Magnetoresistance in single-electron transistors comprising a superconducting island with ferromagnetic leads

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Abstract. We report electric and magnetic field responses of single-electron transistors (SETs) comprising a superconducting island with ferromagnetic (FM) leads. We fabricated two SETs, one of which had relatively high resistance and the other had relatively low resistance. The SETs had two states for the gate charge: SET-ON or SET-OFF. They also had two states for the FM lead magnetization: parallel (P) or anti-parallel (AP) configuration. Current-voltage characteristics of four SET states (“P & SET-ON,” “P & SET-OFF,” “AP & SET-ON,” and “AP & SET-OFF”) were measured at approximately 0.1 K in a compact dilution refrigerator. Magnetoresistance ratio (MRR) values were obtained for the SET-ON and SET-OFF states, respectively. The higher-resistance SET1 exhibited positive MRR values for all measured bias voltages. The MRR enhancement was confirmed for the SET-OFF state, which agreed well with the co-tunneling model. The lower-resistance SET2, on the other hand, exhibited negative and positive MRR values for higher and lower bias voltage conditions, respectively. The bias voltage for the MRR polarity reversal was changed by the gate voltage. It was also confirmed that the co-tunneling model was partially valid for negative MRR values.

1. Introduction
A single-electron transistor (SET), which comprises two tiny tunnel junctions and a capacitive gate, is the most sensitive charge sensor, because its Coulomb blockade (CB) is periodically modulated by the gate charge with a period of the primary charge e [1]. Since the first experimental demonstration [2], aluminum (Al) tunnel junctions have been widely used. Besides Al, ferromagnetic (FM) materials such as nickel (Ni) and cobalt (Co) are also used for electrodes of SETs that exhibit magnetoresistance effects. Such FM SETs respond not only to electric gate charge but also external magnetic field. In addition, it was reported that magnetoresistance effects were significantly enhanced in FM SETs under the CB state [3].

In this paper, we report SETs comprising a superconducting (SC) Al island with FM Co leads. FM-SC-FM SETs have been experimentally investigated since the 2000s [4, 5], in which several unique properties of SC islands are demonstrated.

• Since the spin lifetime in SC Al electrodes exceeds 0.1 ms [6], spin-dependent transport in a long (≥ 1 μm) SC island electrode is possible.
Figure 1. (a) Configuration of the FM-SC-FM SET with external bias sources. (b) Electric properties of an SET switched into either "ON" or "OFF" by tuning the gate charge. (c) Magnetic configurations of FM leads switched into either "Parallel (P)" or "Anti-Parallel (AP)" alignment by using magnetic hysteresis for two different coercive forces.

- Superconductivity in an SC island electrode is modified by spin injection from FM leads. One typical example is that the spin injection reduces superconducting energy gaps, which results in a negative magnetoresistance ratio ($MRR$) \[5, 7\].
- The polarity reversal of magnetoresistance can be modulated by the gate charge \[8, 9\].

Below, we first briefly explain the characteristics of an FM-SC-FM SET from the viewpoint of superconductivity with polarized spin injection. Next, experimental methods including sample fabrication and measurement are described. We present two FM-SC-FM SETs, one of which (SET1) has relatively high resistance and the other (SET2) has relatively low resistance. The polarity reversal as well as the $MRR$ enhancement are evaluated. SET1 exhibits positive $MRR$ values for all measured bias voltages. Those of SET2, on the other hand, are negative and positive respectively for high and low biasing conditions, where the bias voltage for the polarity reversal is changed by the gate voltage. Enhancement of negative $MRR$ is evaluated for the first time as functions of the bias voltages.

2. Magnetoresistance of FM-SC-FM SET

Figure 1(a) shows a schematic drawing of an FM-SC-FM SET that we fabricated. Two Co leads are contacted to an Al island through a thin AlO$_x$ tunnel barrier. A gate electrode is capacitively coupled to the Al island.

In measurements, two voltage sources are connected to the source and drain electrode. By applying voltages of $\pm V/2$, the FM-SC-FM SET is symmetrically biased. The gate charge switches the SET between ON and OFF state as shown in figure 1(b). Besides, external magnetic field is applied parallel to the FM leads. Different widths of the source and drain FM leads result in different coercive forces. Then, by using magnetic hysteresis, two types of magnetization, the parallel (P) and anti-parallel (AP) alignments, are realized as shown in figure 1(c). Combination of the electric and magnetic switchings brings about the four states of the FM-SC-FM SET: "P & SET-ON," "P & SET-OFF," "AP & SET-ON," and "AP & SET-OFF."

Magnetoresistance of the FM-SC-FM SET is described as follows. When spin-polarized electrons are transferred between the FM source and drain electrodes, the magnetization alignment (P or AP) changes the source-drain resistance, which is often evaluated using an $MRR$ value. In this paper, we define the $MRR$ value as

$$MRR = \frac{R_{AP} - R_P}{R_P} = \frac{I_P - I_{AP}}{I_{AP}},$$

where $R_{AP}$, $I_{AP}$, $R_P$, and $I_P$ are the resistance and current values under a certain bias voltage for the AP and P alignment, respectively.
Figure 2. Scanning electron micrograph (SEM) images of two fabricated SETs. SET1 and SET2 have higher and lower tunnel resistance, respectively.

For an FM-FM tunnel junction, the relationship of $R_{AP} > R_P$ is usually observed because of the difference in the density of states for major and minor spins. The situation for an FM-SC-FM SET, however, is not so simple, because the spin imbalance in the SC island may reduce the superconducting energy gap. If the reduction of the superconducting energy gap is dominant, the relationship of $R_P > R_{AP}$ is observed, which results in a negative $MRR$ value [5, 6, 7].

In addition, enhancement of magnetoresistance is often observed in FM SETs [3]. This effect can be explained by a model employing cotunneling events in the CB state [10, 11, 12, 13, 14]. In this model, the 1st-order electron tunneling is dominant for the SET-ON state, where the current is inversely proportional to the tunnel resistance $R_T$. On the other hand, the 2nd-order electron tunneling (co-tunneling) is dominant for the SET-OFF state, where the current is inversely proportional to $R_T^2$. Then, the magnetoresistance of this model, $MRR_{cot}$, is expressed as

$$MRR_{cot} = \frac{I_{P, off} - I_{AP, off}}{I_{AP, on} - I_{P, on}} = \frac{1/R^2_{P, on} - 1/R^2_{AP, on}}{1/R^2_{AP, on}} = \frac{R^2_{AP, on} - R^2_{P, on}}{R^2_{P, on}},$$

where the suffixes “P,” “AP,” “on,” and “off” mean the P alignment, AP alignment, ON state, and OFF state, respectively. That is, $MRR_{cot}$ can be expressed as a function of the resistance values for the SET-ON state.

3. Experimental Method
FM-SC-FM SETs were fabricated on a thermally oxidized silicon substrate by electron beam lithography with a bilayer resist followed by the two-angle shadow evaporation technique [15]. Scanning electron micrograph (SEM) images of two fabricated SETs are presented in figure 2. The thicknesses of the Al islands were 25 and 30 nm for SET1 and SET2, respectively. Different oxidation conditions for tunnel barriers were used for SET1 and SET2: The tunnel barrier of SET1 was formed in 27 Pa of pure oxygen gas for 120 seconds, whereas that of SET2 was formed in 13 Pa of pure oxygen gas for 30 seconds. The thicknesses of the Co leads were respectively 45 and 40 nm for SET1 and SET2.

In measurements, samples were cooled down to 0.1 K in a compact dilution refrigerator [16], in which an external magnetic field $H$ was applied along the Co leads by an SC magnet.

4. Results and Discussion
4.1. Responses to gate voltage and magnetic field
We first checked whether the samples worked as an SET. Figure 3 shows the $I-V_g$ characteristics of SET1 and SET2. In measurements, relatively high magnetic field of 10–20 kOe was applied
Figure 3. Coulomb oscillations ($I$–$V_g$ characteristics) of two SETs. The measurement temperatures were around 0.1 K.

Figure 4. Magnetic field responses ($I$–$H$ characteristics) of two SETs. The measurement temperatures were around 0.1 K.

4.2. Magnetoresistance ratio $MRR$

$I$–$V$ characteristics for four states, “$P$ & SET-ON,” “$P$ & SET-OFF,” “AP & SET-ON,” and “AP & SET-OFF,” are shown in figure 5. For both SET1 and SET2, the current values for “$P$ & SET-ON” are always larger than those for “$P$ & SET-OFF,” which corresponds to our definition for “ON” and “OFF.” The same
Figure 5. Four $I$–$V$ characteristics of two SETs for four states of “P & SET-ON,” “P & SET-OFF,” “AP & SET-ON,” “AP & SET-OFF.” The measurement temperatures were around 0.1 K.

Figure 6. $MRR$–$V$ characteristics of two SETs for “SET-ON” and “SET-OFF” states. Dotted curves are obtained using equation (2) with the results for “SET-ON”. It should be noted that the vertical axes are quite different for two SETs.

relationship is confirmed for “AP & SET-ON” and “AP & SET-OFF.”

Next, to evaluate $MRR$, we compare $I$–$V$ characteristics of different alignments for the same “ON” and “OFF” state.

The $I$–$V$ characteristics of SET1 shown in figure 5(a) demonstrate that the current values for “AP & SET-ON” and “AP & SET-OFF” are always smaller than those of “P & SET-ON” and “P & SET-OFF,” respectively. These are general magnetoresistance effects, for which the calculated $MRR$ values are plotted in figure 6(a). (Equation (1) was used for calculation.) For the voltage range of $V > 0.8$ mV, $MRR$ values for the SET-ON and SET-OFF state are comparable. They increase as $V$ decreases, although they are less than 10%. For the voltage range of $V < 0.8$ mV, $MRR$ values rapidly increases with decreasing $V$. Especially, $MRR$ values for the SET-OFF state are enhanced up to 1000%, whereas those for the SET-ON state are 300% at maximum. Such difference is explained using $MRR_{cot}$ of equation (2), which is plotted in figure 6(a) as a dotted curve.

The reason why negative $MRR$ was not obtained for SET1 can be attributed to the large tunnel resistance that reduces the spin accumulation in an SC electrode [6, 9].

For SET2, on the other hand, the situations are not as simple as those of SET1. That is, the current values for the AP alignment are larger than those for the P alignment in the voltage ranges of $V > 0.47$ mV and $V > 0.53$ mV for the SET-ON and SET-OFF state, respectively. In these voltage ranges, $MRR$ values become negative as shown in figure 6(b). Anomalous current
increase for “AP & SET-OFF” is also confirmed at around \( V = 0.46 - 0.49 \text{ mV} \), which might come from sudden shift of background charge.

In the SET-ON state, negative MRR values are obtained for the voltage range of \( V > 0.47 \text{ mV} \). The dip value is \(-59\%\) at \( V = 0.53 \text{ mV} \). The MRR value increases as \( V \) decreases below \( 0.50 \text{ mV} \), and it becomes positive at \( 0.47 \text{ mV} \). In the SET-OFF state, on the other hand, the voltage for the MRR polarity reversal is \( 0.53 \text{ mV} \), which is larger than that in the SET-ON state. Besides, \( MRR_{\text{cot}} \) of equation (2) is in good agreement with experimental results for \( 0.58 < V < 0.65 \text{ mV} \), while they are negative values.

Finally, it should be noted that the polarities of MRR values for the voltage range of \( 0.50 < V < 0.53 \text{ mV} \) are negative and positive for the SET-ON and SET-OFF states, which suggests that not only the MRR value but also its polarity can be controlled by the gate voltage.

5. Conclusion
We reported electric and magnetic responses of FM-SC-FM SETs. SET1 and SET2, which respectively had higher and lower tunnel resistance, were fabricated with an SC Al island and FM Co leads. \( I - V \) characteristics for four states of “P & SET-ON,” “P & SET-OFF,” “AP & SET-ON,” and “AP & SET-OFF” were measured at around 0.1 K. MRR values were derived from \( I - V \) characteristics and plotted as functions of \( V \). SET1 exhibited positive MRR values for all measured bias voltages, where the MRR enhancement was also confirmed for the CB state. MRR values of SET2, on the other hand, were negative and positive for higher and lower bias voltages. Furthermore, it was demonstrated that the voltage for the MRR polarity reversal was changed by the gate voltage. It was also confirmed that \( MRR_{\text{cot}} \) of equation (2) was partially valid for negative MRR values.

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