Supercurrent through MoS$_2$-based electric double-layer transistor sandwiched between conventional superconductors

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Abstract. Transition metal dichalcogenide molybdenum disulphide (MoS$_2$) is a two-dimensional layered crystal, which has a great potential as a flexible semiconductor device. Recently, manifestation of electrically induced superconductivity at the surface of the MoS$_2$-based electric double-layer transistor (MoS$_2$-EDLT) is reported. The superconducting properties, such as the ultra-high upper critical field, give a sign of unconventional spin-valley locking superconducting state. In this study, we aim to realize the coherent connection of the MoS$_2$-EDLT to conventional superconductors Aluminum (Al). Therefore, we first fabricated and evaluated the properties of Al/MoS$_2$-EDLT configuration/Al junction. At $T = 18$ mK, it is considered that a superconducting current of about 30 pA flows into the Al/MoS$_2$-EDLT/Al junction. We discussed the magnetic field response of this supercurrent.

1. Introduction

Transition metal dichalcogenides (TMDCs) are two-dimensional material that are expected to be utilized in technologies such as field effect transistor (FET) and electric double-layer transistor (EDLT) due to its moderate energy gap [1-4]. Furthermore, TMDCs recently received a wide attention due to the peculiar properties in two-dimensional structure [5-7].

Recently, an FET configuration with atomic layer MoS$_2$ as a channel was fabricated. It was reported that the MoS$_2$-FET is an ultra-low power consumption FET with an on / off ratio of $1 \times 10^8$ at a low temperature [1]. Further, a high mobility of 700 cm$^2$V$^{-1}$s$^{-1}$ was obtained in a MoS$_2$-FET with MoS$_2$ channel of 10 nm in thickness using scandium as a contact [8].

A MoS$_2$-EDLT configuration using ionic liquid instead of a gate insulator of an FET was also fabricated. It was reported that an appearance of electrically induced superconductivity at the surface of the MoS$_2$-based EDLT by applying a gate voltage [9]. Furthermore, this superconducting state is robust against the magnetic field in the direction parallel to the layer, and it is maintained in an ultra-high magnetic field of 50 T or more. This is a unique case of superconductivity, in which the spin of the superconducting Cooper-pair is fixed in the direction of the plane due to the breaking of the inversion symmetry for the crystal structure in the single layer MoS$_2$ [6].
In general, it is known that superconductivity under a non-centrosymmetric crystal structure is often unconventional [10-12]. The method clearly demonstrates that non-centrosymmetric superconducting state is due to the mixing of spin singlet and triplet. It was proposed to fabricate a Josephson junction (S/S' junction) using a conventional superconductor (S) and non-centrosymmetric superconductor (S'), and measure the magnetic field change of a supercurrent through the junction [12, 13].

We choose MoS₂, which breaks the inversion symmetry of the crystal, and its unique superconducting state is due to the mixing of spin singlet and triplet. It was proposed to fabricate a Josephson junction between MoS₂ and conventional superconductor and unconventional superconductor is often used for studying the anisotropic superconducting state.

In this research, we aim to realize a Josephson junction between MoS₂ and conventional superconductor, and elucidate specific superconducting state in MoS₂. To this end, it is necessary to reliably ascertain whether a junction is coherent, which the Cooper-pair in a conventional superconductor can sufficiently penetrate by the intermediary of the junction interface. Therefore, in this study, we aim to realize a coherent junction (Josephson junction) between conventional superconductors Aluminum (Al) and the MoS₂-EDLT.

2. Experimental
We fabricated a conventional superconductor/MoS₂-EDLT configuration/conventional superconductor (S/MoS₂-EDLT/S) junction shown in Figure 1. Bulk MoS₂ was cleaved into thin flakes by using the Scotch tape method, and the flakes were transferred onto Si substrate with a thermally grown SiO₂ layer of 290 nm. Single- or triple-layered flakes were identified by microscopic Raman measurements [14]. The flakes were shaped to be rectangular (2 × 4.5 μm²) by argon plasma etching as shown in Figure 1(a). Superconducting electrodes were composed of multilayer configuration of Ti/Al (100/1000Å), where Ti can reduce the contact resistance for MoS₂. The electrodes and the gate electrodes of Ti/Au (100/1000Å) were formed using electron beam lithography and laser lithography respectively.

A droplet of ionic liquid N,N-Diethyl-N-methyl-N-(2-methoxyethyl)ammonium bis(trifluoromethane sulfon)imide (abbreviated DEME-TFSI) was applied onto the surface of the channel and the gate electrodes as shown in Figure 1(c) and (d). Next, the sample was mounted on a dilution refrigerator and cooled down to 18 mK. For the transport measurement, copper power filters placed on the mixing chamber stage were employed to minimize the electromagnetic noise.
3. Results and discussions

First, the gate voltage $V_G$ dependence of source-drain current $I_{SD}$ at $V_{SD} = 100$ mV was measured. To avoid a chemical reaction between ionic liquid and MoS$_2$ channel, and electrodes, $V_G$ higher than 3 V was applied at 220 K, which is above the glass transition temperature of the ionic liquid. The $I_{SD}$ increased by applying $V_G = 6$ V and the on/off ratio was about 400.

Figure 2(a) shows the current-voltage curve ($I$-$V$ curve) in magnetic field perpendicular to the MoS$_2$ plane $B = -14$ mT to 14 mT at $T = 18$ mK. It is clear from that a supercurrent with the critical current of $I_c \sim 30$ pA through S/MoS$_2$-EDLT/S junction. Moreover, $I_c$ changes by applying a magnetic field.

Figure 2(b) depicts the magnetic field $B$ dependence of $I_c$ at $T = 18$ mK. As can be seen from this Figure 2(b), $I_c$ changes with the application of a magnetic field. In addition, we can observe several jumps in $I_c$. The jumps might be due to the trapping of magnetic flux around the junction.

In addition, if the junction is a Josephson junction, a periodic pattern which is called Fraunhofer pattern can be observed by applying a magnetic field. It is clear from Figure 2(a), a period of magnetic field exhibit, however the next period of magnetic field did not exhibit the expected Fraunhofer pattern. To discuss this issue, we focused on the shape and number of layers in MoS$_2$ sample used in this measurement. As shown in Figure 1(a), the sample has a single layer and three layers mixed in the MoS$_2$ of rectangular (2 $\times$ 4.5 $\mu$m$^2$). Here, we consider the magnetic field of a period in the Fraunhofer pattern in two cases where a current flows uniformly and only through a part of the triple layer, respectively.
As the junction junction length $L$ is 0.1 $\mu$m, the magnetic field penetration length of Al $\lambda$ is about 0.05 $\mu$m and the width $d$ is 4.5 $\mu$m, the effective area $S_1$ of the junction was calculated when flowing uniformly, $S_1 = (d + 2\lambda)$ and $L = 0.9 $ $\mu$m$^2$. As the magnetic field $B$ for one period in the Josephson junction of the effective area $S$ is represented by $\phi_0 / S_{\text{eff}}$, it follows that $B_1 = \frac{\phi_0}{0.9} = \approx 2$ mT.

When it flows through only a part of the triple layer, the effective area $S_2$ of the junction was calculate to be $0.2 \mu m^2$, in a similar the case of uniform flow. We calculate the magnetic field for one period of the Fraunhofer pattern as, $B_2 = \frac{\phi_0}{0.4} \approx 10$ mT using this.

From the above, the magnetic field of a period in the Fraunhofer pattern is 2 mT when a current flows uniformly in the MoS$_2$, and 10 mT when a current flows only through a part of the triple layer. It is considered that the magnetic field of one period in the Fraunhofer pattern is close to the case where the current flows only through a part of the triple layer in MoS$_2$.

![Figure 2](image.png)

**Figure 2.** (a) Magnetic field dependence of $I$-$V$ curve at 18 mK. The external magnetic field applied is parallel to the surface of the junction. (b) Magnetic field dependence of the critical current $I_c$ of the junction at 18 mK.

4. Conclusions

In conclusion, we demonstrated that a supercurrent through a MoS$_2$ sandwiched between conventional superconductors Al using an EDLT configuration. We verified that the device operates as the EDLT as the source-drain current is increased by applying the gate voltage at $V_{SD} = 100$ mV. At $T = 18$ mK, it is considered that a superconducting current of about 30 pA flows into the Al/MoS$_2$-EDLT/Al junction. Furthermore, a vertical magnetic field between -14 mT to and +14 mT was applied to this junction, and the $I$-$V$ characteristic was measured. As a result, the magnetic field response of the supercurrent was confirmed.

**Acknowledgements**

We would like to thank T. Sato, D. Sakuma from Tokyo Univ. of Science, S. Nomura from Univ. of Tsukuba and S. Kashiwaya from AIST for stimulating discussions. This work was supported by JSPS KAKENHI C (Grant No. 17K05551). Device fabrication was supported by the NIMS Nanofabrication platform of the “Nanotechnology Platform Project” sponsored by MEXT.
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