Fabrication of organic thin film transistor using ink-jet printing technology

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Abstract

Here we developed a conductive ink which contains silver nanoparticles from which the electrodes for organic thin film transistor were directly patterned by ink-jet printing. To fabricate a coplanar type OTFT, solution processable semiconducting oligomer, α,ω-dihexyl-quaterthiophene (DH4T) was drop-cast onto between the ink-jet printed silver electrodes and I-V characteristics were measured.

1. Introduction

In the electronic industry, the fabrication of conductive tracks is inevitable and traditionally photolithographic and electroless techniques are widely adopted in the printing circuit board (PCB) industry for manufacturing its conductive circuits. However, this method is not only time consuming but also very complicated and expensive, because many steps are required to construct a layer of the circuit [1,2]. Moreover, the conventional electroplating and etching processes also produce large quantities of chemical waste. Therefore, there is an industrial need for direct digital printing to simplify the processes and to reduce manufacturing costs.

Ink jet printing technique is desirable to fabricate onto polymeric or similar temperature-sensitive substrates by solution-based printing process [1,3] and the development of a solution-based process on a flexible substrate would allow reel-to-reel fabrication, which is an extremely inexpensive way to mass-produce circuits since it eliminates conventional photolithography and complex substrate processing including vapor phase deposition and etching. For these reasons, the ink jet printing as convenient and fast processing techniques to fabricate conductive lines has attracted more and more attention in recent years [4-6].

There has been growing interest in organic thin-film transistors (OTFTs) because of their potential applications in flexible, low-cost integrated circuits, such as smart cards, RF identification tags, and display backplanes, such as liquid crystal displays, electronic paper, and organic electroluminescent displays [7,8]. The possibility of using low-cost solution or liquid fabrication techniques has fuelled the current surge in research interest in organic electronics. Most of the work has however focused on the development of solution processable organic semiconductors. Other OTFT components such as solution processable conductor and dielectric materials have not been receiving much attention, despite their critical roles in all-printed OTFTs.

The conductor materials of electrodes are particularly important as they have decisive impacts on the electrical properties. They have to be energetically compatible with the organic semiconductor layer such that ohmic contact can be established to enable efficient charge injection. Secondly, they must be chemically inert towards the semiconductor and dielectric layers. Thirdly, they should be electrically robust enough to withstand the high stress of the applied voltage and generated current for operational stability. For applications in flexible electronics such as e-paper, the conductors should also be fabricated at a reasonably low temperature that is compatible with the flexible substrate materials such as plastic films [1].

2. Experiment

The silver nano particles were synthesized in our laboratory by the well-known polyol method [9,10]. Silver nitrate (99.9 %, Aldrich) used as a precursor of silver nano particles was dissolved in polyol medium. This solution was stirred vigorously in a reactor with a reflux condenser, followed by heating and reaction. After the reaction completes, the solution was cooled to room temperature, and the silver particles were separated from liquid by centrifugation and repeatedly washed with ethanol.

The synthesized silver nanoparticles were dispersed in our propriety solvent system and the solid loading of the ink was 20 weight %. The formulated ink was ball milled for 24 h, followed by filtration through a 5 μm nylon mesh.

The silver conductive ink was printed by an ink-jet printer onto the heavily doped n-type silicon wafer with 200-nm thick thermal SiO_2 layer as a substrate. The printer set up consisted of a drop-on-demand (DOD) piezoelectric ink-jet nozzle manufactured from Microfab Technologies, Inc. (Plano, TX) and the diameter of orifice was 30 μm. The print head was mounted onto a computer-controlled three-axis gantry system capable of movement accuracy of ± 5 μm. The gap between the nozzle and the surfaces was maintained at about 0.5 mm during printing. The uniform ejection of the droplets was performed by applying ~ 35 V impulse lasting ~ 20 μs at a frequency of 400 Hz.

The shape and size of the synthesized silver nano particles were observed using scanning electron microscopy (SEM, JSM-6500F, JEOL), transmission electron microscopy (TEM, JEM-2010, JEOL) and the particle size distribution was obtained by image analysis. The surface morphology and the structure of the fabricated device were observed by optical microscopy (Leica, DMLM). The resistivity was calculated from sheet resistance which was measured by 4-point probe (Chang Min Co., Ltd., CMT-SR200N) and the thickness of the Ag films which was obtained by SEM observation. The I-V measurements were performed in air using Agilent 5263A source-measure unit.

2. Results

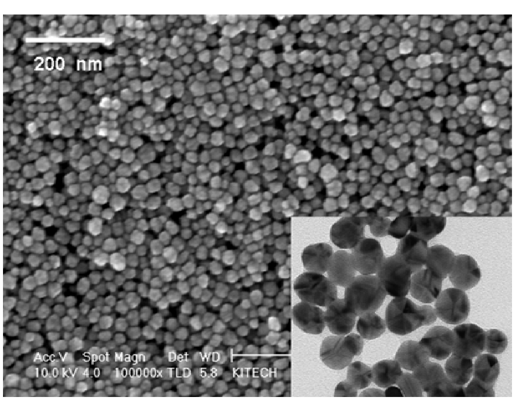
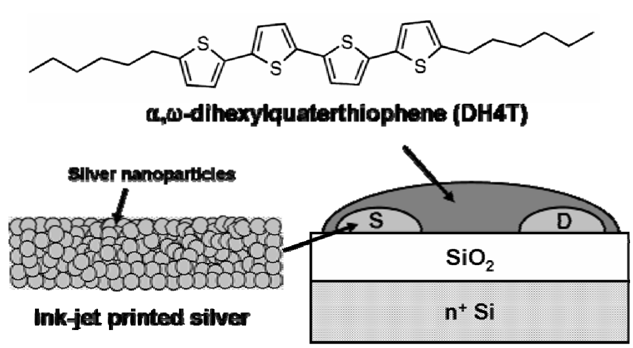


Figure 1. SEM and TEM (inset) images of the synthesized silver nanoparticles for conductive ink.

Figure 1 shows the SEM and TEM (inset) images of the synthesized silver nanoparticles. The size distribution of silver nano particles shows 21 ± 4 nm sized relatively monodisperse particles.

The mixture of main solvent and small amount of co-solvent was used as the solvent for the inks to prevent from forming a coffee-ring shape of the printed patterns. Dispersion stability of the prepared conductive silver inks was excellent and the prepared ink exhibits Newtonian rheological behaviour. The viscosity of silver ink was about 3 mPa·s at shear rate of 100 s^{-1} as measured by cone and plate viscometer and the surface tension of the ink was about 30 mN/m.

To fabricate the coplanar type TFT the prepared silver conductive ink was printed on heavily doped n-type Si wafer. Printed source and drain electrodes were smooth and the line-width was about 200 μm. After the heat-treatment at temperature of about 200 ℃ for 30 min, the printed silver patterns exhibit metal-like appearance and the conductivity of about 6.5 μΩcm and the processing temperature of 200 ℃ is relatively low due to the use of nano-sized particles [11-13], indicating that the printed electrode is suitable for OTFT fabrication.



Figrue 2. Schematic depiction of the fabricated OTFT based on ink-jet printed silver source and drain with DH4T semiconducting layer.

Figure 2 shows the schematic depiction of fabricated OTFT using ink-jet printed silver source/drain and drop-cast DH4T. An active material of α,ω-dihexylquaterthiophene (DH4T), which was dissolved in a proper solvent, was deposited between the ink-jet printed silver electrodes by solution process of drop-casting. Figure 3 shows the top view of the fabricated OTFT device with a channel width of 3000 μm and a channel length of 210 μm (W/L ratio is about 14).

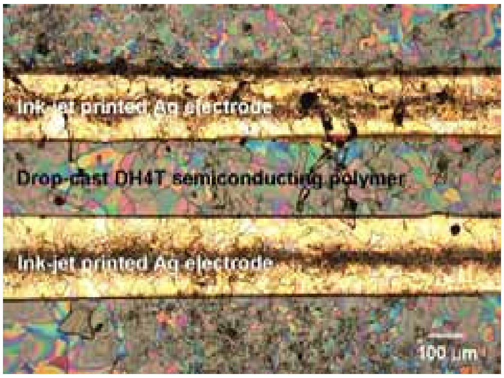


Figure 3. Optical microscopy image of the top view of the fabricated OTFT with ink-jet printed silver electrodes and drop-casted DH4T.

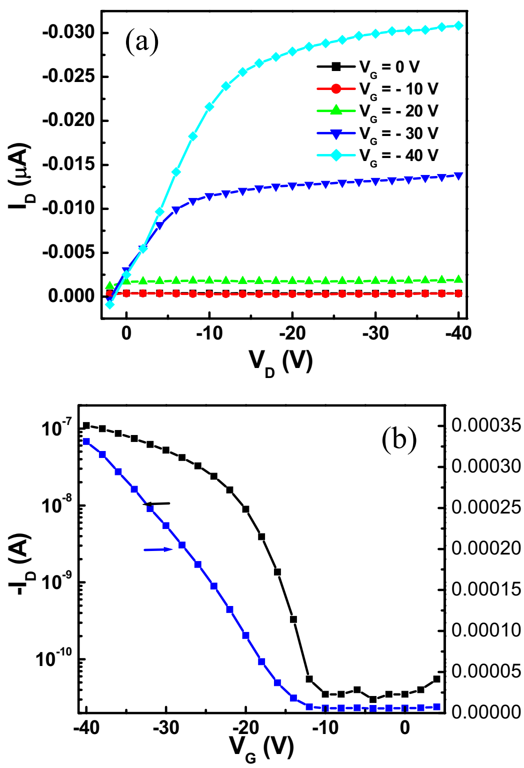


Figure 4. (a) Output Characteristics of the fabricated OTFT having channel width of 3000 μm and channel length of 210 μm. (b) Transfer characteristics at a constant V_D = - 30 V.

The OTFT device was fabricated and measured under ambient conditions. The device exhibited excellent field-effect transistor characteristics, which conformed well to the conventional gradual channel model in both the linear and saturated regimes (Figure 4). The output curve shows good saturation behavior and no significant contact resistance. This device showed a mobility of 1.3×10^{-3} cm^2 V^{-1} s^{-1} in the saturation regime, on/off current ratio over 10^3 and a threshold voltage of about -13 V with subthreshold slope of ~ 3 V dec^{-1}.

3. Conclusion

We fabricated OTFT with ink-jet printed silver source and drain, combined with drop-cast semiconducting oligomer DH4T. Ink-jet printing technology was applied to the TFTs fabrication process in which the conductive track was directly patterned by ink-jet printing of nanoparticles. It is an attractive alternative to photolithography for direct patterning conductive lines owing to low-cost, low-waste and simple process. In addition, semiconducting layer was deposited by solution process of drop-casting, which can also be replaced by ink-jet printing. The source and drain electrodes and semiconducting layer are significant components of TFTs and the replacement of conventional vacuum deposition process by solution process makes all-polymer TFTs to be realized.

4. Acknowledgements

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5. References

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