Meservey-Tedrow effect in ferromagnet/superconductor/ferromagnet double tunnel junctions

Gerd Bergmann,[1] Jia Lu,[2] and Dawei Wang[2]
[1]*Department of Physics, University of Southern California, Los Angeles, California 90089-0484, USA*
[2]*Departments of Materials Science and of Electrical Engineering, University of California, Irvine, California 92697, USA*
(Received 2 November 2004; revised manuscript received 18 January 2005; published 28 April 2005)

Double tunneling junctions of ferromagnet-superconductor-ferromagnet electrodes (FSF) show a step 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 due to spin accumulation. In this paper it is shown that the Meservey-Tedrow effect causes a similar change in the conductance since the magnetic field changes the energy spectrum of the quasiparticles in the superconductor. A reversal of the bias reverses the sign in the conductance jump.

DOI: 10.1103/PhysRevB.71.134521 PACS number(s): 73.23.−b, 73.50.Bk, 73.40.Gk

I. INTRODUCTION

During the last five years single electron transistors (SET) with two ferromagnetic electrodes and a superconducting island have been studied experimentally[1–4] and theoretically.[5] Experimentally one generally uses ferromagnetic-superconductor-ferromagnetic double junctions which consist of an Al strip of length of about 1 μm, width of 50–100 nm and thickness of about 20 nm. The Al is oxidized, and two Co electrodes with a slightly different width and twice the thickness cross the Al strip at a separation of a few 100 nm. They form two tunneling junctions. Figure 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 electrodes. 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 antiparallel to the external field because its coercive field is larger. At the same time the current through the double junctions 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 later 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.[1–3,6]

In the theoretical discussion one generally considers two mechanisms which change the current (i.e. conductance) of the double junctions 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 $\hat{\mathbf{y}}$ 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 $G_{\uparrow\uparrow}=1/(2R_{t\uparrow})+1/(2R_{t\downarrow})$. 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 $G_{\uparrow\uparrow}\geqslant G_{\uparrow\downarrow}$. Therefore the current should drop inside the field window.[7,8]

(2) Gap reduction due to spin accumulation: In the antiferromagnetic 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}).

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 quasiparticles in the Al by $\overrightarrow{\mu_e}\mathbf{B}$ ($\overrightarrow{\mu_e}$=moment of the spin up and down electrons, $\mathbf{B}$=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,[10–12] their group investigated the tunneling I-V-curves for ferromagnet-superconductor tunneling junctions in different magnetic fields. They showed that the I-V-curves were asymmetric with respect to the voltage (because of the different density of the 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.

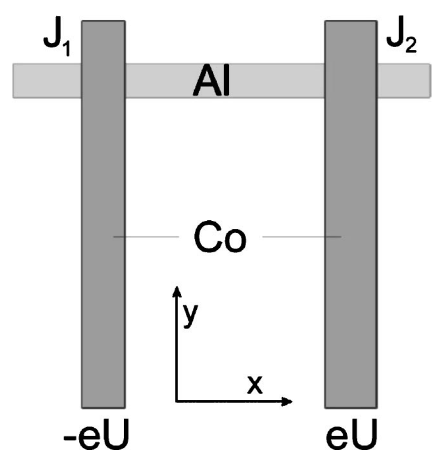

FIG. 1. The schematic geometry of a FSF double junction, consisting of Co/Al/Co.

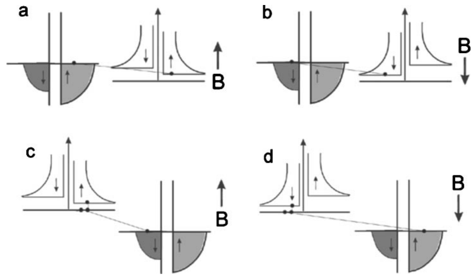

FIG. 2. The tunneling density of spin moment up electrons in a FS tunneling junction for different orientations of the magnetic field and the magnetization **m** of the ferromagnet. (a) **B** and **m** are parallel, both pointing in $\hat{\mathbf{y}}$; (b) **B** and **m** are antiparallel, **B** pointing in $-\hat{\mathbf{y}}$, **m** in $\hat{\mathbf{y}}$; (c) and (d) The bias is reversed.

We want to demonstrate that one has to take the field and spin dependence of the quasiparticles in the Al into account when calculating the current through the double tunneling junctions. To demonstrate this effect we consider a double tunneling junction system 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 1 must be equal to the total current I_2 through junction 2; the spin up and down currents through the two junctions can be quite different.

II. THEORY AND SIMULATION

A. 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*.

In a large body of experiments Merservey 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 $\overrightarrow{\mu_e}\mathbf{B}$ in opposite directions. This Zeeman effect in the superconducting excitation spectrum enhances the current of the majority spin (see Fig. 2(a)) when the electrons are flowing from the ferromagnet to the superconductor. One obtains a net spin current (with moment up). The I-V-curve is not (point) symmetric about the origin.

The tunneling current for spin *moment* up and down is given by the density of states in the superconductor and the majority N_M and minority N_m density of states in the ferromagnet. For the density of states of moment up and down electrons in the superconductor we use the (shifted) BCS density of states $N_S(E\pm\overrightarrow{\mu_e}\mathbf{B})/\sqrt{(E\pm\overrightarrow{\mu_e}\mathbf{B})^2-\Delta(B)^2}$ (N_S is the density of states of the superconductor in the normal state). In the presence of a magnetic field and finite spin-orbit scattering this density is slightly smeared. However, Meservey and Tedrow showed that for Al with its small spin-orbit scattering they obtained a good agreement between experiment and theory by using the shifted BCS density of states. As we see below, our main interest is in the behavior of the tunneling current at the coercive fields of the Co electrodes. The latter are quite small (between 0.1 T and 0.2 T) and its effect on the density of states can be neglected.

At zero temperature one obtains for the moment up and down tunneling currents,

$$I_\uparrow = CN_M N_S \int_{\Delta-\overrightarrow{\mu_e}\mathbf{B}}^{eU} \frac{(E+\overrightarrow{\mu_e}\mathbf{B})}{\sqrt{(E+\overrightarrow{\mu_e}\mathbf{B})^2-\Delta(B)^2}}dE$$
$$= CN_M N_S\sqrt{((eU+\mu_B B))^2-\Delta(B)^2},$$

$$I_\downarrow = CN_m N_S \int_{\Delta+\overrightarrow{\mu_e}\mathbf{B}}^{eU} \frac{(E-\overrightarrow{\mu_e}\mathbf{B})}{\sqrt{(E-\overrightarrow{\mu_e}\mathbf{B})^2-\Delta(B)^2}}dE$$
$$= CN_m N_S\sqrt{((eU-\mu_B B))^2-\Delta(B)^2}.$$

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 Ref. 13 for the dependence of Δ 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.

$$B_c(T) = \sqrt{24}\frac{\lambda(T)}{d}B_{cb}(T).$$

$B_{cb}(T)$ 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 a 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 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

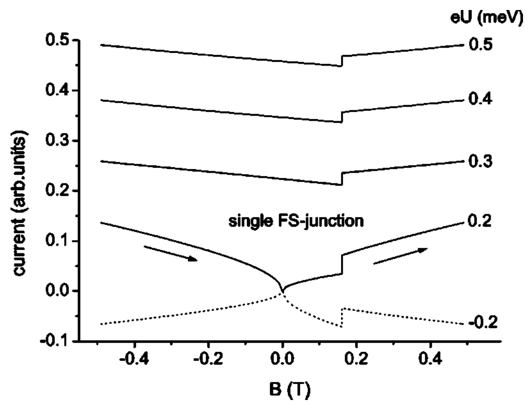

FIG. 3. The simulated current through a FS-tunneling junction while the magnetic field sweeps from -0.5 T to $+0.5$ T. The numbers besides each curve give the different biases. At $B=0.16$ T the magnetization of the Co strip reverses.

takes positive values, the magnetization of the Co and the field are antiparallel and therefore the junction is in an unstable energetic state. Due to its coercive field B_{s0} the Co can maintain the antiparallel orientation up to the field B_{s0}. 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 $\Delta=0.2$ meV, the field that suppresses superconductivity completely $B_c=1.5$ T, the switching field $B_{s0}=0.16$ T, the polarization of the effective density in the Co $p=0.35$. We sweep the external magnetic field from -0.5 T to 0.5 T. When the magnetic field changes sign, the Zeeman term changes sign as well. At the magnetic field B_{s0} 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.

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 biases which are given in meV at the right side of the curves. One recognizes that the current shows a jump at the switching field $B_{s0}=0.16$ 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 $B_m=0.5$ T to -0.5 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 ferromagnet (see Figs. 2(c) and 2(d)). 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.

B. Double junctions

We now want to calculate the current steps in a double junction due to the Meservey-Tedrow effect. In this calculation we ignore the spin accumulation and gap reduction. Such a situation can be experimentally realized by using a long Al island so that the two junctions are relatively far apart. As we discussed above the tunneling current through a single Co/Al junction is polarized. This means that polarized electrons are injected into the Al strip (for example, at J_1). These polarized electrons propagate by diffusion and their polarization decays with the distance from the injection (due to spin-flip processes). If the separation of the two tunneling junctions is larger than the spin diffusion length then the junction J_2 cannot detect the polarization at junction J_1. (The numerical value for the spin diffusion length varies in the literature between 10–100 nm and 1 μm.[9,14]) The two junctions are decoupled and the effects of the spin-accumulation and the gap reduction disappear. In this case all spin-valve effects are also excluded. 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 briefly comment in the conclusion how the Zeemann effect contributes in a full theory of the FSF-SET.

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.

We consider first the special case (a) in Fig. 4 where $\mathbf{m}_1$, $\mathbf{m}_2$ and $\mathbf{B}$ are all pointing in the positive $\hat{\mathbf{y}}$ 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 ϕ (which has to be determined self-consistently). Then the (spin) moment up current through junctions J_1 and J_2 are given by

$$I_{1\uparrow} = CN_S N_M\sqrt{((V_e+\phi+\mu_B B)^2-\Delta^2)},$$
$$I_{2\uparrow} = CN_S N_M\sqrt{((V_e-\phi-\mu_B B)^2-\Delta^2)}. \tag{1}$$

(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 by changing the sign of the term $\mu_B B$ in I_1 and I_2 and exchanging N_M and N_m in Eq. (1).

(2) If $\mathbf{m}_1$ points in the $-\hat{\mathbf{y}}$ direction one has to replace N_M by N_m in I_1.

(3) If $\mathbf{m}_2$ points in the $-\hat{\mathbf{y}}$ direction one has to replace N_M by N_m in I_2.

(4) If $\mathbf{B}$ points in the $-\hat{\mathbf{y}}$ 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 (Eq. (1)) in the alignment of Fig. 4(a). Then the above rules yield the current for moment up and down under all circumstances. For example the corresponding spin moment down currents are

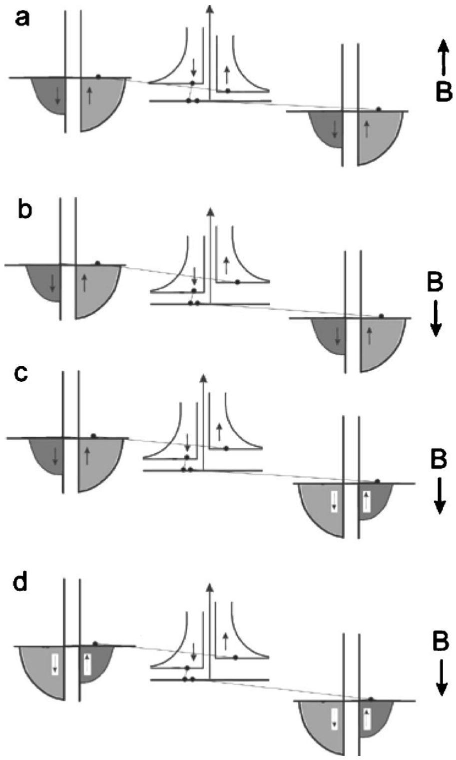

FIG. 4. The current of spin moment up electrons through a FSF-double junction. (a) The moments $\mathbf{m}_1$, $\mathbf{m}_2$ and $\mathbf{B}$ are all parallel, pointing in the $+\hat{\mathbf{y}}$ direction; (b) the magnetic field has changed to the $-\hat{\mathbf{y}}$ direction; (c) the moment $\mathbf{m}_2$ has switched at B_{sw} to the $-\hat{\mathbf{y}}$ direction; (d) the moment $\mathbf{m}_1$ has switched at B_{sn} to the $-\hat{\mathbf{y}}$ direction; $\mathbf{m}_1$, $\mathbf{m}_2$ and $\mathbf{B}$ are all parallel, pointing in the $-\hat{\mathbf{y}}$ direction.

$$I_{1\downarrow} = CN_S N_m \sqrt{((V_e + \phi - \mu_B B)^2 - \Delta^2)},$$
$$I_{2\downarrow} = CN_S N_m \sqrt{((V_e - \phi + \mu_B B)^2 - \Delta^2)}. \tag{2}$$

We calculate the total current perturbatively. For a 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 $\hat{\mathbf{y}}$ direction as a reference direction. The value of B is negative when $\mathbf{B}$ is antiparallel to $\hat{\mathbf{y}}$. We calculate (in perturbation) the currents $I_{\uparrow\uparrow}$, $I_{\uparrow\downarrow}$, $I_{\downarrow\uparrow}$, $I_{\downarrow\downarrow}$ for the four possible orientations of $\mathbf{m}_1$ and $\mathbf{m}_2$. The results are collected in the following equations:

$$I_{\uparrow\uparrow} = CN_S(N_M + N_m)\sqrt{V_e^2 - \Delta^2} \times \left(1 - \frac{2N_M N_m}{(N_M + N_m)^2}\frac{\Delta^2}{(V_e^2 - \Delta^2)^2}(\mu_B B)^2\right),$$

$$I_{\uparrow\downarrow} = CN_S(N_M + N_m)\sqrt{V_e^2 - \Delta^2}\left(1 + \frac{(N_M - N_m)}{(N_M + N_m)}\frac{V_e}{(V_e^2 - \Delta^2)}\mu_B B - \frac{1}{2}\frac{\Delta^2}{(V_e^2 - \Delta^2)^2}(\mu_B B)^2\right),$$

$$I_{\downarrow\uparrow} = CN_S(N_M + N_m)\sqrt{V_e^2 - \Delta^2}\left(1 - \frac{(N_M - N_m)}{(N_M + N_m)}\frac{V_e}{(V_e^2 - \Delta^2)}\mu_B B - \frac{1}{2}\frac{\Delta^2}{(V_e^2 - \Delta^2)^2}(\mu_B B)^2\right),$$

$$I_{\downarrow\downarrow} = CN_S(N_M + N_m)\sqrt{V_e^2 - \Delta^2} \times \left(1 - \frac{2N_M N_m}{(N_M + N_m)^2}\frac{\Delta^2}{(V_e^2 - \Delta^2)^2}(\mu_B B)^2\right). \tag{3}$$

Here the indices of the currents give the direction of the magnetizations $\mathbf{m}_1$ and $\mathbf{m}_2$ with respect to the $\hat{\mathbf{y}}$ direction. For example, $I_{\downarrow\uparrow}$ is the current for $\mathbf{m}_1$ antiparallel and $\mathbf{m}_2$ parallel to $\hat{\mathbf{y}}$. When $\mathbf{m}_1$ and $\mathbf{m}_2$ are antiparallel to each other (i.e., for $I_{\uparrow\downarrow}$ and $I_{\downarrow\uparrow}$) then the chemical potential of the island $e\phi$ is zero. In the parallel orientation one obtains

$$e\phi = -\mu_B B\frac{(N_M - N_m)}{(N_M + N_m)}, \quad \text{for } I_{\uparrow\uparrow},$$

$$e\phi = +\mu_B B\frac{(N_M - N_m)}{(N_M + N_m)}, \quad \text{for } I_{\downarrow\downarrow}.$$

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 $(\mathbf{B}\uparrow\downarrow\hat{\mathbf{y}})$, then both magnetizations, $\mathbf{m}_1$ and $\mathbf{m}_2$, are antiparallel to $\hat{\mathbf{y}}$. In the linear approximation the current is $I_{\downarrow\downarrow} \approx \sqrt{V_e^2 - \Delta^2}(N_M + N_m)$. 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 $I_{\downarrow\uparrow}$ which corresponds to a relative decrease of the current

$$\frac{\Delta I}{I} = -\frac{(N_M - N_m)}{(N_M + N_m)}\frac{V_e}{(V_e^2 - \Delta^2)}\mu_B B.$$

At the higher field B_{sn} the other electrode J_1 also aligns parallel to $\hat{\mathbf{y}}$. Then the current returns to the original curve since $I_{\uparrow\uparrow} = I_{\downarrow\downarrow}$ in this approximation. It is important to point out that the step in the current is positive when the magnetization of the (negatively biased) junction J_1 (i.e., $\mathbf{m}_1$) flips first. Then the current changes from $I_{\downarrow\downarrow}$ to $I_{\uparrow\downarrow}$.

In Fig. 5 we sweep the magnetic field from -0.5 T to $+0.5$ T. The current through the double junction is plotted versus the sweeping magnetic field. The junction J_2 has the switching field $B_{sw} = 0.14$ T while junction J_1 has the larger switching field of $B_{sn} = 0.18$ T. We use different bias voltages in the range of -0.2 meV $\leq -eU \leq 0.7$ meV. 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

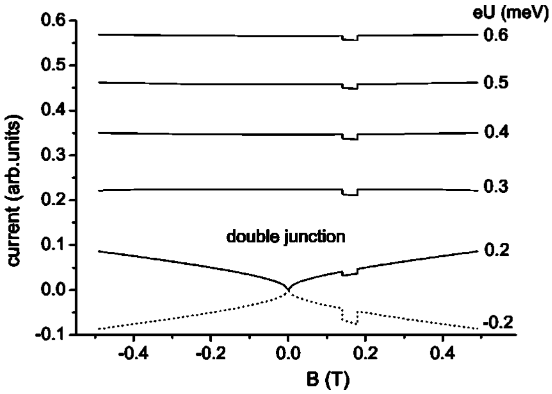

FIG. 5. The current through a FSF-double junction while the magnetic field sweeps from −0.5 T to 0.5 T. The numbers at the curves give the different bias. The switching fields for the two Co strips are 0.14 T and 0.18T.

value of the current increases. This means that the displacement changes sign when the bias is reversed.

III. THE SINGLE ELECTRON TRANSISTOR

When the size of the two tunneling junctions is in the nanometer scale, then their capacitance is small and the tunneling electrons change the Coulomb energy on the island.[15–20] If an electron from the left electrode with the band energy ε_L tunnels onto a state on the island with the band energy ε_I and changes the number of electrons on the island from n to $(n+1)$, then the conservation of energy requires that

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

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

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

Here U_G is the gate voltage and $C_\Sigma = C_1 + C_2 + C_G$, where C_1, C_2, and C_G are the capacitances 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 lose up to n_0 electrons where (at $T=0$) n_0 is given by $n_0 = \mathrm{int}\left[\frac{1}{2}((eU-\Delta)/E_{Cb} - 1)\right]$. 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 $\mathbf{m}_1$ and $\mathbf{m}_2$ parallel to $\hat{\mathbf{y}}$. 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

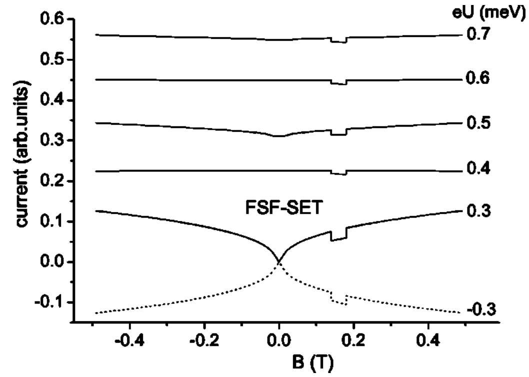

FIG. 6. The current through the FSF-single electron transistor for different biases. The switching fields are identical to Fig. 5, field sweep is from +1.5 T to −1.5 T. Energy gap and Coulomb energy are 0.2 meV and 0.1 meV.

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

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

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

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 outflow (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 $\mathbf{B}$, $\mathbf{m}_1$ and $\mathbf{m}_2$ 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 $E_{Cb} = 0.101$ meV.

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 $[(eU + \mu_B B) - \Delta(B)]/E_{Cb}$ 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.

IV. 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 $\mathbf{m}$ aligns parallel to the magnetic field.
- For electron flow from the superconductor S into the ferromagnet F the current *decreases* when the magnetization $\mathbf{m}$ 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 have 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.

A full theory of I-V curves of FSF-SETs is desirable which includes all effects, spin accumulation, gap reduction and Zeeman splitting. The above calculation can be relatively easily generalized. One needs essentially the reduced gap and the shifted chemical potential as input for the Meservey-Tedrow effect. So the difficulty lies in a quantative theory of spin accumulation and gap reduction which includes a position dependent polarization in the Al island due to the interplay between the injection, diffusion and spin flip of the polarized electrons.

ACKNOWLEDGMENT

The research was supported by the National Science Foundation NIRT program, No. DMR-0334231.

[1] C. D. Chen, W. Kuo, D. S. Chung, J. H. Shyu, and C. S. Wu, Phys. Rev. Lett. **88**, 047004 (2002).
[2] J. Johansson, M. Urech, D. Haviland, and V. Korenivski, J. Appl. Phys. **93**, 8650 (2003).
[3] J. Johansson, M. Urech, D. Haviland, and V. Korenivski, Phys. Rev. Lett. **91**, 149701 (2003).
[4] F. J. Jedema, H. B. Heersche, A. T. Filip, J. J. A. Baselmans, and B. J. van Wees, Nature (London) **416**, 713 (2002).
[5] S. Takahashi, H. Imamura, and S. Maekawa, Phys. Rev. Lett. **82**, 3911 (1999).
[6] D. Wang and J. G. Lu, cond-mat/0410351 [J. Appl. Phys. (to be published).]
[7] S. Takahashi and S. Maekawa, Phys. Rev. Lett. **80**, 1758 (1998).
[8] S. Takahashi, H. Imamura, and S. Maekawa, J. Appl. Phys. **87**, 5227 (2000).
[9] R. Meservey and P. M. Tedrow, Phys. Rep. **238**, 173 (1994).
[10] P. M. Tedrow and R. Meservey, Phys. Rev. Lett. **26**, 192 (1971).
[11] P. M. Tedrow and R. Meservey, Phys. Rev. B **7**, 318 (1973).
[12] R. Meservey, P. M. Tedrow, and J. S. Moodera, J. Magn. Magn. Mater. **35**, 1 (1983).
[13] D. H. Douglass, Jr., Phys. Rev. Lett. **6**, 346 (1961).
[14] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5312 (1988).
[15] D. V. Averin and K. K. Likharev, *Mesoscopic Phenomena in Solids*, edited by B. L. Altshuler, P. A. Lee, and R. A. Webb (Elsevier, Amsterdam, 1991), p. 173.
[16] D. V. Averin and Yu. V. Nazarov, Phys. Rev. Lett. **69**, 1993 (1992).
[17] F. W. J. Hekking, L. I. Glazman, K. A. Matveev, and R. I. Shekhter, Phys. Rev. Lett. **70**, 4138 (1993).
[18] G. Schoen, in *Quantum Transport and Dissipation*, edited by T. Dittrich, P. Haenggi, G. L. Ingold, B. Kramer, G. Schoen, and W. Zwerger (Wiley-VCH Verlag GmbH, Weinheim, 1998), pp. 149–212.
[19] G. Schoen and A. D. Zaikin, Phys. Rep. **198**, 237 (1990).
[20] A. N. Korotov and V. I. Safarov, Superlattices Microstruct. **25**, 259 (1999).