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Thermal stability of synthetic antiferromagnet and hard magnet coupled spin valves

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The magnetic properties of current-in-plane (CIP) giant magnetoresistive (GMR) spin valves employing synthetic antiferromagnet (SAF) pinning have been investigated. The conventional spin valve structure, with a ferromagnetic (FM) layer pinned by an antiferromagnet (AFM) layer, exhibits high electrical resistance, the AFM typically being a high resistivity material. We have investigated pinning with a Co/Ru/Co SAF trilayer only, with no additional AFM pinning. We have also investigated spin valves employing a hard magnet layer in three different configurations as the pinning/pinned layer. Elimination of the AFM-induced parasitic resistance has the potential for yielding a higher GMR ratio in current-perpendicular-to-the-plane (CPP) structures. The full-film properties have been optimized by using vibrating sample magnetometry and CIP magnetotransport measurements. The thermal stability of SAF-pinned spin valves and hard magnet-pinned spin valves has been characterized through magnetotransport measurements of up to 400 K, and found to have measurable MR even at that temperature. A study of the *M-H* loops for the SAF spin valve showed no change up to 500 K. Therefore, these non-AFM-containing spin valves appear to be usable in CPP devices under practical head operating temperatures, representing a significant advance in reduced stack resistance, increased MR ratio, and reduced coupling between free and pinned layers in a small-dimensional patterned structure.
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I. INTRODUCTION

The giant magnetoresistance effect was discovered independently by Baibich *et al.*[1] and Grünberg *et al.*[2] in 1988, where a significant change in resistance occurred when a current was allowed to pass through ferromagnetic layers separated by a nonmagnetic spacer under the influence of an external magnetic field. This discovery, recognized by the award of the Nobel Prize in physics last year, led to rapid advances in the development of spin valves for computer read heads in 1996 (Refs. 3 and 4) and tunnel junctions shortly afterward.[5] Conventional spin valves use an antiferromagnet (AFM) layer to pin one of the ferromagnetic layers. Although AFM based spin valves have large exchange fields at room temperature, the pinning becomes unstable at temperatures close to their blocking temperatures. Several AFMs such as FeMn, IrMn, PtMn, and NiMn have blocking temperatures in the range of 150–250 °C.[6,7] Another disadvantage of AFM-pinned spin valves is that the antiferromagnetic material contributes to the resistance of the total stack, thereby decreasing the magnetoresistance (MR) values. An additional disadvantage of conventional spin valves using AFM pinning layers is the magnetostatic coupling between the two ferromagnetic layers when they are patterned to submicron sizes, schematically shown in Fig. 1(a), thereby introducing a drag on the switching of the free layer. Another important disadvantage, as device dimensions decrease, is the presence of the self-demagnetizing fields at the edges of the pinned and free layers. Both these problems can be overcome by replacing the AFM with two ferromagnetic layers that are negatively coupled, i.e., a synthetic antiferromagnet (SAF) layer. In this article, it is shown that spin valves using non-AFM-based pinning mechanisms, for instance, synthetic AFMs [8–10] or hard magnets,[11–13] have improved magnetic properties and adequate thermal stability of up to 500 K (over 200 °C), which favorably compare with FeMn or IrMn-based spin valves.

II. EXPERIMENTAL DETAILS

Current-in-plane spin valves utilizing two types of non-AFM-based pinning schemes were deposited and characterized in our study, as follows.

(1) A Co/Ru/Co SAF stack was used as the pinning/pinned layer, with the following layers: oxidized Si substrate/Ta/**Co**/**Ru**/**Co**/Cu/Co/NiFe/Ta.
(2) A CoPt hard magnet layer was used as the self-pinned layer. Three versions of this type of hard magnet-based spin valve are reported here with (i) a single self-pinned layer: oxidized Si substrate/Ta/Cr/**CoPt**/Cu/CoFe/NiFe/Ta, (ii) a double-pinned layer: oxidized Si substrate/Ta/Cr/**CoPt**/**CoFe**/Cu/CoFe/NiFe/Ta, and (iii) a hard SAF trilayer, with CoPt coupled negatively to CoFe through a Ru spacer layer: oxidized Si substrate/Ta/Cr/**CoPt/Ru/CoFe**/Cu/CoFe/NiFe/Ta.

Figure 1(a) is a schematic representation of both the single- and double-pinned spin valves detailed in 2(i) and 2(ii) above, while Fig. 1(b) represents both the SAF-pinned spin valves detailed in 1, as well as the hard SAF-pinned spin valves detailed in 2(iii).

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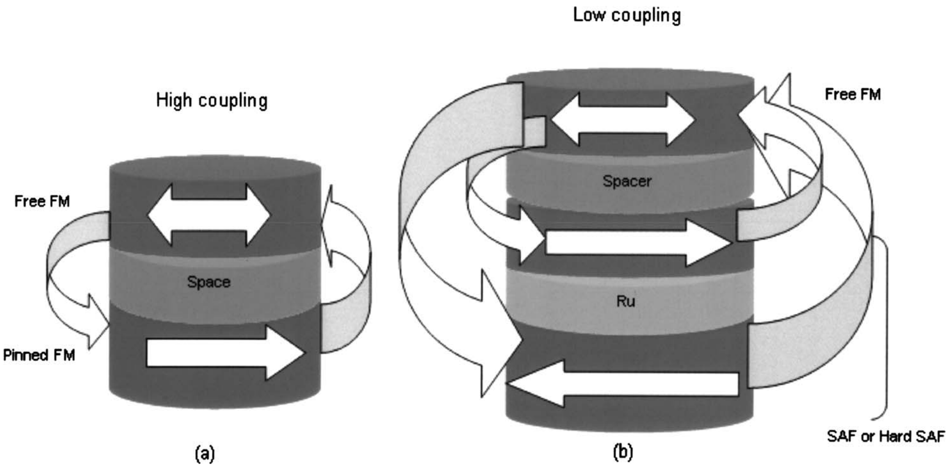

FIG. 1. Schematic of spin valves showing (a) high and (b) low magnetostatic coupling using (a) AFM or self-pinning and (b) SAF or hard SAF pinning.

These spin valves were deposited on the (100) silicon substrates in a seven-target SFI Shamrock planetary sputtering system, using dc magnetron sputtering for all the layers except Ru, which was deposited using ac magnetron sputtering. The reason for using ac sputtering for Ru was to lower the deposition rate for better precision at the low thicknesses investigated. The SAF structure was investigated for both Co and CoFe, varying the Ru thickness in increments of 0.1 nm. The SAF-pinned spin valves had the structure: substrate/Ta(5)/Co(4)/Ru(0.9)/Co(3)/Cu(3)/Co(1)/NiFe(3)/Ta(5) (thickness indicated in nanometers). *M-H* loops were measured using a Digital Measurement Systems vibrating sample magnetometer, and the magnetoresistive measurements were carried out using a Quantum Design physical property measurement system (PPMS). Hard magnet-based spin valves were deposited with either a single self-pinned layer of CoPt [substrate/Ta(5)/Cr(5)/CoPt(5)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5)], or a double hard/soft ferromagnet self-pinned layer of CoPt/CoFe [substrate/Ta(5)/Cr(5)/CoPt(5)/CoFe(0.7)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5)]. Hard SAF-based spin valves consisted of substrate/Ta(5)/Cr(5)/CoPt(5)/Ru(0.9)/CoFe(3)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5). The sputtering system was pumped down to a base pressure of less than 8×10^{-8} Torr (2.4×10^{-6} Pa). Deposition powers ranged from 250 to 450 W, corresponding to deposition rates of 0.6–1.8 nm/s. Deposition pressures were held at 3 mTorr (0.4 Pa). A Ta underlayer of 5 nm was deposited as a smoothing seed layer under all the types of spin valves fabricated in order to decrease the orange-peel coupling effect caused by interface roughness.[14] An external field of 100 Oe was applied during deposition using an assembly of permanent magnets in the substrate holder. This field was rotated by 90° between the pinned and free layers to improve the linearity of the MR response.

III. RESULTS AND DISCUSSION

As the thickness of the Ru in the Co/Ru/Co trilayer is varied, the magnetization of the ferromagnetic layers above and below this nonmagnetic spacer is known to oscillate between parallel (ferromagnetic) and antiparallel (antiferromagnetic) configurations.[8–10] We have seen this oscillatory exchange behavior in Co(4)/Ru(x)/Co(3) nm as a function of Ru thickness, from FM (positive) to AFM (negative) coupling at Ru thicknesses ranging from 0.7 to 1.5 nm in 0.1 nm increments. The planetary motion of the substrates in the Shamrock system allows this level of precision and repeatability in varying the Ru layer thickness. FM coupling is seen at Ru thicknesses of 0.8 and 1.5 nm, while AFM coupling is seen at Ru thicknesses of 0.7, 0.9, 1, and 1.2 nm. A Ru thickness of 0.9 nm was chosen for the SAF-pinned spin valve, Ta(5)/Co(4)/Ru(0.9)/Co(3)/Cu(3)/Co(1)/NiFe(3)/Ta(5), subsequently deposited and characterized by magnetometry and transport measurements, as shown in Figs. 2(a) and 2(b), respectively.

We have previously shown good thermal stability for SAF-based spin valves pinned with a very thin AFM layer (3 nm IrMn).[15] Here, we have studied the thermal stability of a spin valve pinned with a SAF trilayer only, with no AFM at all. Magnetometry measurements as a function of temperature indicated that the structure was stable up to 500 K, as shown in Figs. 2(c) and 2(d). The maximum change in resistance of about 5% was observed at near zero fields and the saturation field of the SAF was about 1100 Oe. Transport measurements shown as a function of temperature in Figs. 3(a)–3(f) indicated that the spin valve was stable up to 400 K (the upper temperature limit of the PPMS system), with the MR decreasing from about 7% at room temperature to about 4% at 400 K at near zero fields.

For the self-pinned spin valve structures, the AFM/FM pinning was replaced by a hard ferromagnet, $Co_{80}Pt_{20}$. In this type of spin valve, the free layer and the hard magnetic, i.e. "self-pinned" layer, switch at different magnetic fields providing a field range where the two ferromagnetic layers are in antiparallel alignment where the resistance is maximum.[11–13] A Cr seed layer was used to grow fcc (111) $Co_{80}Pt_{20}$. Both the double FM-pinned and the single FM-pinned layer spin valves were deposited with various Cu spacer thicknesses, showing optimal MR values at 3 nm of Cu. Finally, hard SAF spin valves were deposited where $Co_{80}Pt_{20}$ was used as the bottom layer of the SAF. The switching field of $Co_{80}Pt_{20}$ was about 1600 Oe and the free layer switched at near zero field, yielding a MR of about 6%

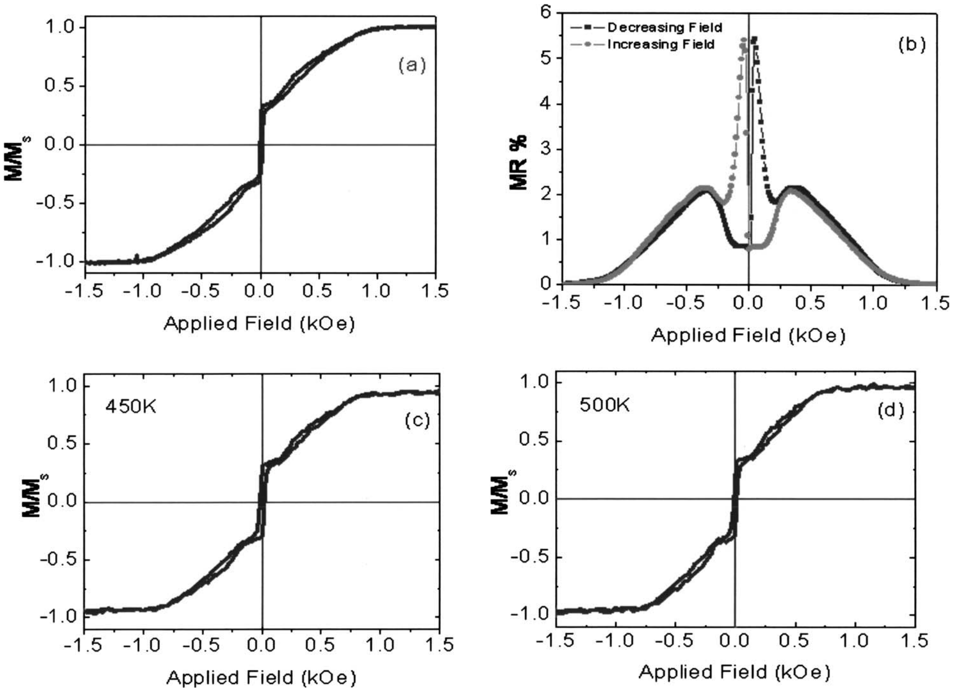

FIG. 2. Experimental (a) *M-H* and (b) MR-*H* curves at 300 K; (c) *M-H* curves at 450 K and (d) 500 K for SAF-pinned spin valve: substrate / Ta(5)/Co(4)/Ru(0.8)/Co(3)/Cu(3)/Co(1)/NiFe(3)/Ta(5) (in nanometers).

at room temperature. Figures 4(a)–4(c) show the *M-H* plots, and Figs. 4(d)–4(f) show the MR-*H* plots of the single FM-pinned, double FM-pinned, and hard SAF-pinned spin valves, respectively. A study of the MR response as a function of temperature is shown for the SAF-pinned, double FM-pinned, and hard SAF-pinned spin valves in Figs. 5(a)–5(c), respectively, indicating that the CoPt-based spin valves were stable up to 400 K with a change in resistance of about 4% near zero field at this temperature. No *M-H* characteristics versus temperature were measured for these CoPt-based samples but they are expected to show thermal stability similar to or greater than that of the SAF-pinned spin valve.

IV. CONCLUSIONS

We have studied various types of pinning mechanisms in current-in-plane spin valves suitable for developing a low resistance, thermally stable structure for current-perpendicular-to-the-plane (CPP) applications. Studied non-

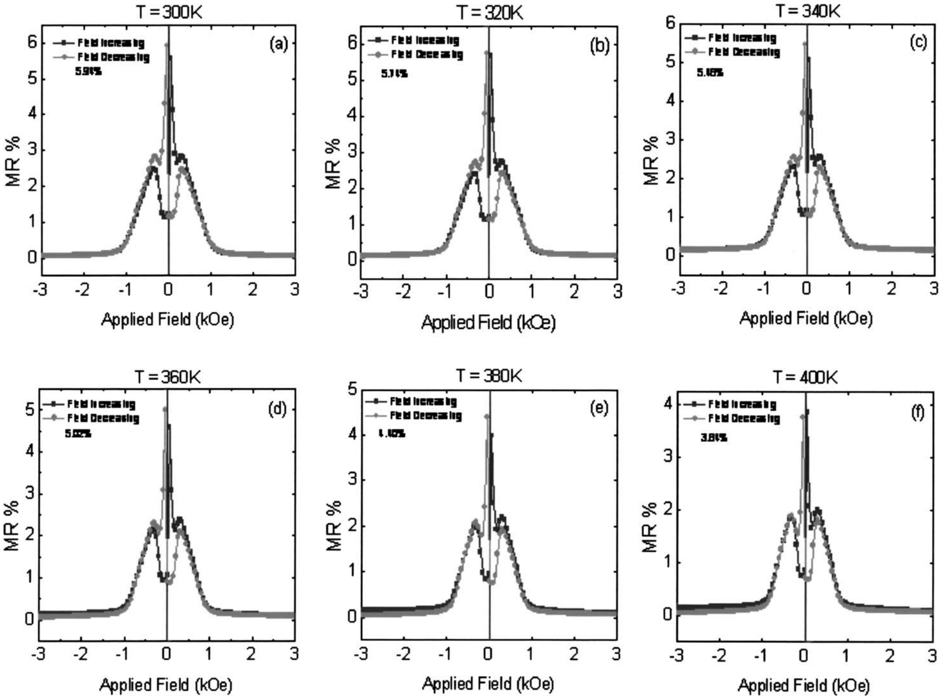

FIG. 3. [(a)–(f)] MR-*H* plots of SAF based spin valve from 300 to 400 K in 20 K increments, respectively.

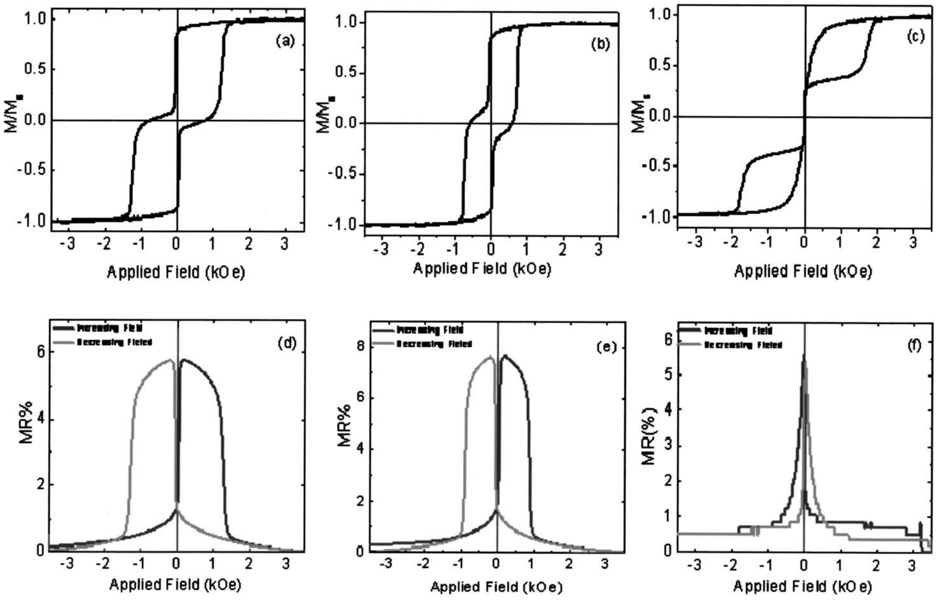

FIG. 4. *M*-*H* plots of Co$_{80}$Pt$_{20}$ based (a) single FM-pinned [substrate/Ta(5)/Cr(5)/CoPt(5)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5)] (in nanometers), (b) double FM-pinned [substrate/Ta(5)/Cr(5)/CoPt(5)/CoFe(0.7)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5)] (in nanometers), and (c) hard SAF-pinned [substrate/Ta(5)/Cr(5)/CoPt(5)/Ru(0.9)/CoFe(3)/Cu(x)/CoFe(1)/NiFe(3)/Ta(5)] (in nanometers) spin valves. Room temperature MR-*H* plots of the same three spin valves are shown in (d)–(f), respectively.

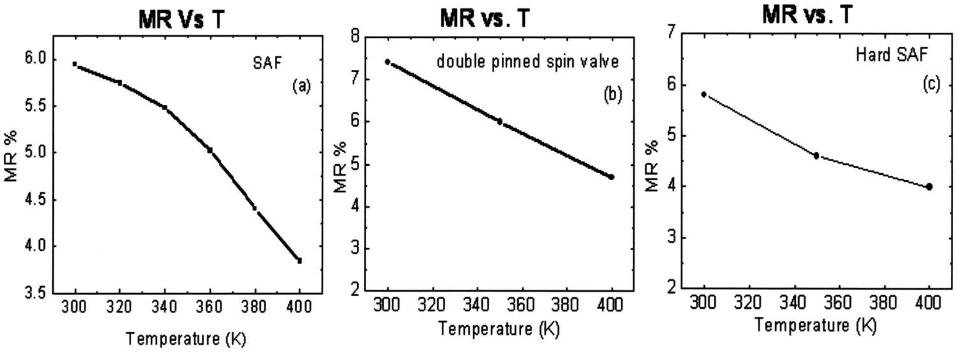

FIG. 5. MR vs temperature measurements of (a) SAF-pinned, (b) double FM-pinned, and hard SAF-pinned spin valves, respectively.

AFM-based pinning schemes include SAF-based and hard magnet-based spin valves. Variations of the hard magnet-based spin valves studied were single FM-pinned layer, double FM-pinned layer, and hard SAF-pinned spin valves. We have optimized the thickness of the spacer layer in the SAF to yield strong negative interlayer exchange coupling. In the case of Co$_{80}$Pt$_{20}$ based spin valves, the seed layer and spacer thickness of the ferromagnet were optimized. A study of the thermal stability has been conducted for both these types of spin valves, showing that both these spin valves retain substantial MR of up to 400 K, and probably 500 K or higher temperatures, verifying that these types of stacks should be easily usable in practical CPP heads.

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