Analysis of actual results of semiconductor layer thickness dependence in organic TFT using device simulation

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Abstract. Semiconductor layer thickness dependence on the electric characteristics of top-gate organic transistors using F8T2 as a semiconductor layer was studied. The field-effect mobility increased and the threshold voltage shifted towards positive with increasing semiconductor layer thickness. Device simulations were performed to analyze these experimental results. By assuming Gaussian distributed donor type traps centered at 0.2eV from the HOMO level at the interface of the semiconductor and the substrate, these experimental results were well explained.

Introduction

Organic TFTs have been widely studied as driving devices in liquid crystal displays, e-paper and other displays [1] because organic TFTs can be manufactured at low cost and with low energy consumption. However, some fundamental principles relating to organic TFTs are not sufficiently understood, such as the carrier injection mechanism from an electrode to an active layer and the transport model inside the semiconductor film.

Semiconductor device simulations are generally considered to be useful tools for analyzing device operation because they can calculate various unmeasurable parameters such as the current path or carrier distribution inside the device. Device simulations have been widely used as an analysis technique for poly-Si TFT [2], and a number of studies on organic TFTs using device simulations have been reported [3,4].

In this paper, we will show the experimental results of semiconductor layer thickness dependence in organic TFTs using F8T2 (poly-fluorene-bithiophene copolymer) as a semiconductor layer, and then we will show the analysis results of this thickness dependence by using device simulations.

Organic TFT fabrication processes and measurement results

The molecular structure of F8T2 and a sectional view of an organic TFT are shown in Fig. 1.
The organic TFTs were fabricated as follows. First, Au was deposited on a plastic substrate by vacuum evaporation. Then, the source and drain electrodes were patterned by using conventional photolithography. Next, F8T2 solution was spin-coated on the substrate and dried on a hot plate to form a semiconductor layer. We fabricated four organic TFTs in which the F8T2 thickness ranged from 8nm to 55nm by changing the F8T2 concentration. An insulating polymer solution was then spin-coated and dried to form the gate dielectric layer. The thickness of the gate dielectric layer is 800nm. Finally, a gate electrode was formed by using an inkjet-printing technique. The channel width and the channel length of the organic TFTs are 1000µm and 20µm, respectively.

Fig. 2 shows the transfer characteristics of the organic TFTs at the drain voltage of –40 V measured in nitrogen atmosphere. The field-effect mobility and the threshold voltage (Vth) extracted from the transfer characteristics in the saturation region are summarized in Table 1.

<table>
<thead>
<tr>
<th>F8T2 thickness [nm]</th>
<th>Mobility [cm²/Vs]</th>
<th>Vth [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1.6 x 10⁻³</td>
<td>-13.1</td>
</tr>
<tr>
<td>15</td>
<td>1.9 x 10⁻³</td>
<td>-10.5</td>
</tr>
<tr>
<td>25</td>
<td>2.4 x 10⁻³</td>
<td>-8.0</td>
</tr>
<tr>
<td>55</td>
<td>2.9 x 10⁻³</td>
<td>-6.2</td>
</tr>
</tbody>
</table>

Fig. 2 and Table 1 clearly indicate that the field-effect mobility increases and the threshold voltage (Vth) shifts towards positive as the semiconductor layer thickness increases. However, it is generally considered that the Vth shifts towards negative as the semiconductor layer thickness increases in the case of p-channel TFTs because there are traps inside the
semiconductor layer and the total number of traps in the channel rises with the increasing semiconductor layer thickness. Therefore, this semiconductor layer thickness dependence is different from the expected results. In order to explain these experimental results, device simulations have been performed. We considered that the semiconductor layer thickness dependence might be caused by the changes in semiconductor film quality. However, we found in other experiments that the transistors with different substrates showed the different transfer characteristics even if the semiconductor layer thicknesses were the same. These results indicate that the interface state between semiconductor and the substrate largely affect the performance of the transistor. Therefore, we conducted the following analyses assuming that the differences of transistor characteristics are due to the interface traps between the semiconductor and the substrate rather than the changes of semiconductor film quality.

**Analysis using device simulation**

We used ATLAS as a device simulation software which was provided by SILVACO Japan Co., Ltd.

![Cross-sectional structure used in this device simulation.](image)

Fig. 3: Cross-sectional structure used in this device simulation.

The simulated schematic structure of an organic TFT is shown in Fig. 3. The top-gate and bottom-contact type device configuration is like that used in actual organic TFTs. The HOMO and LUMO level values of the semiconductor are 5.4eV and 3.0eV, respectively. For the work function of the source and drain electrodes, Wf = 5.4eV were used.

![Interface state density at the back interface.](image)

Fig. 4: Interface state density at the back interface.

The assumed interface state as a function of energy at the back interface is shown in Fig. 4. The Gaussian distribution shaped donor type traps which were centered at the 0.2eV from HOMO level was used. No trap state was assumed at the front interface and inside the semiconductor layer. This trap model enabled the transfer curves to be calculated simply by changing the semiconductor layer thickness and carrier mobility. The simulated results are plotted along with the measured results in Fig. 5.
There is a good agreement of the simulation results with the measured results as noted in Fig. 5. We think that the slight deviations on the subthreshold regime are attributable to the traps at the front interface or inside the semiconductor layer in the actual organic TFTs because those traps are not considered in the device simulations. We also performed device simulations assuming that the traps were present at the interface of the semiconductor and gate dielectric (front interface) or inside the semiconductor layer. However, neither calculated result fit the measured semiconductor layer thickness dependence. These simulation results indicate that the semiconductor layer thickness dependence can nearly be explained by the presence of the traps at the back interface in the actual device.

We shall now look more carefully into the simulation results. The energy of HOMO and LOMO inside the semiconductor layer along the semiconductor depth was extracted from the simulated results at the source and drain voltage of 0 V and at the gate voltage of –40 V. The energy of HOMO and LUMO on the basis of the fermi energy is plotted in Fig. 6 as a function of distance from the back interface.

At the back interface, HOMO nears the fermi level as the semiconductor layer thickness decreases. Therefore, the number of trapped carriers at the back interface increases as the semiconductor layer thickness decreases because the traps distribute near the HOMO. This is why the Vth shifts toward negative as the semiconductor layer thickness decreases.

Meanwhile, the semiconductor layer thickness dependence on the field-effect mobility is still
unclear. Two assumptions may explain these results: (1) The carrier mobility increases as the carrier concentration increases in the organic semiconductor [5]; and (2) the effect of carrier scattering at the front interface decreases with increasing semiconductor layer thickness because it is observed from calculated results that the carrier distribution in the semiconductor becomes deeper from the front surface as the semiconductor layer thickness increases.

Summary

The semiconductor layer thickness dependence of organic transistors was studied. The measurement results show that the field-effect mobility increases and the threshold voltage (Vth) shifts towards positive as the semiconductor layer thickness increases. By using device simulations, we have successfully explained the experimental results by assuming that the traps are present near the back interface. These results indicate that not only the traps at the front interface and inside the semiconductor but also the traps at the back interface are important for analyzing the electrical characteristics of organic TFTs in detail.

Acknowledgments

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References