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Reentrant superconducting behavior of the Josephson SFS junction. Evidence for the π-phase state

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Critical supercurrents, I_c, in $Nb - Cu_{1-x}Ni_x - Nb$ Josephson SFS junctions with F-layers prepared from ferromagnetic $Cu_{1-x}Ni_x$ alloys have been studied. For value x=0.52 and particular F-layer thickness we have observed $I_c(T)$ oscillations with I_c vanishing for some values of T. We associate this reentrant superconducting behavior with a crossover of the SFS junction from '0'- to 'π'-state that is related to temperature dependence of spatial oscillation period of induced superconducting order parameter in the weak ferromagnet. We argue this is the first experimental evidence of the π-behavior of a Josephson junction, that is the special feature of superconducting pair flow through a ferromagnet predicted for SFS junctions by Bulaevskii, Buzdin et al [1].

We present evidences of π-state existing in superconductor-ferromagnet-superconductor (SFS) Josephson junctions [1,2]. Decay of the induced superconducting order parameter enhances with the exchange energy E_{ex} increase in the ferromagnet. The use of ferromagnet alloys tenfold decreases the E_{ex}, thus allowing the fabrication of thin-film SFS sandwiches with homogeneous 10-20 nm thick F-interlayers comparable with the decay length, ξ_{1F}, and observation of supercurrents through the F-interlayer [3]. We have shown that in nonmagnetized specimens the averaging of the domain magnetic structure in F-layer ensures a highly homogeneous passage of supercurrent across the ferromagnet.

$Nb - Cu_{1-x}Ni_x - Nb$ sandwiches were prepared with F-layers sputtered using $Cu_{1-x}Ni_x$ alloy target. Curie temperatures of 10-20 nm thick $Cu_{1-x}Ni_x$ films at $x = 0.52$ were about 18-20 K [4]. Because of low junction resistances ($R_n \simeq 10^{-5}\Omega$) transport characteristics of the SFS sandwiches were measured by SQUID picovoltmeter with a sensitivity 10^{-11} V in the temperature range 1.2-9 K.

Figs.1,2 show two sets of curves that demonstrate unusual $I_c(T)$ behavior. Both sets of the $Nb - Cu_{0.48}Ni_{0.52} - Nb$ sandwiches used were fabricated at different time using the same target. However F-layers in sandwiches of Series I (Fig.1) have slightly stronger magnetism (E_{ex}) than ones of Series II (Fig.2). As a matter of fact the ferromagnetism of the $CuNi$ alloy is due to the intercluster exchange interactions related to Ni-rich clusters [5]. The cluster formation depends on a number of uncontrolled technological parameters. For both sets of sandwiches the increase in F-layer thickness, d_F, causes the decrease in I_c and change of the monotonic $I_c(T)$ dependencies to ones with saturation at low temperature or even oscillating $I_c(T)$ dependencies. Invariability of $I_c(H)$ patterns positions for different T (inset in Fig.1) proves that the $I_c(T)$ oscillations are not associated with residual magnetic induction changes.

The specific behavior of SFS junction is associated with space oscillations of the induced super-

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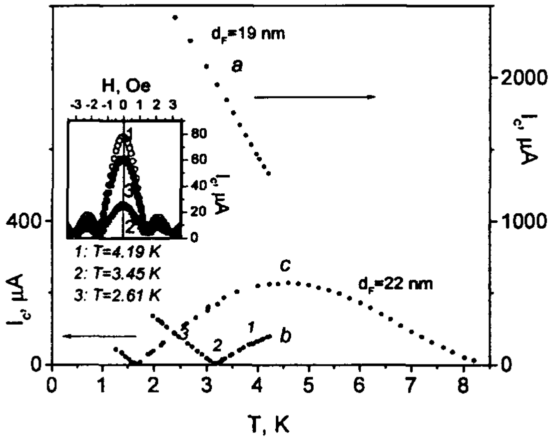

Figure 1. $I_c(T)$ dependencies for Series I sandwiches. Curves **b** and **c** present the data for the same sandwich, but the latter is for the sandwich after 'annealing' during leads re-soldering. Inset shows $I_c(H)$ patterns for the curve **b**.

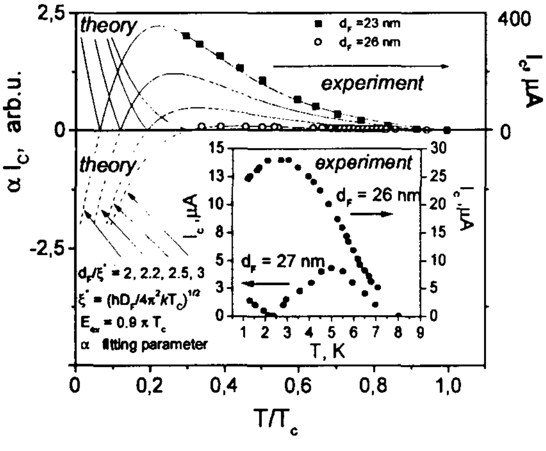

Figure 2. $I_c(T)$ dependencies of Series II sandwiches. Inset shows detailed experimental data for the sandwiches with d_F=26 and 27 nm.

conducting order parameter in the F-layer originated from the exchange field in the ferromagnetic [1,2]. If $E_{ex} \sim k_BT$, the order parameter behavior can be described by the expression

$$\Delta \sim e^{-\frac{x}{\xi_F}} \sim e^{-x\sqrt{\frac{k_BT+iE_{ex}}{D_F}}} \sim e^{-\frac{x}{\xi_{F1}}} e^{-i\frac{x}{\xi_{F2}}}. \quad (1)$$

Here D_F is the diffusion coefficient of electrons in ferromagnet, ξ_F is the complex pair coherence length in ferromagnet, ξ_{F1} and ξ_{F2} are the order parameter decay length and the period of its spatial oscillations. It must be emphasized that ξ_{F1} increases whereas ξ_{F2} decreases with temperature decrease, which provides the possibility of the crossover from '0' to 'π' state of the junction by temperature varying. In order to demonstrate this effect quantitatively we extended the theory [2] for the critical current in SFS junctions, originally developed for large F-layer thicknesses, to the regime of arbitrary F-layer thicknesses. The calculations that will be reported in detail elsewhere confirm the applicability of simple arguments in favour of T-induced '0' to 'π' crossover.

Fig.2 shows calculated curves $I_c(T)$. It is seen that the Josephson coupling energy of an SFS junction indeed can change sign as T decreases, provided that $E_{ex} \sim k_BT$ and $d_F \sim \xi_{F2}$. Thus, the observation of the π-junction behavior of the SFS structure supports fundamental concepts of supercurrent flow through magnetic media. One of the interesting application of the π-junction related to realization of a quantum bit [6].

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