Novel Fine Electrode Patterning Using Ink-jet Method and Its Application to All-printed Organic TFT Backplane

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Abstract

We have developed surface energy controlled ink-jet printing technique with UV irradiation on novel polyimide. Predefined surface energy patterns control the flow and spreading of ink-jetted water-based electrode droplets on the polyimide film. Line width of 20 µm and space of 2 µm has been fabricated. In this study, we have successfully fabricated an active-matrix organic-thin film transistor (AM-OTFT) array in which the channel length is 5 µm on the plastic substrate applying this technique. Moreover, high resolution of 160 ppi flexible electrophoretic displays consisting of this AM-OTFT backplane was demonstrated.

Introduction

In recent years, printing technologies have been applied to the fabrication of various electric devices such as organic thin-film transistors [1, 2, 3], RF-ID tags [4, 5], sensors [6], batteries [7], electronic papers [8], and organic electro-luminescence (EL) displays [9]. This is because printing technologies bring considerable reduction of cost and environment impact as compared to silicon process technology, in which conventional photolithography and etching process are used. Taking into account the required properties such as precision shape, thickness, size, and surface roughness, the most preferred printing method is selected among offset printing, gravure printing, flexo printing, ink-jet printing, micro-contact printing, and so on. In general, the electric devices are fabricated in combination of several printing methods.

We have focused on the ink-jet printing [10]. Because ink droplets are directly applied onto the substrate, consumption of materials is significantly reduced. Accordingly, inkjet printing has a much potential to minimize environmental impact. For conventional ink-jet printing technique, however, typical resolution is around 50 µm. Therefore novel fabrication methods have to be explored to realize high resolution patterning. So far, various methods have been proposed [2, 3, 8, 11, 12].

We have developed surface energy controlled ink-jet printing technique with ultraviolet (UV) irradiation on the newly obtained polyimide film [10]. The exposure of UV light through a photomask can selectively change the surface energy of the film and then form high (hydrophilic) and low (hydrophobic) energy patterns. Water-based electrode ink-droplets ejected from ink-jet head spread only over the high surface energy area and are settled following the shape of mask patterns. It was shown that at least line width of 20 µm has been fabricable and line space has been accessible up to 2 µm. In this study, we have successfully fabricated an AM-OTFT array in which the channel length is 5 µm on the plastic substrate applying this novel ink-jet technique. Moreover, high resolution of 160 ppi flexible electrophoretic displays (EPDs) consisting of this AM-OTFT backplane was demonstrated [13].

Electrode patterning

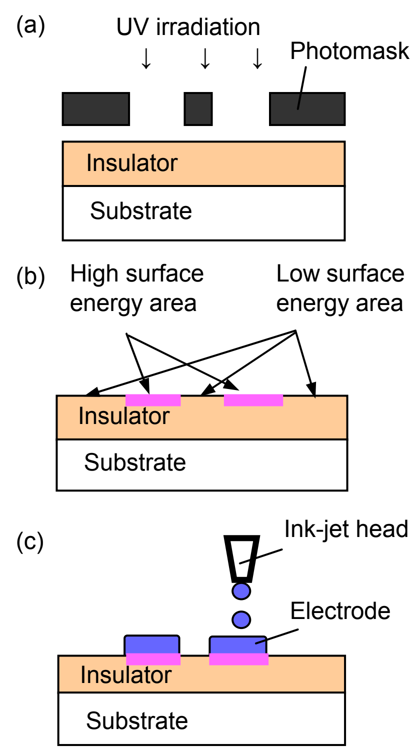

***Figure 1**. Schematic of the surface energy controlled ink-jet printing process (a) UV irradiation, (b) formation of areas with different surface energy, (c) fabrication of electrodes by ink-jet printing*

To obtain well-defined electrode patterns, we have developed surface energy controlled ink-jet printing technique. Figure 1 shows how the fine electrode patterns are formed on the surface of a novel polyimide film by this technique. The polyimide film whose surface has low surface energy after post bake was fabricated on the plastic substrate by spin coating. After UV irradiation from super-high pressure mercury lamp through a photomask from the front side of the substrate (Figure 1a), the high surface energy area corresponding to electrode patterns and the low surface energy area were formed on the novel polyimide film surface (Figure 1b). After water-based Ag nanoparticles ink was ink-jetted onto the high surface energy area, the droplet was spread over the edge of the area (Figure 1c).

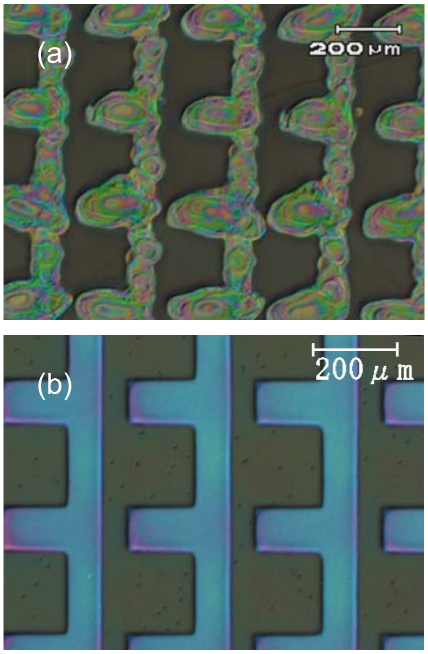

***Figure 2**. Electrode patterns (a) without and (b) with surface energy controlled ink-jet printing method*

Figure 2 shows an optical microscopy image of patterned electrodes (a) without and (b) with surface energy controlled ink-jet printing method. As a polymer film was overlayered on the electrode patterns, the interference fringes depending on the difference of the film thickness due to rough surface of electrodes are observed. While it reflects the spreading of ink droplets in case of (a), electrodes shape in (b) outlines photomask patterns. Interference fringes do not appear, therefore, the electrode turns out to have the flat planar surface.

To investigate the minimum space between lines, we prepared a photomask with various line and space patterns. After UV irradiation on the novel polyimide film through the photomask, water-based Ag nanoparticles ink was ink-jetted. Controlling with ink-jet printing conditions such as drop size and ink volume per unit line, two kinds of electrodes with different thicknesses were fabricated. Figure 3 shows the dependence of the yield with electrode fabricated conditions. Yield means the ratio of separation between the two electrodes and was determined by using an optical microscope with 100 points in one sheet. Figure 3 shows that minimum space up to 2 μm (designed) could be fabricated using surface energy controlled ink jet printing with UV irradiation on the polyimide film. It is superior to conventional ink jet method.

We examined alignment margins of electrode fabrication by our ink-jet technique, increasing the gap between center of high surface energy line pattern and that of ink droplets landing position every 10 μm. Figure 4 shows that the lines in 80 μm width can be successfully formed in accordance with photomask patterns under the condition of 50 μm apart from the center of the ideal landing position. This is because the hydrophilic ink droplets, which land onto the low surface-energy area (hydrophobic area), could be drawn into the high surface-energy area (hydrophilic area).

Thus, surface energy controlled ink-jet printing technique possesses such unique features as fine patterning, good surface roughness, and high alignment margin.

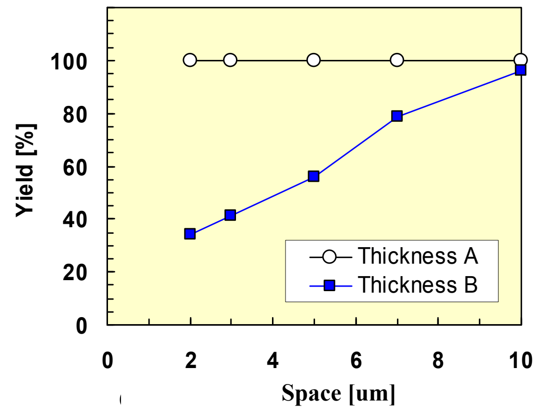

***Figure 3**. Yield on designed space against electrode thicknesses*

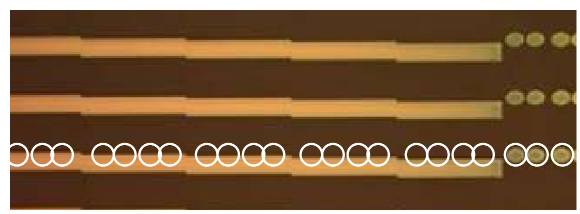

***Figure 4**. Alignment margin of ink droplets ejected from IJ head onto the surface energy controlled polyimide film. White circles show impact positions of ink droplets*

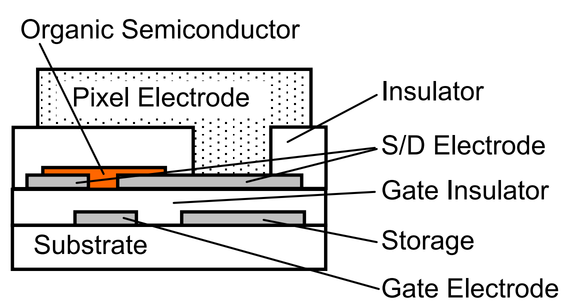

***Figure 5**. Schematic cross-section of the all-printed OTFT backplane*

Fabrication of Organic TFT backplane

Figure 5 shows a schematic cross-section of all-printed OTFT backplane with bottom-gate structure on plastic substrate. The gate electrodes source/drain (S/D) electrodes and these lines were fabricated using water-based Ag nanoparticles ink by the surface energy controlled ink-jet printing method. The gate insulator was a novel polyimide film fabricated by spin coating. The insulator and pixel electrodes were prepared by screen printing.

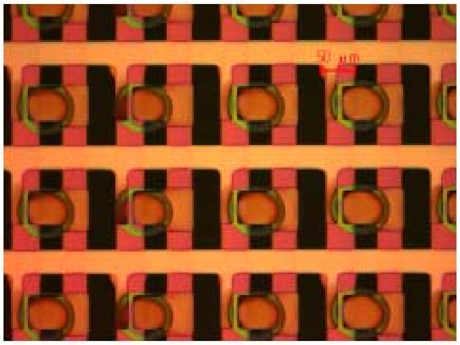

Figure 6*. All-printed OTFT backplane after OSC printing. Pitch of each pixel corresponds to 159 μm (160ppi)*

Figure 6 shows an optical micrograph of a 160 ppi (pixel size 159 μm × 159 μm) all-printed OTFT array on the flexible plastic substrates after organic semiconductor fabrication. Fabricated by the surface energy controlled ink-jet printing with UV irradiation, it has been shown that a minimum electrode width of 20 μm and a channel length of 5 μm can be fabricated with a clear outline of the shape. Typical electrode conductivity and thickness were 16 μΩcm and 100 nm after post-annealing, which was sufficient to function as an electrode.

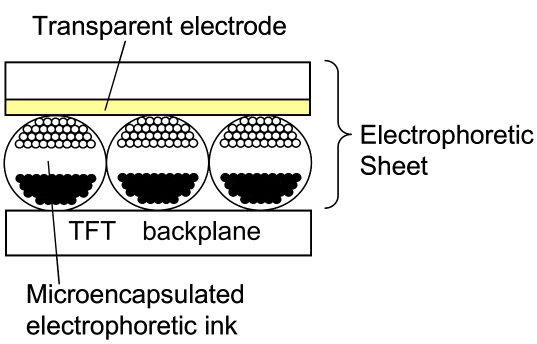

Figure 7*. A 160 ppi EPD driven by all-printed OTFT backplane on flexible substrates*

Amorphous organic semiconductor (OSC) films consisting of stilbene polymer with triarylamine unit and long-chain alkyl group were fabricated by conventional ink-jet printing. Triarylamine unit is for high air stability and high mobility, while long-chain alkyl group is for high solubility. We selected the appropriate solvent for polymer OSC and optimized ink-jet printing conditions. OSC films showed like a coffee stain profile and separated with each others at 159 μm pitch without any bank structures. All-printed OTFT backplane with 160 ppi resolutions contains 5 μm channel length (L) with 432 × 288 pixels and 3.2 inch diagonal.

Integration of 160ppi OTFT backplane and EPDs

In order to demonstrate the performance of our backplanes, original electrophoretic sheet (432 × 288 pixels, 3.2-inch diagonal) was laminated with the 160 ppi all-printed OTFT backplane on plastic substrate. As shown in Figure 7, Japanese characters were driven by OTFT backplane. 10-point character size was successfully displayed. The applied voltages of select line and data line were 30 Vpp and 27 Vpp, respectively.

Conclusions

We developed a novel ink-jet printing technique with the aid of newly obtained polyimide film, whose surface energy is controllable by UV irradiation. It has turned out that this technique has a potential to form electrode patterns with minimum line width of 20 μm and line-to-line spacing of 2 μm, in which these values significantly exceed the resolution limit of the conventional ink-jet method. We have successfully fabricated the high performance all-printed OTFT backplane (channel length of 5 μm) on the plastic substrate with combination of screen-printing and novel ink-jet method as mentioned above. By using this backplane, we have demonstrated a prototype of 160 ppi EPDs on the flexible plastic substrate.

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