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Fabrication of field effect transistor based on deuterated glycinium phosphite crystal and pentacene

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Abstract

We have fabricated a field effect transistor (FET) based on an organic ferroelectric insulator, a deuterated glycinium phoshite (D-GPI) and a pentacene film and have investigated electrical properties on the prepared FETs. It is observed that the FET based on D-GPI and pentacene film becomes a normally-on p-type FET. Moreover, we have observed that the gate electric field E_G dependence of drain current i_{DS} in the prepared FET displays the characteristics of hysteresis. This result indicates that the FET based on the D-GPI and pentacene film shows a memory effect. Furthermore, we have found that the area of the i_{DS}-E_G hysteresis curve in the FET based on the D-GPI and pentacene film is determined by the magnitudes of the spontaneous polarization and coercive electric field of the D-GPI. On the basis of these results, it is also ascertained that the spontaneous polarization in the D-GPI insulator is responsible for the surface charge at the interface between the D-GPI and pentacene film. Furthermore, these results indicate that the values of i_{DS} and the formation of the depletion layer largely depend on the spontaneous polarization and coercive field of the D-GPI insulator. Moreover, it is deduced that we can control the appearance of the depletion layer by controlling the deuterated ratio, which is responsible for the spontaneous polarization and coercive field of GPI insulator.

Keywords: molecular conductor, field effect transistor, memory effect

1. Introduction

Pentacene ($C_{22}H_{14}$), a molecular material, displays interesting properties; for example, (1) a pentacene film prepared by sublimation on a glass substrate becomes a highly orientated layered film [1], (2) pentacene film doped with donor or acceptor becomes the intercalation compound, (3) the electric conductivity becomes more than 10^8 times larger than that of pure pentacene film by doping of a dopant to pentacene film [2]. In addition to these researches, several efforts have been devoted to the fabrication of the field effect transistor that is based on pentacene film. The pentacene FET exhibits a high-carrier mobility, such as 1.0 cm^2/Vs, due to the achievement of the smooth interface between the pentacene and the insulator [3-6]. Recently, a pentacene FET based on triglycine sulfate (TGS) and pentacene film has been fabricated [7,8]. The characteristic feature of this FET is that it displays a memory effect. However, in an FET based on a TGS and pentacene film, we cannot control electrical properties such as the value of a drain-source current i_{DS} and a threshold voltage V_t accompanied by the formation of a depletion layer, because the values of the spontaneous polarization and coercive electric field in TGS are determined by the crystal structure at room temperature. Recently, it has been reported that in an organic ferroelectric material GPI (glycinium phosphite), which displays ferroelectricity below 224.7 K, the ferroelectric phase transition temperature is raised by replacing hydrogen with deuterium. The 100% deuterated D-GPI undergoes a ferroelectric phase transition at 323.0 K and displays ferroelectricity at room temperature [9]. Therefore, we can prepare an organic insulator such that the ferroelectric phase transition temperature can be changed by controlling the ratio of deuteration. The spontaneous

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polarization P_s and coercive electric field E_c at room temperature depends on the ferroelectric phase transition temperature. Therefore, by using the D-GPI insulator in which P_s and E_c are controlled, it is expected that we can control electrical properties such as the values of i_{DS} and V_t in the pentacene FET. In the present study, we have fabricated the pentacene FET based on the organic ferroelectric insulator D-GPI and pentacene and have then investigated its electrical properties.

2. Sample Preparation and Experimental Procedure

2.1 Organic ferroelectric insulator : the deuterated GPI (D-GPI)

Single GPI crystals were grown from an aqueous solution at 304 K by the slow evaporation method. A single D-GPI crystal was dissolved with deuterium and single GPI crystals were prepared by its recrystallization. It is known that the D-GPI crystal undergoes a ferroelectric phase transition from a low-temperature ferroelectric phase to a high-temperature paraelectric phase. In the ferroelectric phase, the D-GPI crystal belongs to the monoclinic system with space group $P2_1$ and has a spontaneous polarization parallel to the monoclinic *b* axis [10]. The ferroelectric phase transition temperature of D-GPI was measured using the LCR meter (HP 4284 A: Hewlett Packard). The ferroelectric phase transition temperature was controlled by the change in the ratio of deuteration. Large optical-quality transparent crystals were grown. As described above, the spontaneous polarization is parallel to the monoclinic *b* axis. Therefore, we have prepared the D-GPI crystal cut along the *b* plate as the organic ferroelectric insulator of the FET.

Figure 1 shows the *D-E* hysteresis loop of the 90% deuterated single D-GPI crystal in which the ferroelectric phase transition temperature is 37 °C. With regard to this measurement, an electric field of 1.3 kV/cm was applied at room temperature. The *D-E* hysteresis loops of the D-GPI single crystal were measured at room temperature using the standard Sawyer-Tower method. As shown in Fig. 1, the 90% deuterated single D-GPI crystal displays ferroelectricity at room temperature.

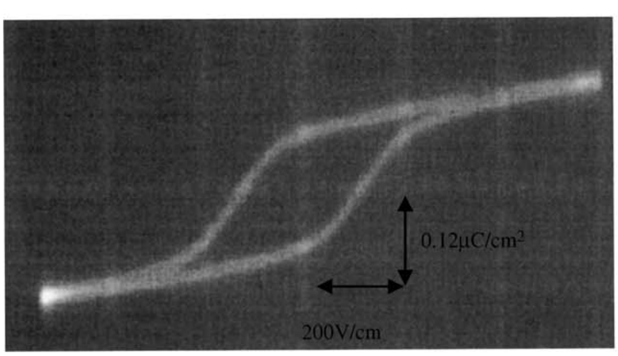

Figure 1 *D-E* hysteresis loop in the 90% deuterated D-GPI

The spontaneous polarization P_S and the coercive field E_C become 0.12 μC/cm^2 and 120 V/cm, respectively. We can observe the *D-E* hysteresis loop in the 75% deuterated D-GPI. In this sample, P_S and E_C are 0.053 μC/cm^2 and 90 V/cm, respectively. This result indicates that the surface charge of approximately 10^{11}/cm^2 is generated on the surface of dielectric material. This surface charge is 10^2 times larger than that of the dielectric material with a relative permittivity of 10. Therefore, in the case of the FET based on pentacene film and the D-GPI, we can easily induce the depletion layer at the interface between the ferroelectric D-GPI and the semiconductor with a low gate-bias voltage. Moreover, as described above, the feature of the D-GPI by which it can change the ferroelectric phase transition temperature by changing the ratio of deuteration is of prime interest. In the present study, we have prepared a 90% deuterated D-GPI and a 75% deuterated D-GPI. The ferroelectric phase transition temperatures of samples A and B are 37 °C and 20 °C, respectively.

2.2 Fabrication of PEN-FET

Figure 2 shows the shape of the FET prepared in the present study. The single D-GPI crystal was approximately 0.02-cm thick. Pentacene films were prepared on the single D-GPI crystal by sublimation in the vacuum of 10^{-6} Torr. The deposition rate was 0.5 nm/s and the thickness of the film was 500 nm. The substrate temperature was 304 K. In the present study, a 20-nm thick Au film was used as the drain, source and gate electrodes. The interval between the drain and source electrodes was 25 μm. In the present paper, the FET based on the 90% deuterated D-GPI and pentacene film is referred to as sample A, and the FET based on the 75% deuterated D-GPI and pentacene film is referred to as sample B. The electrical properties of the FET prepared in this study were analysed with a low noise multimeter (Keithley: 2010) and a programmable DC source (Keithley: 2400).

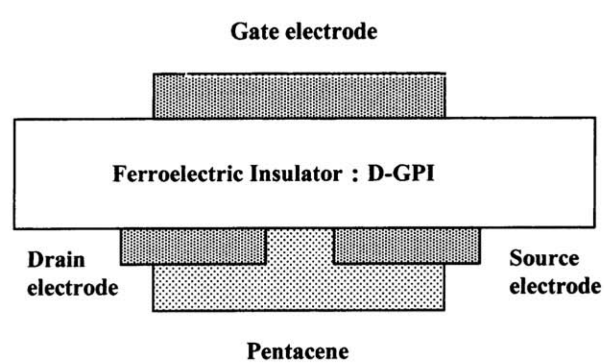

Figure 2 Cross-sectional view of the FET