Re-entrant superconductivity in Nb/$Cu_{1-x}Ni_x$ bilayers

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(Date textdate; Received textdate; Revised textdate; Accepted textdate; Published textdate)

We report on the first observation of a pronounced re-entrant superconductivity phenomenon in superconductor/ferromagnetic layered systems. The results were obtained using a superconductor/ferromagnetic-alloy bilayer of Nb/$Cu_{1-x}Ni_x$. The superconducting transition temperature T_c drops sharply with increasing thickness d_{CuNi} of the ferromagnetic layer, until complete suppression of superconductivity is observed at $d_{CuNi} \approx$4 nm. Increasing the $Cu_{1-x}Ni_x$ layer thickness further, superconductivity reappears at $d_{CuNi}\approx$13 nm. Our experiments give evidence for the pairing function oscillations associated with a realization of the quasi-one dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) like state in the ferromagnetic layer.

The coexistence of superconductivity (S) and ferromagnetism (F) in a homogeneous material, described by Fulde-Ferrell and Larkin-Ovchinnikov (FFLO) [1, 2], is restricted to an extremely narrow range of parameters [3]. So far no indisputable experimental evidence for the FFLO state exists.

In general, superconductivity and ferromagnetism do not coexist, since superconductivity requires the conduction electrons to form Cooper pairs with antiparallel spins, whereas ferromagnetism forces the electrons to align their spins parallel. This antagonism can be overcome if superconducting and ferromagnetic regions are spatially separated, as for example, in artificially layered superconductor/ferromagnet (S/F) nanostructures (see, e.g. [4], for an early review). The two long-range ordered states influence each other via the penetration of electrons through their common interface. Superconductivity in such a proximity system can survive, even if the exchange splitting energy $E_{ex} \sim k_B\theta_{Curie}$ in the ferromagnetic layer is orders of magnitude larger than the superconducting order parameter $\Delta \sim k_BT_c$, with T_c the superconducting transition temperature. Cooper pairs entering from the superconducting into the ferromagnetic region experience conditions drastically different from those in a non-magnetic metal. This is due to the fact that spin-up and spin-down partners in a Cooper pair occupy different exchange-split spin-subbands of the conduction band in the ferromagnet. Thus, the spin-up and spin-down wave-vectors of electrons in a pair, which have opposite directions, cannot longer be of equal magnitude and the Cooper pair acquires a finite pairing momentum [5]. This results in a pairing function that does not simply decay as in a non-magnetic metal, but in addition oscillates on a characteristic length scale. This length scale is the magnetic coherence length ξ_F, which will be specified below.

Various unusual phenomena follow from the oscillation of the pairing wave function in ferromagnets (see, e.g. the recent reviews [6, 7, 8] and references therein). A prominent example is the oscillatory S/F proximity effect. It can be qualitatively described using the analogy with the interference of reflected light in a Fabry-Pérot interferometer at normal incidence. As the conditions change periodically between constructive and destructive interference upon changing the thickness of the interferometer, the flux of light through the interface of incidence is modulated. In a layered S/F system the pairing function flux is periodically modulated as a function of the ferromagnetic layer thickness d_F due to the interference. As a result, the coupling between the S and F layers is modulated, and T_c oscillates as a function of d_F.

The most spectacular evidence for the oscillatory proximity effect would be the detection of the re-entrant behavior of the superconducting transition temperature as a function of d_F, which has been predicted theoretically [9, 10, 11]. There is a sole report on the superconductivity re-entrance as a function of the ferromagnetic layer thickness in Fe/V/Fe trilayers [12]. Due to the very small thickness of the iron layers, at which the re-entrance phenomenon is expected (0.7-1.0 nm, i.e. 2-4 monolayers of iron only), the number of the experimental points $T_c(d_F)$ is very small, with a large scattering of the results.

The oscillation length $\xi_F = \hbar v_F/E_{ex}$ in strong ferromagnets, like iron, nickel or cobalt, is extremely short, because the exchange splitting energy E_{ex} of the conduction band is in the range 0.1-1.0 eV [4]. Here, v_F is the Fermi velocity in the F material and $\hbar$ Planck's constant. Ferromagnetic alloys, with E_{ex} an order of magnitude smaller, allow the observation of the effect at larger thicknesses d_F of about 5-10 nm. Such layers can be easier controlled and characterized. Another advantage using ferromagnetic alloys is that for a long-wavelength oscillation the atomic-scale interface roughness has no longer a decisive influence on the extinction of the T_c oscillations.

The S/F proximity effect has not only been studied using elemental ferromagnetic materials, but also for various ferromagnetic alloys [13, 14, 15, 16, 17, 18, 19]. A non-monotonic dependence of T_c *vs.* d_F has been observed. In the present work, Nb was chosen as a su-