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Point contact Andreev reflection spectroscopy on ferromagnet/superconductor bilayers

F. Giubileo [a,*], F. Romeo [b,a], R. Citro [b,a], A. Di Bartolomeo [b], C. Attanasio [b,a], C. Cirillo [a,b], A. Polcari [c], P. Romano [c,a]

[a] CNR-SPIN Salerno, c/o Dipartimento di Fisica, Università degli Studi di Salerno, 84084 Fisciano, SA, Italy
[b] Dipartimento di Fisica "E.R. Caianiello", Università degli Studi di Salerno, 84084 Fisciano, SA, Italy
[c] Dipartimento di Scienze e Tecnologie, Università del Sannio, 82100 Benevento, Italy

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ABSTRACT

We performed point contact spectroscopy experiment by pushing gold tip on the ferromagnetic side of $Nb/Pd_{0.84}Ni_{0.16}$ bilayers. Several contacts have been measured at temperature 4.2 K evidencing a wide variety of features (zero bias peak, conductance dips, etc.) appearing in the differential conductance spectra at energies up to Nb energy gap. A theoretical model has been developed within the scattering theory for ferromagnetic/superconductor heterostructures to fit experimental data. All different features can be consistently explained in our model by taking into account the spin polarization as well as the thickness of the ferromagnetic layer. We also show that we can give very precise estimation of such ferromagnetic characteristics.

1. Introduction

The rapid advance in the field of spintronics has focused considerable attention on the study of spin-polarized transport properties in magnetic materials, in particular concerning the precise measurement of the spin polarization (P). Electron spin polarization is defined as the ratio of the density of state of spin-up and spin-down at the Fermi level. P is commonly measured in magnetic tunnel junction experiments, but this involves long and complex thin film fabrication processes with reproducibility task related to the quality of the insulating barrier. Moreover, following the idea by Meservey and Tedrow [1], spin-dependent tunneling experiment requires a high external magnetic field in order to Zeeman split the superconducting density of states when tunneling happens from a ferromagnetic electrode to a superconductor. In the last decade, point contact Andreev reflection spectroscopy (PCAR) has been proposed [2–4] as a very simple method to determine the spin polarization in ferromagnetic materials in ferromagnet/superconductor (F/S) point contacts, profiting from the spin-sensitivity of the Andreev reflection [5], a charge transfer process happening at energies below the superconducting energy gap. For a metal/superconductor (N/S) point contact, an electron coming from the normal metal with energy lower than the energy gap Δ cannot enter in S and it is reflected as a hole in the normal metal, while a Cooper pair enters the condensate in the superconducting electrode resulting in an enhancement of the conductance at low bias. A different situation is realized when the normal electrode is ferromagnetic: the probability of Andreev reflection is reduced because of the imbalance in the density of states for spin-up and spin-down electrons. Consequently, conductance at low bias is reduced allowing an estimation of the spin polarization by analyzing such conductance spectra. Experimentally, few papers have reported about the effect of the spin polarization and of the F-layer thickness on the conductance spectra, i.e., on the density of states [6,7]. In this paper we report point contact spectroscopy experiment performed on ferromagnet/superconductor bilayer and we introduce a scattering model based on the Bogoliubov–de Gennes formalism in order to discuss the effects of a nanometric ferromagnetic layer on the conductance spectra. The paper is organized as following: Section 2 is a review on Blonder–Tinkham–Klapwijk (BTK) model [8] for a conventional s-wave superconductor in contact with normal metal and the extension to the case of ferromagnetic electrode [3,9,10]. In Section 3 we report point contact Andreev reflection experiments on S/F bilayers showing conductance curves obtained at low temperature ($T = 4.2$ K). In Section 4 we introduce our theoretical model to take into account the bilayer configuration of the experiment and we show and discuss the achieved theoretical fittings. Finally, in Section 5 we give our conclusions.

* Corresponding author at: CNR-SPIN Salerno, c/o Dipartimento di Fisica, Università degli Studi di Salerno, Fisciano, SA, Italy. Tel.: +39 089969329.
E-mail address: filippo.giubileo@spin.cnr.it (F. Giubileo).

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2. BTK model and its modification to the ferromagnetic case

A point contact junction between a normal metal and a superconductor allows easy modification of the potential barrier and of the contact area between the N and S electrodes tuning a continuous variation from a transparent NS contact to a tunnel junction N–I–S in which an insulating barrier (I) is present in between the two electrodes. Blonder et al. [8] have analyzed this transition within a generalized semiconductor model, using the Bogoliubov–de Gennes equations to treat the transmission and reflection of quasiparticles at the interface. A N/S contact (with S a conventional s-wave superconductor) can be described by only two parameters, the superconducting energy gap Δ and a dimensionless parameter Z to quantify the barrier strength. The $Z = 0$ case corresponds to a completely transparent barrier so that the transport current is predominantly due to Andreev reflections. By increasing Z, the Andreev reflections are partially suppressed and the conductance spectra tend to the case of a N/I/S tunnel junction (see Fig. 1, left panel). According to the BTK model the differential conductance characteristics for a N/S contact is:

$$G_{NS}(\mathrm{eV}) = \frac{dI(\mathrm{eV})}{dV} = G_{NN}\int_{-\infty}^{+\infty} dE[1 + A(E) - B(E)]\left[-\frac{df(E+\mathrm{eV})}{d(\mathrm{eV})}\right] \quad (1)$$

where $A(E)$ and $B(E)$ are the Andreev reflection and normal reflection probabilities, G_{NN} is the normal conductance, $f(E)$ is the Fermi function, V is the voltage bias.

The BTK model has been modified to take into account the spin polarization when the normal electrode is substituted with a ferromagnet [2,3]. In particular, the total current in the contact is considered as the result of two contributions:

$$I_{tot} = P \cdot I_p + (1 - P) \cdot I_{unp} \quad (2)$$

where I_{unp} is the unpolarized component of the current (carrying no net polarization), and I_p is quasiparticle current carrying all of polarization. Consequently, P can be determined by point contact experiments [3] by noting that the conductance spectra $G(V)$, i.e. $dI(V)/dV$ can be written as follows:

$$G_{tot}(V) = (1 - P)\frac{dI_{unp}(V)}{dV} + P\frac{dI_p(V)}{dV} \quad (3)$$

Independently, another group [4] also demonstrated the possibility to use PCAR to extract spin polarization information and opening the route to a well established procedure that nowadays has been widely used to characterize several magnetic materials.

A further step, by Strijkers et al. [9], takes into account also the presence of a weak superconducting layer (with reduced energy gap) at the F/S interface due to the proximity effect. In this case, the Andreev reflection and normal reflection probabilities are modified (see Table 1).

In Fig. 1 we show a comparison between the BTK model (left plot), the effect of spin polarization P of the ferromagnetic electrode on the conductance curves (central plot) and the modification of the spectra due to the proximity effect (right plot).

3. Experiment

The F/S bilayers have been deposited by a three-target dc magnetron sputtering with base pressure of about 10^{-8} mbar. The Nb (40 nm thick) and $Pd_{0.84}Ni_{0.16}$ (4 nm) layers have been grown on Al_2O_3 substrates at typical argon pressures of few microbar, while keeping substrate at 100 °C. Calibrated deposition rate and thickness monitor allow precise estimation of the ferromagnetic layer thickness. The Ni content of the ferromagnetic alloy has been determined by energy dispersion spectroscopy measurements. The superconducting transition temperature was determined by measuring resistive transition by standard four-probe method. 40 nm Nb thin film showed very sharp transition (width ~50 mK) with $T_c^{Nb} = 8.2$ K and low temperature resistivity $\rho_{Nb} = 12\ \mu\Omega$ cm. The critical temperature of the bilayer with 4 nm thick ferromagnetic layer resulted $T_c^{bilayer} = 7.2$ K (for more details see [11]).

Point contact experiments have been realized by pushing a metallic tip (Au) on the sample surface (ferromagnetic side). A scheme of the setup is reported in Fig. 2a. The I vs V curves have been measured in standard four-probe configuration, while the differential conductance spectra dI/dV vs V have been obtained by numerical derivative. The experimental setup for point contact was installed on cryogenic insert directly mounted on a cryostat, allowing measurements in liquid helium. By varying the tip position and pressure on the sample, we have got several different contacts with normal resistance in the range 2–10 Ω. In Fig. 2b and c we report two examples of conductance spectra measured at $T = 4.2$ K. The spectrum in Fig. 2b is characterized by huge peak at zero bias (with conductance ratio $G_{NS}(V = 0)/G_{NN}$ greater than 2) with triangular shape, and large dips at energies around the gap energy. The spectrum in Fig. 2c presents a squared conductance feature (with conductance ratio $G_{NS}(V = 0)/G_{NN} \simeq 1.6$) for energies below the gap energy and two additional maxima above energy gap. At a first qualitative sight, these data can appear puzzling and could suggest large variations of the superconducting properties. We will show that the theoretical fittings of the conductance spectra according to our model (discussed in the next section) give clear explanation of experimental data in terms of effects due to the presence of ferromagnetic layer and of its spin polarization as well as its thickness. In the following, experimental data have been normalized: conductance is expressed as G_{NS}/G_{NN} while energy scale is normalized to the Nb energy gap (eV/Δ_{Nb}). Moreover, we also considered the case of a small resistance in

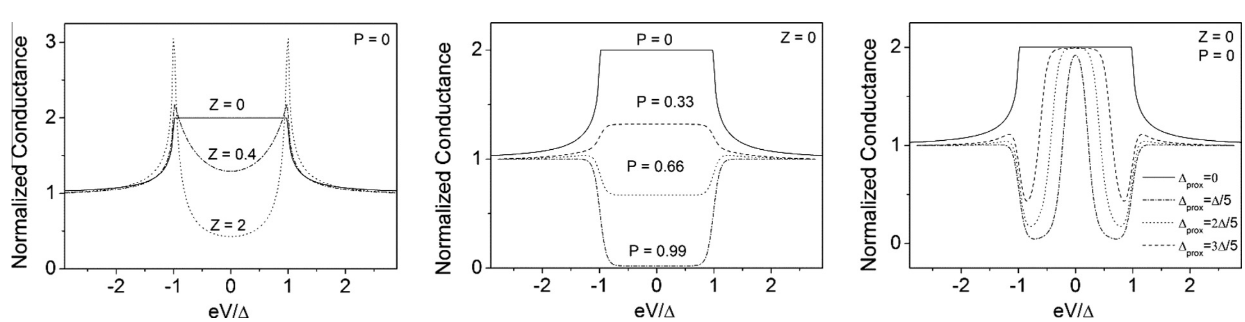

Fig. 1. Conductance spectra calculated within standard BTK model (left panel) for different values of the dimensionless parameter Z; (central panel). Effect of the polarization on the conductance spectra with $Z = 0$; (right panel). Evolution of conductance spectra due to the proximity gap at the F/S interface.

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