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Mechanical Effect of Bending on Flexible Transistors Calculated by Finite Element Calculation

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Abstract

Recent years, organic flexible devices have been extensively studied and sub-millimeter bending durability of the organic thin film devices have been achieved by placing the active layer of the transistor in the neutral strain surface. At around the neutral strain surface, an organic thin film have a high bending durability because in-plane tensile and compressive strain are cancelled each other. However, this type of highly flexible device is also destroyed or cause irreversible degradation by a hard bending. Therefore, we have carried out the finite element analysis on the flexible device. The results predicts that the most possible breaking point for this type of a flexible transistor is the boarder of organic layer and Au electrode.

1. Introduction

Recently, flexible sheet displays, radio frequency identification tags, transistors, memories, and wearable sensors are intensively developed for the ubiquitous electronics. A sufficient bending durability and repetitive stability of organic layer are necessary for flexible devices, however, the bending limitation of these devices is not depend only on the softness of the semiconductor materials. *Sekitani et al.*[1] had demonstrated that placing an organic semiconductor layer at around the neutral strain surface of the elastic film is highly effective to suppress the effect of bending on the electrical properties of semiconductor layer, and to achieve a high bending durability to 0.2 μm of bending radius on the flexible devices. In this range of hard bending, there are many possible factors to cause an irreversible degradation. For example, plastic deformation of substrate films, exfoliation or rupture of contact electrodes and gate electrode, degradation of gate insulating layer, and exfoliation or destruction of semiconductor layer. It is not easy to find a cause of device destruction in experimental way because some kinds of causes of the destruction are buried and invisible. Therefore, mechanical analysis is one better way to investigate this issue[3,4].

We have also carried out experimental works on flexible organic field effect transistors (FET) by thermal press method[2]. The thermal press method is a way to make organic thin film transistors by melting and spreading the organic materials between two flexible films. In this way, thermal press is expected as a non-solvent printing process. Moreover, structural bending stability of the flexible thin film transistor fabricated by the thermal press method is expected because the neutral strain surface is located at around the semiconductor layer by the sandwich structure of base and cover films of equal thickness. In this work, we have analyzed the strain and stress distribution in the flexible transistor using the finite element method (FEM).

2. Finite Element Analysis

The nonlinear FEM calculator of SIMULIA ABAQUS standard was used as a main computational simulator. The real structure of the flexible sheet transistor which we usually fabricate in our laboratory was modeled in the simulator. Au source and drain electrode of FET were prepared on the polyimide film covered by the parylene-C thin layer (cover film). Au gate electrode was prepared on another polyimide film, and parylene-C thin layer was formed as a gate insulating layer on the film (base film). And 80 nm thick organic semiconductor layer (Young's modulus: 13 GPa, Poisson's ratio: 0.28) is located between the base and cover film. The thickness, Young's modulus, and Poisson's ratio of thin polyimide film both in the base and cover film were 7.5 μm, 3.4 GPa and 0.30 respectively. The thickness, Young's modulus, and Poisson's ratio of parylene-C thin film were 900 nm, 2.4 GPa and 0.35 respectively. Three point bending was adopted as an force application configuration. The force was applied at the middle of the source and drain electrode.

3. Results and Discussion

Figure 1(a) shows the device structure of the flexible field effect transistor fabricated by thermal press method. Organic semiconductor layer is put between the base and cover film of equal thickness. Therefore, neutral strain surface should agree with the central plane of the semiconductor thin layer if an effect of the contact electrodes and gate electrode are not considered. However, the existence of Au electrodes are not negligible because Young's modulus of Au is high among all materials in this device. Figure 1(b) shows a result of the calculated compressive (red region) and tensile (blue region) strain. The neutral strain surface is located at the boundary of compressive and tensile strain region. The calculated neutral strain surface bends at around the contact electrode edge. The depth of neutral strain surface is affected by the existence of gate

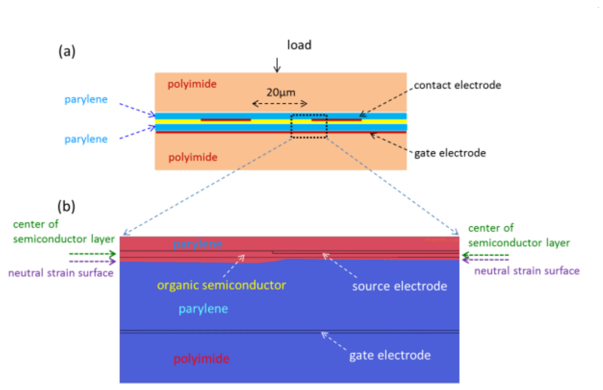

Fig.1 (a) Device structure of the flexible transistor fabricated by the thermal press method and (b) calculated compressive and tensile strain region. The compressive and tensile strain region are colored as red and blue, respectively.

electrode, and as a result, the neutral strain surface is located slightly in the parylene layer of the base film. On the other hand, in the region in which the contact electrodes exist, the effect of the gate electrode is incompletely canceled. Therefore, the neutral strain surface approaches toward the central plane of the device in the vicinity of the contact electrodes. In this way, a depth of the neutral strain surface varies due to the existence of contact electrodes and gate electrode.

Figure 2 shows a calculated strain distribution of the FET under the bending radius of 50 mm. A displayed region is the same with the Fig.1(b). Blue and red region indicate a compressive and tensile strain, respectively. Generally, strain induced in uniform film is uniform in-plane direction. Actually, in most of the region in Fig.2, the strain is uniform except for the contact electrode edge. This non-uniformity is due to the existence of the hard contact electrodes. The strain in the parylene layer at the interface of contact electrode is relatively low compared to other region because contact electrode is relatively hard among the constituent materials so that only weak strain is induced in the parylene layer at the interface of the contact electrode. The most important knowledge in engineering is that the strain inside of the organic layer is the highest around the

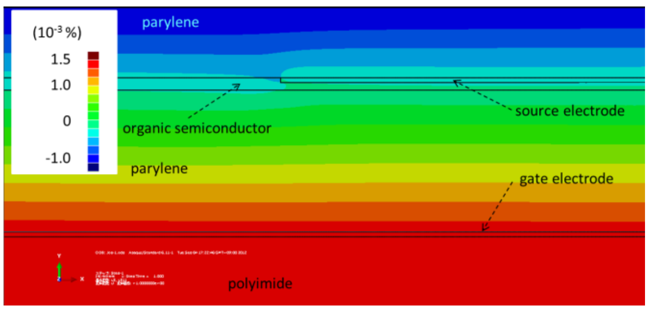

Fig.2 Calculated strain distribution of the modeled flexible thin film transistor around a contact electrode under the bending radius of 50 mm. A non-uniform distribution of the calculated strain exist at outside edge of the contact electrode.

source electrode edge. As a result, preferential folding appears at around the edge of the source electrode.

If grain boundaries of organic layer are taken into consideration, grain boundary near the contact electrode edge is the most possible breaking point under near-limit bending because this region is the weakest in the organic thin layer, and the mechanical stress is maximum at this region. If there is a grain boundary at around the contact electrode edge, concentrated stress promotes inhomogeneous bending at the grain boundary. A strain induced in the active layer is concentrated at around the electrode edge due to the inhomogeneous bending. As a consequence, a small crash at grain boundary around electrode edge begins. Then, sequential crash occurs until a sufficient relaxation of the accumulated strain, which cause a fatal and destructive folding of an organic layer.

4. Conclusions

A depth of the neutral strain surface varies by the distribution of constituent materials, especially gate and contact electrodes because these electrodes have high Young's modulus. However, this structure is still effective for thin organic layer to reduce an average strain. As a result of the inhomogeneous bending, tensile or compressive strain is concentrated in the organic semiconductor only at around the contact electrode edge. Therefore, a fatal folding of an organic layer at around the contact electrode edge will occur under the near-limit bending. Moreover, the fatal folding is assumed to initiate from grain boundaries of an organic thin film. The small crash at the grain boundary will trigger further collapse in the vicinity of the grain boundary because the mechanical strength supporting original structure is lost by the first crash.

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