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Organic thin-film transistors on plastic substrates

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Abstract

In this paper, organic thin-film transistors (OTFTs) were fabricated on polyethersulfone (PES) and silicon (Si) substrates with top-contact geometry. Several kinds of metals with different work functions were used for source and drain electrodes, and optimum fabrication conditions were found. Photo cross-linkable polymeric gate dielectrics and thermal silicone oxide (SiO_2) were used for the plastic and Si OTFTs, respectively. From the electrical measurements, typical *I–V* characteristics of the thin-film transistor (TFT) were observed. The field-effect mobility, μ, was obtained to be 2.59 cm^2/(V s) from the flexible OTFT with polymeric gate dielectrics. Moreover, a possible critical work function of 4.3 eV for the electrode of pentacene OTFT with top-contact geometry.

Keywords: Organic thin-film transistors (OTFTs); Pentacene; Plastic substrate

1. Introduction

Organic thin-film transistors (OTFTs) have been investigated for many years for possible use in low-cost, large-area, flexible electronic applications. Examples are driving circuit elements for active matrix emissive or liquid crystal flat panel displays, large-area sensor arrays, biochemical sensors and radio frequency identification tags [1–9]. Theoretical [10] and phenomenological [11] approaches were also conducted to understand OTFT performance. Pentacene ($C_{22}H_{14}$) a semiconducting organic material with charge carrier mobility of ≥1 cm^2/(V s) is currently attracting much interest for use as a channel layer of OTFTs [12–14]. The mobility is comparable with that in amorphous silicon thin-film transistor (a:Si-TFT) which is used in thin-film transistor driven liquid crystal display (TFT-LCD), and hence, in the mobility point of view, pentacene transistors can be used as a switching device for active matrix display.

One of the most widely promoted applications for plastic electronics is radio frequency identification (RFID) tag. RFID tag is a wireless form of automated identification technology that allows for non-contact reading of data, which makes it effective for manufacturing and other hostile environments where bar code labels may not perform well. The market always needs tags of reasonable prices. The industry consensus is that the price of silicone (Si) RFID tags would fall to US$ 0.1, but it is not yet realized [15]. However, RFID tags with organic semiconductor can be a cost-effective alternative device because it can be printed directly into the retail product along with the antenna [15]. RFID systems are also distinguished by their wide frequency ranges of application. Each frequency has different attributes and thus different suitable applications. Low-frequency (135 kHz) and high-frequency (13.56 MHz) systems are more mature technologies as they were the first RFID frequencies to be commercialized during the 1980s [16]. Based on Si RFID tags, few square millimetres size of Si chip is placed on to the several square inches substrate, which is determined by antenna size. The size of Si chip cannot be enlarged because it must be creaked when

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the substrate is bent. The other reason is that the cost of the Si chip could be lowered when the number of the chip in one Si wafer maximized.

In the case of using organic semiconductors instead of Si, the situation is completely different. The cost of the OTFT is not an issue because it can be fabricated directly on to the substrate at room temperature in air. We need not worry about bending because organic semiconductors can be bent with plastic substrate without any creaking problems. Therefore, electronics for RFID tag on plastic substrate using organic semiconductor can be fabricated over the whole substrate area without limitation in size. Furthermore, in fabrication of OTFTs using direct printing method, top-contact geometry shows superior performance to the bottom-contact geometry due to a lower contact resistance.

In this work, we will report the fabrication conditions of the OTFTs with top-contact geometry for the device with high field-effect charge carrier mobility. Several kinds of metals with different work functions were used for source and drain electrode, and optimum fabrication conditions were found. Photo cross-linkable polymeric gate dielectrics were used for the plastic OTFTs.

2. Experimental

At first, we investigated the effects of the work function of the metal electrodes on the mobility to find out the proper electrode for the best performance of OTFTs. A highly conductive Si wafer (resistivity 5–10 Ω cm) is used both as a substrate and as a gate electrode for this experiments, because the fabrication conditions of OTFT on silicon wafer are well-established and therefore we can extract the work function-effect from the experimental results. The gate dielectric layer for all the devices is a thermally grown 300 nm thick SiO_2 layer (capacitance per unit area $C_0 = 10\,nF/cm^2$). The Si/SiO_2 substrates were treated with hexamethyldisilazane (HMDS) as the self-organizing materials, which had been used to improve the quality of the organic/dielectrics interface.

For the source and drain electrodes, various metals such as Pt, Au, W, Ag, Cr, Zn and Al were used in order to figure out the work function effect on the mobility. The pattern was also defined by a shadow mask such that the ratio of the channel width, *W*, to the channel length, *L*, was 100. Fig. 1 represents the schematic diagrams of the OTFT structure fabricated on Si and plastic substrates. This top-contact geometry has the advantages such as small contact resistance at the interface between metal electrode and organic semiconductor. If we try to fabricate the OTFTs in the electronic circuit such as radio frequency identification tag by graphic printing technique, top-contact geometry should be adopted. The pentacene thin-films were deposited by using conventional thermal evaporator at the pressure below 10^{-8} Torr. The substrate temperature was elevated and maintained at 70 °C during the deposition. Transistor characteristics of the devices were measured with a precision semiconductor parameter analyzer (4156C, Agilent) at room temperature in air.

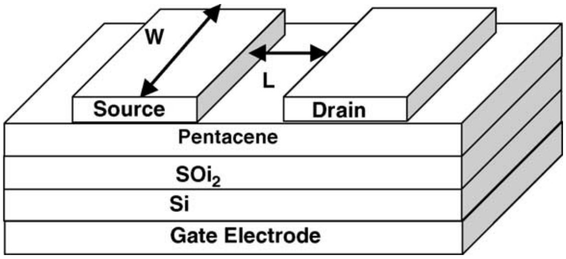

Fig. 1. Schematic diagram of organic thin-film transistors with top-contact geometry.

As the plastic substrates, polyethersulfone (PES) films were used. Ti(10 nm)/Au(90 nm) gate electrode was defined by a shadow mask. For a gate dielectrics of the devices on plastic substrates, poly(4-vinyle phenol) (PVP) was mixed with 16 wt.% of ammonium dichromate which is a photo-initiator, and cured to cross-link under vacuum condition for 1 h. After that, it was exposed by ultraviolet (UV) light for 5 min to get pattern. After the exposure, the film was developed by the mixture of 50:50% (v/v) of acetone and de-ionized (D.I.) water. Further process to fabricate the OTFTs on plastic substrate is the same as that on Si substrate.

3. Results and discussion

There are several factors to affect the electrical properties of the OTFTs; surface energy of the dielectrics, substrate temperature during the active layer deposition, working pressure, deposition rate, surface roughness of the dielectrics and contact resistance between metal electrode and organic semiconductor, etc. To obtain the best performance of the OTFTs, finding the optimum conditions of these factors is mandatory. In this work, pentacene films were fabricated by thermal evaporation in high vacuum with dielectric surface treatment of hexamethyldisilazane ($(CH_3)_3SiNHSi(CH_3)_3$) [17]. HMDS can form self-assembled monolayers on SiO_2 surface during spin-coating or dipping in the solution, and the alkane chains in the materials changes the property of the SiO_2 dielectric layer from hydrophilic to hydrophobic character. In general, most inorganic oxide surface including SiO_2 shows hydrophilic state while most of organic semiconductor (pentacene in this case) shows hydrophobic states. Therefore, this mismatch has bad influence on crystalline formation of organic semiconductor fabricated on oxide substrates. Therefore, HMDS treatments can decrease the surface energy and can affect good influence on increase of crystallinity, and also on increase in carrier mobility [18]. We could improve the mobility more than 10 times with HMDS monolayer.

Pentacene films were deposited with constant deposition rate of 1.0 Å/s to be total thickness of 1000 Å at substrate temperature of 70 °C. Lower deposition rate and higher substrate temperature can make the pentacene grain big. However, the