Chapter 1
Extinction and Recovery of Superconductivity by Interference in Superconductor/Ferromagnet Bilayers

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Abstract In superconductor–ferromagnet (S/F) metallic contacts, the superconducting condensate penetrates through the S/F interface into a ferromagnetic layer. In contrast to the conventional S/N proximity effect, the pairing wave function not only decays deep into the F metal, but simultaneously oscillates. Interference of the oscillating pairing function in a ferromagnetic film gives rise to a modulation of the pairing function flux crossing the S/F interface, which results in oscillations of superconducting transition temperature of the adjacent S layer. In this work, we report on the experimental observation of the superconductivity reentrance phenomenon with double suppression of the superconductivity in $\mathrm{Nb/Cu_{1-x}Ni_x}$ bilayers as a function of the ferromagnetic layer thickness, d_{CuNi}. The superconducting T_c drops sharply with increasing d_{CuNi} till total suppression of superconductivity at $d_{\mathrm{CuNi}} \approx 2.5\,\mathrm{nm}$. At a further increase of the $\mathrm{Nb/Cu_{1-x}Ni_x}$ layer thickness, the superconductivity restores at $d_{\mathrm{CuNi}} \geq 24\,\mathrm{nm}$. Then, with the subsequent increase of d_{CuNi}, the superconductivity vanishes again at $d_{\mathrm{CuNi}} \approx 38\,\mathrm{nm}$.

1.1 Introduction

In superconductor–ferromagnetic metal (S/F) contacts, the superconducting pairing wave function not only exponentially decays into the F metal, as in the superconductor/normal metal (S/N) proximity effect [1, 2], but simultaneously oscillates [3, 4]. A variety of novel physical effects caused by these oscillations was predicted (see reviews [5–8] and references therein). Some of them have already been observed experimentally: nonmonotonous behavior of the superconducting critical temperature, T_c, as a function of the F metal layer thickness [9–13], Josephson junctions with intrinsic π-phase shift across the junction [14], and inverted, cap-sized differential current–voltage characteristics [15]. In this work, we report on results of observation of the reentrant T_c phenomenon with double suppression of superconductivity in $\mathrm{Nb/Cu_{1-x}Ni_x}$ bilayers ($x = 0.59$) for increasing ferromagnetic $\mathrm{Cu_{1-x}Ni_x}$ layer thickness, d_{CuNi}. After a destruction by interference effects of the superconducting pairing wave function and a subsequent recovery, a second suppression of

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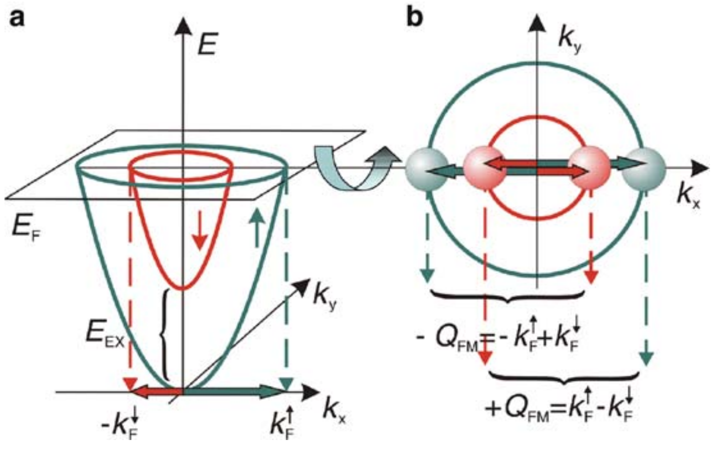

Fig. 1.1 Origin of the FFLO state. (**a**) Spin-splitting E_{ex} of the conduction band of a ferromagnet by the exchange field. Sketch for $k_z = 0$. (**b**) Cross-section of the band energy dispersions for $k_z = 0$ at the Fermi energy. Paired electrons (*green with red balls*) establish from the majority (*green*) and minority (*red*) subbands (wave number vectors indicated in the respective color). The FFLO pairing momentum along the x axis is $\hbar Q_{\mathrm{FM}} = \hbar \Delta k_{\mathrm{F}} = E_{\mathrm{ex}}/v_{\mathrm{F}}$

superconductivity is found, giving an impressive experimental evidence for a quasi-one dimensional Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) [16, 17] like state in the ferromagnetic layer.

At a plane S/F interface, the quasi-one-dimensional FFLO-like state can be generated in the F material [3–8]. Due to the exchange splitting of the conduction band (Fig. 1.1a), one of the singlet Cooper-pair electrons occupies the majority subband, e.g., spin-up, while the other one resides at the spin-down, minority subband (Fig. 1.1b). Although the pairing occurs with opposite directions of the wave number vectors of the electrons, their absolute values are not equal due to the exchange splitting of the conduction band (see Fig. 1.1a). The resulting pairing state acquires a finite momentum of $\hbar Q_{\mathrm{FM}} = E_{\mathrm{ex}}/v_{\mathrm{F}}$, where $E_{\mathrm{ex}} \ll E_{\mathrm{F}}$ is the energy of the exchange splitting of a free-electron-like, parabolic conduction band, E_{F} is the Fermi energy, and v_{F} is the Fermi velocity. Then, the pairing function of this state does not simply decay as it would be in a nonmagnetic metal, but oscillates on a wavelength scale λ_{FM} (i.e., $\lambda_{\mathrm{FM}} = 2\pi/k_{\mathrm{FM}}$) given by the magnetic coherence length ξ_{F}. In a clean ferromagnet ($l_{\mathrm{F}} \gg \xi_{\mathrm{F0}}$), it is $\lambda_{\mathrm{F0}} \equiv 2\pi\xi_{\mathrm{F0}} = 2\pi\hbar v_{\mathrm{F}}/E_{\mathrm{ex}}$ [4, 18], whereas in the dirty case ($l_{\mathrm{F}} \ll \xi_{\mathrm{F0}}$), we get $\lambda_{\mathrm{FD}} = 2\pi\xi_{\mathrm{FD}} = 2\pi\ (2\hbar D_{\mathrm{F}}/E_{\mathrm{ex}})^{1/2}$ [3, 7], where $D_{\mathrm{F}} = l_{\mathrm{F}} v_{\mathrm{F}}/3$ with l_{F} the electron mean free path in the F-metal. The decay length of the pairing wave function is l_{F} and ξ_{FD} in the clean and dirty cases respectively [3, 4, 19].

The oscillation of the pairing wave function in the F-metal is the reason for an oscillatory S/F proximity effect, yielding a nonmonotonous, oscillating dependence of the superconducting critical temperature, T_{c}, on the ferromagnetic layer thickness, d_{F}. The phenomenon can be qualitatively described using the analogy