Feldman, Martha S. and Pentland, Brian T. and D'Adderio, Luciana and Lazaric, Nathalie (2016) Beyond routines as things : introduction to the special issue on routine dynamics. Organization Science, 27 (3). 505–513. ISSN 1047-7039 , http://dx.doi.org/10.1287/orsc.2016.1070

InGaN micro-LEDs integrated onto an ultra-thin, colloidal quantum dot functionalized glass platform

K.Rae[1], C.Foucher[1], B. Guilhabert[1], N.Laurand[1],D. Zhu[2], C.J. Humphreys[2], D.J. Wallis[2,3] and M.D.Dawson[1]

[1]Institute of Photonics, Dept of Physics, SUPA, University of Strathclyde, Glasgow, UK
[2]Dept of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK
[3]Plessey Semiconductors Ltd, Tamerton Road, Roborough, Plymouth, UK

Abstract— We demonstrate an integrated color-converting device by transfer printing blue-emitting micro-sized InGaN LEDs onto an ultra-thin glass platform functionally enhanced with colloidal quantum dots. Color conversion and waveguiding properties of the structure are presented.

I. INTRODUCTION

The transfer printing (TP) technique facilitates the controlled assembly of micro-scale semiconductor structures onto non-native substrates, enabling heterogenous and multi-functional devices with a wide range of applications [1-3]. We recently reported the TP of micro-sized light-emitting diodes (LEDs) with nano-scale printing resolution onto optically passive substrates [4,5]. In this work we apply the technique to print blue-emitting InGaN LEDs onto an ultra-thin glass platform that is itself functionalized with colloidal quantum dots (CQDs) and therefore optically active. This integrated structure fully encapsulates the CQDs (see Fig. 1) while enabling color-conversion of the blue light from the LEDs to longer wavelengths.

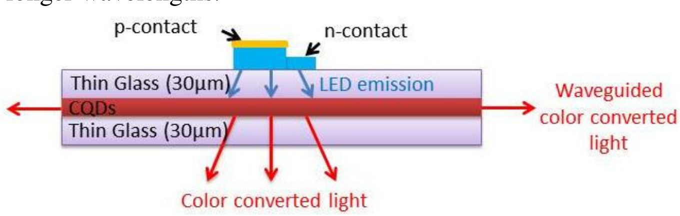

Fig. 1. Schematic of an LED-hybridized CQD color-converter.

The wavelength of color-conversion can be varied at design simply by changing the CQDs and here we demonstrate conversion from blue (450nm) to green (550nm), orange (590nm) and red (640nm).

In the following, we detail the device geometry, fabrication and the properties of the integrated device's constituent parts. Then, color-conversion is described and the capability for the integrated structure to also guide light is discussed; the latter effect could be utilized to create further functionality. Such an integrated device has attractive properties for applications, amongst others, in displays, optical wireless communications and integrated optics for sensing using visible light.

II. DESIGN AND FABRICATION

The integrated device is shown schematically in Fig. 1. It consists of a 'neat' (CQDs only) layer of CQDs enclosed between two flexible glass sheets, each 30µm-thick. The thickness of the CQD film is typically below 1µm and tailored to absorb >95% of normal incidence light at 450nm. The LED here is a 100 x 100µm^2 epitaxial membrane LED with the substrate removed (see section II.B for details) that is printed directly onto one of the glass sheets. Adhesion of the LED to the glass is via van der Waals' bonding using liquid capillarity or via a thin layer of transparent epoxy. As can be seen from Fig. 1, color-converted light is obtained through the second glass sheet and will be referred as the 'forward' emitted light for the characterization in section III. Some of the light converted by the CQDs however is waveguided by the structure, both within the CQD film (refractive index n=1.7) and the thin glass sheets (n=1.46). This is studied as well in section III.

A. Colloidal quantum dot color-converters

CQDs are attractive for color-conversion of LEDs because they are characterized by high photoluminecscence efficiency, a broad absorption spectrum and a narrow emission linewidth, and are processed from solution. They also have typical excited state lifetimes at room temperature at least an order of magnitude shorter than rare-earth phosphors, meaning they can be modulated faster. This latter characteristic, combined with their narrow emission linewidth, makes CQD very interesting for visible light communications. The CQDs utilized in our device are of the CdSSe/ZnS alloyed core/shell design. The emission wavelength is varied through the composition of the CdSSe core. The mean size of these CQDs at all wavelengths used is 6nm in diameter. The CQDs are deposited from toluene solution onto a glass sheet by spin casting. Another glass sheet is used on the other side to encapsulate the CQD layer, the assembly being done in ambient conditions.

B. Ultra-thin InGaN LEDs for transfer printing

An array of suspended 100µm x 100µm ultra-thin InGaN-based LEDs is initially fabricated from an LED epi-structure grown on silicon. The detailed structure can be found in [5].

The LEDs are suspended and held in place by specially designed, pre-patterned, sacrificial anchors. These are defined by a series of plasma etches through the InGaN epi-structure (thickness of 2 µm) and down to the silicon substrate. A hot KOH under-etch is then used to remove the silicon substrate. The LEDs are picked up from this wafer by the use of a PDMS elastomeric stamp. This is used to transfer the LEDs to a receiver substrate, in this case the CQD color-converting glass-encapsulated structures, converting blue light into red, orange or green light, respectively. Once printed on the thin glass, these LEDs typically achieve an optical power density up to 0.3 W/cm^2 at the LED exit surface.

III. INTEGRATED COLOR-CONVERTING DEVICE

After LED printing, the red, orange and green color-converting structures are electrically probed and measured for spectral and light output power performance, the results of which can be seen in Fig. 2(a) to Fig. 2(d).

The TP technique allows direct coupling of the LED light into the CQD color-converters and so increases the obtainable conversion efficiency compared to those obtained with remote (optically-relayed) pumping. The 'forward' (straight through) power conversion efficiency obtained for the red, orange and green color-converters, respectively, is 9%, 12% and 16%. The absorption of blue light is 95% for the red sample, and >97% for the two other samples.

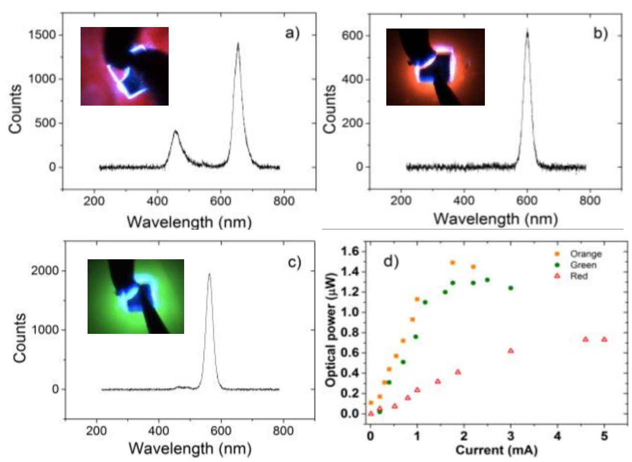

Fig. 2. Spectra from the LED printed (a) on the red CQD color-converter, (b) the orange CQD color-converter and (c) the green CQD color-converter with inset plan view optical images, and (d) L-I curve for forward color-converted light output power from the LEDs printed on each of the three color-converters.

IV. WAVEGUIDED LIGHT

As can be seen in Fig. 1, the TP LED emits light down through the glass and CQD layers. The comparatively high refractive index of the CQDs to the glass encapsulation layers means the structure acts as a waveguide for some of color-converted light; i.e. some light is also guided horizontally through the CQD layer. The emission from this waveguided light was measured at the edge of the glass structure. The far-field spectrum corresponding to the light guided in the CQD film after 20mm of propagation was also measured. There is a red-shift of this spectrum, due to self-absorption, when compared to the forward emission, as illustrated in Fig. 3. It is verified that the magnitude of the shift is affected by the propagation distance.

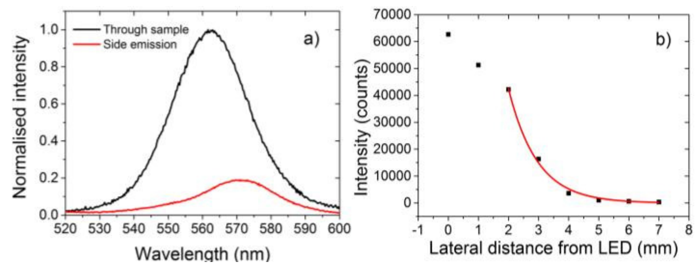

Fig. 3. a) Spectra from the LED printed on the green CQD color-converter, showing emission through the sample and the waveguided side emission. b) Light intensity as a function of lateral distance from the LED

The waveguided losses are measured by collecting the light emission through the color-converter structure, in the forward direction, as a function of the lateral distance from the LED. These losses are partly due to self-reabsorption and because of this they are wavelength dependent. Fig. 3b shows the forward intensity at 555nm versus the lateral distance from the LED for the green sample. When the distance from the LED is large enough so that forward light and leaky modes are not significantly coupled into the detector, the intensity decays exponentially. The loss can be extracted from this exponential decay. The guiding loss for each color-converter waveguide is 1.50cm^{-1}, 0.97cm^{-1} and 1.05cm^{-1} for the red (639nm), orange (594nm), and green (555nm) respectively.

V. CONCLUSION

In this work, we have demonstrated a novel color-converting structure, which has potential for smart lighting, visible light communications and possibly photonic chip applications. We have done this by integrating, through a TP process, an ultra-thin blue-emitting InGaN LED with a thin glass platform functionally enhanced with CQD color-converters. We will report on the fully contacted version of the device.

REFERENCES

[1] T.-H Kim et al., Nature Photonics 5, 2011, pp. 176-182.

[2] D.-H Kim, R. Ghaffari, N. Lu, J.A. Rogers, Annual Revue Biomedical Engineering 14, 2012, pp.113-128.

[3] J. Justice et al., Nature Photonics 6, 2012, pp. 610-614.

[4] A.J. Trindade et al., Applied Physics Letters 103, 2013

[5] A.J. Trindade et al.,Optics Express 23, 2015, pp. 9329-9338

This work is supported by EPSRC, "Ultra-parallel visible light communications" grant EP/K00042X/1.

DOI: 10.15129/28b1e9db-91f4-4787-9ef3-522401895239