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Microbes based printing for fabrication of microlenses for organic light emitting diodes

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ABSTRACT

We have demonstrated a novel method to fabricate microlenses for organic light emitting diodes (OLEDs) using templates of patterned microbes. *Saccharomyces cerevisiae* (Baker's yeast), generally used in a microbiology laboratory, is allowed or restricted to grow in selected areas on a polyvinylidene fluoride (PVDF) membrane, which acts as a substrate. The process comprises of two autonomous approaches, namely, microbial and antimicrobial approaches, which employ inkjet printing for dispensing a suitable ink. The ink is a culture of microbes in the case of microbial approach and an antimicrobial agent in the antimicrobial approach. Once a three dimensional pattern evolves as a consequence of microbial growth, the substrate serves as a template for casting polydimethyl siloxane (PDMS) microlenses. Among the two approaches, antimicrobial approach presents a pattern with low packing density of microlenses. But, microbial approach results into a densely packed array of microlenses with a significant randomness in the distribution of their diameter and height, as required for efficient light out-coupling. The microlenses obtained from both the approaches are attached to the air side of the glass in all three red, green and blue OLEDs. The luminance was measured with and without these microlenses. A maximum enhancement of 1.24X was attained.

1. Introduction

This work discusses and demonstrates a unique idea, that is, controlled three dimensional patterns of microbes prepared in a specific manner can be made amenable for preparing microlenses. Performance of these microlenses is then measured on organic light emitting diodes of red, green and blue colors.

Inorganic light emitting diodes (LEDs), which exhibit extremely high luminance, long lifetimes as well as low power consumption have revolutionized the lighting industry. However, lighting sources need to be diffused and hence additional diffusers have to be added to the lighting fixtures. An alternative is in the form of organic LEDs (OLEDs), which though not as efficient as gallium nitride LEDs, are naturally diffused sources, obviating the need for extra component at the fixture level. In addition, the organic counterparts have advantages of being thin and lightweight, which can be designed into aesthetic forms, or even made flexible. Accordingly, there has been a considerable interest devoted to enhancement of luminous efficiency of OLEDs employing various methods [1,2].

Among these, one simple method for increasing the extraction efficiency is to extract the portion of photons lost in the substrate mode by the use of micron size lenses attached to the air side of the device substrate [3]. Micro-lenses increase the escape cone for photons scattering at various angles inside the device and make a way for their exit from the device. Further the shape and geometry of these lenses along with pattern in which they are arranged also have a great impact on extraction efficiency [4–6].

These micro-lens arrays (MLA) have been fabricated using various techniques, such as photo-lithography, thermal reflow processing, hot embossing, injection molding and imprint lithography [7–11]. All these techniques have their own advantages, but suffer from technical complexities or high cost of materials as well as equipment.

As an attractive alternative to the described techniques, inkjet

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printing is promising because of its ability to write directly and being maskless. Besides depositing functional materials for fabrication of devices such as thin film transistors, solar cells, bioprinted tissues [12], inkjet printing has also been employed for preparing micro-lens arrays [13–15]. The microlenses thus fabricated can find applications such as for focusing in detector arrays, fiber optics and sensors, illumination in flat panel displays and imaging in photocopies and lithography.

Although the use of direct inkjet printing process for fabricating microlenses is extremely simple, but the only difficulty lies in achieving the high aspect ratio of the microlenses (because of low viscosity ink) and high fill factor. In addition to that the materials, being used for this purpose, are difficult to handle as they are generally based on gels and hence can block the nozzles of the cartridge. Also, the printed lenses can only be used once.

Moreover the process is also combined with a surface treatment or surface modifying process along with inkjet printing. So instead of directly printing the lens material, a better method could be preparing a master as a first step and then preparing microlenses out of it repeatedly, avoiding the need for inkjet printing again and again. Such a method also provides flexibility to use a variety of materials for lenses and it fastens the process, without having to develop a separate ink for each material as in direct printing of lenses.

Accordingly, in the present study, we propose printing two dimensional patterns of yeast. Innovation lies in the fact that these would grow into three dimensional patterns as a natural course for yeast's behavior [16]; the patterns would serve as masters for preparing microlenses. This approach raises a possibility of obtaining a significant aspect ratio due to vertical growth of the yeast and a better packing density of microlenses due to its lateral growth. The microbial patterns with the precision of the order of a hundred microns could be achieved by this simple fabrication technique. Moreover, the proposed approach provides the advantage of being extremely simple and at the same time cost effective.

Similar to the concept of using positive or negative photoresist in lithography, where the nature of photoresist decides whether exposed regions will be protected or dissolved away [17], here, two complementary approaches were used to pattern microbes - one where microbial growth is accessed selectively, and second, where the microbial growth is prevented on selected regions.

2. Experimental section

2.1. Printing process

Polyvinylidene (PVDF) membrane (pore size 0.45 μm), purchased from Merck Millipore, is used as substrate and an overnight grown culture of *Saccharomyces Cerevisiae* (yeast, German baker's yeast) is used as inoculant. Printer employed here is a piezo based Dimatix printer (DMP-2831). Aqueous solutions of different concentrations 1%, 10%, 20% of tween-20, triton X-100 (both purchased from SD-Fine Chemicals) as well as their mixtures in the culture were prepared and optimized to get the surface tension and viscosity values meeting the requirements of inkjet printing process in microbial approach. The solution with 10% triton X-100 in the yeast culture was found suitable for printing. On the other hand, in case of antimicrobial approach, iso-amyl alcohol (SD-Fine chemicals) was employed for printing, in which case prior to printing, PVDF substrate was spin coated with culture ink at 100 rpm for 20 s.

In both the approaches, after performing printing step, PVDF membrane was placed in an incubator for growth at 37 °C for 24 h in case of antimicrobial approach and for 36 h in case of microbial approach, unless indicated differently. In the incubator, the PVDF membrane was kept on a media layer consisting of yeast peptone dextrose (YPD) purchased from HiMedia laboratories Pvt. Ltd.

2.2. Fabrication of microlenses

Polydimethyl siloxane (PDMS) was purchased from Dow Corning Sylgard 184 as a kit that consists of a base and a curing agent. Both these components of the kit contain siloxane oligomers terminated with vinyl groups. The base also includes a platinum based catalyst, that leads to the curing of elastomer by an organometallic cross-linking reaction [18]. For fabrication of microlenses, both base and curing agents were mixed in proportion of 10:1. This mixing results into air bubbles in the mixture. To remove these bubbles, we placed the mix in a vacuum desiccator and connected it to a rotary pump for one hour, until the solution became clear, free from any air bubbles. This PDMS solution was then poured over substrate containing patterned microbes and cured at 60 °C for 2 h. After cooling down to room temperature, PDMS was peeled off from substrate, washed with deionized water or ethanol to remove any microbes attached to it and then finally dried in a stream of nitrogen. The PDMS replica thus obtained serves as microlens arrays (MLA) in case of antimicrobial approach, whereas in case of microbial approach this negative replica is further used for preparing positive replica after ozonization treatment (to avoid sticking of PDMS to negative replica). The standard protocol used for ozonization involves three steps - ultra-violet (UV) cleaning for 15 min, followed by oxygen flow in the presence of UV for 20 min and then finally oxygen flow for 10 min.

2.3. Characterization

For ink preparation, surface tension values for various solutions were measured with the help of tensiometer (Dataphysics OCA 15 EC) using pendant drop method with a drop volume of 4 μl. For viscosity measurements, we used viscometer (Anton-paar Lovis 2000M), working on the rolling ball principle using a steel ball of diameter 1.59 mm. After printing, the growth of microbes was observed optically by using stereo-microscope (Leica MZ10F) for the specified time intervals. PDMS microlenses fabricated out of these microbial patterns were characterized using profilometer (Dektak XT- Bruker) for three dimensional scans. The microlenses thus prepared were tested for their potential in luminance enhancement using spectro-radiometer (Konica Minolta CS 1000). For all three-red, green and blue OLEDs-luminance without microlenses were 85 cd/m^2 (at 7 V), 315 cd/m^2 (at 6 V) and 560 cd/m^2 (at 6 V) respectively. The effect of microlenses on the out-coupling efficiency was observed in terms of (%) luminance enhancement.

3. Results and discussion

The basic process for patterning of microbes by two approaches, (a) microbial approach and (b) antimicrobial approach, has been reported earlier [16,19]. Here we specifically discuss the additional details for tailoring the process for fabrication of master for OLED microlenses. Briefly, Fig. 1 shows the schematic of the process used. The first approach, that is, microbial approach, involves printing of yeast cells in a dot pattern on polyvinylidene fluoride (PVDF) membrane, which is maintained on a media layer. The role of PVDF membrane here is to provide support for microbial growth. For OLED microlenses, printing of yeast ink requires a high resolution technique, such as ink jet printing. At the time of printing, it is essential that the nutrient media is already present underneath the PVDF membrane, otherwise the yeast cells would not adhere to the PVDF surface.

When this stack consisting of media layer/PVDF membrane/