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Double re-entrance of superconductivity in superconductor/ferromagnet bilayers

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Abstract. We report on the first observation of a double suppression of superconductivity in a superconductor/ferromagnet layered system. The result was obtained using a superconductor/ferromagnetic-alloy bilayer of Nb/$Cu_{41}Ni_{59}$ with $d_{Nb} \simeq 6.2$ nm. As the thickness of the ferromagnetic alloy gradually increases, the superconducting transition temperature T_c drops sharply until a complete suppression of superconductivity is observed at $d_{CuNi} \simeq 2.5$ nm. At further increase of the $Cu_{41}Ni_{59}$ layer thickness, superconductivity restores at $d_{CuNi} \simeq 24$ nm. Then, with a subsequent increase of d_{CuNi}, superconductivity vanishes again at $d_{CuNi} \simeq 38$ nm. Our experiments give evidence for the realization of the quasi-one dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) like state in the ferromagnetic alloy layer.

1. Introduction

In superconductor-ferromagnet 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, but simultaneously oscillates [1]. A variety of novel physical effects caused by these oscillations were predicted ([1] and references therein). Some of them have already been observed experimentally: non-monotonous and reentrant behavior of the superconducting critical temperature T_c as a function of the F metal layer thickness, Josephson junctions with intrinsic π-phase shift across the junction, inverted differential current-voltage characteristics. In this work we report on results of superconducting proximity effect experiments on Nb/$Cu_{1-x}Ni_x$ $x = 0.59$ bilayers. After a destruction by interference effects of the superconducting pairing wave function and a subsequent recovery, a second suppression of superconductivity is found, giving an impressive experimental evidence for a quasi-one dimensional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) [2, 3] like state in the ferromagnetic layer.

The origin of FFLO state physics lies in the exchange splitting of the conduction band in a ferromagnetic metal. One of the singlet Cooper-pair electrons occupies the majority subband, for example spin-up, while the other one resides at the spin-down, minority subband. Although the pairing occurs with opposite directions of the wave number vectors of the electrons, their