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# Thin-film blue light-emitting diodes for flexible device operation down to a millimetric radius of curvature

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**Abstract**— We report on the fabrication and characterization of flexible blue thin-film micro-LED grown by MOVPE. Two approaches are explored to replace laser lift-off for the micro-LED device liberation from the growth substrate: the release of the micro-LED structures assisted by quasi-van der Waals epitaxy using an interfacial h-BN layer; and the sacrificial etching of the growth substrate starting from LED structures on Si(111). We demonstrate the transfer of micro-LED on a polyimide substrate and their operation down to a millimetric radius of curvature.

**Keywords**— flexible, micro light-emitting diode ( $\mu$ LED), van der Waals epitaxy

## I. INTRODUCTION

The interest in flexible micro light-emitting diodes ( $\mu$ LEDs) is growing for mass-market applications, but specific applications are also found in biomedical research. For example, the performances of cochlear implants could be improved by using LEDs since, contrary to electrical signals, there is no spreading of light in the ear, and the neurons responsible for hearing can be made sensible to blue light [1a]. Thin-film GaN-based  $\mu$ LEDs with a micrometric thickness to ensure high flexibility are promising candidates for such applications [1b]. However, laser lift-off generally used for the LED liberation from the growth substrate [1a, 1b] remains a sequential and costly process. Two alternative approaches are explored in this work: using a Si(111) growth substrate removed with standard silicon-processing techniques [2]; using a sapphire substrate with an h-BN two-dimensional interfacial layer to enable the LED liberation [3a, 3b].

## II. PROCESS

Fig. 1 (a)-(b) shows the metalorganic vapour-phase epitaxy (MOVPE)-grown InGaN/GaN LED structures studied in this work. In the structure grown on Si(111), AlN/AlGaIn/GaN buffer layers were optimized to improve the structural quality while avoiding too many cracks [4], leading to a slightly thicker LED structure. This structure was first bonded to the destination substrate and processed with an annular n-contact for light emission through the n-layer. On the other hand, the MOVPE structure grown on h-BN on sapphire is directly processed on the growth substrate, with two annular p and n contacts, to be mechanically released and transferred to the destination substrate after processing; it is compared to a LED structure directly grown on sapphire. In all cases, LEDs were processed with various dimensions varied from  $700 \times 700 \mu\text{m}^2$  to  $50 \times 50 \mu\text{m}^2$ .

The LED characterization bench, depicted in Fig. 2, allows for quick and accurate measurement of IV characteristics, electroluminescence (EL), or optical power, of flat or bent devices down to a ROC of 3 mm. The LEDs were first characterized in a flat configuration to compare their performances, as illustrated in Fig. 3(a), (c) for the h-BN LED before transfer. The larger overall resistance compared to the LED-on-sapphire reference was attributed to a remaining GaNiO layer at the p-GaN / metal interface after TEM inspection, which increased the p-contact resistivity; the LED emission is homogenous, and the EL-spectrum centered at the targeted wavelength for both the on-h-BN and on-sapphire LEDs. As for the Si-based LED, a larger overall diode resistance was measured, related to more resistive p and n-contacts, with EL spectra centered at a slightly larger wavelength ( $\sim 480$  nm).

First transfers of micro-LED onto a flexible polyimide substrate ( $75 \mu\text{m}$  thick kapton) have been performed, illustrated in Fig.3 (b), (d); no variation was observed on the IV curve and EL spectra in a flat and bent configuration. Bending tests were successful down to a ROC of 8 mm before device cracking. We will further present the opto-electronic characterization down to millimetric ROC of h-BN and Si-grown micro-LED to assess the thin-film LED advantage compared to standard “thick” LEDs.

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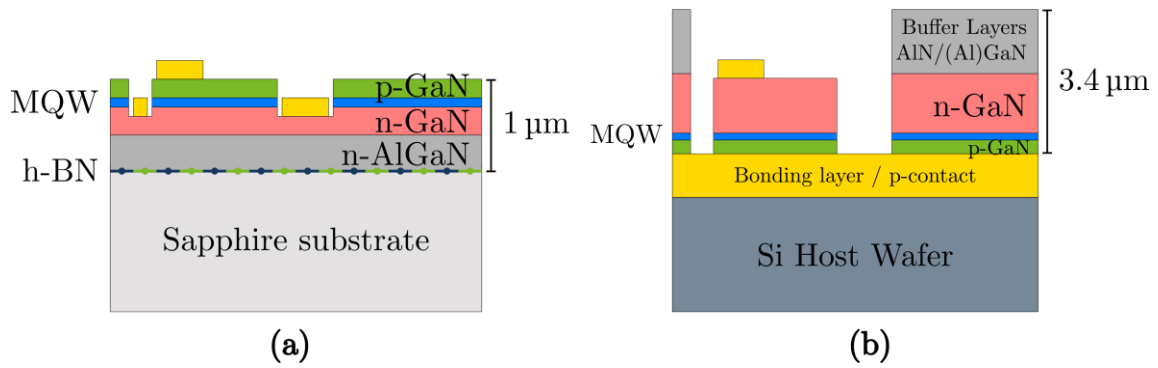


Fig. 1. LED structure grown by metal-organic chemical vapor deposition on a (a) h-BN/c-Al<sub>2</sub>O<sub>3</sub> substrate, and (b) on a Si(111) substrate

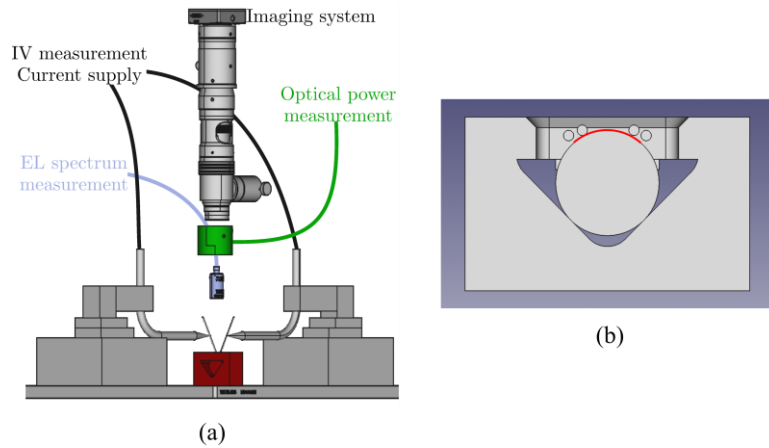


Fig. 2. Representation of the measurement setup with (a) a side view of the setup to show the position of the different detectors, all of them being removable at will and (b) the principle of bending system at the center of the setup, allowing a fixed height of the LED for flat and variable ROC from 10-mm to 3-mm (the position of the sample is shown in red).

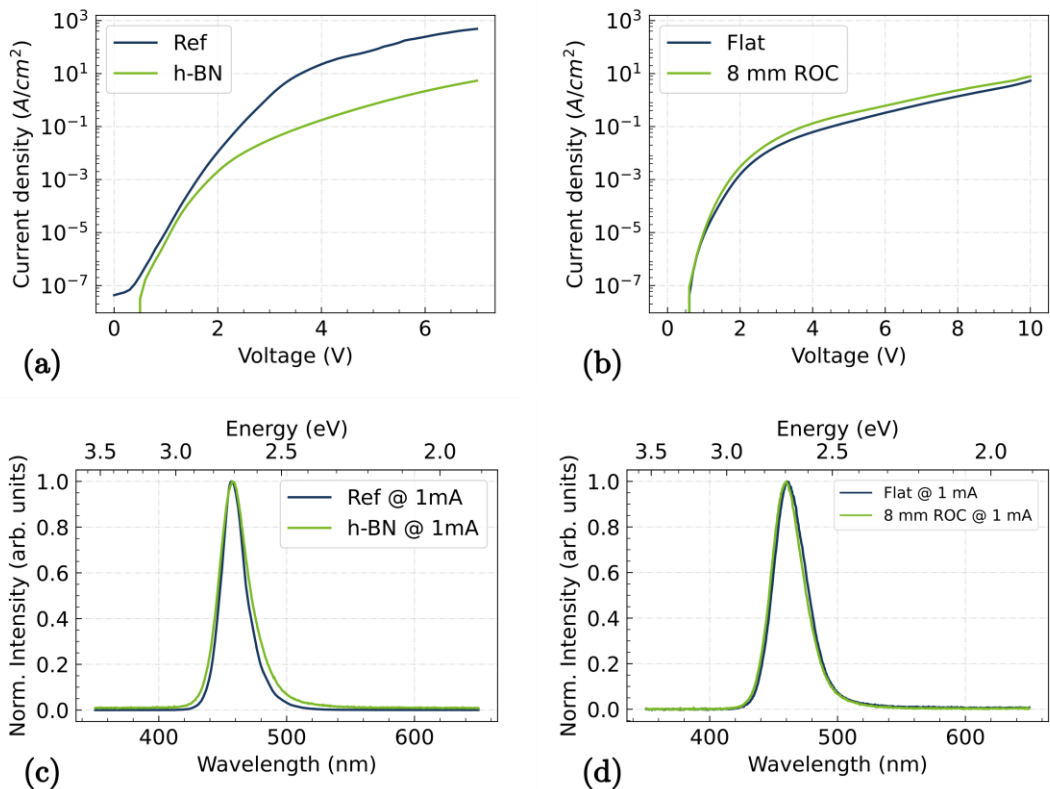


Fig. 3. (a) IV characteristic of the LED grown on sapphire for both reference and grown on h-BN sample, before release (size: 215 μm × 275 μm). (b) IV characteristic of the LED after transfer for flat configuration and bent with 8 mm ROC (size: 170 μm × 170 μm). (c) EL measurement of the same LED as in (a). (d) EL measurement on the same LED as in (b).