High quality ferromagnetic 0 and π Josephson tunnel junctions

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The authors fabricated high quality $Nb/Al_2O_3/Ni_{0.6}Cu_{0.4}/Nb$ 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 π ground state. All junctions have homogeneous interfaces showing almost perfect Fraunhofer patterns. The Al_2O_3 tunnel barrier allows one to achieve rather low damping, which is desired for many experiments especially in the quantum domain. The McCumber parameter β_c increases exponentially with decreasing temperature and reaches $\beta_c \approx 700$ at $T=2.11$ K. The critical current density in the π state was up to 5 A/cm^2 at $T=2.11$ K, resulting in a Josephson penetration depth λ_J as low as 160 μm. 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 π 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 $\omega_p \propto \sqrt{j_c}$, which plays the role of an attempt frequency in the quantum tunneling problem, on the level of a few gigahertz.

The concept of π JJs was introduced long ago,[5,6] but only recently superconductor-ferromagnet-superconductor (SFS) π JJs were realized.[7,8] Unfortunately SFS π 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 $I \gtrsim I_c$) 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_I 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 π ground states were observed depending on d_F.[9] Although, in the π state the specific resistance of the barrier was high ($\rho \sim 3$ mΩ cm^2), j_c was below 7 mA/cm^2 at 1.5 K, resulting

in an $I_c R$ product below 20 μV, as can be estimated from the data in Ref. 9.

In this letter we report on fabrication and characterization of high quality $Nb/AlO_x/Ni_yCu_{1-y}/Nb$ JJs with different d_F having as high as possible j_c and $I_c R$ values. In the π state we reached j_c up to 5 A/cm^2 at $T=2.11$ K and maximum $I_c R$ values ≈ 400 μV. SIFS and reference superconductor-insulator-superconductor (SIS) JJs were fabricated *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_2O_3 barrier (which should be as thin as possible, but without pinholes) we oxidized at 0.015 or at 50 mbars to have $j_c^{(1)} \approx 4.0$ kA/cm^2 (wafer 1) and $j_c^{(2)} \approx 0.19$ 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 100×100 μm^2.

We have used diluted Ni_yCu_{1-y} alloy rather than pure Ni to have suitable d_F (much larger than roughness) for the π

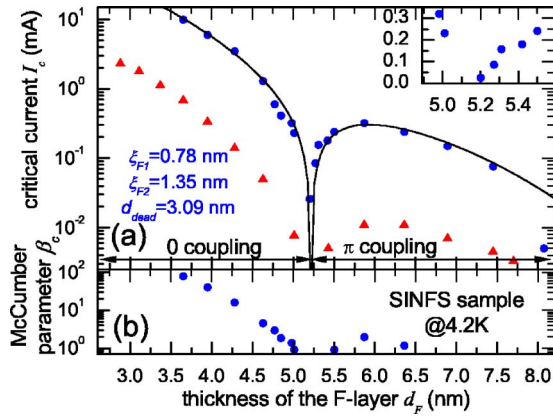---

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FIG. 1. (Color online) $I_c(d_F)$ (a) and $\beta_c(d_F)$ (b) dependences (circles: wafer 1; triangles: wafer 2) and fitting curve for wafer 1. The inset shows magnification of 0 to π transition region for wafer 1 on a linear scale.

FIG. 2. (Color online) I-V characteristics of π SIFS JJ (d_F=5.87 nm) at different T. The insets show I-V characteristic of SIS JJ at T=4.2 K (top) and $I_c(H)$ of SIFS JJ at T=4.2 and 2.11 K.

state. In *very diluted* alloy with $y \leq 0.53$ strong spin-flip scattering[11] and Ni cluster formation are observed.[12,13] To avoid this magnetic inhomogeneity we have used y=0.6, as confirmed by Rutherford backscattering spectroscopy. The Curie temperature $T_C \sim 225$ 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 $\rho_F(10\ \text{K})$=54 $\mu\Omega$ cm are in good agreement with the literature.[14,15] The magnetization of such thin $Ni_{0.6}Cu_{0.4}$ films is in plane. Interpolation of the magnetic moment μ from published data[11,16–18] yields μ=0.15μ_B/at. for our $Ni_{0.6}Cu_{0.4}$ alloy.

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

$$I_c(d_F) \sim \frac{1}{\gamma_{B2}} \exp\left(\frac{-d_F}{\xi_{F1}}\right) \cos\left(\frac{d_F - d_F^{\text{dead}}}{\xi_{F2}}\right), \quad (1)$$

where $\xi_{F1,F2} = \xi_F / \sqrt{\sqrt{1+\alpha^2} \pm \alpha}$ are the decay and oscillation lengths of order parameter,[20] $\xi_F = \sqrt{\hbar D / E_{\text{ex}}}$ is the decay/oscillation length without spin-flip scattering,[19] E_{ex} is the exchange energy, $\alpha = 1/(\tau_s E_{\text{ex}})$, τ_s is the inelastic magnetic scattering time,[21] and γ_{B2} is the transparency parameter of the SIF part treated like a single interface. d_F^{dead} is the magnetic dead layer thickness. Equation (1) is derived assuming that the interfaces are not spin active (cf. Ref. 22), short decay length $\xi_{F1} < d_F$, $\xi_{F1} \ll \xi_{F2}$, and FS interface transparency parameter $\gamma_{B1}=0$ ($\gamma_{B1} \ll \gamma_{B2}$). In comparison with Ref. 23 Eq. (1) takes into account magnetic impurity scattering which enters via τ_s. Since ξ_{F2} weakly depends on temperature T, the 0-π crossover can be observed by changing T.

The spread in j_c among SIFS JJs with the same d_F is about 2%.[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 π crossover. To rule out the possibility of 0-π 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" j_c JJs ($L < 2\lambda_J$) 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 ξ_{F1}=0.78 nm, ξ_{F2}=1.35 nm, and d_F^{dead}=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
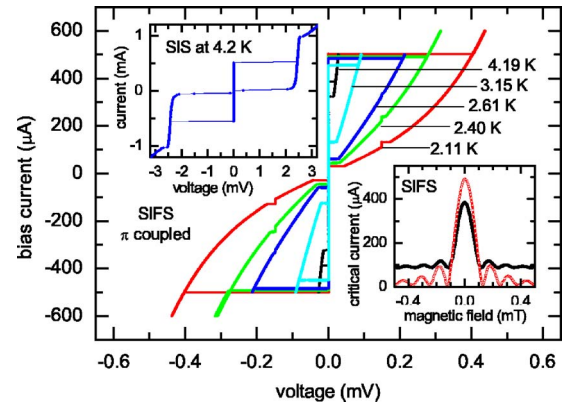
d_F^{dead} supports our claim that we observed 0 to π rather than π to 0 crossover. According to Eq. (1) the coupling changes from 0 to π at the crossover thickness $d_F^{0-\pi}=(\pi/2)\xi_{F2}+d_F^{\text{dead}}$=5.21 nm, the shape of the $I_c(d_F)$ curve does not change with the thickness of the insulator, but the amplitude of $I_c(d_F)$ is proportional to the reciprocal transparency parameter γ_{B2}^{-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 π 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 $\lambda_J \gtrsim 190$ μm, which can be easily *increased* by increasing d_I. Further *decrease* of λ_J by lowering d_I is limited by the appearance of microshorts in the barrier.

For comparison, in Ref. 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 (γ_{B1}=0.52) lead to a different $I_c(d_F)$ dependence than Eq. (1) predicts. Also, the lower E_{ex} lead to larger ξ_{F1}=1.24 nm and ξ_{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_r (return current), at T=4.2 K for wafer 1. The capacitance $C \approx 800$ pF, determined from the Fiske step spacing of 73 μV, is nearly independent from d_F but depends on d_I. Near the 0-π crossover and for large d_F the value of I_c is very low and the junctions become overdamped ($\beta_c < 0.7$). For π 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 μV) for a SIFS π 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 μV 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[24] than originally found by Ambegaokar and Baratoff.[25] Variation of T modifies ξ_{F1} and ξ_{F2} and can even change the ground state.[7,11]
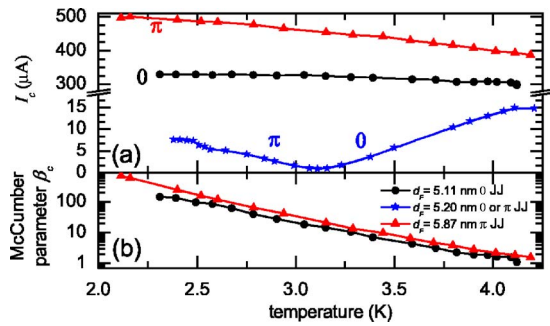
FIG. 3. (Color online) $I_c(T)$ (a) and $\beta_c(T)$ (b) dependences of 0 and π SIFS JJs.

Since E_{ex} 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.[7,11] The $I_c(T)$ 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 $\xi_{F2}(T)$. The JJ with $d_F = 5.20$ nm is 0 coupled at $T = 4.2$ K, but changes coupling to π below 3.11 K. During the 0-π transition its critical current is not vanishing completely ($I_c^{\min} \approx 0.8$ μA) either due to roughness of the ferromagnet or a prominent $\sin(2\phi)$ component in the current-phase relation,[26,27] which can appear intrinsically or again due to roughness.[28,29] 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 π JJs ($j_c = 5$ A/cm^2 at 2.11 K). Up to now the corresponding $\lambda_J = 160$ μm 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 π JJs, indicating very weak Cooper pair breaking in the F-layer for these temperatures. The β_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 $Ni_{0.6}Cu_{0.4}$ layer = 20 and thin Al_2O_3 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 π ground states. For d_F near the 0 to π crossover the ground state can be controlled by changing the temperature. Our SIFS π junctions show critical current densities j_c up to 5 A/cm^2 at $T = 2.11$ K and I_cR products about 400 μV. The achieved π junction's Josephson penetration depth λ_J as low as 160 μm at 2.11 K allows one to fabricate long Josephson 0-π junctions of reasonable size and study half integer flux quanta (semifluxons) that appear at the 0-π boundaries[30–32] and have a size $\sim \lambda_J$. Reasonable λ_J and low damping in such 0-π junctions may lead to useful classical[33,34] or quantum[35–37] circuits based on semifluxons.

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