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Use of bilayer gate insulator to increase the electrical performance of pentacene based transistor

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ABSTRACT

In this study, bottom-gate top-contact pentacene-based organic field effect transistors (OFET) with various spin-coated ultrathin organic dielectrics on anodized aluminum oxide (Al_2O_3) bilayer gate dielectrics were fabricated. We have investigated the influence of the bilayer gate insulator having different combinations on the OFETs performance. Polystyrene (PS), poly-4-methylstyrene (P4MS), Poly-4-vinylphenol (PVP), poly-methylmethacrylate (PMMA) and Poly(4-vinylphenol-co-methyl methacrylate) (PVP_co_PMMA) were used as an organic dielectric. The results indicate that Al_2O_3 gate dielectric with Poly (4-vinylphenol) shows the optimum electrical performance with carrier mobility as large as 0.65 cm^2/Vs, on/off current ratio of 10^6, and threshold voltage as −3.8 V.

1. Introduction

In the last decade, organic field effect transistors (OFETs) have taken considerable attention because of their potential for low-cost fabrication and flexibility over large areas. At the same time, OFETs have become indispensable applications on electronics world, such as sensors, display backplane, electronic papers and rectifiers for radio frequency identification [1–3]. Up to now, dozens of high-performance OFETs have been fabricated and the majority of the electrical performances are equivalent to amorphous silicon [4,5]. However, one of the biggest problems of OFETs with high performance is that the operating voltage, which is necessary for the formation of conduction channel, is high. The main reason of this problem is the using of low-k organic materials as gate insulators at OFETs [2]. Two strategies are applied to reduce drive voltage at OFETs, frequently. First one is using an insulator with a high dielectric constant, and the second one is reducing the thickness of the dielectric layer. Although the device operation with the organic/organic interface is heading towards improvement, organic insulators suffer from small dielectric constant [6] while Al_2O_3, which is an inorganic material, is one of the gate insulators with a high dielectric constant. Al_2O_3 is a good candidate dielectric owing to suitable low-cost deposition process and attractive insulator properties (dielectric constant ~ 8–10, electrical breakdown field of > 8 MV/cm). In this study, Al_2O_3 gate dielectrics were prepared by anodic oxidation method. Also, one of the advantages of the anodizing of Al_2O_3 is that it can be applied on the flexible substrate according to the demand in the organic electronics. However, OFETs have suffered from leakage current and interaction between inorganic insulator-organic semiconductors. In order to overcome these problems, the multi-component dielectric system is utilized. Therefore, inorganic/organic hybrid dielectric layers have been studied intensively to improve OFETs performance [7,8]. Also, the covering by polymer for the modification of surface is more useful because it changes the surface physicochemical features and is an easy process [9]. Low-k polymer dielectrics with smooth surfaces and low trap levels can provide the effective carrier transportation at such interfaces. An addition, the deposition of polymer dielectric layer on a thin inorganic insulator layer can be decreased the leakage current. Therefore, the using of these metal oxide/polymer bilayer gate insulators is a promising way to overcome this problem [10–14].

In this work, bottom-gate top-contact pentacene-OFETs were fabricated and in these OFETs, low-cost organic/inorganic bilayer gate dielectrics, which have high-capacitance values including ultrathin organic layers polystyrene (PS), poly-4-methylstyrene (P4MS), Poly-4-vinylphenol (PVP), poly-methylmethacrylate (PMMA) and Poly(4-vinylphenol-co-methyl methacrylate) (PVP_co_PMMA) that were coated on Al_2O_3 inorganic layer were used. The electrical performances of pentacene based OFETs have been carried out by conventional I–V measurement and the effect of bilayer gate insulators on the electrical performance of pentacene based OFETs has been reported.

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2. Experimental

In this study, pentacene-based OFET with top contacts bottom gate configurations were fabricated using bilayer gate dielectric materials. Initially, 150 nm thick aluminum gate contact was deposited on the pre-cleaned glass surface. For anodization process, the constant electrolyzing voltage of 20 V was applied for 30 min to aluminum film in citric acid/citrate buffer (0.265 g citric acid, 2.57 g sodium citrate in 100 ml DI water) to form aluminum oxide (Al_2O_3), as explained in detail by Stadler et al. and references therein [15]. The constant anodic 20 V creates a thickness of ~32 nm aluminum oxide thin film. Following the anodization, the oxide film was annealed for 30 min at 120 °C in air condition. The process of organic insulator layers was started after the preparation of Al_2O_3 films. As the polymer insulator material, polystyrene (PS), poly-4-methylstyrene (P4MS), Poly-4-vinylphenol (PVP), poly-methylmethacrylate (PMMA) and Poly(4-vinylphenol-co-methyl methacrylate) (PVP_co_PMMA) were used. PMMA, PS, and P4MS were dissolved in toluene, PVP was dissolved in 2-Propanol, and PVP_co_PMMA was dissolved in *N*,*N*-dimethylformamide at a concentration of 5 mg/mL. Then the solutions were stirred for 2 h at 60 °C and filtered using 0.22-µm pore filters. For the fabrication of the bilayer insulator films, the prepared polymer solutions were spin coated with 5000 rpm/60 s onto the Al_2O_3 surfaces under an ambient atmosphere. Then the insulators layers were further dried in a vacuum oven for a day at 100 °C and ultra-thin polymers films on the surface were obtained. As an active layer of 50 nm pentacene was subsequently deposited at room temperature onto each of the bilayer insulators at a base pressure of 10^{-5} torr by using thermal evaporation method (Vaksis PVD Handy-MT/101T, Turkey). Finally, to complete the formation of the device, 100 nm gold was deposited under vacuum through a shadow mask to serve as top contacts (source-drain) electrodes. The channel width and length of the transistor are 1000 µm and 50 µm, respectively. The architecture of the Pentacene-OFETs and the chemical structures of polymers are shown in Fig. 1. These transistors were named OFET1 (with Al_2O_3/PS gate dielectric), OFET2 (with Al_2O_3/P4MS gate dielectric), OFET3 (with Al_2O_3/PVP gate dielectric), OFET4 (with Al_2O_3/PMMA gate dielectric), and OFET5 (with Al_2O_3/PVP_co_PMMA gate dielectric), respectively. The electrical measurements of Pentacene −OFETs were performed using a Keithley 4200 semiconductor characterization system and Signatone probe station. The schematic diagram of setup used in C-F measurements is illustrated in Fig. 2.

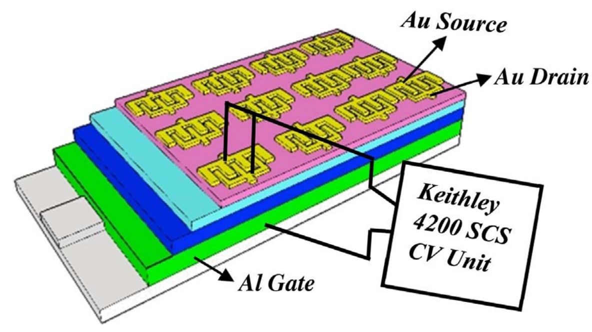

Fig. 2. Schematic diagram of the C–F characteristics.

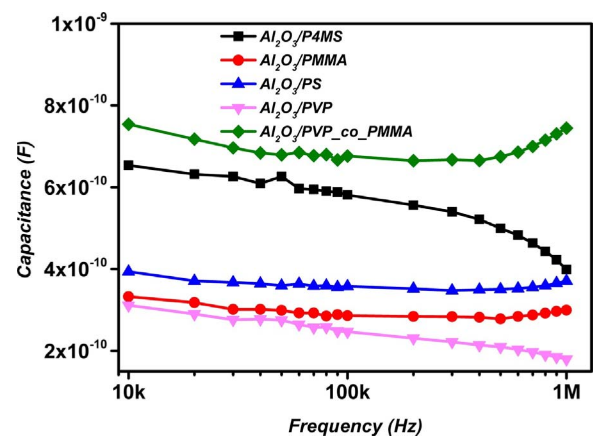

Fig. 3. C–F characteristics of gate insulators.

3. Result and discussion

To obtain the capacitance of per unit area for the bilayer gate dielectric materials, the capacitance-frequency (*C-F*) measurements of metal-insulator-semiconductor structure (MIS) have been performed. Fig. 3 illustrates the *C-F* characteristics. The capacitance of per unit area for the OFET1, OFET2, OFET3, OFET4, and OFET5′s gate dielectric was found to be 45 nF/cm^2, 74 nF/cm^2, 35 nF/cm^2, 38 nF/cm^2, and 85 nF/cm^2 at 10 kHz, respectively. The large capacitance values of bilayer gate dielectric allow the OFET to be controlled in the low voltage range [10]. For example, in a similar study, the capacitance of per unit area value was reported as 115 nF/cm^2 for solution-processed Al_2O_3 (35 nm)/PMMA (10 nm) bilayer insulator [2].

The output characteristics of the OFET under different gate voltages are illustrated in Fig. 4-a. The drain current of Pentacene-OFETs increases with negative drain voltages and reaches saturation because of the channel's pinch-off. The reaction of the transistor to negative gate voltage exhibits that all OFETs indicate typical p-type behavior with a linear region at small source-drain voltages (V_{DS}) and good saturation

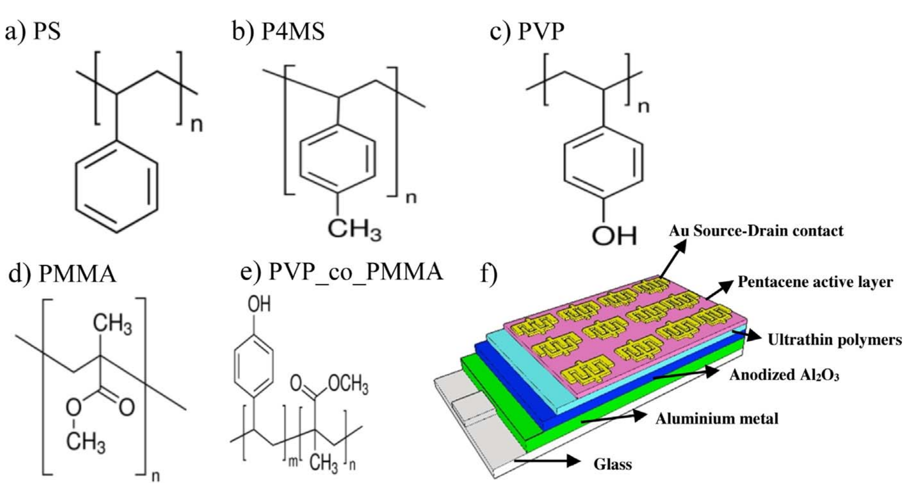

Fig. 1. Chemical structures of (a) PS, (b) P4MS (c) PVP (d) PMMA (e) PVP_co_PMMA (f) Device architecture of the Pentacene-OFET.