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High Temperature Pinning Properties of IrMn vs. FeMn in Spin Valves

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Abstract

The antiferromagnetic pinning properties of IrMn and FeMn have been observed as a function of temperature by building spin valve samples with the structure NiFeCo / CoFe / Cu / CoFe / NiFeCo / (IrMn or FeMn) and measuring their magnetoresistive properties. The pinning strength was evaluated in terms of the break field, defined as the field applied in the direction opposite to the magnetization of the pinned layer at which the pinned layer switches. At room temperature, the break fields for both the IrMn and FeMn samples were about 250 Oe. But with increasing temperature, the break field for samples pinned with IrMn held up considerably better than for those pinned with FeMn. Specifically, the pinning of the FeMn spin valves was gone at 150 ^{0}C while the pinning of the IrMn spin valves persisted to temperatures above 225 ^{0}C. The IrMn spin valves performed as well as the FeMn spin valves in terms of magnetoresistance and lithographic process compatibility.

Introduction

Since the discovery of the Giant Magnetoresistance (GMR) effect ten years ago[1],[2], a number of different types of GMR materials have been fabricated into various thin film magnetoresistive devices. These can be divided into multilayers[3,4] (repeating alternating layers of magnetic and nonmagnetic metals), unpinned sandwiches[5] (magnetic / nonmagnetic / magnetic), and spin valves (pinned sandwiches). Multilayers and unpinned sandwiches have proven to be very useful for making linear unipolar field sensors with ranges on the order of 1 to 100 Oe. Spin valves also appear to have desirable magnetoresistive features, particularly for use in low fields.

The distinguishing feature of a spin valve is its pinning layer. This layer is typically an antiferromagnet which is exchange coupled to one of the two magnetic layers in the sandwich. Several antiferromagnetic materials have been used for pinning the spin valve, each with particular advantages. Most recently, much work has been done with IrMn[6,7,8,9,10,11.] FeMn and IrMn are known to have moderate pinning (200 - 400 Oe) as deposited in thin layers (~10 nm), or after a relatively low temperature anneal. These pinning layers are nominally conductive which results in some shunting of the GMR signal. NiMn, PtMn, and others have somewhat better pinning properties but require an anneal above 270 ^{0}C [12]. This anneal is to facilitate a phase transition from fcc to fct crystalline structure. Such an anneal may degrade other parts of the GMR structure, and should be avoided if possible. Consequently, FeMn and IrMn appear to be the best candidates for making spin valves using an easy deposition process. This paper will discuss results of experiments to test the feasibility of operating FeMn and IrMn spin valve devices at elevated temperatures.

Experimental Procedures

Magnetoresistance measurements were carried out on two spin valve samples. One was pinned with FeMn and the other with IrMn. The samples, grown on 4” Si wafers coated with an atomically smooth 200 nm layer of insulating Si_3N_4, had the following metallic layered structures: (1) NiFeCo 7 / CoFe 1.5 / Cu 3.0 / CoFe 1.5 / NiFeCo 1.5 / FeMn 12.5, and (2) NiFeCo 7 / CoFe 1.5 / Cu 3.0 / CoFe 1.5 / NiFeCo 2.0 / IrMn 12.5 (all thicknesses in nm). A Perkin Elmer 2400 vacuum deposition system was used to make the samples. The baseline pressure in the system was about 1×10^{-7} Torr prior to introducing the Ar sputter gas to a pressure of 20 mTorr. Sputtering was achieved through the use of an RF diode setup using 8” targets with an approximate target-to-substrate spacing of 3 cm. The layers were deposited at room temperature. The target compositions for the deposited metals are in atomic percent as follows: $Ni_{53}Fe_{12}Co_{35}$, $Co_{95}Fe_5$, $Fe_{50}Mn_{50}$, and $Ir_{20}Mn_{80}$. Some magnetic anisotropy was induced in the spin valves as they were being deposited through the application of a 20 Oe field in the plane of the wafers. This field was along the same axis for both NiFeCo and CoFe layers, but was not applied during deposition of the FeMn and IrMn layers. Better pinning could be achieved with the application of a higher field during the sputter deposition, but this cannot be done without unacceptable distortion of the RF diode plasma in this particular deposition system.

The magnetoresistive properties of the wafers were measured using a MicroManipulator wafer probe stand which has been retrofitted with air core coils for applying magnetic fields. For this experiment, an in-line four-point probe was used to make electrical connection to the wafer. Heat was provided to the wafers through the use of a Temptronic brand vacuum “hot chuck.” The temperature of the hot chuck was controlled to the nearest degree by manually adjusting the current provided by an HP dc current source. The wafers were unpatterned, so there are no finite size / shape effects evident in the data. The wafers were initially heated to 250 ^{0}C and then cooled in a field parallel to the easy axis of the ferromagnetic layers in the spin valve. Then, the temperature was systematically increased from room temperature to 250 ^{0}C. At each step in temperature, 500 Oe and 100 Oe magnetoresistance sweeps were performed once the temperature had stabilized. These measurements consisted of voltage readings from a four point probe using a 10 mA dc constant current source.

Results and Discussion

At issue before this work began was whether any easily deposited antiferromagnetic pinning layer would function in a device which operated at 125 ^{0}C. This is critical because many applications in the automotive industry and other commercial areas require stability at such temperatures. Before the introduction of IrMn as a pinning material, the only easily deposited antiferromagnetic pinning material was FeMn. Its pinning is acceptable for room temperature applications. However, it does not have sufficient pinning for operating above 100 ^{0}C.

The main result of this work is that the IrMn pinned spin valve had usable pinning fields at temperatures above 150 ^{0}C while the FeMn pinned spin valve had usable pinning only to 100 ^{0}C. For the purposes of this paper, usable pinning is that which is still in force after applying a 100 Oe field antiparallel to the pinned layer. Data from a single magnetoresistance measurement are plotted in Figure 1 for the IrMn pinned sample at 50 ^{0}C. Many sweeps from individual magnetoresistance traces over a range of temperatures are summarized in Figure 2 for FeMn and Figure 3 for IrMn. In Figure 3, one can see that even at 175 ^{0}C, the free layer of the IrMn spin valve returns to a fully antiparallel state after experiencing a -100 Oe field. Figure 2 shows that the same is true for the FeMn pinned spin valve only up to 100 ^{0}C. The point at which the 100 Oe hysteresis loops begin to open is 100 ^{0}C for the FeMn pinned spin valve, and 150 ^{0}C for the IrMn pinned one.

If one defines the "pinning break field" as the antiparallel field at which the magnetoresistance is at half its maximum value, this parameter can be plotted against temperature for the two spin valve structures. Results of this analysis are shown in Figure 4. The GMR, defined in the usual way as $(R_{\uparrow\downarrow}\ \ R_{\uparrow\uparrow}) / R_{\uparrow\uparrow}$, is plotted versus temperature for both spin valve types in Figure 5. The GMR is essentially the same for the two structures up to the point where the pinning gives way in the FeMn pinned sample.

Another critical issue for spin valve structures is their compatibility with standard semiconductor processes. FeMn is notoriously reactive with a number of common process chemicals such as photoresist developer and reactive ion etch chemistries such as SF_6. It was thought by some that IrMn would not have these problems. However, although we have not done quantitative studies of these effects, we find that IrMn does corrode when exposed to certain process chemistries, the RIE in particular.

Conclusions

The data show that IrMn has significant advantages over FeMn as an antiferromagnetic pinning layer for spin valves which must operate at elevated temperatures. No signs of depinning of the IrMn pinned spin valve are evident at 125 ^{0}C under a reverse field of 100 Oe. Other workers have found that IrMn pinned spin valves have better interdiffusion properties[13]. Generally speaking, IrMn behaves much like FeMn in other regards. While the results shown here focus on spin valves, they can be applied directly to similar magnetic structures such as spin dependent tunnel junctions[14].

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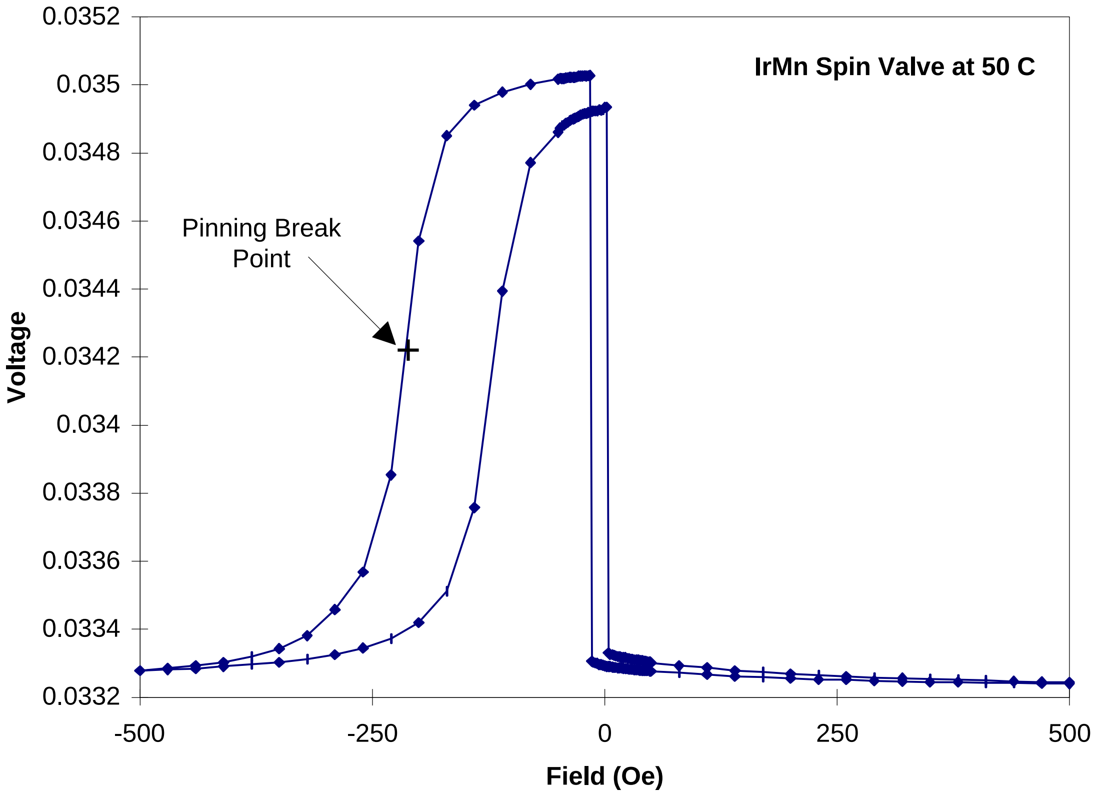

Figure 1: Typical magnetoresistance trace of an IrMn spin valve.

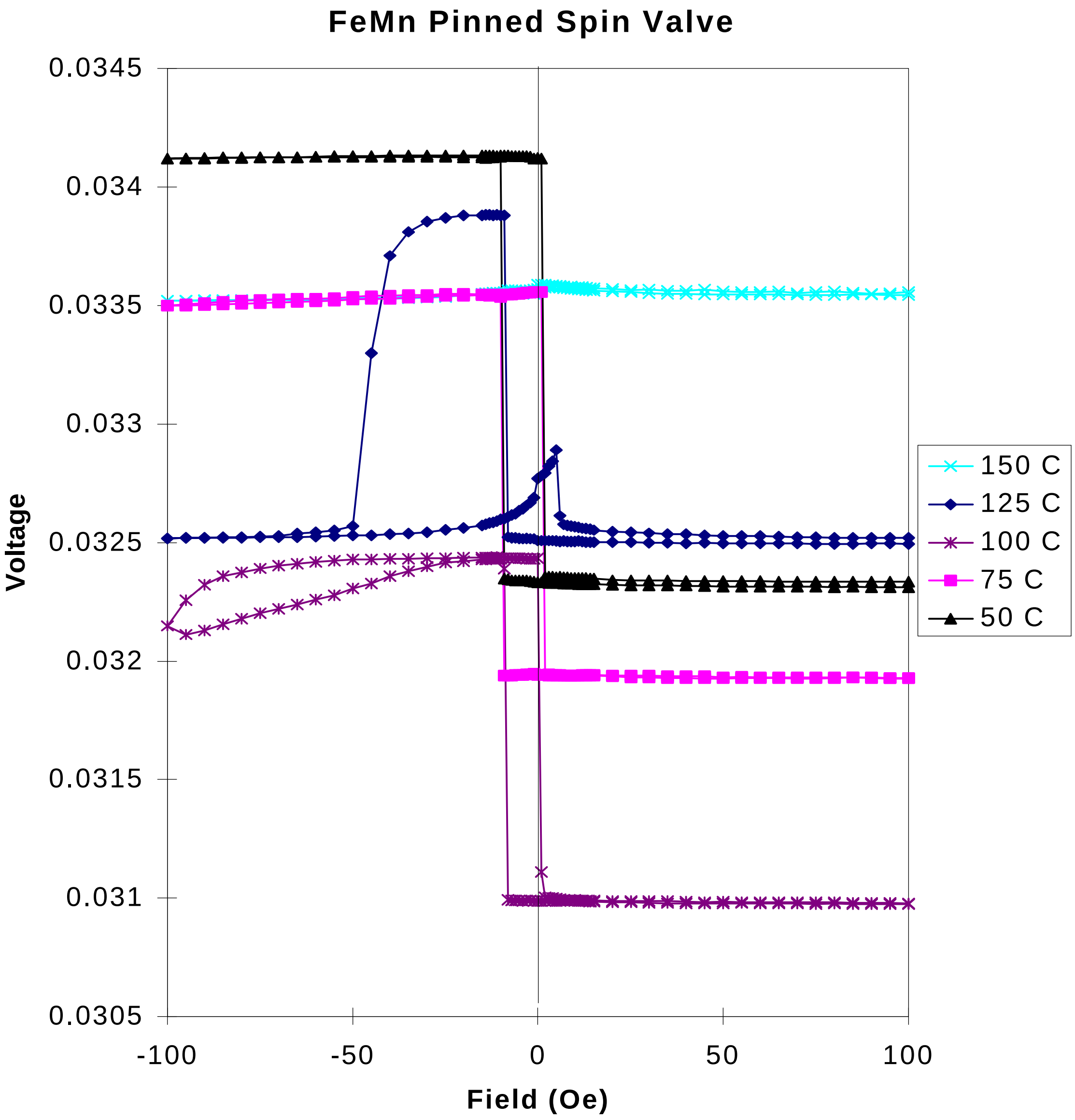

Figure 2: Several magnetoresistance traces for the FeMn pinned spin valve are plotted on the same graph. Note that the switching field of the soft NiFeCo layer does not change appreciably with temperature. The sense current used for this four-point-in-line measurement is 10mA. The corresponding sheet resistance for these measurements is on the order of 9 Ω / square.

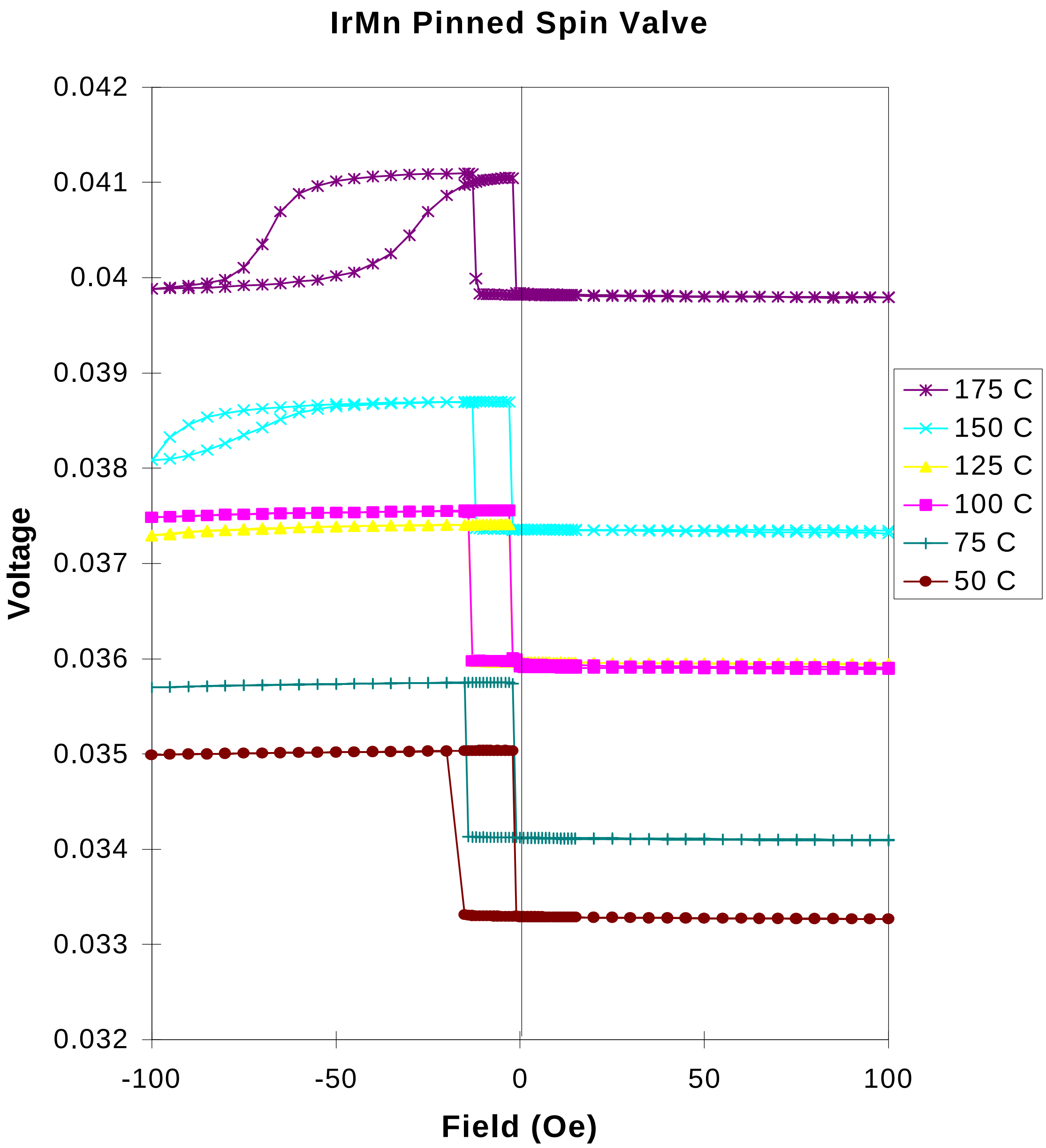

Figure 3: Several magnetoresistance traces for the FeMn pinned spin valve are plotted on the same graph. As in Figure 2, the sense current is 10 mA and the corresponding sheet resistance is on the order of 9 Ω / square.

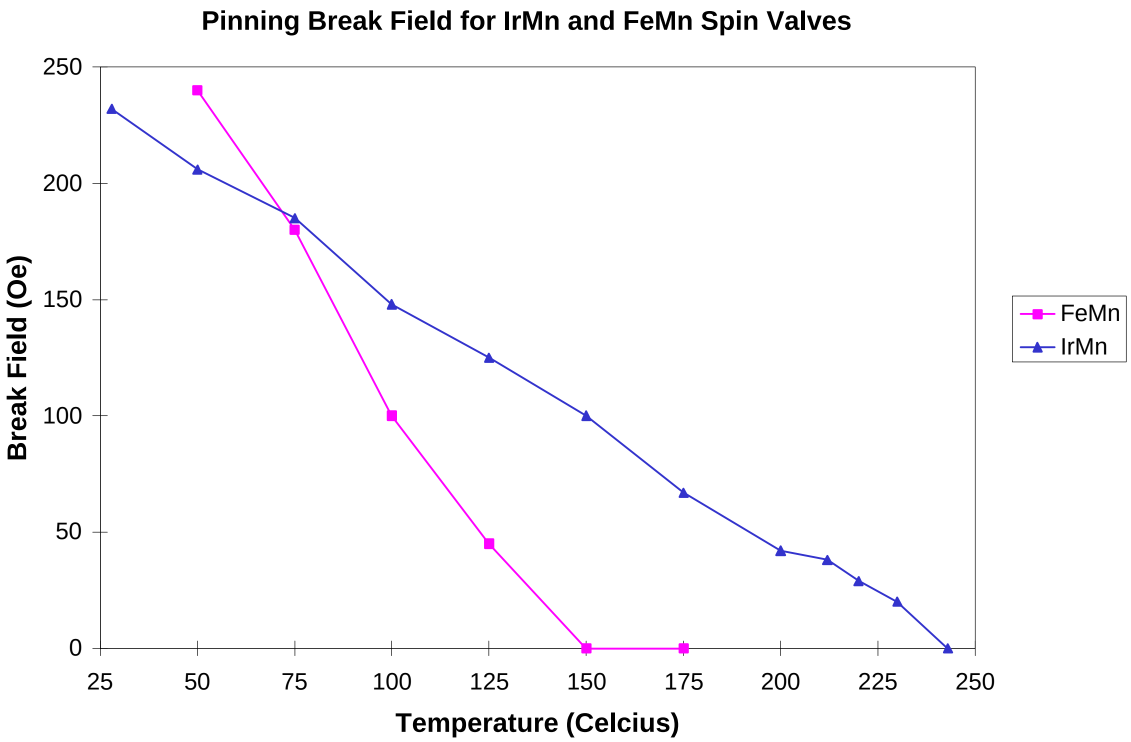

Figure 4: The pinning break field (see Figure 1 for definition) decreases monotonically with temperature for both FeMn and IrMn pinned spin valves. The blocking temperatures are about 150 ^{0}Cand 240 ^{0}C for FeMn and IrMn, respectively.

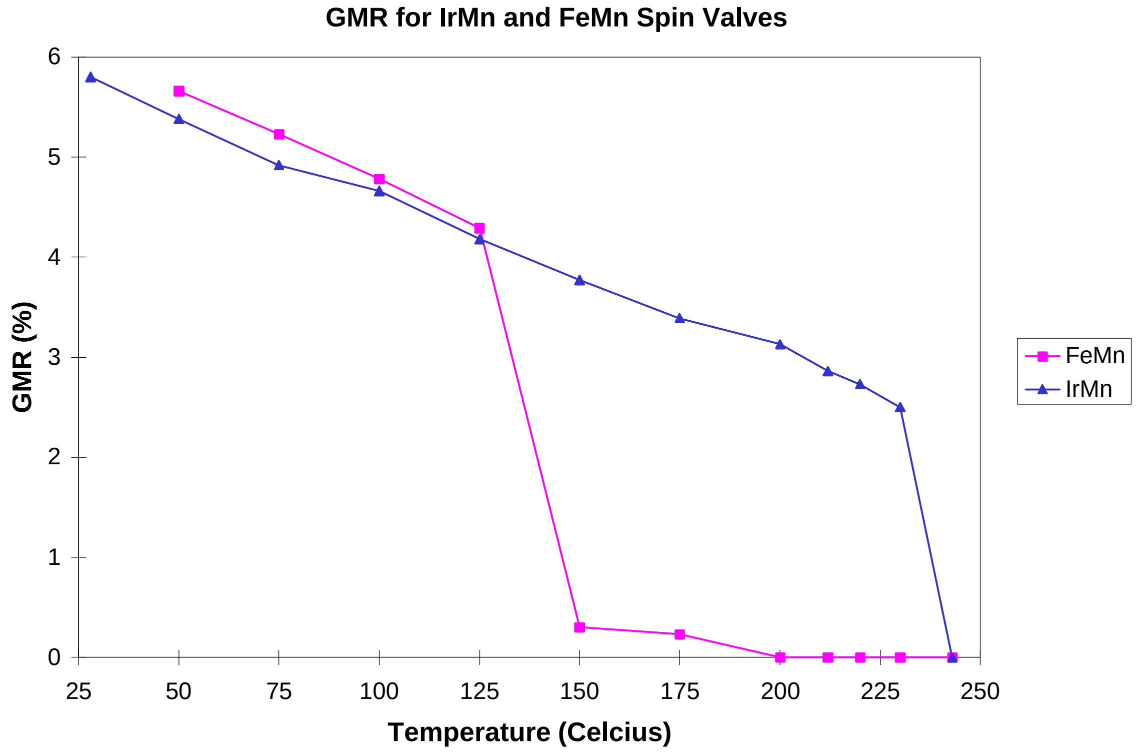

Figure 5: The GMR exists over a significantly wider temperature range for IrMn pinned spin valves. The linear decrease in GMR with temperature (before the catastrophic decrease) is related the temperature dependence of the spin dependent scattering ratio within the spin valves and not to the type of pinning layer.

References

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[1] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Freiderich, and J. Chazelax: “Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices,” PRL 61 (1988), pp. 2472-2475.

[2] G. Binasch, P. Grunberg, F. Saurenback, and W. Zinn “Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange, PRB 39 (1989), pp. 4828-4830.

[3] J.M. Daughton and Y. Chen, "GMR Materials for Low Field Applications," IEEE Transactions on Magnetics, Vol. 29, No. 6, pp. 2705-2710, November, 1993

[4] "Magnetic Field Sensors Using GMR Multilayer", J. Daughton, J. Brown, R. Beech, A. Pohm, and W. Kude, IEEE Trans. Mag., Vol. 30, No. 6, Nov., 1994.

[5] J.M. Daughton, "Weakly Coupled GMR Sandwiches", IEEE Transactions on Magnetics, Vol. 30, No. 2, pp. 364-368, March, 1994.

[6] Takashi Umemoto, Atsushi Maeda, Seiichirou Takahashi, Toshio Tanuma, and Minoru Kume, "Physical Properties of CoFe/IrMn Spin-Valves Prepared Using Ion Beam Sputtering with an Xe-H-2 Mixture Gas," Jpn. J. Appl. Phys. Pt.1 , Vol 36, No. 11, (1997), pp. 6746-6748.

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[7] M. Lederman, "Performance of Metallic Antiferromagnets for Use in Spin-Valve Read Sensors," (not yet published).

[8] H. Iwasaki, A.T. Saito, A. Tsutai, and M. Sahashi, "Excellent Reliability of CoFe-IrMn Spin Valves," IEEE Trans. Mag., Vol. 33, No. 5, Sept. 1997, pp. 2875-2877.

[9] Hironi Niu Fuke, Kazuhiro Saito, Yuzo Kamiguchi, Hitoshi Iwasaki, and Masashi Sahashi, "Spin-valve Giant Magnetoresistive Films with Antiferromagnetic Ir-Mn Layers," JAP Vol. 81 (8), April 15, 1997, pp. 4004-4006.

[10] Ryoichi Nakatani, Hiroyuki Hoshiya, Katsumi Hoshino, Yutaka Sugita, "Relationship between film structure and exchange coupling in Mn-Ir / Ni-Fe films," JMMM 173, (1977), pp. 321-330.

[11] A.J. Devasahayam, P.J. Sides, and M.H. Kryder, "Magnetic, temperature, and corrosion properties of the NiFe/IrMn exchange couple," JAP 83 (11), June 1, 1998, pp. 7216-7218.

[12] Sining Mao, Nurul Amin, and Ed Murdock, "Temperature dependence of

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giant magnetoresistance properties of NiMn pinned spin valves," JAP 83 (11), June 1, 1998, pp. 6807-6809.

[13] Akihiro Maesaka, Nobuhiro Sugawara, Akihiko Okabe, and Masao Itabashi, "Influence of microstructure on thermal stability of spin-valve multilayers," JAP 83 (12), June 15, 1998, pp. 7628-7634.

[14] Mark Tondra, A. Fink, R.S. Beech, D. Wang, J.A. Taylor, J.M Daughton; “Picotesla Field Sensor Design Using Spin Dependent Tunneling Devices,” J. Appl. Phys. **83**, 6688 (1998).