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Positive giant magnetoresistance in ferrimagnetic/Cu/ferrimagnetic films

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Spin valves composed of ferrimagnetic/Cu/ferrimagnetic layers were fabricated with the magnetization perpendicular to the film planes. By changing the composition of ferrimagnetic layers, both negative and positive giant magnetoresistance (GMR) can be observed in ferrimagnetic spin valves. For samples consisting of both transition-metal (TM-) rich TbFeCo and GdFeCo, negative GMR values were obtained. Due to the high resistivity of amorphous ferrimagnetic films, the shunting effect of Cu led to relatively small MR ratio. The negative MR effect was 1% for 1.7 nm Cu. For spin valves consisting of rare-earth (RE-)rich TbFeCo and TM-rich GdFeCo, positive GMR values were observed. A thin layer of Co was inserted between RE-rich TbFeCo and Cu to manipulate the sign of GMR. [DOI: 10.1063/1.1357112]

Typical spin valves consist of ferromagnetic/spacer/ferromagnetic/antiferromagnetic layers with the magnetization lying in the film plane. Differential spin scattering has been adapted for explaining the giant magnetoresistance (GMR) effect in spin valves.[1] Multilayers consist of rare earth metals and transition metals show no GMR,[2] while $(\mathrm{Co/Dy/Co/Cu/Co/Cu})_n$ multilayers show a positive GMR effect[3] (that is, smaller resistance in zero field than in the saturation field) at 4.2 K. The positive GMR effect was attributed to the antiparallel alignment of adjacent Co moments in a high field due to the antiferromagnetic coupling between Dy and Co. Trilayers made of $\mathrm{Co_{65}Fe_{35}/Ag/(Co_{65}Fe_{35})_{50}Gd_{50}}$ also showed a large resistance in a high field.[4] Authors have concluded that the conduction electrons were only scattered by Co or Fe moments. In this work, we fabricated a structure of spin valves composed of ferrimagnetic/spacer/ferrimagnetic layers with the magnetization perpendicular to the film planes. To understand the GMR effect of this perpendicular spin valve, the effects on GMR ratio of spacer thickness and of ferrimagnetic composition were investigated. In these ferrimagnetic spin valves, by changing the composition of ferrimagnets or by inserting a Co layer at the interface, the sign of GMR can be manipulated. The mechanism of positive GMR in these ferrimagnetic spin valves will be discussed.

Spin valves with the structure SiN/200 Å TbFeCo/t Å Cu/100 Å GdFeCo/SiN were prepared by dc magnetron sputtering onto Si wafers at room temperature. The spin valve was sandwiched by SiN protective layers to prevent TbFeCo and GdFeCo oxidation. Ferrimagnetic layers were cosputted using a transition metal ($\mathrm{TM{:}Fe_{80}Co_{20}}$) and a rare-earth target (RE: Tb or Gd). The composition of ferrimagnetic films was controlled by the relative sputtering power of TM and RE, and was calibrated by Rutherford backscattering spectrometry. After depositions, the samples were magnetized in the field of 14 kOe to saturate TbFeCo and GdFeCo. The hysteresis loops were measured using a vibrating sample magnetometer or perpendicular magneto-optical Kerr effect. Magnetoresistance was measured using a four-point probe with the applied field perpendicular to the film plane, which makes current direction perpendicular to the magnetization. Four points were aligned in a straight line. The MR ratio is defined as $(R_0 - R_{\mathrm{sat}})/R_0$, where R_0 and R_{sat} are the resistance at the zero field and the saturation field, respectively. Therefore, the positive MR means that the resistance at the zero field is higher than that at the saturation field. The hysteresis loop and MR curve of 200 Å $\mathrm{Tb_{20.5}(Fe_{80}Co_{20})_{79.5}}$ (TM rich)/17 Å Cu/100 Å $\mathrm{Gd_{22.4}(Fe_{80}Co_{20})_{77.6}}$ (TM rich) are shown in Fig. 1. [The notation ''TM rich'' represents that the magnitude of the TM moments is larger than that of RE moments. The compensation compositions of these ferromagnets are $\mathrm{Tb_{22.7}(Fe_{80}Co_{20})_{77.3}}$ and $\mathrm{Gd_{23}(Fe_{80}Co_{20})_{77}}$.] The hysteresis loops [Fig. 1(a)] clearly demonstrate the characteristic of perpendicular magnetization with the coercivity of $\mathrm{Gd_{22.4}(Fe_{80}Co_{20})_{77.6}}$ and $\mathrm{Tb_{20.5}(Fe_{80}Co_{20})_{79.5}}$ of 110 Oe and 11.5 kOe, respectively. The minor loop and the corresponding $R-H$ curve are shown in Figs. 1(b) and 1(c). The interlayer coupling is 270 Oe, and the MR ratio is -1%. From Figs. 1(b) and 1(c), the parallel state corresponds to a low-resistance state, representing a negative MR effect. Figure 2 shows the dependence of absolute MR ratio and interlayer coupling on Cu thickness (all MR ratios in Fig. 2 are negative). As the Cu thickness increased, MR ratio and interlayer coupling both decreased. Notice that the interlayer coupling is significantly higher than the ferromagnetic spin valves. The coercivity of GdFeCo and TbFeCo oscillates with Cu thickness, as depicted in Fig. 3.

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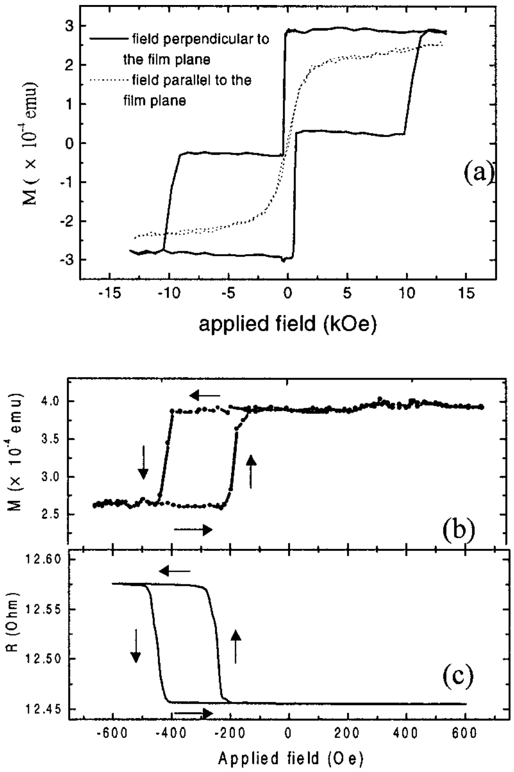

FIG. 1. (a) Hysteresis loop, (b) minor loop of (a), and (c) $R-H$ curve of SiN/200 Å $Tb_{20.5}(Fe_{80}Co_{20})_{79.5}$ (TM rich)/ 17 Å Cu/100 Å $Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$ (TM rich)/SiN. The arrows represent the sequence of the applied field.

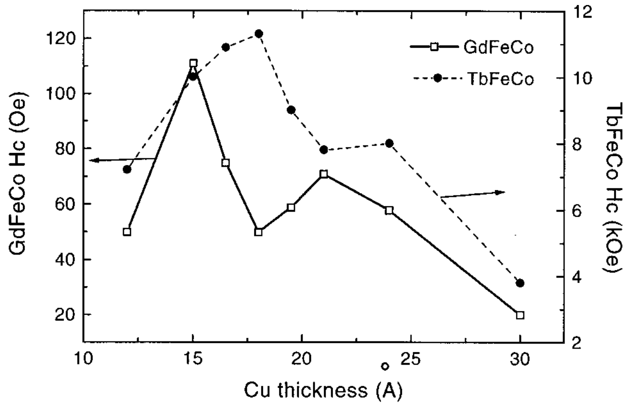

FIG. 3. Variation of coercivity of $Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$ and $Tb_{20.5}(Fe_{80}Co_{20})_{79.5}$ with Cu thickness for SiN/200 Å $Tb_{20.5}(Fe_{80}Co_{20})_{79.5}$ (TM rich)/t Å Cu/100 Å $Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$ (TM rich)/SiN.

For samples consisting of both TM-rich TbFeCo and GdFeCo, negative GMR values were obtained, as shown in Fig. 1. In fact, spin valves consisting of both RE-rich TbFeCo and GdFeCo also showed negative GMR. On the other hand, for samples consisting of RE-rich TbFeCo [$Tb_{27.6}(Fe_{80}Co_{20})_{72.4}$] and TM-rich GdFeCo [$Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$] (or TM-rich TbFeCo and RE-rich GdFeCo), positive GMR values were observed, that is, the resistance is high at the zero field. A thin layer of Co was inserted between RE-rich TbFeCo and Cu to manipulate the sign of GMR. The positive GMR ratio increased with increasing Co thickness, shown in Fig. 4, for thickness less than 1 nm. When the thickness of Co reached 1.5 nm, the negative GMR appeared.

In the spin valves composed of ferrimagnetic layers, the coercivity of ferrimagnetic layers can be manipulated by the composition. The hysteresis loop, shown in Fig. 1(a), showed a distinguished difference in coercivity between ferrimagnets, so the antiparallel state of the net magnetization between ferrimagnetic layers can be achieved. High resistance was observed in the $R-H$ curve corresponding to the antiparallel state [shown in Fig. 1(c)], which suggested that the origin of the observed magnetoresistance be the GMR effect. Since the measuring current is in the film plane, perpendicular to the magnetization, anisotropic magnetoresistance can be excluded. The four-point probes with a linear configuration for current and voltage probes exclude the probability of Hall effect contribution on resistance change. The resistivity of amorphous ferrimagnets ($\rho \sim 200\,\mu\Omega\,\mathrm{cm}^2$) is about 50 times larger than that of Cu, which leads to significant current shunting effect and to a small MR ratio. Figure 2 shows that the MR ratio decreases with increasing Cu thickness, consistent with the shunting effect of Cu. It should be noticed that the interlayer coupling

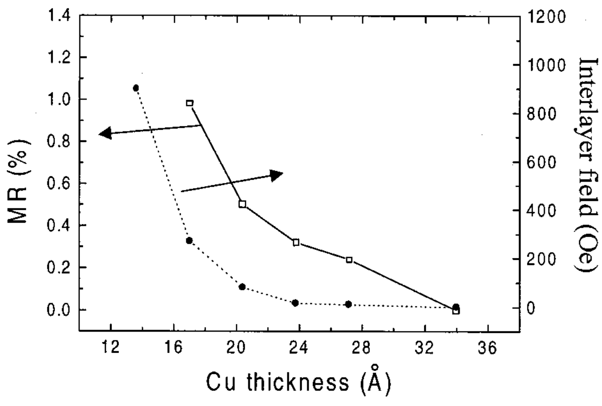

FIG. 2. Dependence of the absolute MR ratio and the interlayer coupling on the Cu thickness for SiN/200 Å $Tb_{20.5}(Fe_{80}Co_{20})_{79.5}$ (TM rich)/t Å Cu/100 Å $Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$ (TM rich)/SiN. (All MR values are negative).

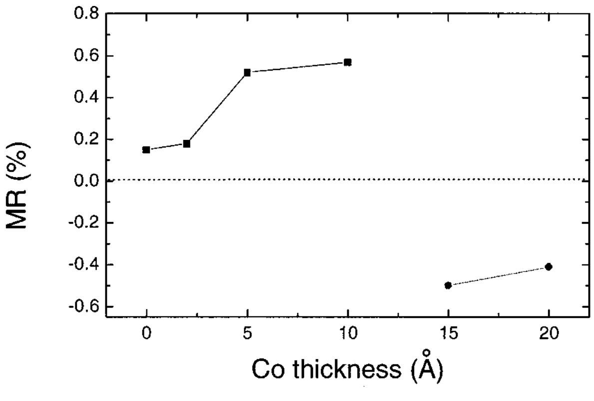

FIG. 4. Dependence of MR ratio on the Co thickness for 200 Å $Tb_{27.6}(Fe_{80}Co_{20})_{72.4}$ (RE rich)/t Å Co/20 Å Cu/100 Å $Gd_{22.4}(Fe_{80}Co_{20})_{77.6}$ (TM rich).

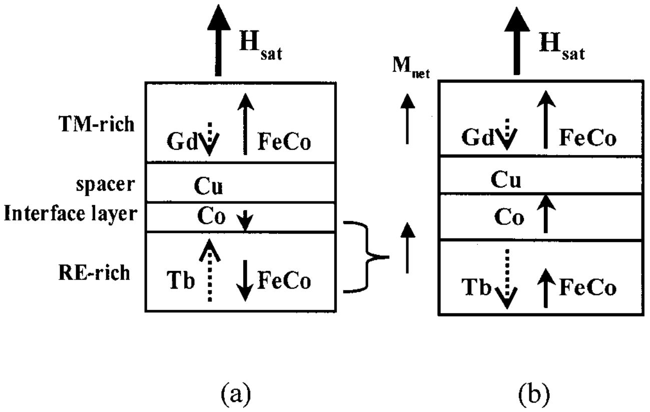

FIG. 5. Schematic diagrams for the direction of moments in TbFeCo (RE rich)/t Å Co/Cu/GdFeCo (TM rich). (a) $t \leq 1$ nm and (b) $t > 1$ nm.

significantly increases as Cu thickness decreases. In ferromagnetic spin valves, maximum GMR occurs at the optimum Cu thickness.[5] For spin valves with thin Cu, the antiparallel state is difficult to obtain due to the strong interlayer coupling; for spin valves with thick Cu, current shunting effect occurs so MR decreases. In ferrimagnetic spin valves, large interlayer coupling limited the minimum Cu thickness.

The oscillation of coercivity with Cu thickness was observed, as shown in Fig. 3. To explain the above-mentioned experimental findings, we propose an indirect exchange coupling model, which was well known in a layered system containing two ferromagnetic layers and a nonmagnetic spacer,[6,7] to relate the oscillatory coercivity to the oscillatory interlayer coupling. As in a FM/spacer/FM system, the coupling between the ferrimagnetic layers will oscillate as a function of the spacer thickness, due to the quantum well effect for conduction electrons in the spacer.[7] For Cu thickness with ferromagnetic coupling, the coercivity of GdFeCo is enhanced for the ferromagnetic coupling from the TbFeCo layer, while the coercivity of TbFeCo decreases since the reversal of magnetic moment within GdFeCo induces the instability of the magnetic moment of TbFeCo. For the antiferromagnetic coupling region, starting from the saturation state, the low coercivity GdFeCo will become unstable easily, but after it reverses the TbFeCo will remain more stable than usual. In other words, the oscillatory coercivities for TbFeCo and GdFeCo should be out of phase and that is shown in Fig. 3. In addition, since the magnetization in our system is perpendicular to the film, the surface magnetic poles are large, which may enhance the long-range dipolar interaction. This strong long-range interaction may enhance the interlayer coupling and results in a strong dependence of interlayer field on Cu thickness, as shown in Fig. 2.

For the samples consisting of TM-rich GdFeCo and RE-rich TbFeCo, when the net magnetizations are parallel in ferrimagnets, the sublattice magnetizations of transition metals are antiparallel. Since $4f$ electrons have little contribution to the differential spin scattering,[2,4] the GMR effect in ferrimagnetic spin valves is mainly contributed from the $3d$ sublattice. When the magnetization of GdFeCo is switched, that is, the net magnetizations of GdFeCo and TbFeCo become antiparallel, the magnetizations of transition metals become parallel. Consequently, the antiparallel state of net magnetizations results in a small resistance, and a positive GMR effect. For the samples inserted with a Co layer between Cu and RE-rich TbFeCo, the magnetization of Co is opposite to the magnetization of the Tb sublattice due to the exchange coupling.[8] For Co thickness less than 1 nm, the composite layer $Tb_{27.6}(Fe_{80}Co_{20})_{72.4}$/Co is still RE rich, so the net moment of the composite layer is opposite to the Co moment [Fig. 5(a)], but is aligned with the applied field. Consequently, for thin Co samples, the moments of two transition metals are opposite at saturation fields, resulting in a positive MR. Due to strong interfacial spin-dependent scattering at Co/Cu, the positive MR increases with Co thickness. For the sample with 1.5 nm (or 2 nm) Co, the composite layer becomes TM rich [Fig. 5 (b)], leading to a parallel alignment of magnetizations of transition metals and to a negative MR.

In conclusion, ferrimagnetic spin valves were fabricated with the magnetization perpendicular to the film planes. For samples consisting of both TM-rich (or both RE-rich) TbFeCo and GdFeCo, negative GMR values were obtained. The coercivity oscillation of ferrimagnets with Cu thickness was observed, and can be presumably explained by the indirect exchange coupling. For the samples consisting of RE-rich TbFeCo and TM-rich GdFeCo, a positive GMR effect was observed. Since the spin-dependent scattering potential for the rare earth was quite weak, the observed GMR effect was mainly contributed by the transition metals. When the applied field switched the magnetization of GdFeCo, the moments of transition metals were parallel aligned, leading to a small resistance and thus positive GMR. A thin layer of Co was inserted between RE-rich TbFeCo and Cu to manipulate the sign of GMR.

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