High quality ferromagnetic 0 and \( \pi \) Josephson tunnel junctions

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The authors fabricated high quality Nb/Al\(_2\)O\(_3\)/Ni\(_{0.6}\)Cu\(_{0.4}\)/Nb superconductor-insulator-ferromagnet-superconductor Josephson tunnel junctions. Depending on the thickness of the ferromagnetic Ni\(_{0.6}\)Cu\(_{0.4}\) layer and on the ambient temperature, the junctions were in the 0 or \( \pi \) ground state. All junctions have homogeneous interfaces showing almost perfect Fraunhofer patterns. The Al\(_2\)O\(_3\) tunnel barrier allows one to achieve rather low damping, which is desired for many experiments especially in the quantum domain. The McCumber parameter \( \beta \) increases exponentially with decreasing temperature and reaches \( \beta = 700 \) at \( T = 2.11 \) K. The critical current density in the \( \pi \) state was up to 5 A/cm\(^2\) at \( T = 2.11 \) K, resulting in a Josephson penetration depth \( \lambda \) as low as 160 \( \mu \)m. Experimentally determined junction parameters are well described by theory taking into account spin-flip scattering in the Ni\(_{0.6}\)Cu\(_{0.4}\) layer and different transparencies of the interfaces. © 2006 American Institute of Physics. [DOI: 10.1063/1.2356104]

The realization of solid state qubits attracts considerable interest. Josephson junctions (JJs) are used to realize charge,\(^1\) phase,\(^2\) or flux\(^3\) qubits. For the “quiet” flux qubit,\(^4\) which is self-biased and well decoupled from the environment, one needs to use high quality \( \pi \) JJs with high resistance (to avoid decoherence) and reasonably high critical current density \( j_c \) (to have the Josephson energy \( E_J \gg k_B T \) for junction sizes of few microns or below). High \( j_c \) is also required to keep the Josephson plasma frequency \( \omega_c \ll \sqrt{j_c} \), which plays the role of an attempt frequency in the quantum tunneling problem, on the level of a few gigahertz.

The concept of \( \pi \) JJs was introduced long ago,\(^5,6\) but only recently superconductor-ferromagnet-superconductor (SFS) \( \pi \) JJs were realized.\(^7,8\) Unfortunately SFS \( \pi \) JJs are highly overdamped and cannot be used for applications where low dissipation is required. The obvious way to decrease damping is to make a SFS-like tunnel junction, i.e., a superconductor-insulator-ferromagnet-superconductor (SIFS) junction. Due to the presence of the tunnel barrier the critical current \( I_c \) in SIFS is lower than in SFS, but both the resistance \( R \) (at \( I \approx I_c \)) and the \( I_c R \) product are much higher. Moreover, the values of \( I_c \) and \( R \) can be tuned by changing the thickness \( d_F \) of the insulator (tunnel barrier).

A set of SIFS JJs with different thicknesses \( d_F \) of the F-layer was recently fabricated and JJs with both 0 and \( \pi \) ground states were observed depending on \( d_F \).\(^9\) Although, in the \( \pi \) state the specific resistance of the barrier was high (\( \rho \approx 3 \) m\( \Omega \) cm\(^2\)), \( j_c \) was below 7 mA/cm\(^2\) at 1.5 K, resulting in an \( I_c R \) product below 20 \( \mu \)V, as can be estimated from the data in Ref. 9.

In this letter we report on fabrication and characterization of high quality Nb/Al\(_2\)O\(_3\)/Ni\(_{0.6}\)Cu\(_{0.4}\)/Nb \( \pi \) JJs with different \( d_F \) having as high as possible \( j_c \) and \( I_c R \) values. In the \( \pi \) state we reached \( j_c \) up to 5 A/cm\(^2\) at \( T = 2.11 \) K and maximum \( I_c R \) values \( \approx 400 \) \( \mu \)V. SIFS and reference superconductor-insulator-superconductor (SIS) JJs were fabricated \( \text{in situ} \) by magnetron sputtering and patterned using optical lithography and (reactive) dry etching.\(^10\) On thermally oxidized Si wafers we deposited 120 nm Nb and 5 nm Al. To form the Al\(_2\)O\(_3\) barrier (which should be as thin as possible, but without pinholes) we oxidized at 0.015 or at 50 mbarss to have \( j_c (1) = 4.0 \) kA/cm\(^2\) (wafer 1) and \( j_c (2) = 0.19 \) kA/cm\(^2\) (wafer 2) for reference SIS JJs. For reference SIS JJs on wafer 1 the \( I_c R \) product was 1.55 mV.

To control the properties of SIFS JJs the thickness and the roughness of the F-layer should be controlled on a sub-nanometer scale. To provide uniform growth of the F-layer, a 2 nm Cu interlayer was deposited between the I-layer and the F-layer. As the F-layer we used diluted Ni\(_{0.6}\)Cu\(_{0.4}\), followed by a 40 nm Nb cap layer. To produce JJs with different \( d_F \) in a single run, during sputtering of the F-layer, the substrate and sputter target were shifted about half the substrate length, producing a wedgelike F-layer with \( d_F \) from 1 to 15 nm across the 4 in. wafer. All other layers had uniform thicknesses. The SIFS junctions had a squared shape with an area of \( 100 \times 100 \) \( \mu \)m\(^2\).

We have used diluted Ni\(_{1-x}\)Cu\(_x\) alloy rather than pure Ni to have suitable \( d_F \) (much larger than roughness) for the \( \pi \).
state. In very diluted alloy with $y \leq 0.53$ strong spin-flip scattering\textsuperscript{11} and Ni cluster formation are observed. To avoid this magnetic inhomogeneity we have used $y = 0.6$, as confirmed by Rutherford backscattering spectroscopy. The Curie temperature $T_C \approx 225$ K was determined by superconducting quantum interference device magnetometry and anisotropic Hall measurements on bare Ni$_{0.6}$Cu$_{0.4}$ films. Both $T_C$ and resistivity $\rho_F(10$ K$) = 54 \, \mu \Omega \mathrm{cm}$ are in good agreement with the literature.\textsuperscript{14,15} The magnetization of such thin Ni$_{0.6}$Cu$_{0.4}$ films is in plane. Interpolation of the magnetic moment $\mu$ from published data\textsuperscript{17,16–18} yields $\mu = 0.15 \mu_B/$atom for our Ni$_{0.6}$Cu$_{0.4}$ alloy.

Following Ref. 19 one can derive that at $T \leq T_C$

$$I_c(d_F) = \frac{1}{\gamma_F} \exp \left( \frac{-d_F}{\xi_{1F}} \right) \exp \left( \frac{-d_F - d_F^\text{lead}}{\xi_{2F}} \right),$$

(1)

where $\xi_{1F}, \xi_{2F} = \xi_F / \sqrt{1 + 4\alpha^2 \pm \alpha}$ are the decay and oscillation lengths of order parameter,\textsuperscript{20} $\xi_F = \sqrt{4D / E_{\text{ex}}}$ is the decay/oscillation length without spin-flip scattering,\textsuperscript{19} $E_{\text{ex}}$ is the exchange energy, $\alpha = 1 / (\tau_0 E_{\text{ex}})$, $\tau_0$ is the inelastic magnetic scattering time,\textsuperscript{21} and $\gamma_F$ is the transparency parameter of the SIF part treated like a single interface. $d_F^\text{lead}$ is the magnetic dead layer thickness. Equation (1) is derived assuming that the interfaces are not spin active (cf. Ref. 22), short decay length $\xi_{1F} < d_F$, $\xi_{1F} < \xi_{2F}$, and FS interface transparency parameter $\gamma_{F1} = 0$ ($\gamma_{F1} \ll \gamma_{F2}$). In comparison with Ref. 23 Eq. (1) takes into account magnetic impurity scattering which enters via $\tau_0$. Since $\xi_{2F}$ weakly depends on temperature $T$, the 0–$\pi$ crossover can be observed by changing $T$.

The spread in $I_c$ among SIFS JJs with the same $d_F$ is about 2%.\textsuperscript{10} The $I_c(d_F)$ dependence of our SIFS JJs is clearly nonmonotonic as shown in Fig. 1. We argue that the minimum of $I_c(d_F)$ at $d_F \approx 5.21$ nm corresponds to 0 to $\pi$ crossover. To rule out the possibility of 0–$\pi$ crossover at smaller $d_F$ we have investigated $I_c(d_F)$ down to $d_F = 2$ nm and did not observe any decrease or oscillation of $I_c(d_F)$. In Fig. 1 we show only data for “low” $I_c$ JJs ($L < 2 \lambda_D$) that we can treat as short JJs to fit experimental $I_c(d_F)$ using Eq. (1). Due to a finite dead magnetic layer the change of phase takes place in an effectively reduced F-layer thickness. By fitting $I_c(d_F)$ for wafer 1 using Eq. (1), we estimated $\xi_{F1} = 0.78$ nm, $\xi_{F2} = 1.35$ nm, and $d_F^\text{lead} = 3.09$ nm. As we see, the inelastic magnetic scattering is strong ($\xi_{F1} < \xi_{F2}$) and the decay length $\xi_{F1} \ll d_F$; thus Eq. (1) is applicable. Also, the found value of $d_F^\text{lead}$ supports our claim that we observed 0 to $\pi$ rather than 0 to $\pi$ crossover. According to Eq. (1) the coupling changes from 0 to $\pi$ at the crossover thickness $d_F = (\pi/2) \xi_{F2} + d_F^\text{lead} = 5.21$ nm, the shape of the $I_c(d_F)$ curve does not change with the thickness of the insulator, but the amplitude of $I_c(d_F)$ is proportional to the reciprocal transparency parameter $\gamma_{F2}^{-1}$. In the interval of $d_F$ from 0 (for SIS) to 9 nm the value of $j_c$ at 4.2 K changes over five orders of magnitude from 4 kA/cm$^2$ to below 0.05 A/cm$^2$ (wafer 1).

The maximum $j_c$ in the $\pi$ state is 3.8 A/cm$^2$ (wafer 1) and $j_c(\pi) = 90$ mA/cm$^2$ (wafer 2) at $T = 4.2$ K. This gives $\lambda_F \approx 190 \, \mu m$, which can be easily increased by increasing $d_F$. Further decrease of $\lambda_F$ by lowering $d_F$ is limited by the appearance of microshorts in the barrier.

For comparison, in 21 SFS JJs were fabricated using the weaker ferromagnet Ni$_{0.53}$Cu$_{0.47}$ ($T_C = 60$ K). Although the spin-flip scattering was also taken into account, the high interface transparencies ($\gamma_{F1} = 0.52$) lead to a different $I_c(d_F)$ dependence than Eq. (1) predicts. Also, the lower $E_{\text{ex}}$ lead to larger $\xi_{F1} = 1.24$ nm and $\xi_{F2} = 3.73$ nm. The magnetic dead layer was 1.4 times larger than in our system.

Figure 1(b) shows the dependence of the McCumber parameter $\beta_c (d_F)$, which was estimated from the values of $I_c$ and $I_c$ (return current), at $T = 4.2$ K for wafer 1. The capacitance $C = 800$ pF, determined from the Fiske step spacing of $73 \, \mu V$, is nearly independent from $d_F$ but depends on $d_F$. Near the 0–$\pi$ crossover and for large $d_F$ the value of $I_c$ is very low and the junctions become overdamped ($\beta_c < 0.7$). For $\pi$ JJs with $d_F$ near the maxima of the $I_c(d_F)$ curve a hysteresis appears on the I-V characteristic.

The I-V characteristics and $I_c(H)$ patterns (voltage criterion of 5 $\mu V$) for a SIFS $\pi$ JJ with highest $I_c$ are shown in Fig. 2, c.f. the I-V characteristic of the SIS JJs shown in the inset. Theoretically, at lower temperature the quasiparticle current decreases and the gap appears at higher voltages. In experiment, due to heating effects at high bias currents, part of the sample became normal before we were able to reach the gap voltage. At $T \leq 2.61$ K the first zero field step at 149 $\mu V$ is visible on the I-V characteristic.

The energy dependences of the density of states in Al, Cu, and NiCu are not exactly BCS-like and $I_c(T)$ for SIFS JJs should show a more linear behavior\textsuperscript{24} than originally found by Ambegaokar and Baratoff.\textsuperscript{25} Variation of $T$ modifies $\xi_{F1}$ and $\xi_{F2}$ and can even change the ground state.\textsuperscript{7,11}
Since $E_{\text{cs}}$ of Ni$_{0.6}$Cu$_{0.4}$ is relatively large, a change of $T$ affects our JJs much less than in previous work on the stronger diluted NiCu alloys. The $I(T)$ dependences for three JJs from wafer 1 are shown in Fig. 3(a). At $d_f=5.11$ nm the JJ is 0 coupled, but we attribute the nearly constant $I_c$ below 3.5 K to the interplay between increasing Cooper pair density and decreasing oscillation length $\xi_F(T)$. The JJ with $d_f=5.20$ nm is 0 coupled at $T=4.2$ K, but changes coupling to $\pi$ below 3.11 K. During the 0–$\pi$ transition its critical current is not vanishing completely ($I_{\text{cmin}}=0.8 \mu$A) either due to roughness of the ferromagnet or a prominent sin$(2\phi)$ component in the current-phase relation, which can appear intrinsically or again due to roughness. At the crossover temperature $T_x=3.11$ K, $I_c(H)$ can still be traced through several minima, so the large scale roughness must be small. The $d_f=5.87$ nm JJ (also shown in Fig. 2) exhibits the highest critical current among $\pi$ JJs ($j_c=5$ A/cm$^2$ at 2.11 K). Up to now the corresponding $\lambda_J=160 \mu$m is the smallest achieved for SIFS JJs. Figure 3(b) shows $\beta_c(T)$ for the same JJs. $\beta_c(T)$ increases exponentially below 4 K for both 0 and $\pi$ JJs, indicating very weak Cooper pair breaking in the F-layer for these temperatures. The $\beta_c$ of the always overdamped JJ with $d_f=5.20$ nm was not estimated.

In summary, we have fabricated and investigated SIFS Josephson junctions with Ni$_{0.6}$Cu$_{0.4}$ tunnel barriers. The critical current $I_c$ changes sign as a function of the F-layer thickness $d_f$ in accordance with theory, exhibiting regions with 0 and $\pi$ ground states. For $d_f$ near the 0 to $\pi$ crossover the ground state can be controlled by changing the temperature. Our SIFS $\pi$ junctions show critical current densities $j_c$ up to 5 A/cm$^2$ at $T=2.11$ K and $I_cR$ products up to 400 $\mu$V. The achieved $\pi$ junction’s Josephson penetration depth $\lambda_J$ as low as 160 $\mu$m at 2.11 K allows one to fabricate long Josephson 0–$\pi$ junctions of reasonable size and study half integer flux quanta (semifluxons) that appear at the 0–$\pi$ boundaries and have a size $\sim \lambda_J$. Reasonable $\lambda_J$ and low damping in such 0–$\pi$ junctions may lead to useful classical or quantum circuits based on semifluxons.

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