The Meservey-Tedrov effect in FSF double tunneling junctions

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March 23, 2022

Abstract

Double tunneling junctions of ferromagnet-superconductor-ferromagnet electrodes (FSF) show a jump in the conductance when a parallel magnetic field reverses the magnetization of one of the ferromagnetic electrodes. This change is generally attributed to the spin-valve effect or to pair breaking in the superconductor because of spin accumulation. In this paper it is shown that the Meservey-Tedrov effect causes a similar change in the conductance since the magnetic field changes the energy spectrum of the quasi-particles in the superconductor. A reversal of the bias reverses the sign in the conductance jump.

PACS: 73.50.-h, 73.50.Bk, 73.23.-b, 73.25.+i

1 Introduction

During the last five years single electron transistors (SET) with two ferromagnetic electrodes and a superconducting island have been studied experimentally \cite{1}, \cite{2}, \cite{3}, \cite{4} and theoretically \cite{5}. Experimentally one generally uses ferromagnetic-superconductor-ferromagnetic double junctions which consist of an Al strip of length of about 1$\mu$m, width of 50-100nm and thickness of about 20nm. The Al is oxidized, and two Co electrodes with slightly different width and twice the thickness cross the Al strip at a separation of a few 100nm. They form two tunneling junctions. Fig.1 shows the schematic arrangement of the two ferromagnetic Co electrodes and Al island. A magnetic field is applied parallel to the Co strips and aligns the magnetization of the two Co strips. Then the magnetic field is reversed. At a magnetic field $B_{sw}$ the wider Co strip flips its magnetization to be parallel to the magnetic field while the narrower Co strip remains anti-parallel to the external field because its coercitive field is larger.
At the same time the current through the double junction changes abruptly at $B_{sw}$. At the field $B_{sn}$ the narrower Co strip also reverses its magnetization and the magnetizations of the two Co strips are again parallel to the external field. (The relative orientations of the magnetic field and the magnetization of the two Co electrodes is shown in Fig.4). If one applies constant bias to the junction then the current shows a jump at each of the fields $B_{sw}$ and $B_{sn}$ (with opposite sign). Such jumps at the fields $B_{sw}, B_{sn}$ have been observed in a number of experiments [1], [2], [3], [6].

In the theoretical discussion one generally considers two mechanisms which change the current (i.e. conductance) of the double junction in the field range $(B_{sw}, B_{sn})$:

1. Spin-valve effect: When the magnetizations of the Co strips $\mathbf{m}_1$ and $\mathbf{m}_2$ are both parallel to $\hat{y}$ then one has a large density of states in both Co electrodes for the spin moment up electrons, while the spin moment down electrons have a small density of states in both electrodes. For the (spin) moment up one has two small resistances $R_{t\uparrow}$ in series and for the other direction two large resistances $R_{t\downarrow}$. The total conductance is then $G_{\uparrow \downarrow} = 1/(2R_{t\uparrow}) + 1/(2R_{t\downarrow})$. If the two Co strips have opposite magnetization then the conductance is $G_{\uparrow \downarrow} = 2/(R_{t\uparrow} + R_{t\downarrow})$. It is easy to show that $G_{\uparrow \downarrow} \geq G_{\uparrow \downarrow}$. Therefore the current should drop inside the field window [7], [8].

2. Gap reduction due to spin accumulation: In the anti-ferromagnetic alignment one obtains spin moment accumulation [5] because the spin moment up electrons have a small resistance for tunneling onto the island and a large resistance to tunnel off the island while the opposite is true for spin moment down electrons. This spin moment accumulation can reduce the superconducting gap of the Al island. This will lead to an increase of the conductance in the field window $(B_{sw}, B_{sn})$. 

2
In this paper we want to show theoretically that there is an additional contribution to the current because of the Zeeman effect which shifts the excitation spectrum of the quasi particles in the Al by $\mu_e B$ ($\mu_e$=moment of the spin up and down electrons, $B$=external magnetic field). This effect has been intensively studied by Meservey and Tedrow in many beautiful experiments (see the review article [9]). In a series of papers [10], [11], [12] their group investigated the tunneling I-V-curve for ferromagnet-superconductor tunneling junctions in different magnetic field. They showed that the I-V-curves were asymmetric with respect to the voltage (because of the different density of spin up and down electron at the Fermi surface). From the asymmetry they derived the polarization of the effective density of states of the tunneling electrons. To our knowledge the magnetic field and the magnetization were always parallel to each other in their measurements.

In this paper we want to demonstrate that one has to take the field and spin dependence of the quasi-particles in the Al into account when calculating the current through the double tunneling junction. To demonstrate this effect we consider a double tunneling junction in which the two junctions are so far separated that the spin-orbit scattering destroys any spin polarization along the diffusion path of the electrons from the first tunneling junction to the second one. This means that only the total current $I_1$ through junction one must be equal to the total current $I_2$ through junction two; the spin up and down currents through the two junctions can be quite different.
2 Theory and Simulation

2.1 Single junctions

We first consider a single ferromagnet-superconductor tunneling junction at zero temperature. In Fig. 2 the density of states for both metals is plotted after lifting the energy bands of the ferromagnet by $eU$.

![Diagram](image)

Fig. 2: The tunneling density of spin moment up electrons in an FS tunneling junction for different orientations of the magnetic field and the magnetization $m$ of the ferromagnet.

a) $B$ and $m$ are parallel, both pointing in $\hat{y}$,
b) $B$ and $m$ are anti-parallel, $B$ pointing in $-\hat{y}$, $m$ in $\hat{y}$
c,d) The bias is reversed.

In large body of experiments Merserey and Tedrow [9] showed that a magnetic field parallel to the tunneling junction shifts the excitation spectra of spin up and down electrons in the superconductor by $\vec{\mu}_B \cdot B$ in opposite directions. This enhances the current of the majority spin (see Fig. 2a) when the electrons are flowing from the ferromagnet to the superconductor. One obtains a spin current (with moment up). The I-V-curve is not (point-) symmetric about the origin.

The tunneling current is for spin moment up and down is given at zero temperature by

$$I_\uparrow = C N_M N_S \int_{\Delta - \mu_B B}^{eU} \frac{(E + \mu_B B)}{\sqrt{(E + \mu_B B)^2 - \Delta(B)^2}} dE = C N_M N_S \sqrt{((eU + \mu_B B)^2 - \Delta(B)^2)}$$

$$I_\downarrow = C N_m N_S \int_{\Delta - \mu_B B}^{eU} \frac{(E + \mu_B B)}{\sqrt{(E + \mu_B B)^2 - \Delta(B)^2}} dE = C N_m N_S \sqrt{((eU - \mu_B B)^2 - \Delta(B)^2)}$$

4
Here $N_M$ and $N_m$ are the majority and minority density of states in the ferromagnet and $N_S$ is the density of states of the superconductor in the normal state. In the superconducting state in the presence of a magnetic field $N_S$ is modified by the factor $(E + \mu_e B) / \sqrt{(E + \mu_e B)^2 - \Delta(B)^2}$. The constant $C$ contains the tunneling matrix elements and universal constants. The energy gap is given by $\Delta(B)$. For thin films and stripes which are aligned parallel to an external magnetic field we use the result from reference [13] for the dependence of $\Delta$ on the magnetic field:

$$\Delta(T, B) = \Delta(T, 0) \sqrt{1 - \left(\frac{B}{B_c(T)}\right)^2}$$

where the field $B_c(T)$ is determined by the ratio of the penetration depth $\lambda(T)$ and the film thickness:

$$B_c(T) = \sqrt{\frac{\lambda(T)}{d} B_{cb}(T)}$$

$B_{cb}(T)$ is the thermodynamic critical field.

The use of the density of states in the tunneling current is a dramatic oversimplification since the tunneling probability of electrons at different parts of the Fermi surface depends strongly on the direction of their group velocity relative to the tunneling barrier. So $N_M$, $N_m$ and $N_S$ have to be interpreted as “effective tunneling densities of states”. In the present paper we only need the relative magnitudes of $N_M$ and $N_m$ which are given by the experimental polarization of the tunneling current.

Merservey and Tedrow obtained a number of interesting results for an FS junction in a parallel magnetic field:

- The I-V-tunneling curve is not (point) symmetric about the origin.
- The tunneling current is polarized and the polarization can be evaluated.
- The polarization is always parallel to the majority moment of the ferromagnet and not proportional to the d-density of states at the Fermi surface.

They obtained a polarization of 35% for Co/Al junctions.

There is another interesting consequence of the energy shift of the Zeeman effect. Let us consider a single Co/Al tunneling junction, i.e. the left half of the Fig.1. We align the magnetic field parallel to the Co strip in the negative y-direction and keep the voltage across the junction constant. For simplicity we assume that the temperature is (close to) zero. We start with the magnetic field $-B_c(0)$ which suppresses superconductivity in the Al completely. Then we sweep the magnetic field towards $+B_c(0)$. As soon as the magnetic field takes positive values the magnetization of the Co and the field are anti-parallel and therefore the junction is in an instable energetic state. Due to its coercitive
field $B_{sw}$ the Co can maintain the anti-parallel orientation up to the field $B_{sw}$. Then the Co film will switch its magnetization. As a consequence the tunneling current will also change.

In Fig.3 we calculate the current through the junction using the following parameters: the energy gap in Al at zero temperature $\Delta = 0.2\,\text{meV}$, the field that suppresses superconductivity completely $B_c = 1.5\,\text{T}$, the switching field $B_{sw} = 0.16\,\text{T}$, the polarization of the effective density in the Co $p = .35$. We sweep the external magnetic field from $-0.5\,\text{T}$ to $0.5\,\text{T}$. When the magnetic field changes sign the Zeeman term changes sign as well. At the magnetic field $B_{sw}$ the direction of the Co magnetization $\mathbf{m}$ becomes aligned parallel to the magnetic field. At the same time the current jumps to a higher value.

![Fig.3: The simulated current through an FS-tunneling junction while the magnetic field sweeps from $-0.5\,\text{T}$ to $0.5\,\text{T}$. The numbers at the curves give the different bias. At $B = 0.16\,\text{T}$ the magnetization of the Co strip reverses.](image)

In Fig.3 the calculated tunneling current through a Co/Al junction is plotted for constant bias as a function of the magnetic field. The different curves are for different bias which is given in $\text{meV}$ at the right side of the curves. One recognizes that the current shows a jump at the switching field $B_{sw} = 0.16\,\text{T}$. For positive bias the current increases at the switching field while for negative bias the (absolute value of the) current decreases. Furthermore the minimum of the I-B-curve is not at $B = 0$ but shifted to positive field values. If the field is then swept from $B_m = 0.5\,\text{T}$ to $-0.5\,\text{T}$ the resulting current curves are just a mirror image of the shown curves.

It is important to note that a reversal of the applied voltage corresponds to a tunneling of electrons from the superconductor to the ferro-magnet (see
Fig. 2b, c). In this case the current is smaller if \( \mathbf{m} \) is parallel to \( \mathbf{B} \) because for an electron with moment up to tunnel from S to F a Cooper pair has to split and the moment down electron is elevated by \( \Delta + \mu_B B \) into an excited state in the superconductor while the moment up electron tunnels into the ferromagnet. The contribution of moment up electrons to the tunneling current is reduced to 
\[
CN_M N_S \sqrt{((eU - \mu_B B))^2 - \Delta (B)^2}.
\]
Therefore the current changes to a smaller value when the magnetization flips.

2.2 Double junctions

We now consider the double junction in Fig. 1. However, we use a long Al strip so that the two junctions are relatively far apart. As we discussed above the tunneling current through a single junction Co/Al is polarized. This means that one has a source of polarized electrons in the Al strip. Meakawa et al. [8] calculated an (opposite) shift in the chemical potential for (spin) moments up and down. The lifetime of an electron in a given spin state is limited by the spin-orbit scattering and the spin state decays as \( \exp \left( -t/\tau_{sf} \right) \) where \( \tau_{sf} \) is the spin-flip lifetime which is 3/2 times the spin-orbit scattering time \( \tau_{so} \). The injected spin polarization at the left tunneling junction diffuses through the Al strip towards the right junction and vice versa. Along this diffusion path the spin decays. For the resulting spin diffusion length one finds different orders of magnitude in the literature, varying between 10-100 nm and 1 \( \mu \)m [9, 14].

As shown in Fig. 1 the total potential difference between the right and the left electrode is \( 2eU \). We consider the bias as positive when the potential on the right electrode is positive. Then the electrons flow from the left to the right side.
as shown in Fig.4.

**Fig.4:** The current of spin moment up electrons through an FSF-double junction.

a) The moments $m_1$, $m_2$ and $B$ are all parallel, pointing in $+\hat{y}$ direction,
b) the magnetic field has changed to the $-\hat{y}$ direction,
c) the moment $m_2$ has switched at $B_{sw}$ to the $-\hat{y}$ direction,
d) the moment $m_1$ has switched at $B_{sn}$ to the $-\hat{y}$ direction,

$m_1$, $m_2$ and $B$ are all parallel, pointing in $-\hat{y}$ direction

In contrast to the goal of the spin valve we choose a large separation of the two junctions (in our virtual experiment) so that each junction is unaffected by the polarized current of the other. In this case we have excluded all spin-valve effects in our virtual experiment. Mathematically this requirement is expressed by the condition that only the total currents through junctions $J_1$ and $J_2$ must be identical; the individual spin currents can be different. As a result both spin directions experience the same shift in the chemical potential.

We consider first the special case (a) in Fig.4 where $m_1$, $m_2$ and $B$ are all pointing in the positive $\hat{y}$-direction. In general the currents through the
junctions $J_1$ and $J_2$ are not identical when their bias is the same, i.e. $eU$. Therefore the chemical potential of the island will shift by $\phi$ (which has to be determined self consistently). Then the (spin) moment up current through junctions $J_1$ and $J_2$ are given by

$$I_{1\uparrow} = C N_S N_m \sqrt{\left( (V_e + \phi + \mu_B B)^2 - \Delta^2 \right)}$$

$$I_{2\uparrow} = C N_S N_m \sqrt{\left( (V_e - \phi - \mu_B B)^2 - \Delta^2 \right)}$$

(The symbol $\uparrow$ stands again for spin moment up.)

The other current contributions can be obtained from these currents by applying simple rules:

1. The contribution of spin moment down electrons is obtained changing the sign of the term $\mu_B B$ in $I_1$ and $I_2$ and exchanging $N_M$ and $N_m$.
2. If $\mathbf{m}_1$ points in the $-\hat{y}$-direction one has to replace $N_M$ by $N_m$ in $I_1$.
3. If $\mathbf{m}_2$ points in the $-\hat{y}$-direction one has to replace $N_M$ by $N_m$ in $I_2$.
4. If $\mathbf{B}$ points in the $-\hat{y}$-direction one has to change the sign of the term $\mu_B B$ in $I_1$ and $I_2$.

It is sufficient to calculate the current for spin moment up (equation (1)) in the alignment of Fig.4a. Then the above rules yield the current for moment up and down under all circumstances. For example the corresponding spin moment down currents are

$$I_{1\downarrow} = C N_S N_M \sqrt{\left( (V_e + \phi - \mu_B B)^2 - \Delta^2 \right)}$$

$$I_{2\downarrow} = C N_S N_M \sqrt{\left( (V_e - \phi + \mu_B B)^2 - \Delta^2 \right)}$$

We calculate the total current perturbatively. For sufficiently large bias, i.e., $eU > \Delta$ the terms $e\phi$ and $\mu_B B$ are small compared to $\sqrt{V_e^2 - \Delta^2}$ and we can expand the different current contributions as a Taylor series in terms of $e\phi$ and $\mu_B B$ up to second order. Since the current depends on the orientation of three vectors, $\mathbf{m}_1, \mathbf{m}_2$ and $\mathbf{B}$ we choose the $\hat{y}$-direction as a reference direction. The value of $B$ is negative when $\mathbf{B}$ is anti-parallel to $\hat{y}$. We calculate (in perturbation) the currents $I_{1\uparrow}, I_{1\downarrow}, I_{2\uparrow}, I_{2\downarrow}$ for the four possible orientations of
of the current through the double junction is plotted versus the sweeping magnetic field. The current returns to the original curve since the field. Then the new current is the switching field of the magnetization of junction J.

At the higher field the linear dependence on the quadratic term is rather weak, so that it is sufficient for a qualitative discussion to restrict ourselves to the weak, so that it is sufficient for a qualitative discussion to restrict ourselves to the weak, so that it is sufficient for a qualitative discussion to restrict ourselves to the weak, so that it is sufficient for a qualitative discussion to restrict ourselves to the weak, so that it is sufficient for a qualitative discussion to restrict ourselves to

The dependence of the currents on the quadratic term \((\mu_B B)^2\) is rather weak, so that it is sufficient for a qualitative discussion to restrict ourselves to the linear dependence on \((\mu_B B)\). When we start with a large negative magnetic field \((B \parallel \hat{y})\) then both magnetizations, \(m_1\) and \(m_2\), are anti-parallel to \(\hat{y}\). In the linear approximation the current is \(I_{\parallel \perp} \approx \sqrt{V_e^2 - \Delta^2} (N_M + N_m)\). At the positive field \(B_{sw}\) the magnetization of the junction \(J_2\) flips and aligns parallel to the field. Then the new current is \(I_{\parallel \perp}\) which corresponds to a relative decrease of the current

\[
\Delta I / I = - \frac{(N_M - N_m)}{(N_M + N_m)} \frac{V_e}{(V_e^2 - \Delta^2)} \mu_B B
\]

At the higher field \(B_{sn}\) the other electrode \(J_1\) also aligns parallel to \(\hat{y}\). Then the current returns to the original curve since \(I_{\parallel \perp} = I_{\parallel \perp}\) in this approximation. It is important to point out that the jump in the current is positive when the magnetization of junction \(J_1\) (i.e. \(m_2\)) flips first. Then the current changes from \(I_{\parallel \perp}\) to \(I_{\parallel \perp}\).

In Fig.5 we sweep the magnetic field from \(-0.5T\) to \(+0.5T\). The current through the double junction is plotted versus the sweeping magnetic field. The junction \(J_2\) has the switching field \(B_{sw} = 0.14T\) while junction \(J_1\) has the larger switching field of \(B_{sn} = 0.18T\). We use different bias voltages in the range of \(-0.2meV \leq -eU \leq 0.7meV\). The \(I - B\)-curve in Fig.5 shows a downward displacement in the field window \((B_{sw}, B_{sn})\). For negative \(-eU\) (i.e. \(U > 0\))
the absolute value of the current increases. This means that the displacement changes sign when the bias is reversed.

Fig. 5: The current through an FSF-double junction while the magnetic field sweeps from \(-0.5T\) to \(0.5T\). The numbers at the curves give the different bias. The switching fields for the two Co strips are \(0.14T\) and \(0.18T\).

3 The single electron transistor

When the size of the two tunneling junctions is in the nano-meter scale then their capacity is small and the tunneling electrons change the Coulomb energy on the island \[15\], \[16\], \[17\], \[18\], \[19\], \[20\]. If an electron from the left electrode with the band energy \(\varepsilon_L\) tunnels onto a state on the island with the band energy \(\varepsilon_I\) and changes the number of electrons on the island from \(n\) to \((n+1)\) then conservation of energy requires that

\[
\varepsilon_L + Ue = \varepsilon_I + (2n + 1) \frac{e^2}{2C_{\Sigma}} C_G eU_G
\]

On the other hand if an electron from the island with the band energy \(\varepsilon_I\) tunnels into a state on the right electrode with the band energy \(\varepsilon_R\) and changes the number of electrons from \(n\) to \((n-1)\) one has to fulfill the condition

\[
\varepsilon_I + Ue = \varepsilon_R - (2n - 1) \frac{e^2}{2C_{\Sigma}} C_G eU_G
\]

Here \(U_G\) is the gate voltage and \(C_{\Sigma}^{-1} = C_1^{-1} + C_2^{-1} + C_G^{-1}\) where \(C_1, C_2\) and \(C_G\) are the capacities of the two tunneling junctions and the gate. The Coulomb
blockade energy is given by $E_{Cb} = e^2/2C_\Sigma$. In the following we consider only zero gate voltage.

At a sufficiently large bias ($2eU > 2(\Delta + E_{Cb})$) the island can gain or loose up to $n_0$ electrons where (at $T = 0$) $n_0$ is given by $n_0 = \text{int}\left[\frac{1}{2} \left(\frac{eU - \Delta}{E_{Cb}} - 1\right)\right]$. The probability for $n$ excess electrons on the island may be $p(n)$ which will be determined self-consistently.

First we calculate the currents for spin moment up and $m_1$ and $m_2$ parallel to $\hat{y}$. For tunneling from the left Co electrode onto the Al island with $n$ excess electrons (prior to the tunneling) the current $I_{1\uparrow}(n)$ of moment up electrons is

$$I_{1\uparrow}(n) = p(n) CN_M N_S \sqrt{((eU - (2n + 1)E_{Cb} + \mu_B B))^2 - \Delta^2}$$

The current from the Al island with $n$ excess electrons onto the right Co electrode is

$$I_{2\uparrow}(n) = p(n) CN_M N_S \sqrt{((eU + (2n - 1)E_{Cb} - \mu_B B))^2 - \Delta^2}$$

The occupation probabilities $p(n)$ are obtained by the condition that the flow of electrons on the island with $n$ excess electrons is equal to the out-flow (see for example the review article [18]). This yields simple linear equations for $p(n)$. The currents for spin moment down and different orientations of $B$, $m_1$ and $m_2$ are obtained by applying the rules which we stated above. The results of this calculation are plotted in Fig.6. We use for the Coulomb energy $E_{Cb}$ the value
$E_{C_{B}} = 0.101 \text{meV}$. 

Fig.6: The current through the FSF-single electron transistor for different bias. The switching fields are identical to Fig.5, field sweep is from $+1.5T$ to $-1.5T$. Energy gap and Coulomb energy are 0.2meV and 0.1meV.

There are a few kinks in the current curves of Fig.6 as a function of the magnetic field. They occur when the maximum number of electrons on the island changes by one. The magnetic field lowers one subband of the superconductor and reduces the energy gap. Whenever $(eU + \mu_B B - \Delta(B))/E_{C_{B}}$ crosses an odd integer $(2n + 1)$ as a function of increasing $|B|$ the maximum number of electrons on the island increases by one. Furthermore one observes that again for negative bias the sign of the relative current jump in the window $(B_{sw}, B_{sn})$ changes sign.

4 Discussion and Conclusion

In the discussion of a single ferromagnet-superconductor junction we arrived at the following conclusions.

- For electron flow from the ferromagnet F into the superconductor S the current increases when the magnetization m aligns parallel to the magnetic field.
- For electron flow from the superconductor S into the ferromagnet F the current decreases when the magnetization m aligns parallel to the magnetic field.
From these facts it follows that the current jump in a double junction changes sign when one reverses the bias. When the source electrode (the electrode from which the electrons tunnel into the island) flips its magnetization first then the conductance of the source-island junction increases and therefore the current through the SET increases. When the drain electrode (the electrode into which the electrons tunnel from the island) flips its magnetization first then the conductance of the island-drain junction decreases and therefore the current through the SET decreases. Since a reversal of the bias exchanges source and drain one finds that the relative change of the current at the field $B_{sw}$ has the opposite sign.

In a nutshell: a flip of the magnetization in the electron source yields an increase of the current and a flip of the magnetization in the electron drain a decrease. The $I - B$-curves for opposite directions of the magnetic field sweep are mirror images of each other.

In this paper we intentionally excluded a spin-coupling between the two tunneling junctions. Such a coupling has been observed for example in the beautiful spin precession experiment by Jedema et al. [4]. The Meservey-Tedrow effect is an additional phenomenon which has to be included in the analysis of FSF-single electron transistors. It can be distinguished from the effect of spin-accumulation and gap reduction because it changes sign when the bias voltage is reversed.

Abbreviations: SET=single electron transistor, FSF=ferromagnet-superconductor-ferromagnet.

Acknowledgement: The research was supported by the National Science Foundation NIRT program, DMR-0334231.

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