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Bending and recovery tests of organic field-effect transistors

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1. Introduction

One of the notable advantages of organic materials is the mechanical flexibility, which attracts much attention in many fields [1] because there are almost no beings as essentially flexible without organic materials. In order to fully utilize such high potentiality, it was an inevitable to use flexible materials for a gate dielectric layer as well as a channel layer and a base film. Recently, we have succeeded in fabricating high-performance organic field-effect transistors (OFETs) utilized solution-processable polymer as a gate dielectric layer, which show the mobility as high as 1.4 cm^2/Vs and an on/off current ratio of above 10^7 [2]. Such flexible transistors will be widely used in a lot of applications [3, 4]. For practical use of organic transistors and its integrated circuits, it is very important to understand the strain effect for OFETs.

In this work, we have investigated the allowed bending radius of high-quality pentacene OFETs manufactured on a plastic substrate, and found that the reduction of mobility due to the application of an expansive stress with a radius of curvature (R) smaller than about 1 mm, was only 20 %. Furthermore, the mobility increase by 7 % on a compressive stress with R=4 mm. We also studied the recovery performance after stressing OFETs. No significant change and residual effect in performance has been found after the removal of the expansive and compressive bending the device down to R = 4 ± 0.5 mm (1.6 ± 0.2 % in strain). Our results can lead to a better understanding of the operation of OFETs under stress, and thereby help produce robust electronic devices that have a higher level of mechanically flexibility.

2. Experiment and discussion

High-performance OFETs with a mobility of ~ 0.3 cm^2/Vs and an on/off current ratio of above 10^5 have been fabricated by a vacuum evaporation process. First, the gate electrode was formed by thermal evaporation of 5 nm Cr and 100 nm Au through a shadow mask on a 125 mm flexible polyethylenenaphthalate (PEN) substrate. Then, a 900 nm polyimide gate dielectric layer was prepared by spin coating and a 50 nm thick pentacene film was deposited. Finally the 60 nm Au drain-source electrodes were formed using a shadow mask in a thermal evaporation system. The cross-sectional illustration is shown in Fig. 1. The channel length and width of OFETs are normally 100 μm and 1 mm, respectively. The sample has three devices, one capacitor and two transistors, which can be fabricated at the same time with identical conditions, and thus

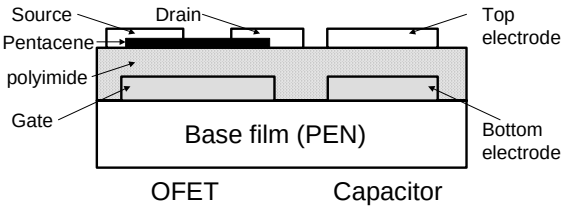

Fig. 1 The cross-sectional illustration of the organic transistor and capacitor on a PEN base film.

are strained at the same time. A capacitor plays an important part to measure the capacitance of a gate dielectric layer as bending stress. Source-Drain electrodes of two transistors are arranged precisely parallel and perpendicular to the direction of strain, respectively. This means that in one transistor, the current is applied perpendicular to the direction of strain, in the following referred to as S ⊥ I (Fig. 2 (a)), while that of the other transistor is parallel to strain, S || I, (Fig. 2 (c)). The electrical properties of the OFETs were measured using a three-lead probe and semiconductor-parameter analyzer (Agilent Technologies 4156c) while the OFETs were stressed using a stress apparatus. The apparatus consists of a variable Z-stage on a flat plate, which can provide systematic stress of a bending radius (R) variable from 20 to 0 mm. OFETs are expansively strained in plane when it is arranged at the outside of a base film. The transistors on the other side are strained in the opposite way, corresponding to a compressive stress (illustration of Fig. 2). Systematic measurements focused on the three aspects: mobility, capacitor, and DC current-voltage characteristics. All the experiments have performed in a light shielding glove box (MBRAUN, UniLab130) with

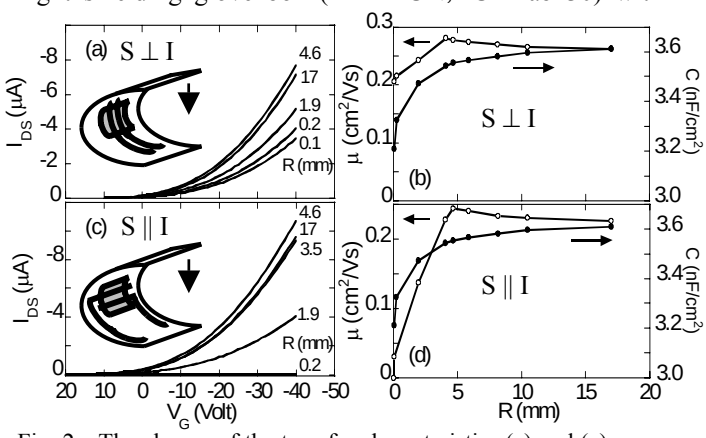

Fig. 2 The change of the transfer characteristics (a) and (c), mobility and capacitance (b) and (d) on the compressive stress (R=17 to 0 mm) at S ⊥ I (top) and S || I (bottom). A capacitor has been made near by OFETs in order to measure the capacitance of a gate dielectric layer as bending stress.

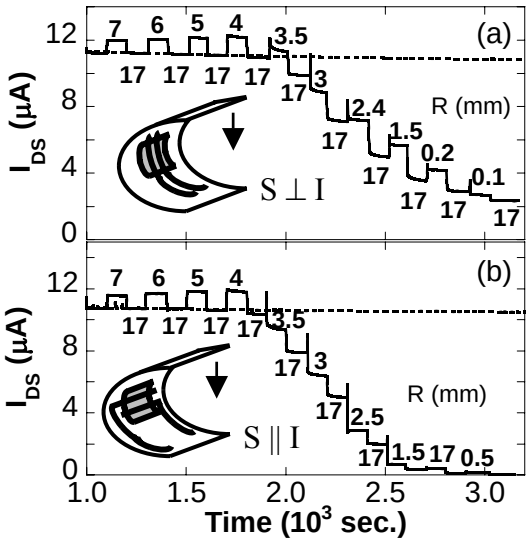

Fig. 3 Continuous I_{DS} monitoring with several compressive bending radii (0.1 mm<R<17 mm) and its relaxation (R=17 mm) at V_{DS}=V_{GS}=-40 V as a function of time (solid line). Dashed line represents I_{DS} taken without stress. (a) and (b) were taken at the geometry of S ⊥ I and S || I, respectively.

less than 1 ppm oxygen and moisture in order to exclude the atmospheric degradation from the experimental data.

Fig. 2 (a)~(d) show the change of the transfer characteristics, mobility and capacitance on the compressive strain (R = 17 to 0.1 mm) at the geometry of S ⊥ I and S || I. Note that the DC characteristics measured in the stress of R=17 mm (I_{DS} = -7.9 μA at V_{DS} = V_{GS}= -40 V, μ=0.262 cm^2/Vs) is almost the same as the data taken without stress. It is interesting that I_{DS} increases by 10 % in the bending radius from 17 to 4 mm, and the mobility also increase by about 7 % to 0.28 cm^2/Vs at the both geometry of S ⊥ I and S || I. Furthermore, OFETs can conserve their performance on the expansive and compressive strain down to R~0 mm at S ⊥ I. On the other hand, at S || I, significant damage in performance has been found when bending the device down to R ~ 1 mm.

Fig. 3 show the continuous I_{DS} monitoring with several compressive bending radii (0.1 mm<R<17 mm) and its relaxation (R=17 mm) at V_{DS}=V_{GS}=-40 V as a function of time. It should be noted that there were no significant residual effects after the removal of the bending stress down to R = 4 ± 0.5mm (1.6 ± 0.2 % in strain).

The three significant features, the increase of I_{DS} and the mobility in the compressive strain of R=17 to 4 mm, the deterioration in the both strain from R = 4 to 0.1 mm, and the conservation in performance down to R~0 mm at S ⊥ I and the complete deterioration down to R~0 mm at S || I, were observed in our experiments. The first feature can be explained by the intrinsic change in pentacene characteristic, instead of by the structural alteration. Detailed explanation was presented in [5]. As for the second feature, it is easy to assume that the extreme strain can induce the disorder and/or crack in pentacene, and extreme bending stress can also induce the crack in a base film, which leads to the disorder in channel layers. As a supplementary experiment in order to elucidate the change of conductivity in Au-electrodes, a 100-nm gold-thin film was also expansively and compressively strained on a 50-nm pentacene layer. It was found that no significant change in conductivity has been observed as far as a unidirectional bending process from R=17 to 0 mm. However, the break gold-line or the deterioration has been observed after the removal of R less than 3 mm. Here we found the fatal detachment of gold thin film (electrodes) from pentacene surface. Crack formation starts from an exfoliated area, followed by buckling. Therefore, the experimental result for the recovery performance is, to some extent, affected from the deterioration of electrodes with strain. Third feature, the conservation in performance down to R~0 mm at S ⊥ I, is striking. However, it is suspected that the homogeneity of strain might be considerably diminished in the R smaller than the size of OFETs (1 mm), resulting in conduction. Now we are under investigation as to this feature by the comparative study with S || I that is completely deteriorated and by using OFETs as small as possible to reduce the strain inhomogeneity.

Finally, we would like to remark about the outlook for getting more flexible OFETs. The most important thing we think is a reliable adhesion between pentacene and gold-electrode. Secondly, in our experiments, the critical bending radius of OFETs fabricated on 125 μm PEN base film is about 4 ± 0.5 mm, which is corresponding to the strain of 1.6 ± 0.2 %. Identifying the critical strain as 1.6 % in pentacene, the critical bending radius will be down to 1 mm by using base films of the thickness of 30 μm. Encapsulation of OFETs as a sandwich construction between a sealant and a base film must be also effective in reducing the stress.

3. Conclusions

We have performed the systematic experiment of the strain effect on the transport properties of OFETs in order to verify how much they can be bent before their performance is affected. It is found no significant residual effects were found after the removal of the bending stress up to 1.6 ± 0.2 %.

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