Comparison of Ionic Liquid and Ion-Gel Top-Gate MoS₂ Field-Effect Transistors

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ABSTRACT

Polymer electrolytes and ionic liquids (ILs) have attracted significant interest in applications as gate dielectrics. In this study, we fabricated top-gated molybdenum disulfide (MoS₂) thin-film transistors using IL and ion-gel (IG) gate dielectrics. Room-temperature Raman spectra measurements indicated a dominant peak spectral emission at 358 cm⁻¹ (E_{2g}^1) and 406.44 cm⁻¹ (A_{1g}) associated with bilayer MoS₂ films. The fabricated thin-film field-effect transistors (FET) with IG gate dielectric exhibited band transport with a highest mobility of 0.5 cm²/V·s, and a poor I_{ON}/I_{OFF} ratio of ~10. By contrast, the FET with IL gate dielectric exhibited a 3400 % improvement in terms of the mobility (17.9 cm²/V·s), and a 1000 % improvement of the I_{ON}/I_{OFF} ratio (~100).

Keywords: MoS₂, Top-gate, Field-effect transistor, Ionic liquid, Ion-gel

1. Introduction

The field effect in top-gate field-effect transistor (FET) configurations comprised of ion-gels (IGs) and ionic liquids (ILs) as gate dielectrics have attracted considerable attention, owing to their flexibility, printability, and high ionic conductivity. Moreover, these devices have the potential to be implemented as two-dimensional materials. IL-gated two-dimensional (2D) molybdenum disulfide (MoS₂) FETs have been fabricated previously [1–3]. Despite the excellent performance of IL-gated FETs, ILs have significant limitations for practical device applications, owing to the volatility. However, IGs can be suitably implemented in applications, as the gel state is significantly less volatile compared to ILs. IG is advantageous in that it has the flexibility of a polymer dielectric and the high capacitance of an ionic liquid. In this study, we report the growth of bilayer MoS₂ thin films on silicon dioxide/silicon (SiO₂/Si) substrates using metal-organic vapor phase epitaxy (MOVPE). Furthermore, to compare the IG and IL dielectrics, we fabricated top-gate MoS₂ FETs with IG and IL as gate dielectrics by forming metal electrodes through an electron beam evaporator using a shadow mask on the obtained MoS₂ thin film.

2. Experiments and discussion

MoS₂ thin films with thickness of a few atomic layers were grown on a SiO₂/p-Si substrate via MOVPE, with a chamber pressure of 10 Torr and susceptor temperature of 400 °C. Hydrogen sulphide and molybdenum hexacarbonyl were used as sources of S and Mo, respectively. The Raman spectra of the bilayer MoS₂ films were recorded using a dispersive Raman microscope (Thermo Scientific). Excitation was induced using a 532-nm laser diode. Moreover, X-ray photoemission spectroscopy (XPS, SES-100, VG-Scienta) was used to record the Mo and S binding energies in the bilayer MoS₂ films.

The ILs considered in this study were 1-Ethyl-3-methylimidazolium bis (trifluoromethylsulfonyl) imide (EMIM-TFSI), purchased from Sig-

ma Aldrich. Poly (styrene-block-methyl methacrylate-block-styrene) (PS-PMMA-PS) triblock copolymer was purchased from Polymer Source, Inc. The IG solution was fabricated by mixing the copolymer PS-PMMA-PS with the IL EMIM-TFSI in dichloromethane as a solvent. Then, the mixtures were baked at 70 °C in a vacuum chamber at a pressure of 10⁻⁶ Torr for 24 h, in order to evaporate the molecular moisture of IL and IG solvent. Then, the IL was immediately transferred for storage in a glove box sustained under a controlled argon atmosphere. All experiments in this study were conducted under dry atmospheres of either argon (glove box), oxygen, or vacuum.

Source and drain electrodes were deposited on the multilayer MoS₂ film using an electron beam evaporator. Further, the 5-nm Ti and 50-nm Au films were deposited separately using a Kapton tape and copper line mask to fabricate a channel of area of 50 × 2,000 μm². The weight ratio of the polymer, IL, and solvent was sustained at 0.7:9.3:20. These solutions were drop-cast onto a SiO₂/Si substrate with the MoS₂ film and electrodes. A top-gate electrode comprised of a gold/tungsten tip directly in contact with the IL and IG was used to measure the electrical transport properties. Electrical measurements of the device were performed using an in-house four-probe station with a commercial parameter analyzer (2636 B, Keithley Inc.) at 300 K.

3. Results and discussion

Figure 1 shows the Raman spectrum of the MoS₂ thin films deposited using MOVPE, which confirms the number of atomic layers. In particular, the peak positions of the observed 358 cm⁻¹ (E_{2g}^1), 406.44 cm⁻¹ (A_{1g}), and the Raman peak difference ($\Delta \sim 21.21$ cm⁻¹), establish our films as bilayer MoS₂ thin films, when compared with previously reported results [1–3]. The results of the XPS measurement confirmed the existence of S and Mo. The 162.05 and 160.85 eV peaks observed in the S2p-scan results in Fig. 2(a), are associated with S2p_{1/2} and S2p_{3/2}, respectively, and are distinctive properties of MoS₂. The

Figure 1. Raman spectra results of the MoS₂ bilayer film.

peak observed at 223.5 eV is generated by S2s. As shown in Fig. 2(b), the Mo3d_{5/2} and Mo3d_{3/2} peaks appear at 228 and 231.15 eV, respectively, which is in good agreement with previously reported results on MoS₂ [3–5].

We fabricated IL and IG-gated FET devices to study the electrical characteristics of the bilayer MoS₂ thin film, as shown in the schematic diagram in Fig. 3(a). The transfer properties of a top-gate MoS₂ FET with IL and IG are plotted in Figs. 3(c) and 3(d), respectively. Here, the electrical transports of the MoS₂ thin films exhibit the characteristics of n-type metal-oxide semiconductor-FETs operating at relatively low gate voltages (~1 V). However, in the case of MoS₂ thin films, the device on-off current ratio, I_{ON}/I_{OFF} , is very low (~2.4). Furthermore, we observed a large hysteresis effect for both FETs with IL and IG. This hysteresis in the counter-clockwise direction can be attributed to the slow movement of ions in the ionic liquid [6–8]. We calculated the mobility of our MoS₂ device with IL and IG dielectrics as 17.9 and 0.5 cm²/V·s, respectively. In these calculations, we considered the slope of the transfer properties for the gate voltage in the range of 1–2 V using the conventional equation for a linear area

$$I_D = \frac{\mu W V_D C_i}{L} (V_G - V_{th}) \quad (1)$$

where μ is the field-effect mobility; I_D is the drain current; W and L are the channel width and length, respectively; C_i is the specific capacitance of the dielectric; which was 4.24 and 1.66 $\mu\text{F}/\text{cm}^2$ for the IL and IG, respectively; V_D is the drain voltage; V_G and V_{th} are the gate and threshold voltages, respectively. As shown in Fig. 3(b), poor mobility arises from the high contact resistance. Notably, the mobility of the MoS₂ FET with IL dielectric is significantly improved compared to that of the IG dielectric. This behavior can be attributed to the decrease in the capacitance of the IG dielectric with increasing polymer content [9].

Figure 2. XPS results of (a) S2p-scan and (b) Mo3d-scan obtained for a MoS₂ bilayer sample.

Figure 3. (a) Schematic image of a top-gate FET with MoS₂. (b) I_{ds} - V_{ds} characteristics of the MoS₂ FET. Electrical transport characteristics of top-gate MoS₂ FET designed using (c) IL and (d) IG dielectrics at room temperature (300 K).

4. Conclusions

In conclusion, we fabricated atomic-layer MoS₂-based top-gate FET devices using IL and IG dielectrics. Raman spectroscopy and XPS measurements confirmed the atomic bilayer MoS₂ structure. The MoS₂ FET with IL indicated the best performance in terms of mobility and I_{ON}/I_{OFF} ratio between the IL and IG dielectrics, which stems from the low capacitance of the IG dielectric compared to that of the IL. The MoS₂-based FET with IL contact exhibits a mobility of 17.9 cm²/V·s and an I_{ON}/I_{OFF} ratio of 10². Our results indicate that the selection of dielectrics can dramatically affect the electrical transport characteristics of 2D MoS₂-based top-gate FET devices. Thus, our results can act as benchmarks for the development of high-performance 2D-MoS₂-based flexible and printable electronic devices.

Conflicts of Interest

The authors declare no conflicts of interest.

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