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Insulator-to-Metal transition in polycrystalline MoS_2 films induced by electric double layer gating

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Abstract

We fabricate electric double layer transistors of large-area polycrystalline molybdenum disulfide (MoS_2) monolayers and observe insulator-to-metal transition (IMT). Although IMT and insulator-to-superconductor transition is already performed in tiny single-crystal MoS_2, we expect that this study will be the first mille stone for future large-area applications of electric field induced superconductors.

1. Introduction

Graphene-like structure of transition metal dichalcogenides (TMDs) have attracted attentions because their electronic properties enable the investigation of interesting physical phenomena and offer a significant potential for future applications. In particularly, electric double layer transistors (EDLTs) of single-crystal molybdenum dichalcogenide films (MoX_2, X = S, Se, Te) has been achieved the electric field induced superconductivity [1] and the peculiar role of strong spin orbit interactions due to high density carrier accumulation [2]. However, until now, the electric field induced insulator-to-metal transition (IMT) in MoX_2 has only been observed in extremely tiny single-crystalline samples and, for future applications, it is very important to apply this technique into large-area samples, they are grown by chemical vapor deposition (CVD) methods. Although we have already succeeded in the fabrication of EDLTs by CVD-grown TMD films [3-10] and observed the metallic behavior above 220 K in CVD-grown MoS_2 films previously [10], the metallicity at low temperature, which is the first important step for the electric field induced superconductivity, have not yet been clarified. Therefore, in this research, we tried to measure field effect induced transition in polycrystalline MoS_2 monolayer films at 1.9 K.

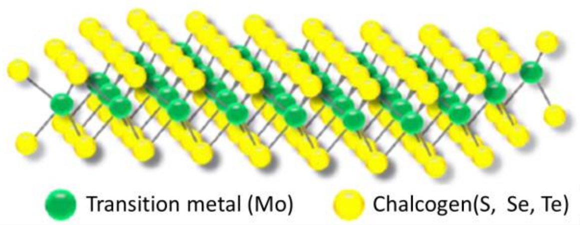

Fig1. Schematic view of TMD monolayer

2. Experiment

Device fabrication

Polycrystalline large-area MoS_2 monolayer films were synthesized onto sapphire substrates by CVD method [3]. Figure 1 shows schematic structure of MoS_2 monolayer. After the sample growth, as shown in Figure 2, we fabricated the EDLT. The Au/Ni source/drain electrodes were deposited on MoS_2 monolayer films. Au side gate electrodes were also deposited on sapphire substrates to disconnect electrically between source/drain and gate electrodes. As the gate dielectric materials, we selected the ion gel electrolyte, which is mixture of ionic liquid organic polymer. In this study, we used ionic liquid of DEME-TFSI, N,N-Diethyl-N-methyl-N-(2-methoxyethyl)ammonium-bis(trifluoromethylsulfonyl)imide. The organic polymer is poly(vinylidene-fluoride-co-hexafluoropropylene), so called P(VDF-HFP). Finally, we spin-coated ion gel films on MoS_2 films.

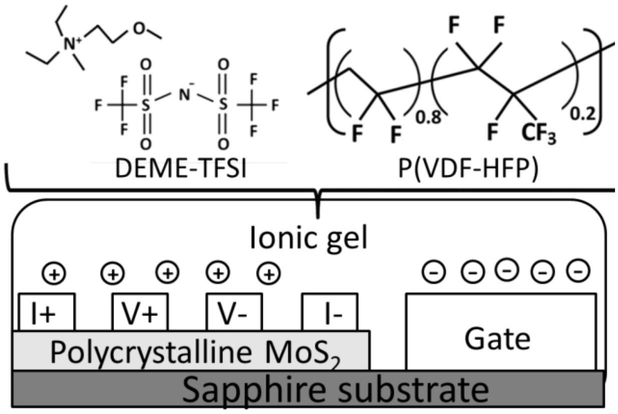

Fig2. Device structure of large-area MoS_2 EDLTs

Measurement

We used semiconductor parameter analyzer to measure transistor characteristics and physical properties measurement system for temperature control.

Results and Discussion

Figure 3 shows the gate voltage dependence of sheetresistance in polycrystalline large-area MoS_2 monolayer. These measurements were carried out in He and at 240K. Although the applied gate voltage is limited by the electrochemical windows of the ionic liquid, we can apply high gate voltage without device degradation at low temperature, possibly owing to the decreased electrochemical activity of the ionic liquid [11]. These characteristics show that our device works as n-type transistor, as reported previously [3-10]. Very importantly, at gate voltage of 6 V, the observed resistance becomes less than the quantum resistance, which strongly suggest the field-effect induced IMT.

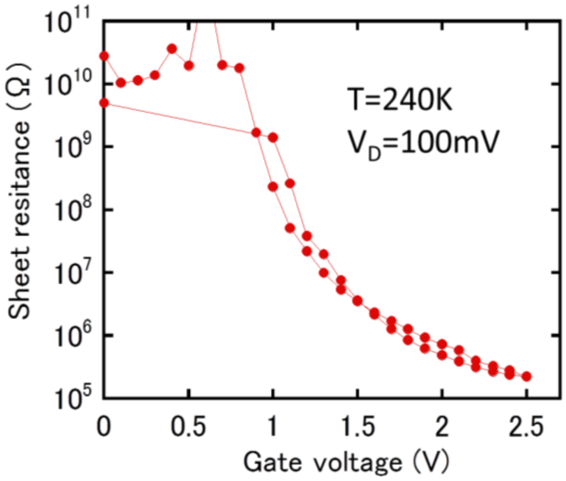

Fig3. Gate voltage dependence of sheet resistance

To confirm the IMT in EDLTs of polycrystalline large-area MoS_2 monolayers, we measured the temperature dependence of sheet resistances. Figure 4 shows the temperature dependence of sheet resistance at various gate voltages and dashed line is the quantum resistance, border between insulator and metal.

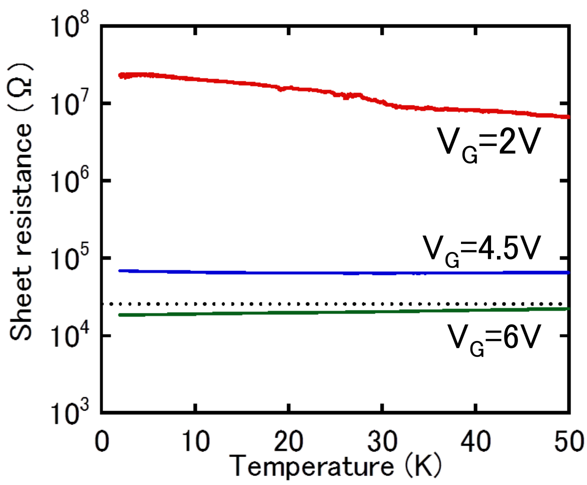

Fig4. Temperature dependence of sheet resistance at various gate voltages

At gate voltage of 2V, the sheet resistance increased with temperature. It is the typical thermally activated behavior, which is commonly observed in semiconductors and insulators. In sharp contrast to the insulating transport in the off state, as presented in Figure 3, metal-like behavior was observed in the on state (gate voltage of 6.0 V) because the current was inversely proportional to the temperature. The estimated carrier density from Hall measurements was approximately $1\times10^{14}/cm^2$, which is also the metallic region in single-crystalline samples and also suggests the possible superconductivity in polycrystalline large-area MoS_2 monolayer.

3. Conclusions

We successfully observed n-type transistor behavior and sheet resistance was less than the quantum resistance at gate voltage of 6V. Finally, by cooling the sample, we observed the solid evidence of IMT in polycrystalline films. Particularly, it remained metallic state at 1.9 K, which is the first mille stone for large-area electric field induced superconductors.

Acknowlegements

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