Measurement of the Current–Phase Relation of SFS Pi–Josephson junctions


양자전도 초전도 연구실, 기동근
Measurement of the Current-Phase Relation of SFS Pi-Josephson junctions

1. Josephson junction?
2. Overview of Pi junction (Theory)
3. Overview of Pi junction (Experiment)
4. Weak points of early experiments
5. Weak Ferromagnet (CuNi)
6. Basic equation and Experimental setup
7. Result
8. Summary and Discussion
Josephson junction?

\[ I_S = I_C \sin \varphi \quad \text{DC Josephson effect} \]

\[ V = \frac{\hbar}{2e} \frac{\partial \varphi}{\partial t} \quad \text{AC Josephson effect} \]

\[ I_{\text{max}} = 2I_C \left| \cos \left( \frac{\pi F_{\text{ext}}}{\Phi_0} \right) \right| \]
Overview of the Pi junction (Theory)

Cooper pairs are spin singlet!!

\[ |\uparrow\downarrow\rangle = e^{iQx} \chi_{\uparrow\downarrow}(x) \]
\[ |\downarrow\uparrow\rangle = e^{-iQx} \chi_{\downarrow\uparrow}(x) \]
Singlet pair

\[ \Psi = \cos[Q(x_1 + x_2)] \times \psi(x_1 - x_2) \]
\[ Q = \frac{2E_{ex}}{\hbar v_f} \]

Overview of the Pi junction (Experiment)

$T_C(d_F)$


$I_C(T, d_F)$: transport


$I_C(T)$: SQIUD

- A. Bauer et al., Cond-mat/0312165 (2003)
Overview of the Pi junction (Experiment)

\[ \psi = e^{-x/\xi} = e^{-x/\xi_1} \times e^{-i\xi_2} \]

\[ \xi = \sqrt{\frac{\hbar D}{2(\pi k_B T + iE_{ex})}} = \xi_1 + i\xi_2 \]

Overview of the Pi junction (Experiment)

FIG. 3. Critical current $I_c$ as a function of temperature $T$ for two junctions with Cu$_{0.48}$Ni$_{0.52}$ and $d_F = 22$ nm [17]. Inset: $I_c$ versus magnetic field $H$ for the temperatures around the cross-over to the $\pi$ state as indicated on curve b: (1) $T = 4.19$ K, (2) $T = 3.45$ K, (3) $T = 2.61$ K.

FIG. 4. (a) Critical current $I_c$ as a function of temperature for Cu$_{0.48}$Ni$_{0.52}$ junctions with different $F$-layer thicknesses between 23 and 27 nm as indicated. (b) Model calculations of the temperature dependence of the critical current in a SFS junction for $E_{\text{ex}} = 0.8\pi T_c$ and various ratios of $d_F/2\pi\xi^*$, where $\xi^* = \sqrt{\hbar D/(2\pi k_B T_c)}$.

Overview of the Pi junction (Experiment)


FIG. 1. Real (upper) and schematic (lower) picture of the network of five SFS sandwiches Nb-Cu$_{0.46}$Ni$_{1.54}$-Nb ($d_F = 19$ nm), which was used in the phase-sensitive experiment.

FIG. 2. Magnetic field dependences of the critical transport current for the structure depicted in Fig. 1 at temperature above (a) and below (b) $T_\pi$. 
Weak points of early experiments

1. Magnetically dead layer?
   - Normal ferromagnets have a very strong exchange field (Fe, Gd ..)

2. Interface transparency

3. Current–phase relation (negative critical current)

   So, we need...

1. 10 ~ 30nm thick ferromagnet → Curie T : 20~100K
   - Weak ferromagnet (CuNi, PdNi, ...)

2. Temperature dependence

3. rf SQUID configuration, phase sensitive experiment
Weak Ferromagnet (CuNi)

$H = 100 \text{ G}$

$M(10^{-4} \text{ emu})$ vs. $T(\text{ K})$

- ZFC
- FC

25K

Cu/Ni
Basic equation and Experimental Setup

\[ I = I_J \left( \frac{2\pi \phi}{\phi_0} \right) + I_L, \phi = L \times I_L \]

At a low inductance region
DC SQUID potentiometer

\[ I_C R_N \approx 100 pV \text{ at maximum } I_C \]

FIG. 2: (a) Circuit for measuring the current-phase relations of an SFS junction. (b) Magnetic flux \( \phi \) in the rf SQUID loop vs. applied current \( I \) showing a transition from hysteretic to non-hysteretic curves as \( |I_c| \) drops. Curves offset for clarity.
Result

FIG. 1: (a) Current vs. voltage for a Nb-CuNi-Nb Josephson junction measured at $T = 1.4$ K. (b) Variation of the critical current with temperature showing re-entrance at $T \approx 2.7$ K characteristic of a transition into a $\pi$-junction state.

FIG. 3: Modulation of the magnetic flux in the rf SQUID loop as a function of current applied across the SFS junction for a series of temperatures. As the temperature is lowered, the critical current vanishes at $T = 3.59$ K, below which the modulation shifts phase by $\pi$. Curves offset for clarity.
Result

**FIG. 4:** Current-phase relation derived from the rf SQUID modulation curves of Fig. 3 showing the transition to a Josephson junction as the temperature is lowered.

**FIG. 5:** Variation of $I_c$ and $I_{c2}$, the $\sin\phi$ and $\sin(2\phi)$ components of the Josephson critical current, with temperature, showing the sign change in $I_c$ and absence of a significant $I_{c2}$.

$$I_S = I_{C2} \sin(2\phi)$$
Summary and Discussion

1. The most clear evidence for the Pi junction
   - Directly show the current–phase relation and negative critical current

2. No dependence in 2\textsuperscript{nd}-order Josephson component
   - It may be seen in a clean limit (Voltage controlled SNS junction)

1. What is the real structure?

2. Spin–orbit Scattering effect?

3. Without the change of T and thickness, can we control?

4. Quantum Computing? (Phase shift..)