Electrical transport between a MoS$_2$-based electric double-layer transistor and normal and superconducting Al

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Abstract. We present fabrication of a junction between an atomic layer molybdenum disulfide-based electric double layer transistor and an aluminum film, and electrical transport measurements between molybdenum disulfide (MoS$_2$) carriers induced by strong electric fields due to its electric double-layer transistor and a conventional superconducting aluminum though Schottky barrier at the interface. A superconducting gap structure was observed in the differential resistance measurement of the dilution refrigerator temperature. Since the gap structures disappeared at about 900mK, the temperature change of this structure is caused due to aluminum superconductivity. However, as for the magnetic field change of the gap structures, the possibility of the coexistence of two kinds of superconducting states at the junction would be considered.

1. Introduction

Since Geim and Novoselov succeeded in cleaving the monolayer of graphene by a Scotch tape method, studies on atomic layered materials have been intensively conducted [1-3]. Graphene has attracted attention as a two-dimensional semiconductor with a high mobility. However, it is not optimal as a semiconductor material because graphene has no band gap. Recently, transition metal dichalcogenides (TMDCs) as two-dimensional materials have attracted attention for diverse properties such as semiconductors, metals, semi-metals, superconductors and topological insulators [4-6]. Molybdenum disulphide (MoS$_2$), which is an abundant natural TMDC mineral and is known to easily realize large crystals and long been used as a lubricant in many applications, is an indirect bandgap semiconductor with $E_g=1.2$ eV at 300 K in bulk. Since the intermediate layer of TMDC is bonded by a weak van der Waals force, MoS$_2$ is also easy to be cleaved [7]. The band gap of a monolayer MoS$_2$ is 1.8 eV at 300K. MoS$_2$ is known to be chemically stable because of few dangling bonds on the cleavage surface.

In semiconductor electronics, a chemical carrier doping method has been commonly used for controlling carriers of semiconductor materials and forming ohmic contacts between the metal electrode and the semiconductor. However, since changes in crystal structure are inevitable in insertion of impurities into 2D material, it is not easy to apply chemical carrier doping method to atomic layer semiconductors to control the carrier. For this reason, electric field carrier doping is more suitable for carrier control and the contact resistance control of atomic layer semiconductor materials.
Field effect transistors (FETs) are best known as an electric field doping device, but in recent years, electric double layer transistors (EDLTs) have attracted attention as an electric field doping device capable of accumulating higher carriers. The EDLT is a kind of electric field-effect transistor (FET) using ionic liquid, which is a salt in liquid state, as gate insulating layer of ordinary FETs.

Electric field doping by EDLT is also effective for reducing contact resistance between metal and semiconductor. Normally, a Schottky barrier is formed at the interface between the semiconductor and the metal, resulting in an increase in contact resistance and rectification. The electric field effect by the EDLT can realize ohmic contact by thinning the Schottky barrier at the interface.

Modulating carrier density of MoS$_2$ and the potential barrier at the interface between MoS$_2$ and aluminum electrode by using EDLT, we aim at coherently connecting conventional superconductivity and the electric field induced state in MoS$_2$.

2. Experimental

As shown in Fig.1 (a), we fabricated a MoS$_2$–based EDLT with superconducting electrodes, which contain two junctions between MoS$_2$ and Al electrodes. Bulk natural MoS$_2$ was cleaved into double-layered flakes by using the Scotch tape method, and the flakes were transferred onto a Si substrate with a thermally grown SiO$_2$ layer of 290 nm. The double-layered flakes were identified by microscopic Raman measurements [8]. The flakes were shaped as rectangular (2.4 × 5.8 μm$^2$) by argon plasma etching and electron beam lithography, as shown in Figure 1(b). Then superconducting Al electrodes, which are composed a multilayered configuration of Ti/Al/Ti (100/1000/50 Å), were formed on the MoS$_2$ flakes by electron beam lithography and electron beam physical evaporation in a high-vacuum chamber with a base pressure of a few 10$^{-6}$ Pa. The lower Ti layer was deposited for reducing the contact resistance between Al electrodes and the MoS$_2$. Gate electrode and bonding pads of Ti/Au (100/1000Å) were formed by laser lithography and electron beam physical evaporation. Immediately before the measurement, ionic liquids were dropped as a gate dielectric on the surface of the MoS$_2$ channel and a part of the gate electrode, as shown in Figure 1(a). N,N-diethyl-N-methyl-N-(2-methoxyethyl) ammonium bis (trifluoromethanesulfonyl) imide (DEME-TFSI) was used as ionic liquids.

A dilution refrigerator with a base temperature of 20 mK was used for cooling the sample to below the critical temperature of aluminum, which is $T_c = 1.2$ K. Chip ceramic capacitors for electrical noise filtering were mounted between the measurement line and electrical ground nearby the sample, and a copper powder filter was installed at the mixing chamber stage in the dilution refrigerator to minimize the electromagnetic noise. We had placed 4 superconducting electrodes on the MoS$_2$ flakes for performing four-terminal measurements method as shown in Fig.1 (b). Unfortunately, two of the four electrodes have broken out, so all measurements were done by two-terminal method. The differential resistance curves were numerically calculated from the $IV$ curves.
The gate voltage of 6 V was sufficient to induce metallic and superconducting state in the MoS$_2$ [9]. However, compared with previous studies, this on / off ratio is somewhat worse, the resistance seems somewhat higher. This is because the applied effective voltage is much lower than 6 V and the induced carrier density might be low. In fact, the resistance measured by the two-terminal method increased with decreasing temperature. This means that at least a part of the MoS$_2$ has semiconductor characteristics.

On the other hand, results of measurement of differential resistance at low temperature indicate that MoS$_2$ is a metallic state. Figure 2(b) shows the differential resistance–voltage curve (d$V$/d$I$–$V$ curve) at $T$ = 100 mK to 9.2 K. There is a peak at zero-bias voltage and two valleys at about $|V|$ = 0.3 mV in the differential resistances at $T$ < 1K. It is thought that the cause of a slight shift of the differential resistance structures in the minus direction is the artifact of current-sweeping from plus to minus. These differential resistance structures would be resulted from the superconducting gap of Al: the structures disappear above the superconducting transition temperature of Al at 1.2K and the superconducting gap energy of Al at 0.1 meV. In other words, it is considered that the metallic state of MoS$_2$ exists near the interface, and a tunnel junction between the superconducting state of Al and the metallic state of MoS$_2$ are realized.

Furthermore, the structures of this differential resistance evolve with the magnetic fields. Figure 2(c) shows the d$V$/d$|I|$–$V$ curves when a magnetic field $B$ = 0 to 24 mT was applied. Here, the peak at zero-bias voltage decreases with the applied magnetic field, and the two valleys at about $|V|$ = 0.3 mV also decrease and the voltage positions of the valleys change in the direction to the zero-bias voltage with the applied magnetic field. Since the critical magnetic field of the Al superconductivity is about 10mT, these variations with the magnetic field seem consistent with suppression of the superconducting gap of Al by the magnetic field.

However, the voltage positions of the two valleys do not change from 7mT to 24mT, Figure 2(d) shows the variation of the voltage positions of the two valleys. Some structures of this differential resistance do not disappear even at $B$ = 24 mT. There is small asymmetry with respect to $V$ = 0 mV, which might be reflected the asymmetry of the normal resistance related to the Schottky barrier or measurement. The strong structure of the differential resistance against magnetic field might be related to superconducting state induced in a part of MoS$_2$ at the interface of the junction.
Figure 2. (a) Dependence of the source-drain current $I_{SD}$ on the gate voltage $V_G$ at $V_{SD} = 10$ mV in MoS$_2$ EDLT. (b) Differential resistance–voltage curve (dV/dI–V curve) at $T = 100$ mK to 9.2K. (c) $dV/dI$–V curve at the applied magnetic field $B = 0$ to 24 mT. (d) Voltage of $+\text{gap } V\text{-valley}$ and $-\text{gap } V\text{-valley}$ and dependence on the magnetic field $B = 0$ to 24 mT.

4. Conclusions
We fabricated the MoS$_2$-based EDLT with a conventional superconductor Al electrodes. We measured the electrical transport of the MoS$_2$-based EDLT by two terminal method, which contain the junction between electrically induced state in the MoS$_2$ and a superconducting Al. The resistance of the EDLT at the gate voltage 6V is higher than the previous reports, and increased with decreasing temperature. This indicates that at least one part of the MoS$_2$ has semiconducting characteristics. On the other hand, the differential resistance indicates that metallic state and superconducting state are induced in the MoS$_2$. These results indicate that the channel of the MoS$_2$-EDLT is not uniform. In other words, semiconducting state, metallic state, and superconducting state coexist in the MoS$_2$. However, at least, the differential resistance structures related to the superconducting gap of aluminum is observed, which means that the tunnel barrier caused by the Schottky barrier between aluminum and MoS$_2$ can be controlled.

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