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Deformation Characteristics of an Organic Thin Film Transistor

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An organic thin film transistor (OTFT) on a flexible substrate with electroplated electrodes has many advantages in the fabrication of low cost sensors, e-paper, smart cards, and flexible displays. In this study, we simulated the mechanical characteristics of an OTFT with various compressive stress conditions using COMSOL. An analysis model, which was limited to channel, source, and drain, was used to investigate deformation and internal stress concentrations. The channel length is 40 μm and the OTFT structure is a top-contact structure. The OTFT was fabricated using pentacene as a semiconducting layer and electroplated Ni as a gate electrode. The deformation characteristics of the fabricated OTFT were predicted in terms of strain and internal stress.

Keywords: OTFT, Neutral Mechanical Plane, Radius of Curvature.

1. INTRODUCTION

Organic thin film transistors (OTFTs) are of increasing interest in a wide range of applications due to their unique properties. Applications include flexible electronic systems such as radio-frequency identification tags; low-temperature and low-cost fabrication processes; light weight; mechanical flexibility; low-cost sensors; and flexible displays.[1–3] Using an OTFT is essential in achieving good mechanical flexibility in each layer with no cracking, and excellent adhesion between the layers without delamination during current flow. Thus, it is important to understand the mechanical characteristics of the OTFT device layer for effective implementation of flexible electronic systems. Until recently, experimental methods have been used to analyze the physical characteristics of thin film. Yanakai et al.[4] studied cracking phenomena in a brittle film nanostructure due to bending forces. Seol et al.[5] studied improvements in the mechanical and electrical stability of OTFTs using an adhesive organic interlayer. However, there are few studies of the bending of OTFT.

We developed an analysis method for OTFT, compared results from numerical analysis with experimental results, and interpreted the physical characteristics of compressive stress conditions.

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2. THEORY

The governing equation relating stress and strain is[6]

$$\sigma = E\varepsilon \qquad (1)$$

where σ is stress (Pa), ε is strain, and E is Young's modulus (Pa). We assume that the OTFT with a thin flat to calculate the radius of curvature, and perform the geometric calculation using dimensions of Figure 1.[7] Radius of curvature of the formula is as follows:

$$p_0 = \frac{L_0}{2pK(p)} \qquad (2)$$

where p_0 is radius of curvature, L_0 is initial length, p is expressed as a $\sin\alpha/2$, α is the angle between the ground and the bent substrate. In addition, $K(p)$ is calculated as follows:

$$K(p) = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-p^2\sin^2\theta}} \qquad (3)$$

3. EXPERIMENTAL DETAILS

Figure 2 shows the OTFT structure profile. The cross section is shown in Figure 3. OTFTs with a pentacene layer (60 nm), gold source-drain electrodes (70 nm), a cross-linked PVP (poly-4-vinyl phenol) gate dielectric

RESEARCH ARTICLE

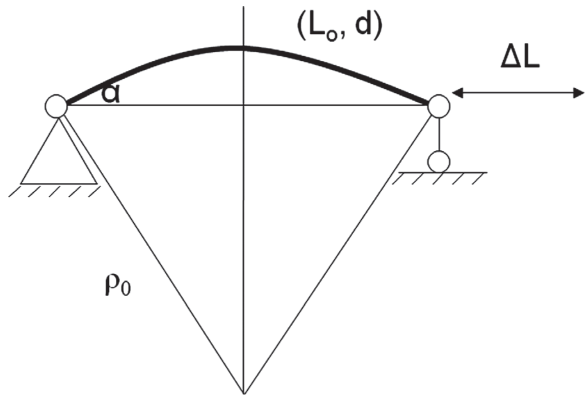

Fig. 1. The diagram of radius of curvature.

layer (400 nm), and electroplated Ni gate electrodes (150 nm) were fabricated on 125 μm PI film (Du Pont, Kapton®). We made the OTFT (5 cm) the same way as described in Ref. [4]. As shown in Figure 4, we compressed the B side until the interval d was 1.5 cm; then, the A side is pinned. We ignored initial state (deformation, twist, stress and strain) to analyze the mechanical characteristics of the OTFT. We have taken pictures of the side of channel and measured α and ε to obtain the radius of curvature.

4. NUMERICAL ANALYSIS

Numerical simulation of elastic deformation was conducted using compressive stress. We considered the multilayer structure, but the cracking and fracture of inorganic materials were ignored. In the present studies we consider using COMSOL Multiphysics 3.5a strain and internal stress.

4.1. Model and Grid Systems

Figure 5 shows a grid for our limited analysis 3-D model.[8] The channel length and width are 40 μm and 800 μm, respectively. The bonding of the inorganic and organic

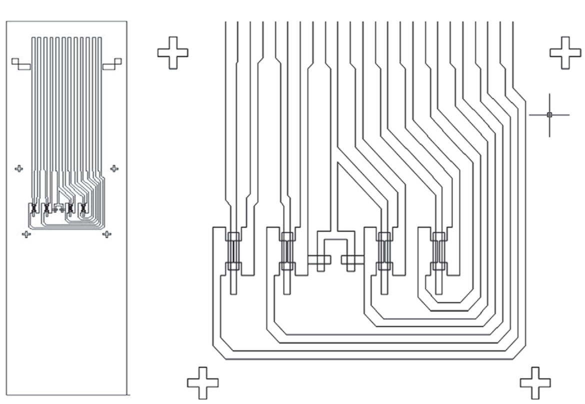

Fig. 2. Structure of OTFT on the polyimide.

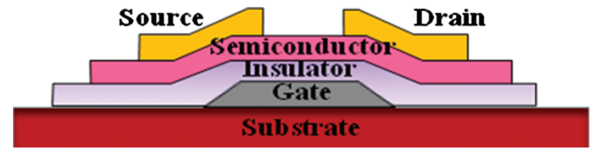

Fig. 3. Schematic diagram of the channel-cross sectional area.

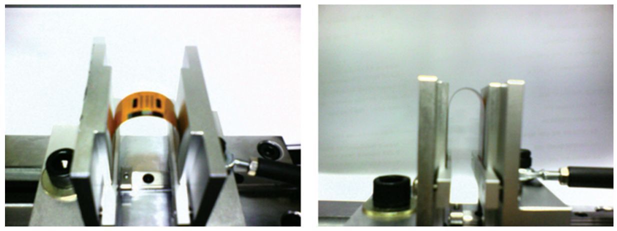

Fig. 4. Equipment for bending experiment.

parts is vulnerable to bending and has the greatest impact on performance, so the analysis model was limited to the channel, source, gate, and semiconductor layers. The domain of all elements was composed of hybrid grid systems in order to establish a discrete system for numerical simulation. We used nearly 100,000 elements for the OTFT structure, with the structural analysis setup as shown in Figure 4. The length of the x-direction was set to be 10^3 times longer than the length of the z-direction. For a narrow region, we formed at least three element layers along the vertical direction.

4.2. Analysis Condition

We use Eq. (1) to calculate substrate deformation caused by external force. As shown in Figure 5, the stress was compressed until 400 MPa. We did not consider a change in strain due to a crack or fracture. It was assumed that nickel and gold did not undergo plastic deformation because most of the OTFT organic and inorganic materials are thin.

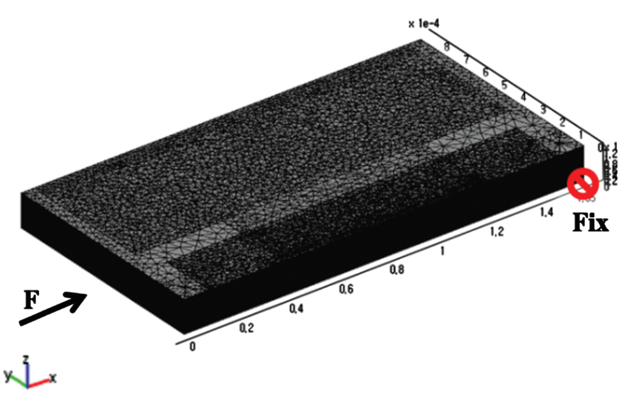

Fig. 5. Limited part of the element system for numerical analysis of the channel.

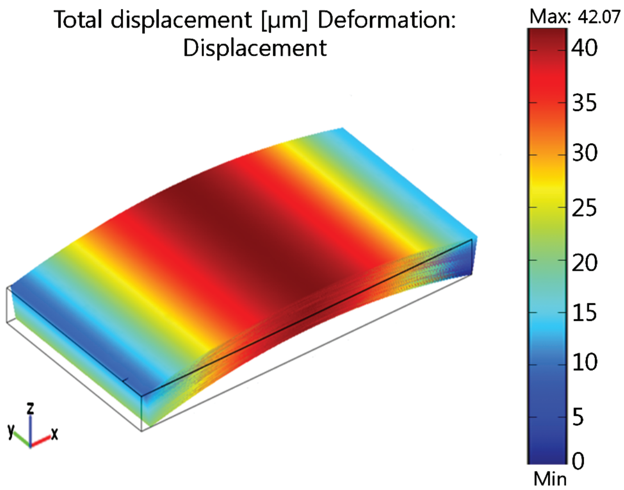

Fig. 6. Result of numerical analysis in compressive stress condition.

5. RESULTS AND DISCUSSION

Figure 6 shows the deformed numerical analysis model in a 20 MPa compressed condition. In the central part of the substrate, buckling occurs due to compressive stress in the x-axis direction. Figure 7 shows the numerical analysis results of the change in compressive stress compared to experimental results based on the strain and the radius of curvature. The radius of curvature of the flat substrate is infinite from the experiment results, but the radius of curvature will converge to 0 as strain increase. Numerical analysis results are also similar to experiment results. The average error between experimental and numerical analysis results is about 0.0199 m in the strain range from 0 to 0.05, and is about 0.00923 m in the strain range from 0.05 to 0.3. Although the average error is big in the range from 0 to 0.05, overall strain-radius trend of curvature graph is similar.

The strain direction of the x-axis is an important element in determining the direction of the stress. The neutral

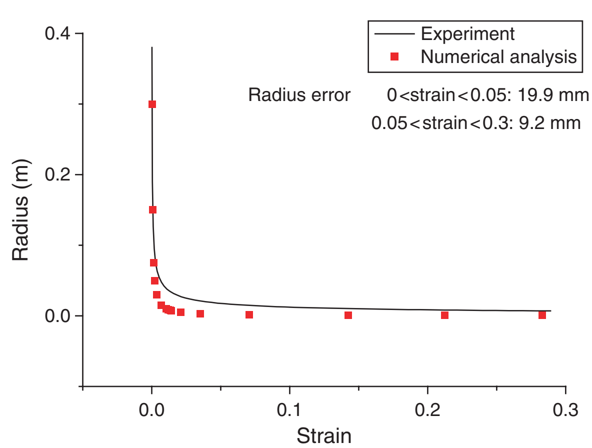

Fig. 7. Similarities between experimental and numerical analysis strain-curvature curve.

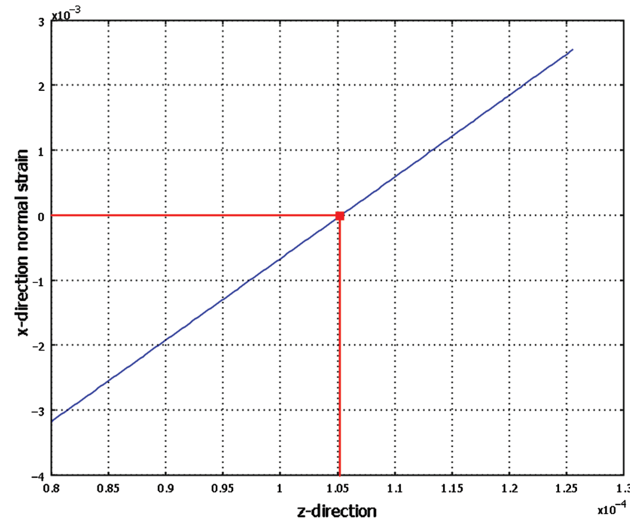

Fig. 8. Neutral plane of OTFT structure (zero strain point).

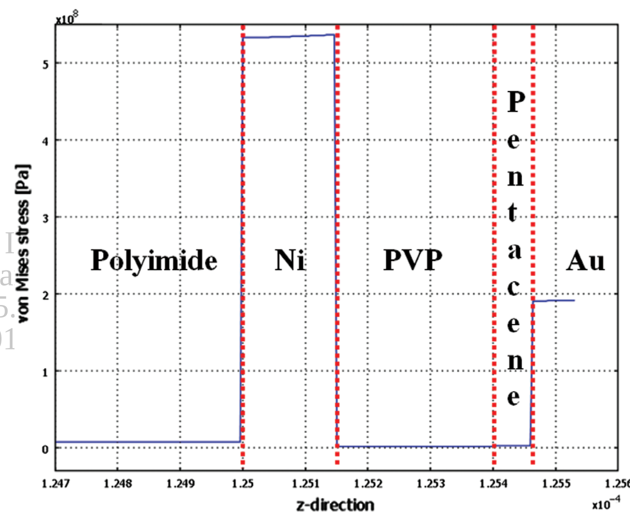

Fig. 9. Von Mises stress distribution on the device.

plane defines the position where the strains are zero. We can see the neutral plane of the OTFT in Figure 8. The neutral plane is the point 1.05 μm from the bottom. Based on the neutral plane, the tensile stress is acting on the upper layer and the compression stress is acting on the lower layer. For this reason, tensile stress is working in the electrode devices. Figure 9 shows the tensile stress distribution at the cross-sectional area of the channel along the z-direction. In general, tensile stress is concentrated on inorganic materials (Ni and Au) because the Young's modulus of inorganic material is larger than that of the organic one.

6. CONCLUSIONS

In this work, the mechanical properties of an OTFT with applied compressive stress were evaluated using the results of strain and internal stress. The following conclusions were drawn:

(1) We have established how to interpret the mechanical OTFT by comparing the experimental results and numerical analysis.

(2) Significantly numerical analysis error occurred after 2% strain, so research considering plastic deformation of inorganic materials is necessary.

(3) Tensile stress on the neutral plane is caused by the external force. Therefore, the crack may occur in the inorganic materials (Ni and Au). It is necessary to do more research with crack in the thin film.

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