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Semi-CNTs-based flexible TFTs fabricated by room-temperature printing with high performance

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Abstract

The flexible field effect transistors (TFTs) play an important role in the application of sensors, artificial intelligence and human-machine interactions and so on. However, the high driving voltage of the TFTs have limited their application in the practical application which require low costs and high performance. Therefore, in our work, the functional semiconducting single-wall carbon nanotubes (f-ss-CNTs) are employed as the semiconducting layer to fabricate the CNTs-based TFTs by room-temperature printing process. The results show that the low driving voltage around 10 V and high on/off ration of 10^6. Therefore, the CNTs-based TFTs are promising to be applied in a much wider field, such as biosensors and other devices which need low driving voltages.

1. Introduction

The ever-increasing demand for next-generation flexible, large-area and low-cost electronic devices requires intensive construction techniques for coating active layer, insulating layer and electrodes. Compared with the traditional fabrication of electronics, printable electronics have become urgent social needs due to the advantages of low-cost, large-area fabrication, time-saving, and eco-friendly. To achieve the fabrication of flexible devices at low cost, we pioneered to develop "room-temperature (RT) printed electronics" process, where we can fabricate thin-film devices and circuits by using selective patterning technique with a novel gold nanoparticles (AuNPs) ink, as shown in Figure 1.[1-3]

However, the low average carrier mobility (~1.0 $cm^2V^{-1}s^{-1}$) and high working voltage (-40~40 V) are the key issues which impede the development of RT-printed TFTs for the biosensor applications. To increase the average carrier mobility, the functional semiconducting sing wall carbon nanotubes (f-SS-CNTs) will be prepared via wrapping polymer semiconductor with functional groups (binding sites for future biosensors) on the surface of CNTs, [4] which is promising for charge carrier transporting without being deeply trapped. Therefore, this research proposes to apply such f-SS-CNTs film in TFTs through printing techniques, thereby ensuring low-voltage and high-mobility TFTs for biosensor application.

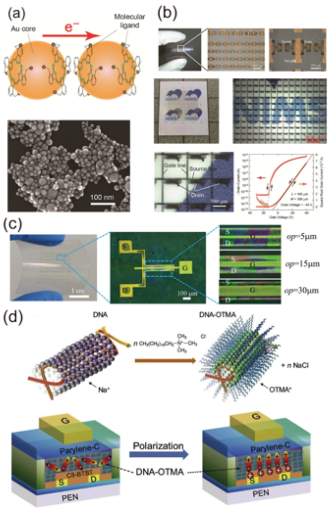

Figure 1 (a) The Au NPs with ligands of pi-conjugated molecules and their SEM morphology. (b) RT-printing of OTFTs on plastic and paper substrates. (c) Advanced OTFT fabricated at RT with 1-µm resolution. (d) RT-printing OTFT combined with DNA as the memory transistor.

2. Experimental processes

According to our previous work, the gold electrodes are printed on the flexible substrates as follows.[3] Firstly, the parylene (KISCO, dix-C) planarization layer was deposited on the poly(ethylene 2, 6-naphthalate) (PEN, Teijin Dupong Film Co. Ltd.) substrate (125 µm, 4 × 4 cm) with the thickenss of 500 nm through a typical chemical vapor deposition (CVD, home-made). The thickness of deposited parylene-C can be controlled by its weight. Secondly, the treated PEN substrate was transferred onto the stage of PVUV system (150-200 nm wavelength, Ushio Inc., SUS740), where selective exposure was performed through a photomask. To make parylene-C surface more hydrophilic requires about the exposure time of around 100 s. After the formation of hydrophilic patterns, the Au nanoparticle ink could be printed on the substrate surface to yield Au lines or gaps automatically through a common bar-coating process. In details, prior to coating, the AuNP ink was first injected into the 200 µm space between the substrate and the coating coater. The ink was stored under the coater, which, during coating, moved at a speed of 100 μm s^{-1} for ink-spreading.

For the CNTs deposition, the channel area was firstly treated by oxygen plasma to form hydroxyl group which can immobilize CNTs through the formation of hydrogen bond between hydroxyl group and oxygen atom in perylene substrate.[4] Then the CNT inks were printed on the substrate by aerosol jet-printing, followed by washing with toluene for twice. The sheath gas flow and atomizer flow are 50 and 15 sccm, respectively. The printing speed was 0.5 mm s^{-1}. The nozzle size of printer head was 150 μm. The printing procedures were performed at room temperature and repeated for three times. Finally, the substrate was heated on a hotplate at 120 °C for 20 min to remove the solvents and impurities and a thin layer of SWCNT film was fabricated.

3. Results and discussions

After fabrication of f-SS-CNT-based TFTs on flexible substrate, the morphology of TFTs were firstly characterized as shown in figure 3 (Left). We prepared the flexible TFTs with the channel length ranging from 1 to 150 μm. Figure 3 shows the optical morphology of single transistor device with the channel length of 8 μm, which contains bottom gate, source and drain electrodes which are printed with gold nanoparticle ink by coating method.

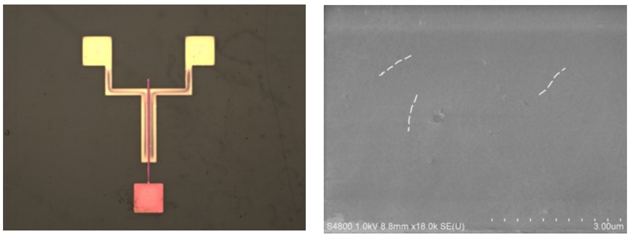

Figure 3 The optical morphology of bottom gate bottom contact CNT devices (Left); and the SEM figure of CNT deposition on the channel area. The white imaginary lines show the location of CNTs (Right).

Further, the f-SS-CNTs were immobilized on the channel area through the hydrogen bond by means of oxygen plasma surface treatment. Aerosol inkjet printing was employed to deliver CNT inks to the pre-treated channel areas, which was repeated for three times to ensure the formation of CNT film between the channel area. With complete washing to remove un-immobilized CNTs and heat annealing to increase the attachment of CNTs to the substrate, the CNTs-based TFTs were completed. Following that, the CNTs distribution on the channel area was characterized by SEM. As shown in figure 3 (right), the CNTs are successfully immobilized and form an interconnected film which is beneficial to the charge carrier transfer between the source and drain electrodes. Some of the CNTs on the SEM figure were marked and taken as an example to show the successful immobilization, as noted by the white imaginary lines in figure 3 (Right).

After characterization of the CNTs-based TFTs, the electric performance was further detected to confirm that the CNTs film could work as the semiconductor layer to activate the TFTs. The transfer curves of the TFTs were detected and plotted as shown in figure 4. Before starting the detection, the relative parameters were set as follows. The voltage between source and drain was set as -0.25 v and the voltage between gate and source was set from 15 to -10 v. From the transfer curve, the threshold voltage could be obtained around 10 v. Besides that, the on/off ratio is as high as 10^6 with a low gate leakage current. The electric performance results show that the CNTs are not only immobilized between the channel layer and show a good charge carrier layer for the TFTs. However, the CNTs-based TFTs are not the ideal transistors which could be activated at the V_{GS} around 0 v. The shifted voltages suggest the traps between the interface layer of CNTs film and substrate, which should be avoided and studied further about the relative mechanisms.

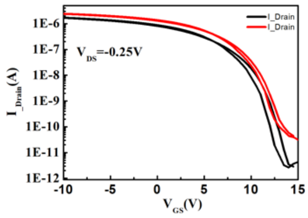

Figure 4 The transfer curves of CNTs-TFTs with the V_{DS} at -0.25 voltage.

4. Conclusions

In this work, the flexible CNTs-based TFTs were fabricate by fully room-temperature printing process. Besides that, the CNTs were successfully immobilized between the channel area with an interconnected network film which was beneficial to the charge carrier transfer. The CNTs-based TFTs showed a low driving voltage around 10 V with a high on/off ratio of 10^6, which shows the CNTs are promising to be the semiconducting layer to activate the TFTs. However, the shift of driving voltage deflecting from 0 V suggests the traps between the interface layer of CNTs film and substrate which may be induced by the impurity of the CNTs. Therefore, the CNTs are promising to be applied as the semiconducting layer of the TFTs. Further, more study should be continued to decrease the driving voltage and improve the mobility for practical application.

Acknowledgements

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