Nanoscale ferromagnet-superconductor-ferromagnet switches controlled by magnetization orientation

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We study clean ferromagnet-superconductor-ferromagnet (FSF) nanostructures in which the magnetization of the F layers can be parallel (P) or antiparallel (AP). We consider the case where the thickness of the S layer is of order of the coherence length, with thinner F layers. We find that reversing the direction of the magnetization in one of the F layers leads in general to drastic changes in the superconductor’s state. Under a wide variety of conditions, the AP geometry favors superconductivity. Magnetization reversal in one of the F layers can lead to the superconductivity turning on and off, or to switching between different states. Our results are obtained via self consistent solution of the Bogoliubov-de Gennes equations and evaluation of the condensation energies of the system.

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Introduction: Within the emerging field of spintronics\textsuperscript{1} considerable interest has developed in devices in which proximity effects are used to control the superconductivity via the spin degree of freedom in ferromagnet (F) and superconductor (S) layered systems. A large part of the motivation for this interest follows from earlier studies of systems that involve nonmagnetic normal metal layers sandwiched between two ferromagnetic layers\textsuperscript{2} (FNF geometry). In such devices the resistance of the system can change substantially in the presence of a perturbing magnetic field. This change mainly arises from the spin-dependent scattering at the interfaces. The ensuing giant magnetoresistance (GMR) effect is found in spin-valves and magnetic multilayers where the relative orientations of the magnetization in alternate ferromagnetic layers change as a function of an applied field. If the local magnetization orientations are antiparallel (AP) the scattering will be stronger for a particular spin component, but if the magnetization vectors are aligned the more weakly scattered spin component carries the current with a lower resistivity.

If the nonmagnetic insert is replaced by a thin superconductor, resulting in a ferromagnet-superconductor-ferromagnet (FSF) junction, a different type of spin-valve or spin-switch can be created\textsuperscript{3}. The proximity effects arising from the mutual influence of the magnetic and superconducting order parameters embody a variety of novel spin-valve effects and device concepts, including high density nonvolatile memory\textsuperscript{4} and magnetic sensors. The mechanism behind such devices is ultimately based\textsuperscript{5,6} on the damped oscillatory nature of the superconductor order parameter in the F regions, and the associated magnetic correlations and destruction of superconductivity in the S layer. In the transport regime, and with AP alignment of the magnetizations in the F layers, a nonequilibrium spin density can accumulate in the superconductor\textsuperscript{7,8,9}, destroying the gap and resulting in a higher resistance state for a given temperature\textsuperscript{2}. Thus the superconducting correlations are controlled by the relative magnetization orientation in the F layers. Also, quasiclassical thermodynamic considerations indicate that the transition temperature, $T_c$, can be modified in a controlled way, thus allowing supercurrent to flow in a predictable manner\textsuperscript{10,11,12} yielding another type of spin switch. The superconducting order parameter and $T_c$ in this case are again greatest when the the magnets are in the AP configuration, a result shown to hold for atomic thickness FSF layers as well\textsuperscript{13}. When the superconducting system goes normal, the phase transition is second order for AP magnetizations in the F layers and can be first order for parallel (P) magnetizations if the F layers are thin enough and the interface transparency is high\textsuperscript{13}. If the outer ferromagnets are semiconducting insulators, the $T_c$ variations have different signatures depending on whether the superconductor is in the singlet or triplet state\textsuperscript{14,15}. An absolute spin-valve effect can occur at spin-active interfaces in which the tunneling current is finite for a range of voltages\textsuperscript{16}.

These types of devices are in general most effective, and the effects most pronounced, for junctions with clean interfaces and thin superconductors\textsuperscript{11}. The lithographic, sputtering, and epitaxial methods used in spin-switch fabrication permit the creation of structures as thin as a few atomic layers that have atomically flat interfaces. Moreover, high quality magnetic and nonmagnetic metallic films with an electron mean free path exceeding 150 Å can also be readily fabricated. One of the earliest experiments using FSF junctions involved CuNi/Nb/CuNi films, and a magnetization direction dependence on $T_c$ was reported\textsuperscript{13}. A spin switch was recently investigated using La$_{0.7}$Ca$_{0.3}$MnO$_3$/YBa$_2$Cu$_3$O$_7$ superlattices that had large magnetoresistance when in the superconducting state\textsuperscript{17}. Spin valve core structures involving Nb/CuNi sandwiches have also very recently\textsuperscript{18}.

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been reported. It is possible, in an FSF sandwich with AP magnetizations, for the electron in one of the magnets to be Andreev reflected as a hole of the opposite spin in the other ferromagnet. This process of crossed Andreev reflection is believed to be behind the results of experiments involving subgap transport in Al/Fe hybrids. An enhancement of the critical current and $T_c$ in Nb/Co was observed and was attributed to a reduced exchange interaction in the domain structure of Co. Likewise, a type of spin-switch involving Nb/Permalloy layers revealed through transport measurements, a decrease in the suppression of superconductivity. It was argued that the superconductivity is increased when the magnetic domains are oriented differently, effectively averaging in a way that reduces the effects of the exchange field.

Spurred by these important advances, we investigate here the effect of reversing one of the magnetizations in clean FSF nanojunctions. We consider the relevant case where the coupling between the S and F regions is appreciable, namely a thin S layer (of order of the BCS coherence length $\xi_0$) and relatively large magnetic exchange fields. Our results are based upon numerical self consistent solution of the microscopic Bogoliubov-de-Gennes (BdG) equations. This method is most appropriate for the situation described above. We calculate the pair potential $\Delta(r)$, the condensation energy, and the local density of states (LDOS) for both the P and AP magnetization configurations, over a range of values of the relevant parameters. Our analysis will demonstrate that under many conditions the system can be made to switch from a superconducting state to a normal one, at low temperatures, by flipping the (collinear) magnetization orientation in one of the F layers, which can be achieved via an applied field. This will be illustrated by calculating the condensation energy as a function of ferromagnet thickness and exchange energy. We find that the AP state is always the lowest energy state, and thus the most favorable. We conclude that the proximity effects that occur with P magnetization in successive F layers become substantially modified when adjacent F layers have AP magnetization alignment. The pair amplitude and LDOS also display experimentally discernible characteristics that depend on whether the magnets are in the P or AP configuration.

Methods: The equations relevant to the microscopic theory of inhomogeneous superconductivity are the Bogoliubov-de Gennes (BdG) equations. We consider here an FSF structure translationally invariant in the $x − y$ plane, with interfaces normal to the $z$ direction. We assume parabolic bands with bandwidths $E_F$ in the S layer and $E_{Fx}=E_F\pm h_0$ in the magnet, where $h_0$ is the Stoner exchange field. In the P geometry the sign of $h_0$ is the same in both layers, while in the AP geometry it is the opposite. The dimensionless parameter $I \equiv h_0/E_F$ characterizes the magnetic strength. We include interface scattering characterized by delta functions of strength $H$ (dimensionless strength $H_B \equiv mH/k_F$). We have written the BdG equations in this geometry and with these assumptions in previous work, where we have also discussed the specific numerical methodology we use. It is therefore unnecessary to repeat these derivations here. The exact quasiparticle energies and amplitudes are thus obtained by repeated iteration of the BdG equations and the associated self consistency condition for $\Delta(z)$.

Once the energy spectra and pair potential are found, the condensation free energy, $F$, (or, in the $T \to 0$ limit the condensation energy) can be calculated. This is in principle straightforward, although numerically quite difficult. We use a particularly convenient approach, which yields for the condensation energy $\Delta E_0$ the result:

$$\Delta E_0 = \sum \epsilon_{n'} - \sum \epsilon_n + \int_0^d dz |\Delta(z)|^2 / g,$$

where $g$ is the BCS coupling constant in S, $d$ the total sample width, $\epsilon_n$ and $\epsilon_{n'}$ are the free-particle energy spectra corresponding respectively to the superconducting and normal ($\Delta(z) \equiv 0$) states, and the indices denote the appropriate quantum numbers. The sums are performed over energies less than the usual cutoff $\omega_D$. Similarly, from the calculated self-consistent eigenvalues and eigenfunctions one can calculate the LDOS, $N(z,\varepsilon)$. This quantity is discussed below.

Results: In the geometry we consider, the inner superconductor layer of width $d_S$ is sandwiched between two ferromagnet layers of equal width, $d_F$. The thickness $d_S$ is chosen to be $d_S = \xi_0$, and we take $k_F\xi_0 = 100$ and $\omega_D = 0.04E_F$. All results correspond to low temper-
I only one spin band is populated at the Fermi level

The oscillatory behavior is complicated, but for both \( H_B \) values the AP state is favored over the whole \( I \) range.

In Fig. 4 we plot the pair amplitude (the average \( \langle \hat{\psi}_\uparrow(\mathbf{r}) \hat{\psi}_\uparrow(\mathbf{r}) \rangle \), where the \( \hat{\psi}_\sigma \) are the usual annihilation operators), normalized to its zero temperature bulk value, as a function of dimensionless distance. Results are plotted both for both the P and AP cases. Two values of the interface scattering parameter are considered, a small one \((H_B = 0.15)\) when the proximity effect is strong, and a larger one \((H_B = 0.6)\) when it is weaker. It is clear that the results depend crucially on the relative magnetization orientation, with the superconducting amplitude being weakest in the P case. The effect is magnified for the smaller \( H_B \) value, where interface scattering is reduced. In that case one can see in the figure that the pair amplitude vanishes in the P case, while being quite robust in the AP situation. The superconductivity can thus be switched on and off by reversing the magnetization in one of the F layers.

This favoring of the AP configuration is, qualitatively, a very general phenomenon. To see this, it is very convenient to analyze the pair condensation energy (Eq. (11)). The trends in the pair amplitude, such as those in Fig. 4, should be reflected in the condensation energy, which should then be lower (higher in absolute value) in the AP case than in the P configuration. \( \Delta E_0 \) is shown in the next two figures, normalized to \( N(0)\Delta_0^2 \) which is twice its bulk zero temperature value. In Fig. 2 this normalized quantity is plotted as a function of \( I \) for two values of \( H_B \). The F width is kept fixed at \( D_F \equiv k_Fd_F = 10 \) (recall that \( D_S \equiv k_F\xi_0 \) always). The entire range of \( I \) from the nonmagnetic \((I = 0)\) limit to the half metallic case \((I = 1)\) is spanned. For all nonzero \( I \), the AP case is always favored. This trend persists even for larger \( H_B \) (not shown) where the proximity effect is weaker. At \( I = 1 \) only one spin band is populated at the Fermi level and consequently \(|\Delta E_0|\) is large, as Andreev reflection is depressed and the Cooper pairs are more restricted to the S region. We also see in the figure that the difference in condensation energies for P and AP geometries at fixed thickness is a weak function of \( I \), except at small \( I \).

The AP configuration continues to be preferred when the thickness \( D_F \) is varied at constant \( I \). This is shown in Fig. 3, where we plot the normalized \( \Delta E_0 \) versus \( D_F \). Results for two values of \( I \) are plotted, and both P and AP configurations are studied. As \( D_F \to 0 \), one is left only with the superconductor and \( \Delta E_0 \) approaches its bulk value. Increasing \( D_F \) causes initially a sharp rise in \( \Delta E_0 \). The condensation energy then saturates, exhibiting damped irregular oscillations, reflecting the competition between magnetism and superconductivity. Again, in all cases superconductivity favors the AP configuration. At small \( I \) \((I = 0.1)\), \( \Delta E_0 \) for the P configuration vanishes beyond \( D_F \gtrsim 4 \), while in the half-metallic limit, \( \Delta E_0 \) is an oscillatory function of \( D_F \). The difference in condensation energies between P and AP configurations at the same \( I \) is a weak function of \( D_F \).

The irregular oscillatory behavior in Figs. 2, 3 reflects the existence of the characteristic length \( \ell = (k_\uparrow - k_\downarrow)^{-1} \) arising from the difference between Fermi wavevectors for up and down spins in the F layers. Such oscillatory behavior depends on the relation between \( d_F \) and \( \ell \). The latter in turn depends on \( I \). Since the ratio \( \ell/d_F \) depends on \( D_F \) in a simpler way than on \( I \), the oscillations are best studied in Fig. 3. There one can see that at larger \( I \) \((I = 1)\) (hence smaller \( \ell \)), the characteristic oscillations have a shorter spatial period than those at \( I = 0.1 \). For SFS sandwiches with small \( D_F \) one finds oscillations in the pair amplitude in F. These can be seen in the left edge of Fig. 4. The situation for \( \Delta E_0 \) is much more complicated, since oscillations in the pair amplitude are only indirectly reflected there.

The strong modifications to the superconducting state of the sample should be easily detected in measurements of the critical current. These switching effects are also
FIG. 4: (Color online) The normalized LDOS (at $D_F = 10$ and $H_B = 0.15$) spatially averaged over the S region and normalized as explained in the text. Results for both P and AP configurations are shown for two $I$ values.

very well reflected in LDOS results. Thus, we show in Fig. 4 the LDOS $N(z, \varepsilon)$ averaged over the S region. The results are normalized to the normal state bulk value.

We display results for two values of $I$, $D_F = 10$, and $H_B = 0.15$. One can plainly see the difference between P and AP configurations: in the AP case the BCS like peaks are much more prominent and the gap fairly well defined. In the P case no gap exists, although a weak BCS like feature is still visible for $I = 1.0$, while the features flatten out nearly completely at small $I$ ($I = 0.1$), when the system is no longer superconducting, as seen by the the vanishing of the condensation energy in this case, (Fig. 2).

The enhancement of superconductivity in the AP configuration is not, as one might naively think, simply a consequence of the magnetic polarizations canceling in the superconductor. As has been found, the magnetic moment induced in the superconductor by the ferromagnetic contacts penetrates into the S material only a few Fermi wavelengths. We have verified that this is also the case here. Thus, the reasons are more subtle. The weakening of superconductivity by ferromagnetic contacts depends in a complicated way on the amplitudes for electron scattering (both normal and Andreev) at the interfaces. These are to a greater or lesser strength pair breaking. The penetration depth for Cooper pairs into the F material is much smaller than for a normal metal and this is reflected in the interface scattering amplitudes. Our self consistent calculation shows then, that the superconducting state (with $d_S = \xi_0$) can better survive proximity to two F contacts that have opposite polarizations.

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