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Bending Effect of Organic Field-Effect Transistors with Polyimide Gate Dielectric Layers

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We manufactured markedly flexible pentacene field-effect transistors (FETs) on a polyethylenenaphthalate base film with polyimide gate dielectric layers, with a mobility of 0.3 cm^2/Vs and an on/off ratio of 10^5. The electric performance of DC current–voltage characteristics was measured by applying compressive and tensile strains while reducing the bending radius down to 3 mm. It was found that the compressive strain leads to an increase in mobility of 10% induced by the change in strain of up to $1.4 \pm 0.1\%$, although the tensile strain leads to a decrease in mobility of 10%. To elucidate the origin of the enhancement of mobility under the compressive strain, we also investigated the strain dependence of capacitance–voltage characteristics for a pentacene channel layer, and almost no change was observed. Our results suggest that the strains markedly affect the spacing between pentacene molecules rather than the number of induced carriers.
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KEYWORDS: organic transistor, pentacene, bending experiment, polyimide gate dielectric layer

Organic materials play an increasing role in many fields. Nowadays, organic field-effect transistors (FETs) have been intensively investigated in order to apply their remarkable attributes to more electronic devices, such as a radio frequency identification (RFID) tag,[1)] a display,[2)] and an area sensor.[3)] The realization of such applications leads to new concepts with light weight, low-cost processability and mechanical flexibility. Although amorphous silicon-based transistors (a-Si FETs) also have benefits similar to organic FETs, their electric and physical characteristics including mechanical flexibility have been well understood for some time.[4–6)] However, the mechanical flexibility of organic FETs has not yet been clarified because of the difficulty of manufacturing them on plastic films.

In this work, we manufactured markedly flexible pentacene field-effect transistors on a plastic base film with polyimide gate dielectric layers, with a mobility of 0.3 cm^2/Vs and an on/off ratio of 10^5. The strain dependence of the electric performance (DC current–voltage and capacitance–voltage characteristics) was characterized by applying compressive and tensile strains, which were obtained by reducing the bending radius down to 3 mm, corresponding to a change in strain of 2%.[7)] It was found that the mobility increases by 10% under compression with a change in strain up to $1.4 \pm 0.1\%$, although it decreases by 10% under tension. Such a change in electric performance with strain can be attributable to a change in spacing between pentacene molecules rather than the number of induced carriers.

High-performance organic FETs were fabricated by vacuum evaporation and spin coating. A cross-sectional illustration of the present FETs is shown in Fig. 1(a). First, a 100-nm-thick gate electrode of gold was formed by vacuum evaporation using a shadow mask on a 125-μm-thick polyethylenenaphthalate base film (PEN, Teonex Q65, Teijin Dupont Films), and second, a polyimide precursor was spin-coated and baked for 1 h to form 900-nm-thick polyimide dielectric layers. Then, a 50-nm-thick pentacene layer and a 60-nm-thick gold layer were deposited to form channel layers and source-drain electrodes, respectively, by vacuum evaporation using a shadow mask. The fabrication process is described in refs. 3 and 8 in detail. The nominal channel length (L) and width (W) of our pentacene FETs were determined to be 100 μm and 1 mm, respectively. The electrical performance of DC current-voltage and capacitance–voltage characteristics was measured using a semiconductor parameter analyzer and an LCR meter (4156C and 4384B, Agilent Technologies). Devices were stressed using a stress apparatus with a precision mechanical stage, as illustrated in Fig. 1(b). Inward bending induced compressive strains and outward tensile strains at the position of FETs. The source-drain current path of the present transistors was precisely arranged parallel to the direction of the strain. All the experiments were performed in a light-shielding glove box (Labmaster130, MBRAUN) of less than 1 ppm oxygen and moisture.

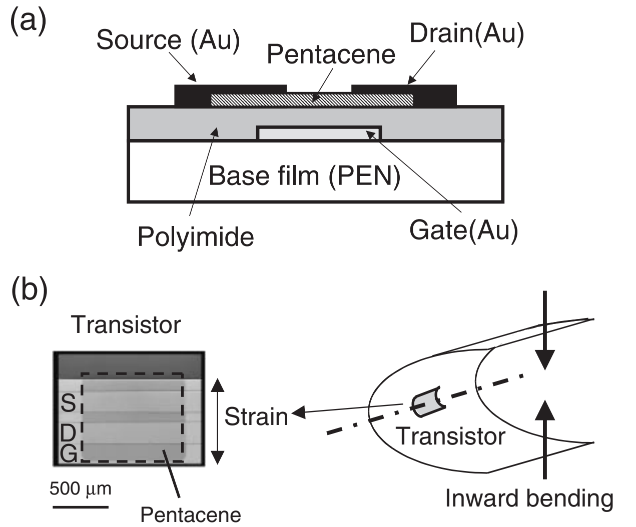

Fig. 1. (a) Cross-sectional illustration of organic FET and capacitor on same PEN base film. (b) Pictures of capacitor and organic FETs with geometry of current applied parallel to the direction of strain.

Figure 2(a) shows the typical DC characteristics of an organic FET without bending stress immediately after fabrication. We monitored the source-drain current (I_{DS}) as a function of source-drain voltage (V_{DS}). The gate voltage (V_{GS}) was changed from 0 to -40 V in -10 V steps. The corresponding transfer curve was also shown in Fig. 2(b) with an application of $V_{DS} = -40$ V. The evaluated mobility

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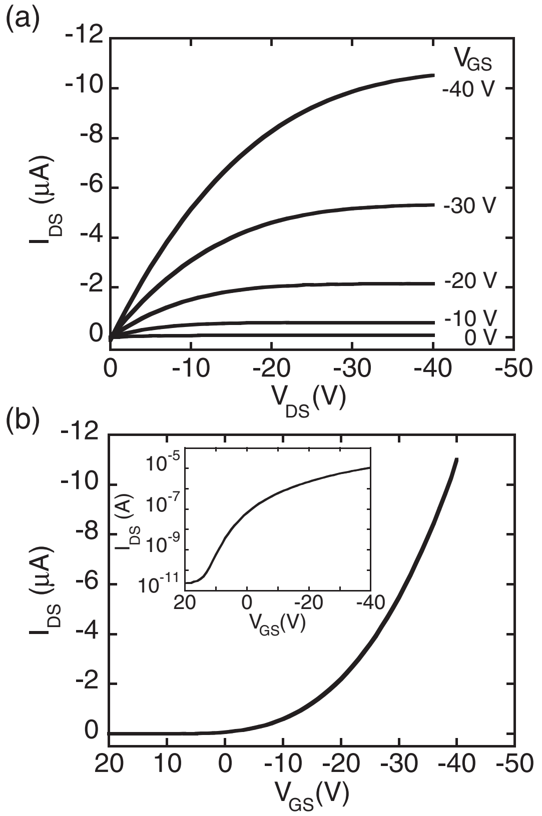

Fig. 2. (a) Typical DC characteristics without stress, which is source-drain current (I_{DS}) as a function of source-drain voltage (V_{DS}). The gate voltage (V_{GS}) was changed from 0 to -40 V in -10 V steps. (b) Corresponding transfer curve with an application of $V_{DS} = -40$ V. The inset of (b) shows I_{DS} plotted on a logarithmic scale.

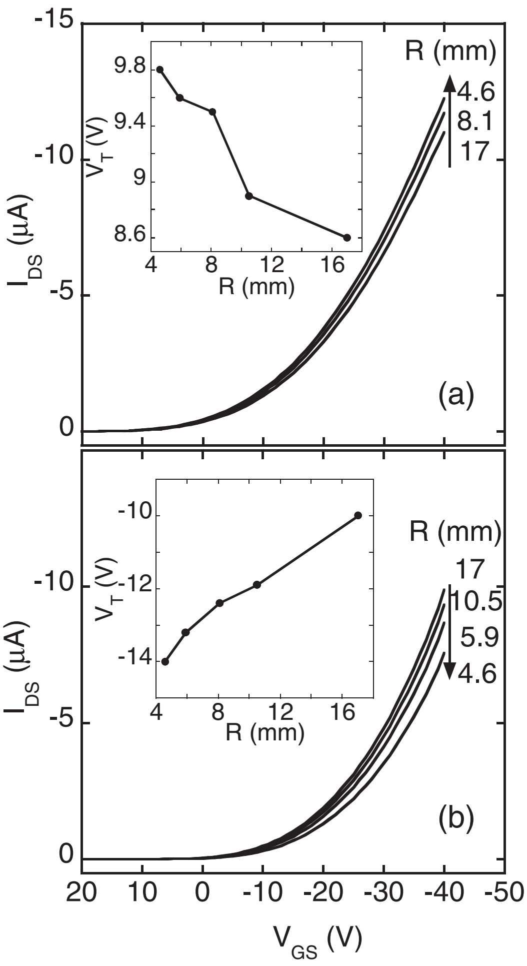

Fig. 3. Transfer curves under (a) compressive and (b) tensile strains with decreasing bending radius from 17 to 4.6 mm. V_{GS} was swept from 20 to -40 V with an application of $V_{DS} = -40$ V. Insets show the threshold voltage (V_T) with changing bending radius.

was as high as 0.3 cm^2/Vs and the on/off ratio was above 10^5.

Figures 3(a) and 3(b) show the transfer curves obtained by applying compressive and tensile strains, respectively, by systematically changing the bending radius. The gate voltage (V_{GS}) was swept from 20 to -40 V by applying $V_{DS} = -40$ V. The saturation current increased monotonically with decreasing compressive bending radius, while it decreased monotonically with decreasing tensile bending radius. The changes in saturation currents were +11% and −26% at the bending radius $R = 4.6$ mm under compressive and tensile strains, respectively. The compressive bending at $R = 4.6$ mm induced the enhancement of mobility of 10%, while the tensile strain caused a decrease in mobility of 10%. Such a large change in mobility cannot be explained only by the deformation of device structures at $R = 4.6$ mm, corresponding to a change in strain of 1.5%.[7)] The threshold voltage was also systematically changed, namely, a positive shift was induced by compression and a negative shift was induced by tension. Furthermore, the strain-induced changes were observed to be reproducible and reversible, namely, almost no residual effects of strain were found after the removal of the bending radius of 4.6 mm, as demonstrated in ref. 9. On the other hand, a further decrease in bending radius to below 4.6 mm (above 1.5% in strain) resulted in the deterioration of transistor performance, which is ascribed to the device failure associated with top-electrode delamination.

To elucidate the origin of the enhancement of mobility, we also measured the capacitance–voltage characteristics of a pentacene channel layer (C_{ch}–V) by systematically changing the bending radius, as shown in Fig. 4. To extract C_{ch}–V, we subtracted the parasitic capacitances of gold electrodes and polyimide dielectric layers from the experimentally measured capacitance. The measurement frequency was 50 Hz with an AC voltage of 80 mV. The bias DC voltage from the gate electrode was swept from 55 to −15 V at which the source electrode was short-circuited to the drain electrode as a ground. It is well known that the total area of the C–V curve reflects the number of carriers induced by the gate voltage and the rising edge represents the threshold voltage (V_T^{CV}).[10)] Although V_T^{CV} under the compressive strain was slightly shifted toward a positive value by decreasing the bending radius from 17 to 4.6 mm, the area of the C_{ch}–V curve was decreased by 1.4–1.6% [Fig. 4(a)]. This change is in agreement with the deformation of the device structure down to the bending radius of 4.6 mm. Actually, the deformation of the area of the pentacene channel layer and the thickness of the polyimide dielectric layers can be fully understood using the classical Poisson model.[7,11,12)] Therefore, we suggest that the enhancement of the mobility under the compressive strain is not associated

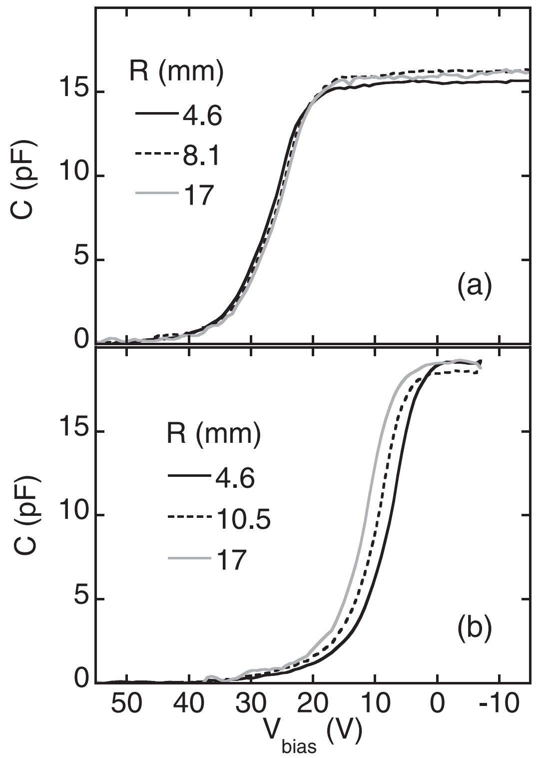

Fig. 4. Capacitance–voltage characteristics of pentacene channel layer with systematically changing bending radius on (a) compression and (b) tension. The measurement frequency was 50 Hz with an AC voltage of 80 mV. The bias DC voltage from the gate electrode was swept from 55 to −15 V at which the source electrode was short-circuited to the drain electrode as a ground.

with the change in the number of carriers, but with other mechanisms. On the other hand, the area of the C_{ch}–V curve obtained under the tensile strain was significantly decreased by 16% [Fig. 4(b)]. Thus, the instantaneous deterioration after the bending of tensile strains might be involved in the reduction in the number of carriers.

Hence, we discuss the strain dependence of the electric performance, particularly in terms of mobility, on the basis of pentacene molecules. The transport properties of many organic molecules are known to be defined by intermolecular carrier hopping. Compressive strains might lead to a shorter spacing between molecules, resulting in easier hole hopping because the energy barrier of carrier hopping strongly depends on the spacing between molecules. On the other hand, tensile strains might lead to a longer spacing. We think this simple mechanism is a more plausible explanation for the origin of the strain-induced change in electric performance. Thus, pentacene molecules and their grain boundary should play an important role in quantitatively understanding the strain effect in pentacene polycrystalline thin films.

Finally, we would like to focus on the carriers induced by the gate voltage. As shown in Figs. 3 and 4, the threshold voltage (V_T) observed from the transfer curve is different from the V_T^{CV} observed from the C–V curve, although such a discrepancy is not observed in Si-based transistors. Actually, it is known that the transfer curve represents the contribution of free carriers to electrical transport, while the C–V curve reflects all carriers including not only free but also deeply trapped carriers. Therefore, one of the possible explanations of this observed discrepancy is that there are a number of deeply trapped carriers in pentacene molecules as contrasted with silicon. However, further investigation is required to understand the mechanism in detail, because the DC transport measurement provides local information from the current flow path, while the information obtained from the C–V characteristics is averaged.

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12) Here, we would like to discuss the strain-induced changes of the structural parameters, which can be associated with a change in transistor performance. In the geometry of the present devices, compressive and tensile strains lead to the decrease and increase in channel length (L), respectively. The magnitude of change can be described by $D/2R$.[4,7] Furthermore, such strains also induce the change in the thickness of polyimide gate dielectric layers due to the Poisson effect. Namely, thickness increases on compression and decreases on tension. This deformation can be estimated using the Poisson model equation, $D\nu/2R(1-\nu)$. These two changes of the structural parameters mentioned above are responsible for the intrinsic changes in DC characteristics.