Magnetoresistance Overview

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HPL-95-60
June, 1995

magnetoresistance,
SAL, dual stripe,
spin valve, GMR

Magnetoresistance, the change of a material's resistivity with the application of a magnetic field, is a well known phenomenon. The magnitude of the effect in materials used in the recording industry has historically been very small, only about 2% at room temperature for "anisotropic" magnetoresistant materials. In 1988, Baibich *et al* reported magnetoresistance effects of up to 50% at low temperature in "giant" magnetoresistive multilayer structures. More recently, effects of 99.9% change in resistivity have been discovered in the perovskite system $La_{1-x}Ca_xMnO_3$, termed "colossal" magnetoresistance. Magnetic read heads utilizing "anisotropic" magnetoresistance have been successfully fabricated and marketed. Prototypes of read heads utilizing "giant" magnetoresistance have also been made. The distinctly different materials and mechanisms responsible for the varied magnetoresistance effects - ordinary, anisotropic, giant and colossal - will be discussed. Also various designs of magnetic read heads utilizing the "anisotropic" and "giant" magnetoresistive materials are presented.

Magnetoresistance, where the resistance of the material changes with applied magnetic field, occurs in all metals. Classically, the MR effect depends on both the strength of the magnetic field and the relative direction of the magnetic field with respect to the current. Four distinct types of magnetoresistance will be reviewed here: ordinary magnetoresistance, anisotropic magnetoresistance, giant magnetoresistance, and colossal magnetoresistance. The materials and mechanisms for these four types of magnetoresistance are distinctly different.

1. Ordinary Magnetoresistance (OMR)

For non-magnetic metals, MR effects at low fields are very small, although the effect can become quite large for high fields. The change in resistivity, $\Delta\rho$, is positive for both magnetic field parallel ($\Delta\rho_{\parallel}$) and transverse ($\Delta\rho_T$) to the current direction with $\rho_T > \rho_{\parallel}$. There are three distinct cases of ordinary magnetoresistance, depending on the structure of the electron orbitals at the Fermi surface:

i) In metals with closed Fermi surfaces, the electrons are constrained to their orbit in **k** space and the effect of the magnetic field is to increase the cyclotron frequency of the electron in its closed orbit. Cyclotron frequencies as large as $\omega_c\tau = 100$ have been achieved. In this case the resistance saturates at very large magnetic fields. Metals which exhibit this behavior include In, Al, Na and Li (see Figure 1a)

ii) For metals with equal numbers of electrons and holes, the magnetoresistance increases with H up to the highest fields measured, and is independent of crystallographic orientation. Examples of metals displaying this behavior are Bi, Sb, W, and Mo.

iii) Metals that contain Fermi surfaces with open orbits in some crystallographic directions will exhibit large magnetoresistance for fields applied in those directions, whereas the resistance will saturate in other directions, where the orbits are closed. This behavior will be found in Cu, Ag, Au, Mg, Zn, Cd, Ga, Tl, Sn, Pb, and Pt (see Figure 1b).

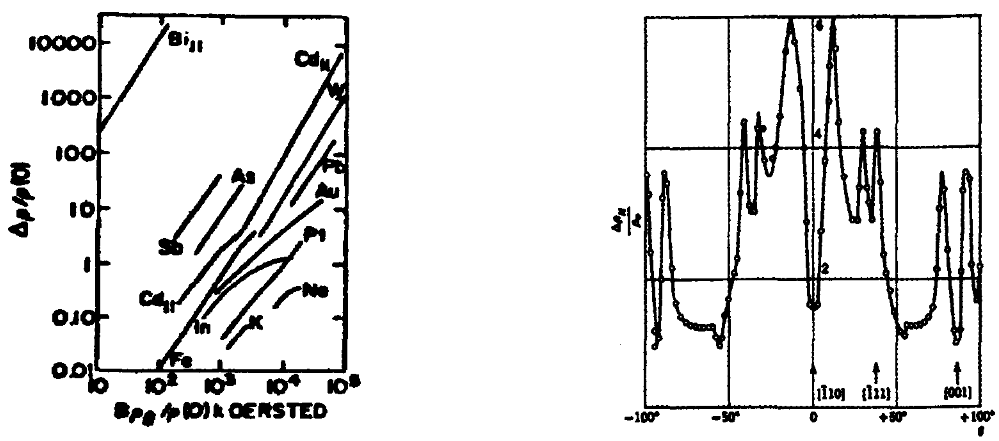

Figure 1: a) reduced Kohler plot giving OMR data for selected metals. $\rho(0)$ = resistance in zero field; ρ_θ = resistance at the Debye Temperature; and B is magnetic field in kOe. [Ref. 1]. b) Variation of transverse MR with field direction for single crystal Au. Current parallel to [110]; B=23.5 kOe. [Ref. 2].

2. Anisotropic Magnetoresistance (AMR)

In ferromagnetic metals and alloys, MR effects on the order of $\Delta\rho/\rho$ of 2% are obtained in low fields. In contrast to OMR, the effect is anisotropic, where $\Delta\rho_{\parallel}$ increases with field, and $\Delta\rho_T$ decreases with field (see Fig. 2).

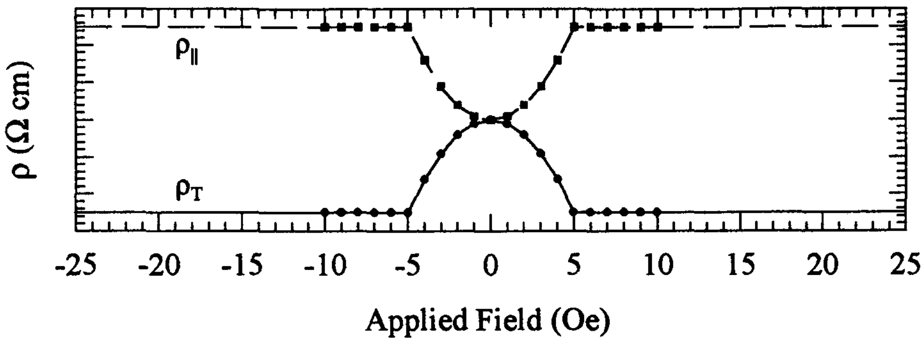

Figure 2: Schematic representation of anisotropic magnetoresistance in permalloy for field applied parallel ($\rho_{\parallel}$) and transverse (ρ_T) to the current direction.

The physical origin of the magnetoresistance effect lies in spin orbit coupling. The electron cloud about each nucleus deforms slightly as the direction of the magnetization rotates, and this deformation changes the amount of scattering undergone by the conduction electrons when traversing the lattice. A heuristic explanation is that the magnetization direction rotates the closed orbit orientation with respect to the current direction. If the field and magnetization are oriented transverse to the current, then the electronic orbits are in the plane of the current, and there is a small cross-section for scattering, giving a low resistance state. Conversely for fields applied parallel to the current, the electronic orbits are oriented perpendicular to the current, and the cross-section for scattering is increased, giving a high resistance state (See Figure 3).

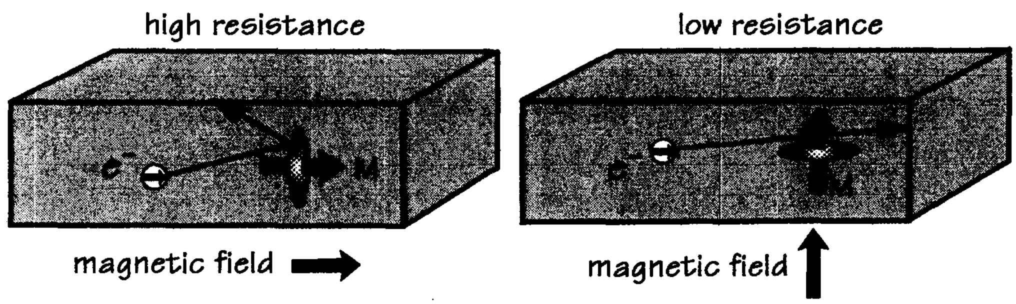

Figure 3: Schematic demonstrating the physical origins AMR. Shaded ovals represent the scattering cross-sections of the bound electronic orbits. When the orbits (and applied field) are transverse to the current direction, the electron scattering cross-section is reduced, giving a low resistance state.

The ferromagnetic material utilized for AMR heads is NiFe (permalloy). This is due to the relatively large effect at room temperature ($\Delta\rho/\rho \sim 2\%$), and the low saturation fields ($H_s \sim 5$-10 Oe) required to obtain the AMR effect. In recording heads, the geometry is such that the field from the media is transverse to the current direction in the head, thus the AMR effect for fields applied transverse to the current direction is utilized (ρ_T in Figure 2). In order to make a useful device, one requires a unique response for both positive and negative applied fields. One therefore wants the operating point (zero applied field) to be either on the increasing or decreasing slope of the AMR response. This is called "biasing" the head. There are two pertinent biasing methods currently used in AMR heads: the Soft Adjacent Layer and Dual Stripe configurations.

2.1 Soft Adjacent Layer (SAL):

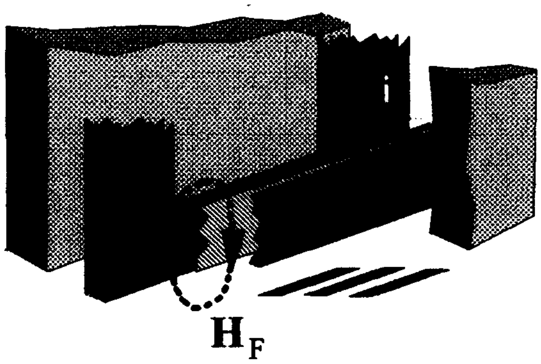

Figure 4: Schematic of recording head utilizing the SAL biasing technique. The fringing field from the SAL layer rotates the magnetization of the AMR element, effectively biasing the head.

The SAL method of biasing the AMR read heads has been developed and utilized by IBM [Ref. 3]. The idea is to place a soft magnetic material adjacent to the AMR material. When the soft magnetic layer is magnetized (field produced by a current is sufficient to magnetize the SAL layer), it produces a fringing field (H_F) that rotates the magnetization of the AMR material with respect to the current (see Fig. 4). Since the change of resistance in an AMR head goes as $\cos^2\theta$, where θ is the angle between the magnetization direction and the current, the optimum bias configuration is to rotate the magnetization of the AMR material to 45 degrees with respect to the current direction. This will shift the resistivity at zero applied field to a value midway between the maximum and minimum of ρ_T. Thus the resistivity will either increase or decrease when sensing positive or negative fields. The response of the head, however is non-linear, since the voltage response is proportional to the negative parabolic field response of the AMR material (Figure 5). Furthermore, the SAL biased head has an asymmetric cross track profile, as well as asymmetric peak heights, making servo techniques more difficult.

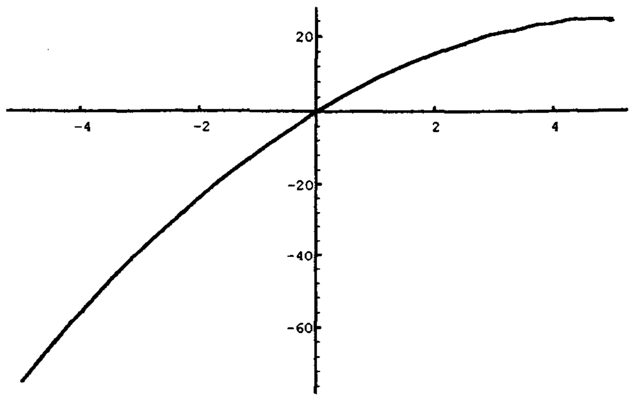

Figure 5: Simulated output of a SAL biased AMR recording head. Function plotted is $V = -[(x-x_0)^2 + y_0]$: the abscissa represents the applied field; the ordinate, the voltage response (arbitrary units). Note the non-linearity of the response - the magnitude is less for positive applied fields than for equally large negative applied fields - giving asymmetric peak heights in the read back signal.

2.2 Dual Stripe

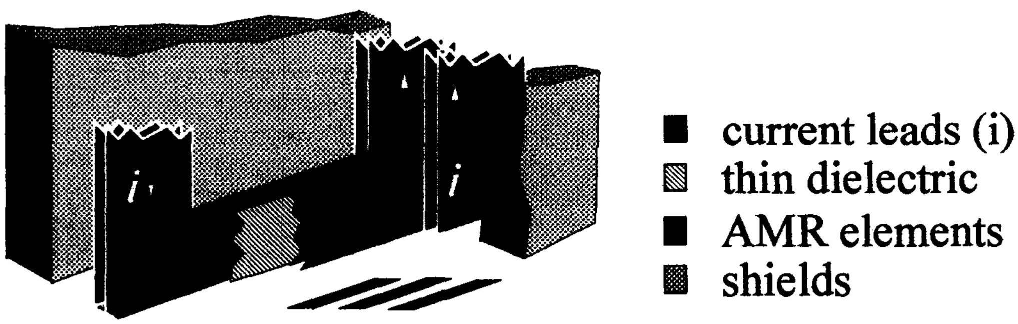

Figure 6: Schematic of Dual Stripe Magnetoresistance head. The magnetic fields generated by the current in each stripe bias the other stripe.

The dual stripe method of producing a biased AMR head was developed and utilized by Hewlett Packard [Ref. [4]]. The design consists of two AMR stripes separated by a thin dielectric (Figure 6). Current is run through both stripes and the leads are shorted at one end. The magnetic fields generated by the current in each stripe bias the other stripe. The advantage of the dual stripe design is that the response of the head is a differential between the responses of the individual AMR elements. Each MR element produces a signal proportional to $-(x-x_0)^2$. Since each of the AMR elements are biased in opposite directions, $x_{01} = -x_{02}$. The ultimate signal is the difference between two offset negative parabolas. Figure 7 shows an output simulated by taking the difference of two negative parabolas with equal and opposite offsets. Note the linearity of the signal. In addition the dual stripe configuration gives a symmetric cross-track signal, facilitating servo techniques. The dual stripe head design is superior to the SAL head design in that it provides higher output per unit track width, common mode noise rejection, superior second harmonic suppression, and linear cross-track profiles.

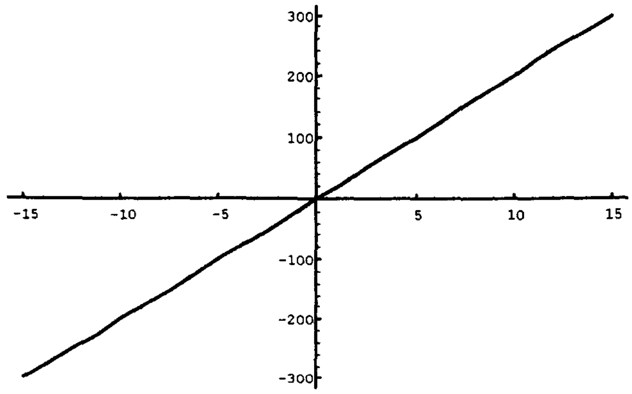

Figure 7: Simulated output of dual stripe magnetoresistive head. Function plotted is $V=[-(x-x_0)^2]-[-(x+x_0)^2]$: abscissa represents the applied field; the ordinate, the voltage response (arbitrary units). Note the linearity of the response.

3. Giant Magnetoresistance (GMR)

Giant Magnetoresistance (GMR) was discovered in 1988 by Baibich *et al.* [Ref. 5], in antiferromagnetically coupled multilayers of Fe/Cr. In this structure, thin layers of magnetic metals are separated by layers of non-magnetic metals. The magnetic layers are coupled through the non-magnetic layers in either a ferromagnetic or antiferromagnetic configuration depending on the thickness of the non-magnetic layers. Magnetoresistance effects of up to ~50% were observed at low temperatures (Figure 8). This effect was subsequently found to occur in a number of multilayer magnetic film systems.

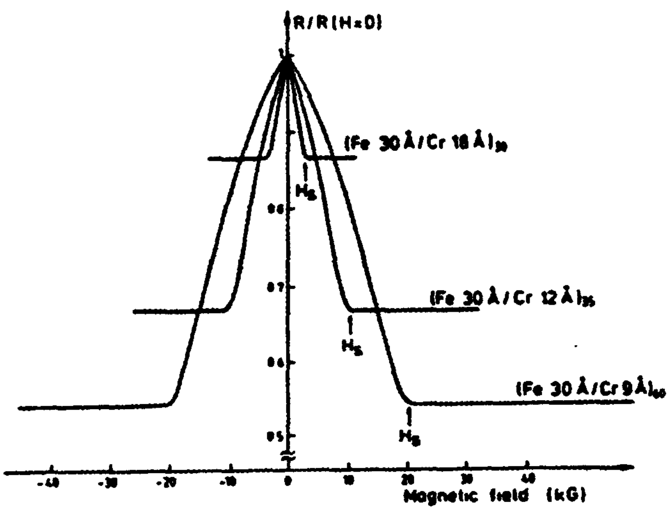

Figure 8: Giant Magnetoresistance effect as reported by Baibich *et al.*

The GMR effect requires that there is a method to change the relative orientations of the magnetization in adjacent magnetic metal layers, and that the thickness of the films must be less than the mean free path of the electrons. A heuristic model of the GMR effect is schematically shown in Figure 9. The GMR effect can be qualitatively understood on the basis of a two fluid model of the conduction process in a magnetic metal. The conduction electrons are divided into two classes: those whose spin is parallel to the local magnetization and those whose spin is antiparallel.

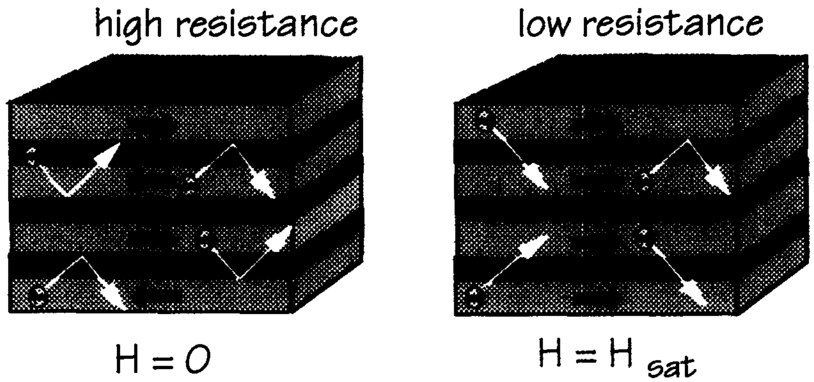

Figure 9: Schematic of the high and low resistance states of the GMR multilayer systems. Gray: magnetic layers; black: non magnetic layers.

The resistance of the material is determined by the scattering processes to which the electrons are subject. Strong scattering processes produce a short mean free path and large resistance, weak processes produce long mean free paths and lower resistance. GMR effects are produced when the scattering processes for one spin orientation of the conduction electrons is more effective than for the other spin orientation, known as spin dependent scattering. In the two fluid picture, electrons with spin oriented parallel to the magnetization of the metal have a lower resistance than those whose spins are oriented antiparallel. The high resistance state of the GMR materials occurs when the magnetic layers are antiferromagnetically coupled, so all electrons experience strong scattering at the interfaces where the magnetization of the material is opposite to the spin orientation. The low resistance state is obtained when a the applied magnetic field is strong enough overcome the antiferromagnetic coupling, and rotates the magnetization of the layers to a ferromagnetic configuration. When the magnetic layers are ferromagnetically aligned, only half of the conduction electrons experience strong scattering processes, while the other half experience weak scattering processes, with the net effect of reducing the overall resistance of the material. Note, in contrast to the AMR effect, the GMR effect depends on the relative orientation of the magnetization in the layers, and not on the direction of the current.

For a multilayer array to be attractive as an MR head sensor, it must have not only a large $\Delta\rho/\rho$, but also have a large dependence of resistance on magnetic field. The original Fe/Cr system shown in Figure 8, requires extremely large fields (20 kG) to rotate the magnetization to the ferromagnetic configuration, and is therefore unattractive as a recording head device. Schemes have been developed, however where *uncoupled* magnetic films can be switched from the antiparallel to parallel configuration. These devices have been termed Spin Valve structures.

3.1 Spin Valves

Spin valves are four layer structures containing an antiferromagnetic "pinning" layer, and two inequivalent, thin, magnetic films which are separated by a non-magnetic spacer. The upper film has its magnetization pinned in one orientation (by exchange coupling to the pinning layer), while the lower magnetic layer (sense layer) is free to switch back and forth in the presence of a magnetic field. The thickness of the non-magnetic spacer layer is large enough to make negligible the coupling between the two magnetic layers; thus, the field dependence of the effect is low. The principle for lowering the resistance is the same as in the GMR multilayer; that is, spin dependent scattering gives a low resistance state when the magnetic layers are ferromagnetically aligned, while a high resistance state is obtained in the antiferromagnetic configuration (Figure 10).

In the spin valve structures, the resistance depends on the angle between the respective magnetization of the two magnetic layers, and not on the angle with respect to the current direction, as in the AMR materials. The resistance changes as a function of $\cos(\theta_1-\theta_2)$, which is $\cong \sin(\theta_1)$, since the angle θ_2 is kept fixed ("pinned") at 90 degrees (Figure 11). Since the response of the device goes as $\sin\theta$, the response of the head is already single valued with respect to the driving field, and the device is self biased, eliminating the need for complicated biasing schemes. However, optimizing the spin valve heads such that the many magnetic fields (demagnetizing fields, fields due to currents, anisotropy fields, etc) are balanced requires extensive research. One of the schemes developed to avoid some of these problems is the "dual spin valve" where two spin valve structures are sandwiched together, with the sense, or free, magnetic layer in the center. This configuration gives twice the $\Delta\rho/\rho$ obtained from the single spin valve structure (Figure 13).

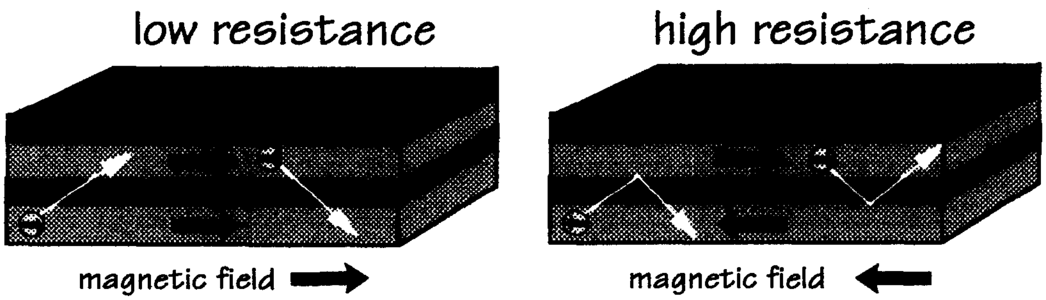

Figure 10: Schematic of the principle of operation of a spin valve system. Two magnetic layers (gray) are separated by a non-magnetic spacer (black). The magnetization of the top layer is pinned by exchange coupling to an antiferromagnet layer (pattern), while the magnetization of the bottom magnetic layer (sense layer) is free to rotate in response to a magnetic field.

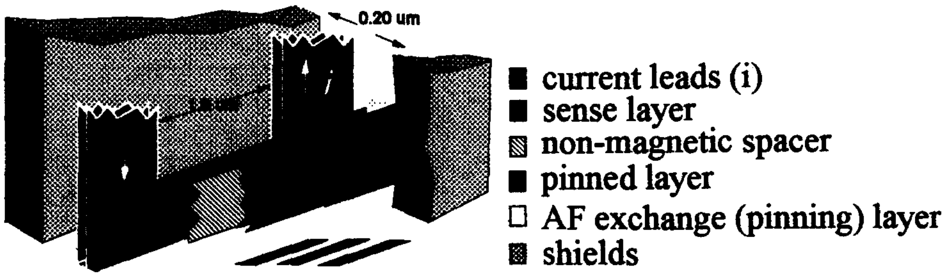

Figure 11: Schematic of a spin valve read head. The magnetization of the pinned layer (pointing up) is set 90 degrees to the zero field state of the sense layer (aligned along the track width). Positive fields decrease the angle between the two magnitizations, decreasing the resistance; whereas, negative fields increase the angle and the resistance.

Spin valve magnetoresistive read heads have been demonstrated by both IBM and HP. The IBM head has reported signals with peak to peak amplitudes of ~750 - 1000 μV/μm of read trackwidth [Ref. 6]. HP has obtained 1200 μV/μm, much greater than those obtained in the AMR heads. Problems with signal symmetry, stabilization, and thermal effects due to high currents have to be addressed. Optimization of the heads is in progress. The output of a HP spin valve head is shown in Figure 12.

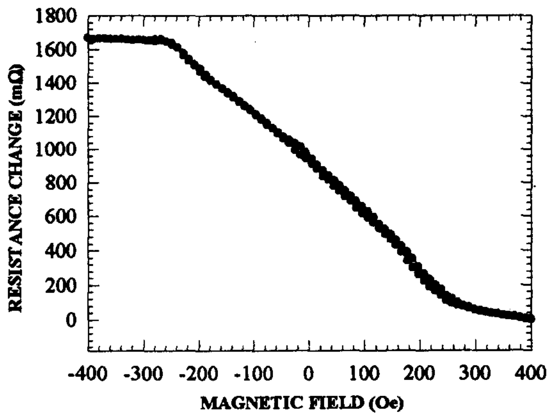

Figure 12: Output of HP spin valve head. Note linearity of signal, lack of hysterysis and lack of noise in the operating region.

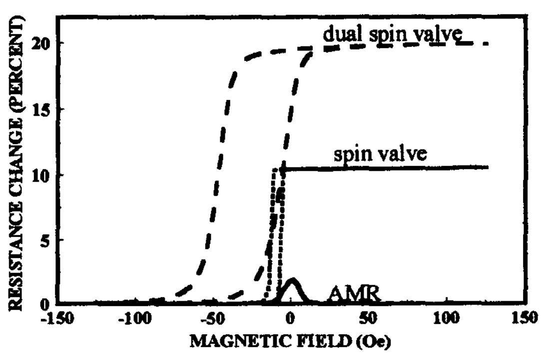

Figure 13: Comparison of the percentage of resistance change for an AMR, spin valve and dual spin valve heads.

4. Colossal Magnetoresistance (CMR)

Colossal magnetoresistance has recently been discovered in $La_{1-x}M_xMnO_{3+\delta}$ (M = Ca, Sr) perovskite structures. The largest effects have been observed for x=0.33. The term colossal has arisen from the huge effects observed, on the order of $\Delta R/R(H)$ = 125,000%. If normalized to the zero field values, the resistance changes by 99.9% Figure 14 shows the data published by Jin *et al.* [Ref. 7] The resistivity of the material undergoes a low temperature transition from an insulating to a metallic behavior. The colossal magnetoresistance effect is observed in the metallic regime. Recent research has shown that the insulating to metal transition and CMR effect can be raised up to room temperature. HP has produced high quality CMR films with room temperature reduction in resistance of about 95%. This resistance reduction is relatively flat in a temperature range of about 50 degrees (Figure 16). These results were reported at the CMR workshop HP hosted at Los Alamos National Laboratory in February, 1995 [Ref. 8]. A significant problem still remaining with these materials is the field dependence of the resistance. Fields on the order of 10^4 Oe are required to obtain the large effect. These issues will be the focus of future research in the precompetitive collaboration HP is hoping to establish with Los Alamos and other researchers.

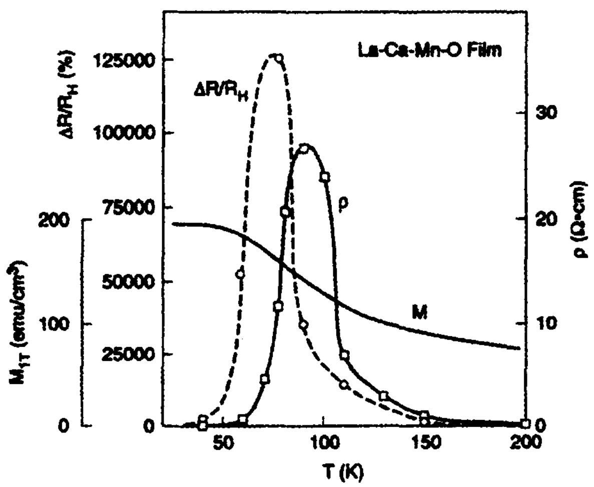

Figure 14: CMR results reported by Jin *et al.*

The CMR materials have the perovskite structure; the structure of $La_{0.67}Ca_{0.33}MnO_3$ is shown in Figure 15. In a simplistic view, the Mn in the MnO planes are aligned ferromagnetically within the **a-b** plane, with planes along the **c** axis aligning in an antiferromagnetic order (Figure 15). The application of a field switches the ordering of the Mn ions along the **c** axis, so that all of the Mn ions are magnetized in the same direction. In actuality, pure antiferromagnetic ordering is only observed in the end members $LaMnO_3$ and $CaMnO_4$. The exact magnetic ordering of the mixed oxides is not known; however, it is known that doping causes the spins to cant and induces both ferromagnetism and conduction. Application of a magnetic field most likely increases the alignment of the spins, and decreases the resistivity. However, alternative mechanisms cannot be ruled out. For instance, the extremely large MR effect is only seen in epitaxially grown materials, with a much reduced effect in bulk materials. It has been shown that the lattice constant in the epitaxially grown materials is smaller than that in the bulk. Thus, it has been hypothesized that the distances between the magnetic ions is what is important, in that it will affect the indirect exchange interaction responsible for conductivity in these materials. Application of a magnetic field may affect the distances between the Mn ions, affecting the frequency of the exchange coupling, and consequently the resistance.

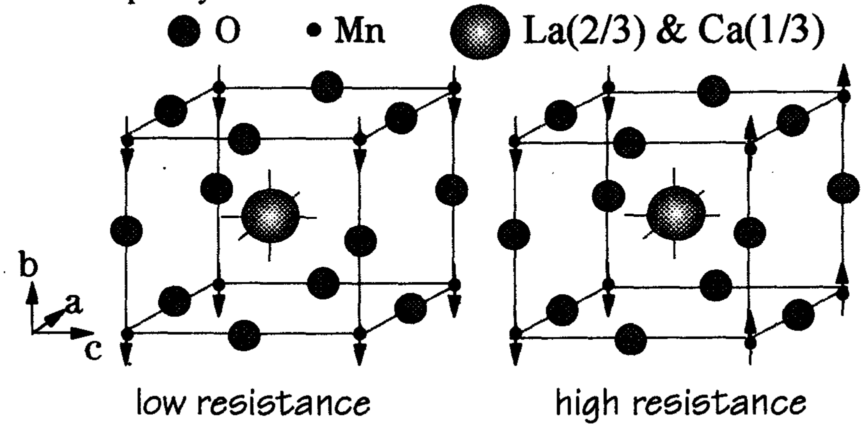

Figure 15: Crystal structure of $La_{0.67}Ca_{0.33}MnO_{3+\delta}$. Center of unit cell: La and Ca ions; corners: Mn ions; edge center: oxygen ions. Magnetization of the Mn ions (for 0% Ca) is indicated in the high resistance state diagram. Canting of the spins, ferromagnetism and conductivity are induced by doping with Ca^{2+}. See text for clarification.

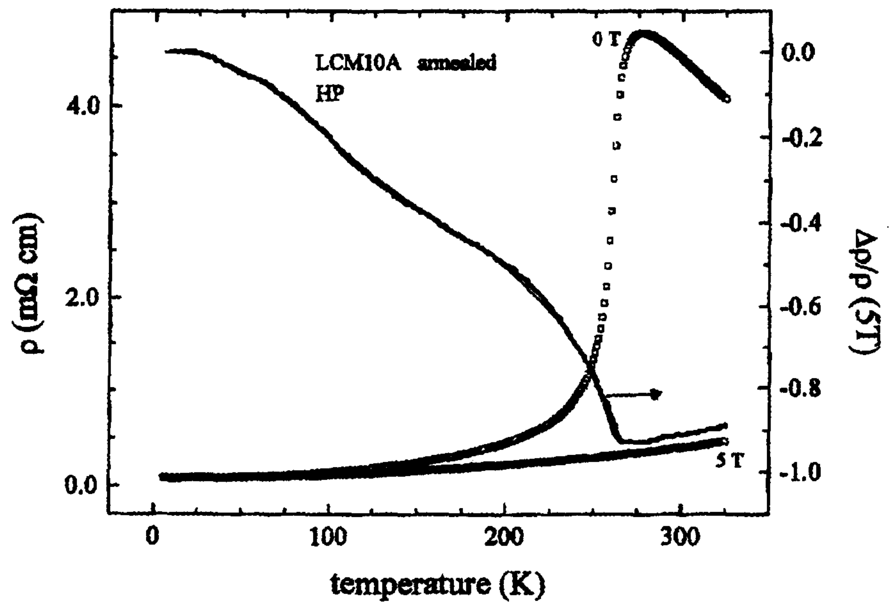

Figure 16: Resistivity at H = 0 and 5 Tesla (squares), and magnetoresistance effects of CMR samples grown at HP Labs. Note a decrease in resistance of over 90% at room temperature. Also, the magnetoresistance effect is relatively constant over a temperature range of ~ 50 degrees.

The mechanism for magnetoresistance in these materials is distinctly different than that in the GMR multilayer systems. In the CMR materials, conduction occurs by hopping (basically by exchanging a Mn^{3+}–Mn^{4+} pair to a Mn^{4+} –Mn^{3+} pair), and not by metallic conduction. The magnetic ordering in the CMR structures occurs on an atomic scale, and is produced by an indirect exchange mechanism; whereas, the magnetic ordering in the GMR materials occurs over tens of Angstroms, and is produced by the RKKY interaction. The mechanism of the CMR effect is certainly not well understood, and there remains much research to be done.

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