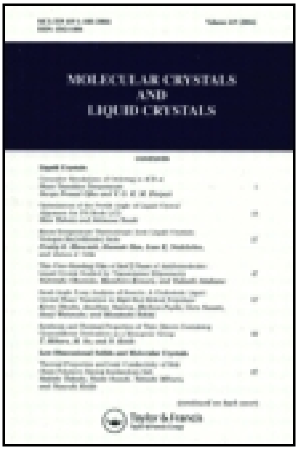

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Evaluation of Electrical Properties in P, N-Type Organic Thin Films by In-Situ Field Effect Measurements

Tsutomu Sumimoto [a], Kouji Hiraga [a], Shigekazu Kuniyoshi [a], Kazuhiro Kudo [a] & Kuniaki Tanaka [a]

[a] Department of Electrical and Electronics Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba, 263, Japan

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EVALUATION OF ELECTRICAL PROPERTIES IN P, N-TYPE ORGANIC THIN FILMS BY IN-SITU FIELD EFFECT MEASUREMENTS

TSUTOMU SUMIMOTO, KOUJI HIRAGA,
SHIGEKAZU KUNIYOSHI, KAZUHIRO KUDO
AND KUNIAKI TANAKA
Department of Electrical and Electronics Engineering, Chiba University,
1-33 Yayoi-cho, Inage-ku, Chiba 263, Japan

Abstract Thin film transistors using several p, n-type organic semiconductors were fabricated and their electrical properties of conduction-type, carrier mobility, electrical conductivity, and carrier concentration were evaluated by in-situ field effect measurements.

INTRODUCTION

Optical and electrical properties of various organic semiconductors have been investigated by several methods. However, there have been very few works deal with the intrinsic electrical parameters of organic semiconductors. It is well known that several organic semiconductors are strongly influenced by atmospheric gasses. Especially, oxygen gas works as an electron acceptor in n-type organic semiconductors and it lowers their conductivities[1]. Therefore, it is significant to investigate the electrical properties of organic materials without the influence of atmospheric gasses and impurities. The field effect measurement is a promising method for the evaluation of conduction-type (p or n), carrier mobility, electrical conductivity, and carrier concentration of thin films[2]. We have carried out in-situ field effect measurements in a same sample structure subsequently to the vacuum evaporation of several kinds of p, n-type organic semiconductors. The materials used as an active component are metal-free phthalocyanine (H_2Pc), copper phthalocyanine (CuPc), lead phthalocyanine (PbPc), C_{60}, 3,4,9,10-perylenetetracarboxylic diimide (PTCDI), and *tris*(8-hydroxyquinolinato) aluminum (Alq_3). Their electrical parameters were estimated by the same analysis of a standard thin film transistor (TFT).

EXPERIMENTAL

The schematic diagram of the sample structure is shown in Figure 1. For the in-situ electrical measurements, interdigital source and drain electrodes using Au/Cr (for p-type organic materials) or In (for n-type organic materials) were formed by standard vacuum evaporation and photolithographic techniques on SiO_2 layer previously formed on the highly doped silicon wafer which served as a gate electrode. The thickness of SiO_2 layer was approximately 2000 Å. Substrates were cleaned with organic solutions in an ultrasonic bath and pre-baked at 373 K over 30 minutes in the vacuum chamber. Subsequently, organic thin films as an active component were evaporated on the substrates. The substrate temperature (T_G) was kept at 300K (room temperature: R.T.) or 373K during the evaporation. Field effect measurements have been performed immediately after the evaporation of organic thin films. All the measurements have been done at R.T. in the dark.

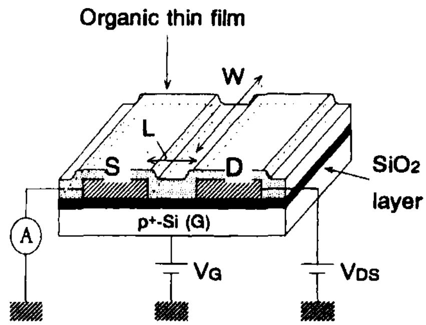

FIGURE 1 Schematic diagrams of sample structure and electric circuit for field effect measurements.

Electrical parameters of organic thin films are estimated according to the same analysis in a standard TFT[3]. The characteristics of the source-drain current (I_{DS}) vs source-drain voltage (V_{DS}) with applying gate voltage (V_G) were measured. I_{DS} in the linear region for a standard p-channel TFT is given by

$$I_{DS}=-\frac{W}{L}\mu C_{ox}\left\{(V_G-V_{th})V_{DS}-\frac{1}{2}V_{DS}^2\right\}$$

where W is the channel width, L is the channel length, μ is the hole mobility, C_{OX} is the capacitance of SiO_2 layer, and V_{th} is the threshold voltage. This equation and the electrical conductivity $\sigma=qN\mu$ lead to μ, σ, and N as

$$\mu=-\frac{L}{WC_{ox}}\cdot\frac{1}{V_{DS}}\cdot\frac{dI_{DS}}{dV_G}\bigg|_{V_{DS}=small}$$

$$\sigma=\frac{L}{Wt}\cdot\frac{dI_{DS}}{dV_{DS}}\bigg|_{V_G=0}$$

$$N=\frac{\sigma}{q\mu}$$

where q is the elementary electric charge, N is the carrier concentration, and t is the thickness of the organic film.

RESULTS AND DISCUSSION

H_2Pc, CuPc, and PbPc belong to the materials called p-type semiconductors or hole transport materials. I_{DS} vs V_{DS} characteristics of the PbPc TFT fabricated at T_G of R.T. are shown in

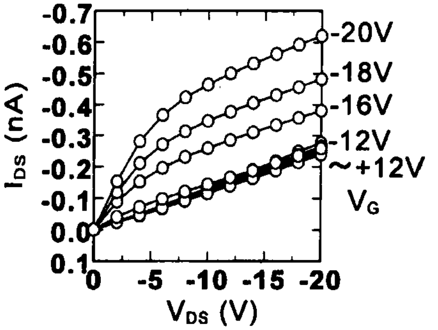

FIGURE 2 Current-voltage characteristics of the PbPc TFT fabricated at T_G of R.T.

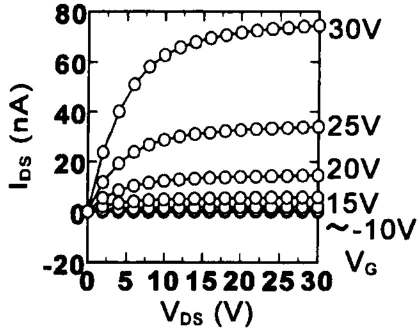

FIGURE 3 Current-voltage characteristics of the C_{60} TFT fabricated at T_G of R.T.

Figure 2. The channel conductivity increased when a negative V_G was applied. This result indicates that a hole accumulation layer (or channel) was formed at the interface of PbPc/SiO_2 and the conductance of the channel can be modulated by negative V_G. It means that PbPc evaporated films show p-type semiconducting properties without the influence of atmospheric gasses and impurities. The PbPc TFT operated in an enhancement mode. Even when a positive V_G was applied, there was no sample which operated in an inversion mode of all the organic TFTs fabricated and the channel conductivity was pinned at a constant value. It is not yet clear why the inversion layer was not appeared. Since the TFT operated in an accumulation mode, I_{DS} involved the current in the accumulation layer which was controlled by V_G and the current in the bulk which was independent of V_G. H_2Pc and CuPc TFTs also showed p-type semiconducting properties. The electrical parameters obtained from the field

TABLE I Electrical parameters of the evaporated films.

Material	T_G	t (nm)	Type	μ (cm^2/Vs)	σ (S/cm)	N ($/cm^3$)
H_2Pc	R.T.	130	p	$< 10^{-9}$	$< 10^{-11}$	———
	373 K	120	p	2×10^{-6}	1×10^{-10}	5×10^{14}
CuPc	R.T.	49	p	2×10^{-9}	$< 10^{-12}$	———
	373 K	100	p	3×10^{-6}	3×10^{-10}	7×10^{14}
PbPc	R.T.	85	p	3×10^{-7}	5×10^{-10}	1×10^{16}
	373 K	125	p	9×10^{-6}	4×10^{-9}	3×10^{15}
C_{60}	R.T.	250	n	3×10^{-5}	7×10^{-10}	1×10^{14}

effect characteristics are shown in Table I.

Similar measurements were performed on the other materials under the same condition. C_{60}, PTCDI, and Alq_3 belong to the materials called n-type semiconductors or electron transport materials. I_{DS} vs V_{DS} characteristics of the C_{60} TFT fabricated at T_G of R.T. are presented in Figure 3. The channel conductivity increased when a positive V_G was applied. Therefore, C_{60} evaporated films showed n-type semiconducting properties without the influence of atmospheric gasses and impurities, where the electron accumulation layer was formed by positive V_G. The electrical parameters of C_{60} are also shown in Table I. The field effect measurements of C_{60} TFTs have been already reported[4-7]. The values of μ reported in other works are $8x10^{-2}$ cm^2/Vs[5], $4x10^{-5}$ cm^2/Vs[6] and $5x10^{-5}$ cm^2/Vs[7]. In our previous work[4], V_G was varied between -6 V and +6 V and μ estimated from the field effect measurement was the value of $1x10^{-6}$ cm^2/Vs. At this region of V_G, the saturation of I_{DS} was not clearly visible. There was a possibility that the electrons were not completely accumulated at the interface of C_{60}/SiO_2. By improving the sample structure, μ estimated in this work increases the value of $3x10^{-5}$ cm^2/Vs and that of annealed sample reaches as large as 0.23 cm^2/Vs.

PTCDI and Alq_3 are well known as n-type semiconductors or electron transport materials. We have fabricated PTCDI and Alq_3 TFTs at T_G of R.T. and 353 K. Although electrical measurements were performed in the same condition as the other materials, an effective current was not observed in all the evaporated films of them. Therefore, we could not evaluate their electrical parameters.

CONCLUSION

We have fabricated thin film transistors using several organic evaporated films. The materials used as an active component are H_2Pc, CuPc, PbPc, C_{60}, PTCDI, and Alq_3. We have evaluated their electrical properties by in-situ field effect measurements in a same sample structure. H_2Pc, CuPc and PbPc TFTs showed p-type semiconducting properties and C_{60} TFTs showed n-type semiconducting properties. However, PTCDI and Alq_3, which are regarded as n-type semiconductors or electron transfer materials, showed extremely low current and the effective field effect was not observed.

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