High-Resolution 128 × 96 Nitride Microdisplay

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***Abstract*—Matrix-addressable arrays of InGaN micro-light-emitting diodes with 128 × 96 pixels and a resolution of 1200 dpi have been fabricated using a novel "sloped sidewall" process. The devices have been fabricated on InGaN blue and green wafers, emitting light at the wavelengths of 468 and 508 nm, respectively. A simple circuit, which enables the display of an arrow pattern with ∼60% of the pixels turned on, was used for device testing. At an injection current of 60 mA, the devices deliver 3.3 (blue) and 2.4 mW (green) of output power, corresponding to a luminance of more than 30 000 Cd/m^2. These high-brightness and highly versatile devices are certainly an attractive form of emissive micro-display.**

***Index Terms*—InGaN, light-emitting diode (LED), micro-display.**

THE EVOLUTION of gallium nitride-based semiconductor micro-displays began with the demonstration of InGaN–GaN multiquantum well (MQW) micro-light-emitting diodes (micro-LEDs) by Jiang *et al.* [1]. Since then, these devices have developed in scale, complexity and performance, with potential applications in a range of advanced technological areas. Arrays of 10 × 10 [2], 16 × 16 [3], 32 × 32 [4], and 64 × 64 [5] elements have now been reported, albeit all at approximately one wavelength (∼470 nm), but differing in processing and performance details. With the exception of the 10 × 10 arrays reported in [2], which utilizes an individual addressing scheme, matrix-addressing technology is favored for arrays of higher densities, as demonstrated in [3]–[5].

In this letter, we report on the fabrication and performance of InGaN micro-displays with 128 × 96 pixels on separate device structures with wavelengths of 468 (blue) and 508 nm (green), respectively. With improved electrical and optical properties, the current devices bridge the gap with other micro-display technologies such as organic LEDs (OLEDs) [6] and liquid-crystal-on-silicon [7] amongst others. Nitride-based micro-displays are potentially advantageous in the areas of lifetime [8], response time [9], power consumption [10], and luminous efficiency [11] for projection applications.

In the devices reported here, advances in matrix-addressing technology [12], process methodology, density of the arrays and performance are demonstrated and described. The centre-to-centre spacing of the pixels is 22 μm, corresponding to a resolution of 1200 dpi and a total active chip area of 3 × 2 mm. The design of the array is based on a matrix-addressing scheme; 128 columns form the basis of the array, with 96 micro-LED elements evenly distributed along each column. Hence, devices on a column share a common n-type region, and, thus, a common n-type electrode. Adjacent pixels in a row (sitting on adjacent columns) are interconnected by metal lines which run across the columns. The total number of contact pads is, thus, 224, much less than if each pixel were to have its individual electrodes. It is technically challenging to lay metal lines across the columns, as metal coverage across step-heights of over 3 μm is often inadequate and unreliable. Planarization is a common technique for this purpose but, as has been demonstrated in [3], the chemical–mechanical polishing step in planarization results in excessive physical damage to the material, rendering deterioration of the electrical and optical properties, including high operation voltages and poor beam profiles. Instead, a novel process has been developed for the interconnections. This involves the formation of sloped sidewalls on the etched features, so as to reduce the sharpness of the facet corners. Conformal coverage of metal across the GaN columns and micro-LEDs is, thus, possible without planarization.

The devices are fabricated on metal–organic chemical vapor deposition-grown nitride LED wafers (using c-face sapphire as a substrate) with specified wavelengths of 470 nm (blue) and 510 nm (green). Both device structures consist of a 25-nm GaN buffer layer, a 3-μm-thick n-type GaN ($n = 3 \times 10^{18}$ cm^{-3}), and a five-period MQW active region capped with a 0.25-μm p-type GaN ($p = 3 \times 10^{17}$ cm^{-3}) contact layer. The blue MQW region consisted of 2.5-nm $In_{0.22}Ga_{0.78}N$ wells/7.5–nm GaN barriers, and 2.5-nm $In_{0.3}Ga_{0.7}N/7.5$ nm GaN for the green MQWs. Processing of the device requires five masking steps. The first step defines the GaN columns, which are subsequently transferred onto the LED material by inductively coupled plasma (ICP) etching. The processing conditions are tuned to etch the mesa structures with sidewalls that have an inclination to the vertical of 30° to 45°. The second masking step defines the individual 12 × 16 μm micro-LEDs acting as pixels in the micro-display, which are also formed by ICP etching. A 40-nm SiO_2 layer is deposited by electron beam evaporation for the isolation of the n and p-doped regions. The top planar p-type GaN surface of each individual pixel is subsequently exposed for contact formation by liftoff. The remaining masking steps are for metal deposition of the current-spreading layer (Ni–Au, 30/30 nm, thermally evaporated), p-region interconnect metal lines (Au, 200 nm, sputtered), and n-region bonding pads (Ti–Al, 20/200 nm, thermally evaporated). Fig. 1(a) depicts the Au metal lines running conformally across the sloped sidewall columns. The contacts were subjected to rapid thermal annealing at 500 °C for 5 min in air after deposition of the current spreading layer, and again in N_2 for 30 s at 500 °C at the completion of device fabrication. Fig. 1(b) shows a microphotograph (at a magnification of 1000 x) of a region of a fabricated device.

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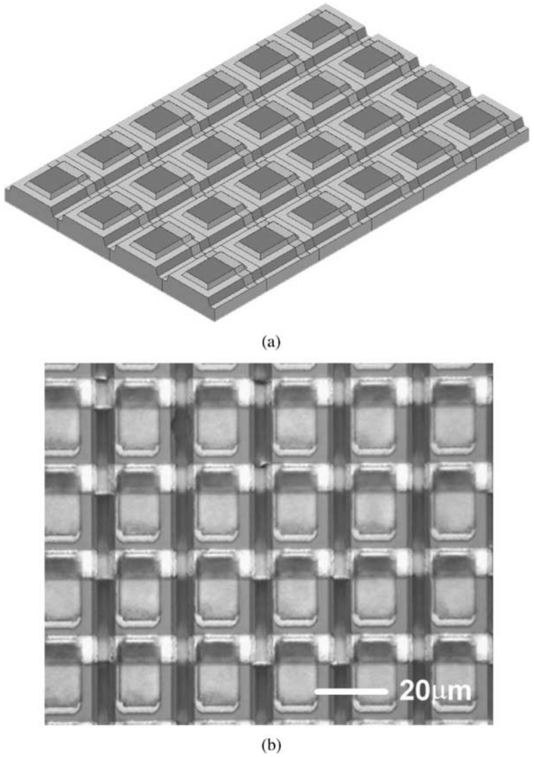
(a)

(b)

Fig. 1. (a) Schematic diagram of the micro-LED array, illustrating the metal lines running across the "sloped sidewalls." (b) Optical microphotograph (x1000 magnification) showing a fabricated device.

A simple circuitry that enables the display of an arrow pattern (with ~60% of the pixels illuminated) was employed for the electrical and optical testing on the green and blue devices, as illustrated in Fig. 2(a) and (b), demonstrating the realization of a high-density nitride-based micro-LED array as a simple micro-display. The current–voltage (*I–V*) characteristics of the arrays (based on the illuminated pattern) are shown in Fig. 3. The blue (green) device turns on at 4.64 (3.41 V), and at a typical operation current of 20 mA, the forward voltage for the blue (green) arrays is 4.87 (3.66 V). A higher operation voltage for the blue-light emitting device compared to the green is expected due to its larger bandgap. Since the devices can be operated at voltages <5 V, the matrix-addressing circuitry can be built using standard CMOS-based components such as timers and decoders. Current flow in the individual micronscale LED devices is physically confined in the vertical direction due to the geometry of the mesa structures, ensuring efficient use of the injected electrons through reduction of the current crowding effect [13]. However, additional current leakage pathways are present in the depletion region alongside the etched sidewalls. Fortunately, the effect of plasma damage on the 12×16 μm micro-LEDs is not significant as the width of the depletion layer (on the sidewall) has been reported to be of the order of 10 nm [14]. Electroluminescence spectra of the devices (at $I = 20$ mA) are shown in the inset of Fig. 3. The peak emission wavelengths (and full-width half-maximum) of the devices are measured to be 468 nm (28.65 nm), and 508 nm (33.97 nm), respectively.

With power consumption levels similar to that of a conventional broad area LED, heating effects are minimal and the devices can be packaged using standard DIL/PGA packages without the need for heat-sinking considerations. The total light output power emitted from the bare chips mounted onto PGA packages (showing the arrow pattern) is collected through an integrating sphere using a calibrated power meter with a Si detector (diameter of 10 mm), and the light output–current (*L–I*) characteristics are plotted in Fig. 4. At an injection current of 60 mA, 3.3 mW, and 2.4 mW of power is emitted from the blue and green devices, respectively, corresponding to a luminance of $> 30\,000$ $\mathrm{Cd/m^2}$ for both devices. Such luminance levels are significantly higher than OLED micro-displays, which are currently capable of producing $\sim$ 1000 $\mathrm{Cd/m^2}$ at

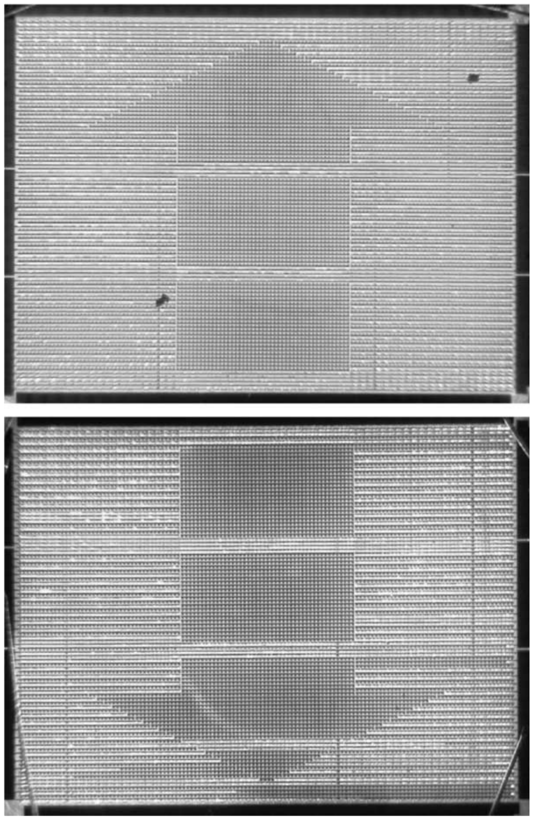

Fig. 2. *I–V* characteristics of the blue and green arrays (based on the arrow pattern).

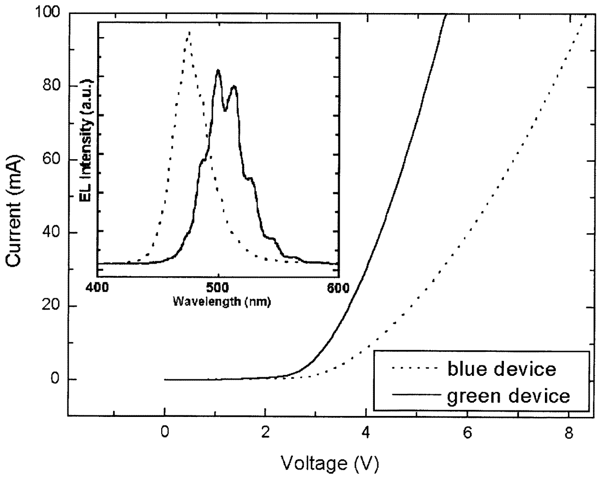

Fig. 3. Operational images of the (top) green and blue arrays, showing an arrow pattern.

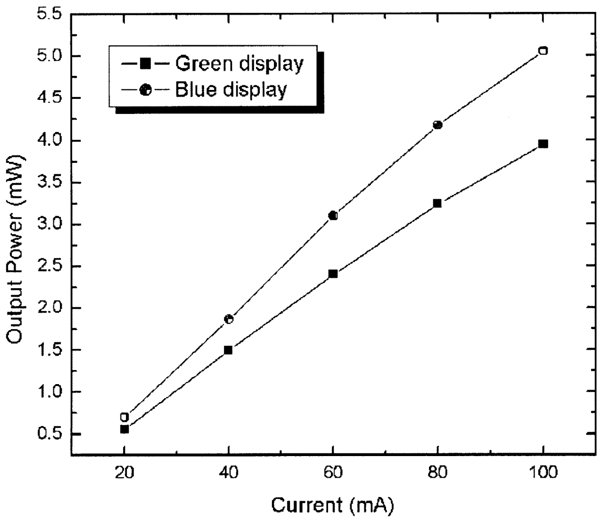

Fig. 4. *L–I* characteristics of the blue and green microdisplays.

5 V [15]. From the *I–V* and *L–I* characteristics, the external quantum efficiencies of the blue (green) device are estimated to be 0.84% (0.80%). Additonally, full-color displays can potentially be realized through color conversion by placing suitable phosphors or polymers onto adjacent individual pixels. The flexibility and scalability of these devices offer plenty of promise for the micro-display market.

In summary, high-resolution 1200 dpi micro-displays with 128 × 96 pixels based on an array of InGaN micro-LEDs have been demonstrated, representing a significant advancement in nitride-based emissive display technology. A novel "slope sidewall" fabrication scheme has been developed, which has successfully overcome the problems posed by previous approaches. The devices operate at voltages below 5 V, with luminance in excess of 30 000 $\mathrm{Cd/m^2}$. Their superior emissive capabilities make them attractive micro-displays.

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