MMM - the fourth decade - to 1995

32th MMM: High-Tc Superconductors, MFM instruments

PREFACE

The 32nd Annual Conference on Magnetism and Magnetic Materials was held in Chicago, Illinois, from November 9–12, 1987. The conference proved exciting and stimulating to a diverse array of researchers, with interests that span the range from the basic physics of magnetism, to applications of magnetic materials and the development of magnetic devices. A total of 788 people registered at the conference, and a total of 575 papers were presented, in either an oral or poster format.

For several decades, the field of magnetism has stimulated the development of fundamental new physical concepts which, in the end, have wide impact outside the field, and devices which utilize new sophisticated magnetic materials play an increasingly important role in our economy. From the technical program of the 32nd MMM Conference, several intriguing new areas of research are evident.

Quite clearly, the new high-temperature superconductors will have an impact on a variety of magnetic devices, and there is evidence that the mechanism which underlies their unique superconducting properties may be intimately related to the magnetic character of spins which reside in the quasi two dimensional sheets of copper and oxygen ions. It is fascinating to see novel and abstract theoretical concepts which have emerged from studies of models of magnetism in less than three dimensions applied to assist in the understanding of a very important new scientific problem of great practical significance. Surely this could not have been foreseen at the time the basic theoretical studies were undertaken. These questions, and presentations of the latest experimental data, were addressed in a very well attended symposium devoted to high temperature superconductivity.

We also see increasing attention devoted to the synthesis and analysis of exotic new magnetic materials, from monolayers for ultra thin films (few atomic layers) of ferromagnetic metals such as iron and nickel, and superlattice structures of exceptional quality synthesized from a variety of magnetically ordered, very thin rare earth films. Numerous experimental and theoretical papers addressed questions in this area; it is evident one can now prepare multilayer magnetic structures with interface quality comparable to that realized in structures fabricated from semiconductors.

There are also new developments in instrumentation evident from papers presented at the meeting. A major new innovation is the development of vibrating read magnetometers with sensitivity some orders of magnitude higher than earlier generations of instruments. The sensitivity of these devices now approaches that of SQUID magnetometers; as few as 10^7 spins may now be detected. We may expect to see these new instruments in many research laboratories in the very near future.

The above remarks touch on only a few aspects of the conference program, but they illustrate that the field of magnetism is alive and vital, repeatedly refreshed by the appearance of new classes of materials that open new applications, and which also cause us to extend our knowledge of the basic principles of physics.

The success of the 1987 MMM Meeting is also a consequence of the efforts of many people. As General Chairman, I was surrounded by many with new ideas and suggestions, and everyone completed their part with close attention to our scheduled deadlines. It was a pleasure to work with such a group. We owe special thanks to the staff of Courtesy Associates, and to that of the American Institute of Physics.

D. L. Mills
General Chairman
1987 MMM Conference

Antiferromagnetism in the high-T_c related compounds (invited)

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Magnetic susceptibility measurements on La_2CuO_{4-y} have revealed maxima in temperature indicative of antiferromagnetic ordering. Powder diffraction measurements have demonstrated the existence of superlattice peaks at temperatures below those corresponding to the susceptibility maxima, and polarized neutron measurements have confirmed that the peaks are indeed of magnetic origin. The deduced antiferromagnetic structure in the orthorhombic (Cmca) phase of La_2CuO_{4-y} consists of ferromagnetic sheets of Cu atoms in the *bc* plane which are alternating in sign along the *a* axis [100]. The moment is parallel to the *c* axis. The Neel temperature is extremely sensitive to the oxygen deficiency *y* and decreases rapidly to zero at *y* goes from 0.02 to 0. The saturated moment is $\sim 0.4\mu_B$/Cu atom for samples with the highest T_N (240 K). Antiferromagnetic spin fluctuations have also been observed by polarized neutron scattering in the paramagnetic phase above T_N. Recent results obtained on magnetic ordering in the $YBa_2Cu_3O_{6+y}$ family of compounds are also discussed, together with the possible implications for novel superconductivity mechanisms.

From the basic physics point of view, perhaps the most interesting question regarding the so-called "high-T_c" superconductors is this: Is the mechanism nonvibrational electron-phonon coupling, or is it different from that in all superconductors known so far? In particular, if the mechanism is not due to phonons, could it be associated with spin fluctuations or magnetic interactions in a general sense? The entire theory advocating the latter point of view for the present group of materials was put forward by Anderson in the form of his resonating valence bond (RVB) theory,[1] and numerous several different theories have been presented which consider superconductivity arising from these same interactions which produce magnetism, and in some cases, even combining with long-range antiferromagnetic order.[2-10] In this paper, we shall describe how antiferromagnetic order is indeed seen by neutron diffraction in this family of compounds, although, as we shall see, the relationship to superconductivity is still unclear at the present time.

We first discuss the case of antiferromagnetism in the parent[11] compound La_2CuO_{4-y} of the A_2BO_{4-y} family of superconductors, where A is lanthanide and B = Cu, Ni, and Pd. Results for transition temperatures and the measured susceptibility of La_2CuO_{4-y} were found several years ago, indicating some kind of phase transition. Systematic recent studies by Johnston and co-workers[12] indicate a strong sample dependence in the temperature of this transition. The temperatures of the susceptibility maxima for samples with the highest transition temperatures for La_2CuO_{4-y} are $T_N = 240$ K for $y \simeq 0$ to $T_N = 295$ K for $y \simeq 0.03$. The anomaly disappears for $La_{1.85}Sr_{0.15}CuO_{4-y}$ samples for Sr concentrations $x \geq 0.1$. The susceptibility data for a 5-0.1 also indicate a broad rise in the susceptibility in the region ~ 250–600 K, as shown in Fig. 1.

La_2CuO_{4-y} is tetragonal at high temperatures and undergoes an orthorhombic distortion at lower temperatures, which doubles the tetragonal unit cell in the basal plane.[13] The transition temperature T_o is highly sensitive to the oxygen vacancy concentration *y* in the material, varying from 450 to 320 K depending on *y*.[14] The orthorhombic space group is Cmca, where (unlike the tetragonal system) the *a* and *c* axis lie in the basal plane and the *b* axis is along the original tetragonal *c* axis normal to the Cu-O layers.

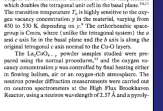

FIG. 1. Magnetic susceptibility χ_g vs temperature for three samples of La_2CuO_{4-y}.

Magnetic imaging by atomic force microscope (invited) (abstract)

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A new method of imaging the surface of magnetic samples on a submicron scale is described and the observation of magnetic domain walls is presented. Measurements in air on a Co-Ni recording media, polycrystalline Ni foil and rapidly quenched alloys are shown. This magnetic microscope is based on the idea of measuring magnetic forces with the recently developed atomic force microscope (AFM). Forces acting on a tip are recorded by the measurement of the deflection of a lever to which this tip is attached. In order to measure ultra weak forces (less than 10^{-9}N), the spring constant of the lever has to be small and the deflection of the lever has to be measured with great sensitivity, i.e., by using interferometry or scanning tunneling microscopy (STM). The lever is made from ferromagnetic Ni foil with an integrated, electrochemically etched tip. Different measuring modes of the AFM are described. The images obtained by the AFM using a para- or ferromagnetic tip and by the STM are compared. Furthermore, the results obtained by the magnetic AFM on Co-Ni recording media are compared with previous studies by scanning electron microscopy with polarization analysis (SEMPA).

34th MMM: AMR recording head

Heads-Interfaces-Systems for Storage — Robert Fontana, Jr., Chairperson

Shielded MR head for high-density magnetic recording (invited)

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A narrow-gap shielded magnetoresistive (MR) head with a 0.5-μm track width has been constructed for high-density magnetic recording. The head consists of a pair of NiFe shields and a trilayered MR element between the shields. In the MR element NiFe, Ti, and amorphous CoZrMo films are used. The thickness of the three layers and the shields, as well as the shield gap length, are optimized with a one-dimensional self-consistent calculation. The oxidized MR head has been fabricated using calculated design parameters for individual layers: 60 nm for CoZrMo with 40 nm NiFe and 20 nm Ti, 1-μm shields, and 0.5 μm for the total shield gap. The reproduced characteristics from the MR head are evaluated with a plated disk. Neither Barkhausen noise nor distortion is observed in the output waveform. The output voltage is 800 μV$_{p-p}$ at a 4 mA/μm sense current with 30 kFCI transition density. The Δt_{50} transition density is 40 kFCI. These values are in good agreement with the calculated values. Assuming a 12-μm track pitch, crosstalk is −29 dB from off-track crosstalk characteristics. This shielded MR head has a potential to achieve high recording density with 40 kBPI and 2000 TPI for small-size disk drives.

INTRODUCTION

Magnetoresistive (MR) heads[1] are very attractive for small-size high-density disk drives, because they can represent a high output signal independent of the disk relative velocity, whereas the output signal of the conventional inductive heads decreases in proportion to the disk relative velocity for small-size disk drives. The resolution of the MR heads has improved by the magnetic shields,[2] which are positioned near both sides of an MR element as shown in Fig. 1. The gap length G_s of the thin film magnetic head can be reduced in order to achieve high transition density.

We previously presented a trilayered MR element,[3,4] which consists of an amorphous CoZrMo film as a soft adjacent layer (SAL), a Ti film as a magnetic separation layer, and a NiFe film as a magnetoresistive layer (MRL). The SAL, which is magnetically the most active layer in the trilayered MR element, is expected to have a high permeability and a high saturation magnetization. The MRL in this trilayered MR element is magnetically inactive because the SAL and the MRL. The thin magnetic separation layer, however, is necessary to prevent exchange coupling between the SAL and the MRL. The total thickness of the MR element consequently can be reduced. The compact structure of this trilayered MR element is suitable for application to a narrow-gap shielded MR head, which enables a high transition density.

In this paper, we describe the design and performance of the narrow-gap shielded MR head which consists of the trilayered MR element between NiFe shields.

DESIGN

Computer simulations were implemented with the modified Jayasuriya–Bertram model.[5] The bias field generated by external field from the media were calculated self-consistent-

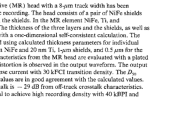

FIG. 1. A shielded MR head with a trilayered MR element.

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40th MMM: Neutron Nobel, Colossal MR, Tunnel MR

Early development of neutron scattering by magnetic materials (invited) (abstract)

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Neutron scattering has established itself as an important tool in studying magnetic materials. The early history of this development will be outlined, ranging from the earliest studies of paramagnetic materials to those of ferromagnetic and antiferromagnetic materials. © *1996 American Institute of Physics.* [S0021-8979(96)16810-7]

Colossal magnetoresistivity in manganese-based perovskites (invited) (abstract)

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Magnetoresistivity values of the order of 10^{3}% (and in some cases even higher) have been obtained in epitaxial $A_{1-x}B_{1-x}MnO_{3-y}$ (A=La,Nd; B=Ca,Sr,Ba) thin films grown by pulsed laser deposition. Ferromagnetic resonance experiments suggest a granular-type behavior with conducting ferromagnetic regions (R_{sample}~10 mΩ cm) in a less conducting matrix (R_{sample}>100 R_{grain}). Ion channeling experiments over a range of temperatures clearly reveal the existence of structural distortion at the peak resistivity temperature T_p. Systematic studies of samples prepared under a variety of oxygenation conditions show that the resistivity above T_p can be modeled with a simple functional form: $R_{sample} \propto e^{\Delta/kT}$, where Δ, the activation energy, is of the order of 50–200 meV. This suggests that these different samples represent the same basic material in a semiconducting matrix, with different volume fractions of the two components which depends on the processing conditions. These "colossal" values of MR have been obtained at temperatures lower than room temperature and at fields of the order of a few Teslas, both of which are impediments to the development of viable MR sensors and nonvolatile storage technologies. We are therefore addressing the critical scientific and technological issues through a variety of materials integration approaches. Using structural chemistry and lattice matching as fundamental guiding principles, we are growing epitaxial heterostructure superlattices consisting of the CMR oxides interleaved with magnetic perovskites such as La–Sr–Co–O (metallic ferromagnet), rare earth–Fe–O (ferromagnetic insulator). We are also exploring the possibility of using the semiconducting properties of these materials in an all-perovskite field effect transistor device. In this presentation, we will describe our progress to date on these studies to enhance the field and temperature dependence of the MR properties and explore new device architectures that utilize this inherently novel properties of these materials. © *1996 American Institute of Physics.* [S0021-8979(96)06000R-4]

Wyndham Franklin Plaza Hotel

Symposium on High Performance Permanent Magnets and Coercivity — George Hadjipanayis, Chairman

Overview of Nd–Fe–B magnets and coercivity (invited)

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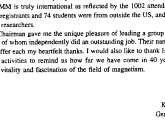
High performance $Nd_2Fe_{14}B$-based permanent magnets are produced with different composition and various processing techniques. The composition and the processing route influence the complex, multiphase microstructures of the magnets, such as grain size, alignment, and distribution of phases. Grain sizes in the range between 10 and 500 nm are observed. Some magnets show preferred alignment, and the HDDR process. Sintered and hot worked magnets exhibit grain sizes above 1 μm. The coercive field *H*c determined by the high uniaxial magnetocrystalline anisotropy as well as the magnetostatic and exchange interactions between neighboring hard magnetic grains. The dipolar interactions between misaligned grains are more pronounced in large-grained magnets, whereas exchange coupling reduces the coercive field in small grained magnets. Transmission electron microscopy has been used to study the influence of substituent and dopant elements on microstructure, coercivity, and corrosion resistance of advanced (Nd,Si)–(Fe,Si)–B(M,M2) magnets. The replacement of the Nd-rich intergranular phase by secondary phases formed after doping by M1 and M2 type elements improves the corrosion resistance, especially in large-grained magnets. Secondary nonmagnetic phases reduce the remanence and the energy product. In addition to the characterization of the microstructure, special attention has been paid to the computer modeling of the interaction between microstructure and coercivity. The simulation of the magnetization reversal process based on the real microstructure reveals a good agreement with experimental values. It is shown that the coercive field depends on grain size, distribution, and misorientation of grains. A strong exchange coupling between hard magnetic grains is desired in nanostructured magnets in order to improve the remanence. This effect is further increased by secondary, soft magnetic phases. Nanocrystalline, compacted Nd–Fe–B based magnets show a remanence enhancement, both in experiments and in model calculations. © *1996 American Institute of Physics.* [S0021-8979(96)06000R-2]



Kristl Hathaway
General Chairman
MMM '95

34th MMM: Exchange coupling in 1952 vs. 1989

Symposium: Computational Magnetics From First Principles — H. N. Bertram, Chairperson

Exchange coupling in metals as understood then and now (invited)

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The first U. S. magnetism conference occurred in 1952 and featured an invited session on exchange coupling in metals with Zener, Slater, Wohlfarth, and Van Vleck speaking. All were concerned with intra- and interatomic exchange with Zener discussing coupling via conduction electron polarization while Wohlfarth and Slater were preoccupied with itinerant ferromagnetism. Van Vleck verbalized the Heisenberg Hamiltonian (prior to its derivation). That meeting may be viewed as the ultimate discussion of magnetism prior to modern day computation and many of the ideas expressed there underlie our computational activities today. Solutions of the Hubbard Hamiltonian and electronic structure calculations, as applied to magnetism, come to mind. We will concentrate on the latter here, since solving the Hubbard Hamiltonian will be of great concern elsewhere in this meeting, and we will attempt to juxtapose current findings with some of the thoughts of that pioneering meeting.

INTRODUCTION

The first digital computers were appearing at Harvard, MIT, and other places at the time of the first U. S. magnetism conference in 1952. In today's session on computation and magnetism, it seems appropriate to spend a moment recalling how things were then. That meeting had a session[1] on exchange coupling in the *3d* metals with talks by Zener and Heisen, Slater, Wohlfarth, and Van Vleck. All were preoccupied with the so-called Slater direct interatomic exchange curve for the ferromagnetic metals, sketched in Fig. 1. Heisen and Zener discussed interatomic coupling via the spin polarization of non-*d* conduction electrons, introducing the first, constant polarization term of what has become the Ruderman–Kittel–Kasuya–Yosida (RKKY) polarization with its Friedel oscillations. Slater and Wohlfarth concentrated on itinerant ferromagnetism while Van Vleck verbalized some of the physics of a Hubbard Hamiltonian for Ni metal, a decade before the Hamiltonian was invented. Slater was also preoccupied with the role of correlation effects in magnetism. The state of computation at that time was such, for example, that not one Hartree-Fock calculation existed for a transition metal atom (the Hartree-Fock, for Mn^{++}, came two years later and was done on hand calculators!). Slater did cite the implications of the arrival of computers in his talk and he did invoke one computer result. A lot has happened since then but many strands of our present day thinking may be found in that session. One of the few things not to survive is Fig. 1. Computer calculations[2] for the exchange coupling between *d* electrons on adjacent atomic sites indicate volume dependences, which vary with the m_s values of the orbitals involved and which, as a rule, do not resemble the figure. Perhaps more to the point, it now seems clear that the figure was derived from what was known in the 1930's concerning the dependence of magnetic moments on volume, e.g., the Invar effect. Present-day local-spin-density[3] (LSD) calculations provide a satisfactory description of this volume dependence without any reference to interatomic exchange.

Huge amounts of computer time have been put to problems in magnetism since 1952 and the consumer market has to grow. The natural evolution of the Stoner–Wohlfarth model of metallic magnetism has been[4] to spin-polarized band-structure calculations employing LSD (Ref. 5). The results have been surprisingly successful even if that success has not been complete. Band-structure calculations are also being increasingly employed to estimate the parameters appropriate to correlated Hamiltonians such as Hubbard's, The Hubbard Hamiltonian, whose essential feature is its electron correlations, has not been amenable to ready solution. As a matter of principle it's very desirable to understand the properties of the solutions to this Hamiltonian and this fact is reflected in the large number of papers appearing in the Magnetism and Magnetic Materials (M^3) meetings over the years. As a matter of practice, the discovery of the high T_c superconductors has raised the question of whether the correlations appropriate to the Hamiltonian are responsible for the superconductivity. Investigating this point has involved massive quantum Monte Carlo calculations[6] as well as investigations employing model wave functions.[7] The issue remains unresolved. Some argue that one has yet to obtain good enough solutions to the Hamiltonian; others argue that the essential multiband complexity of the copper oxide problem has not been built into the versions of the Hamiltonian which have been dealt with; while still others

Symposium: Magnetic Coupling Through Chromium — A. S. Arrott, Chairperson

Magnetic and transport properties of Fe/Cr superlattices (invited)

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We describe the magnetic and transport properties of Fe(001)/Cr(001) superlattices grown on GaAs (001) by molecular-beam epitaxy and characterized by electron diffraction (RHEED), Auger spectroscopy, x-ray diffraction, and electron microscopy. For Cr layers thinner than about 30 Å the magnetic behavior reveals strong antiferromagnetic couplings between the Fe layers across the Cr layers. Polarized neutron diffraction experiments confirm the existence of an antiferromagnetic superstructure. We discuss the origin of the antiferromagnetic (AF) coupling. The Fe/Cr superlattices with AF interlayer coupling exhibit a giant magnetoresistance when an applied field aligns the magnetizations of the Fe layers, the resistivity drops by a factor of 2 for some samples. This giant magnetoresistance effect has been found in Fe/Cr magnetically layered structures for currents in the plane of the layers. The spin-dependent scattering at the Fe/Cr interfaces that comes from interface roughness, as well as that in the bulk of the layers are considered. The resistivity of these magnetic superlattices are calculated by adapting the quantum treatment of the electrical conductivity of ferromagnetic metallic films. We find the resistivity when the Fe moments in adjacent layers are parallel and antiparallel, and compare the results with experimental data.

I. INTRODUCTION

Fe films, Fe/Au films, multilayers, and superlattices, which have been extensively studied for several years, present two kinds of interesting features. First, there are properties associated with the very small thickness of the films or layers, i.e., enhancement or reduction of the magnetic moments, surface or interface anisotropy, low-dimensional effects, etc. In addition, in metallic multilayers and superlattices, there are interesting effects related to the existence of interactions between the layers via the conduction electrons, such as oscillatory exchange coupling, or, for the current-in-plane geometry, giant magnetoresistance. In this paper we shall be concerned with the exchange interactions between the magnetic layers across the nonmagnetic spacer layers.

The Fe/Cr system also presents interesting properties in this respect. Indeed, Grünberg et al.[1] and Fuyuda et al.[2] have shown that the Fe/Cr/Fe sandwiches with a thin Cr layer exhibit AF coupling for Cr thicknesses between 9 and 18 Å. The occurrence of such AF coupling has first been found in Fe/Cr/Fe sandwiches in the high scattering experiments of Grünberg et al.[1] and the spin-polarized low-energy electron diffraction (SPLEED) experiments of Carbone and Alvarado.[3] In this paper we review experimental data on Fe(001)/Cr(001) superlattices grown by molecular-beam epitaxy (MBE).

We describe the preparation and characterization of the Fe(001)/Cr(001) superlattices in Sec. II and the results of magnetization, and electron diffraction experiments[4,5] in Sec. III. AF interlayer couplings appear for Cr layers thicker than about 20 Å. In the magnetization and torque measurements, the signature of the AF couplings is a tilt of the magnetization loops and a change of sign in the torque versus field curves. In the neutron diffraction experiments, the observation of a small-angle Bragg peak at the wave-vector corresponding with twice the chemical period of the superlattice confirms the existence of an AF superstructure.[5] By analyzing the magnetization curves we can derive the corresponding coupling energy. We find the oscillations of the interlayer coupling energy AF_c increases as the Cr thickness decreases (down to 9 Å), and subsists well above the Neel temperature of chromium. It can be ascribed to exchange interactions between the Fe moments across Cr. The preparation of this interlayer exchange interaction raises interesting problems, as discussed in Sec. II C and also in Ref. 1.

An additional and outstanding interest of the Fe/Cr superlattices is the giant magnetoresistance that we observe for antiferromagnetically coupled systems.[6,7] The magnetoresistance data are presented in Sec. IV. The resistivity drops when an applied field overcomes the AF coupling and aligns the magnetic moments of the Fe layers. The resistivity change is surprisingly large: $\rho(\rho_0/H = 0) \simeq 1/2$ for samples with the thinnest Cr layers (9 Å). This turns out to be very promising for applications to magnetoresistive sensors). We have ascribed the large magnetoresistance of the Fe/Cr superlattices to spin-dependent interface scattering,[7,8] an effect related to spin-dependent impurity scattering observed in bulk ferromagnetic transition metals.[9] In Sec. IV B, we describe this interpretation and we discuss recent theoretical models.[7,8] Note that a relatively large (a few percent) magnetoresistance, probably due to a similar mechanism, has also been observed in Fe/Cr/Fe^{2+} and Co/Au/Co^{2+} sandwiches.

II. GROWTH AND CHARACTERIZATION

The growth of our Fe(001)/Cr(001) superlattices and their characterization have been presented elsewhere and are also field curves. In the neutron diffraction experiments, the observation of a small-angle Bragg peak at the wave-vector corresponding with twice the chemical period of the superlattice confirms the existence of an AF superstructure.[5] By analyzing the magnetization curves we can derive the corresponding coupling energy. We find the oscillations of the interlayer coupling energy AF_c increases as the Cr thickness decreases (down to 9 Å), and subsists well above the Neel temperature of chromium. It can be ascribed to exchange interactions between the Fe moments across Cr. The preparation of this interlayer exchange interaction raises interesting problems, as discussed in Sec. II C and also in Ref. 1.

34th MMM: Symposium of Antiferromagnetic Coupling through Cr

Theory of magnetic superlattices: Interlayer exchange coupling and magnetoresistance of transition metal structures (invited)

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Theoretical calculations and models to explain two unusual features of Fe/Cr magnetically layered structures are presented: (1) Strong antiferromagnetic (AF) couplings between Fe layers separated by Cr layers have been found in Fe/Cr/Fe sandwiches and Fe/Cr superlattices. These AF couplings are too strong to be accounted for by dipolar interactions and have to be ascribed to exchange interactions through the Cr layers. The interlayer exchange coupling from numerical simulations of the electronic structures of Fe/Cr superlattices is found to be in good agreement with experiment. (2) Giant magnetoresistance effects have been found in Fe/Cr magnetically layered structures for currents in the plane of the layers. The spin-dependent scattering at the Fe/Cr interfaces that comes from interface roughness, as well as that in the bulk of the layers are considered. The resistivity of these magnetic superlattices are calculated by adapting the quantum treatment of the electrical conductivity of ferromagnetic metallic films. We find the resistivity when the Fe moments in adjacent layers are parallel and antiparallel, and compare the results with experimental data.

The magnetic state of chromium is sensitive to its environment,[1] and we expect that the layers of iron adjacent to the chromium act as a strong perturbation on its magnetism. These observations led us to derive the interlayer exchange coupling from band structure (numerical) calculations of Fe/Cr superlattices as a function of the thickness of the chromium layers t_{Cr}. For example, Herman *et al.*[2] found for Co/Cr superlattices ferromagnetic as well as antiferromagnetic coupling of the orbital layers through the putative antiferromagnetic chromium layers.

Our calculations are based on the augmented spherical wave method[3]; in essence this is a linear combination of atomic orbitals method. The unit cells are divided into slightly overlapping atomic spheres; in each sphere the potential is assumed to be spherically symmetric. The exchange and correlation energies are calculated from the homogeneous interacting electron gas, i.e., in the local spin density approximation. The ensuing spin-dependent one-particle Schrödinger equation is solved self-consistently for the spin-dependent Fermi levels (wave functions). We achieved a convergence in the energy to within less than 10^{-4} Ry. This method, as well as similar ones, have been successful in calculating the magnetic moments and ground state properties of ferromagnetic transition metals and alloys,[4] alloys of ferromagnetic transition metals and rare earths,[5] and layered structures.[6] In this paper, we have considered phenomenological models based on a RKKY like approach or the AF properties of bulk Cr, we found that the sign of the interlayer coupling oscillates as a function of the Cr thickness on a scale of the lattice constant; this is in disagreement with the experimental data.

Observation of magnetic resonance modes of Fe layers coupled via intervening Cr (invited)

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Multiple-frequency (2–14 GHz) ferromagnetic resonance (FMR) has been used to directly observe the coupled resonance modes of a large set of epitaxial Fe/Cr(001) sandwiches grown by molecular beam epitaxy. The FMR data reveal two resonance modes, which have complicated frequency dependences for those samples that show antiparallel Fe layers in zero applied field. Such alignment is only found for samples with 12 Å < Cr(t) < 25 Å. These samples also have antiferromagnetic coupling between the Fe layers across the magnetoresistance curves. Angle-dependent 35-GHz FMR was used to determine the anisotropy and effective magnetization of the Fe layers when they were magnetically aligned. We show that the detailed FMR and M vs H behavior can be quantitatively explained by an AF coupling term of the form $J \cdot M_1 \cdot M_2$ and find that J has a Cr(t) dependence peaked about 16 Å.

INTRODUCTION

Samples containing very thin multiple films of Fe with intervening Cr layers less than 25 Å thick have recently generated much interest since they exhibit a clear oscillatory dependence of the total moments of adjacent Fe layers.[1] They also exhibit unusual magnetoresistive effects which depend on the relative orientation of the magnetization in each layer.[2,3] The antiferromagnetic coupling effect and the magnetoresistive effect both significantly increased when the Fe layer thickness approaches 20 Å, and both vanish when the Cr thickness approaches 25 Å. Since the magnetoresistive effect is a function of the relative orientation of the Fe moments across Cr. The preparation of this interlayer exchange interaction raises interesting problems, as discussed in Sec. II C and also in Ref. 1.

An additional and outstanding interest of the Fe/Cr superlattices is the giant magnetoresistance that we observe for antiferromagnetically coupled systems.[6,7] The magnetoresistance data are presented in Sec. IV. The resistivity drops when an applied field overcomes the AF coupling and aligns the magnetic moments of the Fe layers. The resistivity change is surprisingly large: $\rho(\rho_0/H = 0) \simeq 1/2$ for samples with the thinnest Cr layers (9 Å). This turns out to be very promising for applications to magnetoresistive sensors). We have ascribed the large magnetoresistance of the Fe/Cr superlattices to spin-dependent interface scattering,[7,8] an effect related to spin-dependent impurity scattering observed in bulk ferromagnetic transition metals.[9] In Sec. IV B, we describe this interpretation and we discuss recent theoretical models.[7,8] Note that a relatively large (a few percent) magnetoresistance, probably due to a similar mechanism, has also been observed in Fe/Cr/Fe^{2+} and Co/Au/Co^{2+} sandwiches.

II. GROWTH AND CHARACTERIZATION

The growth of our Fe(001)/Cr(001) superlattices and their characterization have been presented elsewhere and are

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Antiferromagnetic coupling between layers in Co/Cr multilayer (invited)

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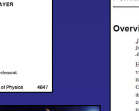
It has been shown by several groups that Fe layers in epitaxial Fe/Cr sandwiches or multilayers (ML) are coupled antiferromagnetically (AF) for very small Cr thicknesses. One way this is manifest in the MLF is that for a fixed Fe thickness (30 Å) the hysteresis curves are progressively flatter as the Cr thickness decreases. This is the opposite behavior to that expected if the Fe layers were uncoupled or ferromagnetically coupled. We have observed the same Fe M behavior in a series of continually 21-Å-thick Co/Cr MLFs where Cr varies from 14 to 28 Å. These MLFs have been fabricated, characterized, and studied in a variety of ways. Sections of high angle x-ray diffraction scans show very highly periodic structure. The etched MLFs with appreciable mixed interfaces. We have determined that Co/Cr MLF have an interface or exchange anisotropy with an average value of −7 kOe in a direction opposite to that of the in-plane magnetization. Such an AF interaction is expected from Cr layers having interface thicknesses comparable to that of the pure Cr regions. It provides a natural mechanism for the Cr layers to align the Co layers either AF or FM depending on the local structural details. Both types of alignment are likely to be present in a MLF and the regions having AF alignment will cause the observed flattening of the hysteresis loops. The temperature dependence of these MLFs has a behavior similar to, but much smaller than, the "giant" magnetoresistance seen in the optimized Fe/Cr MLF and single-crystal Fe whiskers. The temperature dependence in pure Fe has been attributed to the domain structure and it is likely responsible for this effect in the Co/Cr MLF as well.



Giant magnetoresistance in sputtered magnetic superlattices (invited) (abstract)

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Recently, large values of saturation magnetoresistance (SMR) were reported in single-crystal Fe/Cr superlattice structures prepared by molecular-beam epitaxy (MBE) techniques. We have prepared similar polycrystalline superlattice structures by dc magnetron sputtering in a high-vacuum deposition system and find comparably high SMR values of up to 80% for Cr layer thicknesses of ≈ 8 Å. Magnetization-versus-field data suggest that successive Fe layers are coupled antiferromagnetically with one another, as for the MBE-grown films. Magnetic fields of up to 20 kOe are required to align Fe layers 20 Å thick, implying substantial exchange-coupling energies between the Fe layers. While the magnetization curves have a weak temperature dependence even for temperatures above the Neel temperature of bulk Cr, the SMR decreases as the temperature is increased. Work on related structures which do and do not show giant SMR effects will be discussed.

This paper was not produced by the author; however, it has been proofread by one of the Publication Chairpersons.

[1] M. Baibich *et al.*, Phys. Rev. Lett. 61, 2472 (1988).

34th MMM: Symposium on Spin Tunneling and Injection Phenomena — Mark Johnson, Chairman

Ferromagnetic–insulator–ferromagnetic tunneling: Spin-dependent tunneling and large magnetoresistance in trilayer junctions (invited)

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Tunneling between