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Spin Accumulation in FSF Single Electron Transistor

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***Abstract* — The concept of spin accumulation has paved the way for future spin-based devices with important applications in information storage and quantum computing. Spin accumulation induced pair breaking in superconductor attributes to the conductance increase in ferromagnet-superconductor-ferromagnet single electron transistors when the magnetization of the two ferromagnetic leads change from parallel to antiparallel configurations. From theoretical simulation, it is found that the Meservey-Tedrow effect also causes a similar conductance change since the magnetic field changes the energy spectrum of the quasiparticles. Therefore, it is crucial to distinguish the two effects in the experiment. A key feature of the Meservey-Tedrow effect is that the conductance change shows opposite sign under reverse bias. Based on this, a transport measurement through double tunnel junctions is setup with proper bias configuration, thus separating the two effects and demonstrating that spin accumulation is attained.**

***Index Terms* — Hybrid junctions, magnetic materials, single electron transistor, spin accumulation, superconducting films, tunneling**

I. Introduction

Ferromagnetic single electron transistor combines the recent advances of magnetic tunnel junctions [1] and single electron transistors [2]. Various phenomena such as enhanced magnetoresistance, magnetoresistance oscillation with bias voltage, and spin accumulation are predicted [3]. For a ferromagnet-superconductor-ferromagnet (FSF) single electron transistor (SET), when the magnetizations of the two ferromagnetic leads are in anti-parallel (AP) configuration, a non-equilibrium spin density (spin accumulation) will be induced on the superconducting island within its spin diffusion length due to the imbalance of the tunneling current formed by the spin-up and spin-down electrons. This accumulation suppresses the superconductivity with increasing bias voltage [3,4], leading to a conductance increase of the system.

On the other hand, when a superconductor is placed in a magnetic field, the excitation level of spin-up and spin-down electrons shifts by $\mu_B \boldsymbol{B}$ (μ_B=magnetic moment of electron, $\boldsymbol{B}$=external magnetic field) in opposition directions because of the Zeeman effect. This effect has been intensively studied by Meservey and Tedrow [5]. It also contributes to a change in the spin dependent transport in the FSF double tunnel junction system, which has not been taken into account in the previous studies.

In this paper, we present that the Meservey-Tedrow effect causes an asymmetric $I - B$ curve in a FSF SET, and the conductance change at AP configuration shows opposite sign when the polarity of the bias is reversed. The transport measurement carried out based on this result shows that spin accumulation is attained on the superconducting island.

II. Theory

Consider a double junction shown in Fig.1, with spin polarized electrons injecting into the Al island. However, the lifetime of an electron in a given spin state is limited by the spin-orbit scattering, and the spin state decays as exp $(-t/\tau_{sf})$ where τ_{sf} is the spin-flip lifetime. Thus, the injected spin polarization at the left tunnel junction diffuses through the Al island towards the right junction and vice versa. Along this diffusion path, the spin decays. Previous literature had reported different orders of magnitude for the spin diffusion length, varying between 10-100nm and 1μm [5,6]. For simplification, we consider an Al island longer than its spin diffusion length, thus excluding the effects of spin accumulation and spin valve on the current transport.

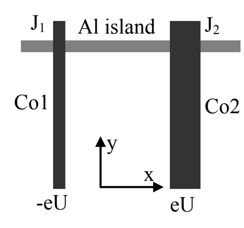

Fig. 1. The schematic geometry of FSF double junctions consisting of Co/Al/Co.

As shown in Fig.1, the total potential difference between the right and the left electrode is 2eU. The bias is taken as positive when the potential on the right electrode is positive. Then the electrons tunnel from the left to the right side as shown in Fig. 2. B_{sw} and B_{sn}

denote the coersive fields of the wider and narrower Co leads, respectively.

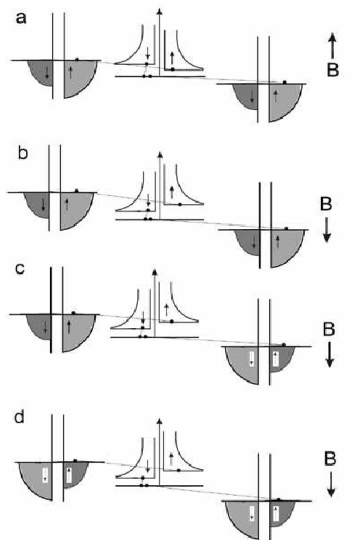

Fig. 2. The tunneling density of states in a FSF double tunnel junction system for four different orientations of the magnetic field **B** and the magnetization **m** of the ferromagnet electrode.

a) The moments $\mathbf{m_1}$, $\mathbf{m_2}$ and **B** are all parallel, pointing in $+\hat{\mathbf{y}}$ 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, so $\mathbf{m_1}$, $\mathbf{m_2}$ and **B** are all parallel, pointing in $-\hat{\mathbf{y}}$ direction

As mentioned earlier, for an Al island longer than its spin diffusion length, the total currents through junction J_1 and J_2 are identical, and the individual spin up and spin down current can be different. When $\mathbf{m_1}$, $\mathbf{m_2}$ and **B** are all in $+\hat{\mathbf{y}}$ direction (Fig. 2a), the spin-up current through junctions J_1 and J_2 are given by

$$I_{1\uparrow} = CN_s N_M \sqrt{\left(eU + \phi + \mu_B B\right)^2 - \Delta^2}$$
$$I_{2\uparrow} = CN_s N_M \sqrt{\left(eU - \phi - \mu_B B\right)^2 - \Delta^2}.$$

The symbol ↑ stands for spin moment up. N_M and N_m are the majority and minority density of spin states in the ferromagnet, and N_S is the density of states of the $e\phi$ is superconductor in normal state. The constant C contains the tunneling matrix elements and universal constants. the chemical potential of the island. The energy gap is given by $\Delta(T, B)$. For thin film which is aligned parallel to an external magnetic field, Δ depends on the magnetic field:

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

where $B_c(T)$ is the thin film critical parallel field determined by the ratio of the penetration depth $\lambda(T)$, film thickness d and the bulk critical field $B_{cb}(T)$:

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

The other current components can be simply obtained using the following methods:

- The contribution of spin moment down electrons is obtained by changing the sign of the term $\mu_B\boldsymbol{B}$ in I_1 and I_2, and replacing N_M by N_m.
- If $\mathbf{m_1}$ points in the $-\hat{\mathbf{y}}$ direction, one has to replace N_M by N_m in I_1.
- If $\mathbf{m_2}$ points in the $-\hat{\mathbf{y}}$ direction, one has to replace N_M by N_m in I_2.
- If **B** points in the $-\hat{\mathbf{y}}$ direction, one has to change the sign of the term $\mu_B\boldsymbol{B}$ in I_1 and I_2.

The total current is calculated perturbatively. When $eU > \Delta$, the terms $e\phi$ and $\mu_B B$ are small compared to $\sqrt{(eU)^2 - \Delta^2}$, thus the different current contributions can be expanded as a Taylor series in terms of $e\phi$ and $\mu_B B$. Since the current depends on the orientation of three vectors, $\mathbf{m_1}$, $\mathbf{m_2}$ and **B**, the $\hat{\mathbf{y}}$-direction is chosen as a reference. The value of **B** is negative when **B** is anti-parallel to $\hat{\mathbf{y}}$. The currents $I_{\uparrow\uparrow}$, $I_{\uparrow\downarrow}$, $I_{\downarrow\uparrow}$, $I_{\downarrow\downarrow}$ are calculated for the four orientations of $\mathbf{m_1}$ and $\mathbf{m_2}$, and the results are shown below. 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 $\mathbf{m_1}$ anti-parallel and $\mathbf{m_2}$ parallel to $\hat{\mathbf{y}}$. 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 take the linear dependence on $(\mu_B B)$.

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

When the system is in the AP state, *i.e.* $\mathbf{m_1}$ and $\mathbf{m_2}$ are anti-parallel to each other, the chemical potential of the island $e\phi$ is zero. In the parallel orientation, we have for $I_{\downarrow\downarrow}$ and $I_{\uparrow\uparrow}$, respectively,

$$e\phi = \pm \mu_B B \frac{(N_M - N_m)}{(N_M + N_m)}$$

At a large negative magnetic field, both magnetizations, $\mathbf{m_1}$ and $\mathbf{m_2}$, are parallel to $\mathbf{B}$. In the linear approximation the current is $I_{\downarrow\downarrow} \approx \sqrt{(eU)^2 - \Delta^2}\,(N_M + N_m)$. At the positive field B_{sw}, the magnetization of the positively biased (wider one in Fig. 1) electrode at junction J_2 flips and aligns parallel to the field, while the magnetization of the negatively biased (narrower) electrode is now anti-parallel to $\mathbf{B}$. Then the new current becomes $I_{\downarrow\uparrow}$, leading to a relative decrease of the current

$$\frac{\Delta I}{I} = -\frac{(N_M - N_m)}{(N_M + N_m)} \frac{eU}{\left((eU)^2 - \Delta^2\right)} \mu_B B \, .$$

At the higher field B_{sn}, the negatively biased electrode becomes aligned parallel to $\mathbf{B}$. Thus, the current returns to the original curve since $I_{\uparrow\uparrow} = I_{\downarrow\downarrow}$. In contrast, if the magnetization of the negatively biased electrode (*i.e.* $\mathbf{m_1}$) flips first, then the jump in the current is positive since the current changes from $I_{\downarrow\downarrow}$ to $I_{\uparrow\downarrow}$.

In Fig.3, the magnetic field is swept from −0.5T to +0.5T. The current through the double junction is plotted versus the sweeping magnetic field. The switching field of junction J_2 is 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 $-0.2\text{meV} \le -eU \le 0.7\text{meV}$. The $I - B$ curve shows a decrease in the field window (B_{sw}, B_{sn}). For negative $-eU$ ($U > 0$), the absolute value of the current increases. This implies that the displacement changes sign when the bias is reversed. [7]

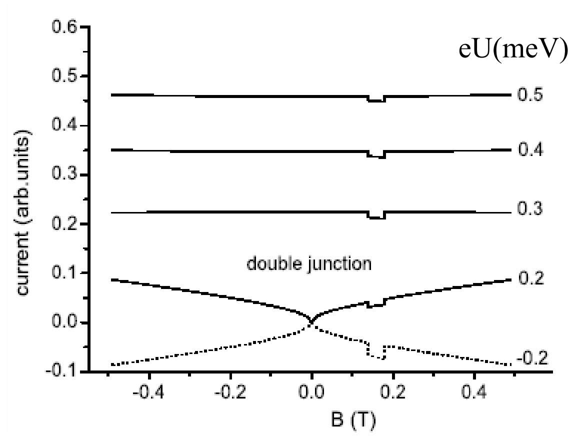

Fig. 3. The current *vs*. the magnetic field from −0.5T to 0.5T. The numbers at the curves indicate the different bias (slightly higher than the actual bias). The switching fields for the two Co leads are taken as 0.14T and 0.18T.

III Experiment

FSF SET consists of two Co leads coupled to an Al island through Al_2O_3 tunnel junctions is fabricated using *e*-beam lithography followed by angled deposition techniques. Fig. 4 is the atomic force microscope (AFM) image of a fabricated device. 25nm Al is first deposited on Si substrate (capped with 200nm oxide) to form the center island. After oxidization, 40nm Co is evaporated at a different angle to form the junctions. The width difference of the Co leads (50 nm and 90 nm, respectively) results in a difference in the coercive field. The width of the Al island is 110 nm, the distance between the two Co leads is ~600 nm. Magnetoconductance measurement is carried out in a He3 cryostat at a base temperature of 0.27 K.

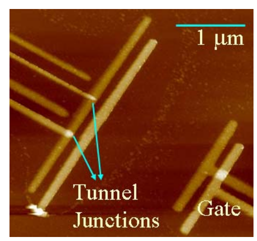

Fig. 4. AFM image of a fabricated device. The two Co leads are 50 nm and 90 nm in width, respectively. The Al island is 110 nm in width, and the distance between the junctions is 600 nm.

IV Results and Discussion

Fig. 5 show the *I–V* curve obtained at two different temperatures. The typical single electron tunneling behavior can be observed. At low temperature, the *I–V* curve shows a gap region at low bias voltages. This high resistance gap is due to both Coulomb blockade ($2E_c/e$) and superconducting energy gap ($2\Delta/e$) of the Al island. At 1.95 K, above the critical temperature of the Al film (~1.46 K), the superconductivity gap disappears, but the *I–V* exhibits still slightly nonlinear due to the Coulomb blockade effect at Vg=0. From these measurement results, the sample parameters are extracted, yielding the total junction resistance $R_T \approx 4.3\ \text{M}\Omega$, total capacitance $C \approx 0.5$ *f*F, and a superconducting gap $\Delta \approx 220\ \mu\text{eV}$. [8]

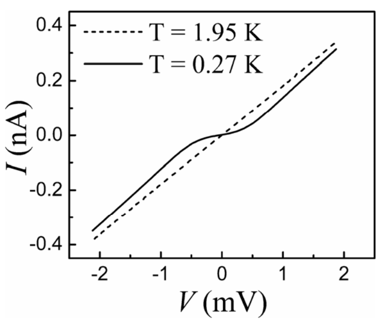

Fig. 5. *I–V* characteristics of a FSF SET. *I–V* curves obtained at different temperatures.

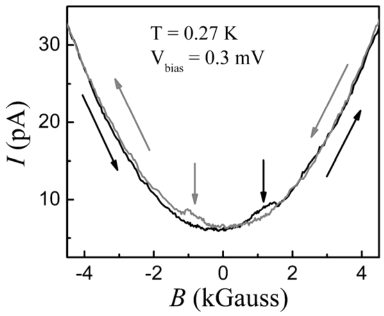

Fig.6. Magnetoconductance curves. The arrows along the curve indicate the sweeping direction of the applied field.

Measurements performed in magnetic fields applied parallel to the leads shows a bell shape $I - B$ curve (Fig. 6), as a direct result of the influence of the external magnetic field on the superconducting gap. The $I - B$ curve is obtained by applying a positive bias on the wide Co lead. According to the Meservey-Tedrow effect discussed in section II, under such bias configuration, the current should decrease when the two Co leads are in anti-parallel configuration. In contrast, as shown in Fig. 6, a current peak appears between ±0.6 and ±1.4 kGauss. This is the window when the magnetizations in the Co electrodes switch from parallel to anti-parallel configurations due to the different coercive fields of the two electrodes. Neglecting spin-flip process, when the two Co leads are in anti-parallel configuration, the electrons in the source electrode with majority spin are easier to tunnel onto the island, however encounter a higher resistance to tunnel off the island. This results in a spin imbalance in the island, leading to a shift in the chemical potential for different electron spins. For a normal metal island, the chemical potential difference, $\delta\mu$, is calculated to be proportional to the voltage drop across the device and the spin polarization of the ferromagnetic electrodes [3]. For a superconducting Al island, this difference gives rise to an imbalance of spin-up and spin-down electrons, which reduces the formation of cooper pairs, and consequently suppresses the superconductivity [4].

V. Conclusion

The current transport in FSF SET consists of a number of mechanisms, thus careful measurement and analysis are necessary to separate them out. In this paper, following a theoretical calculation which shows that the Meservey-Tedrow effect causes a similar conductance change as the magnetic field changes the energy spectrum of the quasiparticles, as compared to the conductance change resulted from spin accumulation. The experiment is performed so that one can distinguish the effect of spin accumulation from that of Meservey-Tedrow, showing the evidence of spin accumulation leading to a reduction of the superconducting gap.

Acknowledgement

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