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Non-monotonic critical current in Nb–Cu–Ni–Cu–Nb junctions

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Abstract

We report on experimental studies of critical current in Nb–Cu–Ni–Cu–Nb layered structures. Strong oscillations of the critical supercurrent were observed with the thickness variation of Ni. Using known microscopic parameters of Ni, we found reasonable agreement between the period of oscillations and the decay of the measured critical current, and theoretical calculations.

Keywords: Critical current; SNFNS junction

The interplay between superconductivity and ferromagnetism is an old subject which was studied extensively over decades [1–3]. The most striking effect in such systems is the formation of the so-called π phase junction in a superconductor-ferromagnet-superconductor (SFS) structure [1]. The recent observation [4] of non-monotonic behavior of the critical current *as a function of temperature* in weak-ferromagnetic layer of Cu_xNi_{1-x} between two Nb layers is considered as an unambiguous proof of the π phase formation. Another interesting theoretical prediction [2,3,5,6] concerns non-monotonic behavior of the critical current as a function of the thickness of the ferromagnetic layer d. According to the above predictions, the critical current I_c is expected to oscillate and decay as d is increased. To the best of our knowledge, such a behavior has not been reported so far.

In this paper, we present the experimental evidence of oscillatory behavior of the critical current vs. thickness variation of ferromagnetic Ni layer. We also show a reasonable agreement between our data and the theories [2,6] in the appropriate limit of $E_{ex} \gg \hbar/\tau \gg k_B T_c$. Here, τ and E_{ex} are the electron relaxation time and the exchange energy of the ferromagnet, and T_c is the critical temperature of the superconductor.

We have studied temperature and thickness dependence of the critical current in Nb–Cu–Ni–Cu–Nb junctions. The junctions with $10 \times 10\ \mu m^2$ area were fabricated with the standard photolithography technique. Nb films were sputtered using a magnetron gun and in situ covered with the Cu layer by thermal evaporation, for preventing the Nb oxidation. The ferromagnet layers of Ni were e-gun evaporated in a separate vacuum chamber, and subsequently covered in situ by Cu. It is important to emphasize that all samples were prepared simultaneously. The variation of Ni thickness was obtained by a specially designed shutter, which exposed the samples in sequence, so that every sample was exposed to the evaporating Ni for additional fragments of time. This method guaranteed that all the interfaces between each layer in our multilayer structure are identical, and the only difference between the samples is their Ni thickness. The thickness of each Nb layer was 2000 Å. The total thickness of the Cu was 2400 Å and the Ni thickness varied from 10 to 90 Å.

Fig. 1 shows the thickness dependence of the critical current in the junctions at $T = 4.2\,K$. In spite of the large error bars, the non-monotonic variation of the critical current is quite evident, namely, the deviations of the data from the exponential decay surmounts by far the uncertainty of each measured point.

A further, and even a stronger evidence for the oscillatory behavior is provided by temperature

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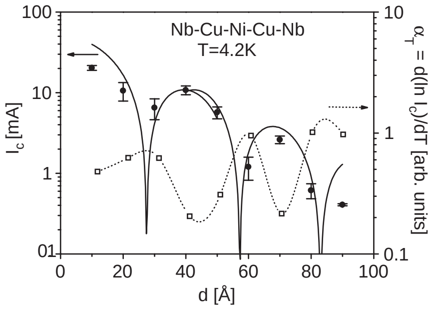

Fig. 1. Critical current of the Nb–Cu–Ni–Cu–Nb junctions as a function of the Ni layer's thickness d at 4.2 K (circles). The dependence of the slope α_T on d is represented by squares. Both the dashed and dotted lines are only for guiding the eye. The solid line represents Eqs. (1) and (2) in their appropriate limits.

dependence of the critical current. Fig. 2 shows a family of I_c vs. T curves for all Ni thicknesses, which are normalized to their values at 4.2 K. We define the slope α_T of temperature variation, namely $\alpha_T \equiv \mathrm{d}(\ln I_c(T))/\mathrm{d}T$, and plot these values as a function of d in Fig. 1 (squares). Oscillations of α_T are very prominent, and are in anti-phase with the oscillations of the critical current. Unlike the critical current, which had quite large experimental error bars, the slope of the temperature dependence had error bars of only few percents. Such a behavior of α_T as a function of d is intimately related to the variation of the critical current oscillations amplitude with temperature.

As mentioned in the introduction, oscillatory behavior of the critical current vs. the thickness of the ferromagnetic layer is predicted theoretically [2,3,6]. The origin of these oscillations is the phase shift acquired by electron-hole Andreev particles upon entrance into the ferromagnet, due to their different spin orientations. Several expressions have been derived for the critical current in various limits of the strength of E_{ex}, thickness of the ferromagnet d and disorder. Since in our experiment we have determined only the magnitude of the critical current I_c, the formulae below will be written for the absolute value $|I_c|$.

In the ballistic limit, the critical current should vary with the thickness as [2]

$$I_c \sim |\sin(2E_{ex}d/\hbar v_f)|/(2E_{ex}d/\hbar v_f). \tag{1}$$

Another expression for the critical current in the limit $l > \hbar v_f/E_{ex}$, is given by [6]

$$I_c \sim \left|\mathrm{Re}\sum_{\omega_n>0}\frac{\Delta^2}{\Delta^2+\omega_n^2}\int_{-1}^{1}\frac{\mu d\mu}{\sinh(k_\omega \mathrm{d}/\mu l)}\right| \tag{2}$$

where $\omega_n = \pi T k_B(2n+1)$ is the Matsubara frequency, n is an integer number, $k_\omega = (1 + 2|\omega_n|\tau/\hbar) - 2iE_{ex}\tau/\hbar$,

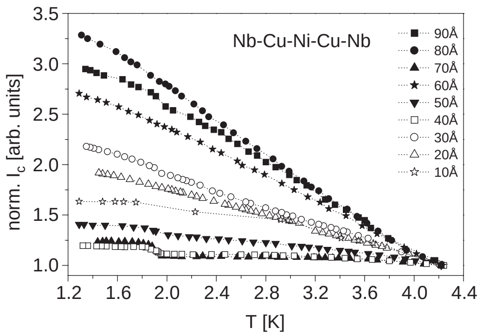

Fig. 2. Critical current as a function of temperature of the junctions for different thicknesses of the Ni layer.

$\mu = \cos\theta$, θ is the angle between the momentum and the normal to the SF interface, and Δ is the order parameter in the superconductor. In fitting our data to the expressions for both limits, we have used [7] $v_f = 2.8\times10^5$ m/s and $l = 48$ Å (based on the resistivity measurements of Ni). Therefore, the only fitting parameter apart from the numerical prefactor was the strength of the exchange interaction E_{ex}. The periodicity of oscillations in Eq. (1), $L_{osc} \sim \pi\hbar v_f/E_{ex} \simeq 54$ Å fits the best our data when $E_{ex} = 107 \pm 3$ meV. This values is close to the recently reported value [7] $E_{ex} = 115$ meV. However, since Eq. (2) is valid only for $d > l$, the data points should follow Eq. (1) for $d < 40$ Å. Therefore, we give the fit of Eqs. (1) and (2) to our data in their appropriate limits in Fig. 1 (solid line).

In summary, we have observed the oscillations and the decay of the critical current in Nb–Cu–Ni–Cu–Nb junctions upon the increase of the thickness of the Ni layer. We found a reasonable agreement with the recent theoretical calculations in the appropriate limit.

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