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Nonvolatile organic field-effect transistors fabricated on Al foil substrates

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Abstract: We fabricated metal-ferroelectric-metal capacitors and bottom-gate, top-contact nonvolatile ferroelectric transistors (FeFETs) using poly-(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] and poly(3-hexylthiophene) (P3HT) on aluminum foil substrates. P(VDF-TrFE) and P3HT layers were formed by the sol-gel method at low temperature. FeFETs on Al foil substrates exhibited similar properties compared with those fabricated on other rigid and flexible substrates.

Keywords: ferroelectric, nonvolatile transistor, flexible, P(VDF-TrFE), P3HT

Classification: Electron devices, circuits and modules

References

[1] R. C. G. Naber, *et al.*: "High-performance solution-processed polymer ferroelectric field-effect transistors," Nat. Mater. **4** (2005) 243 (DOI: 10.1038/nmat1329).

[2] J. H. Kim, *et al.*: "Fabrication and electrical characteristics of metal-ferroelectric-semiconductor field effect transistor based on poly(vinylidene fluoride)," Jpn. J. Appl. Phys. **47** (2008) 8472 (DOI: 10.1143/JJAP.47.8472).

[3] Y. Miyata, *et al.*: "Low-voltage operation of Si-based ferroelectric field effect transistors using organic ferroelectrics, poly(vinylidene fluoride–trifluoroethylene), as a gate dielectric," Jpn. J. Appl. Phys. **55** (2016) 04EE04 (DOI: 10.7567/JJAP.55.04EE04).

[4] B. Jin, *et al.*: "Fabrication and electrical characteristics of P(VDF-TrFE) films on Si(100) substrates using Cyanoethyl Pullulan buffer layers," Ferroelectrics **484** (2015) 25 (DOI: 10.1080/00150193.2015.1059196).

[5] G. G. Lee, *et al.*: "The flexible non-volatile memory devices using oxide semiconductors and ferroelectric polymer poly(vinylidene fluoride-trifluoro-ethylene)," Appl. Phys. Lett. **99** (2011) 012901 (DOI: 10.1063/1.3608145).

[6] G. G. Lee, *et al.*: "Low-voltage operation of ferroelectric gate thin film transistors using indium gallium zinc oxide-channel and ferroelectric polymer poly(vinylidene fluoride–trifluoroethylene)," Appl. Phys. Express **4** (2011) 091103 (DOI: 10.1143/APEX.4.091103).

[7] M. G. Kim, *et al.*: "Solution-processed organic ferroelectric field-effect transistors on ultra-flexible substrates," Appl. Phys. Lett. **109** (2016) 163502 (DOI: 10.1063/1.4964459).

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[8] I. Bae, *et al.*: "Organic ferroelectric field-effect transistor with P(VDF-TrFE)/PMMA blend thin films for non-volatile memory applications," Curr. Appl. Phys. **10** (2010) e54 (DOI: 10.1016/j.cap.2009.12.013).
[9] S. W. Jung, *et al.*: "Flexible nonvolatile organic ferroelectric memory transistors fabricated on polydimethylsiloxane elastomer," Org. Electron. **16** (2015) 46 (DOI: 10.1016/j.orgel.2014.08.051).
[10] K. H. Lee, *et al.*: "Flexible low voltage nonvolatile memory transistors with pentacene channel and ferroelectric polymer," Appl. Phys. Lett. **94** (2009) 093304 (DOI: 10.1063/1.3089379).
[11] B. Gburek and V. Wagner: "Influence of the semiconductor thickness on the charge carrier mobility in P3HT organic field-effect transistors in top-gate architecture on flexible substrates," Org. Electron. **11** (2010) 814 (DOI: 10.1016/j.orgel.2010.01.023).
[12] K. J. Baeg, *et al.*: "High mobility top-gated poly (3-hexylthiophene) field-effect transistors with high work-function Pt electrodes," Thin Solid Films **518** (2010) 4024 (DOI: 10.1016/j.tsf.2010.01.026).
[13] F. Xia and Q. M. Zhang: "Schottky emission at the metal polymer interface and its effecton the polarization switching of ferroelectric poly(vinylidenefluoride-trifluoroethylene) copolymer thin films," Appl. Phys. Lett. **85** (2004) 1719 (DOI: 10.1063/1.1786364).

1 Introduction

Recently, various next-generation memories were investigated. Among them, ferroelectric random access memory (FeRAM) needs to be developed because of its nonvolatile property. Many researchers tried to realize and enhance the properties of ferroelectric field effect transistors (FeFETs). In particular, polyvinylidene fluoride (PVDF)-based polymer, organic ferroelectric material can be formed with a simple process. Because of this simple process, it is widely used as a gate insulator. PVDF, poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)], and poly(vinylidene fluoride-tetratrifluoroethylene) [P(VDF-TeFE)] can be used with the sol-gel method at low temperature and have impressive polarization characteristics [1].

At first, FeFETs using PVDF-based polymer on Si substrates were investigated. Many researchers have studied metal-ferroelectric-Si (MFS) and metal-ferroelectric-insulator-Si (MFIS) structures [2, 3, 4]. However, Si-based FeFETs do not have the flexibility that is essential for state-of-the-art flexible electronics. Therefore, non-Si-based FeFETs are an emerging technology.

In non-Si-based FeFETs, semiconductor materials have an important role. There is a trade-off relation between performance and cost of fabrication. FeFETs with metal-oxide semiconductors exhibit high on/off ratios and mobility [5, 6]. However, they require an expensive process such as sputtering or high temperature annealing, and only a few semiconductor materials can be deposited by a solution process. High temperature makes these FeFETs difficult to fabricate on flexible substrates because of the poor heat resistance of the substrates. On the other hand, organic semiconductors displayed poor properties compared with metal-oxide semiconductors. Nonetheless organic semiconductors can be formed at low temperatures, and most of them can be deposited by a solution process. Thus, many

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researchers used organic semiconductors when they fabricated FeFETs on flexible substrates [7, 8, 9, 10].

For these reasons, we used organic regioregular poly(3-hexylthiophene) (P3HT), which is a popular semiconductor material in organic field-effect transistors and can be formed easily by the spin-coating method. Thus, it doesn't require high-cost vacuum equipment [11, 12]. In addition, it can be deposited on the P(VDF-TrFE) layers without any interference between two layers. By using the spin-coating method only, they can show their original characteristics on P(VDF-TrFE) layers.

We fabricated flexible FeFETs on Al foil. Al foil has merit of flexibility because of ultraflexible and ultrathin properties. It can be bent with small bend radius and even folded. It serves as bottom gate electrode in itself as well. Thus, an expensive fabrication step, evaporation of bottom gate, can be removed. In spite of these merits of Al foil, it is difficult to fabricate FeFETs on it owing to difficulty in handling: Al foil wrinkles easily and cannot be flattened during fabrication. In this study, we solved this problem by adopting Al foil tape, which is attached to thick paper without wrinkles.

2 Experimental procedure

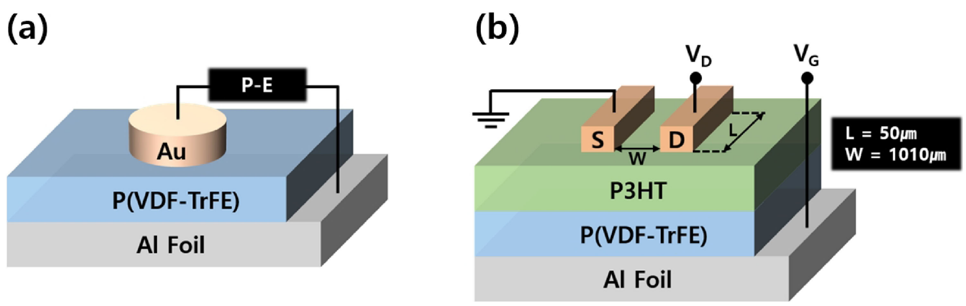

Fig. 1. (a) Structure of a metal-ferroelectric-metal capacitors and (b) FeFETs on Al foil substrate.

In this work, we first demonstrate the polarization characteristics of capacitors with P(VDF-TrFE) insulators. Fig. 1(a) shows the structure of the capacitors. We dissolved P(VDF-TrFE) powder (purchased from Piezotech) with a 75/25 VDF/TrFE molar ratio in dimethylformamide at a concentration of 4 wt%. It was spin-coated at 3000 rpm for 30 s on Al foil tape. To enhance crystallinity, the films were heat-treated at 140 °C for 60 min on a hot plate in an ambient atmosphere. Then, Au electrodes were deposited in a vacuum chamber.

As shown in Fig. 1(b), FeFETs using P3HT were also fabricated. On the P(VDF-TrFE) layers, we formed P3HT channel layers by the spin-coating method. P3HT was dissolved in chloroform at a concentration of 0.5 wt%. P3HT films were also annealed at 120 °C for 60 min. Au channels were evaporated in a vacuum chamber (length: 50 μm, width: 1010 μm). Then, we fabricated FeFETs on Al/Si (rigid) substrates in the same way to compare them with the FeFETs on Al foil substrates.

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3 Results and discussion

Fig. 2 shows the polarization–voltage (*P*–*V*) characteristics of the capacitors on the Al foil, which were measured by a ferroelectric materials analyzer (Precision LC, Radiant Technologies Inc.). We applied voltage from −15 V to 15 V, and the measuring frequency was 100 Hz. Although MFM capacitors were fabricated not on a rigid substrate but on flexible Al foil, they exhibit a hysteresis curve with a high remnant polarization value (approximately 7 μC/cm^2). The slight asymmetry of the curve is caused by the difference in work functions of the Al foil and Au electrode we deposited [13]. The remnant polarization value is sufficient to be used as a gate insulator of an FeFET, and we confirmed that P(VDF-TrFE) layers can be formed even on Al foil.

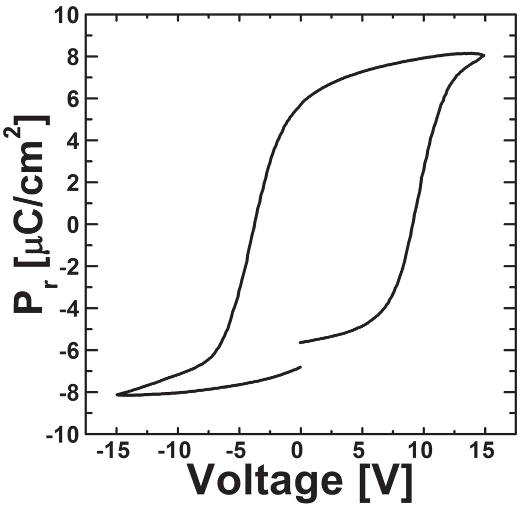

Fig. 2. Polarization-voltage curve of metal-ferroelectric-metal capacitor fabricated on Al foil.

Fig. 3 is a photo of the FeFET fabricated on Al foil. The FeFET is flexible and sufficiently thin to be folded, unlike other flexible substrates. We measured the input characteristics of the FeFET by using a semiconductor characterization system (Keithley, 4200-SCS).

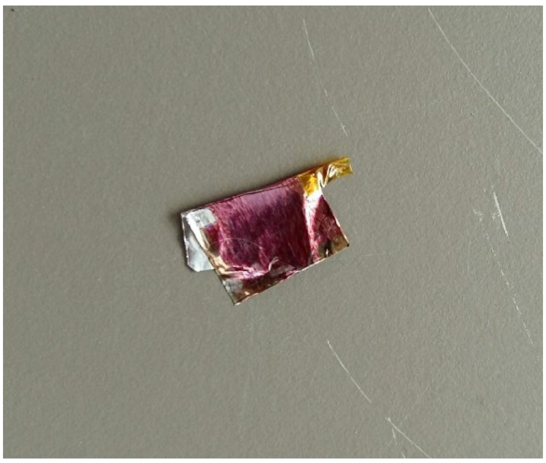

Fig. 3. Photo of FeFET fabricated on Al foil substrate and folded.

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Figs. 4(a) and (b) show the drain current-gate voltage (I_D–V_G) curves of the FeFETs on the Al foil and Si substrates, respectively. The applied gate voltage was from 15 V to −15 V, and the drain voltage was fixed at −10 V. Although they show a little difference in the off-current region, their characteristics in the on-current region are almost similar. The on-current of the FeFETs on Al foil is approximately -2.1×10^{-5}, and the off-current is approximately -2.0×10^{-8}. On the Si substrates, the on- and off-currents are approximately -2.2×10^{-5} and -1.2×10^{-8}, respectively. This means that having an on/off ratio on the order of 10^3, both FeFETs show desirable performance with nonvolatile properties.

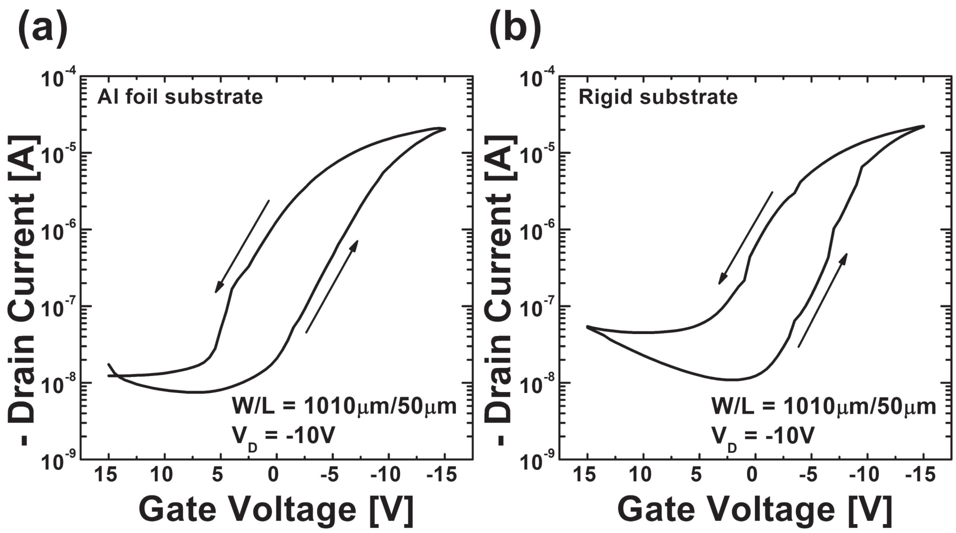

Fig. 4. Drain current–gate voltage curve of FeFET on (a) Al foil substrate and (b) rigid substrate.

Using these curves, we calculated the memory window value, which is an important characteristic of FeFETs. We obtain the value by calculating the threshold shift. As shown in Fig. 5, we used an extrapolation method to calculate the threshold voltage. For the FeFETs on Al foil and rigid substrates, the threshold voltage shifted by approximately 7–8 V when we applied voltage from 15 V to −15 V.

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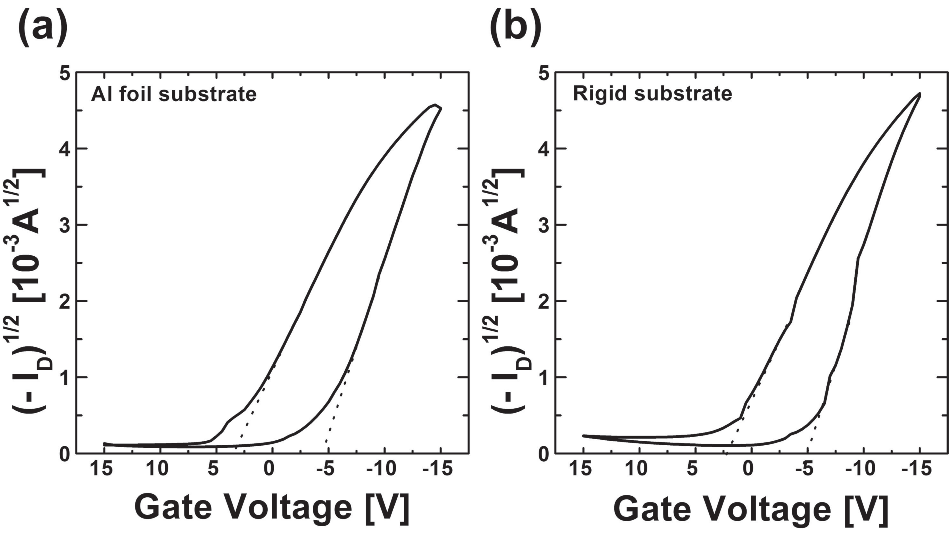

Fig. 5. $(-I_D)^{1/2}$–V_G curves of FeFETs fabricated on (a) Al foil and (b) rigid substrate.

4 Conclusion

FeFETs using P(VDF-TrFE) and P3HT were fabricated on Al foil substrates for the first time. We demonstrated the ferroelectric property of P(VDF-TrFE) layers on Al foil by fabricating a capacitor. The ferroelectricity of P(VDF-TrFE) led to non-volatility in the FeFETs. Compared with FeFETs on rigid substrates, FeFETs on Al foil show good performance. The measured on/off ratio is approximately 10^3, and the threshold voltage (which is known as the memory window) is 7–8 V.

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