Development of the Printed Top Gate Organic Thin Film Transistor (OTFT)

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Abstract

The active layer thickness and curing condition dependent performance of an organic thin film transistor (OTFT) with inkjetted organic semiconductor (OSC) layer is studied. The best performance of the OTFT was found when the thickness of OSC was ~120 nm cured at 60 ℃. The performance enhancement of the OTFT with inkjetted OSC layer was discussed by comparing the OTFT with spin-coated OSC layer.

1. Introduction

For the recent years, organic thin film transistors (OTFTs) have been considered as promising device for the next generation displays, especially for the flexible and low cost displays [1,2]. However, the process cost of OTFTs is expensive yet for the mass production. One of the alternative proposal is inkjet printing method for the reduction of materials consumption. Inkjet printing is also considered as one of the best appropriate method for the patterning of organic semiconductor (OSC), because this method is free from the physical and chemical damages caused by the patterning process of an OSC layer. The issue for the application of the OTFT fabricated by inkjet printing is uniformity and performance degradation compared with the OTFTs fabricated by vacuum evaporation or spin-coating. In this paper, the performance enhancement of the OTFT fabricated by inkjet printing method would be discussed.

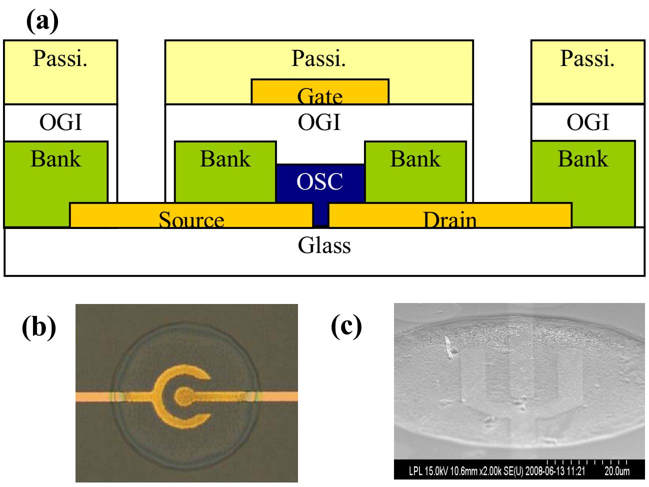

Fig. 1. (a) The schematic diagram of the top gate OTFT using inkjet printing method. (b) The microphotograph and (c) SEM image of the inkjetted OSC layer in the bank

2. Experimental

Figure 1 (a) shows the schematic diagram of the OTFT studied here. Because a top gate structure was hired, source and drain electrodes were firstly fabricated. The Cr layer with the thickness of 2 nm was thermally deposited followed by the deposition of Au with the thickness of 80 nm. The role of Cr layer used here was the good adhesion between a glass substrate and Au. The source and drain electrodes were then patterned by a conventional photolithography and wet etch process. Bank layer was spin-coated and also patterned by usual photolithographic technique. To obtain confined organic semiconductor (OSC) layer inside the patterned bank structures, the surface of the bank structure should have hydrophobic nature. In order to acquire the hydrophobic nature of the bank, we used a fluorinated acryl as the bank material. The OSC was inkjetted by the Litrex 140P with the Spectra SX3 head. The number of nozzles was 128 and the pitch between the nozzles was 508 μm. Drop pitch could be controlled by the rotational angle of the head. The microphotograph and scanning electron microscope (SEM) image of inkjetted OSC layer inside the bank were shown figure 1 (b) and (c), respectively. Organic gate insulator (OGI) was then spin-coated with the thickness of ~400 nm. Gate Cr/Au layers were thermally deposited again and patterned by photolithography and wet etch process. The passivation layer was spin-coated with the thickness of ~2 μm. The passivation layer were used by a photoacryl and patterned by usual photolithographic technique. Finally, the contact holes for the electrical measurement were opened by dry etch process through the patterned passivation layer. The substrate was Corning E2K glass scribed by 100×100 mm^2. The number of the test pattern in this substrate was ~5000 with various structures. Width and length of the OTFTs measured in this paper were 60 μm and 6 μm, respectively. All of the electrical data were measured by the KEITHLEY 4200 in atmospheric environment. The SEM image was obtained by the S-4800 of Hitachi High-Technology Corporation. The thickness of the OSC layer was measured by P11 Long Scan Profiler of KLA TENCOR.

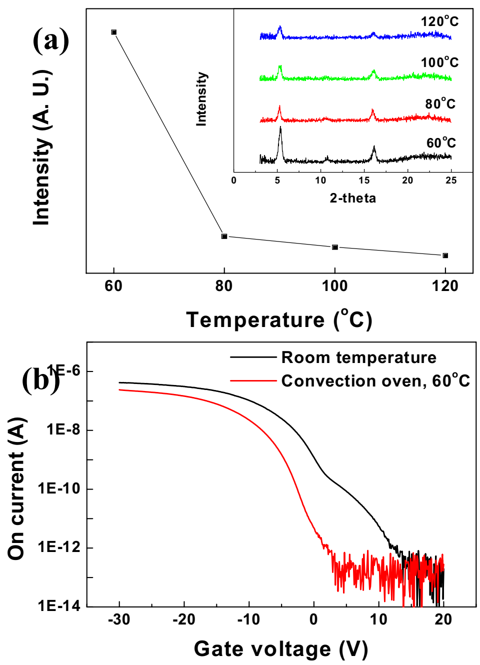

Fig. 2. (a) The intensity of XRD peak with different curing conditions of the OSC layer. The inset is the XRD spectra of each curing temperature from 60℃ to 120℃. (b) The transfer curves of the OTFTs with different curing conditions of room temperature (black line) and 60℃ in N_2 convection oven (red one).

3. Results and discussion

To enhance the performance of the OTFT with inkjet printed OSC layer, the curing condition of the OSC layer were studied. The crystallinity of the soluble OSC layer was closely associated with the curing temperature [3]. Four samples of OSC layer, cured in 60, 80, 100, and 120°C, were prepared and all samples were cured in an N_2 convection oven in 20 min. The XRD peak of the OSC layer was largest when that was cured in 60°C as shown in figure 2 (a). It can be supposed that the slow dry condition would be favorable to the crystallization of the OSC layer. The transfer curves of the OTFT devices with the cured OSC layer at 60°C and just dried one in room temperature were shown in figure 2 (b). The OTFT with the OSC layer dried in room temperature showed larger on current than that with the cured OSC layer at 60°C, which is correspondence with the previous argument for the relationship between the crystallinity and the curing condition. It is noted that the electrical hump was shown around the gate voltage of around -5 V in the transfer curve of the device dried in room temperature. The electrical hump observed in OTFT is often explained by the doping due to air exposure [4]. However, in our experiment, the electrical hump should not be caused by the doping due to air exposure because that is not observed in the OTFT with the OSC layer cured in 60°C. At this present, the electrical hump observed in the OTFT with the OSC layer dried in room temperature would be due to the remained solvent in the OSC layer.

In order to obtain the optimized thickness of the OSC layer, the on-currents at V_{gs} = -25 V and V_{ds} = -10 V were measured from the OTFT with different size of banks as the driving voltage of a nozzle kept constant. The measured thickness of the OSC layer were increased from 55 nm to 176 nm as the diameter of the banks decreased from 80 μm to 46 μm. Assuming the volume of the OSC ink filled in each bank to be same, the thickness of the OSC layer should be proportional to the inverse of the area of the banks. As shown in figure 3 (a), the thickness of the OSC layer was linearly proportional to the inverse of the area of the bank, where the slope means the volume of OSC layer. In this way, the thickness of the OSC layer could be easily controlled by inkjet method. As shown in figure 3 (b) (black), the on-current was largest when the thickness of the OSC layer was around 120 nm. The bank diameter of this OTFT was 56 μm and the surface profile of the OSC layer in the bank was shown in the inset of the figure 3 (b). The thickness of an OSC layer could be also controlled by the driving voltage applied to the nozzle of the inkjet printer. The on-current of the OTFTs with varying driving voltage were shown in figure 3 (b) (red line), where the thickness of the OSC layer was varied in the range from 50 nm to 150 nm. Similar to the previous result on the optimized thickness of the OSC layer in various sizes of bank, the largest value of the on-current was also observed around 120 nm. From the agreement of the two results, it is concluded that the control of the thickness of OSC layer would be one of the most important role for the performance of the OTFT than the other effects such as the size of bank or the jetting conditions. In general, the crystallinity of an OSC layer is directly related to the on-current and thus the mobility of OTFTs because well ordered OSC molecules have less defects than disordered [5]. In this point of view, it is supposed that the appropriate thickness of OSC layer should be necessary for the crystallization of inkjetted OSC layer.

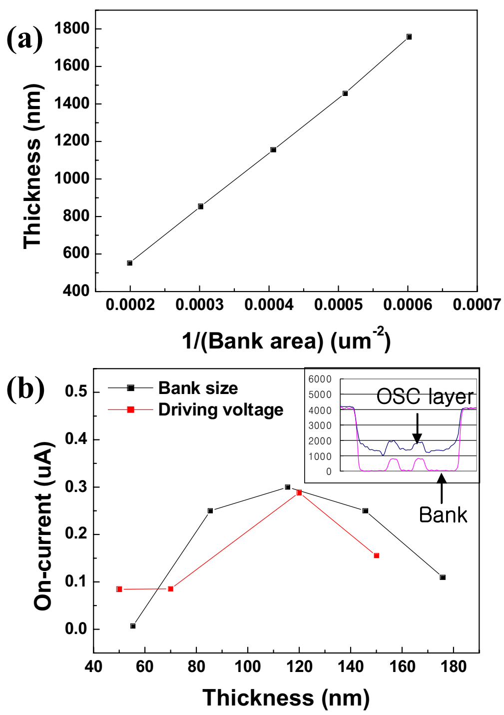

Fig. 3. (a) The thickness of OSC layer verses the inverse of the bank area. (b) On-current of the OTFTs with injetted OSC layer at V_{ds} = -25 V and V_{gs} = -10 V as varying thickness of the OSC layer. The thicknesses of OSC layer were controlled by the size of bank (black line) and driving voltage (red one).

However, the optimized thickness of the OSC layer in a spin-coated OTFT with same structure and materials was about 70 nm, as shown in figure 4 (a). The used material and the dimension of the OTFT with spin-coated OSC layer were all the same as that with inkjetted OSC layer except the bank layer. It was so surprise that the optimized thickness of OSC layer in the OTFT was largely different with each other in spite of the same structure and materials. A current path between source and drain electrode in our OTFT structure, that is top gate / bottom contact, is shown in the inset of figure 4 (a). In this structure, the contact resistance should increase as the OSC layer is thicker because the current must go through the bulk OSC layer vertically. If the channel length of the OTFTs are same, the magnitude of the on-current would be controlled by the contact resistance originate from the resistance of bulk OSC through vertical current path. According to the argument, the contact resistance of the OTFT with inkjetted OSC layer should be about 2 times larger than that of the OTFT with spin-coated OSC layer because the inkjetted OSC layer is about 2 times thicker than spin-coated one. The transfer curves of the OTFTs with spin-coated and inkjetted OSC layer are shown in figure 4 (b). The parameters of the OTFTs were evaluated from the transfer curves. The field effect mobility, threshold voltage, s-factor, and on/off current ratio of the OTFT with inkjetted OSC layer were calculated as 0.04 cm^2/Vs, -2.0 V, 1.6 V/dec., and 7.5×10^5, respectively, and those parameters of the OTFT with spin-coated OSC layer were calculated as 0.3 cm^2/Vs, -1.1 V, 1.3 V/dec., and 6.9×10^6, respectively. The on-current and thus the mobility of the OTFT with inkjetted OSC (red line) was lower by one order of magnitude than that with spin-coated OSC layer (black one). Assuming the crystallinity of OSC layers are almost same in both OTFTs, it could be suggested that the primary reason for the low on-current in the OTFT with inkjetted OSC layer would originate from the large contact resistance. The enhancement of the performance of the OTFT with inkjetted OSC layer would be studied in not only the crystallinity of OSC layer but also the reduction of contact resistance.

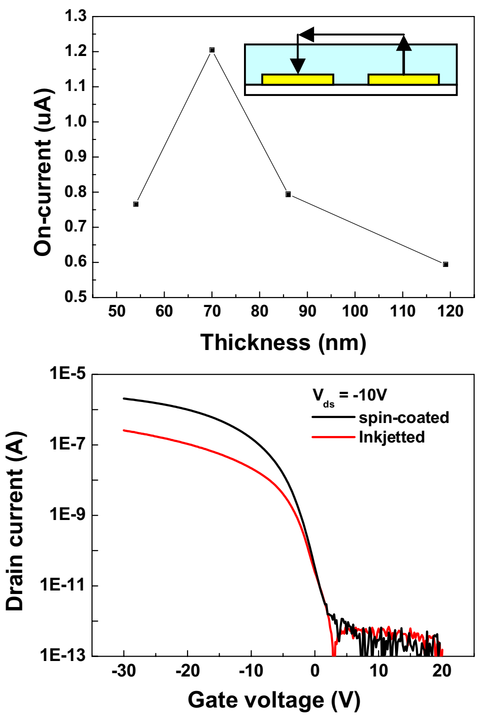

Figure 4. (a) On-current of the OTFT with spin-coated OSC layer versus the thickness of OSC layer. The inset shows the current path of the OTFT with top gate / bottom contact structure. (b) The transfer curves of the OTFTs with inkjetted (red) and spin-coated (black) OSC layer.

4. Summary

We fabricated the OTFTs with inkjetted OSC layer. As the solvent dried slowly the crystallinity of the OSC layer was improved. However, the OTFT of which OSC layer dried at room temperature showed electrical hump due to the remained solvent in the OSC layer. The thickness of the inkjetted OSC layer could be controlled by two methods, that is, the variation of bank size and the driving voltage. In two cases, the on-currents of the OTFT were largest when the thickness of OSC layer was about 120 nm. In this point of view, it is supposed that the appropriate thickness of OSC layer should be necessary for the crystallization of inkjetted OSC layer. In case of the OTFT with spin-coated OSC layer, the on-current was largest when the thickness of the OSC layer was about 70 nm. Considering the current path of our device structure, the OTFT with inkjetted OSC layer should have larger contact resistance than that with spin-coated OSC layer. One of the primary reasons for the low performance found in the OTFT with inkjetted OSC layer would originate from the large contact resistance due to the thick OSC layer. It is supposed that the enhancement of the OTFT with inkjetted OSC layer should be focused on not only the crystallinity of the OSC layer but also the reduction of the contact resistance. Through the enhancement of the performance of the OTFT with inkjetted OSC layer, it is expected that the OTFT with inkjetted OSC layer should be the candidate for the next generation display applications.

5. References

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