Polymer electroluminescent devices processed by inkjet printing: I. Polymer light-emitting logo

Jayesh Bharathan and Yang Yang[a)]
Department of Materials Science and Engineering, University of California—Los Angeles, Los Angeles, California 90095-1595

(Received 22 January 1998; accepted for publication 25 March 1998)

Inkjet printing (IJP) technology is a popular technology for desktop publishing. Since some of the conducting (or conjugated) polymers are solution processable, IJP technology becomes an ideal method for printing polymer light-emitting diodes with high resolution. Unfortunately, the polymer film printed from an inkjet printer usually consists of pin-holes, and this intrinsic character makes it unsuitable for fabricating high quality polymer electronic devices, particularly for devices in the sandwich structure. In this letter, we submit a hybrid structure, which consists of an inkjet printed layer in conjunction with another uniform spin coated polymer layer, as an alternative to the regular inkjet printed structure. The uniform layer serves as a buffer layer to seal the pin-holes and the IJP layer is the layer consisting of the desired pattern, for example the red–green–blue dots for a multicolor display. To demonstrate, we applied this hybrid technology to fabricate efficient and large area polymer light-emitting logos. The use of this concept represents a whole new technology of fabricating polymer electronic devices with lateral patterning capability. [S0003-6951(98)04221-1]

Conjugated polymers are a novel class of semiconducting materials which combine the electronic and optical properties of semiconductors and the processability of conventional polymers.[1] Polymer optoelectronic devices, such as light emitting diodes (LEDs),[2] photodetectors,[3] solar cells,[4] and field-effect transistors[5] have already been demonstrated. Currently spin-casting of polymers is a common processing technique for polymers which utilizes their solution processability property. However, there are many disadvantages associated with this simple technology such as solution wastage and lack of lateral patterning capability, which limits its commercial applications in polymer electronic devices. To overcome these drawbacks we present the inkjet printing (IJP) technology, a popular technology for desktop publishing, as an ideal method for printing polymer light-emitting diodes with high resolution. In this letter, we submit the first successful demonstration of patterning the polymer electroluminescent devices using the IJP technology.

The remarkable advantages of the IJP technology over the conventional spin casting technique can be seen in Table I. The application of IJP to pattern the organics has been demonstrated by Wu *et al.*, however they had to use a very low concentration solution in order to use the existing IJP technology.[6] The result was a poor film forming capability which renders it impractical for making high quality devices. A dramatically different approach by using a buffer layer, prepared by the spin-casting technique, in conjunction with the inkjet printed layer has been demonstrated successfully at the University of California at Los Angeles (UCLA) for the fabrication of high quality polymer electronic devices.[7] This buffer layer, which could be the host conjugated polymer with typical thickness of 1000 Å, is the highlight of this IJP technology that we present here. Figure 1 schematically shows a buffer layer used in the IJP technology. For purpose of comparison, the same IJP device without the buffer layer is also shown and the advantage of the buffer layer can be immediately seen.

This hybrid IJP technology can be easily used to fabricate high quality polymer multicolor electroluminescence (EL) display. The red–green–blue polymers, which are the basic elements for the multi-color display, can be easily patterned by using the IJP technology. In this case, the buffer layer is the electron injection polymer which serves two purposes: (a) it facilitates the electron injection and (b) it seals the pin-holes. Alternatively, high quality polymer light-emitting logos can be realized when the IJP layer is the charge injection layer, such as a conducting polymer, and the buffer layer is the luminescent polymer. Thus the emissive area is defined by the charge injection layer printed directly from the inkjet printer.[8]

In this letter, we demonstrate this concept of using the hybrid IJP technology by fabricating high quality polymer light-emitting logos (PLELs). This logo patterning is achieved by printing the conducting polymer, an aqueous solution of polyethylenedioxy thiophene (PEDOT), by an inkjet printer onto the highly conductive and transparent ITO electrode. Since the charge injection efficiency of the conducting polymer is much better than that of ITO, only the areas which are covered by the conducting polymer light up under the same operating voltage.[7] For this research, the PLELs were fabricated in a sandwich structure with substrate size of 30 mm×30 mm. Poly[2-methoxy-5-2′-ethyl-hexyloxy)-1,4-phenylene vinylene] (MEH-PPV) was used as the active material (or it is the buffer layer), and ITO was the anode and calcium was the cathode. The PEDOT solution was printed onto ITO by using a commercial available inkjet printer. The MEH-PPV films were prepared via spin-casting

[a)]Author to whom correspondence should be addressed. Electronic mail: yy@seas.ucla.edu

TABLE I. Comparison of spin-casting and inkjet printing technologies.

Characteristics	Spin-casting	Inkjet printing
Patterning capability	No patterning capability	Capable of patterning with micrometer resolution
Large device area capability	Sensitive to dust particles and substrate defects, and not suitable for large area processing.	IJP is not sensitive to substrate defects, and it is a better technology for the fabrication of large area device.
Efficiency of using material	More than 99% of the polymer solution is wasted.	Only less than 2% of the material is wasted.
Multi-color display fabrication capability	No multicolor patterning capability.	Ideal for multicolor patterning.

at 2500 rpm from a 1% MEH-PPV solution, and the thickness of MEH-PPV films was determined to be around 1200 Å as obtained using an alpha-step profilometer.

The typical PLEL fabrication process is shown in Fig. 2: the conducting polymer logo is printed onto a pre-cleaned glass/ITO substrate. A MEH-PPV layer is subsequently spin-coated onto the patterned substrate, and the final fabrication process of a PLEL is the deposition of the cathode material. The finished devices are encapsulated by epoxying the active device area with a cover glass.[9]

Figure 3 shows the brightness-voltage ($L-V$) curves of devices with and without the PEDOT conducting polymer layer. It is obvious that the PEDOT layer dramatically enhances the device performance. For example, when the device is operated at 5 V, the ITO/PEDOT/MEH-PPV/Ca device has around 200 cd/m^2 brightness, while the brightness from the ITO/MEH-PPV/Ca device was about three orders of magnitude smaller. This gives a contrast, defined as the brightness ratio of the bright/dark regions, of ~800.

Figure 4(a) illustrates a polymer light-emitting UCLA logo. Since images from a personal computer can be printed directly to form the light-emitting logo, the application of this technology is nearly unlimited. For instance, new and complicated emissive logos can be custom-built for a variety of purposes such as greeting cards or other novelty items. Figure 4(b) shows a Valentine heart logo fabricated from the same technology. This image is generated by a computer and printed by the inkjet printer. To our knowledge, it is the first time that a logo generated directly from a computer has been transformed into a polymer electroluminescent image.

One can easily extend this concept of light-emitting logos to light-emitting image. However, one of the major concerns of applying this technology in achieving high quality light-emitting image is the gray scale. In Fig. 5(a), we demonstrate a four-level gray scale generated from a computer graphic program. This four-level gray scale is defined by the density of emissive dots, and Fig. 5(b) shows the brightness of each level of gray scale. This gray scale can be tuned nearly continuously by changing either the dot size or the density of the dots. Another advantage of this inkjet printing technology is the fabrication of micron size polymer light-emitting diodes without going through the regular patterning of anode and cathode. Usually, small size LEDs can only be fabricated by crossing the cathode and anode fingers with the overlap area defining the pixel size. This unique patterning capability of the conducting polymer using the inkjet printer provides a convenient alternative for the generation of regular arrays of micron size polymer LEDs. Typical emissive dot sizes mentioned in this report ranged from 180 to 400 μm depending on the amount of conducting polymer ink sprayed from the nozzle. The dimensions of the pixels produced by this technology are also a function of the nozzle size of the inkjet head and it can be reduced if the nozzle size is reduced. For displays a dot size in the 100 μm

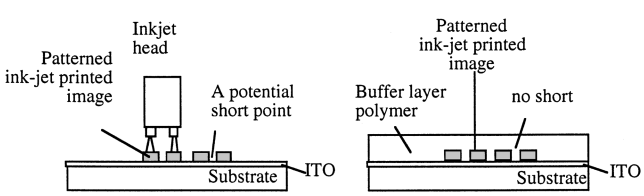

FIG. 1. A buffer layer used in the IJP technology.

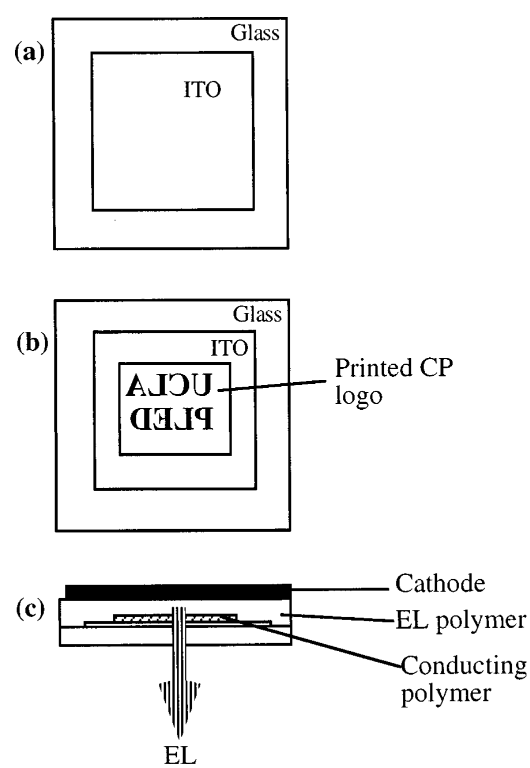

FIG. 2. The polymer light-emitting logo fabrication process: (a) preparation of the substrate; (b) printing of the conducting polymer into desired pattern; (c) deposition of the luminescent polymer and the cathode material.

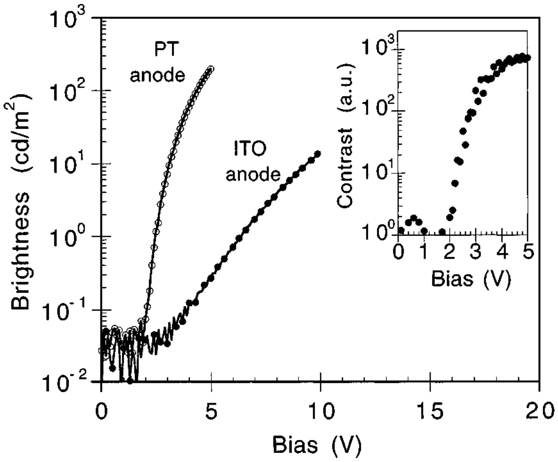

FIG. 3. The brightness–voltage curves of the same device. The contrast–voltage curve is shown in the inset.

range is sufficiently small for monochromatic displays.

In conclusion, we have demonstrated successfully the concept of applying the hybrid inkjet printing technology as an effective tool for the patterning of polymer electroluminescent devices. Polymer light-emitting logos, wherein the emission area is defined by the area of the printed conducting polymer, have been demonstrated. A four-level gray scale has been achieved through the control of the density of dots printed. Finally, we have realized the use of inkjet printing technology to fabricate micron size LED arrays. This technology allows the fabrication of two-dimensional polymer electronic devices, such as multi-color display and transistors, with very high lateral resolution and high material utilization efficiency.

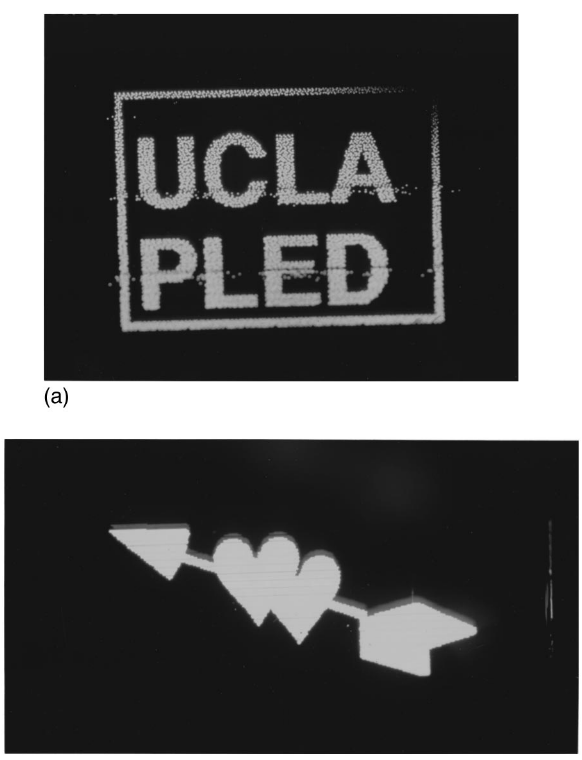

FIG. 4. The polymer light-emitting logo patterned by the IJP technology: (a) a UCLA logo and (b) a Valentine heart logo.

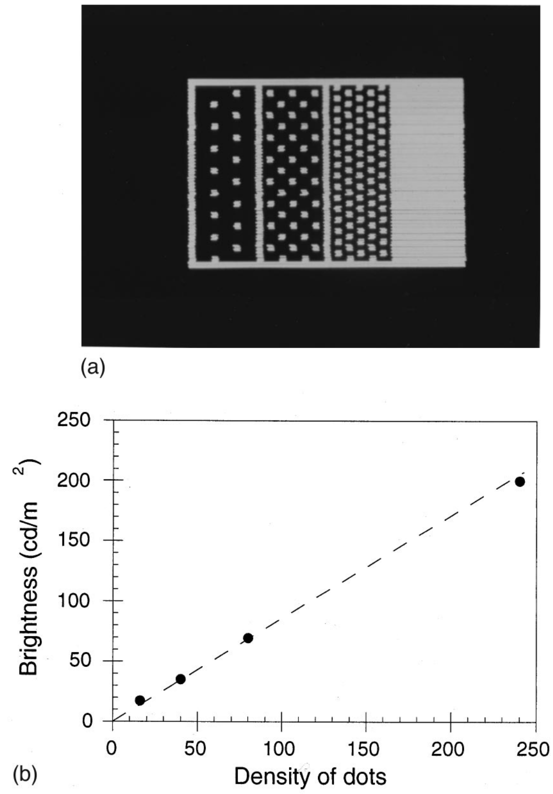

FIG. 5. (a) Four levels of gray scale of the polymer light-emitting logo created by inkjet printing technology. The brightness of these four regions is defined by the density of dots. (b) Brightness vs density of dots.

The authors are very grateful for the fruitful discussions with Dr. T. Shimoda and Y. Miyashita of Seiko-Epson Corporation. The donation of an inkjet printer from Seiko-Epson to UCLA, the MEH-PPV obtained from Professor F. Wudl of the Chemistry and Biochemistry Department of UCLA, and the PEDOT obtained from J. T. Morrison of Bayer Corporation are also acknowledged. This research is partially supported by a research grant from the School of Engineering and Applied Science of UCLA and a grant from the Office of Naval Research (Dr. K. Wynne).

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