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Development, performance and application of novel GaN-based micro-LED arrays with individually addressable n-electrodes

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***Abstract* - We demonstrate the development, performance and application of a GaN-based micro-light emitting diode array sharing a common p-electrode with individual-addressed n-electrodes. These individually-addressed n-electrodes minimize the series-resistance difference from conductive paths, and offer compatibility with n-type metal–oxide–semiconductor transistor-based drivers for faster modulation.**

I. INTRODUCTION

GaN-based micro-light-emitting diode (μLED) arrays, which consist of a number of μLED elements with dimensions of less than 100μm, possess important novel characteristics. Compared with conventional broad-area LEDs, μLED elements can be operated at higher current densities, enabling significantly higher modulation bandwidth for data communications applications [1]. By operating a μLED array in a ganged fashion (multiple μLED elements modulated simultaneously with the same data signal), a higher signal-to-noise ratio and longer data-transmission distance are expected while retaining fast data rate [2]. This makes μLED arrays attractive sources for high-speed visible light communications (VLC) in both polymer waveguide and free-space formats.

Standard GaN-based LED epitaxial structures have the p-side of the junction on top. This epi-structure requires that a conventional μLED array employs a configuration with a common n-electrode and individually addressable p-electrodes for each μLED element. The main shortcoming of this configuration is that the relevant LED drivers are necessarily based on p-type metal–oxide–semiconductor (PMOS) transistors, which have lower operation speed, larger size and larger capacitance than their n-type equivalents. In addition, this configuration employs the n-type GaN layer as a shared conductive path for all μLED elements. Different distances between the common n-electrode and the target μLED element lead to different series resistances contributed from the n-type GaN layer, which results in poor optical element-to-element uniformity and high crosstalk.

In this work, we demonstrate a novel GaN-based μLED array sharing a common p-electrode with individually addressable n-electrodes. Compared with a conventional μLED array, the reversed common and individual electrode structure of this configuration minimises the series-resistance difference from conductive paths, and offers compatibility with NMOS-based LED drivers. We have developed and optimised the fabrication process for such arrays to improve performance. At 10.5kA/cm^2 operating current density, over 414W/cm^2 optical power density and 345MHz electrical-to-optical (E-O) modulation bandwidth are achieved for a single μLED element with a diameter of 24μm emitting at 450nm. This array was also integrated with a custom NMOS-based driver to demonstrate VLC application. Open eye diagrams were recorded at several hundred Mbps in operation with two μLED elements under an on-off-keying (OOK) data transmission scheme.

II. FABRICATION PROCESS FOR μLED ARRAYS

The μLED arrays developed in this work were fabricated from a commercial blue GaN-based LED wafer on a c-plane sapphire substrate. The μLED array consists of 6x6 array of flip-chip μLED elements with a diameter of 24μm on a 300μm centre-to-centre pitch. Fig.1 shows the main fabrication steps. In order to realize the μLED array with individually addressed n-electrodes, each μLED element needs be fully isolated from both p- and n-type GaN layers. To achieve this configuration, two steps of Cl_2-based plasma etching are involved in the fabrication process. Firstly, GaN mesas are etched down to the sapphire substrate [Fig. 1(b)]. Then, a μLED element is created at the centre of each mesa which stops at the n-type GaN [Fig. 1(c)]. Annealed Pd metal layer is used as a metal contact to p-type GaN. The metallization on the isolated n-type GaN mesa is realized by sputtering a Ti/Au metal bilayer. This bilayer is also patterned to make the metal track from the n-type GaN mesa so as to individually address each μLED element through the n-electrode. After isolating each μLED element by a SiO_2 layer, another Ti/Au metal bilayer is used to interconnect μLED elements forming a shared p-electrode. Fig. 1(g) shows a schematic layout of the whole array to emphasise the common p-electrode and individually addressable n-electrodes. Compared with the conventional μLED array design, the conductive paths are formed by Ti/Au metal bilayers rather than the n-type GaN layer. Thus, series resistance differences between elements are much reduced owing to the significant lower sheet resistivity of the metal bilayer.

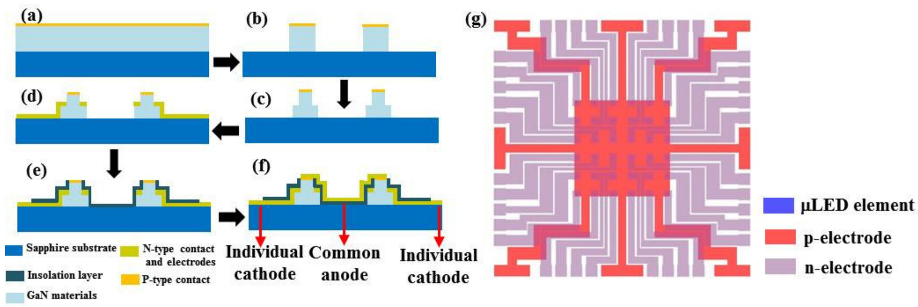

Figure 1: (a)-(f) Schematic diagrams of the fabrication process for the µLED arrays. Part (g) shows a schematic layout of the whole µLED array.

III. PERFORMANCE AND APPLICATION OF µLED ARRAYS

Fig. 2(a) illustrates the current density-voltage and optical power density-current density characteristics of a single µLED element in the array. This µLED element can be operated at a direct-current current density up to 10.5kA/cm^2 and is able to produce a continuous wave optical power density over 414W/cm^2. As mentioned, this high operating current density leads to a high modulation bandwidth as shown in Fig. 2(b). This µLED element has an E-O modulation bandwidth in excess of 350MHz, which is significantly higher than the value of typical commercial LEDs [3]. In order to illustrate the electrical/optical uniformity, the measured current and optical power densities at a fixed voltage of 7V for 5 randomly selected µLED elements are presented in Fig. 2(c). Analysis of the data reveals the variations of current and optical power densities are within 16.3% and 6.8%, respectively. These variations are mainly caused by the different lengths of metal tracks connecting each µLED element to its corresponding n-electrode and can be further reduced by increasing the thickness of metal tracks. The µLED array is further integrated with the custom NMOS-based driver. Detailed information on this driver and integration process can be found in Ref.[2]. Fig. 2(d) shows the open eye-diagram obtained with two µLED elements operating at 250Mbps under OOK data transmission scheme.

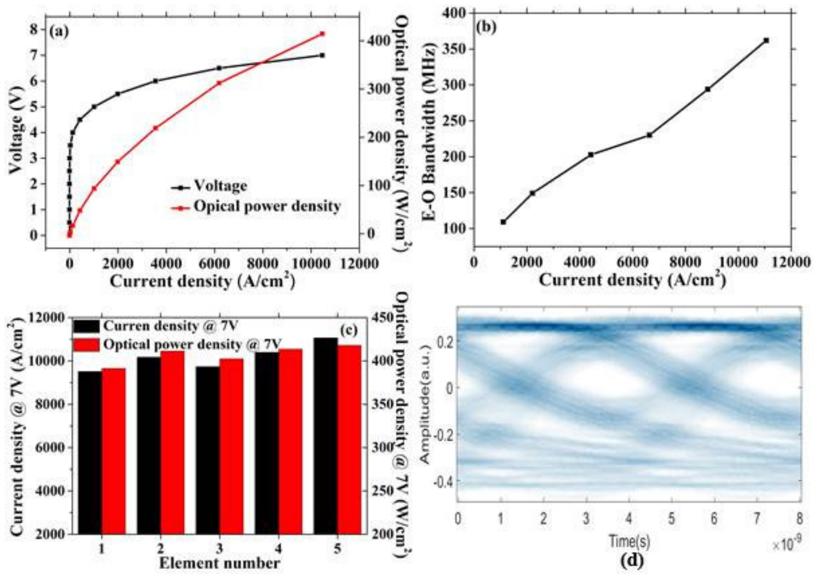

Figure 2: (a) Current density-voltage and optical power density-current density characteristics of a single µLED element; (b) E-O modulation bandwidth characteristic of the same µLED element; (c) electrical and optical uniformities of 5 selected µLED elements in the array; (d) eye-diagram for two µLED elements operating at 250Mbps under OOK scheme by the NMOS-based driver.

IV. SUMMARY

The fabrication, performance and application of the GaN-based µLED array sharing a common p-electrode with individual-addressed n-electrodes are demonstrated in this work. The novel configuration enables this array to be compatible with NMOS-based driver for faster modulation. The fabricated µLED array shows promising performance. The application of this array integrated with an NMOS-based driver in VLC is also presented.

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