Critical Temperature Oscillations and Reentrant Superconductivity due to the FFLO like State in F/S/F Trilayers

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Abstract

Ferromagnet/Superconductor/Ferromagnet (F/S/F) trilayers, in which the establishing of a Fulde-Ferrell Larkin-Ovchinnikov (FFLO) like state leads to interference effects of the superconducting pairing wave function, form the core of the superconducting spin valve. The realization of strong critical temperature oscillations in such trilayers, as a function of the ferromagnetic layer thicknesses or, even more efficient, reentrant superconductivity, are the key condition to obtain a large spin valve effect, *i.e.* a large shift in the critical temperature. Both phenomena have been realized experimentally in the $Cu_{41}Ni_{59}$/Nb/$Cu_{41}Ni_{59}$ trilayers investigated in the present work.

1. Introduction

Since the classical paper of Bardeen, Cooper, and Schrieffer (BCS) [1] it is known that the superconducting state is established by electron pairs (Cooper pairs) with opposite spin and momenta. Magnetism destroys superconductivity. Ferromagnetism requires parallel arrangements of electron spins. Magnetic fields act pair breaking, because they break the time reversal symmetry [2]. Therefore, it was long time not believed that superconductivity can exist on a ferromagnetic background. Nevertheless, Fulde-Ferrell and Larkin-Ovchinnikov (FFLO) showed that superconductivity can establish in the presence of an exchange field [3,4]. In this case pairing occurs with opposite spins but a non-vanishing momentum of the Cooper pair. This so called FFLO state can only be observed for a very narrow set of parameters [5], which is extremely difficult to adjust in experiments [6-11].

Thin film structures of superconductors (S) and ferromagnets (F), however, allow to realize an FFLO like state. In this case the superconducting charge carriers penetrate into the ferromagnetic material, acquiring a non-zero momentum due to the different pairing mechanism, caused by the exchange field, in the F-material. This is different to the widely studied proximity effect at an S/N interface, and it is the reason that the paring wave function in the F material does not only decay exponentially into the non-superconducting material as in a nonmagnetic N metal, but oscillates in addition [12-16]. Thus, in S/F layers an interference of the superconducting pairing wave function can happen in analogy to the case of light in a Fabry-Pérot interferometer [17]. These interference effects lead to new physical observations, such as an oscillation of the critical temperature, T_c, if changing the thickness of the ferromagnetic layer [18,19]. Even a total extinction of superconductivity in a layered structure of superconducting and ferromagnetic materials may happen. This phenomenon was theoretically predicted [20] already a long time ago before it could be realized experimentally. Only recently, distinct oscillations of the critical temperature and a clear observation of an extinction and recovery of the superconducting state (denoted as reentrant superconducting behavior), could be demonstrated in S/F bilayers [21,22] using Nb as a superconducting material (S) and the $Cu_{49}Ni_{51}$ alloy as a ferromagnetic material (F). The multi-reentrant state, expected theoretically [20] seems to be present, too, in these experiments [22-24].

The same phenomena have recently been demonstrated in F/S bilayers of the same materials, where the superconducting film now is grown on top of the ferromagnetic one [24], contrary to the former investigated S/F bilayers. During the investigation we realized that the layers thickness and fitting parameters of the F/S bilayers, at which the oscillatory and reentrant behavior of superconductivity were observed, are not equal to that of the S/F bilayers, probably, because of different growth conditions.

Thus, we could realize both building blocks necessary for the fabrication of the core structure of the superconducting spin valve, nominally consisting of two mirror symmetric bilayers [25]. In other words, the spin valve core consists of a F/S/F trilayer, which can be regarded as a package of a F/$\tilde{S}$ and $\tilde{S}$/F bilayers so that S=2$\tilde{S}$ in the trilayer [22,24].

However, the real system is not symmetric with respect to the median plane because of different growth conditions of the F layers and of different properties of the F/$\tilde{S}$ and $\tilde{S}$/F interfaces as well. Moreover, in reality an F/S/F trilayer is not simply a stack of the F/$\tilde{S}$ and $\tilde{S}$/F bilayers, studied separately before. The properties of the superconducting layer with a thickness of $d_S=2d_{\tilde{S}}$ (e.g. the electron mean free path and the critical temperature of a free standing film, which increase with the thickness) differ from those of the $\tilde{S}$ layers. Thus, a different influence especially on the reentrant superconducting behavior is expected.