Building van der Waals Pi Josephson Junctions

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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

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$_2$Ge$_2$Te$_6$ (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.

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$_2$Ge$_2$Te$_6$ (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 $I_c \approx 63 \mu$A (marked by the red arrows). At a large bias current of $I \sim 500 \mu$A, 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 – π JJs. The observation of the 0 – π 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 – π JJs with zero critical current near zero magnetic field and uniform barrier thickness.

References:

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.