Building van der Waals Pi Josephson Junctions

CNF Project Number: 2633-18

Principal Investigator(s): Jie Shan, Kin Fai Mak

User(s): Kaifei Kang

Affiliation(s): Laboratory of Atomic and Solid State Physics,
School of Applied and Engineering Physics; Cornell University

Primary Source(s) of Research Funding: United States Army Research Office

Contact: jie.shan@cornell.edu, kinfai.mak@cornell.edu, kk726@cornell.edu

Primary CNF Tools Used: Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, SC4500 Odd/Even-Hour Evaporator, DISCO Dicing Saw

Abstract:

At the interfaces of superconductors (SC) and ferromagnets (FM), exotic Cooper pairs with finite center-of-mass momentum can be realized [1]. Here we build van der Waals ferromagnetic Josephson junctions using atomically thin $NbSe_2$ and $Cr_2Ge_2Te_6$ (CGT) flakes. We observe a damped-oscillatory dependence of the Josephson critical current density on the CGT barrier thickness, which is the definitive evidence for a thickness-driven 0 to π transition. Near the transition, we observe 0 – π Josephson junctions with zero critical current at zero magnetic field. Our work demonstrates the thickness-driven 0 to π transition in van der Waals Josephson junctions and 0 – π Josephson junctions with uniform barrier thickness.

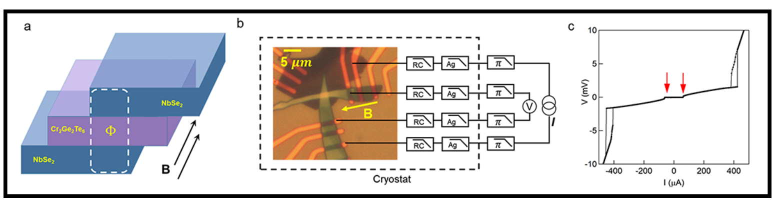

Figure 1: $NbSe_2/Cr_2Ge_2Te_6/NbSe_2$ Josephson Junctions. a, Schematics of the device structure. The magnetic field is applied to the in-plane direction, which produces a magnetic flux through the cross-sectional area of the device (marked by the white dashed rectangle). b, Schematics for the electrical measurements. All electrical lines are filtered by π, silver-epoxy, and low-temperature RC filters. c, I-V *characteristic of a device with a CGT barrier thickness of about 3.6 nm.*

Summary of Research:

The recent discovery of two-dimensional (2D) layered superconducting and magnetic materials provides a new platform to realize π Josephson junctions (JJs) with atomically uniform thickness and sharp interfaces via van der Waals stacking [2,3]. In this project, we fabricate JJs using van der Waals superconductor $NbSe_2$ and semiconducting ferromagnet $Cr_2Ge_2Te_6$ (CGT) (Figure 1a).

Figure 1b shows the schematics for the electrical measurements. The JJs are current-biased, and the voltage drop across the JJs is measured. Radiation with frequencies above 30 kHz is filtered to avoid unwanted quasiparticle excitations. Figure 1c shows the current-voltage characterization of a JJ with a 3.6-nm CGT barrier. The voltage drop V across the JJ vanishes when the bias current I is smaller than the Josephson critical current of $I_c \approx 63$ µA (marked by the red arrows). At a large bias current of $I \sim 500$ µA, a second voltage jump of about 3 mV is observed, corresponding to the superconducting critical current of the $NbSe_2$ flakes.

We study the thickness dependence of the Josephson critical voltage $V_c = I_c R_n$. Here R_n is the resistance of the JJs when $I > I_c$. Figure 2 shows V_c as a function of the CGT thickness, d. As d increases, V_c first decreases for $d <$ 8.4 nm, increases for 8.4 nm $< d <$ 9.9 nm, and then vanishes when $d \approx$ 12.3 nm. Such a thickness dependence of V_c is consistent with the thickness-driven 0 to π transition with a critical barrier thickness of d_c = 8.4 nm.

We also examine the magnetic interference patterns in JJs with different barrier thicknesses. Figures 3a-3d show the sample differential resistance as a function of magnetic field (B) and bias current in JJs with selected CGT barrier thickness of 5.2, 7.7, 9.1, and 9.9 nm. For JJs with CGT thicknesses away from the critical thickness (Figure 3a and Figure 3d), regular Fraunhofer patterns are observed with pronounced central lobes near $B = 0$ T. However, for JJs with CGT barrier with just one layer thinner (Figure 3b) or one layer thicker (Figure 3c) than the critical thickness d_c, we observe zero critical current near $B = 0$ T, which signifies the formation of $0 - \pi$ JJs. The observation of the $0 - \pi$ JJs with uniform barrier thickness is attributed to the inhomogeneous magnetization induced by the magnetic domain walls in CGT, which is reported by a recent Lorentz TEM study [4].

In conclusion, we have fabricated high-quality van der Waals ferromagnetic Josephson junctions. By varying the thickness of the ferromagnetic barrier, we observe a damped oscillatory behavior for the JJ critical current density and thus a thickness-driven 0 to π transition. Near the transition, we identify $0 - \pi$ JJs with zero critical current near zero magnetic field and uniform barrier thickness.

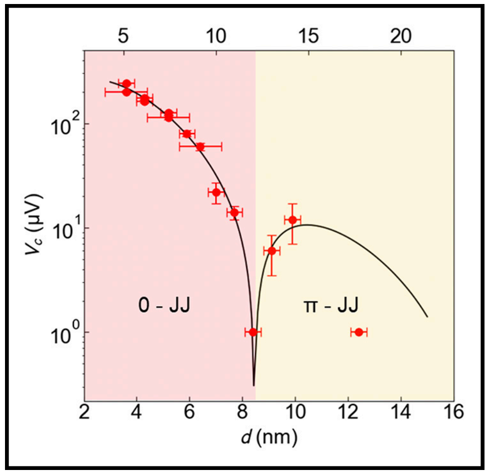

Figure 2: Thickness-driven 0 to π transition. Critical voltage V_c as a function of CGT barrier thickness. JJs have zero phase difference in red dashed region and π phase difference in the orange region.

References:

[1] Buzdin, A. I. Proximity effects in superconductor-ferromagnet heterostructures. Rev. Mod. Phys.77, 935 (2005).

[2] Saito, Y. et al. Superconductivity protected by spin-valley locking in ion-gated MoS_2. Nat. Phys. 12, 144-149 (2016).

[3] Mak, K. F., Shan, J. and Ralph, D. C., Probing and controlling magnetic states in 2D layered magnetic materials. Nat. Rev. Phys.1, 646-661 (2019).

[4] Idzuchi, H. et al., Unconventional supercurrent phase in Ising superconductor JJ with atomically thin magnetic insulator. Nat. Comm.12, 5332 (2021).

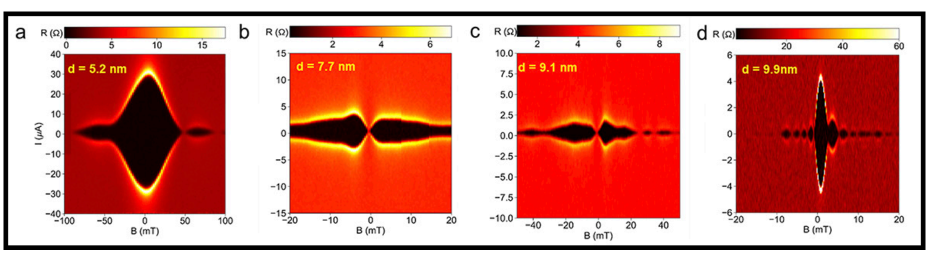

Figure 3: Magnetic interference pattern of the Josephson supercurrent. a – d, Magnetic interference pattern of the supercurrent in JJs with barrier thickness of 5.2 nm (a), 7.7 nm (b), 9.1 nm (c), and 9.9 nm (d). The magnetic field is scanned in the forward direction.