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Proximity effect between superconductors and ferromagnets

H.v. Löhneysen [a,b,*], D. Beckmann [c], G. Goll [a], F. Pérez Willard [d], H. Stalzer [a], M. Stokmaier [a], C. Sürgers [a]

[a] Physikalisches Institut and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany
[b] Forschungszentrum Karlsruhe, Institut für Festkörperphysik, D-76021 Karlsruhe, Germany
[c] Forschungszentrum Karlsruhe, Institut für Nanotechnologie, D-76021 Karlsruhe, and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany
[d] Laboratorium für Elektronenmikroskopie and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany

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Abstract

Superconductors (S) can be employed to probe the spin polarization of ferromagnetic metals (F) by virtue of Andreev reflection. Using nanocontacts defined by e-beam lithography, the spin-polarization of the current across an S/F interface can be determined reliably. Via non-local Andreev reflection, an incident electron from a nanocontact is retroreflected as a hole in an adjacent contact, forming spatially separated but entangled Einstein–Podolski–Rosen pairs. Finally, the proximity-induced superconductivity can be probed by magnetization measurements.

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1. Introduction

The proximity effect of a superconductor (S) in contact with a ferromagnet (F) has attracted considerable new interest, after an oscillatory behavior of the Cooper pair amplitude in the ferromagnet was theoretically predicted to occur in S/F multilayers [1,2]. Due to the exchange field in the ferromagnet, the pair-breaking parameter is complex and causes a spatial modulation of the superconducting order parameter in the ferromagnetic interlayer. This spatial modulation arises from the finite momentum transfer for Cooper pairs due to the splitting of spin-up and spin-down bands in F. For certain thicknesses d_F of the ferromagnetic layer the phase of the order parameter changes by $\Delta\phi = \pi$ across the barrier (so-called π-junction) leading to a non-monotonic dependence of $T_c(d_F)$ [3].

Although $T_c(d_F)$ measurements on sputtered Nb/Gd multilayers and triple layers have been interpreted in terms of this mechanism [4], the loss of ferromagnetic order at thin interlayer thicknesses [5] or a magnetically ‘‘dead’’ interface region [6] can also result in a non-monotonic behavior of $T_c(d_F)$. Clear evidence for π-coupling was obtained, *inter aliter*, from the non-monotonic T dependence of the critical Josephson current between S/F/S structures [7].

A new pitch came into the field when S/F contacts were investigated towards possible applications in spintronics [8] where the experimental determination of the degree of current spin polarization has become a key issue. Recently, the analysis of Andreev reflection [9] in S/F point contacts has been used to extract this spin polarization in a variety of materials [10–15]. The theoretical analysis of these S/F point-contact experiments has been mainly carried out in the spirit of the Blonder–Tinkham–Klapwijk (BTK) theory

* Corresponding author. Address: Physikalisches Institut and Center for Functional Nanostructures, Universität Karlsruhe, D-76128 Karlsruhe, Germany. Tel.: +49 721 608 3450; fax: +49 721 608 6103.
E-mail address: H.vL@pi.uka.de (H.v. Löhneysen).

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[16] for Andreev reflection at a S/normal-metal (N) interface. This is the coherent process by which an electron from N enters S and a hole of opposite spin is retro-reflected, creating a spin-singlet Cooper pair in the superconductor. The sensitivity of the Andreev process to the spin of the carriers leads in a spin-polarized situation to a reduction of its probability [17]. An issue of considerable importance is how the spin polarization of the Andreev reflection is related to the ferromagnet's bulk spin polarization [18].

Here we review our recent work on S/F nanostructures prepared in a controlled fashion [19,20]. Very recently, evidence for crossed Andreev reflection was found, i.e. a splitting of a Cooper pair (or more precisely an Andreev pair, as will be discussed below) into two spatially separated leads [21]. In S/N layers, the proximity-effect-induced superconductivity in N gives rise to diamagnetic screening currents well below the superconducting transition temperature T_c. The field-screening response of N is remarkably different from that of S [22,23]. An interesting issue is the fate of N when a ferromagnetic layer is attached to the opposite face of N.

2. Current spin-polarization through Al/F point contacts

Andreev reflection can be observed directly by point-contact spectroscopy. In fact, even contacts with "diameter" down to a single atom exhibit subgap features in the current–voltage characteristics that are well described by multiple Andreev reflection [24]. In order to probe ferromagnetism by Andreev reflection, the superconducting properties of S should not be affected by F. Hence it is necessary to prepare nano-sized S/F contacts. In our work, Al/Co point contacts were fabricated by structuring a hole of 5–10 nm diameter into a 50 nm thick Si_3N_4 membrane, evaporating on one side a 200 nm Al layer, and on the other side a Co/Cu double layer with $d_{Co} + d_{Cu} = 200$ nm and $d_{Co} = 6$–50 nm [19]. For the interpretation of Al/Co point-contact spectroscopy data, a minimal model was developed in terms of a straight-forward extension of the BTK model [16] employing two spin-dependent transmission coefficients $\tau_\uparrow$ and $\tau_\downarrow$.

Fig. 1 shows the measured differential conductance $G = dI/dV$ for a sample with $d_{Co} = 6$ nm at various temperatures normalized to the normal-state conductance G_N together with fits where $\tau_\uparrow$, $\tau_\downarrow$, and the superconducting energy gap Δ are fit parameters. For transmission coefficients $\tau < 1$, a finite probability amplitude $1 - \tau$ exists that an electron experiences ordinary reflection. This leads to a minimum of G at zero bias and sharp maxima at voltages corresponding to the energy gap. Fits to the data of Fig. 1 and similar data for other samples yield $\tau_\uparrow = 0.40 \pm 0.02$, $\tau_\downarrow = 0.98 \pm 0.01$, and $\Delta = (190 \pm 10)$ μeV independent of d_{Co}, demonstrating that one is indeed observing an S/F interface effect [19]. The current spin polarization $P = |\tau_\uparrow - \tau_\downarrow|/(\tau_\uparrow + \tau_\downarrow)$ is found to be 0.42 ± 0.02. The above analysis in terms of the $\tau_\uparrow - \tau_\downarrow$ model was extended successfully to describe the magnetic field dependence of G in Al/Co point contacts [19].

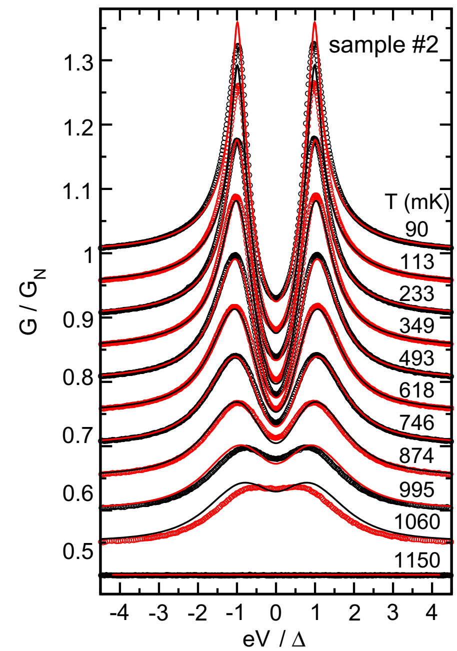

Fig. 1. Differential conductance G normalized to the normal-state value G_N for a nanostructured Al/Co point contact for different temperatures. For clarity, the curves are shifted downwards successively by 0.05 units with increasing temperature. The solid lines are calculated with the $\tau_\uparrow - \tau_\downarrow$ model.

In order to explore the relation between bulk spin polarization in F and the spin polarization P of the Andreev current, we studied the dependence of the Andreev conductance across Al/Fe interfaces on the contact resistance R [20]. Assuming ballistic transport through a spherical orifice between Al and Fe, the contact radius r is directly related to R via $R = (4/3\pi)\rho l/r^2$ where ρ is the electrical resistivity and l is the electron mean free path [23]. In our Al/Fe samples, R measured at 4.2 K varied between 2.68 Ω and 24.2 Ω, corresponding to a change in r by a factor of 3. In view of the fact that all samples were prepared in the same fashion and that the product ρl enters the expression of R, we are confident that it is chiefly r that determines R. Across this series of samples, P increases systematically from 0.452(9) to 0.487(5) where the statistical error reflects the scatter of a number of measurements, all taken below 200 mK $< 0.2T_c$. A possible explanation for this dependence is as follows. For a small R (large r) the Andreev-reflected electrons probe a larger volume than for a large R (small r). If spin–orbit scattering – with a constant scattering length – is operative, the spin polarization of carriers will decrease more strongly for larger volumes, leading to a reduction of P for small R.

3. Crossed Andreev reflection in S/F hybrid structures

A very recent development is the observation of crossed, i.e., non-local, Andreev reflection in Al/Fe nanostructures