Using a hybrid superconducting-ferromagnetic tip as a magnetic scanning tunneling microscope

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Abstract

Approaching a two-component tip made of a superconductor (S) and a ferromagnet (F) from a magnetic sample allows for two distinct tunneling processes between the ferromagnets, through S: i) Charge and spin are conserved; ii) Charge and spin are reversed, e.g. a Cooper pair flows from S, one electron going into F, the other into the sample. At subgap voltages, this allows two currents to flow from the tip: one is insensitive to the spin polarizations and allows for surface topography, the other directly tracks the relative spin polarizations of F and the sample. The whole device acts as a STM sensitive to the spin polarization at the Fermi level (MSTM). Its sensitivity is studied and optimized with respect to the tip geometry.

I. INTRODUCTION

Nanoscale characterization of magnetic surfaces is nowadays a major challenge. Scanning Tunneling Microscopy (STM) is required, but face the difficulty of measuring the spin polarization (SP) at the atomic scale, and simultaneously recording the topographic information like a standard STM. The simplest (in principle) method uses a ferromagnetic tip, forming
a F/I/F junction through vacuum, the tunnel current between two ferromagnets depending on their relative SP’s. This technique has been successfully implemented by Wiesendanger’s group [1,2]. Different proposals rely on ferromagnet-semiconductor junctions [3], or spin-orbit coupling in a two-terminal tip [4].

In a different context, superconducting-ferromagnetic tunnel junctions (S/I/F) were used by Tedrow and Meserwey [5] to measure the exchange field, using the spin splitting of the superconducting density of states peaks. For good contacts, Andreev reflection offers an alternative access to SP: at a normal metal-superconductor (S/N) interface, subgap conductance is nonzero if an electron (hole) coming from N can be reflected as a hole (electron) and form a Cooper pair in S [6,7]. This involves spin reversal in the conventional case of singlet superconductor (considered here), e. g. the Andreev current requires electronic channels for opposite spin close to the Fermi level. Therefore SP must reduce the Andreev conductance [8]. Measurement of SP through this reduction was realized by Soulen et al [9] and Upadhyay et al. [10]. The first experiment uses a superconducting point contact on a ferromagnetic surface, with a high energy sensitivity at the Fermi level, below the superconducting gap. However, contrarily to the spin valve principle which uses another ferromagnet as a reference and can measure also the direction of SP, the S/F interface only allows to measure the absolute value of the polarization, an obstacle against direct domain imaging. Moreover, operating the superconducting tip as a STM rather than a point contact (forming a S/I/F interface through vacuum) would result in an extremely small Andreev conductance, as it is basically a two-electron tunneling process through vacuum.

II. PROPOSAL FOR A MIXED S/F TIP

We propose here to use a mixed superconductor-ferromagnetic tip, and combine the energy resolution of the superconductor and the SP direction sensitivity of the spin-valve effect. A superconducting tip (S) forms two interfaces: one with a magnetic layer (denoted as B) coating the tip, except for its end, and one (vacuum) tunnel interface with the sample
The whole tip (S and B) is biased at the voltage $V < \Delta$, the superconducting gap. Some properties of such an F/S/I/F double interface have been recently studied \cite{11,12}: if the interfaces S/A and S/B are close enough, coherent transfer of single quasiparticles can occur at both interfaces \cite{13}, and depend on the relative SP’s of A and B \cite{11,12,14-16}. For instance, quasiparticles of the same spin tunnel from B to A through S, and the two resulting currents at the interfaces S/A and S/B are just opposite, carrying the same SP \cite{Fig.1(b)}. This "normal" channel, conserving spin and charge, can be called elastic cotunneling (EC) \cite{17}. It can be compared with usual spin-dependent tunneling at a F/I/F interface, and is hindered by antiparallel polarizations of A,B. On the contrary, the latter situation favours an "anomalous" channel, exclusively opened by the superconductor: a Cooper pair can leave S, made of one quasiparticle going into A and another into B, with opposite spins. This mechanism can be also viewed as tunneling from B to A, but reversing spin and charge: it can be denoted as crossed Andreev (CA), and generalizes \cite{18} the usual Andreev process which may take place at each electrode separately \cite{7}. Both processes EC and CA probe the single particle propagators (normal for EC, and anomalous for CA) in S, in the narrow region between the two contacts, and decay over the coherence length $\xi$ \cite{13,15,12}. Since $\xi$ can exceed hundredths of nanometers, the range of both tunneling channels drastically exceeds that of usual tunnel effect through an insulator.

To modelize this geometry, one may assume that tunneling occurs at the end of a nanometric protuberance \cite{Fig.2(a)}. Neglecting curvature effects, this can be schematized in a planar geometry, with the superconductor connected to two ferromagnets by one point-like interface A of size $a$ (corresponding to the tip-surface tunnel barrier at the protuberance), and a larger ring-like interface B, with internal radius $R$ \cite{Fig.2b}. At radius larger than $R + d$, the F layer is assumed to be isolated from S by an insulating layer (region B’). The tip contains a few conduction channels and we assume $a << R$. 
FIG. 1. a) A superconducting tip covered by a ferromagnetic layer (B), except for its end, is biased at a voltage $V$ with respect to a magnetic sample (A). b) Sketch of the two basic processes: elastic cotunneling (spin-conserving) and crossed Andreev, with decay of a Cooper pair in A and B (opposite spins).

III. CALCULATION OF THE CONDUCTANCE MATRIX

The currents $I_A$, $I_B$ flowing from S to the ferromagnets A(B) can be expressed as functions of the external bias $V$. Notice that a small bias $\delta V_B = V_S - V_B$ will also be generated at the SB interface, due to the voltage drop in B induced by $I_B$, but as we show later it can be neglected under specific conditions. At voltages $V$ smaller than the gap $\Delta$, and at low temperature, single-particle contributions are negligible, and $I_A, I_B$ are linear functions of $V$, as the result of four kinds of two-particle currents: i) the Andreev currents at
contacts A,B separately, \( I_{2A} = G_{2A}V \), \( I_{2B} = G_{2B}\delta V_B \); ii) the crossed Andreev (CA) currents \( I_{CA,A} = I_{CA,B} = G_{CA}(V + \delta V_B) \) flowing into A and B; iii) the cotunneling (EC) currents \( I_{EC,A} = -I_{EC,B} = G_{EC}(V - \delta V_B) \) flowing from B to A (Fig. 1). As a result, setting \( G_\pm = G_{CA} \pm G_{EC} \), one has

\[
I_A = (G_{2A} + G_+)V + G_- \delta V_B \quad (1)
\]

\[
I_B = G_- V + (G_{2B} + G_+) \delta V_B \quad (2)
\]

The single-junction Andreev conductances \( G_{2i}, i = (A, B) \) are given for each spin channel \( \sigma \) by \[19\] \( G_i^\sigma \approx \frac{\hbar}{\pi} G_i G_{i}^{-\sigma} k_F^2 S_i \log(k_F^2 S_i) \), where \( k_F \) is the Fermi number in S, \( S_i \) is the area of contact \( i \) and the \( G_i^\sigma \)'s are the single particle conductances per unit area for S being in the normal state (Eq. (8)), given by

\[
G_i^\sigma \sim \frac{4\pi e^2}{\hbar} N_i^\sigma(0) N_S(0) \frac{|t_i|^2}{k_F^2} \quad (3)
\]

where \( N_i^\sigma \) is the spin-dependent density of states at the Fermi level in A or B, \( N_S(0) \) the normal state density of states in S and \( t_i \) tunneling matrix elements at the interfaces S/A, S/B. \( G_{EC} \) and \( G_{CA} \) have been recently calculated for two separated contacts of size much smaller than \( \xi \), as a function of the relative position \( \vec{R} \) of the contacts and their spin polarizations \[12\]. In multichannel junctions with normal (non magnetic) A, B electrodes one finds \( G_{CA} = G_{EC} \), thus the crossed conductance \( dI_B/dV \) vanishes \[20\]. This symmetry is broken if A, B are spin-polarized ferromagnets and in particular the crossed conductance can be either positive or negative.

The calculation can be performed in the geometry of Fig. 2b. The transition rates \( \Gamma^\sigma_{B\rightarrow A} \) and \( \Gamma^\sigma_{S\rightarrow AB} \) respectively associated to EC and CA processes can be calculated, using Fermi’s golden rule \[12,19\]

\[
\Gamma^\sigma_{B\rightarrow A} = \frac{2\pi}{\hbar} \int d\varepsilon d\varepsilon' d\zeta d\zeta' \delta(\varepsilon - \varepsilon') f(\varepsilon + e\delta V_B) [1 - f(\varepsilon' + eV)] \left( F_{EC}(\zeta, \varepsilon) F_{EC}(\zeta', \varepsilon') \Xi_{EC}^\sigma(\varepsilon + e\delta V_B, \varepsilon' + eV, \zeta, \zeta') \right) \quad (4)
\]

and
\[ \Gamma_{S \rightarrow AB}^\sigma = \frac{2 \pi}{\hbar} \int d\varepsilon d\varepsilon' d\zeta d\zeta' \delta(\varepsilon + \varepsilon') f(\varepsilon + e\delta V_B) f(\varepsilon' + eV) \]

\[ F_{CA}(\zeta, \varepsilon) F_{CA}(\zeta', \varepsilon') \Xi_{CA}^\sigma(\varepsilon + e\delta V_B, \varepsilon' + eV, \zeta, \zeta') \]  

(5)

where \( f(\varepsilon) \) is the Fermi function, \( F_{EC}(\zeta, \varepsilon) = (\zeta + \varepsilon)/(\zeta^2 + \Delta^2 - \varepsilon^2) \) and \( F_{CA}(\zeta, \varepsilon) = \Delta/(\zeta^2 + \Delta^2 - \varepsilon^2) \). Quasiparticle propagation in the specific geometry is described by the functions \( \Xi(\varepsilon, \varepsilon', \zeta, \zeta') \). Assuming planar uniform tunnel junctions, local tunneling, \( t(\vec{r}, \vec{r}') = t \delta(\vec{r} - \vec{r}') \) and ballistic propagation in S, A and B for simplicity, both functions \( \Xi_{EC} \) and \( \Xi_{CA} \) can be expressed as

\[ \Xi^\sigma(\varepsilon, \varepsilon', \zeta, \zeta') = |t_{AB}|^2 \int_A d\vec{r}_1 d\vec{r}_2 \int_B d\vec{r}_3 d\vec{r}_4 \ J_{A}^\sigma(12, \varepsilon) J_{S}^\sigma(31, \zeta) J_{S}^\sigma(24, \zeta') J_{B}^\sigma(43, \varepsilon') \]  

(6)

where \( +\sigma (-\sigma) \) in \( J_{B}^{\pm \sigma} \) applies for EC (CA) and the spectral functions are defined as \( J_{A}^\sigma(12, \omega) \equiv J_{A}^\sigma(\vec{r}_1, \vec{r}_2, \omega) = \sum_k \delta(\omega - \varepsilon_{k\sigma}) \psi_{k\sigma}(\vec{r}_1)\psi_{k\sigma}^*(\vec{r}_2) \). The integrals in (6) run on the contact surfaces.

At low temperature and voltages, a low-energy expansion yields the cotunneling and CA currents \( I_{EC}^\sigma = e\Gamma_{B \rightarrow A}^\sigma \) and \( I_{CA}^\sigma = e\Gamma_{S \rightarrow AB}^\sigma \). Let us for simplicity assume equality of the Fermi wavevectors on each sides of the interfaces. This allows to write the two-electron conductances \( G_{EC}^\sigma \) and \( G_{CA}^\sigma \) for spin \( \sigma \) as

\[ G_{EC}^\sigma \approx \frac{\pi^2 h}{16e^2} G_{A}^\sigma G_{B}^\sigma \frac{S_A}{k_F^2} f\left(\frac{R}{\xi}, \frac{d}{\xi}\right) \]  

(7)

\[ G_{CA}^\sigma \approx \frac{\pi^2 h}{16e^2} G_{A}^\sigma G_{B}^{-\sigma} \frac{S_A}{k_F^2} f\left(\frac{R}{\xi}, \frac{d}{\xi}\right) \]  

(8)

which have the same geometrical dependence, and only differ through the spin-dependent conductances \( G_{\ell}^\sigma \). In the ring contact geometry (Fig. 2b), the dependence on the internal radius \( R \) and the width \( d \) of contact B is determined by \( f\left(\frac{R}{\xi}, \frac{d}{\xi}\right) = \int_0^{2(R+d)/\xi} e^{-x} dx/x \), thus \( G_{CA}, G_{EC} \) vanish for \( R \gg \xi \). If \( R < \xi << d \), \( f\left(\frac{R}{\xi}, \frac{d}{\xi}\right) \approx \log(\xi/2R) \). And in the case \( R, d < \xi \), one finds \( f\left(\frac{R}{\xi}, \frac{d}{\xi}\right) \approx \log(1 + \frac{d}{R}) \).
FIG. 2. a) Enlarged view of the tip end, where one of the crossed process (CA) is represented.
b) Two-dimensional modelization of the interfaces S/A (small region A) and S/B (shaded area).
The region B' is isolated from S (see text).

IV. DISCUSSION

The logarithmic dependence of the crossed conductances $G_{\pm}$ with the size of B has important consequences in terms of the sensitivity of the proposed device. Let us discuss the various contributions in Eqs. 1,2. First, if the S/A interface is tunnel-like and if S/B is good, $t_A << t_B$ therefore $G_{2A}/G_{\pm} \approx \frac{G_A}{G_B} << 1$, showing that crossed processes dominate over Andreev processes at the tip end (two-electron tunneling into A). On the other hand, $G_{2B}/G_{\pm} \approx \frac{G_{B}}{G_{A}}$ is negligible in practice. In fact, $\delta V_B \sim -R_B I_B$ where $R_B$ is the ferromagnetic thin film resistance, thus $I_B = \frac{G}{1+G_{2B}R_B} V$. And $G_{2B}R_B \approx \left( \frac{e^2}{h} R_B \right) \frac{1}{Z_B} N_B$ where $Z_B \sim \frac{e}{I_B}$ can be identified with the BTK parameter for the S/B interface \[7\], $N_B \approx k_F^2 S_B$ being the number of conduction channels in B. The potential drop $\delta V_B$ can be safely neglected if $R_B Z_B^{-4} (k_F^2 S_B) << 10^4$ ($R_B$ expressed in Ohms) which can be reasonably fulfilled, since
the area of contact B can be reduced without affecting much the crossed conductances $G_{\pm}$
which vary logarithmically with $d/R$ (for instance $R_B < 10\Omega$, $Z_B^2 \sim 10$ and $k_F^2S_B \sim 10^3$).

In these conditions, one has $I_A \approx G_+ V$ and $I_B \approx G_- V$. Let us briefly explain the physical
mechanism allowing a current to pass through the S/B interface in absence of a bias applied
directly at this interface: the tip bias $V$ at the S/A interface forces a quasiparticle to tunnel
from S to A under the condition that another quasiparticle is pulled simultaneously through
S/B, due to the EC and CA processes described above. Either process increase the effective
conductance $I_A/V$ at contact A. Conversely, the EC and CA contributions to the current
induced at S/B have opposite signs [Fig.1(b)].

Let us now examine the spin sensitivity of the proposed device. Eqs. (7,8) show that for a
given spin the processes EC and CA have identical rates, except that EC connects channels
with the same spins in A and B while CA connects channels with opposite spins. Still
assuming the equality of Fermi vectors on both sides of the interfaces, let $P_{A,B} = \frac{N_{\sigma A,B}^{\sigma} - N_{\sigma A,B}^{\sigma}}{N_{\sigma A,B}^{\sigma} + N_{\sigma A,B}^{\sigma}}$
be the spin polarizations in the densities of states at the Fermi level. Then one verifies
that $G_{EC}$ is proportionnal to $(1 + P_A P_B)$ while $G_{CA}$ is proportionnal to $(1 - P_A P_B)$. It
follows that $G_+$, therefore $I_A$, is independent on SP, while $G_-$, thus $I_B$, is proportionnal to
$(-P_A P_B)$, and allows the comparison of the SP’s of A and B. The sign and amplitude of $I_B$
will reflect the local surface SP of A. As a consequence, and this is the central result of this
Letter, measuring simultaneously the currents $I_A$ and $I_B$ allows:

i) To operate as a STM, since the current $I_A$ is spin-independent thus permits the topo-
graphic imaging of the surface at the atomic scale.

ii) To measure the local spin polarization and image the domain structure of surface A.

Notice that the spatial resolution is here by no means limited by $\xi$, but instead by the
atomic-like scale $a$, like an usual STM. The response of the device is governed by the crossed
conductances $G_{\pm}$. Taking $G_A \sim 10^{-7}$, $V \sim 10^{-4}V$ (typically one tenth of the gap for
Niobium) and $Z_B^2 \sim 10$ leads to currents $I_{A,B}$ of the order of $1pA$, while the direct Andreev
current between the tip and the surface is about 100 times smaller thus hardly observable.

Nevertheless, using a good interface B to enhance the subgap current has a drawback:
although the direct Andreev current $I_{2B}$ in B is negligible on average, its fluctuations dominate the Johnson-Nyquist noise, given respectively in A and B (the various contributions $I_{2A}$, $I_{2B}$, $I_{CA}$, $I_{EC}$ are uncorrelated) by $S_A \approx 4k_B T (G_{2A} + G_{CA} + G_{EC}) \approx 4k_B T G_\pm$ and $S_B \approx 4k_B T (G_{2B} + G_{CA} + G_{EC}) \approx 4k_B T G_{2B}$. Notice that it is essential here to avoid conductance noise across the region of the ferromagnetic layer situated at a distance larger than $\xi$ from A. Therefore region $B'$ on Figure 2 must be isolated from S by an insulating layer. An estimate of the largest noise contribution gives $\delta I_{1B} / I_{1B} \approx 10^{-9} \sqrt{\frac{c^2 k_F^2 S_B \log(k_F^2 S_B)}{\log(1+d/R)}} / \sqrt{Hz} \ (T \ \text{in Kelvins, } V \ \text{in volts})$. One finds an optimal noise/signal ratio when $R \sim d$ and $a < R, d < \xi$. With $G_A \sim 10^{-7} S$, $V \sim 10^{-4} V$ and $T \sim 0.1 K$, it is of the order of $10^{-2} \sqrt{N_B}$ at 10Hz. This implies that the dimensions of the ring contact B must be nanometric, in order to carry not more than a few hundred channels. For a given geometry, a better sensitivity is realized if the superconductor has a low density of carriers. Let us remark here that the ring geometry achieves a major improvement with respect to two point contacts of sizes $a << \xi$, distant by $R$ [12,15], where the conductance drops by a factor $(k_F R)^2$ : in the ring geometry presented in this Letter the measured currents are higher by a factor $\sim (R/a)^2$ while the signal/noise ratio is improved by a factor $R/a$, ranging from 10 to 100 depending on the chosen materials.

V. CONCLUSION

In summary, we have shown how a new principle for a magnetic STM results from non-local two-particle tunneling processes at two S/F interfaces. Let us discuss the validity of our simplifying assumptions. First, beyond the simple ballistic regime considered here, in a dirty superconductor the crossed processes will decay on $\xi \approx \sqrt{\xi_0 l}$ where $l$ is the mean-free path and $\xi_0$ the BCS coherence length ($l < \xi_0$), as EC and CA processes directly probe the one-particle correlation functions in the superconductor. Secondly, proximity effect should be considered : due to the ferromagnet B, the gap function might be reduced in the superconductor. Recent theoretical results [22,23] for a clean interface do not show dramatic effects, which should be even smaller for an imperfect interface S/B (we assumed above
a value $Z^2 \sim 10$). One might also worry about vortices induced by the stray field from B. If created, vortex cores, of size $\xi$, should penetrate in the bulk and hardly affect the gap in the tunneling region, a priori smaller. More directly, experiments reported in [9,10] demonstrate that the presence of a ferromagnet does not destroy the Andreev reflection, even with a superconducting tip pressed on a bulk ferromagnet. We thus believe that the present proposal could be realized if choosing properly the material and geometry parameters. Low temperature superconductors, with a large coherence length and possibly a low carrier density are preferable. As an S/F couple, one may try Nb/Fe, or Al/Fe. One also notices that the interactions between ferromagnets B and A due to stray field effects should be much less serious when they sit at a typical distance $\xi$ which can exceed hundredths of nanometers. In a configuration of parallel magnetization especially, this can be a sensible improvement with respect to the “all ferromagnet” MSTM principle where the AB distance is a few Angstroems. This is allowed by the coherence in the superconductor, allowing propagation of quasiparticles on distances much larger than the width of a usual tunnel barrier.

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