Ring Edge in Film Morphology: Benefit or Obstacle for Ink-Jet Fabrication of Organic TFTs

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Abstract

To be a high performance device, the ink-jet printing of organic layer faces to the challenge of ring edge behavior which makes the uneven film and deteriorate device, due to the capillary force driving from center toward to edge. Another difficulty is the narrowing of channel width by ink-jet printing of organic layer meets the tough to be under micrometer scale. The limitation comes from state-of-the art of ink-jet printing because of its large drop size and jetting variation. In this study, a novel process by inkjet printing of dilute PMMA solution to form separation bank as confined boundary for the subsequent depositing PEDOT was proposed, where the PEDOT was as the source and drain electrode with gap of several micrometers due to the innate characteristic of ring edge of ink jetted PMMA. Using this technique, the organic device constructed with bottom gate and evaporation of Pentance shown satisfactory performance.

Introduction

Inorganic semiconductor technology and its related application have already been attained to a mature stage in the past decades. Because of the revolution advancement, science and technology can grow vigorously. Demand of light-weight and flexible electronic products are gradually increasing; however, high temperature process of inorganic semiconductor is difficult to apply to above-mentioned appliance. Low-temperature direct patterning technology and organic electronics have been intensively developing. In respect of organic electronics, pentacene and regioregular poly (3-hexylthiophene) (RR-P3HT) are the most popular material used in organic TFT research. The electrical performance of pentacene is outstanding in organic material now, but it is always processed by vacuum evaporation processes, such as thermal evaporation or organic vapor phase deposition. Despite of the lower mobility of polymer material, P3HT, than pentacene, the soluble capability makes it compatible with printing process, which has many advantages of low temperature process and large area manufacturing capability and so on.

Among patterning technology, inkjet printing is considered to be the most potential candidate to industrial mass production. In recent years, inkjet printing is not only used in paper and wide format media, but also widely applied to pattern deposition of organic and inorganic electronics. There are many research of inkjet printing patterning, like deposition of insulator, organic semiconductor[1] or formation of conductive paste circuit[2] and microlens array[3] etc. reported in literature and electronic news. Fabrication of organic TFT, a stacked device, should integrate several printed steps and therefore make it more difficult and complicated than single material deposition process. Even though these challenges, use of inkjet printing to make good polymer TFT devices has already been discussed in many papers[4][5].

Most of the OTFT research was about new material development, surface modification, or the structure design to promote the electric characteristics better. From equation $I_{DS}=(1/2)(W/L)\ TC_{ox}\ [V_{GS}-V_T]^2$, the current I_{DS} is inversely proportional to the channel length. It is favorable to shorten channel length instead of increasing channel width to get better TFT array resolution. However, the printed feature is always limited by the drop size and directionality of inkjet droplet. The printed line width is usually greater than 80 um by use of printhead of 35pl droplets volume like spectra SE-128. The variation of inkjet printing directionality also makes it difficult to get small and uniform gate channel lengths in whole printing area. Here we use the ridge of ring-shaped edge after the liquid drying, and then print PEDOT on both sides of the resulting ridge. We can obtain gate length of smaller than 10 um by using IJP method.

Formation of Ring Ridge

Phenomenon of ring-shape patterns from dried solution is common in our daily life. When a liquid droplet landing on a substrate, there are three interface interactions governing the droplet drying behavior. These interactions happen between the individual interface of solid to liquid, liquid to gas, or gas to solid. When the solvent gradually evaporates, liquid droplets are getting dry to the solid state. Finally, the solute accumulates around the peripheral boundary is much thicker than the solute remains in the center, generally called coffee ring shape.

Much effort has been devoted to explaining the coffee ring phenomenon. Deegan's[6] hypothesis is the most acceptable to describe the ring-shape formation behavior. He assumes that the liquid evaporates faster around the peripheral than the center part. This makes the peripheral boundary easier to dry than the center area and therefore to form a contact line around the liquid peripheral. This results in a concentration gradient of dissolving solute and the solution accompanying the solute begins to diffuse from the center to the edge. When the drying process completes, the most of solute in the liquid is carried to the edge and forms a ring-shape profile. The mechanisms are shown in Figure 1 and Figure 2.

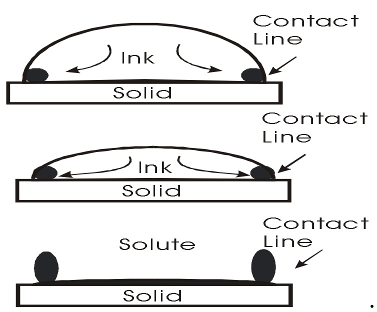

Figure1. Ring-shaped forming mechanism(□)

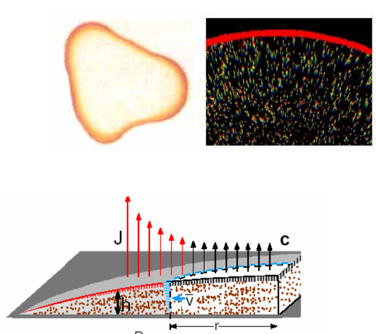

Figure2. Coffee Ring forming mechanism(□)

The nature behavior of liquid droplet is an obstacle for getting a smooth film for organic electronics, such as polymer light emitting diodes (PLED) and organic thin film transistors. Here we use this bad behavior as a beneficial micro-patterning method to define the gate length of OTFT. Through this method, OTFTs with several um channel length were obtained with acceptable transistor characteristics.

Experiment

In this study, the structure of the organic thin-film transistor (OTFT) is shown in Figure 3. The bottom gate is heavily doped Si with thermal oxide, SiO_2, of 300 nm thick. Sputtered Au of 70 nm thick with Cr of 30 nm, as adhesive layer, was used as the interconnection tracks whose spacing was about 100 um defined by stainless shadow mask. Poly (methylmethacrylate) (PMMA) ridge around several um wide is formed by coffee-ring edge effect. After suitable plasma treatment to remove the PMMA thinner film from the surface, the diluted PEDOT 4071 was inkjet printed on both sides of the ridge as the source and drain electrodes. The PEDOT was purchased from Bayer and the thermal bubble print heads of 80 pl droplets were developed by OES/ITRI.

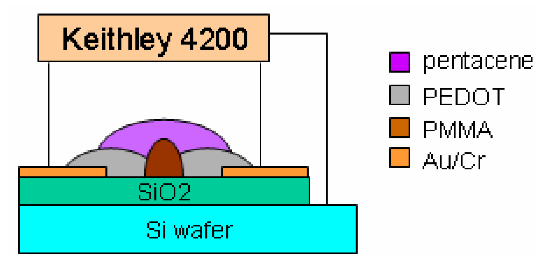

Figure3. The structure of the organic thin-film transistor device (OTFT) with a ridge of PMMA ring edge

The fabricating procedure of ring ridges, electrodes and active layer, pentacene, is shown in Figure 4. In Fig4(a), the Si/SiO_2 substrates with Au/Cr interconnection pads are treated with oxygen plasma at 200W, 800 SCCM for 1min to make the wettability better of the surface. In Figure 4 (b), 1 wt% PMMA solution dissolved in anisole was printed on and one ridge was located between the two Au/Cr pads. Oxygen plasma was used to etch the thinner part inside the ring ridge and therefore two ridges were left on both sides. Sequentially, carbon tetrafluoride plasma was applied to make the PMMA surface liquid-repellent as shown in Figure 4(c). After the dry etching and repellent treatment, a ridge with 5.37 um wide was afforded in Figure 5. And then inkjet printed PEDOT solution on both sides of ridge to connect to each Au/Cr pad was used as source or drain electrode. Thermally evaporated HMDS and pentacene in sequence onto the above substrate were to complete the OTFT devices, as shown in Figure4 (d) and (e). In order to prevent source/drain electrodes from interconnection, it is better to make the PMMA ridge as more repellent to PEDOT solution as possible.

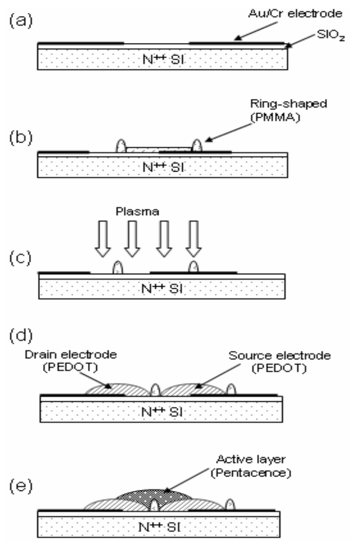

Figure4. Schematic illustration of the process flow of ring ridge patterned organic thin film transistors

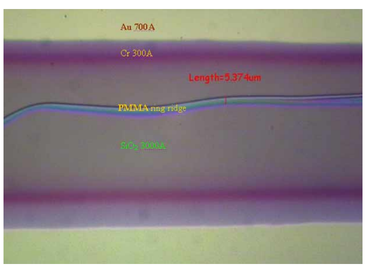

Figure5. The microscopy of a coffee ring after plasma etching

Besides the patterning process, the plasma charging effect on oxide layer should be concerned because it also treated on the insulator layer when applied to etching and repellent treatment. This issue was checked on the capacitance variation of devices with MIM structure, doped Si/oxide/Al, with or without plasma treatment on oxide layer. After being examined by HP 4194 impedance analyzer, we found the capacitance without dramatic change after plasma treatment as used in patterning process, as shown in Figure 6. Most devices have similar capacitance, even though some have a maximum variation less than 5%.

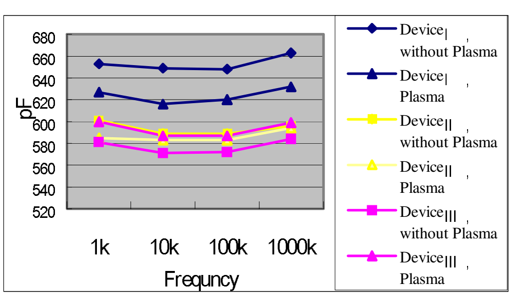

Figure6. The resulting capacitance of doped Si/SiO2/Al devices with and without plasma treatment on the oxide layer

Results and Discussion

According to the above mention, utilizing IJP technique incorporated with ring edge effect can get a narrow line less than 10um. Applying this patterning method to fabricate OTFT device, we can get devices with good MOS characteristics. The I_d-V_d and I_d-V_g is measured by Keithley 4200 semiconductor parameter analyzer and shown in Figure 7. The field-effect mobility can be calculated at the saturation regions from the following equation (1):

$$I_{DS} = (WC_i/2L)\mu(V_G - V_T)^2 \qquad (1)$$

where C_i is the capacitance per unit area of the insulator, and V_T is the threshold voltage.

The mobility, on/off ratio and threshold voltage is about 3.6E-4 cm2/v-s, 2E2, and 22V, respectively. It is found that off current and threshold voltage is relatively high in the device. Maybe this phenomenon can be attributed to the negative charging into PMMA ridge after plasma treatment In addition, pentacene cannot form a better alignment upon HMDS/PMMA ring ridge for the poor mobility of these devices. Further effort is needed to clarify the above mentioned problems.

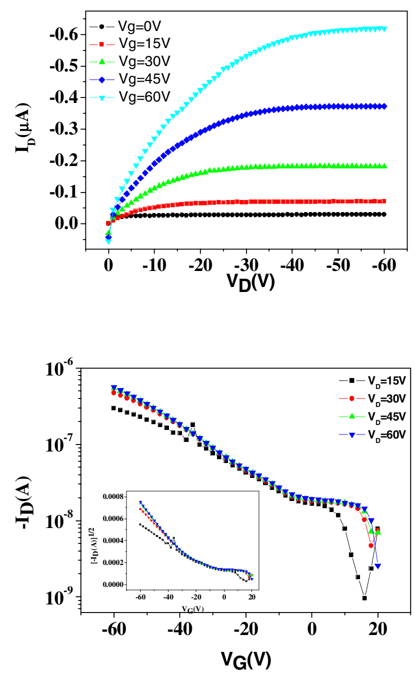

Figure7. Characteristics of a ring-ridge patterned organic thin film transistor with pentacene as the active layer

Conclusion

In this paper, we have overcome the restriction of line width by directly inkjet printing technique (generally with droplets of 35pl, the line width is around 80um~150um) to obtain fine lines of 5 um using ring-edge effect. We have successfully applied this novel method to fabricate OTFT devices with small channel length of several micrometers. This patterning method has be proved feasible and devices with common characteristics of transistors are achieved, though the result is yet to be optimized, where the mobility and on/off ratio are about 3.6E-4 cm^2/V-s and 2E2, respectively. It is believed that this patterning method of inkjet printing can have more applications after further study in the future.

References

[1] B.-J. de Gans , P. C. Duineveld , U. S. Schubert , Adv. Mater.,16, No 3 , 203(2004)

[2] K. Cheng, M. Yang, W. Chiu, C. Huang, J. Chang, T. Ying, Y. Yang, Macromolecular Rapid Communications, 26, 4, 247(2005)

[3] D. Hayes, T. Chen, OFC 2005 March 6-11(2005)

[4] H. Sirringhaus et al., Science 290, 2123 (2000).

[5] Christoph W. Sele, Timothy von Werne, Richard H. Friend, and Henning Sirringhaus, Adv. Mater., 17, No. 8, 997 (2005).

[6] Robert D. Deegan, Olgica Bakajin et al., Nature, Vol.389, (1997)

Biography

Jhih-Ping Lu received his B.E. degree in Industrial Design from National Cheng-Kung University, Tainan, Taiwan in 1996 and M.S. degree in Industrial Engineering from National Tsing-Hua University, Hsinchu, Taiwan in 1998. He is now a process and integration engineer in the Display Process Integration Technology Division, Display Technology Center of Industrial Technology Research Institute in Taiwan and has been engaged in research of Inkjet Printing technology for 6 years.