Effects of Alternating Magnetic Field Assisted Annealing of Pentacene Film for Organic Thin Film Transistor Applications

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In this article, a novel annealing technique using alternating magnetic field (AMF) is adopted to improve the electrical characteristics of pentacene film, thereby enhancing the performance of pentacene-based organic thin film transistors (OTFTs). According to the investigation results, the electrical conductivity in the pentacene film could be increased from 0.32 to 1.18 S/cm by annealing the pentacene film using AMF. And also, OTFTs with the pentacene film annealed by AMF exhibited an improved performance compared to the device without annealing. These results suggest that an annealing using AMF can be an effective method to improve the performance of devices based on organic semiconductors.

Keywords : OTFTs, Pentacene, Alternating magnetic field, Electrical conductivity

1. INTRODUCTION

Organic thin film transistors (OTFTs) are of increasing interest for applications as low-end data storage, identification tags, or flat panel displays[1]. The performance of OTFTs has been improved dramatically over the past ten years, and optimized OTFTs show electrical characteristics similar to those obtained with amorphous silicon devices[2]. Among many organic semiconductors, pentacene, as an active layer, has provided the highest field-effect mobility of TFTs. However, the transport properties of OTFTs significantly depend on molecular ordering and crystallinity of organic semiconductors, and there is copious room for characteristic improvement of pentacene TFTs[3,4].

In this study, we focus on the characteristic improvements of pentacene-based TFTs by applying alternating magnetic field (AMF) to pentacene films. The effects of AMF on pentacene films and the characteristics of pentacene-based TFT treated by AMF will be discussed.

2. EXPERIMENTAL DETAILS

For this study, two kinds of devices were fabricated as shown in Fig. 1. One of them is the metal-semiconductor-metal (MSM) device for the electrical conductivity measurement of pentacene films and the other is the pentacene-based TFT. For the MSM devices, pentacene films were prepared on a glass substrate by thermal evaporation from pentacene powder (Sigma-Aldrich Co.). The deposition rate was about 1.0 Å/s under a base pressure of 1.6×10^{-6} Torr and its thickness was about 600 Å. Deposited pentacene films were treated by AMF in an argon ambient. After the AMF treatment, 1500-Å-thick Al electrodes were deposited onto the pentacene film. For the fabrication of pentacene-based TFTs, 1500 Å-thick Al layer was thermally deposited on the glass substrate as a gate electrode. The gate dielectric, 2500 Å-thick polystyrene (1 wt% in chloroform) layer was formed by spin-coating, and baked at 90 °C for 5 min. and consecutively at 95 °C for 1 hr in a dry vacuum oven. The pentacene film as an organic semiconductor layer was deposited at the rate of 1.0 Å/sec, and its thickness was about 600 Å. And then, deposited pentacene films were also treated by AMF in an argon ambient prior to source/drain electrode formation. For the source and drain contacts, Au was thermally evaporated. The channel length and width of the fabricated TFTs are 150 μm and 5 mm, respectively.

The AMF system is schematically presented in Fig. 2, where the ac current with the maximum amplitude up to 50 A can flow through the water-cooled copper tubes of 10 ϕ and 14 turns. The magnitude of the current applied to the induction coil was varied from 30 to 50 A and its frequency was 13.56 kHz.

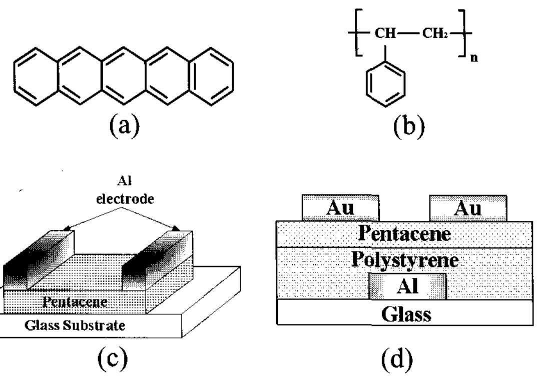


Fig. 1. Schematic representations of molecular structures and devices used in this study. (a) pentacene ; (b) polystyrene; (c) MSM device for measuring the electrical conductivity in pentacene film; (d) pentacene-based TFT.

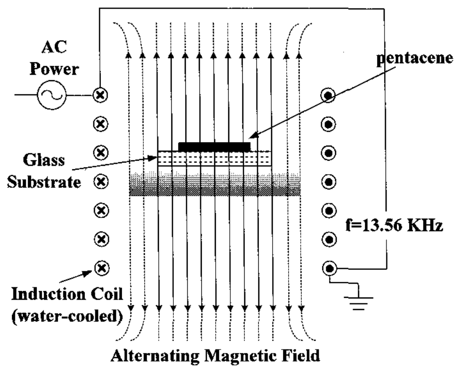


Fig. 2. Schematic illustration of AMF impression system.

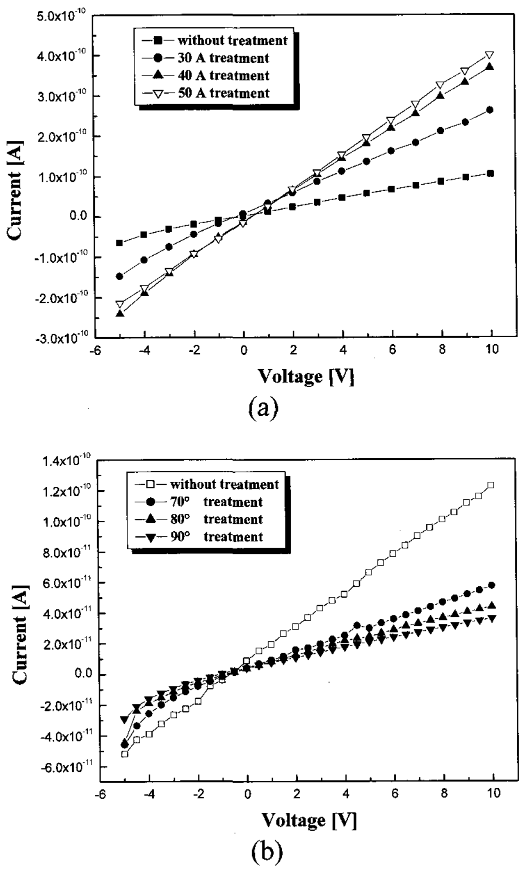


Fig. 3. The current-voltage (*I-V*) characteristics for the MSM devices for various treatment conditions. (a) the *I-V* characteristics for the MSM devices treated by AMF with varying the amplitudes of ac currents.; (b) the *I-V* characteristics for the MSM devices by simple thermal treatment with varying the temperature.

3. RESULTS AND DISCUSSION

When an electrically conducting object is placed in a time-varying magnetic field, induction heating takes place in the object. Induction heating of the object is due to eddy current losses[5]. The current-voltage characteristics of the MSM devices are shown in Fig. 3 and their electrical properties are also summarized in Table 1. The highest conductivity, 1.18×10^{-6} S/cm, is obtained when the MSM devices were treated by applying the ac current of 50 A amplitude to the induction coil. However, it is observed that the electrical conductivities even deteriorate when MSM devices were treated by a simple thermal annealing as shown in Fig. 3 (b) and summarized in Table 2. There must be certain effects of AMF on pentacene films other than simple heating during the AMF treatment, which may include rapid thermal annealing, different from conventional thermal annealing, or some other field effects. The measured temperatures of the pentacene film elevated by applying AMF are summarized in Table 1 for the three applied current levels to the induction coil.

Table 1. Electrical properties of pentacene films and elevated temperature according to AMF annealing conditions.

	R [Ω]	σ [S/cm]	Temperature [°C]
No treatment	8.82×10^{10}	0.32×10^{-6}	
30 A treatment	3.65×10^{10}	0.78×10^{-6}	≈ 70
40 A treatment	2.46×10^{10}	1.16×10^{-6}	≈ 80
50 A treatment	2.43×10^{10}	1.18×10^{-6}	≈ 90

Table 2. Electrical properties of pentacene films according to simple thermal annealing conditions.

	R [Ω]	σ [S/cm]	Comparison to AMF
No treatment	8.22×10^{10}	0.28×10^{-6}	
70 °C treatment	2.06×10^{11}	0.11×10^{-6}	≈ 30 A
80 °C treatment	2.50×10^{11}	0.09×10^{-6}	≈ 40 A
90 °C treatment	3.11×10^{11}	0.07×10^{-6}	≈ 50 A

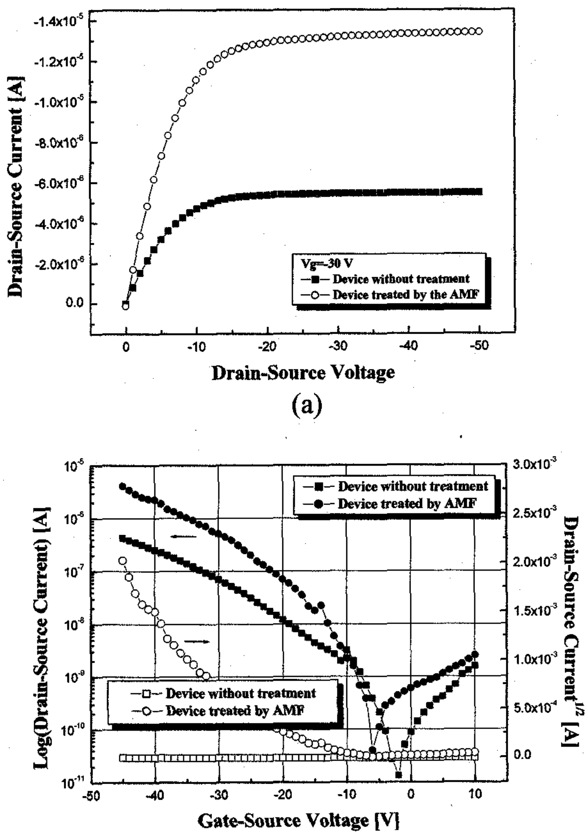
The electrical conductivity was calculated using equation (1), where L is the thickness of organic layer, R is the resistance, and S is the area for carrier conduction.

$$\sigma = \frac{L}{R\times S} \quad [\text{S/cm}] \tag{1}$$

According to the aforementioned results, it is obvious that electrical properties of pentacene films can not be improved by simple thermal annealing process but can be improved by the AMF treatment. Based on the above results, pentacene-based TFTs were fabricated with and without applying the AMF to pentacene films prior to the deposition of source/drain electrodes. The ac current with an amplitude of 50 A was applied to the induction coil. The drain current of the fabricated OTFTs as a function of the drain voltage at the gate voltage of -30 V is shown in Fig. 4(a). The drain current of the fabricated OTFTs as a function of the gate voltage at the drain voltage of -30 V is shown in Fig. 4(b). The field-effect mobility is extracted from Fig. 4(b) using the saturation drain current equation (2):

$$I_{D,sat} = \frac{W\mu_{eff}C_i}{2L}(V_G - V_T)^2 \tag{2}$$

where W is the channel width, μ_{eff} is the field-effect mobility, C_i is the capacitance of the insulating material per unit area, L is the channel length, V_G is the gate voltage, and V_T is the threshold voltage[6]. For the TFT with the pentacene layer treated by AMF, the saturation current ($I_{D,sat}$) is about 13.3 μA and the field-effect mobility is about 0.14 cm^2/Vs, which are substantially improved values compared to those of TFT without the AMF treatment. Consequently, it can be confirmed that the AMF treatment could be the novel method for improving the characteristics of OTFTs. Detailed device properties are summarized in Table 3.



(b)

Fig. 4. *I-V* characteristics of the fabricated OTFTs. (a) output characteristics at V_G=-30 V.; (b) transfer characteristics at V_D=-30 V.

Table 3. Electrical properties of TFTs with or without the AMF treatment.

	μ_{eff} [cm^2/Vs]	$I_{D,sat}$ [μA]	on/off ratio
Untreated TFT	0.004	-5.4	$> 10^4$
Treated TFT	0.14	-13.3	$\sim 10^5$

The structural changes might occur by applying the AMF to pentacene. For the inspection of the structural changes, atomic force microscopy (AFM) and X-ray diffraction (XRD) were used and presented in Fig. 5. AFM images showed that the surface roughness of pentacene film became smoothened and the grain size of pentancene significantly got larger by the AMF annealing process. The root-mean-square roughness of the treated pentacene film is about 48 Å and that of the untreated pentacene film is about 153 Å. However, there was little change in the crystallinity of the pentacene film even with the AMF treatment. Therefore, it is thought that the large grain size of the pentacene film

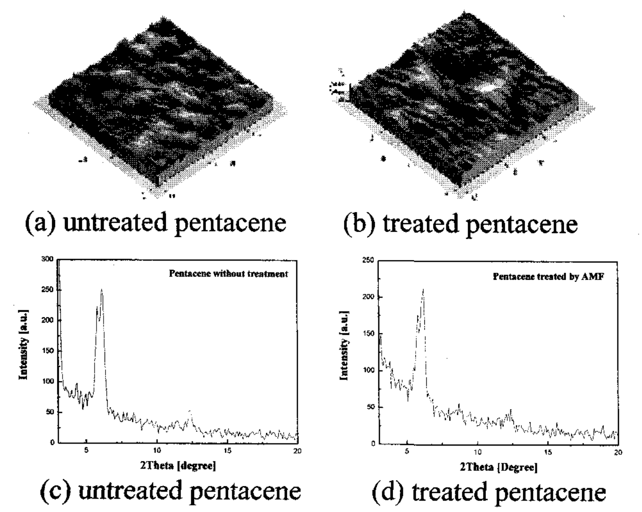


Fig. 5. AFM images and XRD spectrum of pentacene film according to AMF treatment.

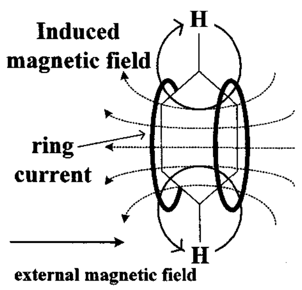


Fig. 6. The schematic representation of benzene ring according to external magnetic field.

and the modified contact property between metal electrode and pentacene layer might lead to the characteristic improvements, even though the crystallinity of pentacene layer was not changed.

And the pentacene films annealed by AMF might be also affected by the applied magnetic fluxes. Indeed, when π-electrons in benzene molecule are placed in magnetic fields, π-electrons circulate around the aromatic ring and generate a ring current, which can induce additional magnetic fields in benzene molecule (see Fig. 6). As a result, hydrogen atoms in the benzene ring become deshielded by diamagnetic anisotropy[7]. Other experiments are now in progress to investigate whether any chemical change might occur or not.

4. CONCLUSION

So far the AMF treatments of organic thin films have never been tried and this is the first report of the AMF treatments on pentacene films. It was demonstrated that the electrical properties of pentacene films and pentacene-based TFTs could be improved by the AMF treatment. The enhanced electrical conductivity and field-effect mobility were 1.18×10^{-6} S/cm and 0.14 cm^2/Vs, respectively, which present substantial characteristic changes from those of the devices without the AMF treatment. It is thought that these characteristic improvements are resulted from morphological change and/or enlargement in the grain size of pentacene film. Further investigations on the chemical structure of pentacene are required to fully explain the effects of AMF on pentacene molecules.

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