Biquadratic Coupling Effect on Magnetoresistance Response Curves of Spin Valves with a Synthetic Antiferromagnet

G. Mankey – University of Alabama

et al.

Journal of Applied Physics

Biquadratic coupling effect on magnetoresistance response curves of spin valves with a synthetic antiferromagnet

Cite as: Journal of Applied Physics **89**, 6814 (2001); https://doi.org/10.1063/1.1360679
Published Online: 07 June 2001

K. Zhang, T. Kai, T. Zhao, H. Fujiwara, and G. J. Mankey

Biquadratic coupling effect on magnetoresistance response curves of spin valves with a synthetic antiferromagnet

K. Zhang,[a)] T. Kai, T. Zhao, H. Fujiwara, and G. J. Mankey
Department of Physics and Astronomy and Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama 35487

Both normal and inverse magnetoresistance (MR) response curves were observed for synthetic spin valves with the structure of Si(100)/Ru/Co(t_1)/Ru(0.7 nm)/Co(t_2)/Cu(3 nm)/Co(t_3)/Ru. Under the assumption of a coherent rotation of the magnetization in the three Co layers, the hysteresis loops, magnetization response, and MR response curves were calculated as a function of the parameters of the system. The parameters include antiferromagnetic coupling of Co(t_1) and Co(t_2) through Ru layer, a weak ferromagnetic coupling of Co(t_2) and Co(t_3) through Cu spacer, giant magnetoresistance of the Co/Cu/Co and Co/Ru/Co systems, and AMR contribution of each Co layer. The uniaxial anisotropy of each Co layer and a distribution of the coupling strength of Co(t_1)/Ru/Co(t_2) were also included. To fit the experimental data well, it was necessary to include a biquadratic coupling in the Co(t_1)/Ru/Co(t_2) trilayer.
[DOI: 10.1063/1.1360679]

Spin valves (SVs) with a synthetic antiferromagnetic (SyAF) layer[1] are of strong interest for the read heads in extra high-density magnetic recording. Compared with conventional spin valves, spin valves with a SyAF offer a stronger pinning of the pinned layer. The latter spin valves are typically of the structure of substrate/AF/$F1$/Ru/$F2$/Cu/$F3$/capping layer or substrate/buffer/$F3$/Cu/$F2$/Ru/$F1$/AF/ capping layer, where $F1$ and $F2$ are two ferromagnetic layers (typically CoFe alloys) antiferromagnetically coupled through a thin Ru layer, forming a SyAF structure, and $F3$ is a soft ferromagnetic layer. Normally $F1$ is exchange biased by an adjacent AF layer. To study the behavior of the SyAF layer, the structure of our samples did not include the AF layer.

Much work has been performed on SyAF layers. However, their detailed behavior is yet to be fully investigated. In this article, the magnetic behavior of the Co/Ru/Co SyAF layers in a SV structure is monitored by observing both hysteresis (M–H) loops and magnetoresistance (MR) response curves. Further, the analysis of the results reveals that biquadratic coupling[2–4] between the Co layers of the synthetic AF structure should be taken into account to explain the observed M–H loops and the MR response curves.

SV films were prepared at room temperature on 2 in. (100) Si wafers by magnetron sputtering. The depositions were done in an UHV sputtering system with a base pressure of 5.0×10^{-9} Torr. The argon pressure during the deposition was kept at 2.5 mTorr. All the samples have the generic configuration of Si(100)/Ru(2.1)/Co(t_1)/Ru(0.7)/Co(t_2)/Cu/Co(t_3)/Ru(3.0) (in nm).

The giant magnetoresistance (GMR) measurements were then carried out using the standard dc four-point probe technique with both current and field applied parallel to the pinning direction. The magnetization measurements were performed using the vibrating sample magnetometer.

[a)]Author to whom correspondence should be addressed; electronic mail: zhang004@bama.ua.edu

Typical M–H loops and MR response curves for the samples of Si(100)/Ru(2.1)/Co(3.2)/Ru(0.7)/Co(3.8)/Cu(3)/Co(7.5)/Ru(3.0) (in nm) (sample I) and of Si(100)/Ru(2.1)/Co(3.8)/Ru(0.7)/Co(3.2)/Cu(3)/Co(7.5)/Ru(3.0) (sample II) were measured at room temperature and the results are shown in Figs. 1(a), 1(b), 1(c), and 1(d), respectively. Note that for sample I, $t_1<t_2$, while for sample II, $t_1>t_2$. As shown in Figs. 1(a) and 1(c), a field in excess of 5.0 kOe is necessary to saturate the M–H loops due to the strong antiferromagnetic coupling between the Co layers of the Co/Ru/Co SyAF structure. The MR response curves, for the same samples respectively, are shown in Figs. 1(b) and 1(d), within a ±2 kOe range. Because of the similarity of the samples, the M–H loops do not show much difference between the two. However, the MR response curves are quite different. The origin of the difference is the ratio of t_1/t_2. When $t_1/t_2<1$, $F1$(Co(t_1)) switches first with decreasing applied field from saturation due to the strong AF coupling between $F1$ and $F2$, resulting in a normal MR response as in Fig. 1(b), while for $t_1/t_2>1$, $F2$(Co(t_2)) switches first, causing an inverse MR response as shown in Fig. 1(d).

In order to explain our experimental results semiquantitatively, we calculate the magnetic response of the spin valves with a SyAF under the assumption that the reversal of the magnetization in the three Co layers occurs via a coherent rotation mechanism. The easy axes of the Co layers are assumed to be parallel to each other. A schematic drawing of the angular relationship among the magnetization directions of $\mathbf{M}_1$, $\mathbf{M}_2$, $\mathbf{M}_3$, corresponding to those of Co(t_1), Co(t_2), and Co(t_3), applied field H, current I, and the easy axis direction is shown in Fig. 2.

Thus, the total energy of the spin valve with a SyAF can be written as

$$\begin{aligned}E=&-M_1t_1H\cos\theta_1-M_2t_2H\cos\theta_2+j_1\cos(\theta_1-\theta_2)\\&+j_2\cos^2(\theta_1-\theta_2)+K_{u1}t_1\sin^2\theta_1+K_{u2}t_2\sin^2\theta_2\\&-M_3t_3H\cos\theta_3+j_3\cos(\theta_2-\theta_3)+K_{u3}t_3\sin^2\theta_3.\end{aligned}\tag{1}$$

In the above formula, M_1, M_2, and M_3 are the magne-

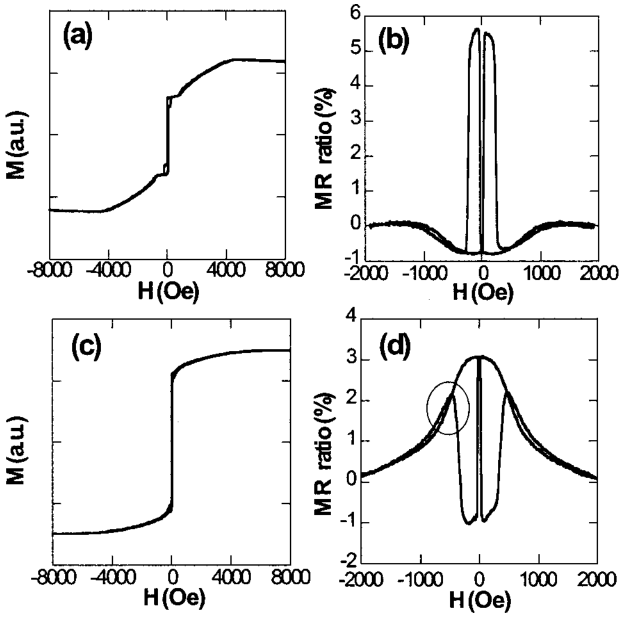

FIG. 1. (a) $M-H$ loop of the spin-valve sample I with the composition of Si/Ru2.1/Co3.2/Ru0.7/Co3.8/Cu3.0/Co7.5/Ru3.0 (in nm); (b) MR curve of sample I; (c) $M-H$ loop of the spin valve sample II with the composition of Si/Ru2.1/Co3.8/Ru0.7/Co3.2/Cu3.0/Co7.5/Ru3.0 (in nm); (d) MR curve of sample II.

tizations of the Co(t_1), Co(t_2), and Co(t_3), respectively. H is the applied field parallel to the easy direction. The angles of θ_1, θ_2, and θ_3 are the angles of those moments with respect to the applied field. j_1 and j_2 are, respectively, the bilinear and biquadratic exchange coupling constants between Co(t_1) and Co(t_2) through the Ru spacer. The bilinear coupling strength j_1 depends on the Ru thickness. For a Ru thickness around 0.7 nm, it can be on the order of 1 erg/cm^2.[5] The biquadratic coupling constant j_2 can also have the same range of value.[6] j_3 is the bilinear exchange coupling constant between the Co(t_2) and Co(t_3), which is typically of the order of 10^{-3}–10^{-2} erg/cm^2. The biquadratic coupling between Co(t_2) and Co(t_3) is neglected because of the relatively thick Cu layer existing between them. K_{u1}, K_{u2}, and K_{u3} are the field induced uniaxial anisotropies of the Co(t_1), Co(t_2), and Co(t_3) layers.

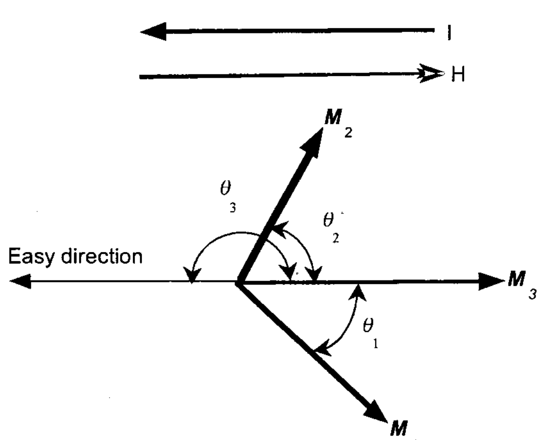

FIG. 2. Schematic drawing of angular relationship between the directions of the magnetization M_1, M_2, M_3, and the easy direction. The field direction and the current direction are set to be parallel to the easy direction.

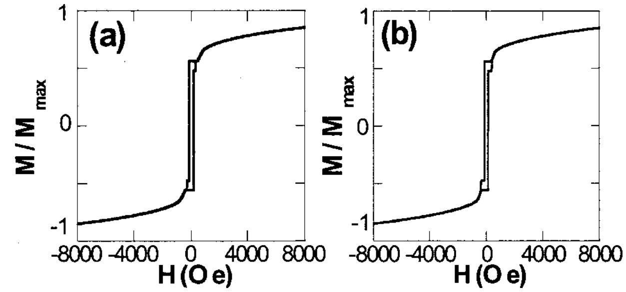

FIG. 3. Calculated magnetization curves of the spin-valve samples: (a) sample I with $t_1=3.2$ nm and $t_2=3.8$ nm; (b) sample II with $t_1=3.8$ nm and $t_2=3.2$ nm.

As for the total magnetoresistance of the whole system, it should be a superposition of the GMR of the Co(t_2)/Cu/Co(t_3) and Co(t_1)/Ru/Co(t_2) systems and the AMR contributions of each Co layer. It is then given by

$$\begin{aligned} R = R_{\mathrm{sat}} &+ (\Delta R)_{F2,F3}[1-\cos(\theta_2-\theta_3)]/2 \\ &+ (\Delta R)_{F1,F2}[1-\cos(\theta_1-\theta_2)]/2 - \mathrm{AMR}_{F1}\sin^2\theta_1 \\ &- \mathrm{AMR}_{F2}\sin^2\theta_2 - \mathrm{AMR}_{F3}\sin^2\theta_3, \end{aligned} \tag{2}$$

where R_{sat} is the total AMR ratio at saturation field, and the $(\Delta R)_{F1,F2}$ and $(\Delta R)_{F2,F3}$ are the GMR ratios of the Co(t_1)/Ru/Co(t_2), and the Co(t_1)/Cu/Co(t_2) trilayers.

Based on the above model, the $M-H$ loops of the SV with a SyAF were calculated and plotted against H in Fig. 3. The following parameters were used: $M_1=M_2=M_3=1400$ emu/cm^3, $j_1=3.0$ erg/cm^2, $j_2=1.4$ erg/cm^2, $j_3=-0.02$ erg/cm^2, and $K_u=1\times10^6$ erg/cm^3. The exchange coupling constants were chosen to match the experimental results semiquantitatively. As for the MR contributions, the AMR of each Co layer is assumed to be 2%, GMR of Co/Ru/Co 5%, and GMR of Co/Cu/Co 20%.

Based on the same parameters, the magnetic angles of the three Co layers and the MR response curves of samples I and II were also calculated and are shown in Fig. 4. For sample I, Fig. 4(a) shows the angles of $\mathbf{M}_1$, $\mathbf{M}_2$, and $\mathbf{M}_3$ as a function of the descending field after saturation, and (b) shows the MR response curve corresponding to (a). At a positive field larger than the saturation field H^+_{sat}, the magnetization angle of the three Co layers are parallel to each other, which results in the lowest MR ratio (not shown in the figure). As the field decreases, $\mathbf{M}_1$ and $\mathbf{M}_2$ start to rotate in the opposite direction from their initial directions to an intermediate tilted direction making some angle with each other. In this case, the AMR ratios of the Co(t_1) and Co(t_2) start to decrease, while the GMR ratio of the Co(t_2)/Cu/Co(t_3) structure increases, resulting in a gradual increase in the MR ratio. However, when the field is further decreased until a positive critical field H^+_0, for sample I, $\mathbf{M}_1$ tends to align antiparallel to $\mathbf{M}_2$, keeping the total moment almost parallel to the positive applied field. This forces $\mathbf{M}_2$ back to 0°, resulting in a decrease of MR. When the applied field becomes negative, first $\mathbf{M}_3$ switches with a jump up of MR and at a critical value H^-_0 a sudden flip of $\mathbf{M}_2$ occurs, causing a jump back of MR accompanied by the flip back of $\mathbf{M}_1$. From then on, $\mathbf{M}_1$ and $\mathbf{M}_2$ behave just as in the opposite case of a

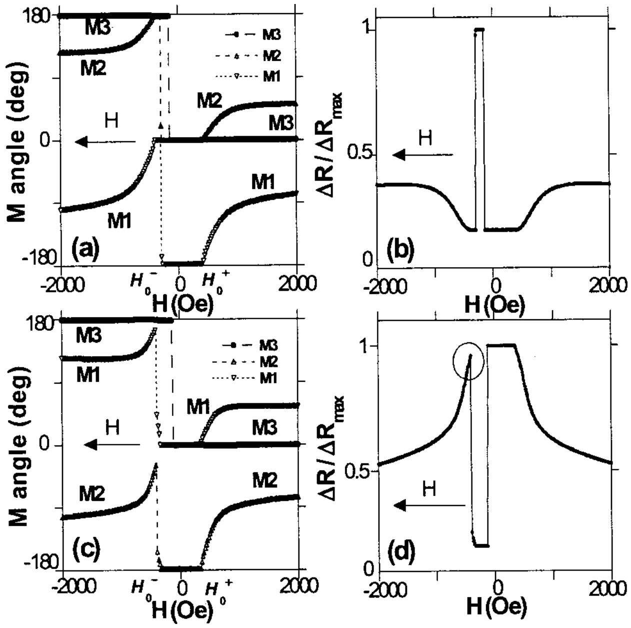

FIG. 4. Calculated magnetization angles of the three Co layers and the corresponding MR response curves. Only those in the descending H direction are shown: (a) M angles for sample I; (b) MR curve for sample I; (c) M angles for sample II; (d) MR curve for sample II.

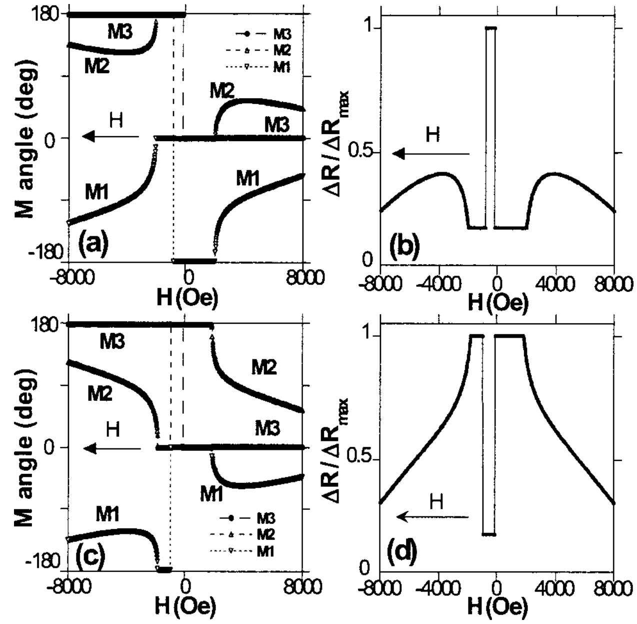

FIG. 5. Calculated magnetization angles of the three Co layers and the corresponding MR response curves without considering the biquadratic coupling of the Co/Ru/Co. Only those in the descending H direction are shown: (a) M angles for sample I; (b) MR curve for sample I; (c) M angles for sample II; (d) MR curve for sample II.

positive high field region. However, for sample II, $\mathbf{M}_1$ and $\mathbf{M}_2$ behave oppositely from sample I. The slight difference between the two comes from the difference of the effect of $\mathbf{M}_3$ on the behavior of the $\mathbf{M}_1$ and $\mathbf{M}_2$ coupled systems. For instance, in the negative field region where $\mathbf{M}_3$ has already switched into the negative direction, $\mathbf{M}_3$ assists the flipping of the magnetization configuration for sample I, while for sample II it hinders it. This causes the critical field for flipping to be higher for sample II than for sample I. The MR response for sample II can be understood by following the angles of $\mathbf{M}_1$, $\mathbf{M}_2$, and $\mathbf{M}_3$ as was done for sample I. The results are shown in Figs. 4(c) and 4(d). Note that $\mathbf{M}_2$ does not go back to 0° in the positive field region.

In the above analysis we included the contribution of the biquadratic term j_2. This was because without it we could not explain the feature of the MR response curves, especially for sample II. Looking at the descending curve of the MR response where a sudden increase occurs in the negative field region, one finds that the MR ratio does not reach the saturation value [see the circled part in Figs. 1(d) and 4(d)]. This has to do with the relative value of H_0^+ and H_0^-. In order to obtain such a feature as we see in Fig. 1(d) the relation $|H_0^-|>|H_0^+|$ should hold. This means that when the magnetization configuration of $\mathbf{M}_1$ and $\mathbf{M}_2$ flips from $\theta_1=\pi,\ \theta_2=0$, at H_0^-, the configuration that $\mathbf{M}_1$ and $\mathbf{M}_2$ can take is not $\theta_1=0,\ \theta_2=\pi$ but with both angles at intermediate values. It is shown that this situation does not occur for $j_2=0$.

The critical field H_0^+ and H_0^- are obtained based on the energy expression Eq. (1) as

$$MH_0^{\pm}=\frac{1}{2}\left(\frac{1}{t_2}-\frac{1}{t_1}\right)j_1\pm\sqrt{\left[\frac{1}{2}\left(\frac{1}{t_2}-\frac{1}{t_1}\right)j_1+2K_u\right]^2+\frac{4K_uj_1}{t_1}}$$

for $j_2=0$.[7] Thus $|H_0^+|$ is always greater than $|H_0^-|$. This means that when $\mathbf{M}_1$ and $\mathbf{M}_2$ flip in a negative field, θ_1 changes from 0 to π, and θ_2 from π to 0, which forces the MR value to saturation. Shown in Fig. 5 are the calculated magnetization curves and MR response curves of the set of samples without including the biquadratic coupling of $\mathrm{Co}(t_1)/\mathrm{Ru}/\mathrm{Co}(t_2)$. There can be an argument that the ferromagnetic coupling of $\mathbf{M}_2$ with $\mathbf{M}_3$ may act similarly to the biquadratic coupling. However, usually, it is not considered to be strong enough to have a substantial effect. As a matter of fact, the value of j_3 employed in the calculation was the largest conceivable value.

Therefore, from the comparison, it is concluded that some biquadratic coupling between the Co layers of the synthetic AF structure, Co/Ru/Co, seems to be playing a decisive role in the evolution of the feature observed in the MR response curves, especially the one for sample II. When the magnetization configuration of $\mathbf{M}_1$ and $\mathbf{M}_2$ flips from $\theta_1=\pi,\ \theta_2=0$ at H_0^-, the configuration that $\mathbf{M}_1$ and $\mathbf{M}_2$ can take is not $\theta_1=0,\ \theta_2=\pi$ but with both angles at intermediate values because of the biquadratic coupling of $\mathrm{Co}(t_1)/\mathrm{Ru}/\mathrm{Co}(t_2)$. This results in a rounded-off shape in the MR response curves.

This work is partly supported by NSIC (EHDR) and made use of the NSF MRSEC Shared Facilities (Grant No. 542417-55139).

[1] D. Heim and S. S. P. Parkin, U.S. Patent No. 5465185.
[2] H. Fujiwara and M. R. Parker, J. Magn. Magn. Mater. **135**, L23 (1994).
[3] K. Pettit, S. Gider, S. S. P. Parkin, and M. B. Salamon, Phys. Rev. B **56**, 7819 (1997).
[4] S. M. Rezende, C. Chesman, M. A. Lucena, M. C. de Moura, A. Azevedo, F. M. de Aguiar, and S. S. P. Parkin, J. Appl. Phys. **85**, 5892 (1999).
[5] B. Dieny, M. Li, S. H. Liao, C. Horng, and K. Ju, J. Appl. Phys. **87**, 3415 (2000).
[6] M. Parker, H. Fujiwara, S. Hossain, J. Yang, M. T. Kief, and S. Gangopadhyay, J. Mag. Soc. Jpn. **18**, s1 (1994).
[7] T. Zhao, K. Zhang, and H. Fujiwara, J. Appl. Phys. (these proceedings).