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Josephson coupling in $NbSe_2/NbSe_2$ van der Waals junction

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Abstract

Supercurrent flow between the two superconductors with different order parameters; this phenomenon is known as Josephson effect. This can be realized by fabricating Josephson junction where non-superconducting material is inserted between the two superconductors to decouple the wave functions. These Josephson junctions have been employed in fields ranging from digital to quantum electronics, yet their functionality is limited by the interface quality and use of non-superconducting material. Here we show that by exfoliating layered dichalcogenide superconductor $NbSe_2$ and make van der Waals (vdW) contact between freshly cleaved surfaces, vdW Josephson junction can be built. Recent advances in the vdW heterostructure technology make this fabrication possible. By eliminating all the heat treatment during junction preparation, atomically flat vdW interface without signature of oxidation and inter-diffusion is demonstrated. We show that artificially created vdW interface is sufficient to de-couple the wave functions of the two $NbSe_2$ crystals. At the same time, we demonstrated vdW Josephson junction exhibited nearly ideal transparency for supercurrent.

1. Device fabrication

We fabricated vdW junction between the two different freshly cleaved $NbSe_2$ crystals as schematically illustrated in Fig.1. We selected layered dichalocogenide 2H-$NbSe_2$ as a superconductor material. A 2H-$NbSe_2$ is layered crystal structure so that each of monolayer NbSe2 is separated by vdW gap and thus makes this material to be suitable for vdW Josephson junction. The nm-thick $NbSe_2$ flakes are mechanically exfoliated from bulk crystal (HQ Graphene Inc.) and deposited on the 300 nm SiO_2/highly *n*-doped Si substrate. Subsequently, by using dry-transfer technique, another $NbSe_2$ is transferred onto the $NbSe_2$ crystal. The freshly cleaved surfaces of both $NbSe_2$ crystals are made contacted with vdW interaction in atmosphere. To minimize surface oxidation of both $NbSe_2$ layer, the average time to fabricate vdW junction is as fast as an hour. Using standard electron beam lithography and EB evaporation, 30 nm Au/50 nm Ti electrode is fabricated. Entire device fabrication process is done at room temperature and without introducing any intentional heating of $NbSe_2$ crystals; this is crucial to minimize the surface oxidation of $NbSe_2$ crystals.

2. Results

The photograph of the fabricated vdw Josephson junction is shown in Fig. 2(a). The current-voltage characteristic of the vdW junction measured under current biasing at 2 K and result is presented in Fig. 2(b). The *I-V* curve exhibits clear hysteresis and suggests typical behavior of under-damped Josephson junction. The vdW junction introduces discontinuity of superconducting order parameter at the interface and enables us to observe Josephson effect. Noticeably, despite of such simple fabrication method we observed large critical current I_c of 0.53 mA corresponding to the current density of 6600 A/cm^2. This value is comparable to the value used in modern Josephson junction for single flux quantum circuits; suggesting that vdW interface is highly transparent for phase coherent transport of supercurrent. Thus from the slope of the *I-V* curve, normal state resistance is determined as $R_N = 1.97\ \Omega$

The application of a magnetic field within the junction plane induces phase shift in supercurrent; therefore induces a variation of I_c. In-plane magnetic field dependence of *I-V* curve is measured at 2 K and results are shown in Fig. 3. Periodic modulation of I_c on magnetic field (Fraunhofer pattern) is clearly visible as indicated by the red dashed line. Noticeably, another Fraunhofer pattern is also visible in the figure (indicated by blue dashed line). These features are due to Fiske resonance; coherently coupled mode between ac-Josephson current and electromagnetic wave within the junction. The appearance of both Fraunhofer pattern and Fiske resonance provides another piece of evidence such that a Josephson junction with well-defined cavity is achieved.

3. Conclusions

We revealed that the vdW interface between the exfoliated-$NbSe_2$ crystals works as Josephson junction. From *I-V* data, the $R_N I_c$ product of our junction is determined as 1.04 mV. The maximum $R_N I_c$ expected from the AB theory is $\pi\Delta/2$ = 1.14 meV; the $R_N I_c$ product value we experimentally obtained is close the maximum value expected from the bulk properties of constitute materials. These results are another piece of evidence of the demonstration of high quality Josephson junction at the vdW interface between the $NbSe_2$ crystals. Just exfoliate bulk crystal with Scotch tape and connect the cleaved sur face with vdW force exhibits exceptionally high quality Josephson effect at the interface. Moreover, most of large gap superconductors such as Nb and YBCO have a difficulty to integrate into the heterostructure with ordinal evaporation technique due to its low vapor pressure and structural complexity. Our finding shows a route for building single crystalline heterostructure of superconductor with other material connected with vdW junction.

Figures

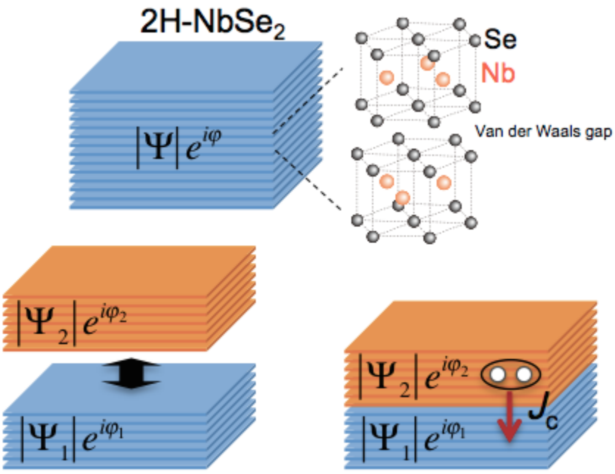

Fig. 1 Schematic illustration of the fabrication method of vdW Josephson junction.

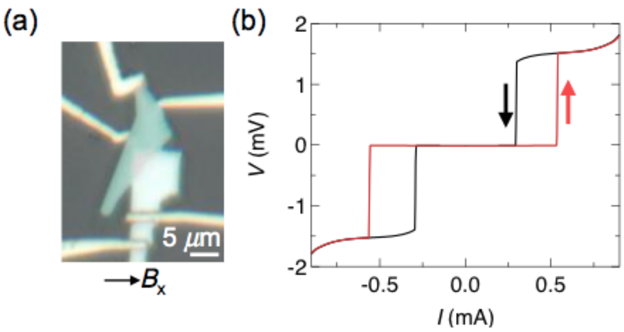

Fig. 2 (a) Photograph of the fabricated device. (b) *I*-*V* curve of the fabricated junction measured by sweeping current at 2 K.

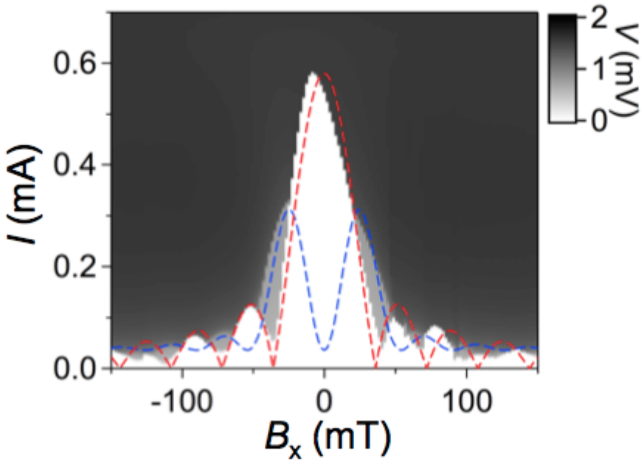

Fig. 3 Dependence of critical current with respect to the B_x measured at 2 K.