FM/SC/FM Double Tunnel Junctions: Suppression of Superconductivity due to Spin Imbalance

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Abstract

I review the spin-dependent transport in Ferromagnet/Superconductor/Ferromagnet double tunnel junctions. The tunneling current can give rise to spin accumulation in the superconductor depending on the alignment and values of the magnetizations in the ferromagnets. The resulting nonequilibrium spin density suppresses the superconductivity with increase of the bias voltage. The theory and some experiments with the comparison to it are presented; so are some of the proposed applications proposed.

Spin-polarized tunneling is of vital importance in magnetic junctions and multilayers. First demonstrated in FerroMagnet/SuperConductor (FM/SC) tunnel junctions, it causes a large magnetoresistance effect in ferromagnetic single tunnel junctions FM/FM. In FM/SC or FM/N (N=Normal metal) spin polarized tunneling current creates a nonequilibrium spin polarization (spin imbalance) in SC or N. More recently it has been seen that superconductivity is strongly suppressed by injection of spin-polarized electrons in a superconductor.

A double tunnel junction containing SC sandwiched between two FM (FM/SC/FM) is a convenient system to study the nonequilibrium phenomena of spin and charge imbalance in SC caused by the tunneling currents. When below the critical temperature T_c, the strong competition between superconductivity and magnetism induced by the spin accumulation in SC will be the most interesting feature.

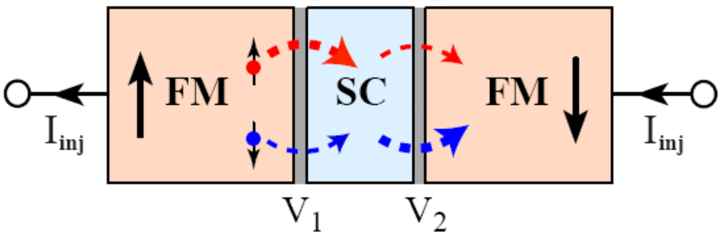


Fig.1. R_1, R_2: tunnel resistances; V_1, V_2: voltage drop across the barriers ($V=V_1+V_2$) [1]

We are considering the device in Fig.1: two ferromagnetic electrodes and a superconducting island separated by two tunnel barriers. Let us consider in the first place the symmetric device, i.e. the case in which both ferromagnets are made of the same material (same polarization) and the tunnel barriers have the same resistance. The electrons are injected from the left, and we are above the critical temperature of the superconductor, normal state. In the case of antiparallel alignment of the magnetizations in the electrodes, spin-up electrons mainly go into the island from the left electrode, while spin-down electrons go out to the right, causing a spin imbalance in the island (see Fig.2). This spin accumulation makes the island get magnetized, causing TMR. Therefore, spin accumulation can be probed using TMR, as it was done in [X], where this fact has been studied experimentally in GaMnAs/GaAs/GaMnAs double tunnel junctions. In the case of parallel alignment, the "bottleneck" effect is not present anymore, and no spin accumulation is produced.

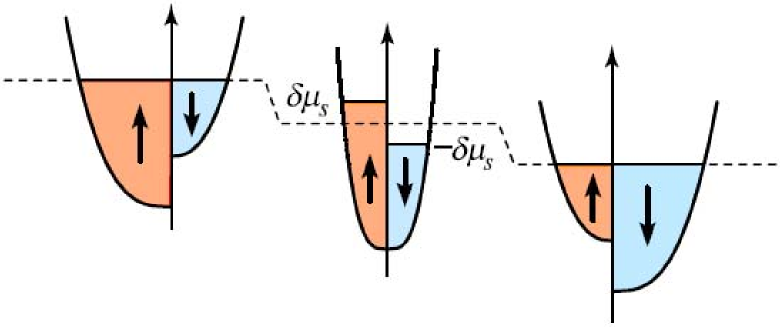


Fig. 2. Densities of states of FMs and SC (normal state). $\delta\mu_s$: shift in the chemical potential of the spin subbands [1]

Consider now the situation when the island is in the superconducting regime, i.e. the temperature below T_c. The superconducting gap appears as depicted in Fig.3. In this situation, competition between spin accumulation and superconductivity occurs. Spin accumulation prevents the formation of Cooper pairs, and the presence of the gap shifts the energy needed to accommodate electrons in the majority subband.

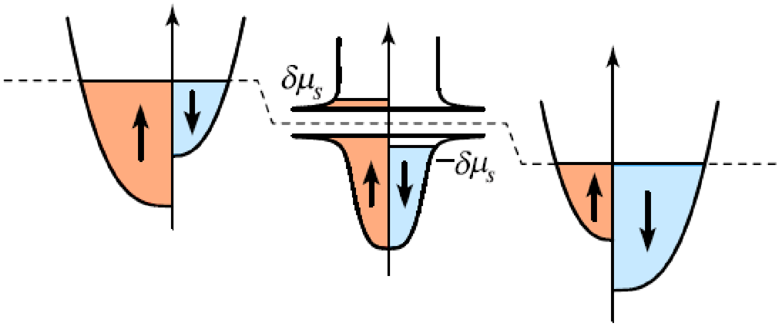


Fig. 3: Densities of states of FMs and SC (superconducting state) [1]

The theory which explains the superconductivity suppression was developed mainly by S. Takahashi, H. Imamura and S. Maekawa [1,2,3,8,9,10]. A very brief sketch follows. The tunneling current is calculated using a phenomenological tunneling Hamiltonian, in which the Bogoliubov transformation is applied, convenient to deal with the superconducting state. Then using the Fermi's golden rule they calculate the spin-dependent tunnel currents across the junctions.

The quasiparticle QP spin density accumulated in SC is given by:

$$S = \int_{-\infty}^{\infty} N_{\mathrm{BCS}}(E)[f_{\uparrow}(E) - f_{\downarrow}(E)]\,\mathrm{d}E$$

where N_{BCS} is the BCS density of states and f_σ is the distribution function of QP in SC.

The gap Δ in the SC is determined with the BCS gap equation:

$$\frac{1}{N(0)V_{\mathrm{BCS}}} = \int_{-\hbar\omega_D}^{\hbar\omega_D} \frac{1 - f_{\uparrow}(E_k) - f_{\downarrow}(E_k)}{2E_k}\,\mathrm{d}\xi_k$$

where N(0) is the normal density of states. In the FM/SC/FM tunnel junction, the energy relaxation time τ_E can be shorter than the characteristic time τ_t of an electron passing through SC, so that electrons that enter SC relax to the Fermi distribution before leaving SC. In addition, the thickness d of SC is smaller than λ_S, so that the distribution of QPs is spatially uniform in SC. Then, the distribution function $f_{k\sigma}$ is described by f_0 (the Fermi distribution), thereby shifting the chemical potentials of the spin-up and spin-down QPs in opposite directions by $\delta\mu_S$ from the equilibrium one:

$$f_{\uparrow}(E_k) = f_0(E_k - \delta\mu_S)$$

$$f_{\downarrow}(E_k) = f_0(E_k + \delta\mu_S)$$

which creates spin accumulation according to the Fig.3.

Now we solve for $\delta\mu_S$ and Δ: In the F (ferromagnetic) alignment, as we expected there is no spin accumulation $\delta\mu_S=0$, so Δ_F is exactly the BCS gap Δ_{BCS}. In the AF (antiferromagnetic) alignment we have to solve the equations selfconsistently. The results are shown in the following Fig.4:

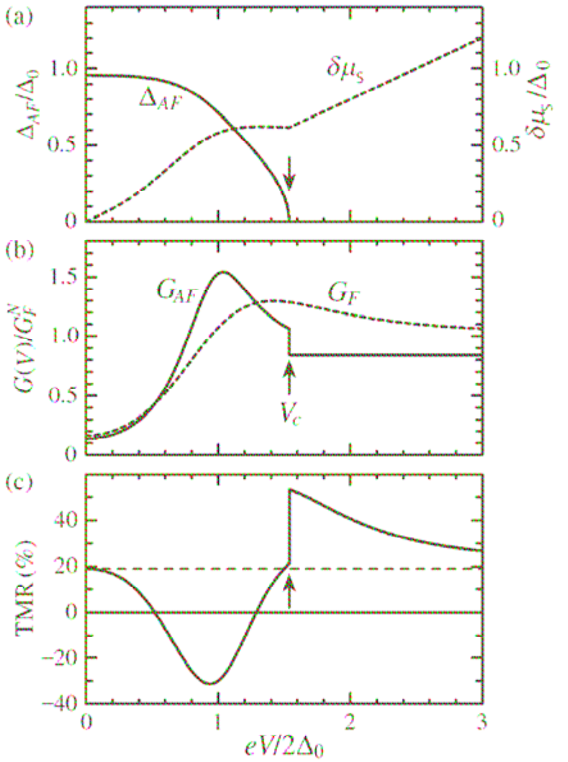


Fig.4. (a) Superconducting gap parameter Δ_{AF} and the shift of the chemical potential $\delta\mu_S$. (b) Tunnel conductance in the F and AF alignment. (c) TMR as a function of bias voltage. The thin dashed line indicates TMR=$P^2/(1-P^2)$ in the normal state.[1]

The voltage dependence of the superconducting gap Δ_{AF} and the chemical potential shift $\delta\mu_S$ are shown in Fig.4a As the bias voltage V increases, the gap Δ_{AF} decreases by the pair breaking effect due to the increase of $\delta\mu_S$, and vanishes at the critical voltage $V_C \approx eV/2\Delta_0$. Fig.4b shows the voltage dependence of the conductance in the AF and F alignments. With this it is easy to compute the TMR, it is simply

$TMR = (G_F / G_{AF}) - 1$. At zero bias, where $\Delta_{AF} = \Delta_F$, TMR takes the same value as in the normal state. A negative dip appears at $eV/2\Delta_0 \approx 1$, exhibiting inverse TMR effect, and is followed by the discontinuous jump at V_C, above which TMR is highly enhanced compared to that in the normal sate.

Let us move on to the asymmetric case. The theory is pretty similar to the one in the latter case and the details are in ref. [3]. When P_1=P_2 the injected spins vanish in the F alignment irrespective of the asymmetry of the tunnel resistances, and are accumulated only in the AF alignment. However, when the FMs are different, the injected spins are accumulated in proportion to (P_1-P_2) for the F alignment and (P_1+P_2) for the AF, and thus the pair breaking effect may occur in both alignments.

We can see the suppression of the superconductivity by measuring the superconducting critical current J_C. According to the Ginzburg-Landau theory, J_C is proportional to Δ_3. Fig.5 shows the cube of the normalized gap $(\Delta/\Delta_0)^3$ and thus the normalized critical current (J_C / J_{C0}), as a function of the injection current for some different values of the polarization of the ferromagnetic electrodes. In the case that P_1 and P_2 are the same (Fig.5a), the critical current J_C in the AF alignment steeply decreases and vanishes at a relatively small value of Iinj, whereas J_C in the F alignments shows no dependence on Iinj, as we expected due to the lack of accumulation. In the case that P_1 and P_2 are different (Fig.5b) the critical current decreases and vanishes in both alignments, being the suppression faster in the antiparallel alignment.

If we substitute one of the ferromagnetic electrodes with a normal metal, we end up with a heterostructure junction FM/SC/N, which in this theory corresponds to set P_2=0. The solid line in Fig.5c shows the present theory in this case, the circles are the experimental result for $Nd_{1-x}Sr_xMnO_3/YBa_2Cu_3O_7$/Au [5]. $Nd_{1-x}Sr_xMnO_3$ is a ferromagnetic electrode and $YBa_2Cu_3O_7$ a common high temperature superconductor with T_C=89K.

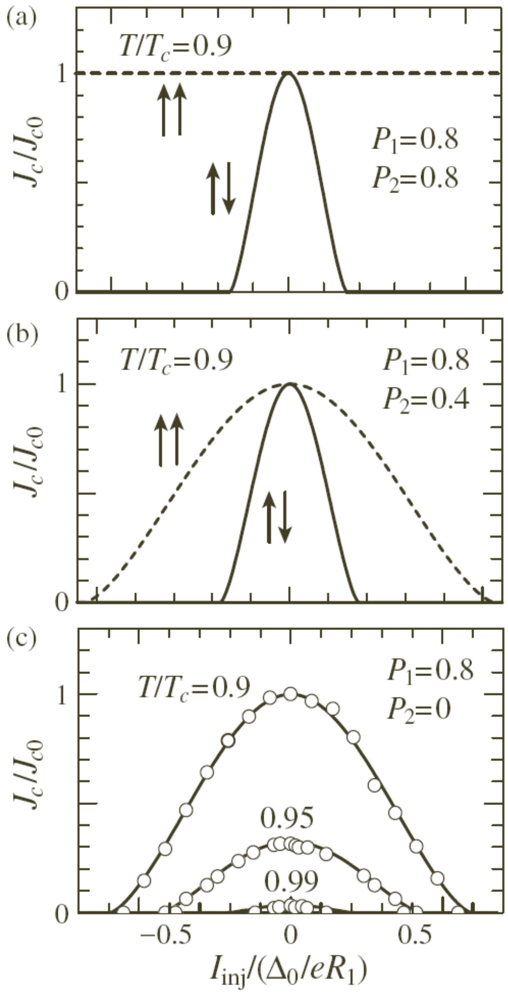
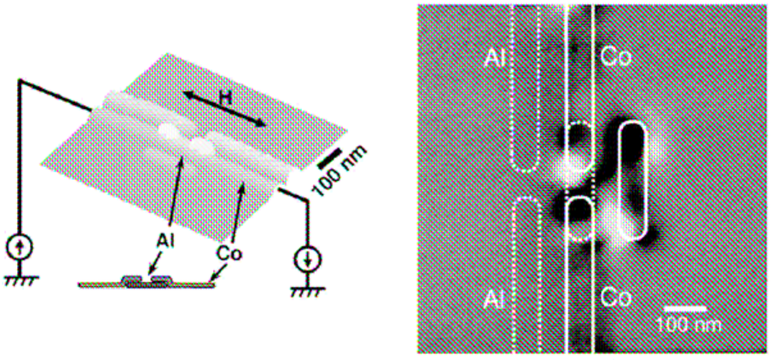


Fig.5. Dependence of the critical current JC on the injection current Iinj for different spin polarizations of the electrodes. In (c) the open circles indicate the experimental results in $Nd_{1-x}Sr_xMnO_3/YBa_2Cu_3O_7/Au$ junctions [5] and the solid line the present theory.[3]

After having sketched the theory for the FM/SC/FM double tunnel junctions is very convenient to compare it with some of the recent experiments done so far. The first I am going to review was done by Chen *et al.* [6] in Co/Al/Co single electron transistors. The samples were fabricated by standard electron-beam lithography techniques and by the angle evaporation method, see Fig.6. The barriers were two Al_2O_3 layers, which have been shown not to have spin-flip tunneling processes.



(a) (b)

Fig.6.(a) AFM and (b) MFM images of the sample. Because of the technique used for fabrication, there are electrically unconnected structures aside the measured device. [6]

The samples were current biased, and a parallel magnetic field was applied to decrease the size of the superconducting gap, and monitored this decrease by measuring the voltages. The results are in Fig.7. Two thing are important to notice in this graph: i) The hysteresis in the middle of the curves is due to the magnetization reversal of the Co single domains lying on top of the Al island (the “horns” in Fig.6); ii) The dips in V(H) curves indicate a reduction of the superconducting gap of the Al island.

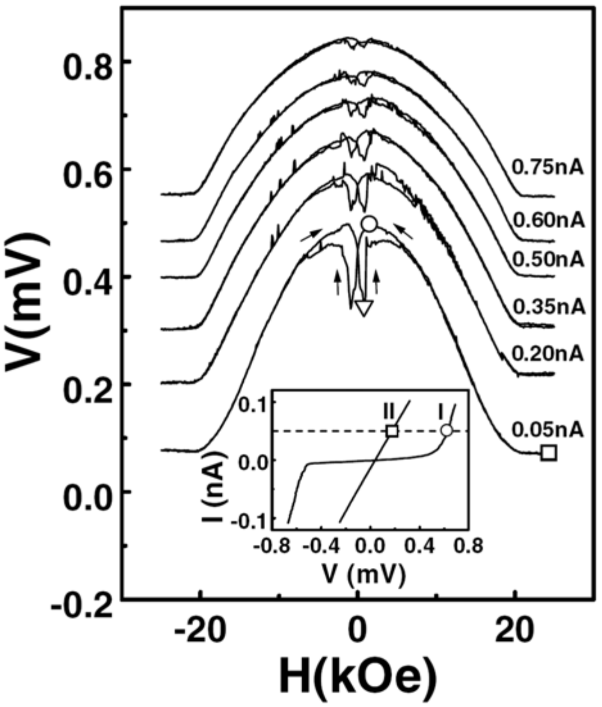


Fig.7. Measured V(H) curves for several selected bias current at $T \approx 250mK$.[6]

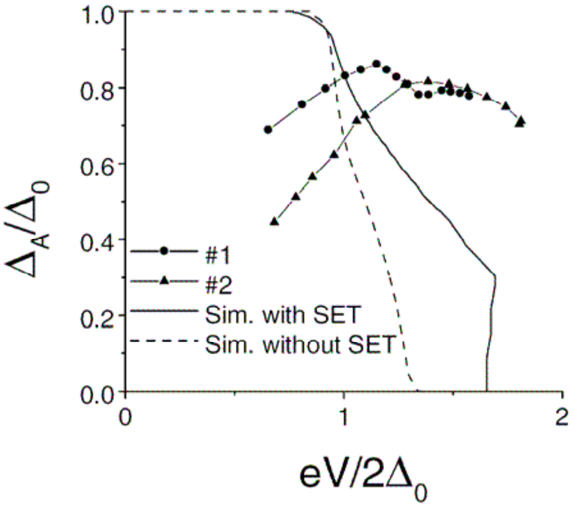


Fig.8. Normalized superconducting gap as a function of the bias voltage. Curves with symbols are data from two measured samples. The solid and dashed lines are calculated curves.[6]

From Fig.7 we calculate Fig.8 where we can see directly the comparison with the theory developed before. The agreement is pretty bad, especially at low bias, where in the real sample the superconducting gap increases with V. The authors attribute this fact to charging effects (neglected in the theory), short spin relaxation time τ_S… (see [6]). Moreover the uncertainties involved in deriving the $\Delta_A(V)$ dependence from Fig.7 were large. Despite the clear deviations, this experiment suggests a suppression of Δ_A with increasing bias voltage.

Another independent experiment in Co/Al/Co double tunnel junctions was done by Johansson *et al.* [7]. The device is pictured in Fig.9. Notice the difference in width of the Co electrodes that results in different magnetostatic shape anisotropy, which causes different switching fields for the electrodes. Due to this, the magnetization orientation (parallel or antiparallel) is easy to control, and a measurement of the TMR is found to be very convenient. The results are shown in Fig.10. The spin-valve effect is most pronounced at a low bias of $\approx 200\mu V$, which approximately equals the superconducting gap. Above and below this voltage the effect is weaker, and asymptotically goes to zero for large bias. This measured behavior is qualitatively consistent with the theoretical results (compare with Fig.4c).

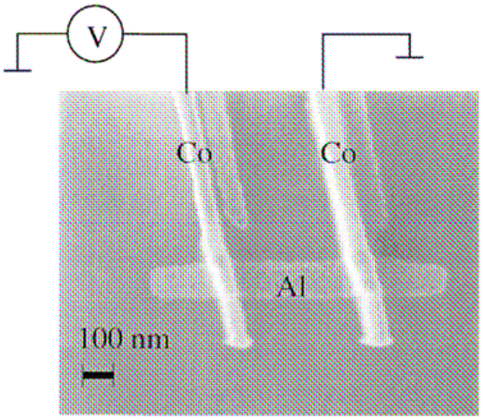


Fig.9. SEM image of the device. [7]

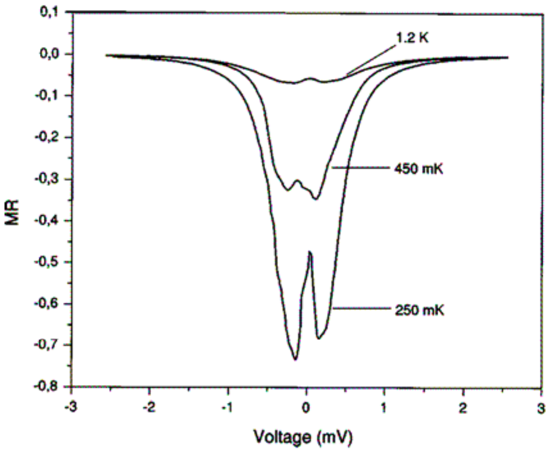


Fig.10. Magnetoresistance as function of bias voltage. [7]

A very interesting potential application of this type of devices is obtained in the following manner. The gap equation is completely analogous to the one corresponding to a superconducting film in a parallel magnetic field *H*, which acts as a Zeeman field for the QP spins. We only have to map $2\mu_B H$ with $2\delta\mu_S$. $\delta\mu_S$ is approximately $0.6\Delta_0$ at the critical voltage V$_c$ (see Fig.4a). Therefore it corresponds an effective magnetic field $H_{eff} = 0.6\Delta_0 / \mu_B$. For example, in aluminum with a gap $\Delta_0 \approx 0.4 meV$ the H_{eff} is 4T. In the case of HTC SCs $\Delta_0 \approx 40 meV$ H_{eff} is ≈100T. This suggests the possibility of generating huge effective magnetic fields by means of spin injection in the FM/SC/FM junctions, simply by applying a voltage across the junction.

The possibility to control superconductivity by applying a bias voltage is exciting. Moreover, new magnetoresistivity effects have been observed, and the direct control of TMR is also possible (see Fig.4c). All these have interesting potential applications in the world of magnetoelectronics and magnetic nanostructures.

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