Output properties of C_{60} field-effect transistors with different source/drain electrodes

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C_{60} field-effect transistors (FETs) have been fabricated with source/drain electrodes of three different materials, indium tin oxide (ITO), Au, and Pt. High field-effect mobility μ_{FE} of FETs with ITO electrodes, 1.6×10^{-1} cm^2/V s, shows that ITO is a potential material for the electrodes of organic electronics. Although the highest Schottky barrier and the lowest μ_{FE} were expected, μ_{FE} of FET with Pt electrodes (1.4×10^{-1} cm^2/V s) is higher than that of FET with Au electrodes (9.6×10^{-2} cm^2/V s). The result suggests that modification of local electronic structure at the interface between electrodes and C_{60} affects device performance. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2709523]

Organic field-effect transistors (OFETs) have great potential for next-generation electronic devices because of their inexpensive price, light weight, mechanical flexibility, and high-shock resistance.[1] Performance of OFETs has been dramatically improved, and the mobility has become comparable to that of amorphous Si (*a*-Si) during recent years.[2–5] From the systematic and detailed characterization of OFETs,[6–11] it has been clarified that the device performance of OFETs strongly depends on parasitic resistance at the interface between the source/drain electrodes (an inorganic metal) and the channel (an organic semiconductor). Dominant origin of the parasitic resistance was thought to be the Schottky barrier at the interface between electrodes and the channel. Simply, the barrier height is estimated by Mott-Schottky relationship, namely, the energy difference between the Fermi energy (E_F) of an electrode and the energy level of the lowest unoccupied molecular orbital (LUMO) E_{LUMO} of an organic semiconductor for electrons, and that between E_F of an electrode and the energy level of the highest occupied molecular orbital (HOMO) E_{HOMO} of an organic semiconductor for holes. Actually, by reducing the energy difference between the E_F and E_{LUMO} (E_{HOMO}), the device performance of *n*-type (*p*-type) FETs including field-effect mobility μ_{FE} was improved.[9,10,12–14]

Local electronic structure at the interface between an inorganic metal and an organic material has also been vigorously investigated.[15] Experimental[16,17] and theoretical[18,19] studies showed that charge transfer between metals and molecules occurs, and the valence of molecules at the interface is not neutral. Appearance of dipole moment at interface induced by a charge transfer was also proposed.[20] From these studies, it was clarified that the carrier injection barrier can be attributed not only to the Mott-Schottky relationship but also to the effects of vacuum-level shift and local electric dipole due to the charge transfer and hybridization between an inorganic metal and an organic material. The fact that the carrier injection barrier depends on the molecular orientation near source/drain electrodes provides evidence of these additional effects.[21]

For the application of OFETs to electronic devices, such as complementary metal-oxide semiconductors (CMOS), detailed characterization of contact resistance and development of electrodes available to both *p*- and *n*-type OFETs are required. Indium tin oxide (ITO) is well known as a transparent anode for organic light emitting diodes. Furthermore, it is also expected to be used for source/drain electrodes of *n*-type OFETs, because work function ϕ of ITO is smaller than those of typical electrode materials of *n*-type OFETs such as Au. In the present study, we have fabricated C_{60} FETs with source/drain electrodes of three different materials, ITO ($In_2O_3+SnO_2$ 10 wt %), Au, and Pt, and have investigated their output properties.

C_{60} FETs were fabricated with a bottom contact configuration, as shown in Fig. 1(a). A heavily doped *n*-type silicon wafer with 400 nm thickness of thermally oxidized SiO_2 layer on the surface was used as substrate. The source and drain electrodes were patterned on insulating SiO_2 layer, using a photolithography method: the channel length *L* and the channel width *W* were designed to be 10 and 500 μm, respectively. For the devices with electrodes of ITO, a film was deposited using rf magnetron sputtering (Tokuda CFS-4ES) at a nominal deposition rate of 0.4 nm/s under argon flow at the pressure of 0.50 Pa. For the devices with electrodes of Au or Pt, films of Au and Pt were deposited using dc sputtering (Elionix ECS101) at deposition rates of about 0.06 and 0.08 nm/s, respectively. The thickness of source/drain electrodes was fixed to be 100 nm independent of the electrode materials. The doped silicon layer of the wafer was used as a

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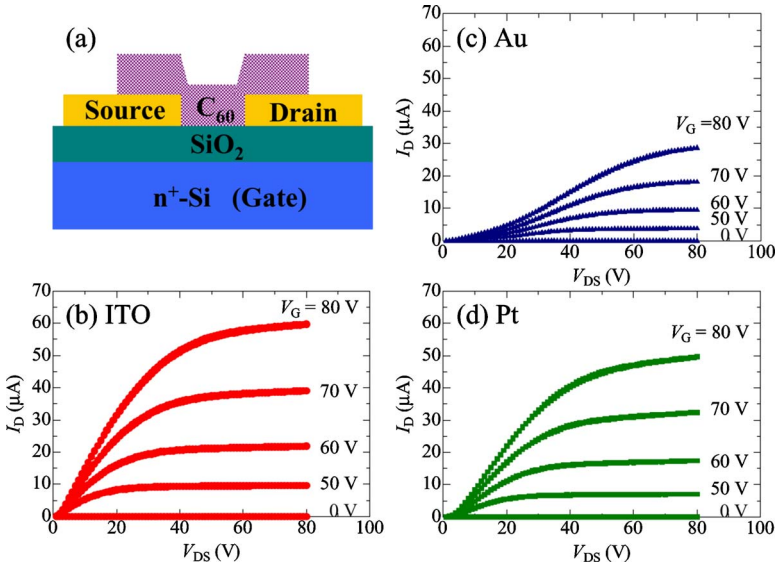

FIG. 1. (Color online) (a) Device structure of C_{60} thin-film FET. I_D vs V_{DS} plots for C_{60} FET with source/drain electrodes of (b) ITO, (c) Au, (d) Pt. Gate voltages were applied from 0 to 80 V.

gate electrode. Commercially available C_{60} (99.98%) was used for the formation of the thin film channel layer. A C_{60} thin film of 150 nm thickness was formed using vacuum ($<10^{-5}$ Pa) vapor deposition at the deposition rate of 0.1 nm/s. FETs fabricated by this procedure were exposed to air during the transfer from the deposition chamber to a measurement chamber. Before measurements, therefore, the samples were annealed at 120 °C under 10^{-3} Pa for 24 h in order to remove adsorbed O_2 and/or H_2O molecules. Transport properties of C_{60} FETs were measured at room temperature under 10^{-3} Pa without exposure to air after annealing using prober system (Desert TT-prober, Keithley 4200-SCS). In this study, in order to reduce the influence of the small number of adsorbed O_2 and/or H_2O molecules, all fabrication and experimental processes of three types of devices except for the deposition of source/drain electrodes was performed under the same condition. In addition, more than three series of these experiments were repeated, and data were compared within the same series. For the estimation of ϕ of ITO, Au, and Pt, the films of these materials fabricated by the same procedure were investigated by photoemission (PE) spectroscopy (Riken Keiki AC-2).

Figures 1(b)–1(d) show the output characteristics, namely, the drain current I_D versus the drain-source voltage V_{DS} plots, for C_{60} FET with source/drain electrodes of ITO, Au, and Pt. I_D increases almost linearly with increasing V_{DS}, followed by saturation due to the pinchoff of the accumulation layer; all FETs in this work show typical *n*-type normally off characteristics. Hysteresis of I_D's with V_{DS} sweep was very small. The plots of $I_D^{1/2}$ versus the gate voltage V_G for all devices at V_{DS}=80 V are shown in Fig. 2. The μ_{FE} and threshold voltage V_T were determined from the relation, $I_D=(\mu_{FE}WC_0/2L)(V_G-V_T)^2$, at saturation regime. μ_{FE} and V_T were 1.6×10^{-1} cm^2/V s and 36 V for the device with ITO source/drain electrodes, 9.6×10^{-2} cm^2/V s and 42 V for that with Au electrodes, and 1.4×10^{-1} cm^2/V s and 41 V for that with Pt electrodes, respectively. Here, we use 1.0×10^{-8} F/cm^2 as the capacitance per area of gate insulator SiO_2 (C_0) estimated from dielectric constant and thickness of SiO_2, because this estimation is consistent with experimental results.[22] The current on-off ratios, $I_D(V_G=80\text{ V})/I_D(V_G=0\text{ V})$, are 4.0×10^6 (ITO), 2.5×10^6 (Au), and 3.3×10^6 (Pt). Derived device parameters for all devices are summarized in Table I.

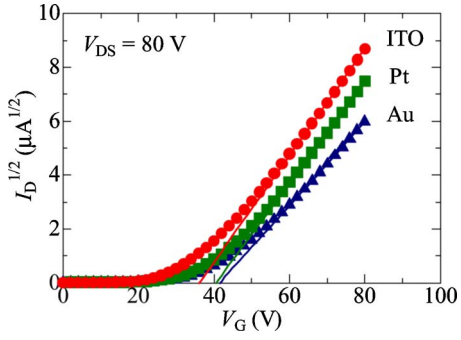

FIG. 2. (Color online) $I_D^{1/2}$ vs V_G plots at V_{DS}=80 V for all C_{60} FET devices. Solid lines are the fitting results of data for $V_G>60$ V, using the equation in the text.

PE spectra of the films of ITO, Au, and Pt are shown in Fig. 3(a). The square root of intensity $I_{PE}^{1/2}$ was proportional to energy of incident light E for all samples. ϕ was determined as threshold energy E_T from the relation, $I_{PE}^{1/2}=a(E-E_T)+b$, where a is just a fitting parameter, and b is background. Values of estimated ϕ are summarized in Table I, and in Fig. 3(b) with energy diagram. They are consistent with those in the literature.[23–25] E_{LUMO} and E_{HOMO} of C_{60} are taken from Refs. 26 and 27 as 3.57 and 6.17 eV, respectively. From these values, the expected Schottky barrier heights at the interface between electrodes (ITO, Au, and Pt) and the channel (C60) are 1.13, 1.33, 1.43 eV, respectively. It was reported that the device performance of C_{60} FETs is affected by large contact resistance between electrodes and the channel of C_{60},[11] which results in lower values of μ_{FE}.[10] FETs with lower carrier injection barriers show higher values of μ_{FE}. Consistent with this analogy, μ_{FE} of a FET with ITO

TABLE I. Device characteristics and work function ϕ of source/drain electrodes for all devices.

Source/drain electrodes	ITO	Au	Pt
μ (cm^2/V s)	1.6×10^{-1}	9.6×10^{-2}	1.4×10^{-1}
V_T (V)	36	42	41
On-of ratio	4.0×10^6	2.5×10^6	3.3×10^6
ϕ (eV)	4.7	4.9	5.0

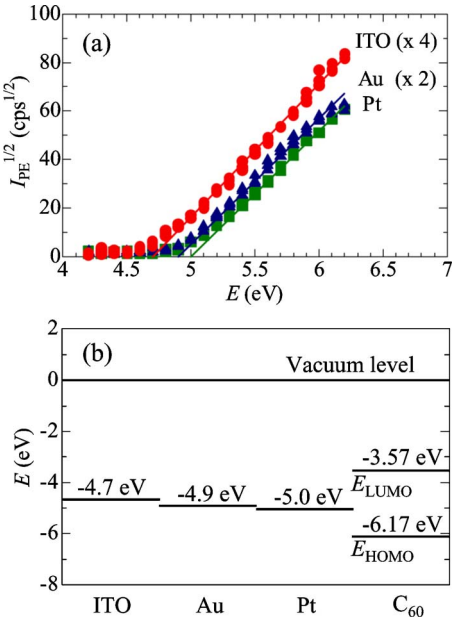

FIG. 3. (Color online) (a) PE spectra of the films of ITO, Au, and Pt. Solid lines are the fitting results of data, using the equation in the text. (b) Energy diagram of ITO, Au, Pt, and C_{60}. Work function ϕ of ITO, Au, and Pt are experimental data estimated from PE spectra. E_{LUMO} and E_{HOMO} of C_{60} are taken from Refs. 26 and 27.

electrodes is the highest among the three types of FETs in this study. The result shows that ITO, which is one of the typical hole-injection electrodes for *p*-type organic semiconductors, can also be a good electron-injection electrode for *n*-type organic semiconductors such as C_{60}. In addition, ITO provides very stable electrodes with small ϕ, whereas metal electrodes with small ϕ are very sensitive to air and should be used in vacuum.[9,10] This implies that the use of ITO as an electrode is very effective for transparent organic electronic devices containing both *p*- and *n*-type FETs, such as CMOS.

μ_{FE} of the FET with Pt electrodes, which was expected to be the lowest among FETs in this work, is higher than that of FET with Au electrodes and is very close to that of FET with ITO electrodes. We repeated the same series of experiments more than three times. In these experiments, the trend was invariant, although absolute values of device parameters varied slightly in each series. The origin of this discrepancy from Mott-Schottky limit may be attributed to modification of local electronic structure at the interface between electrodes and C_{60} due to charge transfer and/or hybridization of orbitals such as π-*d* interaction.[16–20] Our results show that device performance of organic FETs can be greatly improved by precisely controlling the electronic structure at the interface between electrodes and active layer of organic semiconductors.

In conclusion, we have succeeded to fabricate C_{60} FETs with source/drain electrodes of three different materials, ITO, Au, and Pt. The highest μ_{FE} value of 1.6×10^{-1} cm^2/V s in this work has been obtained in the C_{60} FETs with ITO electrodes, showing that ITO can be used not only for the hole-injection electrodes for *p*-type organic semiconductors but also for the electron-injection electrodes for *n*-type organic semiconductors such as C_{60}. This implies that the use of ITO as an electrode will contribute to development of transparent organic electronics. μ_{FE} of the FET with Pt electrodes, which was expected to be the lowest among FETs in this work, is higher than that of FET with Au electrodes. The result suggests the modification of local electronic structure at the interface between electrodes and a channel of C_{60} due to charge transfer and/or hybridization of orbitals.

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