Enhancement of tunnel magnetoresistance in ferromagnetic single-electron transistors

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Abstract

Magnetoresistance of ferromagnetic single-electron transistors (SETs) is known to increase at low temperatures. In this paper, we investigate systematically how the TMR enhancement changes as a function of the tunnel resistance R_T using Ni/Co/Ni-SETs. We find the enhancement almost independent of R_T as far as $R_T >\sim 30$ kΩ, while it is small for devices with $R_T <\sim 7$ kΩ. These results are not explained by the theories based on the higher-order tunneling.

Key words: tunnel magnetoresistance; single-electron transistor; ferromagnetic tunnel junction

1. Introduction

The electron transport in ferromagnetic small tunnel junctions are attracting lots of interest. The electron has two natures, an electric charge e and a spin. The quantization of the charge causes the Coulomb blockade of conduction when $kT < E_C$, where E_C is the single-electron charging energy. The spin-polarized tunneling causes the tunnel magnetoresistance (TMR) effect, because the tunneling probability varies depending on the relative orientation of magnetizations in electrodes. The TMR is characterized by the TMR ratio defined as $\gamma = (R_A - R_P)/R_P$. Here, R_P (R_A) denotes the resistance when the relative alignment of magnetizations in both electrodes is parallel (anti-parallel).

In 1997, Ono *et al.* reported that the TMR of a Ni/Co/Ni-SET was largely enhanced when it was cooled to the Coulomb blockade regime [1]. In their experiment, the TMR ratio that was about 4 % at 4.2 K grew up to 40 % at 20 mK, which is even larger than the maximum TMR ratio expected from spin polarized tunneling experiments. Similar enhancements of TMR had been observed in two-dimensional arrays of a ferromagnetic tunnel junction [2]. Subsequently enhancement of the TMR was found in other systems including ferromagnetic granular films [3] and the small tunnel junctions [4]. The enhancement of TMR is not explained by the so-called orthodox theory of single-electron tunneling. Ono *et al.* presented an idea on the mechanism of the enhancement based on the quantum fluctuation of charge. Several theoretical papers based on the higher-order tunneling appeared and predicted the enhancement of TMR [5] [6] [7] [8]. However, the experimental investigations of the TMR enhancement have not been done systematically yet and the check of the theories remains insufficient.

In this paper, we fabricated ferromagnetic-SETs made of Ni and Co having various R_T ranging from 600 Ω to 3.3 MΩ, and investigated systematically how the TMR enhancement changes as a function of R_T.

2. Experiment

Ni/Co/Ni-SETs were fabricated by means of the electron-beam lithography followed by the double-angle evaporation. The metal films were 30 - 45 nm

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thick. We adopted two sorts of tunnel barriers, Al_2O_3 and NiO. In the latter case, NiO barrier was formed by plasma oxidation of Ni electrode using O_2. (The suspended Ge mask was employed for such process because the Ge film was resistant to O_2 plasma.) The size of tunnel junctions is about 0.1μm × 0.1μm. Electrical measurement was done at temperatures between 4.2 K and about 25 mK in magnetic fields up to 2 Tesla. We set the direction of the magnetic field parallel to the long axis of the island and the lead electrodes to realize the most distinct flip of the magnetization. The devices were characterized by the tunnel resistance R_T and the charging energy E_C. They were determined from the resistance at 4.2 K assuming both junctions were same, and from the offset voltage in the *I*-*V* curve at the lowest temperature.

3. Results and Discussion

Figure 1 shows the temperature dependence of the TMR enhancement factor of various devices. Their tunnel resistance ranges between 600 Ω and 3.3 MΩ. Here, the enhancement factor means the TMR ratio at each temperature divided by that at 4.2 K. As not only the electron temperature T_e but also E_C is different among devices, we plot the data against E_C/kT_e, which is determined from the resistance using a theoretical temperature dependence of resistance by the orthodox theory. We find E_C/kT_e determined in this way is not in inverse proportion to the fridge temperature near the lowest temperature, which is probably because the electron temperature is raised by the external noise. We see in Fig.1 that the TMR ratio in various Ni/Co/Ni-SETs becomes large at low temperatures. We also note the devices with R_T larger than 22 kΩ have roughly similar temperature dependence of the enhancement. Namely, $\gamma(T)/\gamma(4.2\mathrm{K})$ increases noticeably above $E_C/kT_e \approx 4$ and reaches about 10 at $E_C/kT_e \approx 6$. We find no systematic differences between, for example, the devices with R_T = 36 kΩ and 3.3 MΩ. In Fig.1 we also plot the data for samples R_T smaller than $R_Q = h/2e^2 = 12.9$ kΩ. The resistance of these samples increases slightly at low temperature, and the enhancement of TMR is not so evident. Obviously, the orthodox theory is not applicable to such devices, and the abscissa E_C/kT_e loses its original meaning. Nevertheless, interestingly enough, the plot in Fig.1 seems to suggest a kind of an universal curve of enhancement.

Theoretical models of TMR enhancement based on the higher-order tunneling have been proposed [5] [6] [7] [8]. If the enhancement relates to the higher-order tunneling, it is expected to be large for devices with $R_T \approx R_Q$, or at least it varies depending on R_T. Therefore, the results depicted in Fig.1 is not consistent with such

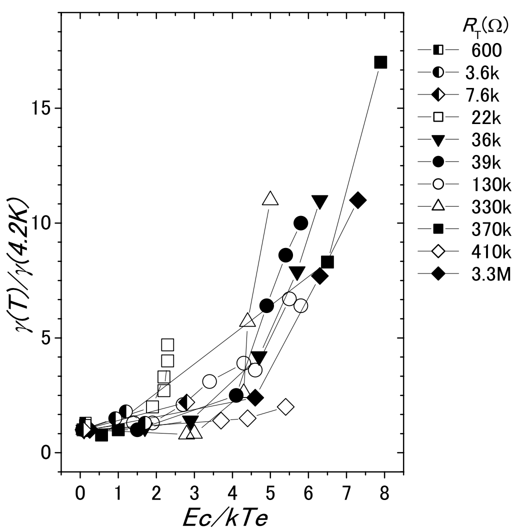

Fig. 1. Temperature dependence of TMR ratio

picture. Quantitatively, we have reported [6] that the estimation of enhancement using the renormalization of E_C [9] gave effects much smaller than experiment. It is also the case for the present experiment. The TMR enhancement estimated from the renormalization is 1.3 at most. Thus the theory based on the higher-order tunneling is not consistent with the experimental results. Wang *et al*. [8] performed Monte-Carlo simulation for strong tunneling and predicted very large enhancement of TMR for devices with $R_T < R_Q$. The temperature range where they predict such enhancement is, however, too low to check experimentally at present.

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