The trade-off between large magnetoresistance and small coercivity in symmetric spin valves

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(Received 26 January 1996; accepted for publication 22 February 1996)

We have investigated the use of various alloys as substitutes for pure Co in the center film of symmetric spin valves of the type NiO/Co/Cu/Co/Cu/Co/NiO. The aim of this work is to identify magnetic materials that exhibit smaller coercivities than pure Co for the center or ''valve'' film but which retain much of the giant magnetoresistance associated with a pure Co film. The materials investigated include $Co_{95}Fe_5$, $Co_{90}Fe_{10}$, $Ni_{80}Fe_{20}$, $Co_{86}Fe_{10.5}Ni_{3.5}$, and $Co_{85}B_{15}$. It appears that each of these alloys scatters electrons more strongly than does pure Co as they cross the center film. This scattering degrades the dual spin-valve effect, which is the primary advantage of the symmetric spin valve. As a result, a tradeoff exists between large GMR and small coercivity when using these materials. © *1996 American Institute of Physics.* [S0021-8979(96)03511-6]

I. INTRODUCTION

Symmetric[1] (or dual[2]) spin valves are important in the field of giant magnetoresistance (GMR) because they offer the possibility of achieving large GMR values in magnetic multilayers which exhibit relatively small saturation fields. They differ from simple spin valves in having two copper films, hence the term dual. It is this dual attribute that permits large GMR values. In an earlier publication we reported the achievement of GMR values exceeding 21% (at room temperature) in symmetric spin valves with coercivities of ~5 mT (5 mT=50 Oe).[3] These values may be put into context by noting that GMR values as large as 80% (at room temperature) have been achieved in Co/Cu superlattices but at the cost of very large saturation fields, e.g., ~1 T, or 10^4 Oe.[4] Saturation fields as small as 0.2 Mt (2 Oe) have been reported for simple spin valves (containing only one Cu film), but the GMR of such structures is only 3%.[5] Symmetric spin valves represent a compromise between these two extremes.

In the present work, we have investigated possible extensions to the limits of this compromise by using alternatives to pure Co as the center film in symmetric spin valves. The basic idea is that low magnetostriction alloys such as $Co_{95}Fe_5$, $Co_{90}Fe_{10}$, $Ni_{80}Fe_{20}$, or $Co_{86}Fe_{10.5}Ni_{3.5}$ and amorphous (or very fine grained) compounds such as $Co_{85}B_{15}$ may lower the coercivity without greatly reducing the GMR.

II. EXPERIMENT

The NiO substrates used in this work were polycrystalline films ~50 nm thick, deposited on 3 in. Si wafers by reactive magnetron sputtering.[6] The wafers were cleaved into ~1 cm^2 squares, cleaned ultrasonically in a glassware cleaning solution, rinsed in distilled water, dried with a heat gun, and installed in the deposition chamber. The base pressure before depositing a spin valve was typically 2×10^{-8} Torr (~2×10^{-6} Pa) of which ~95% was H_2 and the remainder primarily H_2O (as indicated by a mass spectrometer). The presence of H_2 during deposition has no apparent effect on spin valve properties unless the partial pressure exceeds ~10^{-6} Torr. The base pressure is achieved partly by depositing a ~1.5 nm Ti film on the inside of the deposition chamber from a centrally mounted Ti filament just prior to deposition of each spin valve.

The magnetoresistance (MR) measurements were made *in situ* at room temperature using the four-point probe dc mode. Several symmetric spin valves were checked *ex situ* in two separate facilities and were found to have the same MR values.

Substrates were cleaned by gentle (100 eV) sputtering with a neutralized-beam Ar-ion gun until the carbon was removed (as judged by *in situ* x-ray photoelectron spectroscopy). The metal films were deposited at room temperature by dc-magnetron sputtering in 2 mTorr Ar at a rate of ~0.1 nm/s. The top NiO layer was deposited by sputtering a Ni target with an 85/15 mixture of Ar/O_2.

Additional details about the experimental methods have been published elsewhere.[3,7–10]

III. RESULTS AND DISCUSSION

Figure 1 presents an illustration of the symmetric spin valve structure used in this work. In previous work, we optimized this structure using pure Co as the center layer.[3,7] In the present work, only the material in the center film was

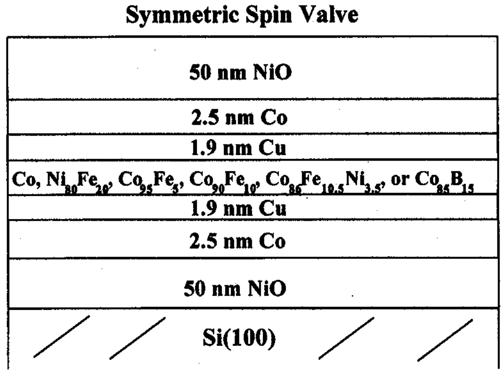

FIG. 1. An illustration of the symmetric spin valve structures typical of those investigated in the present work. The center or valve layer is typically 3–6 nm thick.

changed. The materials investigated are shown in the center film in Fig. 1. For all of these materials (including pure Co), the GMR exhibits a maximum in the thickness range 3–5 nm. However, the value of this maximum and of the coercivity vary significantly from material to material. Table I presents typical results for this variation for a center film thickness of 4 nm.

It should be emphasized that the results in Table I are typical. For example, using pure Co as the center film, the largest GMR we have achieved is 23.4% and the smallest coercivity we have achieved is 3.5 mT (35 Oe). However, for present purposes, the values in Table I are generally averages over several samples and give a representative view of the material dependencies.

The results in Table I follow the expected pattern. The GMR drops for materials other than pure Co because the poorer conductivity of these materials limits the transport of electrons across the center film and thereby reduces the advantage of the dual aspect of the symmetric spin valve. The coercivities are generally equal to or smaller than that for pure Co and the sheet resistances (of the entire structure, measured in a saturation field) are generally larger. The only exception to these trends is $Co_{90}Fe_{10}$ for which the coercivity is slightly larger than for pure Co and the sheet resistance is slightly smaller. No explanation for this anomaly is apparent.

A further indication of the limited electron transport across the center film for materials other than pure Co may be found in the ratio of the GMR values for symmetric and bottom spin valves of the same composition. A bottom spin valve in the pure Co case would consist of Co/Cu/Co/NiO. The term bottom refers to the NiO pinning film being the substrate or bottom of the spin valve. In the pure Co case, typical GMR values are 22% (symmetric) and 15% (bottom) for a ratio of 1.47, a value which quantifies the advantage of the dual aspect of the symmetric spin valve. For $Ni_{80}Fe_{20}$, we found this ratio to be only 1.16, and this small value is an indication of the limited advantage of the dual character of the symmetric spin valve design when a high resistivity alloy is used as the center film.

TABLE I. Typical values of the GMR, coercivity, and sheet resistance at saturation (of the entire spin valve) for various choices of materials for the center film in a symmetric spin valve of the type illustrated in Fig. 1. The center layer film was 4 nm thick in each case.

Center film material	GMR (%)	Coercivity (mT)	Sheet resistance at saturation (Ω/□)
Co	22	4.5	25.8
$Co_{95}Fe_5$	17	4.5	28.7
$Co_{90}Fe_{10}$	15	6.0	24.2
$Ni_{80}Fe_{20}$	12	1.2	30.0
$Co_{86}Fe_{10.5}Ni_{3.5}$	15	4.5	29.5
$Co_{85}B_{15}$	5	3.6	40.4

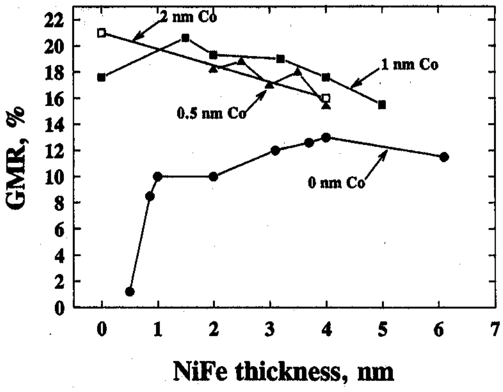

FIG. 2. A plot of the GMR vs $Ni_{80}Fe_{20}$ thickness for symmetric spin valves in which the center film was a Co/$Ni_{80}Fe_{20}$/Co structure. The thicknesses of the two Co films is indicated by the arrows for each series of data points.

The smallest coercivity in Table I occurs for $Ni_{80}Fe_{20}$, and the largest GMR for pure Co. This observation suggests a combination of these materials might be useful as the center film in a symmetric spin valve, and indeed this idea was proposed in Ref. 1. Figures 2–4 present the results we have obtained for various combinations of Co/$Ni_{80}Fe_{20}$/Co as the center film.

Figure 2 presents the results for GMR vs $Ni_{80}Fe_{20}$ thickness for different Co thicknesses. The solid circles labeled "0 nm Co" are for pure $Ni_{80}Fe_{20}$ as the center film. The most noteworthy aspect of Fig. 2 is the rather small amount of Co that is needed to obtain the maximum GMR. A Co thickness of 0.5 nm is as effective as a thickness of 2 nm. We have performed several additional experiments to establish

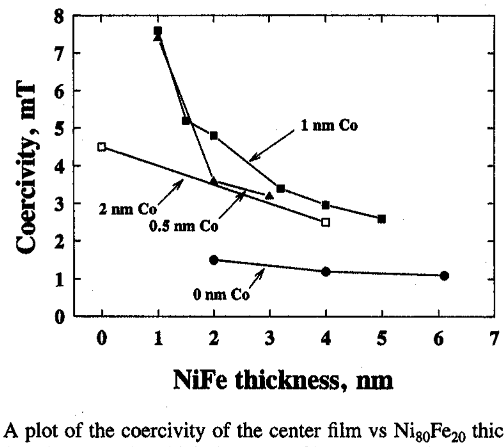

FIG. 3. A plot of the coercivity of the center film vs $Ni_{80}Fe_{20}$ thickness for symmetric spin valves in which the center film was a Co/$Ni_{80}Fe_{20}$/Co structure. The thicknesses of the two Co films is indicated by the arrows for each series of data points. Note 1 mT=10 Oe.

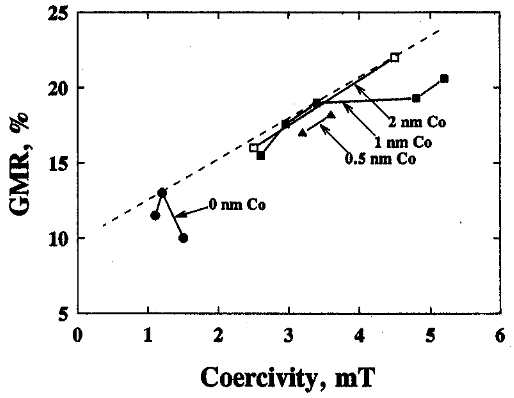

FIG. 4. A plot of the GMR vs the coercivity of the center film using the data of Figs. 2 and 3. The dashed line connects the results for a center film of 4 nm of pure Co (open square) and a center film of 4 nm of pure $Ni_{80}Fe_{20}$ (solid circle). Note 1 mT=10 Oe.

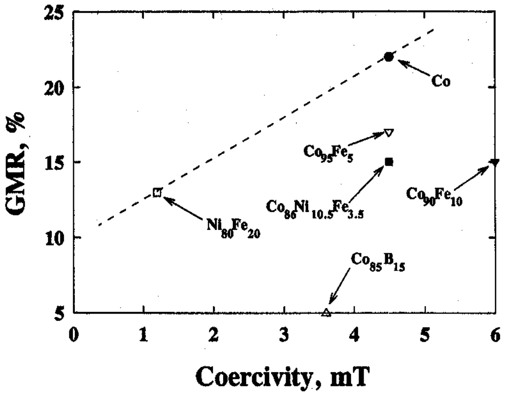

FIG. 5. A plot of the GMR vs the coercivity of the center film using the data of Table I. The dashed line is from Fig. 4, and is included for comparison. Note 1 mT=10 Oe.

how thin this Co can be before the GMR declines noticeably, and the data suggest the decline begins for a Co thickness between 0.2 and 0.1 nm. This result is similar to previous measurements made on GMR superlattices.[11]

Figure 3 presents the measurements of coercivity vs $Ni_{80}Fe_{20}$ thickness for different Co thicknesses. Again, it is seen that there is not a large dependence on the Co thickness in the 0.5–2 nm range. However, a Co thickness of 0.5 nm Co produces a sharp increase in coercivity compared to a film entirely of $Ni_{80}Fe_{20}$. This result could indicate that an interfacial anisotropy of the Co/Cu interface is primarily responsible for the large coercivity. Since an anisotropy of this type would probably have a strong dependence on crystalline orientation, manipulation of the crystalline texture of these spin valves might be a route to smaller coercivity.

There are fewer data points in Fig. 3 than in Fig. 2 because it was not always possible to determine a reliable value of the coercivity. In some samples, the coupling field (probably due to a magnetostatic effect) between the center film and the Co films at the top and bottom of the structure dominated the switching. In these cases, the hysteresis loop of the center film collapses, and a reliable value of the coercivity cannot be determined. See Ref. 8 for further discussion of this collapse.

Figure 4 presents the data of Figs. 2 and 3 in the form of GMR vs coercivity. The trade-off between GMR and coercivity is immediately apparent in Fig. 4. The dashed line passes through the results for a center film of 4 nm of pure $Ni_{80}Fe_{20}$ (a solid circle) and 4 nm of pure Co (an open square). To avoid confusion here, note that the 4 nm pure Co film is designated in Figs. 2–4 as two Co films, each 2 nm thick, with 0 nm of $Ni_{80}Fe_{20}$ between them. None of the combinations of Co/$Ni_{80}Fe_{20}$/Co are above the dashed line. This result suggests that no net improvement, in the sense of larger GMR and smaller coercivity, has been achieved. However, it is apparent that the values labeled "1 nm Co" and "2 nm Co" are very close to the dashed line. Thus, there is some opportunity to select a desired combination of GMR and coercivity by adjusting the thicknesses of the Co/$Ni_{80}Fe_{20}$/Co center film.

Figure 5 presents a comparison of the dashed line from Fig. 4 with the results from Table I. Again, no net improvement is found for the alloys studied in this work. This result might suggest that future efforts to improve symmetric spin valves should concentrate on attempts to reduce the coercivity of pure Co when it is used as the center film.

IV. CONCLUSIONS

The major conclusions of this work may be summarized as follows: (1) The coercivity of the center film in symmetric spin valves can be reduced by the use of low magnetostriction alloys instead of pure Co, but in every case a reduction in GMR is found. (2) The GMR reduction appears to be due to scattering of conduction electrons in the alloy, an effect which reduces the advantage of the dual-Cu-film for the symmetric spin valve structure. (3) If a Co/$Ni_{80}Fe_{20}$/Co structure is used as the center film, a trade-off between GMR and coercivity exists as the relative thicknesses of Co and $Ni_{80}Fe_{20}$ are varied. (4) This trade-off permits desired combinations of GMR and coercivity to be selected. (5) Future research on improving symmetric spin valves should focus on reducing the coercivity of pure Co when it is used as the center film.

ACKNOWLEDGMENTS

This work has been supported in part (W.F.E. and R.D. McM.) by the NIST Advanced Technology Program and in part (A.E.B.) by NSF Program No. DMR-9400439.

[1] T. C. Anthony, J. A. Brug, and S. Zhang, IEEE Trans. Mag. **30**, 3819 (1994).

[2] P. M. Baumgart, B. Dieny, B. A. Gurney, J.-P. Nozieres, V. S. Speriosu, and D. R. Wilhoit, U.S. Patent 5,287,238; Feb. 15, 1994.

[3] W. F. Egelhoff, Jr., T. Ha, R. D. K. Misra, T. Ha, Y. Kadmon, J. Nir, C. J. Powell, M. D. Stiles, R. D. McMichael, C.-L. Lin, J. M. Sivertsen, J. H. Judy, K. Takano, A. E. Berkowitz, T. C. Anthony, and J. A. Brug, J. Appl. Phys. **78**, 273 (1995).

[4] H. Kano, K. Kagawa, A. Suzuki, A. Okabe, K. Hayashi, and K. Aso, Appl. Phys. Lett. **63**, 2839 (1993).

[5] Th. G. S. M. Rijks, W. Folkerts, J. C. S. Kools, W. J. M. de Jonge, and R. Coehoorn, in Colloquium Digest, 14th Int. Coll. on Mag. Films and Surf., Dusseldorf, 1994, p. 29.

[6] M. J. Carey, F. E. Spada, A. E. Berkowitz, W. Cao, and G. Thomas, J. Mater. Res. **6**, 2680 (1991); M. J. Carey and A. E. Berkowitz, Appl. Phys. Lett. **60**, 3060 (1992); J. Appl Phys. **73**, 6892 (1993).

[7] W. F. Egelhoff, Jr., P. J. Chen, R. D. K. Misra, T. Ha, Y. Kadmon, C. J. Powell, M. D. Stiles, R. D. McMichael, C.-L. Lin, J. M. Sivertsen, J. H. Judy, K. Takano, A. E. Berkowitz, T. C. Anthony, and J. A. Brug, J. Appl. Phys. (in press).

[8] W. F. Egelhoff, Jr., P. J. Chen, R. D. K. Misra, Y. Kadmon, C. J. Powell, M. D. Stiles, R. D. McMichael, C.-L. Lin, J. M. Sivertsen, and J. H. Judy, J. Appl. Phys. **79**, 282 (1996).

[9] W. F. Egelhoff, Jr., P. J. Chen, C. J. Powell, M. D. Stiles, and R. D. McMichael, J. Appl. Phys. (in press).

[10] R. D. K. Misra, T. Ha, Y. Kadmon, C. J. Powell, M. D. Stiles, R. D. McMichael, and W. F. Egelhoff, Jr., Proc. Mat. Res. Soc. Symp. **384**, 373 (1995).

[11] S. S. P. Parkin, Phys. Rev. Lett. **71**, 1641 (1993).