Inhomogeneous superconductivity in a ferromagnet

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Abstract

We have studied a new superconducting state where the condensate wave function resulting from conventional pairing, is modified by an exchange field. Superconductivity is induced into a ferromagnetic thin film (F) by the proximity effect with a superconducting reservoir (S). We observed oscillations of the superconducting order parameter induced in F as a function of the distance from the S/F interface. They originate from the finite momentum transfer provided to Cooper pairs by the splitting of the spin up and down bands. We measured the superconducting density of states in F by tunneling spectroscopy and the Josephson critical current when F is coupled with a superconducting counter-electrode. Negative values of the superconducting order parameter are revealed by capsized tunneling spectra in F and a negative Josephson coupling (π-junction).

Key words: π-superconductivity, proximity effect, spin polarization, tunneling

1. Introduction

More than 30 years ago, Fulde and Ferrel [1], and Larkin and Ovchinnikov [2] (FFLO), showed independently that the superconducting order parameter may be modulated in real space by an exchange field. A Cooper pair, in the singlet state, acquires a finite momentum $Q = 2E_{ex}/\hbar v_F$, where $2E_{ex}$ is the exchange energy corresponding to the difference in energy between the spin-up and spin-down bands, and v_F the Fermi velocity. Therefore the phase of the Cooper pair wave function changes continuously generating an oscillating order parameter. We shall call the state corresponding to a positive order parameter the "0-state" and that corresponding to a negative order parameter the "π-state".

As pairing and coherence occurs together in bulk superconductors, the FFLO state occupies a tiny part of the phase diagram and it is fragile to atomic disorder. The Superconductor/Ferromagnet (S/F) proximity effect allows to overcome this difficulty since only phase coherence is required in F. However, this artificially generated FFLO-state vanishes on a scale given by the coherence length in F, $\xi_F = \hbar v_F/2E_{ex} = 1/Q$ [3], which is typically of the order of a few nm. Progress in the thin film deposition technology has made possible controling the layer thickness and homogeneity down to this scale.

2. Experimental

We measured the critical current, I_c, and the density of states in F, where the FFLO state is induced, as function of the ferromagnetic layer thickness. To do so, we used Superconductor Insulator-Ferromagnetic-Superconductor (SIFS) and Normal-Insulator-Ferromagnetic-Superconductor (NIFS) planar junctions, respectevely. Planar NIFS junctions allow to achieve unsurpassed energy and amplitude resolution in the tunneling spectra. Therefore small variations from the normal state background conductance can be resolved.

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The junctions were fabricated [4] by e-gun evaporation on a Si wafer in a typical base pressure of 10^{-9} Torr, with film thicknesses being monitored during growth to better than 1 Å by a quartz balance. The insulating layer was obtained by oxidazing a thin Al layer (1500Å). Tunnel junction areas (500μm x 500μm) were defined by evaporating 500 Å of SiO through shadow masks just after oxidation. A $Pd_{1-x}Ni_x$ thin layer (50 - 150 Å ; $x \sim 10\%$) was then deposited, hereafter called PdNi, and backed by a 500 Å layer of Nb ((T_c=8.8 K). The Nb and the PdNi respectively provide the Cooper pair reservoir and the ferromagnetic thin film. The four terminal cross-junction geometry is reported in the inset of Fig. 1b. The PdNi Curie temperature ~ 100K was measured by Anomalous Hall Effect. For the Josephson measurements, the Al (500Å) was evaporated on a Nb buffer (1500 Å ; T_c=9.15 K).

3. Josephson effect

The Josephson coupling, I_cR_n, at T=1.5 K as a function of the thickness of the ferromagnetic layer, d_F, is presented in the main body of Fig. 1a [5]. R_n is the junction resistance (50 $m\Omega$ - 400 $m\Omega$). The Josephson coupling is of the order of 10-20 μV, i.e. 100 times lower that that measured on junctions without PdNi. We observe damped oscillations of I_cR_n that follows the order parameter oscillations in F. As the sign of I_c cannot be determined from the I-V characteristics, the transition from positive or "0" to negative or "π" coupling is revealed as a zero of the I_cR_n product that occurs at $d_F \simeq 65$ Å. Fig. 1a also shows the best fit to the theory in which we have calculated the I_cR_n product by integrating the spectral current density found solving the Usadel equations for a SIFS junction [5]. The coherence length in F obtained from the fit is ξ_F= 28Å.

4. Tunneling spectroscopy

In Fig. 1 the superconducting density of states (DOS) at T=300 mK is presented for two different thickness of PdNi corresponding to the "0" and "π"-state [4]. The Al counter-electrode is driven into the normal state by applying a magnetic field of 100 Gauss perpendicular to the film. For the thinner ferromagnetic layer (50Å) ("0-state") the DOS displays a maximum at the Nb gap edge and a minimum at the Fermi level set to zero in our spectra. As a result of the finite interface resistance between PdNi and Nb ($\approx 10^{-10}\Omega cm^2$), the pair amplitude is small, corresponding to a few per cent difference from the background conductance. Increasing the thickness of the ferromagnetic layer (75Å)("π-state"), the DOS is flipped with respect to the normal state.

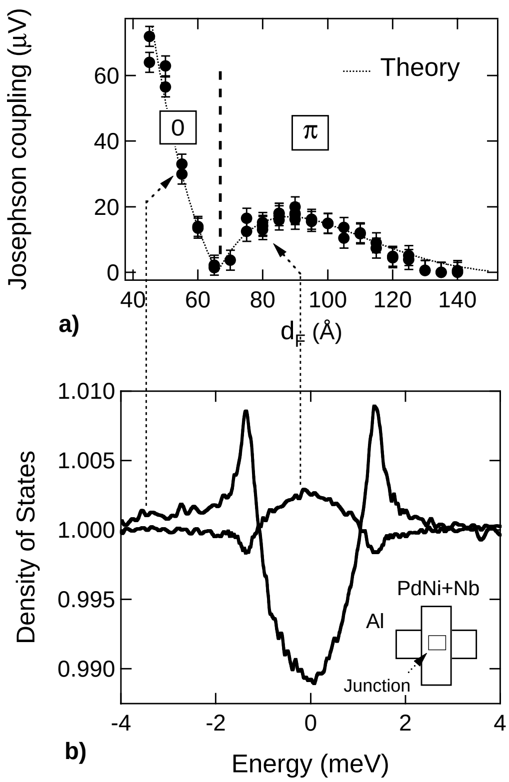

Fig. 1. a) Exponentially damped oscillations of the Josephson coupling in SIFS planar junctions. "0" and "π" junctions correspond to positive and negative coupling respectively. b) The differential conductance vs. bias of SIFN junctions shows capsized tunneling spectra in the π-state.

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