A 200 ppi All-printed Organic TFT Backplane for Flexible Electrophoretic Displays

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ABSTRACT

A 200 ppi all-printed organic thin film transistor (OTFT) backplane was fabricated with a channel length of 5 μm and mobility of over 0.1 cm^2/Vs by a surface energy controlled Ink-Jet printing and several printing methods on plastic substrate. A flexible electrophoretic display (EPD) driven by the all-printed OTFT backplane was successfully demonstrated.

1. INTRODUCTION

In recent years, it has been demanded for flexible electronic paper to be low cost, easy to read like traditional paper, lightweight and robustness. Printing technology is suitable for low cost and low environmental impact, and large area fabrication. Low cost and low environmental impact are because of small number of process steps, small amount of materials and high through-put. Several printing methods such as screen printing [1] and ink-jet printing [2, 3] have been developed to fabricate organic thin film transistors (OTFTs). In general, the resolution of these conventional printing is much lower for the applications of electronic paper. But recently, higher resolution such as 80 ppi [4], 76 ppi [5] and 150 ppi [6] of advanced printing process was reported.

In previous work we developed a surface energy controlled ink-jet printing with ultraviolet (UV) irradiation [7] and demonstrated a 160 ppi all-printed OTFT backplane [8] with polymer organic semiconductor (OSC), which has high solubility and high air stability [9,10]. Moreover, flexible electrophoretic displays (EPDs) with high resolution of 160ppi were demonstrated (see Fig. 1). In this paper, we have fabricated a 200 ppi all-printed OTFT with high field-effect mobility of over 0.1 cm^2/Vs with small-molecule OSC. The pixel size and the mobility are sufficient for a monochrome electronic paper. Then, a flexible EPD with 6-point character size has been driven by a 200ppi all-printed OTFT backplane.

2. FABRICATION OF ALL-PRINTED OTFT BACKPLANE

Fig. 2 shows a cross sectional view of the all-printed OTFT backplane with bottom-gate structure on plastic substrate. The gate electrode and the storage capacitor electrode were fabricated using 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 source/drain (S/D) electrode consist of Ag were also fabricated by the surface energy controlled ink-jet printing method. Small-molecule OSC was fabricated by ink-jet printing under ambient conditions. After the formation of OSC layer, the insulator and pixel electrodes were fabricated by screen printing. All of these layers were fabricated by several printing processes under ambient conditions. Maximum process temperature was 180˚C.

Fig. 1 Optical micrograph of a flexible EPD driven by a 160 ppi all-printed OTFT backplane.

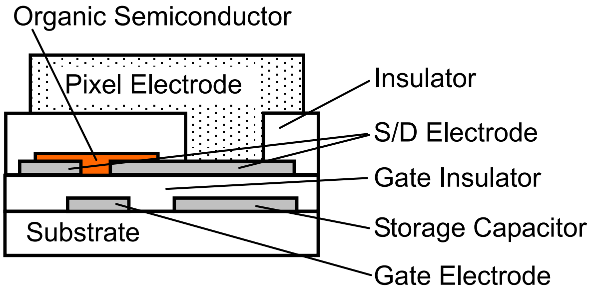


Fig. 2 Cross Sectional view of the all-printed OTFT backplane

To obtain the fine electrode patterns, we have developed the surface energy controlled ink-jet printing technique (see Fig. 3). The novel polyimide film was fabricated on the plastic substrate by spin coating, whose surface had low surface energy after post-baking in N$_2$ condition at 180˚C. After UV irradiation from super-high pressure mercury lamp through a photo mask from the front side of the substrate (Fig. 3a), the high surface energy area corresponding to electrode patterns and the low surface energy area were formed on the novel polyimide film surface (Fig. 3b). Hydrophilic Ag nanoparticles ink was ink-jetted onto the high surface energy area and spread over the edge of the area (Fig. 3c). After post-baking under ambient condition at 180˚C, the fine electrode patterns were obtained. Using this novel polyimide as an insulating layer, additional fabrication process of wiring is only exposure process without such wet process as development and etching. Then, the surface energy controlled ink-jet printing takes advantage of practical number of process steps.

Fig. 4 shows an optical micrograph of electrode patterns overlaid with the gate insulator (a) without and (b) with the surface energy controlled ink-jet printing method. Electrodes without the surface energy controlled ink-jet printing (Fig. 4a) show droplet-like shape and rough surface with interference fringes, which depends on the difference of the film thickness due to surface roughness of electrodes. On the other hand, electrodes with the surface energy controlled ink-jet printing (Fig. 4b) show photo mask-like shape and very smooth surface because of no interference fringes.

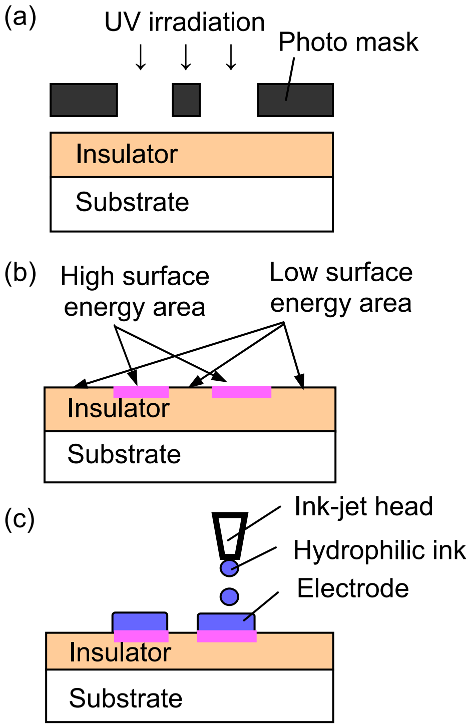


Fig. 3 Schematic of the surface energy controlled ink-jet printing process (a) UV irradiation, (b) Formation of areas with different surface energy, (c) Fabrication of electrodes by ink-jet printing.

We examined alignment margins of electrode fabrication by this ink-jet technique, increasing the distance between the center of high surface energy line pattern and that of ink droplet impact position every 10 μm. Fig. 5 shows that the lines in 80 μm width can be successfully formed same as photo mask patterns apart from the center of the ideal impact position by a distance of 50 μm or less. This is because the hydrophilic ink droplets, which land onto the low surface energy area, could be drawn into the high surface energy area.

Thus, the surface energy controlled ink-jet printing technique possesses such unique features as good surface roughness, high-resolution patterning and high alignment margin because of using a photo mask.

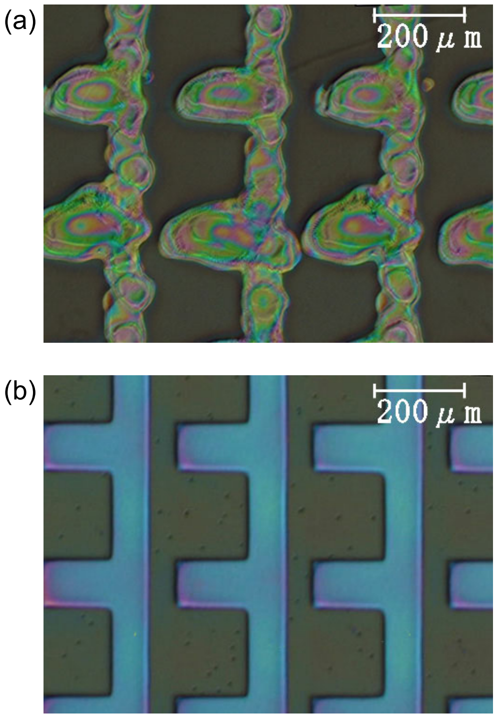


Fig. 4 Optical micrograph of electrode patterns (a) without and (b) with the surface energy controlled ink-jet printing method.

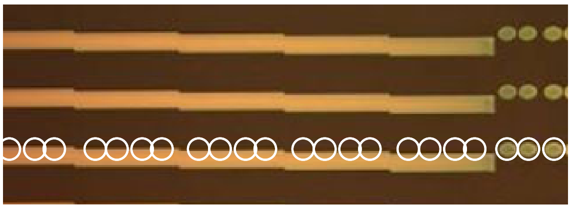


Fig. 5 Alignment margin of ink droplets ejected from IJ head onto the surface energy controlled polyimide film. White circles show impact positions of ink droplets.

In order to shrink the TFT size to 200 ppi (pixel size 127 μm × 127 μm) from 160 ppi (pixel size 159 μm × 159 μm), we have optimized TFT design such as the line and space of the gate electrode and the S/D electrode. However, it is difficult to achieve fine electrode patterning and low resistivity at same time. We have optimized the electrode thickness and the curing time. The electrode thickness was controlled by ink-jet condition such as ink volume per unit line. Fig. 6 shows an optical micrograph of a 200 ppi all-printed OTFT array on plastic substrate after S/D electrode fabrication. It is shown the minimum line width and space of the gate line were 30 μm and 15 μm, respectively. Those of the source line were same. A minimum width of the source electrode was 15 μm, channel length was 5 μm. Resistances per unit line of the gate line and the source line were 1 kΩ/cm and 0.5 kΩ/cm at 30 μm line width respectively, which were enough for 3.2 inch EPDs.

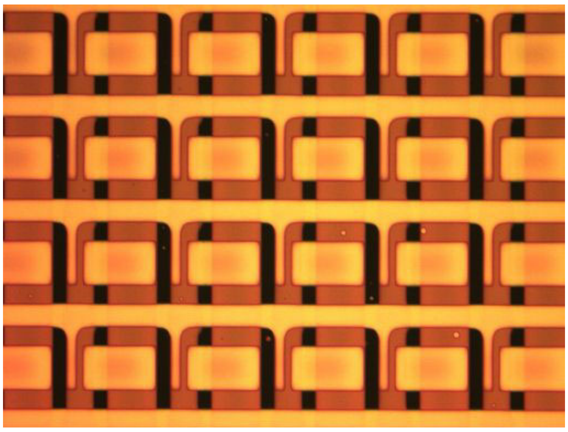


Fig. 6 Optical micrograph of a 200 ppi all-printed OTFT array on flexible substrate after S/D electrode fabrication (L = 5 μm).

3. CHARACTERISTICS OF ALL-PRINTED OTFT

After S/D electrode printing, small-molecule OSC was fabricated by ink-jet method. Patterning is important both for polymer OSC and for small-molecule OSC to obtain a high on/off current ratio. Small-molecule OSC is more difficult to print than polymer OSC because of the crystallization on the channel region in the TFT. We optimized the OSC ink formulation such as the solvent and the concentration. We also controlled the surface energy of the gate insulator by the pre-treatment and the novel polyimide. Fig. 7 shows the transfer characteristics of a 200 ppi all-printed OTFT with W/L = 57 μm/5 μm after OSC printing and pixel electrode printing. Mobility of 0.25 cm^2/Vs, V_{th} of 1.3 V, an on/off current ratio of 10^6 at V_{ds} = -20 V were obtained after small-molecule OSC printing. Although a slight reduction in the on-current and a small Vth shift were observed after pixel electrode printing, mobility of 0.12 cm^2/Vs, V_{th} of 3.9 V were still maintained, which is sufficient for driving high resolution EPDs.

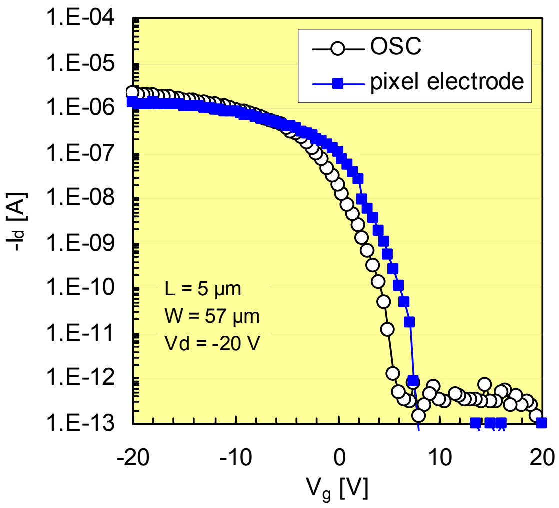


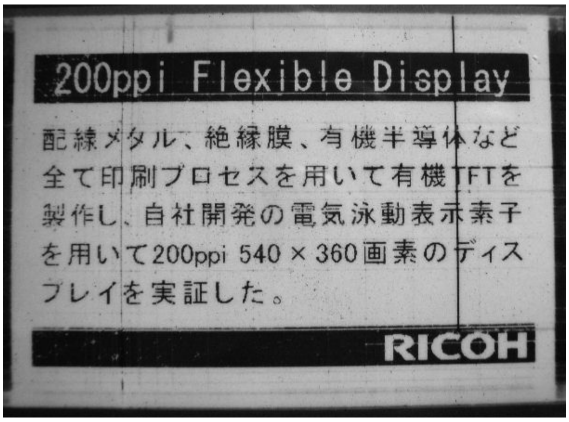
Fig. 7 Transfer characteristics of a 200 ppi all-printed OTFT after OSC printing and pixel electrode printing. Channel length L = 5 μm.

4. APPLICATION TO FLEXIBLE EPDS

For demonstration of flexible EPDs, an electrophoretic sheet was laminated with a 200 ppi all-printed OTFT backplane on plastic substrate. The size of EPDs is 3.2 inch diagonal with pixel number of 540 × 360 and the resolution is 200 ppi with pixel size of 127 μm × 127 μm (see Table 1). As shown in Fig. 8, Japanese characters with 9 point were successfully driven by the OTFT backplane. Furthermore, 6, 7, 8-point Ming-style font characters were displayed (see Fig. 9). The applied voltages of select line and data line were 30 V_{pp} and 20 V_{pp}, respectively.

Table 1. Specifications of a flexible EPD driven by the all-printed OTFT.

Display size	3.2 inch diagonal
Resolution	200 ppi
Pixel number	540 × 360
Pixel size	127 × 127 μm



200ppi Flexible Display

配線メタル、絶縁膜、有機半導体など全て印刷プロセスを用いて有機TFTを製作し、自社開発の電気泳動表示素子を用いて200ppi 540 × 360画素のディスプレイを実証した。

RICOH

Fig. 8 Photograph of a 3.2 inch flexible EPD driven by a 200 ppi all-printed OTFT backplane (540 × 360 pixels).

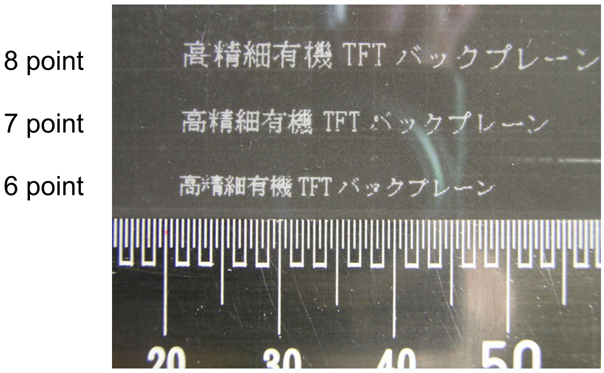


Fig. 9 Photograph of 6, 7, 8-point Ming-style font characters on a 200 ppi flexible EPD.

5. CONCLUSIONS

We have succeeded in fabricating a 200 ppi all-printed OTFT backplane for flexible EPDs. The resolution of 200 ppi and mobility of over 0.1 cm^2/Vs are enough for a monochrome electronic paper. To achieve such a high-resolution and high-mobility backplane on plastic substrate, we have improved the surface energy controlled ink-jet printing with UV irradiation for Ag electrodes and small-molecule OSC. This printing technology is promising for high-resolution, low-cost and low-environmental impact manufacturing process.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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