Performance improvement of pentacene based organic field-effect transistor with HfON gate insulator

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Abstract: Pentacene based organic field-effect transistors (OFETs) with SiO₂ and HfON gate insulators have been fabricated, and the effect of deposition temperature and deposition rate on the grain sizes of pentacene films was investigated. It was found that the grain sizes of pentacene films increase with increasing deposition temperature and decreasing deposition rate. Due to the increase in grain size, pentacene based OFET with HfON gate insulator shows enhanced electrical properties, such as a low subthreshold swing of 0.14 V/decade and a large on/off current ratio of 1.1×10^4 . Moreover, the hole mobility of pentacene based OFET with HfON gate insulator is $0.39 \text{ cm}^2/\text{Vs}$ at an operating voltage of -2 V .

Keywords: pentacene, OFETs, HfON, grain size, electrical properties

Classification: Electronic materials, semiconductor materials

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1 Introduction

Organic field-effect transistors (OFETs) have attracted considerable interest in the electronics industry due to their potential advantages such as light-weight, high flexibility, low cost, and high volume throughput compared to conventional Si devices [1]. Pentacene is one of the most widely investigated organic semiconductors for OFETs because of its high intrinsic hole mobility [2]. But the operating voltages required to achieve high hole mobility (μ) from pentacene based OFETs are generally higher than 20 V. In order to address this issue, high-k gate insulators were employed in the pentacene based OFETs [3, 4]. However, high-k gate insulator usually has a large surface energy [5], which results in small grain size for pentacene films. Due to

the small pentacene grain size, the μ of pentacene based OFET with high- k gate insulator is generally low. In addition to the carrier mobility, subthreshold swing (SS) and on/off current ratio (I_{on}/I_{off}) must also be optimized to ensure proper operation of the OFETs. However, trap states are usually formed by air exposure and fabrication process at grain boundaries and the gate insulator interface [6, 7, 8, 9], which will decrease I_{on}/I_{off} and increase SS of organic devices. Although some reports revealed that large I_{on}/I_{off} can be obtained by using hybrid gate insulators, such as PMMA/ZrO₂ and PMMA/PVA/SiO₂, the SS values for these kinds of OFETs are high [10, 11], which would result in low switching speed when used in logic circuit.

In this paper, we reported that the grain sizes of pentacene films increase with increasing deposition temperature and decreasing deposition rate. Due to the increase in grain size, pentacene based OFET with HfON gate insulator exhibits enhanced electrical properties, such as a low SS of 0.14 V/decade, a large I_{on}/I_{off} of 1.1×10^4 and a high μ of 0.39 cm²/Vs at an operating voltage of -2 V.

2 Experimental procedure

In our investigation, pentacene based OFETs were fabricated on n⁺-Si(100) substrates with a top-contact bottom-gate device geometry [12]. HfON gate insulators were fabricated on n⁺-Si(100) substrates by electron cyclotron resonance (ECR) plasma sputtering [13]. Firstly, n⁺-Si(100) substrates were chemically cleaned followed by the formation of chemical oxide layers, and the thickness of chemical oxide layer is 0.7 nm. Then, HfN thin films (5 nm) were deposited on the substrates by ECR plasma sputtering at room temperature, and the gas pressure in the chamber during the deposition was 0.19 Pa (Ar/N₂ flow rate: 25/1 sccm). In order to form HfON films, the HfN films were oxidized by ECR Ar/O₂ plasma irradiation, and the gas pressure for oxidation was 0.18 Pa (Ar/O₂ flow rate: 20/8 sccm). Finally, HfON films were annealed by silicon-wafer-covering rapid thermal annealing (SWC-RTA) method at 800°C for 1 minute in N₂ ambient [14]. The final thickness of HfON gate insulator was 9.5 nm.

For comparison, SiO₂ (9.5 nm) films were grown on n⁺-Si(100) substrates by wet thermal oxidation at 850°C. After the fabrication of gate insulators, pentacene films (from Aldrich without any purification) were deposited on gate insulators by thermal evaporation at room temperature and 70°C, respectively. The pressure in the chamber was 2×10^{-6} Torr. The deposition rate was changed from 0.1 to 0.01 nm/s. The thickness of the pentacene films was 20 nm. After the pentacene deposition, Au electrodes were evaporated through a shadow mask to form source and drain electrodes for OFETs. Channel width (W) and length (L) of the OFETs were 1400 and 50 μ m, respectively. Atomic force microscopy (AFM) was employed to characterize the morphologies of pentacene films, and the electrical properties of the OFETs were evaluated by semiconductor parameter analyzer (Agilent 4156C). And the measurements were carried out in air.

3 Results and discussion

Figures 1(a) and 1(b) show the AFM images of pentacene films deposited on SiO₂ and HfON gate insulators at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s. Clearly, the grain size for pentacene film deposited on HfON gate insulator is much larger than that for pentacene film deposited on SiO₂ gate insulator. The average grain sizes for pentacene films deposited on SiO₂ and HfON gate insulators at this condition are 0.9 and 2.5 μm , respectively.

The average grain sizes of pentacene films deposited on SiO₂ and HfON gate insulators as a function of deposition temperature and deposition rate are summarized in Figs. 2(a) and 2(b). It is found that the grain sizes of pentacene films increase with decreasing the deposition rate when the deposition temperature is kept at room temperature. The grain sizes of pentacene films further increase when the deposition temperature increases to 70°C. And pentacene films deposited at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s show the largest grain size. However, the increment in grain size for pentacene film deposited on HfON gate insulator

Fig. 1. AFM images of pentacene films deposited on (a) SiO₂ and (b) HfON gate insulators at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s. The scanning size is 5 × 5 μm .

Fig. 2. Average grain sizes of pentacene films deposited on (a) SiO₂ and (b) HfON gate insulators as a function of deposition temperature and deposition rate.

Fig. 3. I_D - V_G characteristics of pentacene based OFETs with (a) SiO_2 and (b) HfON gate insulators, in which pentacene films were deposited at room temperature and a deposition rate of 0.1 nm/s. I_D - V_G characteristics of pentacene based OFETs with (c) SiO_2 and (d) HfON gate insulators, in which pentacene films were deposited at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s.

is more remarkable than that for pentacene film deposited on SiO_2 gate insulator. It is attributed to the lower surface energy of HfON compared to SiO_2 [5, 15].

Figure 3 shows the I_D - V_G characteristics of pentacene based OFETs with SiO_2 and HfON gate insulators, in which pentacene films were deposited at different conditions. The off current (I_{off}) for OFETs in this paper is defined as the drain current at zero gate bias. As shown in Fig. 3, the fabricated OFETs can successfully operate at a low operating voltage of -2 V. However, the magnitude of I_{off} shows a dependence on the gate insulator, and pentacene based OFET with HfON gate insulator shows a lower I_{off} compared to pentacene based OFET with SiO_2 gate insulator. For pentacene films deposited at room temperature and a deposition rate of 0.1 nm/s, the μ , $I_{\text{on}}/I_{\text{off}}$ and SS of OFET with SiO_2 gate insulator are $0.16 \text{ cm}^2/\text{Vs}$, 15 and 0.93 V/decade , respectively. The performance of the pentacene based OFET can be enhanced by using HfON gate insulator, which leads to a μ of $0.19 \text{ cm}^2/\text{Vs}$, an $I_{\text{on}}/I_{\text{off}}$ of 5.0×10^3 and a SS of 0.18 V/decade . From Fig. 3, the electrical properties of the pentacene based OFETs are found to

be enhanced by increasing deposition temperature and decreasing deposition rate. For pentacene films deposited at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s, OFET with SiO₂ gate insulator shows a μ of 0.25 cm²/Vs, an I_{on}/I_{off} of 17 and a SS of 0.44 V/decade, respectively. The μ and I_{on}/I_{off} of pentacene based OFET with HfON gate insulator increases to 0.39 cm²/Vs and 1.1×10^4 , respectively, while the SS of the OFET decreases to 0.14 V/decade.

As shown in Figs. 2(a) and 2(b), the average grain sizes for pentacene films deposited on SiO₂ and HfON gate insulators at room temperature and a deposition rate of 0.1 nm/s are 0.3 and 0.6 μ m, respectively. It is known that the grain boundaries in pentacene films can act as trapping sites [6], and such trapping sites may lead to low μ , high SS and small I_{on}/I_{off} [7, 8, 9]. On the other hand, the average grain sizes for pentacene films deposited on SiO₂ and HfON gate insulators at a deposition temperature of 70°C and a deposition rate of 0.01 nm/s are 0.9 and 2.5 μ m, respectively. Due to the increased grain sizes of pentacene films, the grain boundaries which act carrier traps are reduced. Therefore, the electrical properties of pentacene based OFETs are improved greatly by increasing deposition temperature and decreasing deposition rate. However, because of the remarkable increase in pentacene grain size, pentacene based OFET with HfON gate insulator shows excellent electrical properties, such as a lower SS of 0.14 V/decade, a larger I_{on}/I_{off} of 1.1×10^4 and a higher μ of 0.39 cm²/Vs at an operating voltage of -2 V. Meanwhile, due to the larger pentacene grain size, the hole mobility of pentacene based OFET with HfON gate insulator in this paper is higher than the results (0.17 cm²/Vs) reported by Tsai *et al.* [15].

4 Conclusion

In conclusion, pentacene based OFETs with SiO₂ and HfON gate insulators have been fabricated, and the effect of deposition parameters on the grain sizes of pentacene films was investigated. Our results show that the grain sizes of pentacene films increase with increasing deposition temperature and decreasing deposition rate. However, the grain size for pentacene film deposited on HfON gate insulator is larger than that for pentacene film deposited on SiO₂ gate insulator. The large grain size of pentacene film should play an important role in the good electrical properties of pentacene based OFET with HfON gate insulator.

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