Low-voltage Organic Field-effect Transistors with a Gate Insulator of Ta_2O_5 Formed by Sputtering

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The Ta_2O_5 film prepared on silicon by RF sputtering has been used as a gate insulator for the top-contact field-effect transistors fabricated with poly(2-methoxy-5-(2′-ethylhexyloxy)-1,4-phenylenevinylene) (MEH-PPV) or pentacene. Good transistor characteristics have been obtained with saturation at low drive voltages (about -3 V) and with hole mobilities of 5.2×10^{-4} cm^2/Vs (MEH-PPV) and 0.8 cm^2/Vs (pentacene).

Organic field-effect transistors (OFETs) have recently received increasing interest because of their potential applications including flat-panel displays, IC tags, and smart cards.[1,2] Important parameters characterizing OFETs are carrier mobility, on/off current ratio, and drive voltage. Silicon dioxide thermally grown on heavily doped Si is commonly used as the gate insulator material of OFETs. Most of the OFETs with SiO_2 operate at a few tens of volts, which exceed drive voltages for many applications. One of promising ways to enable device operation at low drive voltages is to use an insulator with high dielectric constant such as barium zirconate titanate (ε_r, 17),[3] tantalum oxide (ε_r, 20–23),[4–6] titanium oxide (ε_r, 41),[7] and aluminum oxide (ε_r, 10) instead of SiO_2 (ε_r, 3.9). Tantalum oxide layers have been made by anodization,[4,6] electron-beam evaporation,[5] sputtering,[8] and low-pressure chemical vapor deposition.[9] In this work, we report the performance of organic field-effect transistors with a tantalum oxide layer formed by RF sputtering as a gate insulator.

Top-contact OFETs were fabricated on a doped n^+-Si(100) plate, as shown in Figure 1. A SiO_2 layer on the doped Si substrate was removed with a 5% aq. solution of HF. A film of Ta_2O_5 was formed onto this Si surface by RF sputtering with an ANELVA SPF-332H apparatus. Sputtering was performed from a Ta_2O_5 target (99.99%, Toshima Seisakujo) in the atmosphere of Ar, O_2, and Ar–O_2 mixtures (50 and 20% O_2 contents) at the total pressure of 1.0 Pa. The thickness of the Ta_2O_5 layer was about 130 nm. Poly(2-methoxy-5-(2′-ethylhexyloxy)-1,4-phenylenevinylene) (MEH-PPV) and pentacene, which were purchased from Aldrich, were used as active layers of the OFETs. A film of MEH-PPV was prepared by the spin-coating method on the Ta_2O_5 layer from a 0.4 wt % $CHCl_3$ solution. Pentacene purified by vacuum sublimation was deposited on the Ta_2O_5 layer in a vacuum chamber with the base pressure of 10^{-5} Pa. The thicknesses of the MEH-PPV and the pentacene films were typically 100 and 50 nm, respectively. Interdigital Au electrodes, which consisted of 25 pairs with 25 μm in spacing, 4 mm in width, and 50 nm in thickness, were prepared on the organic layer and used as the source and drain electrodes. Thus, the length (L) and width (W) of the channel region were 25 μm and 196 mm, respectively. The drain current (I_D) vs the drain-to-source voltage (V_D) characteristics for various values of gate voltage (V_G) from the OFETs were measured with a Keithley Model 6487 picoammeter in vacuum (1.0×10^{-3} Pa). Leak currents of the Ta_2O_5 films were also measured between the doped Si electrode and the electrode formed on the Ta_2O_5 surface from the droplet (2 mm in diameter) of Ag paste.

Leak currents measured for the Ta_2O_5 film (260-nm thickness) formed in the atmosphere of 80% Ar and 20% O_2 are plotted with closed circles in Figure 2. The applied electric field ranges from -0.3 and 0.3 MV/cm, corresponding to about -8 and 8 V, respectively. The Ta_2O_5 film shows low leak currents in the whole range of the applied voltages, while leakage is observed for the film prepared in Ar (open circles). Kozawaguchi et al.[8] showed that the RF sputtering in an atmosphere of 80% Ar and 20% O_2 suppresses the formation of oxygen defects which become electron traps. The Ta_2O_5 films prepared in the atmosphere of O_2 and Ar (50%)–O_2 (50%) mixture have been easily

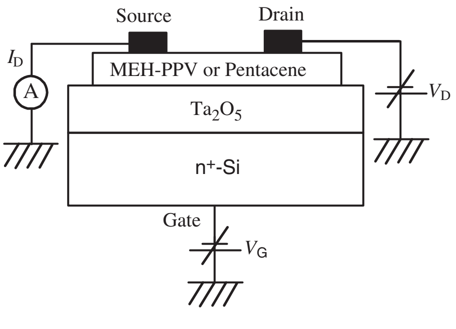

Figure 1. Schematic structure of an organic field-effect transistor based on Ta_2O_5 as a gate insulator.

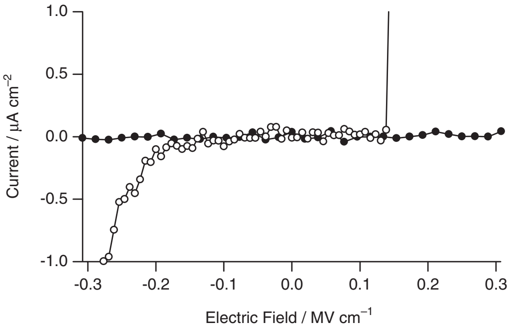

Figure 2. Leak currents for the Ta_2O_5 films formed by sputtering in the atmosphere of Ar (○) and 80% Ar–20% O_2 mixture (●).

destroyed by the application of a voltage. The observed images of SEM and AFM show that the surface of the Ta_2O_5 layer is very smooth and uniform. The root-mean-square roughness of the surface in the AFM image is 0.045 nm. These results indicate that the Ta_2O_5 films formed by sputtering in the atmosphere of 80% Ar and 20% O_2 are suitable for use as the insulator layer of OFETs.

Figure 3 plots the I_D versus V_D characteristics for an FET based on MEH-PPV. When the gate electrode is biased negatively with respect to the source electrode, the FET operates in the accumulation mode and the accumulated charges are holes. The observed results indicate that MEH-PPV behaves as a p-type semiconductor. No n-type behaviors are observed for positive gate voltages. Saturation behaviors in the drain current are observed at very low voltages of -3 V. Iino et al.[6] reported that the FET based on Ta_2O_5 formed by anodization of Ta shows the best performance at an operating voltage of -5 V. The hole mobility μ_h has been calculated form the observed saturation current $I_{D,\,sat}$ by using the following equation:[10]

$$I_{D,\,sat} = \frac{WC\mu_h}{2L}(V_G - V_T)^2 \qquad (1)$$

where V_T is the threshold voltage; C is the capacitance per unit area of the gate insulator; the capacitance is 163 nF/cm^2. From the least-square fitting, the hole mobility in MEH-PPV is found to be 5.2×10^{-4} cm^2/Vs and the threshold voltage -0.8 V. The on/off current ratio is defined as the ratio of the drain currents between the on state (V_G, -3 V) and the off state (V_G, 0 V) at the drain-to-source voltage of -4 V. The observed on/off ratio is 1500.

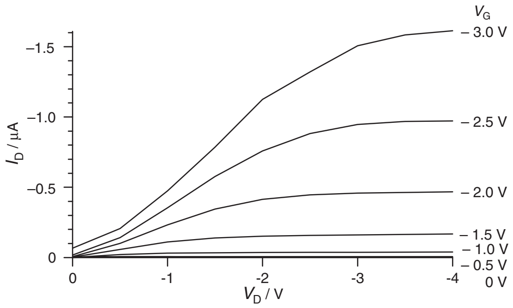

Figure 3. Plot of drain current (I_D) versus drain-to-source voltage (V_D) for various gate voltages from an MEH-PPV FET with Ta_2O_5 as a gate insulator.

Figure 4 shows the I_D–V_D characteristics for a pentacene FET. The observed result means that pentacene behaves as a p-type semiconductor. No n-type behaviors are observed for positive gate voltages. Saturation behaviors in the drain current are observed. From the observed drain currents in the saturation regime, the hole mobility in pentacene is calculated to be 0.8 cm^2/Vs and the threshold voltage -0.3 V. The obtained field-effect mobility is similar to those reported in the literature (0.6–2.4 cm^2/Vs).[2] The on/off current ratio means the ratio of the drain currents between the gate voltages of -2 and 0 V at the drain-to-source voltage of -3 V. The observed ratio is 66. The observed on/off ratio is much smaller than that for the MEH-PPV FET. Probably, this result originates from the low purity of pentacene. It should be noted that the primary goal here is to examine the operating voltages of OFETs with Ta_2O_5 as a gate insulator.

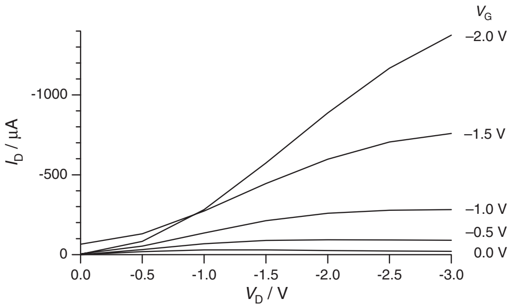

Figure 4. Plot of drain current (I_D) versus drain-to-source voltage (V_D) for various gate voltages from a pentacene FET with Ta_2O_5 as a gate insulator.

In summary, it has been demonstrated that the OFETs with Ta_2O_5 prepared by RF sputtering as gate insulator material operate at low gate voltages of about -3 V.

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