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# Micro-spherically textured organic light emitting diodes: A simple way towards highly increased light extraction

Tobias Bocksrocker *, Jörg Hoffmann, Carsten Eschenbaum, Andreas Pargner, Jan Preinfalk, Florian Maier-Flaig, Uli Lemmer

*Light Technology Institute, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, D-76131 Karlsruhe, Germany*

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ABSTRACT

We demonstrate a method to increase the efficiency of white organic light emitting diodes (WOLEDs) by a factor of up to 3.7. By fabricating the WOLED on top of a monolayer of $SiO_2$-microspheres we texture the WOLEDs spherically. We attribute the significant increase of the device efficiency to a larger area on the same footprint and to an enhanced outcoupling of waveguide and substrate modes. Measurements reveal that the *I–V* characteristic of the device as well as the emissive characteristic remains unchanged.



## 1. Introduction

Organic light emitting diodes (OLEDs) are already commercially available in display applications and they are also promising candidates for general lighting. OLEDs have been of great interest in research over the last years [1–4] and highly efficient devices have been reported [5–7,22]. The progress made in materials development [8,9] has to be accompanied by new device architectures to overcome the high optical losses in an OLED. Both, the organic layers as well as the transparent conductive oxides used as electrodes in an OLED possess high refractive indices (typically 1.7–2.1 [10]). Hence, an OLED forms a slab waveguide and about 50% of the generated light is coupled to waveguide modes and surface plasmon polaritons. Another ~30% of the generated photons are coupled into substrate modes [11,12]. These optical losses are to date the highest loss channel in OLEDs. Different approaches have been reported to enhance the outcoupling efficiency. While coupling out substrate modes can be relatively simply achieved by the use of microstructured [13] or roughened substrate/air interfaces [14], coupling out waveguide modes is more challenging. To scatter guided modes, micro- or nanostructures underneath [15], on top [16] or implemented in the anode [17] have been reported. Other approaches such as the use of stochastic scattering via nanoparticles have been shown [18]. Many of the reported methods to enhance the outcoupling in OLEDs suffer from disadvantages, such as complicated fabrication [16], change of the electrical behavior [19] or angular spectral dependencies [20].

Here we report an elegant way to significantly enhance the efficiency of white organic light emitting diodes. By building the OLED not on a flat substrate, but on a monolayer of $SiO_2$ microparticles, we texture the OLED spherically. This leads not only to a larger area on the same footprint but also to an enhanced outcoupling due to the curved waveguide. This method enhances the device efficiency up to a factor of ~3.7 without changing the electrical behavior of the OLEDs. This indicates that this method addresses both optical loss channels: waveguide and substrate modes.

* Corresponding author.
*E-mail address:* tobias.bocksrocker@kit.edu (T. Bocksrocker).

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## 2. Fabrication

### 2.1. Spherical monolayer fabrication

For the fabrication of the spherical textured substrate we started with 25 mm × 25 mm glass substrates, which were subsequently cleaned with acetone and isopropyl alcohol in an ultrasonic bath for 10 min each. After cleaning, we treated the substrate with oxygen plasma for 2 min. We used monodisperse $SiO_2$–microparticles (purchased from Microparticles GmbH) dispersed in $H_2O$ at a weight ratio of 5% and a diameter of 1.55 μm as forming spheres. We dispensed 75 μl of this solution equally distributed on the substrate (see Fig. 1a), and waited for 30 s before starting to spin the substrate at a very slow rotation speed of 100 rpm for 1 min (Fig. 1b). We then ramped up the speed to 2000 rpm with 500 rpm/s (Fig. 1c) and immediately stopped the rotation when the 2000 rpm were reached. The substrates with the resulting monolayer were then heated up to 100 °C for 2 min to get rid of any water residues. Fig. 1d shows an SEM image of a resulting monolayer.

### 2.2. Device fabrication

On the substrate with the $SiO_2$ spheres we spincoated a ~1 μm thick layer of the photoresist SU-8 (SU-8 2000.5, MicroChem). This was necessary to fill the gaps in between the spheres, so that the following layers processed on top of the spheres are uninterrupted. SU-8 was chosen, because it is transparent in the visible range, very stable with all the used solvents and the refractive index of SU-8 (~1.55) is close to substrate and spheres (~1.5) so that the substrate, the spheres and the "filling material" can be considered as almost index matched. After spincoating, the substrates were completely illuminated with a UV source (proMa UV-source) and heated up to 95 °C for 2 min to crosslink the SU-8 (see Fig. 2a). To get rid of any non-crosslinked residues the samples were then immersed in the SU-8 developer mr-Dev 600 for 1 min and afterwards rinsed with $H_2O$.

As the processing of conductive and transparent ITO requires high temperatures [21], which would burn off the SU-8 we decided to use a ~80 nm thick layer of highly conductive poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, PH 1000, purchased from H. C. Starck) as an anode in our devices. The deposition was done under nitrogen atmosphere to avoid any degradation due to oxygen and moisture. We added 5 vol.% dimethylsulfoxide (DMSO) to the PEDOT:PSS dispersion to enhance the conductivity and 5 vol.% isopropyl alcohol to increase the wetting of the substrates. The solution was spincoated for 120 s at 2000 rpm resulting in a ~80 nm thick layer (see Fig. 2b). The resulting sheet resistance of the conductive layers was 310 Ω/□.

The substrates were then heated in a vacuum oven at 100 °C for 10 min to get rid of any water residues. As an emitting layer, the white emitting co-polymer SPW093 (from Merck OLED Materials GmbH) was spincoated at 1000 rpm for 55 s. The SPW093 was dissolved in toluene at a weight/volume ratio of 4 mg/ml resulting in a ~50 nm thick layer. As a cathode we evaporated 1 nm lithium fluoride and 200 nm aluminum (see Fig. 2c) under vacuum ($10^{-7}$ mbar). The devices were then encapsulated with an epoxy and a glass cover to characterize them under ambient atmosphere. In Fig. 2d a SEM image of a focused ion beam (FIB) cross section of a device is shown.

### 2.3. Microlens array fabrication

We spincoated a ~17 μm thick SU-8 layer on a silicon wafer and processed hexagonally packed columns (20 μm in diameter) into the photoresist via a standard photolithography process. The resulting columns were molded into polydimethylsiloxane (PDMS). The hardened PDMS was removed and served as a stamp to form the columns into poly(methyl methacrylate) (PMMA) which was dissolved in anisol. The resulting PMMA columns were then

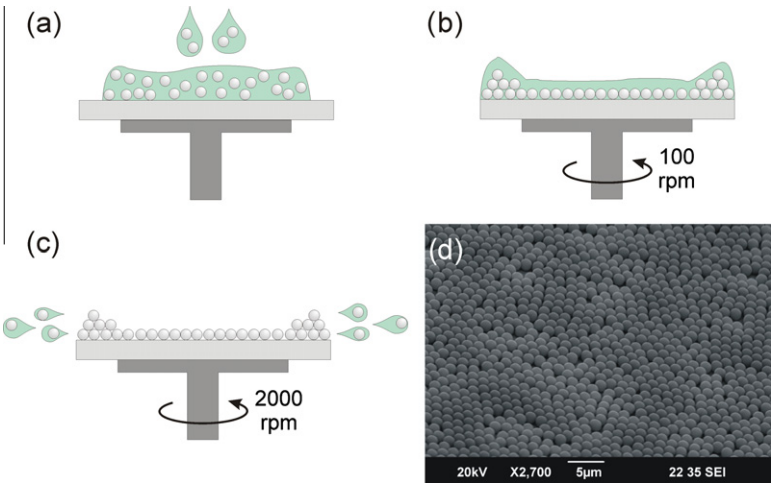


**Fig. 1.** Fabrication scheme of the $SiO_2$-microsphere monolayer. (a) The in $H_2O$ dispersed microspheres were distributed on the substrates. (b) After 1 min waiting period, the substrate was rotated at 100 rpm for 1 min. (c) The substrate was accelerated and the rotation was immediately stopped when 2000 rpm were reached. (d) SEM image of a resulting monolayer.