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Small contact resistance using doping for top contact type organic transistor with liquid crystalline organic semiconductor, Ph-BTBT-10

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Abstract

We have investigated the characteristics of top contact type field effect transistors (FETs) fabricated with liquid crystalline organic semiconductor, 2-decyl-7-phenyl-benzothienobenzothiophene (Ph-BTBT-10) and p-type dopant, tetrafluoro-tetracyano-quinodimethane (F_4-TCNQ). We found that contact resistances between semiconductors and electrodes reduce from 3.0 kΩcm to 1.2 kΩcm by contact doping with F_4-TCNQ, and to 0.9 kΩcm by thermal annealing the films where dopants diffuses from surface to bulk. In addition, we found that the both FETs fabricated with contact doped and thermal annealed showed high mobility of 12.0 cm²/Vs. We conclude that it is important technique for thermal diffusion of dopants to improve characteristics of FETs.

1. Introduction

Uniform and flatness crystalline organic semiconductor thin films can be formed by a solution process by utilizing its liquid crystallinity. In the liquid crystalline organic semiconductor, 2-decyl-7-phenyl-benzothienobenzothiophene (Ph-BTBT-10, shown in Fig.1(a)), the uniform polycrystalline thin films prepared by spin coating have high field-effect mobility over 10 cm^2/Vs [1]. On the other hand, the problems of bottom-gate and top-contact (BGTC) type field effect transistor (FET) using Ph-BTBT-10 are high contact resistance and high threshold voltage. If the contact resistance between organic semiconductor and electrodes is high, it is difficult to operate in short channel FET, and if the threshold voltage is high, FETs do not operate in low voltage region. In particular, the organic semiconductor materials for FETs are not amorphous materials but crystal line materials, which show high mobility and anisotropy carrier transport properties. In the case of the polycrystalline thin film of Ph-BTBT-10, the molecules stand vertically to substrates and the carrier transport in parallel direction to substrate is good because of the favorable alignment of π-π stack of Ph-BTBT π-conjugated core moiety, while carrier transport in perpendicular direction to substrates is bad. In the bottom-gate and top-contact type FET, the contact resistance is increased by carrier transport in the vertical direction from source/drain electrodes to the channel on the gate insulator surface *via* the film as shown in Fig. 1(e).

In order to reducing contact resistance, vacuum-evaporated acceptor dopants on the surface of organic semiconductors is a common technique [2]. In this case, it is difficult to reduce the vertical resistance in the film because the dopant molecules are simply located on the surface of the organic semiconductor layer. On the other hand, in liquid crystalline organic semiconductor, Ph-BTBT-10, the flexible alkyl chain can move relatively freely at the liquid crystal phase temperature, it is expected that the acceptor dopant molecules are easily diffused in Ph-BTBT-10 thin films, and the vertical resistance of thin films can be reduced.

Therefore, in this study, tetrafluoro-tetracyano-quinodimethane (F_4-TCNQ, shown in Fig.1(b)) which was one of the most representative p-type dopants, was deposited between the Ph-BTBT-10 and the source/drain electrodes for BGTC type FET. We aimed to reduce the contact resistance by diffusing F_4-TCNQ molecules into the Ph-BTBT-10 thin films under the electrode by thermal annealing.

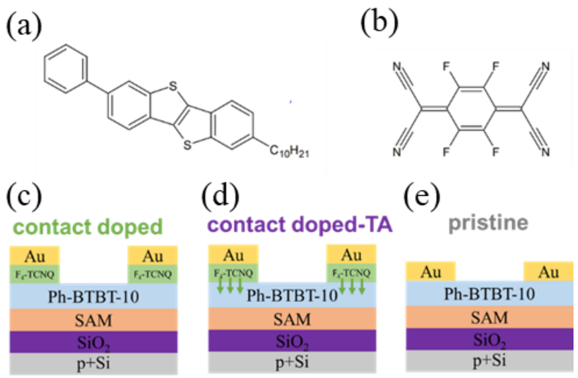

Fig.1 (a) Chemical structure of (a) Ph-BTBT-10 and (b) F4-TCNQ. (c)-(e) The structure of top contact type FET.

2. Experimental method

In BGTC type of FETs as shown in Fig. 1 (c)-(e), polycrystalline thin films of Ph-BTBT-10 were fabricated by spin-coating on the substrate at a given temperature of SmE phase and at 3000rpm for 30 seconds. We used a 0.5wt% p-xylene solution of Ph-BTBT-10. The substrate was modified with self-assembly monolayer (SAM), dodecyltriethoxysilane. F_4-TCNQ was heated at 160℃ for 10 minutes and vapored in petri dish with a height of a few centimeters and deposited on the thin films of Ph-BTBT-10 using shadow mask to be patterned under source/drain electrodes. When F_4-TCNQ heated, substrates temperature was at about 70℃. Au with thickness of 30nm was vacuum evaporated at 3×10^{-4} Pa to form source/drain electrodes using shadow mask. Before depositing F_4-TCNQ, Ph-BTBT-10 was thermal annealed at120℃ for 5minutes, and after depositing Au, the thin films were thermal annealed at 90℃ for 5 minutes.

The FET performance was characterized by two source measurement units (8282, ADCMT). The mobility (μ) was estimated by plotting the square root of the source-drain current (I_{ds}) as a function of gate voltage (V_g) and using the equation for the saturation regime,

$$I_{ds} = \frac{WC_i}{2L}\mu(V_g - V_{th})^2 \qquad (1)$$

where C_i is the capacitance of gate insulator, V_{th} is the threshold voltage and L/W is channel length/width.

3. Result and discussion

In order to evaluate the contact resistance of these devices, we fabricate several transistors which have difference channel length from 30 μm to 80 μm. The contact resistance was estimated by transfer length method (TLM) from the transfer characteristics in the linear region of the devices with channel lengths of 30 , 40 , 50 , 60 , and 80 μm as shown in Fig.2(a). The contact resistances were 3.0 kΩcm for the pristine device as shown in Fig.1(e), but decreased to 1.2 kΩcm for the contact-doped-device as shown in Fig.1(c). It is suggested that the contact doping reduced the contact resistance between organic semiconductor and source/drain electrodes. Furthermore, the contact doped device was further annealed at 90°C for 5 minutes to further reduce the contact resistance to 0.9 kΩcm. From the reducing of contact resistances by thermal annealing, it is suggested that F_4-TCNQ dopants are diffused into the Ph-BTBT-10 thin film below the electrode by short thermal annealing at 90 ºC for 5minutes.

We evaluated the gate voltage dependence of the contact resistance of each device as shown in Fig.2(b). In contact doped devices and pristine devices, the contact resistance rapidly increased at low gate voltage, but in contact doped and thermal annealing devices, the contact resistances were constant at about 1 kΩcm at even low gates voltage, which strongly indicates the improvement of contact characteristics.

The transfer characteristics of device with channel length of 80 μm in the saturation region are shown in Fig. 3 (a). It showed a high mobility of over 10 cm^2/Vs with and without doping as shown in Table.1. Compared with the pristine-de vice, the threshold voltage of the contact-doped-device was reduced from -49 V to -36 V, and the SS was reduced from

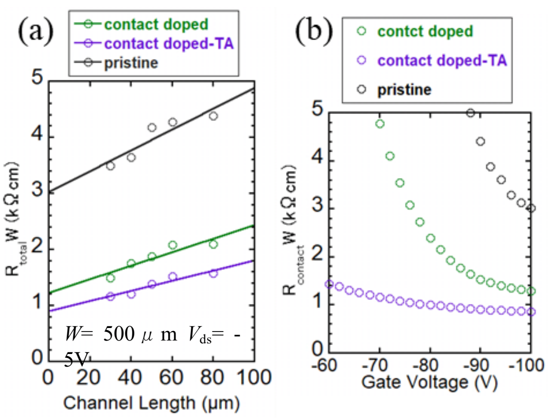

Fig.2 (a) The evaluation of contact resistance of FET by TLM (a) Total resistance as a function of channel length. (b) Contact resistance as a function of gate voltage

5.0 V/dec. to 1.3 V/dec. Furthermore, the threshold voltage was further reduced to -16 V by annealing the contact-doped-device at 90℃ for 5 minutes. It is suggested that F_4-TCNQ molecules diffuse to Ph-BTBT-10 thin films not only under source/drain electrodes but also near gate insulators because generated carriers work as not only increasing conductivity of Ph-BTBT-10 thin film under source/drain electrodes but also reducing the interface traps at the gate insulator/Ph-BTBT-10 semiconductor interface.

The shorter channel devices, 30 μm, also show similar characteristics to device of longer channel length, 80 μm, as show in Fig. 3(b) and Table 1. The mobility in FET with shorter channel length, 30 μm, is smaller than that with longer channel length, 80 μm. These results indicate that we need further improvement of contact properties in shorter channel length FET.

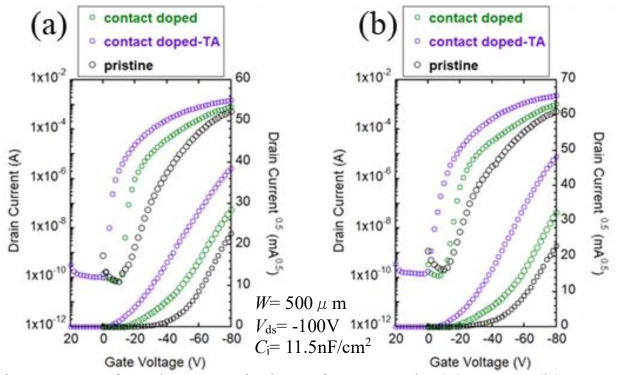

Fig.3 Transfer characteristics of FET. L is (a)80μm (b) 30μm.

Table I Characteristics of FETs (L=80μm/30μm Vds= -100V)

	μ (cm^2/Vs)	V_{th} (V)	SS (V/dec.)
Contact-doped	12.5/7.7	-36/-42	1.3/2.2
Contact-doped-TA	12.0/8.6	-16/-22	1.1/2.2
Pristine	15.9/6.3	-49/-50	5.0/4.8

4. Conclusion

We fabricated bottom-gate and top-contact type FETs using polycrystalline thin films of Ph-BTBT-10 inserted p-type dopant, F_4-TCNQ into the semiconductor/electrode interface and then annealed the FET to reduce the contact resistance. The contact resistances were evaluated by TLM, and the contact resistances were successfully reduced from 3 kΩcm to 1.2 kΩcm by contact doping, and further reduced to 0.9 kΩcm by thermal annealing. These results come from the diffusion of dopant molecules in the Ph-BTBT-10 thin films by thermal annealing. The contact doped and thermal annealing, which had the lowest contact resistance, showed good FET characteristics with high mobility,12.0 cm^2/Vs, good threshold voltage -16 V, and small subthreshold swing 1.1 V/dec.. Thermal diffusion of dopants is an important technique for improving FET characteristics.

References

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