# **JAIST Repository**

https://dspace.jaist.ac.jp/

Title	電極材料の異なるC60電界効果トランジスタの作製と評 価
Author(s)	髙橋,延也
Citation	
Issue Date	2007-03
Туре	Thesis or Dissertation
Text version	none
URL	http://hdl.handle.net/10119/3667
Rights	
Description	Supervisor:藤原 明比古,材料科学研究科,修士



Japan Advanced Institute of Science and Technology

# Fabrication and device characteristics of $C_{60}$ field-effect transistor with electrodes of different materials

Nobuya Takahashi

School of Material Science, Japan Advanced Institute of Science and Technology

# Abstract

### Introduction

Organic field-effect transistors (OFETs) have great potential for next-generation electronic devices because of their inexpensive price, light weight, mechanical flexibility. Performance of OFETs has been dramatically improved, and the mobility has become comparable to that of amorphous Si (a-Si) during recent years.<sup>1-3</sup> From the systematic and detailed characterization of OFETs,<sup>4-8</sup> 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  $\mu_{FE}$  was improved.<sup>6,7</sup>

Local electronic structure at the interface between an inorganic metal and an organic material has also been vigorously investigated. Experimental<sup>9</sup> and theoretical<sup>10,11</sup> 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. 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.

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 (OLEDs). Furthermore, it is also expected to be used for source/drain electrodes of *n*-type OFETs, because work function  $\phi$  of ITO is smaller than those of typical electrode materials of *n*-type OFETs such as Au.

In the present study,  $C_{60}$  FETs with source/drain electrodes of three different materials, ITO ( $In_2O_3 + SnO_2 10$  wt%), Au, and Pt have been fabricated, and devices characteristics were investigated.

# **Experiments**

 $C_{60}$  FETs were fabricated with a bottom contact configuration as shown in Fig. 1. A heavily doped n-type silicon wafer with 400 nm thickness of thermally oxidized SiO<sub>2</sub> 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 5-25 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 a deposition rate 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 gate electrode. Commercially available  $C_{60}$  (99.98 %) was used for the formation of the thin films 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<sup>-3</sup> Pa for 24 hours in order to remove adsorbed O<sub>2</sub> and/or H<sub>2</sub>O molecules. Transport properties of C<sub>60</sub> FETs were measured at room temperature under 10<sup>-3</sup> 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  $\phi$  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).



Fig.1. Device structure of C<sub>60</sub> FET in this work.

### **Results and Discussions**

Figure 2 (a)-(c) shows the output characteristics, namely the drain current  $I_D$  versus the drain-source voltage  $V_{DS}$  plots, for C<sub>60</sub> 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 pinch-off 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.



Fig.2.  $I_D$  vs  $V_{DS}$  plots for C<sub>60</sub> FET with source/drain electrodes of (a) ITO, (b) Au, (c) Pt. Gate voltage were applied from 0 to 80 V with 10 V step.

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. 3. The  $\mu_{FE}$  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.  $\mu_{FE}$  and  $V_T$  were 1.6 x 10<sup>-1</sup> cm<sup>2</sup>/Vs and 36 V for the device with ITO source/drain electrodes, 9.6 x 10-2 cm<sup>2</sup>/Vs and 42 V for that with Au electrodes, and 1.4 x 10-1 cm<sup>2</sup>/Vs and 41 V for that with Pt electrodes, respectively. Here, we use 1.0 x 10<sup>-8</sup> F/cm<sup>2</sup> as the capacitance per area of gate insulator SiO<sub>2</sub> ( $C_0$ ) estimated from dielectric constant and thickness of SiO<sub>2</sub>.



Fig.3.  $I_D 1/2$  vs  $V_G$  plots at  $V_{DS} = 80$  V for all C<sub>60</sub> FET.

PE spectra of the films of ITO, Au, and Pt are shown in Fig. 4(a). The square root of intensity  $I_{\rm PE}^{1/2}$  was proportional to energy of incident light *E* for all samples.  $\phi$  was determined as threshold energy  $E_{\rm T}$  from the relation,  $I_{\rm PE}^{1/2} = a(E-E_{\rm T}) + b$ , where *a* is just a fitting parameter, and *b* is background. Values of estimated  $\phi$  are summarized in Fig. 4(b) with energy diagram. They are consistent with those in the literature.<sup>12,13</sup>  $E_{\rm LUMO}$  and  $E_{\rm HOMO}$  of C<sub>60</sub> are taken from Refs. 14 and 15 as 3.57 eV, and 6.17 eV, respectively.



Fig.4. (a) PE spectra of the firm of ITO, Au, and Pt. (b) Energy diagram of ITO, Au, Pt, and C<sub>60</sub>.

From these values, the expected Schottky barrier heights at the interface between electrodes of ITO, Au, Pt and  $C_{60}$  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  $C_{60}$ ,<sup>8</sup> which results in lower values of  $\mu_{\rm FE}$ .<sup>7</sup>: FETs with lower carrier injection barriers show higher values of  $\mu_{\rm FE}$ . Consistent with this analogy,  $\mu_{FE}$  of an FET with ITO 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<sub>60</sub>. In addition, ITO provides very stable electrodes with small  $\phi$ , whereas metal electrodes with small  $\phi$  are very sensitive to air and should be used in vacuum.<sup>6,7</sup> 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.  $\mu_{\rm FE}$  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  $\pi$ -d interaction.<sup>9-11</sup>

### Conclusion

In conclusion,  $C_{60}$  FETs with source/drain electrodes of three different materials, ITO, Au, and Pt have been fabricated and investigated. The highest  $\mu_{FE}$  value of 1.6 x 10<sup>-1</sup> cm<sup>2</sup>/Vs 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.  $\mu_{FE}$  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<sub>60</sub> due to charge transfer and/or hybridization of orbitals.

# References

- S. Kobayashi, T. Takenobu, S. Mori, A. Fujiwara, and Y. Iwasa, *Appl. Phys. Lett.* 82, 4581 (2003).
- [2] V. Podzorov, E. Menard, A. Borissov, V. Kiryukhin, J. A. Rogers, and M. E. Gershenson, *Phys Rev. Lett.* 93, 086602 (2004).
- [3] K. Itaka, M. Yamashiro, J. Yamaguchi, M. Haemori, S. Yaginuma, Y. Matsumoto, M. Kondo, and H. Koinuma, *Adv. Mater.* 18, 1713 (2006).
- [4] I. Yagi, K. Tsukagoshi, and, Y. Aoyagi, Appl. Phys. Lett. 84, 813 (2004).
- [5] B. H. Hamadai and D. Natelson, J. Appl. Phy. Lett. 95, 1227 (2004).
- [6] T. Ohta, T. Nagano, K. Occhi, Y. Kubozono, E. Shikoh, and A. Fujiwara, Appl. Phys. Lett. 89, 053508 (2006).
- [7] K. Ochi, T. Nagano, T. Ohta, R. Nouchi, Y. Kubozono, Y. Matsuoka, E. Shikoh, and A. Fujiwara, *Appl. Phys. Lett.* 89, 083511 (2006).
- [8] Y. Matsuoka, K. Uno, N. Takahashi, A. Maeda, N. Inami, E. Shikoh, Y. Yamamoto, H. Hori and A. Fujiwara, *Appl. Phys. Lett.* 89, 173510 (2006).
- [9] B. W. Hoogenboom, R. Hesper, L. H. Tjeng, and G. A. Sawatzky, Phys. Rev. B57, 11939 (1998).
- [10] L. -L. Wang, and H. -P. Cheng, Phys Rev. B69, 045404 (2004).
- [11] L. -L. Wang, and H. -P. Cheng, Phys Rev. B69, 165417 (2004).
- [12] H. B. Michaelson, J. Appl. Phys. 48, 4729 (1977).
- [13] I. D. Parker, J. Appl. Phys. 75, 1656 (1994).
- [14] N. Sato, Y. Saito, and H. Shinohara, Chem. Phys. 162, 433 (1992).
- [15] N. Hayashi, H. Ishii, Y. Ouchi, K. Seki, J. Appl. Phys. 92, 3784 (2002).