Spin dynamics in a superconductor / ferromagnet proximity system

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The ferromagnetic resonance of thin sputtered Ni_{80}Fe_{20} films grown on Nb is measured. By varying the temperature and thickness of the Nb the role of the superconductivity on the whole ferromagnetic layer in these heterostructures is explored. The change in the spin transport properties below the superconducting transition of the Nb is found to manifest itself in the Ni_{80}Fe_{20} layer by a sharpening in the resonance of the ferromagnet, or a decrease in the effective Gilbert damping coefficient. This dynamic proximity effect is in contrast to low frequency studies in these systems, where the effect of the superconductor is confined to a small region in the ferromagnet. We interpret this in terms of the spin pumping model.

PACS numbers: 74.45.+c, 76.50.+g, 72.25.Mk, 73.40.-c

Most of the experiments in the field of superconductor (S) / ferromagnet (F) hybrids rely on measuring their electrical transport characteristics. In S/F/S Josephson junctions the measured quantity is mainly the supercurrent, which is for instance used to show the existence of π-junctions (where the phase of the order parameter undergoes a change of phase by π). More recently, experiments involving a half-metallic ferromagnet found the supercurrent in that case to be long-ranged, possibly due to the occurrence of spin-triplet superconductivity. In hybrids of normal metals (N) and ferromagnets similar questions are currently addressed by ferromagnetic resonance (FMR) experiments in the microwave regime, which study the dynamic behavior of the precessing ferromagnetic spin of the F-layer in good electrical contact with an N-layer. The decay of the precessing ferromagnetic spin of the F-layer is mostly measured and analyzed by following the changes in electrical resistance of the device.

Both for questions involving spin transport and for studying the nature of the superconducting correlations inside the ferromagnet, it would be advantageous to avail of a method which measures changes of the F-layer properties as a consequence of the superconductivity. In hybrids of normal metals (N) and ferromagnets similar questions are currently addressed by ferromagnetic resonance (FMR) experiments in the microwave regime, which study the dynamic behavior of the precessing ferromagnetic spin of the F-layer in good electrical contact with an N-layer. The decay of the precessing ferromagnetic spin of the F-layer is mostly measured and analyzed by following the changes in electrical resistance of the device.

The Gilbert constant which controls the power absorption can be written in terms of the spin pumping model. In this Letter we address the proximity effect of a superconductor (Nb) on the FMR behavior of a strong ferromagnet (Ni_{80}Fe_{20}, Permalloy, Py) and find significant changes in the lineshape, implying that the entire magnetic layer is affected rather than the small distance of the superconducting coherence length in the ferromagnet.

Our samples are grown on 0.5 mm thick Suprasil®2 quartz (lateral dimensions ∼ 3mm × 5mm) by d.c. magnetron sputtering at room temperature, in a vacuum system with a base pressure < 2×10^{-9} mbar. Deposition rates were ∼ 0.12 nm/s for the Nb and ∼ 0.14 nm/s for the Py, as calibrated from low angle x-ray reflectivity. First we focus on three different samples. Sample A consists of q/Nb(70)/Py(5), where q stands for the quartz substrate and the numerals give the layer thickness in nm; sample B is q/Nb(9)/Py(5), and sample C is q/Nb(70)/Py(2)/Nb(5). The critical temperature T_C ∼ 8.2 K of sample A was measured in an in-plane magnetic field of μ_0H = 100 mT. The transition width was < 30 mK, and the resistance ratio R(300K)/R(10K) = 3.07. For sample B the 9 nm thick Nb layer is below the critical thickness of such a polycrystalline sample, and does not superconduct in the measurement range of temperatures presented. Sample B thus serves as a reference with similar interface characteristics, but no superconductivity. Both samples have an unprotected F-layer; sample C has a thinner Py layer as well as a non-superconducting (Nb) protection cap.

Due to stray magnetic fields in the sputtering chamber, the Py possesses an in-plane uniaxial induced anisotropy, giving a coercive field μ_0H_C^{easy} = 3.5 mT for sample A (T = 10 K), with H_C^{easy} ∼ 0.8 × H_C^{hard}. All data presented are measured with the applied field nominally along the easy axis. The FMR measurements were made in a Bruker
ElexSys E680 X-band electron paramagnetic resonance (EPR) system operating at 9.5 GHz, equipped with a rectangular TE$_{102}$ cavity and a liquid helium continuous flow cryostat. The input power was nominally 220 mW, attenuated before the resonance cavity by a factor of 10$^4$ (40 dB). The d.c. magnetic field was applied with a modulation of $\mu_0H = 0.5$ mT at 100 kHz. The samples were secured with teflon tape onto a quartz rod mounted vertically on a goniometer to allow control of the film normal direction with respect to the applied field: this was optimized at room temperature to be 90°± 2° by minimizing the center field of the FMR. Some typical EPR spectra taken for sample A are shown in Fig. 1 above and below the superconducting transition. The lineshape is close to the derivative of a Lorentzian line, with the ratio of the amplitudes of the lobes above and below the baseline around 0.8. This asymmetry has been observed in many other systems [11], and is associated with the polycrystalline nature of the samples, and variations of saturation magnetization and anisotropy fields over the sample. In the figure we also define the two parameters used to quantify changes in the resonance conditions. They are the zero-crossing field $H_0$ and the linewidth $\Delta H_{pp}$ (the field separation between the peak and dip position).

Fig. 2 shows the central result of our paper. Here we plot $\Delta H_{pp}$ versus temperature $T$ around $T_C$ for all three samples. The first thing to note is that the superconducting samples (A,C) both show a significant non-monotonous decrease in linewidth when cooling through $T_C$, while the non-superconducting sample (B) does not show such an anomaly. This indicates a strong decrease of the damping experienced by the precessing magnetization in the F-layer when the adjacent S-layer becomes superconducting. Before discussing this further we comment first on some other details of the data.

The values of $\Delta H_{pp}$ in the normal state are different for all samples. The larger linewidth in sample C is simply due to the much smaller thickness of the F-layer; the different values for samples A and B are caused, we believe, by the thicker Nb-layer present in sample A and the influence of that layer on the spin-pumping effect, as will be discussed below. Furthermore, still in the normal state, $\Delta H_{pp}$ for samples A,B show a clear temperature dependence which is absent in sample C. This is caused by the difference between the capped and uncapped Py. To illustrate this point more clearly we show the temperature dependence over a wider range in Fig. 3(a). For the uncapped samples, $\Delta H_{pp}$ actually goes through a maximum around 40 K, while the linewidth of the uncapped sample is only weakly temperature dependent. This is in agreement with earlier work on single Py films, where similar variations were found for films with a native oxide or with a magnetic (NiO) cap, while no temperature dependence was observed for Cu-capped Py [12]. The native oxide apparently acts as a different magnetic system which influences the Py, and this can also be seen in the temperature dependence of $H_0$, Fig. 3(b). For the uncapped samples $H_0$ shows a decrease below 50 K, while $H_0$ for sample C is again changing only slightly in this regime. Around $T_C$ however, no anomalies are found in the behavior of $H_0$ (inset of Fig. 3(b)); the variations in $\Delta H_{pp}$ are thus not due to variations in the effective field experienced by the samples.

Returning to our main observation of the change in FMR linewidth at $T_C$, we wish to argue that this is due to suppression of the spin-sinking mechanism which is provided by the normal layer, when this layer becomes superconducting. For this, we first refer to a set of studies by Mizukami et al. [13] who showed that the Gilbert damping coefficient $G$ slightly increased when a Cu layer...
This mechanism is partially suppressed, however, since reflected spin-down holes combine into a Cooper pair. Dreev reflections, in which a spin-up electron and a retro-particle enter, cannot enter in the superconductor as quasi-particles. Therefore, spin transport is reduced. Electrons ejected from the ferromagnet have energies well below the superconducting gap of Nb (1.5 meV at T = 0 K) and cannot be emitted as efficient as in the normal state, spin accumulation occurs at the S/F interface \[14,12\], and the amount of backscattering of electrons with opposite spin is reduced. The ensuing decreased damping leads to the observed smaller linewidth. A similar change in spin transport has also been found in d.c. magnetoresistance measurements of Py/Nb/Py structures: below the superconducting transition the effective spin diffusion length in the Nb decreases from around 50 nm to about 20 nm, close to the coherence length \(\xi_S\). This is to be expected since it is over this range that electrons are converted into Cooper pairs \[3,14\].

In our data we can now explain the difference between \(\Delta H_{pp}\) for samples A and B in the normal state: the thicker Nb layer of sample A is a slightly more effective in backscattering opposite spins. This is still also the case below \(T_C\), which is fully consistent with a picture of a 20 nm spin diffusion length in the Nb. One drawback to using Nb as the S layer is the relatively poor spin sink that it provides in the normal state. In the limit of the spin sink thickness \(d > \ell_{sd}\), the parameter \(\epsilon = \frac{1}{2}(\ell/\ell_{sf})^2\) for Nb can be calculated using typical values for electron mean free path \(\ell\) and spin flip length \(\ell_{sf}\) \[3\] giving \(\epsilon = 0.005\). This value is low compared to \(\epsilon \geq 0.01\) which is required for efficient spin sinking \[4\]. We must also consider the possible effects of the presence of in-plane vortices in the superconductor. At 9.5 GHz vortices will in general not depin, but locally oscillate in the local minima of the pinning potential. Any vortex motion would be expected to absorb microwaves over a relatively broad field range, and thus broaden the resonance which is not observed in the present data.

In this model for spin pumping, a change in the Gilbert damping as a result of the normal metal-to-superconducting transition can be understood since in the superconductor, spin transport is reduced. Electrons ejected from the ferromagnet have energies well below the superconducting gap of Nb (1.5 meV at T = 0 K) and therefore cannot enter in the superconductor as quasiparticles. The other mechanism to enter is through Andreev reflections, in which a spin-up electron and a retro-reflected spin-down hole combine into a Cooper pair. This mechanism is partially suppressed, however, since the spin subbands in the ferromagnet are not equally populated. Electrons therefore cannot be emitted as efficiently as in the normal state, spin accumulation occurs at the S/F interface \[14,12\], and the amount of backscattering of electrons with opposite spin is reduced. The ensuing decreased damping leads to the observed smaller linewidth. A similar change in spin transport has also been found in d.c. magnetoresistance measurements of Py/Nb/Py structures: below the superconducting transition the effective spin diffusion length in the Nb decreases from around 50 nm to about 20 nm, close to the coherence length \(\xi_S\). This is to be expected since it is over this range that electrons are converted into Cooper pairs \[3,14\].

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\(\Delta H_{pp}(T)\) for samples D and E. Lines are best fits above and below 7.7 K. Inset: \(\Delta H_{pp}\) versus input power attenuation at T = 5.2 K for sample D. The heavy scale bar represents the equivalent shift in \(\Delta H_{pp}\) for a 1 K temperature change from the best fit line below 7.7 K.
We have argued that it is variations in spin sinking efficiency which leads to the changes in linewidths when passing through $T_c$. We finish by showing that, just as in normal metals, the effects of added spin scattering by spin-orbit coupling can be utilized for further studies. To this end we fabricated two more samples. Sample D consists of $q$/Pt(20)/Nb(70)/Py(5nm) with a $T_c = 8.0$ K. The Py layer is uncapped while the Nb layer is thick, with Pt as an underlayer. Sample E is $q$/NbN(50)/Pt(5)/Nb(25)/Py(5), with $T_c = 10.6$ K. The Py layer is also uncapped while here the Pt layer is in contact with a much thinner Nb layer. Since this considerably lowers the superconducting transition we then boost the superconductivity again by a NbN layer. The extracted values for $\Delta H_{pp}$ for these samples are shown in Fig. 1. The $\Delta H_{pp}(T)$ for sample D is essentially the same as the data for sample A (although no clear saturation is observed at the lowest temperatures). This weak effect of Pt is caused by the relatively thick Nb layer, meaning that most of the spin memory is in the Nb before reaching the Pt. For sample E, however, the Pt sits no more than the (Nb) spin diffusion length away from the Py-layer, spin sinking is quite efficient, and the T-dependence of $\Delta H_{pp}$ is suppressed even below $T_c$. We note that the EPR spectra for sample D were significantly more noisy than the other samples, for reasons which are not clear at this time. Finally we show in the inset of Fig. 1 that there is no direct heating of the films by the microwaves at low T until an attenuation of $10 \sim 15$ dB, which is greater than the power used for our measurements.

To summarize, we have shown that a superconductor in good metallic contact with a ferromagnet can influence the dynamics of the whole ferromagnetic layer by decreasing the spin sink efficiency, leading to a decreased Gilbert damping of the FMR. This is consistent with a picture of suppressed Andreev reflections at the S/F interface due to the spin polarization of the Py causing a reduced spin transport. Although currently there is no theoretical description of this system, a full theoretical treatment is forthcoming [17]. The decrease in the damping of the F layer is highly relevant for S/F hybrid devices with strong ferromagnets [18, 19, 20, 21, 22] at high frequencies, in for example possible coupling between the FMR and the a.c. Josephson effect [23], as well as enhanced magnetic noise in devices utilizing S/F/S junctions. These issues have not been addressed so far. We would like to stress the potential usefulness of the EPR technique in the S/F field, as well as for research into spin pumping. These S/F systems can be used beneficially to access a range of spin transport properties in a single system, foregearing the need for many samples where variations in film properties can give rise to non-intrinsic contributions [13].

Although the effects presented here can be satisfactorily explained by the superconducting gap opening in the Nb layer, an interesting question is if any additional effects can be observed due to the inhomogeneous induced superconducting state in the Py. Recent measurements indicate a superconducting coherence length in Py of 1 $\sim$ 1.5 nm [20, 21], meaning that a significant fraction of the Py in this experiment has some superconductivity induced in it. It is also therefore interesting to measure the FMR in weak ferromagnets where the induced superconductivity is relatively long range [24, 25]. In this case the lower spin polarization of the F layers will lead to less spin accumulation at the S/F interface, hence a weaker suppression of the spin pumping, and thus a relatively large contribution from any novel effects. Further studies with F/S/F trilayers with non-collinear F layers or a S/half metal system would also be especially interesting since any triplet superconducting components [2, 26] are expected contribute to the FMR damping in a different way to the singlet component [6].

We are very happy to thank J. Schmidt, G.E.W. Bauer, A. Brataas and J.P. Morten for stimulating discussions and suggestions, and R.W.A. Hendriks for x-ray measurements. This work was supported by the Dutch “Stichting FOM”.

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