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Flexible Printed Organic TFT Devices and Potential Applications

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Abstract

In order to realize flexible and printed electronic applications, research and development in areas including materials, fabrication processes and devices are required. The latest results obtained by our research group will be briefly reviewed in this paper.

1. Introduction

Smart labels and wearable biosensors based on thin-film transistor (TFT) devices fabricated on thin plastic film substrates with various printing processes have garnered significant consideration in research and development. In particular, TFT devices based on organic semiconductors (OSCs) can be fabricated at low temperatures and are more compatible with printing methods than inorganic semiconductors. However, there have been a limited number of reports on high performance organic TFT (OTFT) devices and integrated circuits fully fabricated with printing processes. To accomplish this, solution-processable conducting, semiconducting, and dielectric materials are required, as well as the exclusive use of printing technologies without photolithographic patterning processes. Here, we will report briefly on printable materials, printed OTFT devices and their application to integrated circuits and biosensors.

2. Printable Materials Development

Silver (Ag) nanoparticle inks have become important materials for the fabrication of electrode and interconnect layers in printed electronics. Accordingly, we developed an Ag nanoparticle ink that was optimized for OTFT applications. A low resistivity of less than 10 μΩcm could be obtained by thermal sintering at 120° C or photonic sintering.

In order to realize OTFT devices we adopted newly developed p-type organic semiconductor, DTBDT, based on dithienobenzodithiophene, which is soluble in common organic solvents and highly crystalline. Two-dimensional crystal growth and large crystal domains are observed in a thin OSC layer drop-casted on a glass substrate. HOMO level is around 5.3 eV indicating highly stability in air. We also developed a n-type OSC material, TU-X, based on benzobisthiadiazole moiety. This is also solution-processable and highly crystalline, as well as stable in air. LUMO level of TU-3 (Fig.1) is as deeper as 4.3 eV which is effective for electron injection from electrode.

These OSC materials were blended with common polymers, such as polystyrene (PS), to formulate the OSC ink, then printed on the substrate.

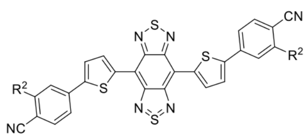

Fig. 1 Molecular structure of n-type OSC material, TU-3.

3. Printed OTFT Devices and Integrated Circuits

Inkjet printing, nozzle dispensing and spin-coating methods were largely employed in fabricating the electrodes, confinement bank and OSC layers, resulting in fully or nearly fully-printed OTFT devices. In these OTFT devices we used one of two types of gate dielectrics: a spin-coated crosslinked-PVP layer or a vapor-deposited Parylene layer. By optimizing the ratio of OSC and PS, the annealing conditions for the OSC layer and the thickness of gate dielectric layer, we fabricated printed OTFT devices that can be operated at very low voltages below 0.5 V.

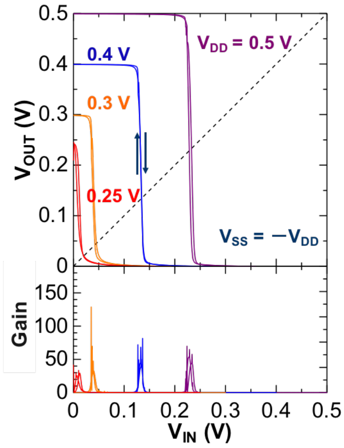

Fig. 2 Electrical characteristics for a pseudo-CMOS inverter.

One of the more important applications of OTFT devices is integrated circuits for radio-frequency identification (RFID) labels. We successfully fabricated depletion-load and pseudo-CMOS inverters, NAND logic gates, as well as ring oscillators using p-type OTFT devices. Fig. 2 shows a pseudo-CMOS inverter that can be operated at voltages below 0.5 V, and exhibits excellent performance with a high gain of over 100. A five-stage ring oscillator was also demonstrated using depletion-load inverters which was operated at 0.3 V.

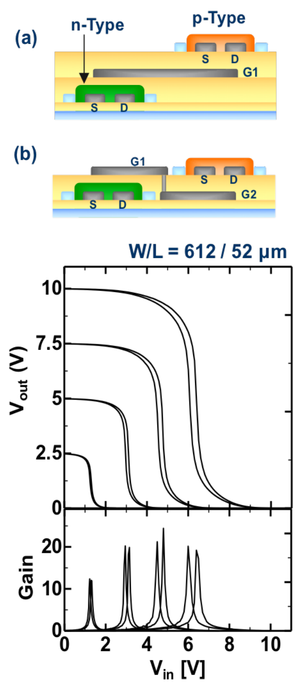

Fig. 3 Stacked TFT device structures employed in CMOS inverters and representative electrical characteristics.

Conventional CMOS inverters using both p-type and n-type OSC materials are quite important for the fabrication of integrated circuits with both low power consumption and high-speed operation. We have proposed a stacked TFT CMOS inverter structure, shown in Fig. 3, which was fabricated using an n-type OSC material (TU-3) and a commonly used p-type OSC material (diF-TES-ADT). Good switching characteristics were observed and a high gain over 11 was obtained at operating voltages below 10 V. Based on this CMOS inverter, a three-stage ring oscillator and D-type flip-flop circuits were also successfully fabricated using 36 transistors. In order to make the circuit layout more compact, we employed clocked inverters and demonstrated good electrical characteristics with 18 transistors, as shown in Fig. 4.

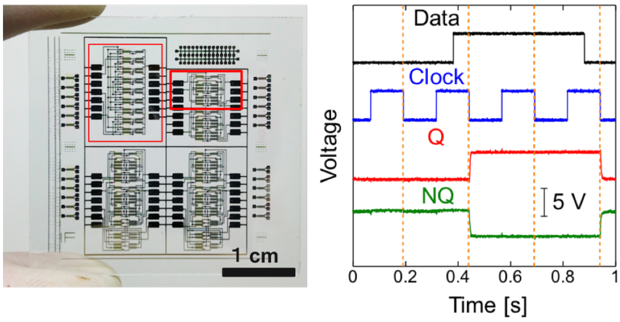

Fig. 4 Photograph and characteristics of a clocked inverter based D-type flip-flop circuit.

To further increase the degree of circuit integration, we chose to employ the reverse offset printing method. The electrodes and interconnects were precisely patterned on a glass substrate. SEM observations of the printed electrode layers showed flat surfaces and distinctly patterned edges. With this printing technology, OTFT devices with submicron channel lengths could be fabricated and good operation was observed. Fig. 5 shows a layout with a variety of integrated circuit types, including ring oscillator, NAND logic gate, CMOS inverter, operational amplifier, and comparator circuits.

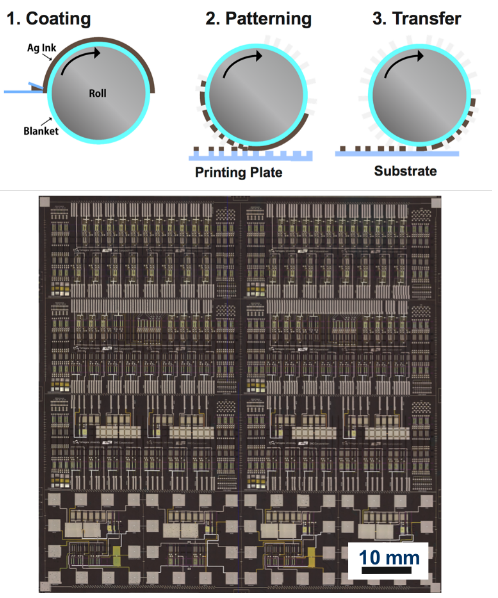

Fig. 5 A variety of integrated circuits fabricated on glass substrate with reverse offset printing.

Ultra-thin OTFT devices can also be fabricated using Parylene film substrates, which are prepared on a supporting glass carrier plate. The resulting printed OTFT devices and inverter circuits are extremely lightweight, flexible and compressible. Moreover, virtually no changes can be observed in the electrical characteristics, even under 50% compression. The bending radius of the device under compression is about 5 μm, which corresponds to a tightly folded state.

4. IoT-Sensor Applications

One of our goals has been to realize smart sensor systems that combine both circuits and sensors, and can be connected wirelessly to the internet. We have already succeeded in detecting several biomarkers related to human illnesses, infections or vital signs. The basic device structure of the sensors is an organic field effect transistor (OFET) with an extended gate electrode, upon which a biosensing, pressure or temperature sensing layer is formed.

Immunoglobulin (Ig) A and G were successfully detected in an aqueous solution by the OFET-based biosensors. Here, antibodies were immobilized on the extended gate electrode. Glucose and lactate were also detected by using an enzyme reaction in similar OTFT-based sensors. Fig. 6 shows the resulting improvements in the lactate sensor by employing Prussian blue (PB) and carbon black (CB) as a redox mediator.

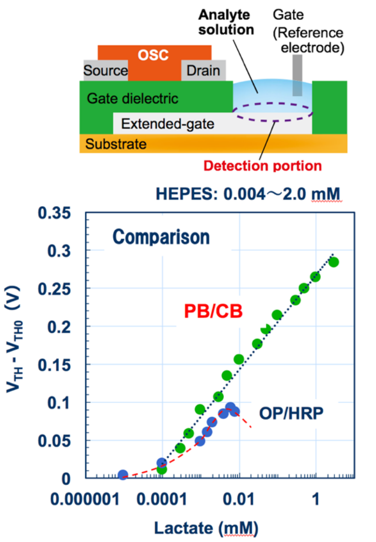

Fig. 6 Biosensor based on OFET device and results of lactate detection.

More recently, we have focused on the development of flexible hybrid sensors, whereby mature Si-LSI die are used for the signal processing and wireless communication circuits, and integrated on a plastic film substrate. Near-field communication (NFC) or Bluetooth low energy communication (BLE) protocols were used for wireless communication. Human body temperature and pulse rate could be continuously monitored and the data were transmitted to a smartphone or tablet device.

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