Dependence of electrical properties of pentacene Thin-Film Transistor on active layer thickness

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Abstract: The electrical properties of Organic thin-film transistor (OTFT) with a pentacene active layer of 3 nm and 50 nm were examined. By a new estimation method of applied voltage in channel layer of OTFT, it was found that the ratio of potential drop to lateral direction of channel at on-state is smaller than that at off-state and also that of 3 nm thickness OTFT is larger than 50 nm thickness. The on-state current of 3 nm thickness OTFT was larger than that of 50 nm thickness. The main reason of this phenomenon is due to the difference of the resistance of hole injection from Au to pentacene. The quantum-mechanical effect is also discussed.

Keywords: pentacene, OTFT, injection resistance, quantum effect

Classification: Electron devices, circuits, and systems

References
[7] D. Gupta and Y. Hong, “Understanding the effect of semiconductor thickness on device characteristics in organic thin film transistors by way of two-
1 Introduction

Recently, performance of organic thin-film transistors (OTFTs) has improved and is comparable to amorphous silicon TFTs. Therefore, it is expected that OTFTs can be applied to special applications such as flexible displays and IC tags. And also it is important to improve the driveability from a viewpoint of current drive of organic light emitting diode (OLED) displays. The characteristics of pentacene TFT has been examined [1, 2, 3, 4, 5, 6, 7]. The influence of pentacene thickness on TFT performance were reported: The bias-stress effect of OTFT has a close relation with the pentacene thickness ranging from 10 to 80 nm [5] and field-effect mobility of OTFT is affected by pentacene thickness ranging from 15 to 100 nm [6]. However, for further downsizing pentacene thickness such that quantum effect is accompanied, the TFT performance is not yet examined. Because the interface properties between the gate dielectric and pentacene affect the OTFT performance, we developed a new surface modification method of gate dielectric in pentacene TFT [8, 9]. In this work, a novel method to estimate the applied voltage for vertical and lateral direction in active layer of OTFT is presented. And, we investigate the electrical properties of the OTFTs with the pentacene film of 3 nm and 50 nm by this method.

2 Experimental methods

Si (111) wafer (n-type, 0.2 – 0.4 Ωcm) was cleaned and 100 nm thick SiO₂ film was formed by thermal oxidation at 1000°C for 540 s. Pentacene OTFT was fabricated on the SiO₂/Si substrates. The thicknesses of pentacene film were from 1 to 50 nm. These thicknesses were measured by quartz crystal unit during deposition. The pentacene films and Au electrodes were deposited by
The sample-holder temperature was RT and base pressure was lower than $2 \times 10^{-4} \text{ Pa}$. The deposition rate of the pentacene film was $0.15 \text{ nm/s}$. The deposition rate of Au film and its thickness were $1 \text{ nm/s}$ and $100 \text{ nm}$, respectively. OTFT pattern ($L = 1 \text{ mm}$ and $W = 5 \text{ mm}$) was fabricated by a metal-shadow mask during pentacene and Au deposition for pentacene thicknesses of 1, 3 and 50 nm. Dependences of drain currents ($I_D$) on drain voltage ($V_D$) and gate voltage ($V_G$) for pentacene TFT were evaluated at RT in air. The total time from the pentacene deposition to the measurement of the electrical properties for OTFT is several days, and the samples with the pentacene film were kept in the vacuum chamber of approximately $1 \text{ Pa}$. We already confirmed that the condition of the sample storage does not affect the reliability of the OTFT. The degradation of the on-state current of the OTFT is proportional to the time, and the degradation ratio was $0.2\%$ per day under the present condition. The sample for vertical direction evaluation was prepared. In this sample, the pentacene film was deposited on Si substrate (n-type, $0.2 - 0.4 \Omega\text{cm}$). Au electrode ($1 \times 2 \text{ mm}^2$) was formed on pentacene/Si substrate. The electrical property was measured from Au electrode (ground) to Si substrate. From IV characteristic of this sample and the $I_D - V_D$ for OTFT, the applied voltages for both directions are estimated precisely. For OTFT, the contact area of Au and pentacene side wall in the source/drain area is neglected, because the area ratio of the side wall and front surface of pentacene film in the source/drain is $5 \times 10^{-5}$. In addition, film properties were measured by atomic force microscope (AFM) and X-ray diffraction (XRD) in the region between source and drain electrodes for pentacene thicknesses of 1, 3 and 50 nm.

### 3 Results and discussion

Fig. 1 (a), (b) and (c) are AFM images of pentacene films on SiO$_2$/Si substrate and XRD patterns of them with variety of film thicknesses. The grain size of pentacene film with $50 \text{ nm}$ thickness is approximately 1.5 times larger than that with $3 \text{ nm}$ thickness. The XRD patterns show that the intensity of (001) peak corresponding to the standing molecules increases proportional to pentacene thickness and also the (110) peak corresponding to the lying molecules were observed at $50 \text{ nm}$ thickness. These results indicate that the thin pentacene films with thicknesses of 1, 3 and 5 nm were formed successfully as well as the thick films of 10 and 50 nm, and also the carrier transported through standing molecules at the SiO$_2$/Pentacene interface. The $I_D - V_D$ and $I_D - V_G$ characteristics of the OTFTs with the pentacene thicknesses of $3 \text{ nm}$ and $50 \text{ nm}$ are shown in Fig. 2 (a) and (b). The driverbility of the OTFT with $3 \text{ nm}$ thickness is superior to that with $50 \text{ nm}$ thickness. The $I_D$ was increased with decreasing film thickness. Although this tendency agrees to the reported result [6] that $I_D$ increases with decreasing the thickness of the pentacene fabricated on the SiO$_2$, it is not clarified in our experiment that the reason of the dependency of $I_D$ on the pentacene thickness is due
to its grain size. The grain size of pentacene film with 50 nm thickness is larger than that with 3 nm thickness. In the present case, the grain boundary is not the dominant factor to affect the resistance. For polycrystalline pentacene, the crystal orientation as well as the grain size influences the field effect mobility [9].

The OTFT with 1 nm thickness did not show the transistor characteristic. It is considered that the crystal grain did not link other grains because the $R_a$ roughness was as same as film thickness. Next, the origin of this phenomenon is discussed from viewpoints of both distribution of the drain voltage and quantum-mechanical effect. Fig. 3 (a) and (b) show $I_D - V_D$ characteristics of OTFT and IV characteristic (thick solid curve) of evaluation sample for vertical direction transport with a structure of Au/pentacene (3 nm)/Si and calculated potential distribution at interface between pentacene film and $\text{SiO}_2$.

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**Fig. 1.** AFM images of pentacene films with film thicknesses of 3 nm (a) and 50 nm (b) and XRD patterns of then with variety of film thicknesses (c).

**Fig. 2.** $I_D - V_D$ characteristics (a) and $I_D - V_G$ characteristics (b) of the pentacene OTFTs with thickness of 3 and 50 nm.
film at \( V_G = -20 \) V (on state) for pentacene film thickness of 3 and 50 nm. First, the applied voltage for vertical and lateral direction in active layer of OTFT was estimated. The detailed method to give the potential drop to lateral direction of the channel, \( V_{\text{lateral}} \), and the potential drop from Au electrode to the channel, \( V_{\text{vertical}} \), which are shown in the inset, is explained. “A” is defined as the point on the \( I_D - V_D \) characteristic at the drain voltage of \(-20\) V. By tracing the IV characteristic of Au/pentacene (3 nm)/Si sample so as to intersect the point “A”, the potential drop between A and B shown by the arrow (→) is equal to \( V_{\text{vertical}} \), and therefore, \( V_{\text{lateral}} \) is given by \( V_D - 2V_{\text{vertical}} \).

The lateral and vertical voltage for on and off state are summarized as follows in case of \( V_D = -20 \) V. For off state with \( V_G \) of 20 V, \( V_{\text{lateral}} \) and \( V_{\text{vertical}} \) are 19.6 and 0.2 V for 3 nm thickness and 19.8 and 0.1 V for 50 nm thickness, respectively. \( V_D \) was almost applied to lateral direction. For on state with \( V_G \) of \(-20\) V, \( V_{\text{lateral}} \) and \( V_{\text{vertical}} \) are 15 and 2.5 V for 3 nm thickness and 12 and 4 V for 50 nm thickness, respectively. The voltage of vertical direction, which includes the potential drop due to the contact resistance, was increased compared with off state. It was found that the ratio of potential drop to lateral direction of channel at on state is smaller than that at off state and also that of 3 nm thickness OTFT is larger than 50 nm thickness. The resistance of hole injection from Au to pentacene for OTFT with 3 nm thickness is smaller than that with 50 nm. The injection resistance include both the contact resistance at Au/pentacene and the hopping resistance of pentacene from Au electrode to the channel. This effect may contribute to the increase of on-state current for OTFT with 3 nm thickness as compared to that with 50 nm. Second, the phenomenon is discussed by quantum-mechanical effect. The active layer is thin enough to form quantum well as shown by the energy diagram of the cross section perpendicular to the channel. The quantum level at SiO\(_2\)/Pentacene interface was also calculated at \( V_G = -20 \) V. The dielectric constant and effective mass of pentacene film were assumed to 6.7 [10] and 1.55m\(_0\) [11], respectively. From this estimation, a triangle potential is formed at thickness of 3 nm and the energy levels of ground and excited states were 0.03, 0.11 and 0.24 eV. It is considered that peak of the wave function at these levels are located away from the SiO\(_2\)/Pentacene interface and therefore the probability of the carrier scattering decreases. This effect also increases the on-state current of OTFT with 3 nm thickness compared with those with 50 nm thickness. The threshold voltage of OTFT with 3 and 50 nm thicknesses are 19 and 9 V, respectively. This tendency of the threshold voltage is also reasonable considering the effect such as quantization of energy for electron and hole [12]. The idea that the quantum-mechanical effect appeared at room temperature in the present structure is thought to be correct considering the small carrier density in the intrinsic pentacene and the calculated potential difference between each quantum level.
Fig. 3. $I_D - V_D$ characteristics of OTFT and IV characteristic (thick solid curve) of evaluation sample for vertical direction transport with a structure of Au/pentacene (3 nm)/Si (a) and calculated potential distribution at interface between pentacene film and SiO$_2$ film at $V_G = -20$ V (on state) (b).

4 Conclusion

Carrier transport in OTFTs was investigated by the new estimation method of applied voltage in channel layer of OTFT with pentacene film thicknesses of 3 and 50 nm. It was found that the resistance of hole injection from Au to pentacene with 3 nm thickness on SiO$_2$ gate dielectric is smaller than that with 50 nm. The resistance consists of the contact resistance at Au/Pentacene
and the hopping resistance of pentacene from Au electrode to channel. This effect may contribute to the increase of $I_D$ for OTFT with 3 nm thickness as compared to that with 50 nm. This phenomenon was also discussed from a viewpoint of the carrier localization at the triangle potential and, as a result, the decrease of scattering probability at the interface. OTFT with a thin active layer equal to several nano meter is very attractive because of an improvement of the driverbility and the field effect mobility.