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Superconductivity and magnetism/Supraconductivité et magnétisme

The effects of magnetization switching on the superconducting properties of S/F bilayers and $F/S/F$ trilayers

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Abstract

We discuss different effects which are experimentally found in superconductor (S)/ferromagnet (F) hybrids when the magnetization of the F-layers is inhomogeneous, or when the magnetization directions in different F-layers are not parallel. In bilayers consisting of Nb and Permalloy (Py), we find a lowering of the resistance in the superconducting transition at the coercive field H_{co} of the Py layer, which we attribute to the effects of domain walls. In trilayers of $Cu_{0.46}Ni_{0.54}$/Nb/$Cu_{0.46}Ni_{0.54}$ we find an increase of the depairing current in the superconducting state around H_{co}, which is probably also due to domain walls. In trilayers of Py/Nb/Py, however, we find, besides domain wall effects from individual layers, a strong increase of the resistance in the transition when the magnetization directions of the two Py layers are switched to an antiparallel geometry. We ascribe this to the presence of spin-polarized quasiparticles. ***To cite this article: J. Aarts, A.Yu. Rusanov, C. R. Physique 7 (2006).***

Résumé

Des effets des changements de l'aimantation sur les propriétés supraconductrices des bicouches *S/F* et des tricouches *F/S/F*. Nous discutons certains effets expérimentaux rencontrés dans les hybrides supraconducteur (S)/ferromagnétique (F) quand l'aimantation des couches F est inhomogène, ou quand les directions d'aimantation des différentes couches F ne sont pas parallèles. Dans les bicouches Nb/Permalloy (Py), nous trouvons une diminution de la résistance à la transition supraconductrice sous le champ coercitif de la couche Py, que nous interprétons comme un effet des parois de domaines. Dans les tricouches $Cu_{0.46}Ni_{0.54}$/Nb/$Cu_{0.46}Ni_{0.54}$, nous trouvons une augmentation du courant de dépairage dans l'état supraconducteur autour de H_{co}, qui est probablement aussi due aux parois de domaines. Cependant, dans les tricouches Py/Nb/Py, nous trouvons, en plus de l'effet des parois de domaine présentes dans les couches individuelles, une forte augmentation de la résistance à la transition quand les directions d'aimantation des deux couches Py sont commutées dans des directions non parallèles. Nous atribuons cet effet à la présence de quasiparticules polarisées en spin. ***Pour citer cet article : J. Aarts, A.Yu. Rusanov, C. R. Physique 7 (2006).***

Keywords: Superconducting spin switch; Domain-wall-enhanced T_c

Mots-clés : Changements de spin supraconducteur ; Augmentation de T_c due aux parois de domaines

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1. Introduction

When a superconductor (S) is in contact with a ferromagnet (F), the superconducting order parameter is suppressed on the S-side of the interface due to the proximity effect. The suppression can be strong, because in the F layer the pair breaking effect of the exchange field h_{ex} of the ferromagnet is added to the thermal dephasing present in normal (N) metals. On the F-side of the interface this leads to a damped pairing function, as in the N case, but the damping has an oscillatory component which can be described as the interaction of a Cooper pair with h_{ex} [1]. These oscillations lead to the well-known change in the phase difference between the two S banks in an $S/F/S$ geometry from 0 to π for certain thicknesses d_F of the F-layer [2]. This in turn leads to such phenomena as an oscillatory superconducting transition temperature as function of d_F [3], or non-monotonic behavior of the Josephson current of an $S/F/S$ or $S/F/I/S$ junction (with I an insulator) as function of d_F or temperature T [4,5]. Also on the S side of the interface the interaction can lead to interesting phenomena, in particular when the Cooper pair can sample different directions of h_{ex} within its coherent volume. This can happen, for instance, in an $F/S/F$ geometry with an S-layer of thickness d_S of the order of the coherence length ξ_S, in which the magnetization of one F-layer can be rotated with respect to the other. In that case, the suppression of the order parameter in S will be larger when both magnetizations are parallel (P) and smaller when they are antiparallel (AP) [6], leading to a superconducting transition temperature for the P-state T_c^{P} which is lower than that for the AP-state, T_c^{AP}. This difference can even be boosted by making use of the oscillatory order parameter and under special circumstances, including a particular choice for the thicknesses d_F and d_S, the mechanism could allow full switching between the superconducting and the normal state [7]. A realization of this so-called superconducting spin switch was reported by Gu et al. [8], and more recently by Potenza and Marrows [9]. Both experiments were conducted with a device consisting of weakly ferromagnetic CuNi and superconducting Nb, and in both cases the reported T_c^{AP} was only about 5 mK [8] or 2.5 mK [9] higher than T_c^{P}, less than the width of the transition. The smallness of the effect is probably due to the difficulty of producing highly transparent interfaces with these and similar alloys.

Here, we want to address two related aspects of the issues of spin switching and the simultaneous sampling of different magnetization directions. One is that also domain walls in the ferromagnet should affect the superconductor. Such walls intrinsically offer different directions of h_{ex} and they also separate domains with different directions of h_{ex}. Below we present results on two different types of systems. The first is an S/F bilayer of Nb and $Ni_{80}Fe_{20}$ (Permalloy, Py), a strong ferromagnet with sharp switching behavior at low coercive fields H_{co} and relatively wide domain walls. The second is an $F/S/F$ trilayer of Nb and $Cu_{46}Ni_{54}$, which is a weak magnet with somewhat larger values for H_{co}. In the first system, we observe that in the resistive transition the superconductivity is enhanced around H_{co}, when the amount of domains is largest. In the second system we observe no effects in the transition, but below T_c the critical (depairing) current is enhanced around H_{co}. The other aspect we want to address has to do with the strength of the ferromagnet. Both theory and experiments for the superconducting spin switch are mainly performed in the limit of weak spin polarization P_s or weak h_{ex}, and it is not clear what happens when P_s is increased. If more highly transparent interfaces are advantageous for spin switching, combinations of elemental metals such as V/Fe should be considered [10], but Fe has a considerable larger P_s than weak ferromagnets such as CuNi or PdNi. Following up on the experiments on Nb/Py bilayers, we also performed measurements on Py/Nb/Py trilayers. Since the Py layer on top of the Nb layer can have a significantly different switching field than the bottom Py layer, a well-defined field range can exist for the P- and the AP-states. Again measuring in the resistive transition, we now find enhanced *resistance* in the AP-configuration instead of enhanced superconductivity. This is opposite to the predicted spin switch effects and apparently due to the spin polarization of the quasiparticles, as will be discussed.

2. Experimental

Some of the details can be found in earlier publications [11–13]. All samples were prepared by sputter deposition in an ultrahigh vacuum system with a base pressure of about 10^{-9} mbar. Samples are denoted as s/A(d_A)/B(d_B), with s the substrate, A, B the different materials, and d_A, d_B the layer thickness in nm. Thick Nb films have a T_c of 9.2 K, similar to the bulk. The Ginzburg–Landau coherence length, as extracted from measurements of the upper critical field, varies slightly over time but on average it is $\xi_{\mathrm{GL}}(0) \approx 13$ nm. Using $\xi_{\mathrm{GL}}(0) = 0.86\sqrt{\xi_0 \ell_N}$, with the BCS coherence length $\xi_0 \approx 40$ nm, this yields a value for the normal state elastic mean free path $\ell_N \approx 5.5$ nm. Ferromagnetic Py possesses a large spin polarization (45% [14]), and shows well-defined magnetization switching at low fields. All samples were shaped in bars or bridges, and for the samples involving Py, care was taken to align the long axis of the bars with the easy axis of magnetization $\hat{e}_e$, which is induced by the residual magnetic fields in the sputtering machine. Magnetic fields were applied in the plane of the sample, along the bars and therefore along $\hat{e}_e$. The switching field of the Py layers mostly depends on the underlying layer and somewhat on the thickness. For 50 nm Py on Si we find switching fields around 1–2 mT, for 20 nm Py on Nb they are larger, around 8–10 mT. Weakly ferromagnetic CuNi films were sputtered from a target of $Cu_{50}Ni_{50}$ which resulted in a slightly different Ni concentration in the films of $Cu_{46}Ni_{54}$. Magnetization measurements on unstructured samples yielded a Curie temperature of $T_{Curie} \approx 105$ K and a saturation moment of 0.11 μ_B (with μ_B the Bohr magneton) [11]. Samples were structured by optical or e-beam lithography. Different geometries were used, as will be discussed in the relevant sections. Transport measurements were performed by a standard four-point measurement technique, except for the critical current measurements. These were performed with a pulse technique which we developed in order to avoid heating problems [15].

3. Results

3.1. Bilayers of Py/Nb

Fig. 1 shows some typical results for bilayers of Py/Nb, structured by optical lithography as bars of 0.5 mm × 4 mm ('large' sample). Contacts were not included in the geometry in order to minimize problems with stray fields from contact pads or arms. Instead, Au contacts were added in order to measure in four-point geometry. Fig. 1(a) shows the variation of resistance R with applied in-plane magnetic field H_a for a sample s/Py(20)/Nb(20) at 10 K, above the transition to the superconducting state. The bar is aligned along $\hat{e}_e$, and the in-plane field is either parallel

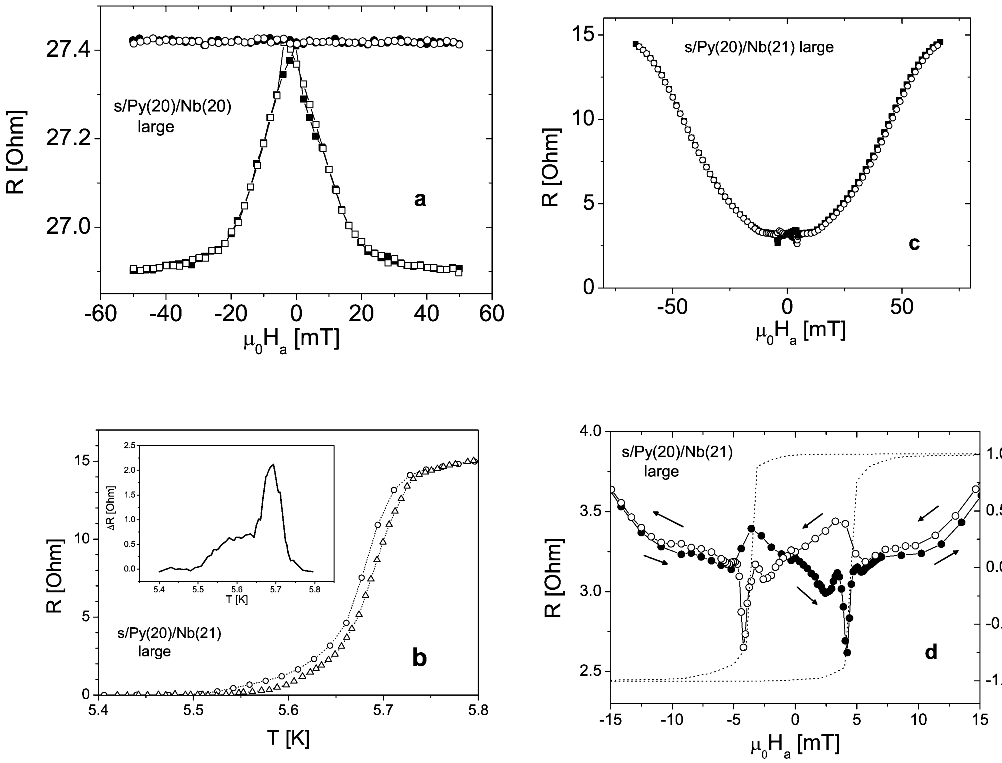

Fig. 1. (a) Resistance R versus applied magnetic field H_a for a large sample s/Py(20)/Nb(20) for $H_a \perp$ to the current j (squares) or $\parallel j$ (circles); filled symbols are in the positive field (forward) direction, open symbols in the backward direction. (b) R versus temperature T of a 'large' sample s/Py(20)/Nb(21) in zero field (circles) and in a field of 4.2 mT (triangles); the inset shows the difference between the two data sets. (c) R versus H_a of the 'large' sample s/Py(20)/Nb(21). (d) Left: enlargement of the low-field range of (c); filled symbols are in forward direction, open symbols in backward direction; right: magnetization M (dotted lines) normalized on the saturation magnetization M_s versus H_a, measured at 8 K. In both cases, $H_a \parallel \hat{e}_e$ (the easy axis of magnetization).

or perpendicular to $\hat{e}_e$ and therefore to the measurement current j. For $j \parallel H_a$, no magnetoresistance is witnessed, while for $j \perp H_a$, the resistance at high fields is lower than around zero field, and also shows some hysteresis. This is the standard behavior for anisotropic magnetoresistance (AMR) and due to domain effects. It is empirically found that the resistance in most transition metal magnets is lower when the magnetization M is perpendicular to j [16]. In our case, with the saturation magnetization M_s in the plane of the sample, we have the following cases. For $j \parallel H_a$, M_s is $\parallel j$, leading to high R. Also the domain magnetizations around zero field are preferentially $\parallel j$ (due to the shape anisotropy) and therefore $R(H_a)$ shows little or no variation. For $j \perp H_a$, the high-field resistance is lower since $j \perp M_s$, but the rotation of the magnetization now involves domains with a preferential direction $\parallel j$ and therefore an increase of R around the coercive field. The data presented below are taken with $j \parallel H_a$, so that AMR effects do not play a role.

Fig. 1(b) shows the transition to the superconducting state of a similar sample, s/Py(20)/Nb(21). The width of the transition is about 100 mK. From a fluctuation analysis we estimate T_c to be close to the top of the transition at around 5.7 K, depressed from the value for pure Nb by the presence of the F layer. We shall come back to this point, but we want to remark that the relatively large width of the transition is at least partly due to the gap suppression close to the S/F interface, and the resulting large excitation probability for quasiparticles. After stabilizing the temperature at 5.65 K, close to the bottom of the transition, $R(H_a)$ is measured by sweeping H_a from +65 to −65 mT and back. The result is given in Fig. 1(c). At 65 mT, R is close to the normal state value, and the value of the critical field at this temperature can be estimated at about 40 mT, using a 50% criterion. The transition is reversible, except at low fields where two small dips can be seen at ±5 mT. This region is enlarged in Fig. 1(d). Decreasing the field from +15 mT, R initially goes down, shows a small increase around 5 mT, but then goes through a steep dip in a very small field regime around $H_{\mathrm{dip}} = -4.2$ mT. Reversing the sweep from the negative field side, the behavior is symmetric, with a resistance dip now at +4.2 mT. Also shown is the magnetization of the sample at 8 K, normalized by the saturation magnetization M_s. The loop width is about 8 mT and the switch is quite sharp. The deep dips in $R(H_a)$ occur precisely at the switching field of the magnetic layer, which indicates that the domain state of the ferromagnet is involved, which is most prominent in the steep part of the magnetization reversal. We can also measure $R(T, H_{\mathrm{dip}})$ and compare this with $R(T, 0)$ in Fig. 1(b). We find that $R(T, H_{\mathrm{dip}})$ lies consistently *below* $R(T, 0)$, with a maximum difference of about 10 mK. Note also that the deviation between the two curves starts at 5.72 K, where we estimate T_c. Other samples (notably also samples where Nb is the bottom layer) show basically the same behavior [13] and the explanation we offered for these observations is that domain walls are formed in the Py-layer during the switching of the magnetization, which lead to the enhanced superconductivity. This is also suggested by measurements on a 'large' sample s/Nb(20)/AlOx(8)/Py(20), where a thin Al layer was deposited and oxidized before the Py layer was grown. No dips are found in this case, showing that proximity coupling is a necessary ingredient. Further support for this idea comes from measurements on a sample s/Nb(17)/Py(20), structured as a bar of 1.5 µm width and 20 µm length. Here, no dips were found either; micromagnetic calculations on this geometry with its large aspect ratio indicate that no stable domain structure is formed during the switching of the magnetization.

The mechanism we believe to be responsible for the enhancement of the superconductivity is basically that the pair breaking experienced by a Cooper pair is smaller when it samples different directions of the exchange field, due to the presence of a domain state. In a sense, this is the same mechanism as that responsible for the $F/S/F$ spin switch, but in the lateral case we have to consider two types of averaging of the exchange interactions. One is by sampling of the domain wall itself; the other is by sampling the domains (with different magnetization directions) on both sides of the wall. For the case of the domain wall we qualitatively expect this to be optimal when $\xi_{\mathrm{GL}}(T) \approx \delta_w$ (with $\xi_{\mathrm{GL}}(T)$ the Ginzburg–Landau superconducting coherence length and δ_w the domain wall width): for $\delta_w \ll \xi_{\mathrm{GL}}(T)$ the domain wall is too small to be sampled, while for $\delta_w \gg \xi_{\mathrm{GL}}(T)$ the change in the average direction of the magnetization is too small to contribute. Averaging over different domains on the other hand should be optimal simply when $\delta_w \ll \xi_{\mathrm{GL}}(T)$. With respect to the present data, since we are measuring very close to T_c, ξ_{GL} is much larger than the low-temperature value. Using the aforementioned value of $T_c \approx 5.72$ K the reduced temperature $t_r = T/T_c$ at 5.65 K is 0.988, which makes $\xi_{\mathrm{GL}}(t_r) = \xi_{\mathrm{GL}}(0)/\sqrt{1 - t_r}$ about 0.12 µm. For a sample s/Nb(19)/Py(20) discussed in [13] we found 0.15 µm, a very similar value. This has to be compared to δ_w, which is a somewhat elusive parameter depending on the film thickness d_{Py} and the shape of the sample. It is generally agreed that for $d_{\mathrm{Py}} = 20$ nm, the walls are of Néel type, which means that the magnetization rotates in the plane of the sample. For $d_{\mathrm{Py}} \to 0$, $\delta_w = \pi\sqrt{A_{\mathrm{ex}}/K_a}$, with A_{ex} the exchange stiffness (1.3×10^{-11} [J/m] for Py) and K_a the anisotropy constant (500 [J/m^3]) for our films. This yields a value of $\delta_w \approx 0.7$ µm. At $d_{\mathrm{Py}} = 20$ nm, this value has decreased to about 0.35 µm [16]. Actual measurements by scanning electron microscopy with polarization analysis on thick Py films with surface Néel walls yielded 0.25 µm for the half-width of the walls [17]. It is only in the transition, therefore, that the condition $\xi_{GL}(T) \approx \delta_w$ is approximately met, while below T_c we have $\delta_w \gg \xi_{GL}(T)$. The observed enhancement of superconductivity therefore appears to be due to the domain *wall*. For other materials combinations this may be different. In Fe and Co, for instance, K_a is two and three orders of magnitude larger, respectively, and the domain walls are at least an order of magnitude smaller than in Py. In the transition, this could yield enhancement by the domains rather than by the walls, while the walls might be dominant *below* T_c. Superconductivity enhancement actually has been observed below T_c in the critical current of Nb/Co bilayers [18]. Enhancement effects are not necessarily confined to strong magnets, however. We therefore next look at Nb in combination with $Cu_{46}Ni_{54}$.

3.2. Trilayers of $Cu_{46}Ni_{54}$/Nb/$Cu_{46}Ni_{54}$

As already mentioned in the introduction, weakly ferromagnetic CuNi has been used for the experimental verification of π-coupling in $S/F/S$-junctions [5], and for investigating spin-switch effects in $F/S/F$ systems [8,9]. We used sputtered films of $Cu_{46}Ni_{54}$, which have a saturation moment of 0.11 μ_B/at and a Curie temperature of 105 K [11]. Designating such films with CN, we investigated a sample s/CN(9)/Nb(23)/CN(9). For spin-switching, the maximum effect is expected when $d_F \approx 0.5\xi_F$, with ξ_F the coherence length in the F-layer [7], which sets the wavelength for the induced inhomogeneous order parameter. This value for d_F is around 3–4 nm, as follows from the minimum in the variation of $T_c(d_F)$ in CN/Nb bilayers [11]. The value for d_F used by Gu et al. was 5 nm, which should be close to the optimum [8]. In our case d_F is much larger, and the difference between T_c^{P} and T_c^{AP} should be very small [19]. In order to find variations in the superconducting order parameter below T_c, we determine the depairing current of the sample I_{dp} from a current (I) – voltage (V) measurement. The currents are large, but by using pulses and small samples, we showed that I_{dp} can be measured reliably as the current where the jump to the normal state occurs [15]. This has an obvious advantage over measurements using an arbitrary voltage criterion, where spurious effects such as vortex motion may play a role. The sample was structured by e-beam lithography into a 4-point geometry, this time with contacts included, with the bridge between the voltage contacts 2 µm wide and 20 µm long. Fig. 2(a) shows $M(H_a)$ of the unstructured sample with the magnetic field applied in the sample plane, taken at a temperature of 5 K, which is just above T_c as shown in the insert. The hysteresis loop is not very sharp and $\mu_0 H_{co} \approx 19$ mT. Both layers appear to show the same switching behavior, which means there is no clearly definable regime where both magnetizations would be P or AP. Fig. 2(b) shows I_{dp} at $T = 3.8$ K as function of the in-plane applied field H_a which was oriented along the bridge. Upon lowering H_a from the positive high field side, I_c rises, flattens slightly near zero field, but then rises again and reaches its maximum at a negative value of about -20 mT, followed by a monotonic decrease. The maximum value of ≈ 300 µA corresponds to a current density of 6.5×10^9 A/m^2 (using $d_{Nb} = 23$ nm as the thickness of the layer), which is a reasonable value for Nb close to T_c. When increasing H_a from a large negative field, similar

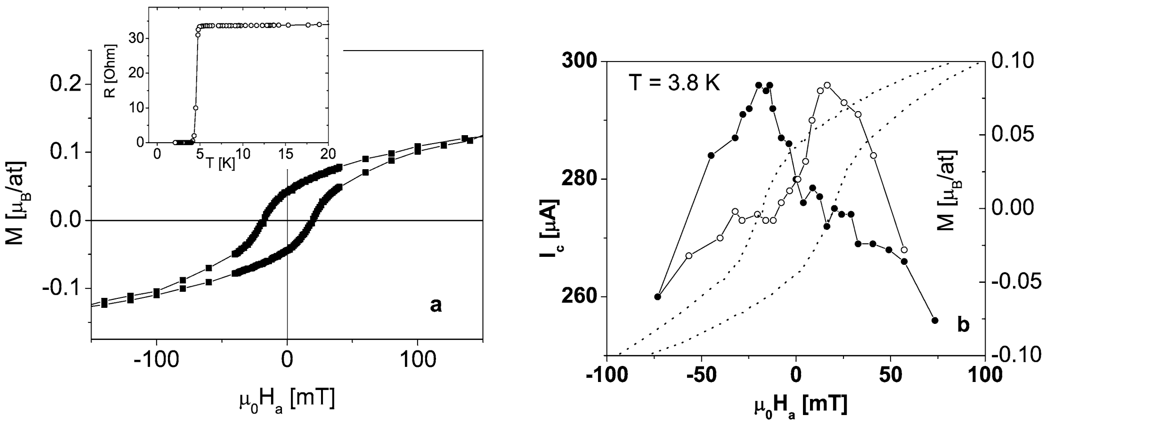

Fig. 2. (a) Magnetization M versus applied magnetic field H_a for a trilayer CN(9)/Nb(23)/CN(9) at 5 K. Insert: Resistance R versus temperature T for the same sample. (b) Depairing current I_c of the trilayer CN(9)/Nb(23)/CN(9) as function of H_a at $T = 3.8$ K. Filled symbols are in forward direction, open symbols in backward direction. The dotted line shows M versus H_a (right-hand scale).

flattening occurs, followed by a maximum at +20 mT, with clearly hysteretic behavior. By overlaying the data for M in Fig. 2(b) (dotted line) it is clear that I_{dp} peaks exactly at H_{co}, meaning that the suppression of superconductivity in the S-layer by the proximity effect is least when a domain structure is present in the outer F-layers. Note that the effect is quite strong. The increase from zero field to the maximum is of order 10%. In principle, this could be a manifestation of spin switching; around H_{co} both layers are in a domain state, and the directions of the magnetizations on either side of the Nb-layer may well be different. On the other hand, since the thickness of the banks is far from the optimal one for spin switching it seems more likely that the enhancement is due to independent domain wall effects at both S/F interfaces. For $\xi_{GL}(t)$ at $t = T/T_c = 0.95$ we find 60 nm. The domain wall width is unknown, but since the exchange stiffness $A_{ex} \propto$ the exchange energy E_{ex} and $K_a \propto M_s$ (the saturation magnetization) $\propto E_{ex}$ it should be of the same order of magnitude as in Ni, around 50–100 nm. That implies that the condition $\delta_w \approx \xi_{GL}(T)$ is also fulfilled. The effect therefore may well be due to the domain walls, although averaging effects between the two F-layers cannot be excluded. Also, the explanation assumes that domains still exist, even though the size of the bar and its shape anisotropy will tend to a single magnetization state. Research on bilayers is now in progress to resolve these issues.

3.3. Trilayers of Py/Nb/Py

The last case we want to address is that of $F/S/F$ trilayers where F is a strong ferromagnet, such as Py. Due to the different morphology of the F-layers deposited on the substrate or on the Nb layer, both layers will have different switching fields and it is quite possible to have well-defined P- and AP-regimes. Although it is not a priori clear whether spin switch effects could be observed (as was remarked in the Introduction), from the previous two sections it can be expected that in the resistive transition large trilayer samples still show the enhancement effects due to domain formation. This is observed, but we also find a very different effect. Switching from the P to the AP configuration in the transition leads to an increase rather than a decrease of R. The effect is similar to recently reported findings on trilayers of ferromagnetic $La_{0.7}Ca_{0.3}MnO_3$ (L), which is a half-metallic ferromagnet, and superconducting $YBa_2Cu_3O_7$ (Y) [20]. Fig. 3(a) shows measurements of $R(H_a)$ and $R(T)$ (inset) on a sample s/Py(50)/Nb(25)/Py(20). The sample is 'large', and was structured as a bar with gold contacts with its long axis along $\hat{e}_e$. From magnetization measurements it is known that the 50 nm layer switches at $\pm H_{c,50} \approx 1.5$ mT, and the 20 nm layer at $\pm H_{c,20} \approx 9.5$ mT. The sample

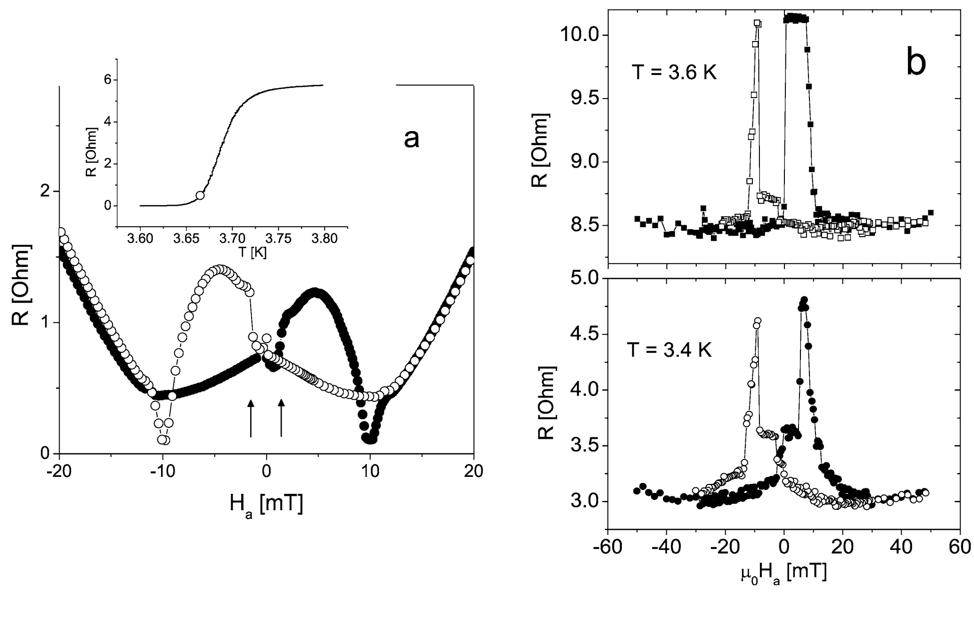

Fig. 3. (a) Resistance R vs. applied magnetic field H_a for a trilayer sample s/Py(50)/Nb(25)/Py(20). Filled symbols are in forward direction, open symbols in backward direction. The arrows denote the fields where the Py(50) layer switches. The insert shows R vs. temperature T for this sample with the circle denoting the temperature of the $R(H_a)$ measurement. (b) R vs. H_a of a 2 μm × 20 μm bridge (contacts included) of a sample s/Py(50)/Nb(26)/Py(20) at 3.6 K (upper) and 3.4 K (lower).

therefore is in the AP-state over a large range. It shows a resistive transition around 3.7 K with a width Δ_{tr} of 100 mK. The resistance R was measured as function of the in-plane field H_a at a temperature of 3.66 K. Coming from high fields, R decreases until $+H_{c,20}$ where it starts to rise slowly. At $-H_{c,50}$ a small but clear upward jump occurs. This is the field where the alignment of the Py layers becomes AP. In this regime R rises further to a peak, followed by a steep decrease to a dip at around $-H_{c,20}$. Now the sample is in the P state and R starts to rise slowly again. The behavior is mirrored in increasing fields. The strong peaks in the resistance therefore appear to be connected to the AP alignment, just as in the case of the L/Y/L trilayers of Ref. [20]. The dips at $\pm H_{c,20}$ are of course again due to the domain state (in this case of the 20 nm Py layer) demonstrated above. The rise in R at $+H_{c,20}$ when coming from high fields is presumably due to the fact that domain formation already starts to set in, which leads to small amounts of AP orientations. Note that, due to the hysteresis, the resistive transition depends on the domain state. The transition in the inset was measured at 5 mT, coming from high fields, in the P-state of the sample.

The data therefore suggest that the AP state shows larger resistance than the P state, but for the large sample the behavior is sluggish because of domain effects. Fig. 3(b) shows measurements on a sample s/Py(50)/Nb(26)/Py(20), structured as a bridge of 2 μm × 20 μm with contacts included in the geometry, at two temperatures in the transition (not shown). The switching behavior, with a larger resistance in the AP configuration, is now clear, although not perfect. The jump in R is quite large, more than 1 Ω, which is of the order of 10% of the normal state resistance. The data have not been corrected for a small offset field of 1 mT, but if that is taken into account, the switching fields $\pm H_{\text{sw},50}$ and $\pm H_{\text{sw},20}$ are 1.5 and 12 mT, respectively, which coincides well with the coercive fields for this sample. Also noticeable is the absence of the dips which we ascribed to the domains, in agreement with our earlier observations. Such switching behavior has not been reported before. More recent data on similar samples show that switching actually can be single-step, but these will be presented elsewhere. The behavior is very reminiscent of the Giant Magnetoresistance effect (GMR), where a similar increase in R for the AP configuration is due to the larger spin scattering in both spin channels as compared to the P configuration [22]. However, in the normal state no GMR effects are seen, which is actually not surprising. In our current-in-plane (CIP) geometry the attenuation of a possible GMR effect is $\propto \mathrm{e}^{-d_N/\ell_N}$, with ℓ_N the elastic mean free path of the normal metal [21,22]. For Nb, we estimated that $\ell_N \approx 5.5$ nm, much smaller than the spacer thickness of 25 nm. Apparently, this changes in the superconducting transition. To understand this, we offer a similar line of reasoning as in [20]. In the transition, spin-polarized quasiparticles appear with a much longer range. It was already shown by Blonder, Tinkham and Klapwijk that the characteristic decay of quasiparticles inside the gap (the current-to-supercurrent conversion length) is given by $1.22\xi_{\text{GL}}(T)$ [23], which diverges close to T_c. In the AP configuration, a larger number of quasiparticles experiences reflection at the other interface than in the P configuration. This increased amount of quasiparticles on the S-side of the interface leads to increased suppression of the gap near the interface, and therefore to an increase in the resistance. A more detailed analysis will be given elsewhere. Here, we simply want to direct attention to a mechanism which is generically different from that of the spin switch, and which occurs in the case of strong spin polarization.

4. Conclusions

In conclusion, we have reviewed some diverse effects which can be encountered in F/S or $F/S/F$ geometries when the magnetization of the layers is switched. One is the enhancement of superconductivity due to the occurrence of domain walls. This is visible in the superconducting transition of Nb/Py bilayers, since the domain walls in Py are relatively large. It is also visible in the behavior of the depairing current in Nb/CuNi/Nb trilayers (although the effects of spin switching here cannot be ruled out fully). Now the effect is observed below T_c, presumably because the domain wall thicknesses in CuNi are smaller. Finally, we show that a different phenomenon occurs in Py/Nb/Py trilayers. Here we find, in the superconducting transition, a larger resistance in the AP configuration than in the P configuration, which is opposite to the spin switch. We suggest this is due to the large spin polarization in the system; spin polarized quasiparticles with energies below the gap are reflected back into the superconductor more strongly in the AP configuration, which leads to increases suppression of the developing gap.

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