operating blue pixel, in this case of 72µm diameter. Fig 1(c) shows representative operating UV pixels, this time of 30µm diameter. One can see from these pictures that the light emission is quite uniform not only within each pixel but also across the array due to the good current spreading.



Figs 1 – Optical micrographs from the back side (through the sapphire substrate) of (a) a 16x16 LED array, (b) a 72µm diameter switched-on blue pixel, and (c) of three adjacent 30µm diameter switched-on UV pixels.

3. Experimental results and discussion

Fig. 2 (a) shows typical current vs. voltage (I-V) characteristics of a single pixel performed under direct current (DC) bias conditions at room temperature. The device A emitting at 470nm presents the best performance

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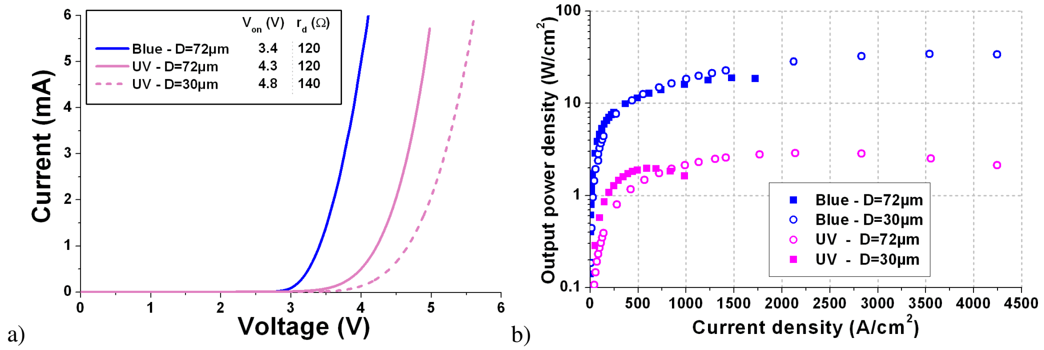
with a turn-ON voltage $\mathbf{V_{on}}$ of 3.4V and a diode series resistance $\mathbf{r_d}$ of 120Ω. The results reveal that $\mathbf{V_{on}}$ and $\mathbf{r_d}$ increase when the emission wavelength decreases and also when the size of the micropixel is reduced. A number of factors are thought to contribute to this, including differences in bandgap and carrier confinement, poorer crystalline quality of the UV active structure and higher sheet resistance of the p-contact. Light output power characteristics were measured by placing the devices directly above a calibrated Si-photodetector. Fig. 2 (b) shows the output power density vs. current density of our devices for both wavelengths under DC bias. As expected, the results show that at the same injection current density the blue emission devices present an output power much higher than the UV ones (roughly one order of magnitude), but we can also see that whatever the emission wavelength and despite their slightly higher turn-on voltages, the micro-LEDs with reduced size are able to sustain a much higher injection current density before roll-over (power saturation) appears. Indeed, whereas the blue (respectively UV) device A output power starts to decrease from a current density of 1.5kA/cm^2 (0.7kA/cm^2), the blue (UV) device B output power increases continuously with current densities up to 3.5kA/cm^2 (2kA/cm^2). The blue device B reaches a maximum output optical power density of 34.5W/cm^2. We tentatively associate this improvement of the device robustness when the pixel size is reduced to better thermal dissipation. The reasons for this thermal enhancement are still under investigation, but our initial presumption is that this comes from better current spreading, increased surface area to volume ratio, and a reduced self-heating effect in small mesa structures [5]. We would like also to emphasize that device type B has shown the capability to endure *extremely high current densities up to 4.3kA/cm^2* before breakdown for both wavelengths.

Given that one objective for these devices is to pump polymer lasers, we also investigated device A under nanosecond pulsed operation with the idea of obtaining maximum output power. With a 500 kHz Kentech Ltd. high-speed LED driver, the micro-LEDs were able to deliver 10ns-width optical pulses with a maximum energy per pulse of 20pJ at 470nm and of 10pJ at 370nm. These results are very close to the state of the art for polymer laser pumping which required energy for threshold of 45pJ/pulse with pulse width of 10ns in a spot size readily achievable with our devices [6]. We also made some preliminary tests with a custom laser diode driver [7] enabling us to apply higher voltages and lower repetition rates. In this case, at a repetition rate of 1 kHz and for a pulsewidth of 36ns at 470nm, we obtained optical pulses with an energy as high as 150pJ (peak output power density of 100W/cm^2 averaged over the output surface of the micro-LED pixel). We expect further improvements with the smaller pixel devices and more optimised driving conditions currently under investigation and will report fully on this.



Figs 2 – Typical I-V (a) and L-I (b) characteristics of a single pixel emitting at 470nm or at 370nm and respectively for the devices A (D=72µm) and B (D=30µm). $\mathbf{V_{ON}}$ and $\mathbf{r_d}$ for each I-V curve are also indicated on (a).

4. Conclusions

In summary, we have presented the characteristics of blue and UV flip-chip micro-LED array devices. Experimental results show that, whatever the emission wavelength, the decrease of the pixel size enables the micro-LED to provide much higher optical power density and to sustain very high current density. We have also demonstrated that pulsed output with energy up to 150pJ/pulse in 36ns can be achieved which opens the way to integrated polymer laser pumping.

References:

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