Strong increase of the effective polarization of the tunnel current in $Fe/AlO_x/Al$ junctions with decreasing Fe layer thickness

K. Mizushima, T. Kinno, K. Tanaka, and T. Yamauchi
Advanced Research Laboratory, Research and Development Center, Toshiba Corporation, Kawasaki, Kanagawa 210, Japan
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The voltage dependence of the magnetoresistance ratio in a three-terminal device that consists of an Fe/AlO_x emitter, an Al/Fe/Au base, and an *n*-type Si collector, was measured while changing the thickness of an Fe layer in the emitter. The ratio increased with decreasing the Fe thickness and was as large as 100% for a thickness of 0.8 nm. The results were analyzed by a phenomenological model that took into account the spin-polarized tunneling of electrons from the emitter into the base as well as the spin-dependent hot electron transport in the base. The spin polarization of electrons injected from the 0.8-nm Fe was estimated to be about 40% even at the injection voltage of 1 V. It was suggested that the large polarization was caused by the suppression of spin-flip scattering for electrons tunneling from the two-dimensional Fe electrodes.
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I. INTRODUCTION

In the preceding paper (hereafter denoted as I), we reported on the hot-electron transport across an Al/Fe/Au/Fe/Au multilayer that was incorporated as a base in a three-terminal device.[1] The device was composed of an Al/AlO_x emitter, the multilayer base, and an *n*-type Si collector (type *A*). Hot electrons were injected into the base by tunneling from the emitter. From the voltage dependence in the magnetoresistance (MR) ratio of the device, the following was suggested. (1) *s* electrons mainly contribute to the hot-electron current across the multilayer base. (2) Electron refraction at the base/collector interface enhances the MR ratio of the device up to 3 (200%). We also reported preliminary results for another type of device that consisted of an Fe/AlO_x emitter, an Al/Fe/Au base, and an *n*-type Si collector (type *B*), where the emitter was backed by a thick Au layer. MR ratio in type *B* was, however, an order of magnitude smaller than that in type *A*. The small MR ratio in type *B* suggested the strong spin-flip scattering for electrons tunneling from the emitter into the base.

In this paper we report that the MR ratio in type *B* depends strongly on the Fe thickness in the emitter. Although the ratio was only a few percent for thickness above 3 nm, it increased steeply below 2 nm up to around 2 (100%) for 0.8 nm. The marked increase in the MR ratio for the ultrathin Fe emitter suggested that the spin flip was suppressed by the two dimensionality of the Fe layer. The possibility that the spin-dependent energy quantization of tunneling electrons might suppress the spin-flip scattering is discussed. Spin polarization of the tunneling electrons was estimated from the MR ratio by using transport parameters in the base that were obtained from a phenomenological analysis of type *A*.

II. EXPERIMENTS AND RESULTS

Details of device preparation and the method of measurement have been reported in I.[1] Device structures of types *A* and *B* are shown schematically in Figs. 1(a) and 1(b), respectively. The base layers in types *A* and *B* consist of Al(4.5 nm)/Fe(1.5 nm)/Au(10 nm)/Fe(1 nm)/Au(1 nm) and Al(10 nm)/Fe(1.5 nm)/Au(1.5 nm), respectively. In both types, the Al surface was oxidized at room temperature in a flow of pure O_2 (1 atm.) for 1 h to form a tunneling barrier. The $Fe(d\ \mathrm{nm})/AlO_x$ emitter in type *B* was backed by a thick Au layer of 100 nm. The Schottky junction was 1×4 mm in area and its resistance was about 10 MΩ at 77 K. The BaF_2 (300 nm) insulation layer was used to define a tunnel junction area of $50\times500\ \mu$m. Although the thickness of AlO_x was not measured, the magnitude of the tunneling current (emitter current) was in the range of 10^{-3}–10^{-4} A (0.4–4 A/cm^2) at 1.5 V. The measurement was performed at 77 K. The collector current changed with hysteresis under application of external magnetic field. The ratio of saturated to minimum col-

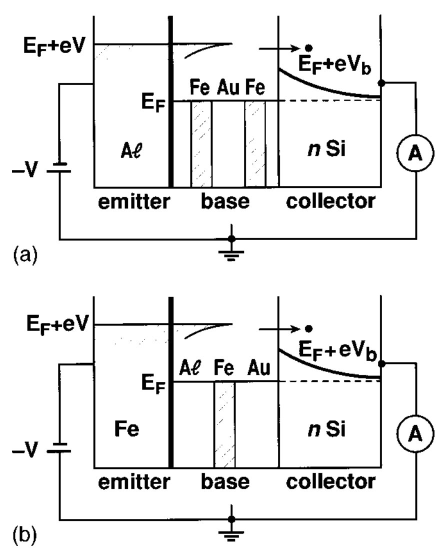

FIG. 1. (a) Schematic energy diagram of the three-terminal structure of type *A*. Hot electrons are injected into the base by applying a voltage *V* to the emitter. Hot electron current that flows into the collector is detected as a collector current. eV_b is the Schottky barrier height. (b) Schematic energy diagram of the three-terminal structure of type *B*. Spin-polarized electrons are injected from an Fe emitter into an Al/Fe/Au base.

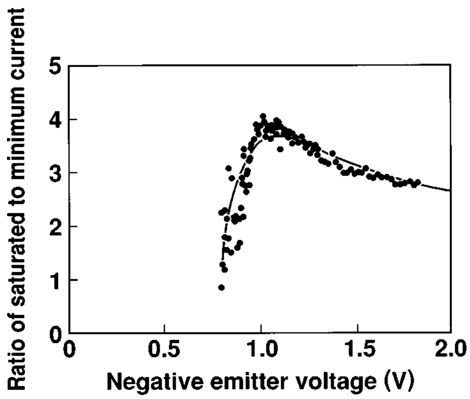

FIG. 2. Dependence of the ratio of saturated to minimum collector current (MR ratio) on the emitter voltage in type A measured at 77 K. The solid curve is a plot of Eq. (8) with the approximation for $I_e(V)$ of Eq. (10), where three parameters, $l_\uparrow$, $l_\downarrow$, and l_{sf}, are set at 5.3, 2.9, and 106 nm, respectively.

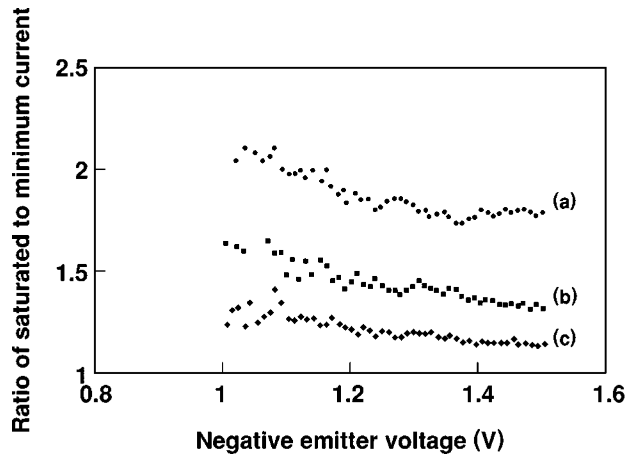

FIG. 4. Dependence of the MR ratio on the emitter voltage in type B measured at 77 K. Thickness of Fe in the emitter is (a) 0.8 nm, (b) 1 nm, and (c) 2 nm, respectively.

lector current (MR ratio) in type A is plotted in Fig. 2 as a function of emitter voltage. In the figure, the ratio below 1 V was added to that above 1 V, which has already been reported in I. For the measurement of MR ratio below 1 V where the collector current was reduced down to a few picoampere, a low-pass filter with cutoff frequency of 3 Hz was inserted in the collector circuit. Figure 3 shows the voltage dependence of the saturated and minimum collector current below 1 V. A steep decrease of MR ratio was found below 1 V, suggesting strong spin-flip scattering in the base in this voltage range. The results were fitted by the solid curve in the figure, which was obtained by a phenomenological analysis described below.

The voltage dependence of the MR ratio in type B is shown in Fig. 4. Plots of Figs. 4(a), 4(b), and 4(c) are for Fe thickness d in the emitter of 0.8, 1, and 2 nm, respectively. We observed the decrease of MR ratio below 1 V as in the case of type A, although it is not shown in Fig. 4. Figure 5 shows the dependence of the MR ratio at 1 V on the thickness d. The values of spin polarization of tunneling electrons that were estimated from the analysis described below are also shown on the right-hand side ordinate in the figure. The MR ratio increased steeply with decreasing thickness below 2 nm, except for a sudden drop at 0.6 nm. The ratio of more than 2 (100%) was observed for a sample of 0.8 nm, indicating strong suppression of the spin-flip scattering for tunneling electrons in this sample even at the voltage as high as 1 V. The ratio in type B was found to decrease with time, especially in the device with the ultrathin Fe emitter. For example, the ratio for Fe thickness of 0.8 nm, which had been more than 2 (100%) just after the preparation, decreased to about 1.5 (50%) after two weeks. This degradation as well as the small MR ratios for a thickness of 0.6 nm suggest that the ratio is sensitive to the atomic diffusion in the emitter. On the contrary, the ratio in type A did not change even after a year.

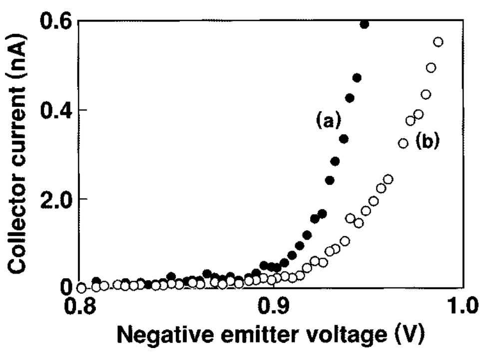

FIG. 3. Voltage dependence of the collector current below 1 V. Curves (a) and (b) are for the saturated and minimum current, respectively.

III. DISCUSSIONS

A. A phenomenological analysis of type *A*

As shown in Fig. 2, no anomaly in the MR ratio was observed in the voltage range around 1.5 V where the minority spin density of d states has a large and sharp peak in Fe.[2] We, therefore, assume in the following analysis that s electrons mainly contribute to the hot-electron current in the base, as discussed in I. In the analysis, we take into account the refraction at the base/collector interface; that is, electrons

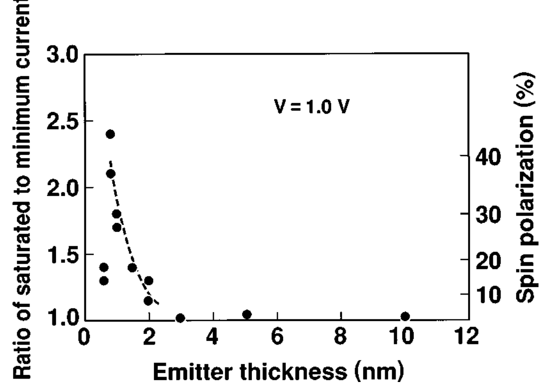

FIG. 5. Dependence of the MR ratio at 1 V on the thickness of Fe in the emitter. The values of spin polarization of tunneling electrons estimated by using Eqs. (14) and (15) are also plotted on the right-hand side ordinate. A broken curve in the figure is a guide to the eye.

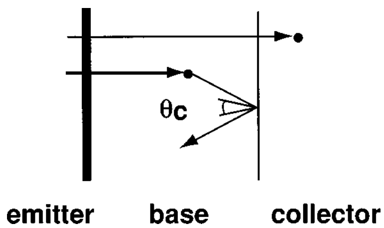

FIG. 6. This figure shows schematically that most electrons scattered outside θ_c in the base cannot flow into the collector. These electrons decay in the base as a result of inelastic scattering and flow out as a base current.

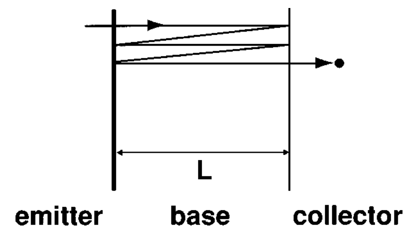

FIG. 7. This figure shows schematically that electrons with energy close to $eV_b = 0.8$ eV have a small transmission coefficient T at the base/collector interface and that their path length is long owing to the multiple reflection in the base with thickness L.

scattered outside the critical angle θ_c do not contribute to the collector current as shown in Fig. 6. The angle is given by

$$\sin^2 \vartheta_c = e \frac{m_t}{m} \frac{V - V_b}{E_F + eV}, \tag{1}$$

where m is the free-electron mass in the multilayer base, m_t is an effective mass in Si parallel to the interface, $E_F \sim 5$ eV is the Fermi energy in Au, $eV_b \sim 0.8$ eV is the Schottky barrier height, and V is the applied emitter voltage.[3] The angle is less than 10° in the voltage range of experiment. We, therefore, adopt an approximation that any electron that is scattered in the base does not flow into the collector. For electrons with energy close to eV_b, the quantum mechanical reflection at the interface is substantial. We take into account this effect by approximating the transmission probability with the one-dimensional expression,

$$T = \frac{4k_1k_2}{(k_1+k_2)^2} = \frac{4k}{(k+1)^2}, \tag{2}$$

where $k = k_1/k_2 = \sqrt{(eV + E_F)/(eV - eV_b)}$ is the ratio of wave number of electrons in Au and in Si. Due to the quantum mechanical reflection, multiple reflection occurs in the base as shown in Fig. 7 and the effective path length in the base may be expressed as $L(2/T - 1)$, because the number of reflection is $1/T - 1$.

Under the approximations mentioned above, the collector current carried by the up-spin electrons with energy eV may be expressed as[3]

$$I^P_{0\uparrow}(V) \propto \Omega \exp\left[-\frac{L}{l_\uparrow}\left(\frac{2}{T} - 1\right)\right] I_e(V) = A(V) I_e(V), \tag{3}$$

in the case that the magnetizations in Fe layers are parallel with each other, where $I_e(V)$ is the tunneling current spectrum, $\Omega = \pi \sin^2 \theta_c = \pi(V - V_b)/(V + E_F/e)$, L is the thickness of the base, and $l_\uparrow$ is the effective mean free path (MFP) for the up-spin electrons. Similarly, the current by the down-spin electrons is expressed as

$$I^P_{0\downarrow}(V) \propto \Omega \exp\left[-\frac{L}{l_\downarrow}\left(\frac{2}{T} - 1\right)\right] I_e(V) = B(V) I_e(V), \tag{4}$$

where $l_\downarrow$ is MFP for the down-spin electrons. In the antiparallel configuration of magnetization, the current may be approximated as

$$I^{AP}_{0\uparrow}(V) = I^{AP}_{0\downarrow}(V) \propto \Omega \exp\left[-\frac{L}{2}\left(\frac{1}{l_\uparrow} + \frac{1}{l_\downarrow}\right)\left(\frac{2}{T} - 1\right)\right] I_e(V) = C(V) I_e(V), \tag{5}$$

and the ratio of the collector current in the parallel and antiparallel configurations is

$$\frac{I^P_0}{I^{AP}_0} = \frac{I^P_{0\uparrow} + I^P_{0\downarrow}}{I^{AP}_{0\uparrow} + I^{AP}_{0\downarrow}} = \frac{A(V) + B(V)}{2C(V)}. \tag{6}$$

In the above, we neglected spin-flip scattering in the base. The effect of spin-flip scattering may be taken into account by

$$\begin{aligned} I^P - \frac{I^P_0 + I^{AP}_0}{2} &= \frac{I^P_0 - I^{AP}_0}{2} \exp\left[-\frac{L}{l_{\mathrm{sf}}}\left(\frac{2}{T} - 1\right)\right], \\ \frac{I^P_0 + I^{AP}_0}{2} - I^{AP} &= \frac{I^P_0 - I^{AP}_0}{2} \exp\left[-\frac{L}{l_{\mathrm{sf}}}\left(\frac{2}{T} - 1\right)\right], \end{aligned} \tag{7}$$

where l_{sf} is a characteristic length of spin-flipping for hot electrons. In the limit of long l_{sf}, I^P and I^{AP} approach I^P_0 and I^{AP}_0, respectively, and they approach $(I^P_0 + I^{AP}_0)/2$ at the limit of short l_{sf}. Integrating by the energy of electrons, the ratio of saturated to minimum collector current is expressed as

$$\frac{I_c^{\mathrm{sat}}}{I_c^{\mathrm{min}}} \cong \frac{\int I^P(V')dV'}{\int I^{AP}(V')dV'} = \frac{\int\{(A+B+2C) + (A+B-2C)\exp[-(L/l_{\mathrm{sf}})(2/T-1)]\} I_e(V')dV'}{\int\{(A+B+2C) - (A+B-2C)\exp[-(L/l_{\mathrm{sf}})(2/T-1)]\} I_e(V')dV'}. \tag{8}$$

For calculating Eq. (8), we must know the spectrum of the injected hot electrons $I_e(V')$, which depends on the injection voltage V. According to the conventional (WKB) theory of electron tunneling, the probability of tunneling for an electron with energy E across a barrier with the height E_v and the width s is expressed as[4]

$$D(E) = \exp(-2KS),$$

$$K = \left\{\frac{2m[E_v - E_z]}{\hbar^2}\right\}^{1/2}, \tag{9}$$

where E_z is the component of energy E normal to the barrier. The spectrum $I_e(V')$ at the injection voltage V could, therefore, be approximated for nearly normal injection by

$$I_e(V')=\begin{cases}\text{const}\times D(E_F-eV+eV') & 0\leqslant V'\leqslant V\\ 0, & V<V',\end{cases} \tag{10}$$

where we neglected the distortion of the barrier with applying voltage. For the Al/AlO$_x$/Al tunnel junction, we assumed typical values of $(E_v-E_F)=3$ eV and $s=1.5$ nm. Equation (8) includes three fitting parameters, $l_\uparrow$, $l_\downarrow$, and l_{sf} for which the values of $l_\uparrow=5.3$ nm, $l_\downarrow=2.9$ nm, and $l_{\text{sf}}=106$ nm were chosen. Although we did not take into account the energy dependence of these parameters, a reasonable fitting was obtained as shown by the solid curve in Fig. 2. Recently, we calculated the scattering cross section of an electron due to Fe impurities in Au by extending the formulation of Yafet.[5] The results showed a considerable energy dependence. It is, therefore, considered that a further study is necessary for the energy dependence of electron scattering in the multilayer. The ratio of Eq. (8) was not sensitive to the spectrum $I_e(V)$. Almost the same result was obtained even in the case where Eq. (10) was replaced by the monochromatic spectrum of

$$I_e(V')=\text{const}\times\delta(V'-V). \tag{11}$$

The numerical difference in both cases is less than 3%. The steep decrease of the ratio below 1 V can be attributed to the increase of spin-flip probability caused by the increase of the path length $L(2/T-1)$. The mean free path in the Au film formed on n-type Si has been reported to be about 20 nm at 77 K.[6] The much smaller values of $l_\uparrow$ and $l_\downarrow$ in the multilayer base indicate strong scattering in Fe and at the Fe/Au (Al) interfaces. In this model, we neglected the spin dependence of the effective path length in the base. It can be spin dependent, because the band mismatch at the Au/Fe interface is much larger for down spin than that for up spin,[2] causing the stronger interface reflection for the down-spin electrons. Therefore, it may be better for $(L/l_\uparrow)(2/T-1)$ and $(L/l_\downarrow)(2T-1)$ in Eqs. (3)–(5) to be replaced by $(L_\uparrow/l_\uparrow)\times(2/T-1)$ and $(L_\downarrow/l_\downarrow)(2/T-1)$, and for $(L_\uparrow/l_\uparrow)$ and $(L_\downarrow/l_\downarrow)$ to be regarded as fitting parameters instead of $l_\uparrow$ and $l_\downarrow$. In that case, the values of parameters of $(L_\uparrow/l_\uparrow)$ and $(L_\downarrow/l_\downarrow)$ for the solid curves in Fig. 2 are $18/5.3=3.4$ and $18/2.9=6.1$, respectively.

B. An analysis of type *B*

An analysis similar to that for type A was applied to type B. The current expressions are as follows:

$$\begin{aligned}
I_{0\uparrow}^{P}(V)&\propto\Omega\ \exp\left[-\frac{L_\uparrow'}{l_\uparrow'}\left(\frac{2}{T}-1\right)\right]I_{e\uparrow}(V),\\
I_{0\downarrow}^{P}(V)&\propto\Omega\ \exp\left[-\frac{L_\downarrow'}{l_\downarrow'}\left(\frac{2}{T}-1\right)\right]I_{e\downarrow}(V),\\
I_{0\uparrow}^{AP}(V)&\propto\Omega\ \exp\left[-\frac{L_\downarrow'}{l_\downarrow'}\left(\frac{2}{T}-1\right)\right]I_{e\uparrow}(V),\\
I_{0\downarrow}^{AP}(V)&\propto\Omega\ \exp\left[-\frac{L_\uparrow'}{l_\uparrow'}\left(\frac{2}{T}-1\right)\right]I_{e\downarrow}(V),
\end{aligned} \tag{12}$$

where $L_\uparrow'(2/T-1)$ and $L_\downarrow'(2/T-1)$ are the effective path length, and $l_\uparrow'$ and $l_\downarrow'$ are the MFP of the electrons with up and down spins, respectively, in the base in type B. $I_{e\uparrow}$ and $I_{e\downarrow}$ are the tunneling current spectra of up and down spins, respectively, injected into the base, and the polarization of tunneling electrons is defined as[7]

$$P(V)=\frac{I_{e\uparrow}-I_{e\downarrow}}{I_{e\uparrow}+I_{e\downarrow}}. \tag{13}$$

Neglecting the spin-flip scattering in the base, which is substantial only near the threshold voltage V_b (below 1 V) and using the approximation of the monochromatic spectra for $I_{e\uparrow}$ and $I_{e\downarrow}$, the ratio of the saturated and the minimum collector current is expressed as

$$\begin{aligned}
\frac{I_c^{\text{sat}}}{I_c^{\text{min}}}&\cong\frac{I_{0\uparrow}^{P}+I_{0\downarrow}^{P}}{I_{0\uparrow}^{AP}+I_{0\downarrow}^{AP}}\\
&=\frac{\exp[-(L_\uparrow'/l_\uparrow')(2/T-1)]I_{e\uparrow}+\exp[-(L_\downarrow'/l_\downarrow')(2/T-1)]I_{e\downarrow}}{\exp[-(L_\downarrow'/l_\downarrow')(2/T-1)]I_{e\uparrow}+\exp[-(L_\uparrow'/l_\uparrow')(2/T-1)]I_{e\downarrow}}\\
&=\frac{\exp[-(L_\uparrow'/l_\uparrow')(2T-1)](1+P)+\exp[-(L_\downarrow'/l_\downarrow')(2/T-1)](1-P)}{\exp[-(L_\downarrow'/l_\downarrow')(2/T-1)](1+P)+\exp[-(L_\uparrow'/l_\uparrow')(2/T-1)](1-P)}.
\end{aligned} \tag{14}$$

As mentioned above, it is considered that dominant electron scattering in the base is the scattering in Fe and at the Fe/Au (Al) interfaces. Because the numbers of the Fe layers and the interfaces in the base in type B are half of those in type A, the following relations are expected:

$$\frac{L_\uparrow'}{l_\uparrow'}\approx\frac{1}{2}\frac{L_\uparrow}{l_\uparrow},$$

$$\frac{L_\downarrow'}{l_\downarrow'}\approx\frac{1}{2}\frac{L_\downarrow}{l_\downarrow}. \tag{15}$$

In reproducing the results in Fig. 2 by Eq. (14), which includes two fitting parameters of $(L_\uparrow'/l_\uparrow')$ and $(L_\downarrow'/l_\downarrow')$ and a function $P(V)$, we fixed the values of $(L_\uparrow'/l_\uparrow')$ and $(L_\downarrow'/l_\downarrow')$ to $1/2\times3.4=1.7$ and $1/2\times6.1=3.05$, respectively, assuming

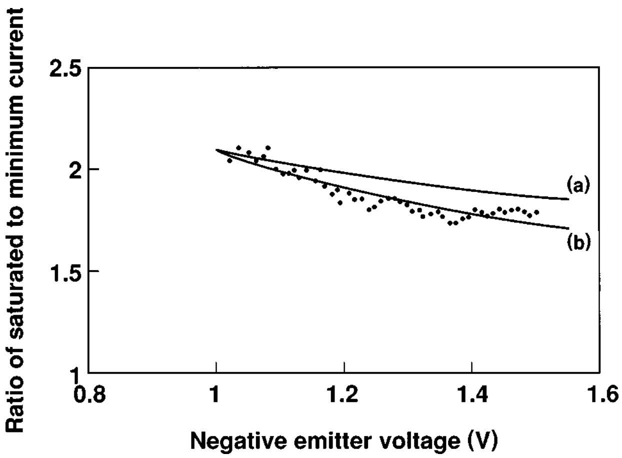

FIG. 8. The voltage dependence of the MR ratio observed in type *B*. Thickness of Fe in the emitter is 0.8 nm. Curve (a) is a plot of Eq. (14) with $P=0.37$. In curve (b), P changes linearly with voltage from 0.37 at 1 V to 0.25 at 1.5 V.

the relations of Eq. (15). An example of fitting is shown for thickness $d=0.8$ nm in Fig. 8. At first, a constant value was assumed for P, because we had no knowledge on its voltage dependence. Curve (a) is a plot of Eq. (14) with $P=0.37$. The voltage dependence of the calculated results is considerably smaller than that of the experimental results. For curve (b), it was tentatively assumed that P decreased linearly from 0.37 at 1 V to 0.25 at 1.5 V. The better fitting of curve (b) can be reasonable, because the probability of spin-flip scattering is considered to increase with voltage. The spin polarization of tunneling electrons at 1 V, which is related to the MR ratio by Eq. (14), is plotted on the right-hand side ordinate in Fig. 5, assuming the values of $(L'_{\uparrow}/l'_{\uparrow})$ and $(L'_{\downarrow}/l'_{\downarrow})$ to be 1.7 and 3.05, respectively. The above estimation of the polarization is very rough, especially assuming the values of $(L'_{\uparrow}/l'_{\uparrow})$ and $(L'_{\downarrow}/l'_{\downarrow})$. It is, however, noted that even in the limit of

$$(L'_{\downarrow}/l'_{\downarrow})\rightarrow\infty, \tag{16}$$

Eq. (14) predicts the MR ratio of only 50% for the case of 20% polarization. In other words, it can be said that the observed MR ratio of as large as 100% indicates very large polarization of tunneling electrons.

C. Spin polarization of tunneling electrons

It has been reported that the MR ratio of ferromagnetic tunnel junctions decreases with increasing applied voltage.[8] The decrease is believed to be caused by spin-flip scattering of tunneling electrons, which reduces their spin polarization. It is also well known that the tunneling current in Al/AlO_x/Al junctions shows a zero-bias anomaly caused by the spin-flip interaction between electrons and paramagnetic impurities that exist in the AlO_x barrier or in the Al electrodes.[9] As shown in Fig. 5, the spin polarization of tunneling electrons in type *B* was estimated to be less than 0.05 (5%) in the case of Fe emitters whose thickness is above 3 nm. We believe the small spin polarization in these samples is due to the spin-flip interaction of tunneling electrons with some magnetic excitations in the Al/AlO_x/Fe junctions. A steep increase of spin polarization was observed below 2 nm. At 0.8 nm, spin polarization reaches around 0.4 (40%), which is comparable with that observed in Al/AlO_x/Fe in the range of millivolts below the critical temperature (1.2 K) of the superconducting aluminum.[10] Although the values of spin polarization estimated above are, of course, not accurate, the spin-flip scattering is strongly suppressed in this sample.

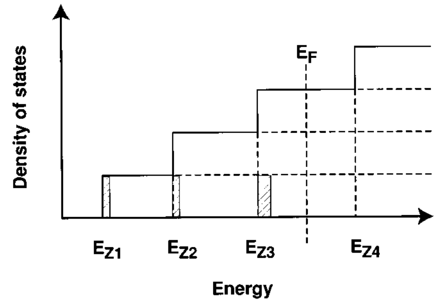

FIG. 9. Schematic density of states in a two-dimensional system. Only electrons in the hatched areas take part in tunneling due to the strong forward focusing effect of tunneling electrons.

The suppression of the spin-flip scattering in the junction with an ultrathin Fe electrode may be ascribed to the two dimensionality of electron states. In the following discussion, we assume that s electrons mainly take part in tunneling.[11,12] The density of states of a two-dimensional system of an s band is shown schematically in Fig. 9, where

$$E_{zn}=\frac{\hbar^2}{2m}\left(\frac{n\pi}{d}\right)^2. \tag{17}$$

Owing to the strong forward focusing effect of tunneling electrons, the only electrons in the hatched areas in the figure take part in tunneling, that is, the energy of tunneling electrons is quantized in discrete levels in a two-dimensional system. The height of the area is the two-dimensional density of states of subband $m/(2\pi\hbar^2)$, and the width depends on the tunneling probability $D(E)$. By using the expression for the angular distribution of the tunneling current derived from Eq. (9),

$$J_\theta \propto \exp[-\beta^2 \sin^2 \theta], \tag{18}$$

where $\beta^4=2ms^2E^2/h^2(E_v-E)$,[3,4] the angular width $\Delta\theta=\Delta k_t/k_z$ of tunneling electrons is given by

$$(\Delta\theta)^2=\left(\frac{\hbar^2}{2m}\right)^{1/2}\frac{1}{s}\,\frac{(E_v-E)^{1/2}}{E}, \tag{19}$$

where $k_z=n\pi/d$ and k_t is the component of the wave vector parallel to the barrier. The energy width of the nth hatched area is, therefore, expressed as

$$\Delta E_{zn}=\left(\frac{\hbar^2}{2m}\right)^{1/2}\frac{1}{s}\,(E_v-E_{zn})^{1/2}, \tag{20}$$

in the present approximation. The width is estimated to be 0.1–0.3 eV in the energy range of the experiment. The density of states for s electrons in bulk Fe, which is shown schematically in Fig. 10(a), is quantized as shown in Fig. 10(b) in the ultra-thin film of about 1 nm. In the figure, Fermi energies of the up and down spin electrons in Fe were

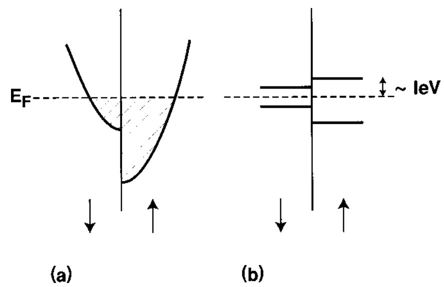

FIG. 10. (a) Schematic density of states of *s* bands in Fe. (b) Quantized energy levels of *s* electrons in an ultrathin Fe film.

assumed to be 5 and 1 eV, respectively.[2] The energy difference Δ between up and down spin levels is as large as several hundreds of millielectron volts near the Fermi level. It is considered that tunneling electrons can change their spin direction in the electrode only by inelastic scattering with energy larger than Δ and, therefore, the spin-flip probability is much reduced in the electrode. The spin-flip probability may be reduced even in the barrier in the case that the interaction with magnetic excitations is strong only near the barrier/Fe-electrode interface where the quantization of the electron states could still be substantial. In the above discussion on two dimensionality, we assumed implicitly the existence of a barrier at the Fe/Au interface in the emitter. Although we have not intentionally introduced the barrier, it might be formed at the interface in the relatively low vacuum of 10^{-6} torr for sample preparation. Another possibility is the intrinsic barrier due to the large band mismatch of about 4 eV for down-spin electrons at the interface.[2] The transmission probability at the interface is estimated to be about 0.2 and the down-spin band can be quantized. Even in this case, considerable reduction of spin-flip probability is expected. It will be possible to confirm the two dimensionality by observing directly the discrete levels by STM.

D. Stability of the structures

At the end of Sec. II, we mentioned that the devices of type *B* degraded with time, although no degradation was noticed in type *A*. We discuss these results in the framework of the present model. Equation (6), which describes the MR ratio in type *A* in the absence of spin-flip scattering in the base, includes only two transport parameters, $l_\uparrow$ and $l_\downarrow$. It is noticed that the ratio does not change when $1/l_\uparrow$ and $1/l_\downarrow$ are replaced by $1/l_\uparrow + 1/l_0$ and $1/l_\downarrow + 1/l_0$, respectively. In other words, the creation or the destruction of spin-independent scattering centers in the base does not change the ratio. The same is also applied to Eq. (8), which includes another parameter, l_{sf}. On the contrary, Eq. (14) includes not only $1/l_\uparrow$ and $1/l_\downarrow$ but also *P*. The instability of type *B* suggests that the polarization of tunneling electrons is sensitive to the structure or the two dimensionality of the emitter.

IV. CONCLUSION

The voltage dependence of the MR ratio in the devices of types *A* and *B*, which are shown in Figs. 1(a) and 1(b), respectively, was measured and a phenomenological analysis was performed for the obtained results. The spin polarization of tunneling electrons in type *B* was also estimated in the analysis. The MR ratio in type *B* depended strongly on the thickness of the Fe layer in the emitter. For the thickness of 0.8 nm, the ratio was more than 2 (100%), indicating large spin polarization in the sample. The large spin polarization observed even above 1 V was tentatively ascribed to the suppression of spin-flip scattering in the junction with two-dimensional Fe electrode.

The ferromagnetic tunnel junctions are expected to be useful in practical applications such as magnetic recording heads and magnetic random access memories. In these applications, the voltage applied to the junctions is considered to exceed 100 mV. We showed a possibility that the spin-flip scattering of tunneling electrons might be suppressed even in the practical voltage range by using ultrathin ferromagnetic electrodes.

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