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Giant magnetic tunneling effect in $Fe/Al_2O_3/Fe$ junction

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Abstract

A giant magnetoresistance ratio of 30% at 4.2 K and 18% at 300 K was observed for the first time in an $Fe/Al_2O_3/Fe$ junction. The conductance at room temperature was expressed well by $G = 96.2\ (1 + 0.09\cos\theta)\ (\Omega^{-1})$, where θ is the angle between the magnetizations of two iron electrodes. The dependence of the magnetoresistance ratio, saturated resistance and also the tunneling current on temperature were measured in the range 4.2–300 K. The results support the claim that the giant magnetoresistance is due to the magnetic tunneling of electrons between the electrodes through the thin Al_2O_3 insulator.

Julliere [1] has reported for the first time that the tunneling conductance between electrodes of Fe and Co separated by an artificial Ge barrier at 4.2 K depends on whether the magnetic moments are parallel or antiparallel. The relative change of the conductance, $\Delta G/\overline{G}$, is approximately 14% at 4.2 K, where ΔG is the difference between the two conductance values corresponding to parallel and antiparallel magnetizations of the two ferromagnetic films and $\overline{G}$ is the average of the two. In 1982 Maekawa and Gäfvert [2] reported a spin polarized tunneling of electrons through a Ni/NiO/Ni junction and demonstrated a new interplay of electronic and magnetic properties in ferromagnetic metals. Suezawa has extended the study to Ni/NiO/Co [3] and $Ni/Al_2O_3/Co$ [4] junctions. The finding of a giant magnetoresistance effect in many artificial superlattice multilayers promotes also the study of tunneling resistance in junctions of two ferromagnets separated by a nonmagnetic tunneling barrier. One of the authors [5] demonstrated the good correlation between the magnetoresistance curve and magnetization curve for a $82Ni\text{-}Fe/Al_2O_3/Co$ tunneling junction and obtained a relative large magnetoresistance ratio even at room temperature. Yaoi et al. reported the dependence of the tunneling conductance on the angle between the magnetizations of two magnetic layers [6] and also on temperature and on applied voltage [7]. Nowak et al. [8] measured the relative change of conductance at 4.2 K for $Gd/GdO_x/Fe$ and $Fe/GdO_x/Fe$ junctions. Their values were 5.6 and 7.7%, respectively.

Theoretical treatments have been done for the first time by Maekawa and Gäfvert [2]. Their result indicates that the relative tunneling conductance ratio which is nearly equal to the magnetoresistance ratio can be expressed as

$$\Delta G/\overline{G} = 2P_A \cdot P_B, \tag{1}$$

$$P_{A(B)} = \left(D_+^{A(B)} - D_-^{A(B)}\right)/\left(D_+^{A(B)} + D_-^{A(B)}\right), \tag{2}$$

where $D_+^{A(B)}$ and $D_-^{A(B)}$ are the density of states of the majority and minority spin electrons of metal A

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(B) at the Fermi surface. Slonczewski [9,10] also discussed the magnetic tunneling effect (he named first this effect magnetic-tunneling-valve effect) in the light of band theory and showed how the expression for conductance ratio of Maekawa et al. may be modified by consideration of wave-function matching at the interfaces between sublayers. He also demonstrated the dependence of the tunneling conductance on the angle between the magnetizations of two magnetic layers. Eq. (1) shows that the relative conductance ratio (magnetoresistance ratio) is proportional to the product of spin polarization of the tunneling electrodes. The spin polarization of electrons tunneling for Fe, Co, Ni, and Gd films was obtained experimentally by Tedrow and Meserbey [11]. The result suggests that the spin polarization of Fe, Co and Ni is proportional to their magnetic moments. Therefore, it is expected that a magnetic tunneling junction with a large magnetoresistance ratio can be formed by using a material with a large intensity of magnetization as magnetic electrodes.

The iron electrodes and aluminum were prepared by electron beam evaporation and by rf sputtering, respectively. First, a 1000 Å thick Fe layer was evaporated in a form of 1×15 mm^2 onto a glass substrate kept at 200°C in order to reduce the magnetic anisotropy and/or coercive force. The pressure during evaporation was approximately 1×10^{-6} Torr. Then, a 55 Å thick Al layer was sputtered onto the center of the Fe film in a circular form with a 5 mm diameter. The system base pressure was lower than 1×10^{-6} Torr and the Ar sputtering gas pressure was 1.5 mTorr. Typical growth rate was 5.6 Å/s. The aluminum was oxidized in air at room temperature for 24 h. On the Al_2O_3 layer, a 1000 Å thick Fe layer was formed in the rectangular shape of 1×15 mm^2 perpendicular to the long axis of the first Fe film. In this case the substrate was kept at room temperature. In this way we can vary the induced magnetic anisotropy and/or coercive force for both iron electrodes. The experimental evidence of the different magnetic anisotropy will be shown in Fig. 2 and the magnetization curve explained. The magnetoresistance was measured by a dc four probe method in magnetic fields up to 200 Oe in the temperature range 4.2–300 K. The magnetization hysteresis curve was measured by a vibrating sample magnetometer.

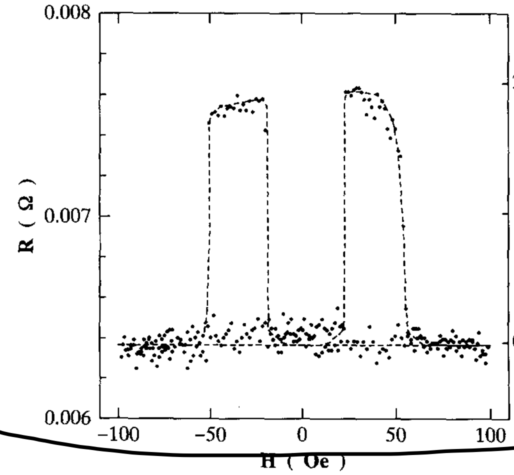

Fig. 1. Resistance as a function of the magnetic field for 1000 Å Fe/Al_2O_3/1000 Å Fe junction.

Fig. 1 shows the dependence of the resistance on the intensity of magnetic field at room temperature. The resistance increases sharply at ±20 Oe and decreases gradually up to about ±52 Oe, followed by a rapid decrease with further increase of the magnetic field.

The magnetoresistance ratio $\Delta R/R_s$ is approximately 18%, where ΔR is the resistance change from the antiparallel to parallel magnetization and R_s is the resistance at saturated magnetization. The value is one order higher than that reported previously for other magnetic tunneling junctions. Here it should be noted that other samples prepared at the

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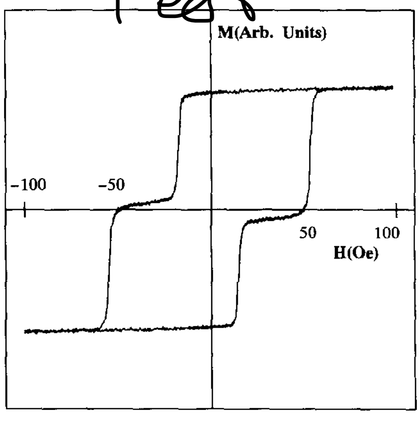

Fig. 2. Hysteresis curve corresponding to the magnetoresistance curve in Fig. 1.

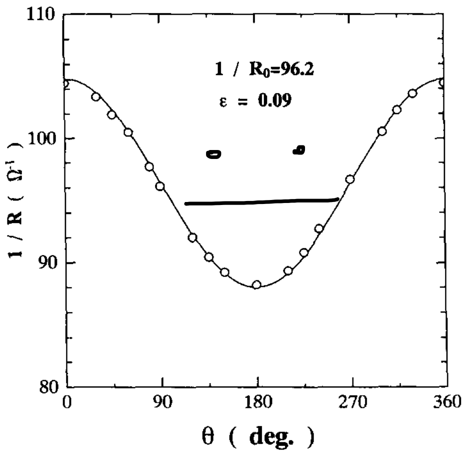

Fig. 3. Dependence of the tunneling conductance on the angle, θ, between the magnetizations of two iron electrodes.

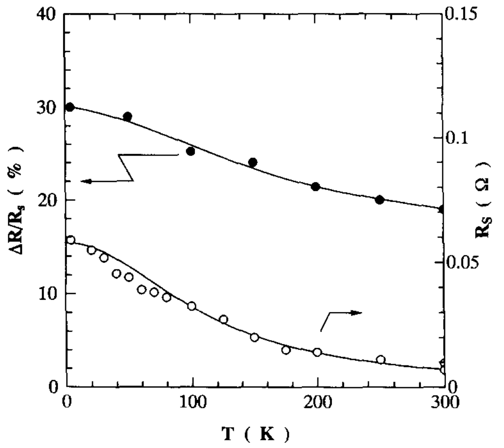

Fig. 4. Magnetoresistance ratio and the saturation resistance as a function of temperature.

same time with the sample shown in Fig. 1 exhibited a very similar shape of R vs. H, but the $\Delta R/R_s$ values were between 1 and 6%.

Fig. 2 shows the hysteresis curve of the Fe/Al_2O_3/Fe sample. The magnetization changes at about ± 20 and ± 52 Oe which corresponds well with the changes in the magnetoresistance curve of Fig. 1. The change of magnetization at the smaller magnetic field is due to that of the Fe film prepared at 200°C. The result indicates that the magnetic anisotropy and/or coercive force is easily controllable by the temperature of substrate during the evaporation. Furthermore, the magnetization proceeds by two steps which is reproducible by the two hysteresis curves with different coercive force. This result suggests that there exist no interaction between two magnetic layers. Since the coercive force for both Fe layers differs clearly, we are able to control easily the angle θ between two magnetization directions and measure the conductivity at various angles. Fig. 3 shows the inverse resistivity (conductivity) with open circles as a function of the angle θ. The solid curve is expressed as $G(\cong 1/R) = G_0(1 + \varepsilon \cos \theta) = 96.2(1 + 0.09 \cos \theta)$. The result is consistent with the theoretical prediction [9] and supports the claim that the giant magnetoresistance effect observed originates from the magnetic tunneling.

Fig. 4 shows the dependence of magnetoresistance and the saturation resistance on temperature between 4.2 and 300 K. The MR ratio is expressed by $\mathrm{MR} = 30\ T^{-0.12 \pm 0.02}$. On the other hand R_s is expressed by $R_s = 0.058/(1 + 8 \times 10^{-4} T^2)$.

Usually the tunneling current can be expressed by the relation $I(T) = I(0)(1 + CT^2)$ [12], where $I(0)$ is the tunneling current at 0 K and C is a constant which depends on the barrier height and thickness. In order to confirm the relationship, the normalized tunneling current is plotted as a function of T^2 in Fig. 5. It is seen that $I(T)/I(0)$ is roughly proportional to T^2, also suggesting the tunneling phenomenon.

From Tedrow and Meservey measurement, the spin polarization for iron is 44% [11]. By using Eq. (1) we have reduced $\Delta G/\overline{G} \cong \Delta R/R_s = 39\%$. The

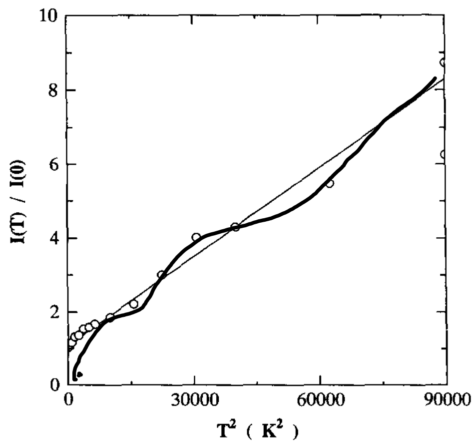

Fig. 5. Normalized tunneling current as a function of T^2.

maximum experimental value of $\Delta R/R_s$ is 30% at 4.2 K which is nearly the same as evaluated by using the value of spin polarization. As described above, most samples exhibited much smaller value of $\Delta R/R_s$ than the theoretical prediction. The discrepancy can be considered as a result of the magnetic coupling between the ferromagnetic iron films. The magnetic coupling may be due to the nonuniform structure of Al_2O_3 insulator. Therefore, further study may be required to fabricate uniform insulator films and reduce the conductance except for the magnetic tunneling. Detailed experimental data and discussions will be published elsewhere.

Acknowledgments

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