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Fabrication of planar GaN-based micro-pixel light emitting diode arrays

D. Massoubre, J. McKendry, B. Guilhabert, Z. Gong,
I. M. Watson, E. Gu and M. D. Dawson
Institute of Photonics, University of Strathclyde, Glasgow, Scotland, UK, G4 0NW
Email address: david.massoubre@strath.ac.uk

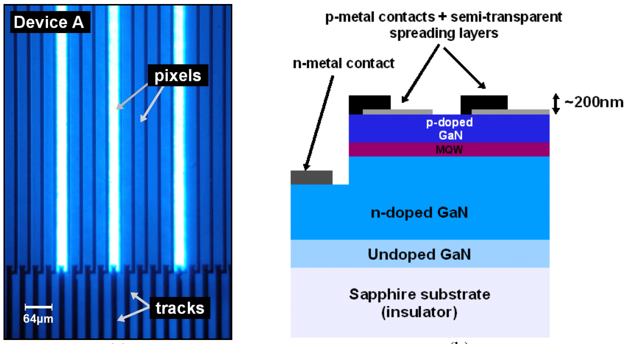
Abstract: We report a new processing approach which enables the fabrication of planar GaN-based micro-pixel LED arrays. This process is based on selective passivation of the p-doped GaN surface by a CHF_3 plasma treatment.

1. Introduction

Micro-pixelated GaN light-emitting diodes ('micro-LED's) offer attractions for a wide range of applications including microdisplays, mask-free photolithography, lab-on-a-chip and bioinstrumentation [1]. Mesa dry etching methods have underpinned the development of this technology to date. Here we propose and demonstrate a new planar process which simplifies the process flow and permits individually-addressable pixelated devices to be fabricated without any obvious degradation of electrical and optical performance. The approach is based on the intrinsic high resistivity of the p-type GaN layer for pixel to pixel electrical isolation and on a CHF_3 plasma treatment to dramatically reduce current leakage through the p-GaN/metal interface. Consequently, this process requires a lower number of fabrication steps than previously used processes using mesa etching for pixel definition and dielectric deposition for electrical insulation [2]. It leads to a planar active area well suited for further integration of functional micro-elements, including microfluidic-channels, micro-optics or luminescent materials for colour conversion [3, 4]. This new fabrication route has been validated by fabricating and characterizing an individually addressable micro-stripe LED array emitting at 470 nm.

2. Design and fabrication of the devices

In order to demonstrate the efficiency of the CHF_3 plasma passivation treatment for the fabrication of planar GaN-based micro-LED arrays, two devices emitting at 470 nm were fabricated, with (device A) and without (device B) plasma treatment and directly compared. For purposes of comparison, a micro-LED array layout corresponding to an earlier type of mesa-etched device was chosen and consists of 120 pixels, each 20 µm wide by 3.6 mm in length, with a gap between adjacent stripes of 14 µm [5]. This geometry allows also critical evaluation of issues such as cross-talk and current spreading. Micro-stripes were defined by a standard lift-off procedure on a current spreading layer of semi-transparent Ni/Au (8 nm/16 nm) metallization deposited by electron beam evaporation and annealed to form ohmic contacts to the p-GaN. Subsequently, two 600 µm x 600 µm trenches were created on the edge of the active area by inductively coupled plasma (ICP) dry etching, giving access to the n-type GaN layer below the active region. Next, a single photoresist mask was applied defining the n-pads, p-pads and tracks. The room-temperature plasma treatment was applied to device A only, with this photoresist mask in place, and used a reactive ion etch (RIE) system with gas flows comprising 10 sccm of Ar and 5 sccm of CHF_3. The plasma power and the chamber pressure were set at 200 W and 30 mTorr, respectively, for a total treatment period of 60 s. Fig. 1(a) illustrates the array layout with the highly localized light emission obtained from individually addressed pixels of device A. Fig. 1(b) gives a schematic cross-sectional view of the device structure.



(a) (b)

Figs 1. (a) Optical microscope image of a region of device A with three working pixels. (b) Schematic cross-sectional layer structure of one micro-pixel.

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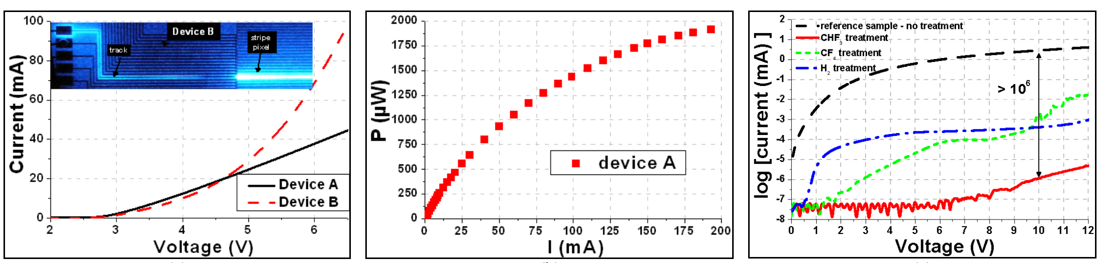
3. Experimental results and discussion

The I-V characteristics of individual pixels from the plasma-treated device A and the reference device B are shown on Fig. 2.a. The results show that while both devices show a similar threshold voltage around 3V, the current increases much faster with device B than with device A. An explanation is suggested by the image shown in the inset to Fig. 2.a. This micrograph shows that light is emitted from directly underneath the p-pad and the track of a pixel in operation, indicating significant current leakage at the p-GaN – metal interface in device B. This behavior is expected, as the p-GaN – Ti interface forms a Schottky contact and so the current can flow through it once the applied voltage is higher than the Schottky barrier. As no such leakage is visible from device A (see Fig. 1.a), this demonstrates that the CHF_3 pre-metallization plasma treatment prevents current leakage through the p-GaN–metal interface, equivalent to a very effective electrical passivation of the p-GaN surface. With a series resistance of ~80Ω, device A presents electrical characteristics as good as those previously reported for micro-stripe LEDs made with the standard mesa-etch process [5]. Optical measurements were also performed and results are plotted on Fig 2.b. An averaged output power of ~500μW at 20mA was obtained which is twice as high as the power already reported for a similar micro-stripe design made with the standard process [5]. We believe that the lower number of fabrication steps in the planar process may result in improved current spreading, and so to better efficiency.

To further investigate the proposed passivation effect from the CHF_3 plasma treatment, simple co-planar Ti-Au structures were made on the p-GaN surface of samples from the same wafer as that used to fabricate the LEDs. Each structure comprised circular pads with a concentric outer electrode, separated by a 10 μm gap and different pre-metallization plasma treatments were tested. The resulting DC I-V characteristics are plotted in Fig. 2.b. Comparing the structure given the CHF_3 plasma treatment with the non-treated reference sample, a dramatic current reduction, by a factor exceeding 10^6 between 6 and 10 V, was observed (comparisons are limited by the noise at lower currents). These results demonstrate that the CHF_3 plasma treatment is a very effective method to locally passivate the p-GaN layer. While complete investigation of this effect has yet to be undertaken, two complementary physical effects may contribute. The first is the well-known de-activation of Mg acceptors by hydrogen, which results in a decrease of the mobile hole concentration and thus of the p-GaN conductivity. A second effect could be an increase of the effective metal-semiconductor barrier height due to the implantation of fluorine into the p-GaN layer [6]. In order to evaluate these two possible effects in isolation, H_2 and CF_4 plasma treatments were applied to two more structures, and the results are included in Fig 4. In both cases, a significant reduction in current is seen compared to the non-treated structure. However, the resistivity increase is significantly higher with the CHF_3 plasma treatment than with either of the H_2 and the CF_4 treatments.



(a) (b) (c)

Figs. 2. (a) I-V characteristics of corresponding individual pixels with the same track length from micro-stripe LED arrays A and B. The inset shows light emission from an operational pixel of device B. (b) P-I characteristics of an individual micro-stripe pixel from device A. (c) I-V characteristics of co-planar Ti/Au electrode structures deposited onto p-GaN given different pre-metallization plasma treatments.

4. Conclusions

A new process allowing the fabrication of individually-addressable GaN-based micro-LED arrays with an intrinsically planar emitting area was demonstrated. This process is based on the intrinsic high resistivity of the p-GaN layer for pixel-to-pixel electrical isolation, and on a CHF_3 plasma treatment to electrically passivate the p-GaN layer. Such planar LED arrays are suitable for the realization of a range of applications including lab-on-chip systems with integrated optical sources.

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