Temperature dependence of the normal and inverse magnetoresistance in magnetic multilayers

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The temperature dependence of the giant magnetoresistance (GMR) in $M_1/N/M_2$ multilayers consisting of magnetic M_i ($i = 1, 2$) and nonmagnetic N layers, is discussed with the use of the finite-temperature band theory in which the effect of spin fluctuations is taken into account by means of the static functional-integral method combined with the coherent potential approximation. It is shown that the temperature dependence of the MR ratio, $\Delta R/R$, shows a variety of behaviors depending on the values of a_1 and a_2 where $a_i = \Delta_{i\uparrow}/\Delta_{i\downarrow}$ and Δ_{is} is the imaginary part of the coherent potential of an s-spin electron at the interface of the M_i layer. In the *normal* MR where $a_1 > 1$ and $a_2 > 1$ (or $a_1 < 1$ and $a_2 < 1$), $\Delta R/R$ decreases as the temperature is raised. On the contrary, in the *inverse* MR where $a_1 > 1$, $a_2 < 1$ (or vice versa) and $\Delta R/R < 0$, it increases although its absolute magnitude decreases. In a multilayer where normal and inverse MR's coexist, $\Delta R/R$ may show a maximum or almost constant behavior in a fairly wide temperature range.

I. INTRODUCTION

In recent years giant magnetoresistance[1] (GMR) in layered structures has been intensively studied. One of the important aspects of GMR is its temperature dependence. A careful study of the temperature dependence of GMR is not only important in understanding its mechanism, but also beneficial to its practical applications. In a previous paper,[2] we discussed the temperature dependence of the MR ratio $\Delta R/R$ of M/N multilayers consisting of magnetic M and nonmagnetic N layers, by using finite-temperature band theory[3] in which the static functional-integral method is employed to include the effect of spin fluctuations at finite temperatures. Our model calculations[2] have shown the following features: (1) The MR ratio is more significantly temperature dependent than the (average) layer moment, (2) the temperature dependence of the MR ratio is more considerable in a multilayer with a larger ground-state MR ratio, and (3) it is quasilinear near the Curie temperature. These features are commonly observed in many transition-metal multilayers.[4–9] It has been shown[9] that our theory well explains the temperature dependence of the MR ratio of NiFe/Cu, NiCo/Cu, and CoFe/Cu multilayers. Our approach is recently extended[10] to account for the temperature- and layer-thickness dependences of the MR ratio of Fe/Cr multilayers.[8]

The purpose of this paper is to apply our approach[2] to $M_1/N/M_2$ multilayers where M_i ($i = 1, 2$) and N are magnetic and nonmagnetic layers, respectively. As will be shown shortly, such magnetic multilayers may show a variety of behavior depending on the parameters characterizing them.

The paper is organized as follows: In Sec. II we present our formulation applying finite-temperature band theory to MR. Numerical results are presented in Sec. III, where the semiphenomenological approach is employed. Section IV is devoted to supplementary discussions.

II. FORMULATION

We adopt an N_f-layer thin film with a sandwiched $M_1/N/M_2$ structure. The layer parallel to the interface is assigned by the index n ($= 1 - N_f$). The magnetic M_1 and M_2 layers are assumed to be predominantly consisting of magnetic A_1 and A_2 atoms, respectively, but they are allowed to include a nonmagnetic B atom, particularly near their interfaces. The magnetic A_i ($i = 1, 2$) atom and nonmagnetic B atom are assumed to randomly distribute on the layer n with concentrations of x_{in} and y_n, respectively ($x_{in} + y_n = 1$). The film is described by the single-band Hubbard model, in which atomic potentials (on-site interactions) are assumed to be given by ε_1, ε_2, and ε_0 (U_1, U_2, and $U_0 = 0$) for A_1, A_2, and B atoms, respectively. The hopping integral is assumed to be the same for all the atoms.

In order to study the finite-temperature properties of the magnetic film, we apply the functional-integral method within the static approximation to the model Hamiltonian.[3] We can evaluate the partition function by calculating the partition function of the effective one-electron system including the random charge and exchange fields with the Gaussian weight. We take account of the charge field by the saddle-point approximation and the exchange field by the coherent potential approximation (CPA),[11] details having been reported elsewhere.[2,3]

By using the CPA,[11] the conductivity for currents parallel to the film layer has been shown to be given by[12]

$$\sigma_n = \left(\frac{\pi e^2}{N_f \hbar^2}\right) \sum_s \sum_{nl} \int d\varepsilon \, \left(-\frac{\partial f}{\partial \varepsilon}\right) \frac{\nu_s a_{nls}\, \tau_{nls}}{(\Delta_{ns} + \Delta_{ls})}, \tag{1}$$

with

$$\tau_{nls} = \delta_{nl} + (1 - \delta_{nl}) \left(\frac{(\Delta_{ns} + \Delta_{ls})^2}{[(\Lambda_{ns} - \Lambda_{ls})^2 + (\Delta_{ns} + \Delta_{ls})^2]} \right), \tag{2}$$

which is valid within the Born approximation. In Eqs. (1) and (2) $\Lambda_{ns} = \text{Re}\ \Sigma_{ns}(\varepsilon)$, $\Delta_{ns} = |\text{Im}\ \Sigma_{ns}(\varepsilon)|$, Σ_{ns} is the coherent potential of an electron with spin s $(=\uparrow, \downarrow)$ on layer n, and a_{nls} and ν_s are specified by the electronic structure of the film [see Eqs. (19) and (20) in Ref. 12]. The expression given by Eqs. (1) and (2) has a clear physical meaning. An s-spin electron propagating from a site on layer n to a site on layer m is successively scattered with the strength proportional to Δ_{ns} and Δ_{ms}. The total conductivity is given as a sum of such processes with the weight of $a_{nms}\tau_{nms}$.

When magnetic moments on the magnetic M_1 and M_2 layers are in the antiferromagnetic (AF) configuration, the conductivity is given by

$$\sigma^{\rm AF} = 2c_{MM}\left[\frac{1}{(\Delta_{1\uparrow}+\Delta_{2\downarrow})} + \frac{1}{(\Delta_{1\downarrow}+\Delta_{2\uparrow})}\right], \quad (3)$$

if the interface scattering is assumed to be predominant, c_{MM} denoting the transmission coefficient between magnetic layers. We employed the $T = 0$ limit of Eqs. (1) and (2) because the relevant temperature is much less than the Fermi energy. On the contrary, when moments on the magnetic M_1 and M_2 layers are in the ferromagnetic (F) configuration, the conductivity is given by

$$\sigma^{\rm F} = 2c_{MM}\left[\frac{1}{(\Delta_{1\uparrow}+\Delta_{2\uparrow})} + \frac{1}{(\Delta_{1\downarrow}+\Delta_{2\downarrow})}\right]. \quad (4)$$

By using Eqs. (3) and (4), we get the MR ratio $\Delta R/R$, given by

$$\frac{\Delta R}{R} \equiv \frac{(R^{\rm AF} - R^{\rm F})}{R^{\rm F}} = \frac{h(a_1-1)(a_2-1)}{(1+h)(a_1+ha_2)}, \quad (5)$$

with

$$a_i = \Delta_{i\uparrow}/\Delta_{i\downarrow}, \quad h = \Delta_{2\downarrow}/\Delta_{1\downarrow}. \quad (6)$$

The temperature dependence of $\Delta R/R$ arises from those of a_1, a_2, and h in Eq. (5). The imaginary part of the coherent potential in the magnetic layers is given within the Born approximation by[2]

$$\Delta_{is} = \Delta_{is}^r + \Delta_{is}^s + \Delta_{is}^p \quad (s = \uparrow, \downarrow), \quad (7)$$

with

$$\Delta_{is}^r = \pi\rho_s x_i\, y_i\, (\tilde{\varepsilon}_{is} - \tilde{\varepsilon}_0)^2, \quad (8)$$

$$\Delta_{is}^s = \pi\rho_s\, x_i \left(\frac{U_i}{2}\right)^2 [\langle (M_i)^2\rangle - \langle M_i\rangle^2], \quad (9)$$

where $\tilde{\varepsilon}_{is} = \tilde{\varepsilon}_i - s(U_i/2)\langle M_i\rangle$, $\tilde{\varepsilon}_i$ and $\tilde{\varepsilon}_0$ are the spin-independent Hartree-Fock potentials of atoms A_i and B, respectively, ρ_s is the density of states at the Fermi level of an s-spin electron, and $\langle M_i\rangle$ and $\langle (M_i)^2\rangle$ are the average and amplitude of magnetic moments at the A_i atom, respectively. The first term (Δ_{is}^r) in Eq. (7) arises from the scatterings due to random Hartree-Fock potentials for an s-spin electron, the second term (Δ_{is}^s) from the effect of spin fluctuations, and the third term (Δ_{is}^p) from the electron-phonon scatterings.

For a simplicity of our model calculation, we neglect the phonon contribution given by Δ_{is}^p in Eq. (7) and assume that $\rho_\uparrow = \rho_\downarrow = \rho$ in Eqs. (8) and (9). We get a_1, a_2, and h given by

$$a_i = \frac{y_i(B_i+m_i)^2 + (\mu_i^2 - m_i^2)}{y_i(B_i-m_i)^2 + (\mu_i^2 - m_i^2)}, \quad (10)$$

$$h = d\,\frac{y_2(B_2-m_2)^2 + (\mu_2^2 - m_2^2)}{y_1(B_1-m_1)^2 + (\mu_1^2 - m_1^2)}, \quad (11)$$

with

$$m_i = \langle M_i\rangle/M_{i0}, \quad (12)$$

$$\mu_i = \sqrt{\langle (M_i)^2\rangle}/M_{i0}, \quad (13)$$

$$B_i = \left(\frac{2}{U_i M_{i0}}\right)(\tilde{\varepsilon}_0 - \tilde{\varepsilon}_i), \quad (14)$$

$$d = \left(\frac{x_2}{x_1}\right)\left(\frac{U_2 M_{20}}{U_1 M_{10}}\right)^2, \quad (15)$$

where M_{i0} is the ground-state moment at the A_i atom. At $T = 0$ K where $m_i = \mu_i = 1$, Eqs. (10) and (11) become

$$a_{i0} = a_i(T=0) = [(B_i+1)/(B_i-1)]^2, \quad (16)$$

$$h_0 = h(T=0) = d\,(y_2/y_1)[(B_2-1)/(B_1-1)]^2, \quad (17)$$

from which the coefficients B_i and d are given by

$$B_i = (\sqrt{a_{i0}}+1)/(\sqrt{a_{i0}}-1), \quad (18)$$

$$d = h_0\,(y_1/y_2)[(B_1-1)/(B_2-1)]^2. \quad (19)$$

Substituting Eqs. (18) and (19) to Eqs. (10) and (11), we can express a_i and h in terms of a_{i0}, h_0, and y_i as

$$a_i = \frac{\left[\left(\frac{\sqrt{a_{i0}}+1}{\sqrt{a_{i0}}-1}\right) + m_i\right]^2 + y_i^{-1}(\mu_i^2 - m_i^2)}{\left[\left(\frac{\sqrt{a_{i0}}+1}{\sqrt{a_{i0}}-1}\right) - m_i\right]^2 + y_i^{-1}(\mu_i^2 - m_i^2)}, \quad (20)$$

$$h = h_0\left(\frac{\sqrt{a_{20}}-1}{\sqrt{a_{10}}-1}\right)^2 \times \frac{\left[\left(\frac{\sqrt{a_{20}}+1}{\sqrt{a_{20}}-1}\right) - m_2\right]^2 + y_2^{-1}(\mu_2^2 - m_2^2)}{\left[\left(\frac{\sqrt{a_{10}}+1}{\sqrt{a_{10}}-1}\right) - m_1\right]^2 + y_1^{-1}(\mu_1^2 - m_1^2)}. \quad (21)$$

III. CALCULATED RESULTS

The temperature dependence of the MR ratio can be calculated for given band parameters such as $\tilde{\varepsilon}_0$, $\tilde{\varepsilon}_i$, and U_i with the use of Eqs. (5) and (10)–(15), if we adopt simple, analytic expressions for $m_i(T)$ and $\mu_i(T)$ given by[2,10]

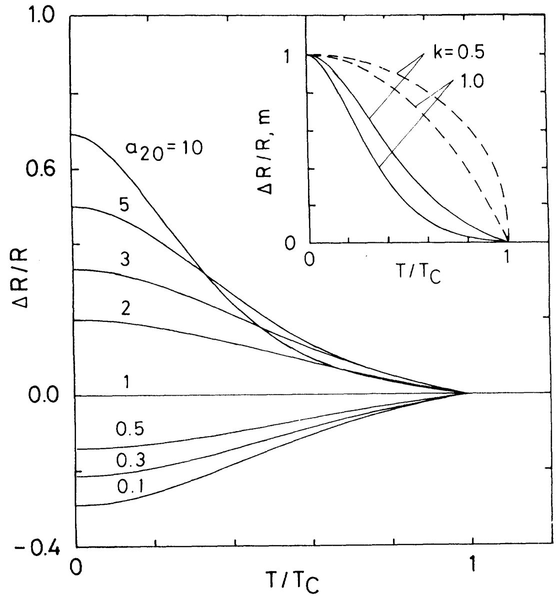

FIG. 1. The temperature dependence of the MR ratio $\Delta R/R$ [$= (R^{\mathrm{AF}} - R^{\mathrm{F}})/R^{\mathrm{F}}$] for various a_{20} with $a_{10} = 3$, $h_0 = 1$, and $y_1 = y_2 = 0.1$. The inset shows the magnetic moment m (dashed curves) and $\Delta R/R$ (solid curves) with $k = 0.5$ and 1.0 in Eq. (22) as a function of T for $a_{10} = 3$, $a_{20} = 5$, $h_0 = 1$, and $y_1 = y_2 = 0.1$; they are normalized by their values at $T = 0$ K.

$$m_i(T) = [1 - (T/T_C)^2]^k, \quad \mu_i(T) = 1, \tag{22}$$

where k is a parameter. Alternatively, we can discuss $\Delta R/R$ treating h_0, a_{i0}, and y_i ($i = 1, 2$) as input parameters, by using Eqs. (5), (20)–(22).[13]

Equation (22) with $k = 0.5$, $m_i(T) = \sqrt{1 - (T/T_C)^2}$, is not so different from the Brillouin function for spin 1/2, which simulates the overall temperature dependence of magnetization in ferromagnets such *bulk* Fe, Ni, and Co. It is, however, well known that magnetic moments on the free surface decrease more rapidly than in the bulk, particularly at low temperatures. This is also expected for moments in the interface of layered structures, as the recent band calculation has shown for Fe/Cr multilayers.[14] The dashed curves in the inset of Fig. 1 show $m(T)$ with $k = 0.5$ and 1.0. We note that $m(T)$ with $k = 1.0$ decreases more rapidly than that with $k = 0.5$ and it may simulate the interface magnetization. In the model calculation to be presented in the following, we show the result with the use of $k = 0.5$ otherwise noticed.

A. Normal MR

When $a_1 > 1$ and $a_2 > 1$ (or $a_1 < 1$ and $a_2 < 1$) in Eq. (5), we get a normal, positive MR ratio. In particular, when $a_1 = a_2 = a$ and $h = 1$, Eq. (5) becomes

$$\frac{\Delta R}{R} = \frac{(a-1)^2}{4a}, \tag{23}$$

which is the result obtained previously.[2,12,15,16]

Calculated $\Delta R/R$ for normal MR are shown in Fig. 1, where the MR ratio is positive for $a_{20} > 1$ with $a_{10} = 3$, $h_0 = 1$, and $y_1 = y_2 = 0.1$. When a_{20} is increased, the MR ratio increases and its temperature dependence becomes more significant. When the value of y_1 and/or y_2 is reduced more, the temperature dependence of $\Delta R/R$ becomes more considerable (e.g., Fig. 3 of Ref. 2). The solid curves in the inset show $\Delta R/R$ with $k = 0.5$ and 1.0. The MR ratio with $k = 1.0$ decreases faster than that with $k = 0.5$ as expected, although both results show similar behavior in the *qualitative* sense.

B. Inverse MR

When $a_1 > 1$ and $a_2 < 1$ (or vice versa) in Eq. (5), we get a negative $\Delta R/R$, which has been recently pointed out[17] and which is referred to as inverse MR hereafter.

The calculated $\Delta R/R$ for inverse MR is shown in Fig. 1, where it is negative for $a_{20} < 1$ ($a_{10} = 3, h_0 = 1$). When the temperature is raised, $\Delta R/R$ increases although its absolute value decreases.

The temperature dependence of MR is studied in more detail in Fig. 2 for a typical case of $a_{10} = 3$, $a_{20} = 0.1$, $h_0 = 1$, and $y_1 = y_2 = 0.1$. Solid curves express a_1, a_2, and h as a function of the temperature while dashed curves denote Δ_{is}, the imaginary part of the coherent potentials of an s-spin electron at the M_i interface. At $T = 0$ K, $a_1 = 3$, $a_2 = 0.1$, and $h = 1$, which yields $\Delta R/R = -0.29$. The negative MR ratio implies that the resistivity in the AF configuration (R^{AF}) is smaller than that in the F configuration (R^{F}), in contrast with normal MR.[17] When the temperature is raised, a_1 (and h) decreases whereas a_2 increases. This difference arises from the difference in the temperature dependences of Δ_{1s} and Δ_{2s} as clearly seen in Fig. 2. The increase in Δ_{is} is mainly due to the contribution from the spin-fluctuation term.

C. Coexistence of normal and inverse MR

We have shown in the previous two subsections that when the temperature is raised, $\Delta R/R$ increases in in-

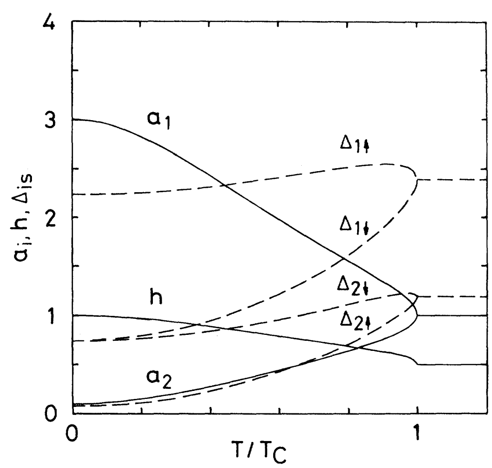

FIG. 2. The temperature dependence of a_1, a_2, h (solid curves), and Δ_{is}, the imaginary parts of s-spin coherent potentials on interfaces of the magnetic M_i layer (dashed curves, in arbitrary units) for $a_{10} = 3$, $a_{20} = 0.1$, $h_0 = 1$, and $y_1 = y_2 = 0.1$.

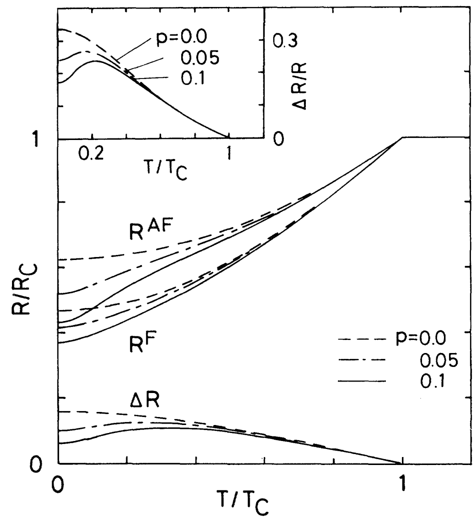

FIG. 3. The temperature dependence of resistivities in the antiferromagnetic (R^{AF}) and ferromagnetic phases (R^{F}), and their difference ΔR ($= R^{\mathrm{AF}} - R^{\mathrm{F}}$) of a multilayer in which normal and inverse MR coexist with $p = 0.0$ (dashed curves), 0.05 (dot-dashed curves), and 0.1 (solid curves) for $a_{10} = 3$, $a_{20} = 0.3$, $h_0 = 1$, $y_1 = 0.1$, $y_2 = 0.001$, and $p = 0.1$; R^{AF}, R^{F}, and ΔR are normalized by R_C, the resistivity at T_C. The inset shows the MR ratio when changing p with $a_{10} = 3$, $a_{20} = 0.3$, $h_0 = 1$, $y_1 = 0.1$, and $y_2 = 0.001$ (see text).

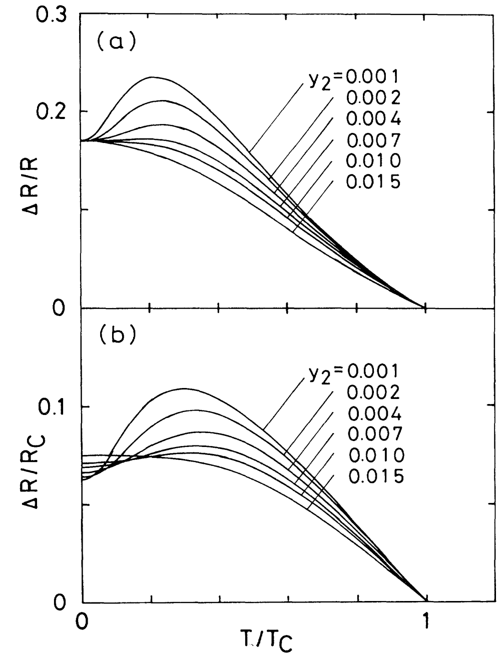

FIG. 4. The temperature dependence of (a) the MR ratio $\Delta R/R$ and (b) $\Delta R/R_C$ of a multilayer in which normal and inverse MR coexist, for various y_2 values with $a_{10} = 3$, $a_{20} = 0.3$, $h_0 = 1$, $y_1 = 0.1$, and $p = 0.1$.

verse MR whereas it decreases in normal MR. We may expect that the temperature dependence of $\Delta R/R$ shows a variety of behavior if a given multilayer includes both normal and inverse MR. In order to investigate this possibility, we assume that there are three regions in a given multilayer: $a_1 > 1$ and $a_2 > 1$ in region I, $a_1 < 1$ and $a_2 < 1$ in region II, and $a_1 > 1$ and $a_2 < 1$ and vice versa in region III. These three regions are assumed to coexist with the probabilities of $(1-p)^2$, p^2, and $2p(1-p)$, respectively, where the parameter p stands for the degree of the coexistence of the region with inverse MR (p =0 or 1 corresponds to normal MR only). When the three regions are assumed to yield additive contributions to the total conductivity, we obtain $\Delta R/R$ for various p values with $a_{10} = 3$, $a_{20} = 0.3$, $h_0 = 1$, $y_1 = 0.1$, and $y_2 = 0.001$, which is shown in the inset of Fig. 3. When $p = 0$, $\Delta R/R$ behaves as normal MR. If the presence of the region of inverse MR is allowed to some extent, $\Delta R/R$ *increases* at low temperatures and then decreases at higher temperatures. Figure 3 shows the temperature dependence of the resistivities in the antiferromagnetic (R^{AF}) and ferromagnetic states (R^{F}), and their difference ΔR ($= R^{\mathrm{AF}} - R^{\mathrm{F}}$) normalized by R_C, the resistivity at T_C. The maximum in $\Delta R/R$ arises from that in ΔR, which is due to the competition between normal and inverse MR. Figures 4(a) and 4(b) shows $\Delta R/R$ and $\Delta R/R_C$ for various y_2 values with $a_{10} = 3$. $a_{20} = 0.3$, $h_0 = 1$, $y_1 = 0.1$, and $p = 0.1$. We note that $\Delta R/R$ for $y_2 = 0.007$ (or $\Delta R/R_C$ for $y_2 = 0.015$) is almost constant below $T/T_C \sim 0.3$, where a decrease in normal MR as the temperature is raised is nearly compensated by an increase in inverse MR. This *compensated* MR with a small temperature coefficient would be beneficial for its practical application. A maximum in $\Delta R/R$ was recently observed in CuNi/Co (Ref. 18) and NiCo/Cu multilayers,[19] although it is not clear at the moment whether the observed phenomena is due to the mechanism discussed above.

IV. DISCUSSION

In order to make a multilayer showing inverse MR, we have to adopt proper elements which satisfy the conditions $a_1 > 1$ and $a_2 < 1$ (or vice versa) which implies $(\tilde{\varepsilon}_{1\uparrow} - \tilde{\varepsilon}_0)^2 \rho_\uparrow > (\tilde{\varepsilon}_{1\downarrow} - \tilde{\varepsilon}_0)^2 \rho_\downarrow$ and $(\tilde{\varepsilon}_{2\uparrow} - \tilde{\varepsilon}_0)^2 \rho_\uparrow < (\tilde{\varepsilon}_{2\downarrow} - \tilde{\varepsilon}_0)^2 \rho_\downarrow$. One of candidates would be a combination of M_1 = Ni, M_2 = Fe, and N =Pt (or Pd) for which $\mid \tilde{\varepsilon}_{\mathrm{Ni}\downarrow} - \tilde{\varepsilon}_0 \mid \simeq \mid \tilde{\varepsilon}_{\mathrm{Fe}\uparrow} - \tilde{\varepsilon}_0 \mid \simeq 0$ because numbers of d electrons with spin s per atom, N_{ds}, are $N_{d\downarrow}(\mathrm{Ni}) \simeq N_d(\mathrm{Pt}) \simeq N_{d\uparrow}(\mathrm{Fe}) \simeq 4.5$. Goerge *et al.*[17] have adopted a sophisticated Fe/Cr/Fe multilayer as M_1 with M_2 = Fe and N=Cu. They have claimed that the global spin asymmetry a_1 may be greater than unity because a huge a_{FeCr} at inner Fe/Cr interfaces overcomes that at outer Fe/Cu interfaces ($a_{\mathrm{FeCu}} = a_2 < 1$) of M_1. It would be not easy to find simple transition-metal elements satisfying the condition mentioned above. Despite such a difficulty, it is beneficial for practical applications to fabricate a multilayer with compensated MR whose $\Delta R/R$ or ΔR has a small temperature coefficient in a fairly wide temperature range.

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