THE STUDIES OF BILAYERS AND TRILAYERS OF FERROMAGNETS AND SUPERCONDUCTORS IN A SPIN VALVE CORE STRUCTURE

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Abstract

Superconductor (S) critical temperature oscillations and reentrant superconductivity with increasing thickness of ferromagnetic (F) layer in F/S nanolayered structures are based on interference effects of the superconducting pairing wave function. The Fulde–Ferrell Larkin–Ovchinnikov (FFLO) like state establishing in these geometries is the origin of the phenomenon. Up to now it has been extensively investigated on thin film S/F bilayers with first superconducting layer (S-layer is grown on the substrate). Recently, we have also observed the oscillating phenomena in F/S bilayers where Nb as the S-metal now is grown on the top of the Cu\textsubscript{41}Ni\textsubscript{59} as F-material. Junction of both kinds of bilayers yields an F/S/F trilayer, being the core structure of a superconducting spin valve. For all mentioned cases, we observed deep oscillations of superconducting critical temperature, \( T_c \), and reentrant superconductivity, which are the necessary condition to obtain a large spin switching effect, i.e., a large shift in \( T_c \), if the relative orientation of the magnetizations of the F-layers is changed from parallel to antiparallel.

1. Introduction

The superconducting thin film sandwiched by two ferromagnetic layers is the core structure of the pronounced theoretically superconducting spin valve [1]. The magnetization directions of the F-layers might be different at certain magnitudes of applied external magnetic field. The superconducting transition temperature is affected by the angle between the F-layers magnetizations. The maximal difference in \( T_c \) is predicted for the parallel \( P \) and antiparallel \( AP \) alignment of F-layer magnetizations (\( \Delta T_{c}^{AP-P} \)). Superconductivity can be switched on and off if \( \Delta T_{c}^{AP-P} \) exceeds the width of epy superconducting transition.

Contrary to the extensively-studied S/N case (N is a normal conducting, nonmagnetic material) the peculiarity of the S/F proximity effect, which is also the base of the superconducting spin valve phenomenon, is that a quasi-one dimensional FFLO-like state [2, 3] is generated in the ferromagnetic layer [4, 5].

The FFLO state in a bulk material is restricted to a very extreme and narrow range of parameters [6, 7] and is hardly achievable in experiments [8, 9]. The quasi-one dimensional FFLO-like state is induced in F/S nanolayered structures providing not only the decay of the superconducting pairing wave function but also oscillations over the thickness. In induced FFLO state, the Cooper pairing is the result of the combining of electrons with antiparallel spin as in the BCS theory [10]. Their moments, although being in opposite directions, do not have the same absolute value. This yields non-vanishing pairing momentum and the oscillating pairing wave function...
function mentioned above.

Interference phenomena of the oscillating superconducting pairing wave function arise, if the thickness of the F-material has a limited value and the superconducting pairing wave function is reflected at the outer surface of the F-material of a (e.g.) F/S bilayer [11]. With changing thickness of the F-layer, this interference becomes constructive or destructive. As a result, the superconducting critical temperature oscillates as a function of the thickness $d_F$ of the F-layer for a given thickness $d_S$ of the S-layer. In a certain range of fairly thin $d_S$ even an extinction of the superconducting state with a subsequent recovery, i.e., a reentrant superconducting state, is predicted [12].

The phenomenon was studied in detail experimentally beginning from Nb/Ni bilayers [13], further on F/S (Nb/Cu$_{41}$Ni$_{59}$) [14, 15] and S/F (Cu$_{41}$Ni$_{59}$/Nb) [16] bilayers, where the sequence of the layers is different, and F/S/F Cu$_{41}$Ni$_{59}$/Nb/Cu$_{41}$Ni$_{59}$ trilayers [17]. The F/S/F trilayers are the core of the superconducting spin valve. In all cases of the Cu$_{41}$Ni$_{59}$ compound as F-metal, deep critical temperature oscillations were detected experimentally. Moreover, the reentrant superconducting state was also observed. These are the key conditions for creating a spin valve with a large $\Delta T_c^{AP-P}$ [15]. The most important results of these investigations are overviewed in the present paper.

2. Sample Preparation and Characterization

The wedge technique [13-17] was applied to fabricate all sample series discussed in the present work. After achieving the base pressure of about $2 \times 10^{-6}$ mbar the Si substrate was covered by an amorphous Si buffer layer using Ar as a sputter gas. In the case of an S/F bilayer, then the S-material (Nb) was deposited by dc magnetron sputtering, applying a operating magnetron, which is moved by a dc motor drive along a $80 \times 7$mm$^2$ substrate. This spraying procedure increases the homogeneity of the S-material. Next, utilizing the intrinsic gradient of the sputtering rate by placing the substrate out of the symmetry axis of the sputtering target, a wedge shaped F-metal (Cu$_{41}$Ni$_{59}$) layer was deposited using the RF-mode of the magnetron. Finally, the F-layer is covered with a thin silicon cap layer to avoid the degradation at atmospheric conditions of the wedge-like basis sample. Then, a series of samples was cut perpendicular to the thickness gradient of the wedge.

To fabricate F/S bilayers, the S-layer was deposited over the wedge type F-layer, what means different growth conditions in comparison to the above described preparation of S/F bilayers. In the case of F/S/F trilayers, two different kinds of sample series were produced, namely the single wedge geometry, with a flat bottom F-layer and a wedge type top F-layer (see sample FSF1 no. 5 in Fig. 1, for critical temperature measurements see Ref. [17]) and the double wedge geometry, with both wedge-like F-layers. S-layer has a constant thickness for each case. For S/F and F/S bilayers, also a different type of samples was investigated, where an S-wedge is covered with a physically infinite F-layer of constant thickness. Thus, the critical thickness of the Nb-layer below which superconductivity is suppressed [15, 16] was derived.

The determination of the thickness of the different layers was performed by Rutherford Backscattering Spectrometry (RBS). The results for the samples of series FSF5 of double wedge geometry trilayers are presented on the left part in Fig. 1. For both types of bilayers (S/F and F/S), the Ni-Cu percentage of the F-layer was evaluated by this method [13-16].

Cross sectional Transmission Electron Microscope (TEM) image of sample no. 9 of the same FSF5 series is presented in Fig. 1 on the right part, demonstrating the perfect smooth boundaries between the layers. A detailed analysis of the High Resolution Electron Microscopy
(HRTEM) images allows getting some knowledge about the growth direction of the layers [16]. More detailed information is obtained from electron diffraction patterns performed in the TEM [17].

![Image of HRTEM and cross-sectional TEM image](image)

**Fig. 1.** Results of RBS measurements for the thickness of the samples in the series FSF5 (left) and cross sectional TEM image (right) of (Cu₄₁Ni₅₉/Nb/Cu₄₁Ni₅₉) double wedge geometry trilayer (series FSF5, sample no. 2).

3. **Superconducting Properties**

The core structure of the superconducting spin valve structure may be regarded as an arrangement of F/S-S/F bilayers. This means that the thickness of the S-material in the resulting F/S/F trilayer is about twice compared to the respective bilayers.

Dependences of $T_c(d_F)$ for different fixed thicknesses of the S-material in F/S/F trilayers and F/S and S/F bilayers are shown in Fig. 2. In all cases, deep oscillations of superconductor critical temperature could be realized. If the thickness of S-layers is thin enough, even the reentrant, and moreover, evidence for a multi-reentrant superconducting state, is observed. The experimental data are described by the theory [12] elaborated for the different kinds of sample series and parameterized for the use of measurable physical parameters [13, 15, 17].

The fit parameters of the theory are: $T_c0,Nb$ is the critical temperature of a free standing Nb film of the given thickness, according to Fig. 5 of Ref. [15]; $\xi_S$, the superconducting coherence length in the S-metal, as defined, e.g., in Eq. 1 of [15]; $N_{FV_F}/N_{S\tau_S}$, the ratio of Sharvin conductances at the S/F interface, $\xi_{F0}$, the coherence length for Cooper pairs in a F-metal; $l_F$, the mean free path of conduction electrons in a F-material and $T_F$, the interface transparency parameter. Furthermore, $\xi_{BCS} = 42$ nm was used for the BCS coherence length [18]. The fit parameters are of similar size, except for $l_F/\xi_{F0}$, which is extensively large for the S/F bilayers and for the top layer of the samples of series FSF5. Since $\xi_{F0}$ is similar for all samples, this means that $l_F$ is larger for these samples, where the F-film is grown on the top of the S-layer.
Fig. 2. Superconductor critical temperature, $T_c$, of S/F and F/S bilayers and F/S/F trilayers (S-layer is Nb, F-layer is Cu$_{41}$Ni$_{59}$) as a function of the F-layer thickness for different constant S-layer thicknesses $d(Nb)$, according to Refs. [15-17]. In the case of F/S/F trilayers $d(CuNi)$ denotes the sum of the thicknesses of the bottom (B) and top (T) layers, $d(CuNi) = d_{CuNi-B} + d_{CuNi-T}$. The Table summarizes the fitting parameters used for the theoretical curves, as defined in the text. For samples FSF3 and FSF5, the upper rows refer to the top ferromagnetic layer, whereas the lower ones to the bottom F-layer.

4. Conclusions

It was demonstrated that the building blocks (i.e., S/F and F/S bilayers) of the superconducting spin valve core could be realized and even the F/S/F core structure itself. All of them show the required superconducting critical temperature dependence on the F-material layer thickness to get a functioning AF-F/S/F spin valve.

The next step is to realize the antiparallel alignment for F-layer magnetizations at an applied magnetic field. It could be achievable by means of sufficient exchange bias between the bottom F-layer and the AF-sublayer or using a possible difference in magnetic anisotropy of F-layers. Then the spin valve is expected to exhibit critical temperature shift, $\Delta T_c^{AP-P}$, in the Kelvin range for the states with antiparallel and parallel mutual magnetization directions of the top layer and the bottom layer, as already theoretically calculated [15].
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