One-Dimensional Edge Contact to Encapsulated MoS$_2$ with a Superconductor

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Establishing ohmic contact to van der Waals semiconductors such as MoS$_2$ is crucial to unlocking their full potential in next-generation electronic devices. Encapsulation of few layer MoS$_2$ with hBN preserves the material’s electronic properties but makes electrical contacts more challenging. Progress toward high quality edge contact to encapsulated MoS$_2$ has been recently reported. Here, we evaluate a contact methodology using sputtered MoRe, a Type II superconductor with a relatively high critical field and temperature commonly used to induce superconductivity in graphene. We find that the contact transparency is poor and that the devices do not support a measurable supercurrent down to 3 Kelvin, which has ramifications for future fabrication recipes.

Recently, progress has been made in one-dimensional edge contact to MoS$_2$ with normal metal through in situ Ar+ sputtering$^{12,20}$. It would be highly desirable to develop superconducting edge contact to MoS$_2$, which could enable the study of the Josephson junction physics taking advantage of MoS$_2$’s spin-orbit and spin-valley couplings.

In this work we make one-dimensional edge contact to encapsulated MoS$_2$ using molybdenum-rhenium (MoRe), a Type II superconductor known to form high transparency contact to MoS$_2$ for a 2D interface$^{22,23}$. We utilize a recipe known to make ohmic edge contacts to hBN-encapsulated graphene$^{22,23}$. Our measurements show low transparency contact to MoS$_2$ that is improved neither by Ar+ sputtering pre-treatment of the contact interfaces nor by annealing. These results indicate the probable presence of interfacial tunnel barriers. This result may prove informative for groups developing hybrid samples made of van der Waals heterostructures with superconducting contacts.

We study two MoS$_2$ devices encapsulated within hBN. Both samples are contacted by several MoRe electrodes, which define a series of Josephson junctions of different lengths. The first device uses bilayer MoS$_2$, while the second device uses monolayer MoS$_2$. Figure I shows an optical image of the first device as well as a schematic view of the one-dimensional edge contact between the MoS$_2$ and MoRe, created via reactive ion etching and sputtering. The second device underwent an in situ Ar+ sputtering pre-treatment immediately before MoRe deposition. Both van der Waals heterostructures were assembled from mechanically exfoliated flakes using a dry transfer technique utilizing a polyethylene terephthalate stamp. Polymer residue was removed by immersion in dichloromethane for one hour at 70 °C followed by several hours at room temperature.

The one-dimensional interface between the MoS$_2$ and the MoRe was prepared via standard electron-beam lithography techniques, reactive ion etching (RIE), and sputtering. RIE consisted of three steps, all carried out with a process pressure

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FIG. 1. (a) Optical image of the first sample. The black outline shows the location of the encapsulated MoS$_2$. Scale bar 5 μm. (b) Schematic side view of the one-dimensional edge contact between the encapsulated MoS$_2$ and the sputtered MoRe (not to scale).

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of $10^{-1}$ Torr. First, a ten second CHF$_3$ / O$_2$ (10:1 flow rate ratio) step removed leftover e-beam resist (PMMA) residue from the top surface of the heterostructure. This was followed by a ten second SF$_6$ process to etch through the top hBN. Finally, a ten second CF$_4$ step was used to etch the MoS$_2$ in the contact region. While a CF$_4$ etch is a typical process for MoS$_2$, SF$_6$ may itself be sufficient. In order to limit the device’s exposure to atmosphere, and so the formation of MoO$_x$ along the interface, the device was not removed from the system and imaged between these steps.

The devices had minimal exposure to air before being transferred to the sputtering system. The second sample was treated with Ar+ sputtering before metal deposition to refresh the contact interface. The chamber was pumped to a pressure of $\sim 10^{-8}$ Torr and 100 nm of MoRe (50-50% by weight) was sputtered on both devices. To minimize processing, the Josephson junctions were not shaped with further etching, so the flakes of MoS$_2$ continue beyond the boundaries of the junctions. This is visible in Figure 1a, which shows an optical image of the first device.

The samples are cooled in a closed-cycle cryocooler with a base temperature of 3 K. Unless otherwise noted, a voltage $V_{\text{applied}}$ is applied to the junction in series with a protective $R_S = 10$ M$\Omega$ resistor. The drain current, $I_D$, is measured, and the source-drain voltage is calculated as $V_{SD} = V_{\text{applied}} - R_S I_D$; as a result the curves in Figures 2 and 3 have different horizontal extent.

Figure 2a shows the effects of electrostatic gating on the $I$−$V$ curves of a 200 nm long and 5 µm wide junction made on the first device. The gate voltage ($V_{BG}$) increases the Fermi level in the MoS$_2$, causing it to approach the conduction band. We observe that for increasing $V_{BG}$, the threshold of $V_{SD}$ required to achieve a linear slope decreases. Figure 2b demonstrates the $I$−$V$ curves measured for three junctions of different length at the maximal gate voltage of 42 V. (See the schematic in the inset: $J_1$ is 200 nm long, and $J_{2,3}$ are 500 nm long.) It is clear that 1) the curves show no significant length dependence, indicating that the current is limited by the contact barriers; and 2) the measurements are consistent between the three junctions, indicating uniform properties of the contacts. These initial measurements are consistent with the presence of barriers (likely Schottky barriers) at the interfaces. At the highest gate voltage (42 V) the resistance is 2.4 M$\Omega$, corresponding to the contact resistance of $R_c \approx 6$ M$\Omega$ µm.

Due to this high contact resistance, we next anneal the sample at 200°C for 17 hours in a vacuum of $10^{-6}$ mbar. Annealing processes have been shown to decrease contact resistance in similar devices. This may be due to a host of phenomena which change the bonding or structure at the interface. In this study, the annealing resulted in higher contact resistance, with an increase of as much as 40% at high bias and $V_{BG} = 42$ V. This decrease in contact quality may be due to the MoRe flowing away from the contact edge, as seen in gold junctions without an additional metal sticking layer.

We study the behavior of the junction as a function of temperature to gain insight into the poor contact quality. Figure 3a plots the $I$−$V$ characteristics of the same junction from 3 to 290 K. A clear reduction in low-bias resistance spanning more than a decade is seen as the temperature rises (Figure 3b). Such behavior is consistent with thermionic transport across a barrier. This interpretation is supported by an approximately linear relation between the log of the current and the square root of the bias voltage in the device (Figure 3c) as expected, e.g., for a triangular Schottky barrier. This relation breaks down for low bias voltages at higher temperatures.

Due to the contact characteristics of this device, we study a second device utilizing Ar+ sputtering immediately prior to the deposition of the MoRe contacts, focusing on a 500 nm long and 5 µm wide junction. Despite this change in deposition parameters and an overnight anneal at 300°C in $10^{-6}$ mbar, this second device also displays high contact resistances at low temperature. Utilizing a direct voltage biasing scheme without a 10 M$\Omega$ series resistor, we measure gate sweeps for...
FIG. 3. Temperature dependencies measured in the 200 nm long, 5 µm wide junction in the first device. (a) Post-anneal $I−V$ characteristics. (b) Low bias ($V_{SD} = 0.05$ V) resistance $R$, plotted in linear and (inset) log scale, which shows $R$ decaying with temperature. $V_{BG} = 42$ V throughout. (c) $\ln(I_D)$ vs $(V_{SD}/\text{Volts})^{1/2}$ plot of the same data showing an approximately linear relationship in the intermediate temperature range. This is consistent with thermionic transport across the contact interfaces.

FIG. 4. Current vs $V_{BG}$ sweeps measured in a 500 nm long by 5 µm wide junction in the second device following the annealing, which show the induced highly resistive behavior. The three curves correspond to $V_{SD} = 1.5, 3, \text{ and } 5$ V. Inset: the same data in log scale.

different $V_{SD}$ (Figure 4). Even at the highest applied $V_{SD}=5$ V, the currents supported by the junction are orders of magnitude lower than comparable or longer junctions made with both top contacts\textsuperscript{25,26} and high quality normal metal edge contacts\textsuperscript{19,20}.

In summary, we tested a methodology for making one-dimensional edge contact to encapsulated MoS$_2$ with MoRe, and found high contact resistances on the order of MΩ·µm. This contact was not improved by annealing at 200–300 °C. In situ Ar+ sputtering of the interface before the deposition of MoRe also did not improve the contact quality. We conclude that the presence of tunnel barriers limits the performance of these devices. The lack of length dependence, consistency between different junctions, insensitivity to Ar+ pre-cleaning, and the lack of improvement upon annealing all point to the presence of intrinsic Schottky barriers at the interfaces.

Higher transparency contacts may be achieved in the future by replacing MoRe with superconductors having a significantly higher or lower work function. Nevertheless, the current contact recipe could support the use of MoS$_2$ in more complex superconducting heterostructures. Namely, TMDs, including MoS$_2$\textsuperscript{27}, are already used to induce the spin-orbit coupling in graphene\textsuperscript{28,29}. One can extend these studies to Josephson junctions by making superconducting contacts that would selectively contact the graphene but not the TMD layer. In this context, our work establishes an order of magnitude estimate for the (very small) current expected to be shunted through an MoS$_2$ layer in such a complex van der Waals heterostructure.

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