REVIEW OF GIANT MAGNETORESISTANCE IN FERROMAGNETIC CRYSTALS

By

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The undersigned hereby certify that they have read and recommend to the school of Graduate Studies for acceptance a project entitled "**Review of Giant magnetoresistance in ferromagnetic crystals**" by **Tadesse Lakew Zeru** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Abstract

This project contains a brief review of the giant magnetoresistance in ferromagnetic crystals, the transport properties of ferromagnets with a brief discussion of magnetic properties of crystals such as magnetization susceptibility, diamagnetism, paramagnetism, and ferromagnetism as well as the magnetization dynamics in ferromagnetic systems. Giant magnetoresistance materials have magneto transport properties which determine their suitability for applications in magnetic field sensors, read heads, random access memories. The discovery of giant magnetoresistance has been a huge impact on our life, especially for mass data storage devices. Details of giant magnetoresistance applications, such as hard-disk read-heads, sensors and magnetic memory chips are presented. One of the important aspects of giant magnetoresistance discovery was that it was immediately turned into commercially available products with a giant market share. The highest storage capacity in the modern computers is attributed to the discovery of giant magnetoresistance. This review covered a simple model of giant magnetoresistance and dependence of it on structure and magnetic layer thickness with a brief discussion of interlayer exchange coupling and giant magnetoresistance in magnetic multilayers including the giant magnetoresistance effect in ferromagnets (organic semi-conductors).

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Chapter 1

Introduction

Magnetism is a very old field of research still an extremely active area, which has come to play a very important role in modern life. One of the most illustrative example is the ability of magnetic materials to store information through charges in magnetization directions. This property is at the heart of today's computer technology (rigid disks, flexible disks), computer electronics (tapes for audio and video apparatuses) and many other important applications (such as magnetic strips for personal data on credit cards, etc). The performance of magnetic devices is obviously largely determined by the properties of magnetic solid involved. Since the properties depend heavily on the type of atoms and their environment, a high degree of control of composition and structure is desired.

The study of electrical transport in magnetic materials has a long history. However, since the discovery in 1988 of the so called giant magnetoresistance in metallic multiplayers [1], the subject has generated a great deal of interest. This was important not only from the basic research point of view but also from the applied research point of view. In the hard disk technology magnetoresistive read heads based on the giant magnetoresistance effect, which has allowed the increase in the density of the stored

information in hard disks at a rate much beyond previous technology [2]. Giant magnetoresistance can be considered to be the first paradigm of the so called spintronics, where in sharp contrast with semiconductor for technologies, the spin as well as the charge transport is taken in to account.

In this review we start by introduce the basic concepts to understand the basic transport properties of magnetic crystals. And we revise the concept of magnetic properties of crystals; magnetization susceptibility, diamagnetism, paramagnetism, ferromagnetism and also we discus magnetization dynamics in ferromagnetic systems (dynamics equation, ferromagnetic resonance and magnetic damping) as well as some transport properties of ferromagnetic transition metals such as the residual resistivity, Hall effect, magnetoresistance, and high temperature effect will be discuss. Thereafter, we briefly discuss giant magnetoresistance with in a simple model of it and the dependence of giant magnetoresistance on structure and magnetic layers of thickness. Giant magnetoresistance was observed in multilayers composed of alternating magnetic and non magnetic layers. Basic ingredients to understand this effect are the different bulk and interface scattering probability of spin up and spin down conduction electrons, the spin diffusion length compared to the layers thickness, the magnetic exchange coupling between the magnetic layers [2, 3]. We revise some very general properties of ferromagnetic and magnetic materials. We will concern with the transport properties of the transition ferromagnetic metals Fe,Co,Ni and the inter layer exchange coupling of giant magnetoresistance on magnetic layers with the study of giant magnetoresistance in ferromagnets (semiconductors).

And then after completing this study we will be able to outline the theoretical and the practical aspects of giant magnetoresistance.

Chapter 2

Transport Properties of Ferromagnets

2.1 Magnetic Properties of Crystals

There are a few basic concepts and ideas concerned with magnetic materials. The fundamental types of magnetic properties observed in an experiment in which magnetization, **M**, acquired in response to application of a magnetic field, **H**, is monitored. The fact that some atoms have atomic magnetic moments because of orbital and spin motions of electrons. Atomic magnetic moments are quantized. Because of unfilled 3d electron orbital, transition element solids have the common crystals with atoms possessing a magnetic moment.

2.1.1 Magnetization and Susceptibility

Inside a long solenoid the magnetic field **H** of N turns per unit length l is equal to nI. (Here: $n = \frac{N}{l}$) where I is the current through the solenoid If there is a vacuum inside the solenoid, the magnetic flux density **B** is $\mu_0\mathbf{H} = \mu_0 nI$. If we place an iron rod of permeability μ inside the solenoid, this doesn't change **H**, which remains nI. The magnetic flux density **B**, however, is now $\mathbf{B} = \mu\mathbf{H}$. This is greater than $\mu_0\mathbf{H}$

and we rewrite [4, 5]

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{2.1}$$

where the quantity $\mathbf{M}$ is called the magnetization of the material. We see that there are two components to $\mathbf{B}$. There are $\mu_0\mathbf{H} = \mu_0 nI$, which is the externally imposed field and the component $\mu_0\mathbf{M}$, originating as a result of something that has happened within the material. It might have occurred to you that you would have preferred to define the magnetization from $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, so that the magnetization would be the excess of $\mathbf{B}$ over $\mu_0\mathbf{H}$. The ratio of the magnetization $\mathbf{M}$ (the result) to the magnetic field $\mathbf{H}$ (the cause), which is obviously a measure of how susceptible the material is to becoming magnetized is called the magnetic susceptibility χ_m of the material [6] :

$$\chi_m = \frac{M}{H} \tag{2.2}$$

The magnetic susceptibility can be dependent on the applied magnetic field $\mathbf{B}$. All magnetic materials grouped into three magnetic classes (diamagnetic, paramagnetic or ferromagnetic), depend on the magnetic order and the sign, magnitude and temperature dependence of the magnetic susceptibility.

2.1.2 Diamagnetism

Substances which have weak negative susceptibility are called diamagnetic substance. Usually its magnitude is of the order of -10^{-6} to -10^{-5}. The negative value of the susceptibility means that in an applied magnetic field diamagnetic materials acquire the magnetization, which is pointed opposite to the applied field. In diamagnetic materials the susceptibility nearly has a constant value independent of temperature. Diamagnetism is associated with the tendency of electrical charges partially to shield

magnetic fields. There is no magnetic order at any temperature in diamagnetic materials. When the flux through an electrical circuit is changed an induced current is set up in such a direction as to oppose the flux change. In a superconductor or in an electron orbit with in an atom, the induced current persists as long as the field is present. The magnetic field of the induced current is opposite to the applied field, and the magnetic moment associated with the current is a diamagnetic moment. Even in a normal metal there is a diamagnetic contribution from the conduction electron, and diamagnetism is not destroyed by collision of the electrons. In a magnetic field the motion of the electrons around a central nucleus is, to the first order in the magnetic field **B** the same as a possible motion in the absence of **B** except for the superposition of the electrons with angular frequency $\omega = eB/2m$ [6, 7]. If the field is applied slowly, the motion in the rotating reference systems will be the same as the original motion in the rest system before the application of the field. If the average electron current around the nucleus is zero initially, the application of the magnetic field will cause a finite current around the nucleus. The current is equivalent to a magnetic moment opposite to the applied field. The diamagnetic response to application of a magnetic field is acquisition of a small induced magnetization, **M**, opposite to the applied field, **H**. The magnetization depends linearly on the applied field and reduces to zero on removal of the field. This condition is not satisfied in free carrier cyclotron resonance [7].

2.1.3 Paramagnetism

In paramagnetic materials the susceptibility χ is positive; that is, for which **M** is parallel to **B**. The susceptibility order is 10^{-4} to 10^{-5}. Diamagnetism makes itself evident in atoms and molecules that have no permanent magnetic moment. Some atoms or

molecules, however, do have a permanent magnetic moment, and such materials are paramagnetic [7]. They must still be diamagnetic, but often the paramagnetism will outweigh the diamagnetism. The magnetic moment of an atom or a molecule is typically in order of a Bohr magnetos. The presence of a permanent magnetic moment is often the result of unpaired electron spins. An example often quoted is the oxygen molecule O_2. Liquid oxygen indeed is paramagnetic. When a paramagnetic material is placed in a magnetic field, the magnetic moments experience a torque and they tend to orient themselves in the direction of the magnetic field $\mathbf{B}$ [6, 7]. The effect is greatest at low temperatures, where the random motion of atoms and molecules is low. At liquid helium, temperature (of order 1K), susceptibilities can be of order $+10^{-3}$ or $+10^{-2}$ thus greatly exceeding the small negative susceptibility. At room temperature, paramagnetic susceptibilities are much less typically about $+10^{-5}$, barely exceeding the diamagnetic susceptibility. Paramagnetic solids contain atoms with atomic magnetic moments and acquire induced magnetization, $\mathbf{M}_i$, parallel to the applied field, $\mathbf{H}$. For any geological relevant conditions, $\mathbf{M}_i$ is linearly dependent on $\mathbf{H}$. As with diamagnetic materials, magnetization reduces to zero when the magnetizing field is removed. In paramagnetic solids, atomic magnetic moments react independently to applied magnetic fields and to thermal energy. At any temperature above absolute zero, thermal energy vibrates the crystal lattice, causing atomic magnetic moments to oscillate rapidly and randomly in orientation.

2.1.4 Ferromagnetism

Ferromagnetic solids have atoms with magnetic moments, but unlike the paramagnetic case, adjacent atomic moments interact strongly. The effect of interaction is to produce magnetization in ferromagnetic solids that can be orders of magnitude

larger than for paramagnetic solids in the same magnetizing field. For a given ferromagnetic material and temperature there is a maximum magnetization referred to as saturation magnetization, $\mathbf{M}_s$ increasing $\mathbf{H}$ beyond the level needed to reach $\mathbf{M}_s$ will not result in increased magnetization [6, 7]. The susceptibilities of ferromagnetic materials are typically of order $+10^3$ or $+10^4$ or even greater. In ferromagnetic materials the critical temperature is called the Curie temperature. Above the Curie temperature the susceptibility follow relationship equation 2.2 with a negative sign. When temperature approaches T_c the magnetic susceptibility tends to be infinite. However, the ferromagnetic susceptibility of a material is quite temperature sensitive, and above a temperature known as the Curie temperature, the material ceases to become ferromagnetic, and it becomes merely paramagnetic. Among the elements, only cobalt, iron and nickel are strongly ferromagnetic, their Curie temperatures being about 1400K, 1040K and 630K respectively. There are many artificial alloys and ceramic materials which are ferromagnetic. As with paramagnetic materials, the atoms have permanent magnetic moments, but with the difference that these moments are not randomly oriented but are strongly aligned to the crystallographic axes. Within a single crystal, there exist domains, within which all the magnetic moments are parallel and are aligned with a particular axis. For an isolated atom of a transition element there is no confusion about the electron states occupied. However, for a collection of atoms within a crystal lattice, the situation can be complex. Electron orbital are probability distributions that can have elongate shapes. Partial overlaps of electron probability distributions occur when atoms are packed together in a crystalline solid. The result is that electron states and magnetic moments of

the adjacent atoms become strongly coupled. This simple view suggests how crystal structure and density of packing determine whether a solid containing transition elements is paramagnetic (no overlapping orbital and no exchange coupling) or ferromagnetic (significant orbital overlap and resulting exchange coupling). Because inter atomic distance increases during thermal expansion, strength of exchange coupling and resultant $\mathbf{M}_s$ decrease with increasing temperature. At the Curie temperature, T_C, inter atomic distances have increased to the point at which exchange coupling is destroyed [8]. Atomic magnetic moments are then independent, and the material becomes paramagnetic. In general, the process is reversible, with exchange coupling $\acute{d}$ ferromagnetism again appearing when the material is cooled below the curie temperature T_C. Exchange energy may produce either parallel or anti parallel exchange coupling. The sense of coupling depends on the transition element involved and on crystal structure. One can regard the general term ferromagnetism as applying to all three types of solids with coupling of atomic magnetic moments. Strictly speaking, ferromagnetism refers to solids with parallel coupling of adjacent atomic magnetic moments.

2.2 Magnetization Dynamics in Ferromagnetic Systems

If one considers the simple experience of applying an external magnetic field $\mathbf{H}$ in a region where there are present isolated magnetic moments $\mathbf{m}$, one may observe an alignment of $\mathbf{m}$ with $\mathbf{H}$. When one treats a magnetic structure, it is convenient to define the magnetization vector as the total magnetic moment per unit volume ($\mathbf{M} = \sum(\mathbf{m}_i)/vol$). Magnetization dynamics describes the time evolution of the

magnetization $\mathbf{M}$ out of equilibrium. The application of the magnetic field $\mathbf{H}$ out of the direction of $\mathbf{M}$ will produce a torque on this $\tau = \mu_0(\mathbf{M} \times \mathbf{H})$. This torque is equal to the change of the angular momentum, i.e. $\tau = dL/dt$. Relationship $\mathbf{M} = \gamma L$ describes the evolution of the magnetization [9]

$$\frac{d\mathbf{M}}{dt} = \mu_0\gamma(\mathbf{M} \times \mathbf{H}) \tag{2.3}$$

where $\gamma = ge/2m_e$ is the gyromagnetic ratio which is proportional to the ratio between the charge e $(1.602 \times 10^{-19}C)$ and the mass $m_e(9.109 \times 10^{-31}kg)$ of the electron. The constant g represents the spectroscopic splitting factor that for a free electron its value is $g = 2 \times 1.001159657$.

2.2.1 Magnetization Dynamics Equations

Equation 2.2.1 does not describe a real ferromagnetic correctly. It is necessary to define a new term that adds the damping to the system. The first approach in this direction was given by [9, 10] with the following expression

$$\frac{d\mathbf{M}}{dt} = -\mu_0\gamma\mathbf{M} \times \mathbf{H}_e - \frac{\mu_0\lambda}{M_s^2}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}_e) \tag{2.4}$$

where M_s is the saturation magnetization and the constant $\lambda = \frac{1}{\tau}$ (τ is relaxation time) and λ is the Landau and Lifshitz (LL) damping parameter, whose value will give information about the dissipation mechanisms. The LL equation describes the magnetization dynamics in bulk ferromagnets with two terms; the first one describes the precession of the magnetization around the field $\mathbf{H}_e$, the effective magnetic field inside the material that in general will be different from the external magnetic field applied. One can obtain this effective magnetic field such as the negative gradient of the free energy of the system with respect to the magnetization $\mathbf{H}_e = \nabla_M U$. The

first term conserves the energy of the system. On the other hand, the second term introduces the energy dissipation or damping and describes the motion of $\mathbf{M}$ towards $\mathbf{H}_e$. Several alternatives dynamic equations have been proposed by changing the form of damping term. In this subsection the Landau-Lifshitz-Gilbert (LLG) equation will be used [9, 11]

$$\frac{d\mathbf{M}}{dt} = -\mu_0\gamma\mathbf{M} \times \mathbf{H}_e + \frac{\alpha}{M_s}(\mathbf{M} \times \frac{d\mathbf{M}}{dt}) \tag{2.5}$$

where α is the dimensionless Gilbert damping parameter. This term describes viscous damping in which damping is proportional to the magnetization velocity. Equation 2.2.3 consist of a precessional and a damping term. As a result of the damping term, the motion of the magnetization follows a helical trajectory. In the limit of $\alpha \ll 1$ both equations, LL and LLG, are identical defining α such as $\alpha = \frac{\lambda}{\gamma \mathbf{M}_s}$. In the other extreme, when $\alpha \gg 1$; LL equation predicts the magnetic moments will loose energy quickly and rapidly reach its low energy state, whereas the LLG equation predicts that dissipation of the energy and approaches to the low energy state will become increasingly slow [9].

2.2.2 Ferromagnetic Resonance(FMR)

One of the most established techniques to study spin waves in magnetic systems is Ferromagnetic resonance. A magnetic system is exposed to a sinusoidal electromagnetic radiation at a fixed frequency typically in the microwave range. The resonance frequency is determined by the effective field which includes the external field. Therefore, by sweeping a static external field the magnetic system can be driven through the ferromagnetic resonance by the external field. When measuring the absorption of the microwave radiation by the magnetic sample the resonance field is found at maximum

absorption. In order to enhance the signal to noise ratio the external magnetic field is modulated to allow for lock-in detection. Due to its high sensitivity ferromagnetic resonance is a technique to study spin waves in magnetic bulk material and extended films exhibiting a single domain magnetization configuration. However, this technique is not applicable to investigate magnetic elements with a complex domain configuration, since sweeping an external field would alter the magnetization configuration and thereby the resonance condition during the measurement. The magnetization is slightly disturbed from its equilibrium position, for example using a transverse oscillating magnetic field called pumping field, the magnetization will precess about the field direction [9]. The magnetization motion will cause the precession to be damped, or undergo relaxation. Unless the frequency $\omega = 2\pi f$ of the pumping field is nearly equal to the precessional frequency ω_0 of the magnetization, the energy coupled into the precessing magnetization will be small. When $\omega \sim \omega_0$; the coupling is large and the amplitude of precession is limited only by the damping of the system. One needs to obtain the resonance frequency and the line width of ferromagnetic resonance.

2.2.3 Magnetic Damping

Due to the technological relevance in spintronic, in the past several years there has been a revival of interest in the theory of magnetization damping [12]. The knowledge of the typical magnetization relaxation times is one of the most important parameters of interest for ferromagnetic systems. Measurements of the resonance line width is one of the main techniques used to investigate these phenomena [12, 13, 14]. In a ferromagnetic resonance experiment, the line width of the resonance $\triangle H$, measured in units of magnetic field, consists of intrinsic and extrinsic contributions.

A. Intrinsic Damping Mechanism

The mobile electrons, combined with spin-orbit coupling, are the agents which first transfer energy out of the spin system. Formal treatments [15, 16] agree that spin-orbit coupling enables relaxation in ordinary spin conserved scattering (confined to electronic states within either spin-up (↑) and spin-down (↓) sub-bands) and in spin-flip scattering. The electron-hole interactions involve three particle scattering. The excitations are either accompanied by electron spin-flip or the spin remains unchanged. Spin-flip excitations can be caused by the exchange interaction between magnon and itinerant electrons (s-d exchange interaction), during which the total angular momentum is conserved. The spin conserving scattering is caused by spin orbit interaction which leads to a dynamic redistribution of electrons in the electron k-momentum space. Other possible contributions to the intrinsic damping may be caused by induced currents [17] and by direct magnon phonon scattering [12]. In a metallic ferromagnetic system any change in the magnetization induced currents which tend to compensate this change, and thus provides a damping mechanism.

B. Extrinsic Damping Mechanism

Surface defects, surface roughness, grain boundaries and atomic disorder are potentially important sources of the two magnon scattering [18]. That is one of the most important sources of relaxation in materials with inhomogeneities. The basic idea is that such inhomogeneity result in a coupling between the other orthogonal uniform precession and degenerate spin waves (SW) modes and that the energy transfer out of the uniform precession to the degenerate modes is important in the initial stages of relaxation. The total number of magnon remains unchanged since one magnon is

annihilated and another is created. The interaction is sensitive to the nature of the inhomogeneity. As a general rule, the coupling is large for spin wave wavelengths greater than the dimensions of the inhomogeneity. In the idealized ferromagnetic resonance experiment, a uniform precession mode is excited whose wave vector $k_{\|}$ parallel to the surface is zero. Arias and Mills reported [19] a detailed theory of the two magnon processes in the ferromagnetic resonance response of ultra thin films when the magnetization and the applied magnetic field were in plane. In the presence of dipolar couplings between spins, there will be short wavelength spin waves degenerate with the ferromagnetic resonance mode.

2.3 Some Transport Properties of Ferromagnetic Transition Metals

Ferromagnetic transition metals have so many properties. In this subsection we revise some properties which are related with the topic of this project. Such as residual resistivity, Hall effect, magnetoresistance and high temperature effect.

2.3.1 Residual Resistivity

Electrons in a given domain of ferromagnets can be strictly classified as having spin up or spin down, if the spin orbit coupling is ignored and the spin transitions supposed not too frequent. Hence the conduction is by the currents in parallel with different resistivity, this different resulting mainly from the difference in the possibilities of s-d scattering for the s electrons. In the low temperature limit, as only scattering with conservation of spin direction is allowed, the conduction is by two independent

currents [20]. Hence the residual resistivity ρ_0 is given by:

$$\frac{1}{\rho_0} = \frac{1}{\rho_{0\uparrow}} + \frac{1}{\rho_{0\downarrow}} \Rightarrow \rho_0 = \frac{\rho_{0\uparrow}\rho_{0\downarrow}}{\rho_{0\uparrow} + \rho_{0\downarrow}} \tag{2.6}$$

where $\rho_{0\uparrow}$ and $\rho_{0\downarrow}$ are the residual resistivity for the spin up and the spin down electrons respectively. Measurements of residual resistivity of iron or nickel containing various pairs of impurities show very large deviations corresponding to a considerable dispersion of the α value $\alpha = \rho_\downarrow/\rho_\uparrow$ [21]. And as the temperature is increased, a thermal contribution must be added to each resistivity: $\rho_\sigma = \rho_{0\sigma} + \rho^i_\sigma(T)$ but also spin non conserving scattering will occur in electron-magnon or electron-electron collisions and mix the two currents [21, 22];

$$\rho = \frac{\rho_\uparrow\rho_\downarrow + \rho_{\uparrow\downarrow}(\rho_\uparrow + \rho_\downarrow)}{\rho_\uparrow + \rho_\downarrow + 4\rho_{\uparrow\downarrow}} \tag{2.7}$$

the resistivity ρ depending on the resistivity $\rho_\uparrow$, $\rho_\downarrow$ and in the case where $\rho_\uparrow$ is not equal to $\rho_\downarrow$ on a term $\rho_{\uparrow\downarrow}$. $\rho_{\uparrow\downarrow}$ expresses the strength of the $spin_\uparrow - spin_\downarrow$ mixing processes and normally increase with temperature [21]. The dependance of the resistivity on $\rho_{\uparrow\downarrow}$ can be described as follows: suppose, an alloy where residual resistivity $\rho_{0\uparrow}$ and $\rho_{0\downarrow}$ are very different at low temperature, one current will short circuit the other; when the temperature increase the fast current will be brake by mixing with the slow current and the resistance will increase much faster than in pure metal.

2.3.2 Hall Effect

The Hall effect is an effective method to investigate the motion of charge carriers in metals and semiconductors. Moreover, the Hall effect gives information about concentration of charge carriers and nature of semiconductors' conductivity. This phenomenon is caused by the influence of the Lorentz force on the free charges in the

conductor [23]. The Hall effect is the production of a transverse voltage (a voltage change along the y direction) due to a transverse magnetic field **B** (in the z direction) with current flowing in the x direction. It is useful for determining information on the sign and concentration of carriers [24]. If an electric current is passed along the x-direction through a conductor in which there is a magnetic field along the z-direction then an electric field is set up along the y-axes, at right angles to both the applied electric field and the magnetic field. This effect is the Hall effect. The Hall coefficient is define as [25]

$$R_H = \frac{E_y}{j_x B} \tag{2.8}$$

This is equivalent to the magnetoresistance. i.e the variation with resistance in a magnetic field. It can be shown that the carriers of two types if we retain terms of the second order then we have a magnetoresistance. So far we have no considered the distribution of velocities as in the Boltzman approaches [26].

2.3.3 Magnetoresistance

The phenomenon called magnetoresistance (MR) is the change of resistance of a conductor when it is placed in an external magnetic field. W. Thomson (Lord Kelvin) [27] measured the behavior of the resistance of iron and nickel in the presence of a magnetic field. The trajectory of the charge carriers deviates from the straight line in the magnetic field. This effect is called magnetoresistance [23]. This causes a change of electrical resistivity of a material. In ordinary metals at room temperature resistance can vary by a few tenths percent, but in semiconductors the magnetoresistance is much larger and it depends on the impurity concentration, mobility of charge carriers and temperature. Magnetoresistance quantitatively is characterized by a scalar $\frac{\triangle\rho}{\rho_0}$,

where $\triangle\ \rho$ is the change of the resistivity in magnetic field, and ρ_0 is the resistivity with out magnetic field. Let us consider the case of an infinite semiconductor. The deviation of the carriers from the direction of electric field $\bar{E}$ is equivalent to decrease of the mean free path of the carriers, λ_o, in the direction of $\bar{E}$ [1, 23]

$$\triangle\ \lambda = \lambda_0 \frac{\mu^2 B^2}{2} \tag{2.9}$$

where B is magnetic field, and μ is carriers mobility. Decrease of λ_o is equivalent to the decrease of the carrier drift velocity, which in turn is proportional to the conductivity of the semiconductor,σ. Consequently

$$\frac{\triangle\ \lambda}{\lambda_0} = \frac{\triangle\ \sigma}{\sigma} \Rightarrow \frac{\triangle\ \rho}{\rho} \sim \frac{\mu^2 B^2}{2} \tag{2.10}$$

As a result, the relative change in electric resistance of semiconductor is determined by

$$\frac{\triangle\ \rho}{\rho} = c\frac{\mu^2 B^2}{2} \tag{2.11}$$

where c is a coefficient depending on the geometry of the semiconductor wafer. Now let us consider a finite sample. In this case the charge carriers moves along the straight lines since the Hall field compensates the influence of the magnetic field and therefore, magnetoresistance should not exist. However, magnetic field influences stronger than Hall field, especially to the fast carriers. So, the slow carriers deviate under the influence of Hall field. It is known that the velocities of electrons and holes are different so that the dispersion in the carriers' velocities leads to increase the resistivity.

2.3.4 High Temperature Effect

Around and above curie temperature T_c, comparison of resistivity for ferromagnetic and paramagnetic transition metals spin disorder effects are important [28]. Results

for $d\rho/dT_c$ in Ni show a lambda peak at T_c ; a tail to this peak for $T > T_c$ shows that spin-spin correlations continue to exist above T_c. In [29] it was suggest that (in Ni in any case) behavior is dominated by short range correlations below T_c by zero range correlations, so magnetic resistivity depends on m^2, and above T_c by the same short range correlations that dominate the enthalpy. Experimentally, above T_c, $d\rho/dT_c$ is proportional to C_v [30] and the magnetoresistance is proportional to the magnetocaloric effect [31] ; both observations support the relation between magnetic disorder resistivity and enthalpy. It would be interesting to fill in the gap between low temperatures, where spin disorder appears as the mixing term $\rho_{\uparrow\downarrow}$, and high temperatures where spin disorder is a direct resistivity.

Chapter 3

Giant Magnetoresistance (GMR)

Giant magnetoresistance is a drastic change in electrical resistivity when applying a magnetic field. It is a known magnetotransport phenomenon which has no counterpart in nature. It is observed for samples consisting of ferromagnetic entities which are separated from each other by non magnetic material in such a way that the relative magnetization directions of the entities can be changed by an applied magnetic field of moderate strength [21]. The most important systems which show this behavior are magnetic multilayers consisting of a stack of alternating ferromagnetic and non-magnetic layers. The phenomenon also occurs in granular systems in which ferromagnetic clusters are dissolved in a non magnetic matrix. However, we restrict our attention to the multilayer systems since in these structures the phenomenon is most pronounced and more importantly because these systems allow more systematic investigations of the effect. The magnetization direction and size of each individual entity (ferromagnetic layer) as well as the distance between the entities can be controlled in a much higher degree than in the granular systems. The giant magnetoresistance effect is employed in magnetic field sensors in the read heads of data recording devices.

3.1 A Simple Model of Giant Magnetoresistance

As we discuss above giant magnetoresistance is the change of resistance of a conductor when it is placed in an external magnetic field. For ferromagnets like iron, cobalt and nickel this property will also depend on the direction of the external field relative to the direction of the current through the magnet [32]. This effect has been of substantial importance technologically; especially in connection with read out heads for magnetic disks and as sensors of magnetic fields. The resistance of the structure is a function of the relative orientation between the magnetization of the adjacent layers. The different resistance state can be used as data storage bits, which may be written by using an applied magnetic field produced by an adjacent current carrying line. It was discovered by [33] independently in anti ferromagnetic coupled Fe/Cr/Fe trilayers. The giant magnetoresistance effect is generally attributed to spin dependent scattering in successive ferromagnetic (FM) layers. Classically the antiferromagnetic alignment of the ferromagnetic layers is provided by exchange coupling of antiferromagnetic interlayers placed between the ferromagnetic layers. The magnetic state is changed in to the ferromagnetic alignment by applying a magnetic field. The resistance R of the device will be reduced dramatically when the applied magnetic field aligns the magnetization of different layers in the same direction. The resistance of the multilayers is significantly higher in small fields as compared with high fields. The variation in resistance is related to a change in the relative orientation of neighboring ferromagnetic Fe/Co layers with applied magnetic field [27]. The resistance is higher when adjacent magnetic layers are aligned antiparallel to one another, as compared

with parallel alignment. Giant magnetoresistance is expressed by [9]:

$$GMR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} \tag{3.1}$$

where $R_{\uparrow\downarrow}$ and $R_{\uparrow\uparrow}$ denotes the resistance for antiferromagnetic and ferromagnetic alignment respectively. Giant magnetoresistance is a quantum mechanical effect observed in composed of alternating layers of ferromagnetic and nonmagnetic layers. The detailed origin of giant magnetoresistance has provoked considerable interest. Many theoretical models have been developed, but most of them are based on a model of the electrical conduction in ferromagnetic metals [34]. [35] hypothesized that the electrical current in ferromagnetic metals is carried independently in two conduction channels that correspond predominantly to the spin-up and spin-down s-p electrons. These electrons are in broad energy bands with low effective masses. This assumption is believed to be good at temperatures significantly below the magnetic ordering temperature of the magnetic material so that there is little spin mixing between the two conduction channels. And he theorized that the conductivity can be significantly different in the two spin channels because the conduction-electron scattering rates in these two channels will be related to the corresponding spin-up or spin-down density of empty states at the Fermi level. These states will be largely of d character, and as a result of the exchange split d bands, the ratio of spin-up to spin-down density of empty states at the Fermi level can be significantly different in the ferromagnetic ordered states of Fe, Ni, Co, and their alloys. Consequently, this leads to the possibility of substantially different mean free paths $\lambda^{\pm}$ and conductivities $\sigma^{\pm}$ in the two channels. In Co, for example, the density of states at the Fermi level is ten times higher for down-spin (minority) electrons as compared with up-spin (majority) electrons [36]. In this model [34] shown in figure 3.1, each of the ferromagnetic and

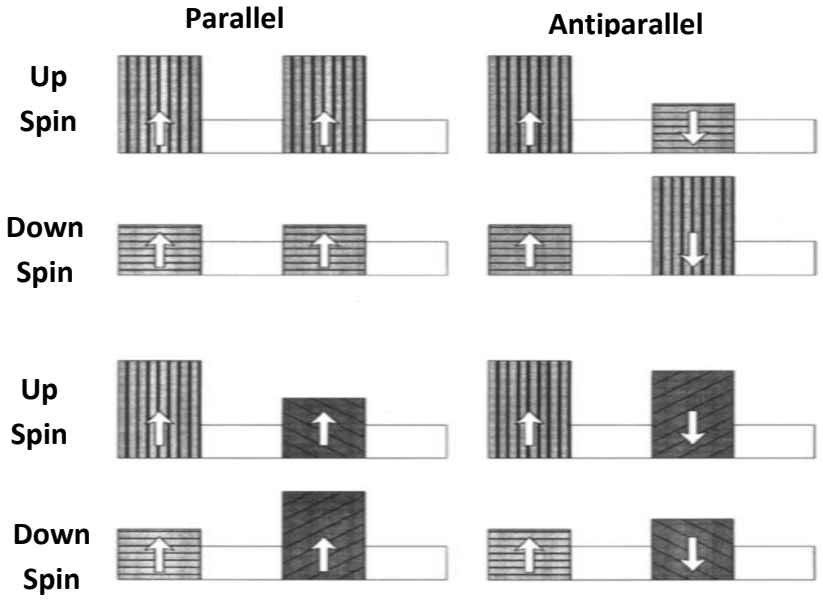

Figure 3.1: A simple resistor network model of giant magnetoresistance in which the height of the columns is proportional to the resistivity of the magnetic (arrows) and spacer layer (white boxes) metals for the two independent up and down spin channels. The magnetic orientation of the magnetic layers is shown by the direction of the arrow inscribed in the relevant box. Two different multilayers are considered. In the top portion of the figure, a simple multilayer containing one type of magnetic layer is described. In the bottom portion, a resistor network model is shown for a magnetic multilayer containing two different types of magnetic layers separated by the same spacer layer

nonmagnetic spacer layers consists of two resistors corresponding to the two channels associated with the up-spin and down-spin electrons. In ferromagnetic layers, the resistivity is spin dependent, $\rho_M^{\pm}$, whereas in the spacer layers, the resistivity in the two channels is identical, ρ_s. The resistance of the multilayer is then equivalent to that of a total of eight resistors, with four resistors in each channel. The net resistivities of the two channels can be treated as resistors in parallel. Appropriately summing the resistors within a given channel is more complicated, but there are two simple

cases [37]. For short mean-free paths compared with the thickness of the layers, the resistors are independent and should themselves be added in parallel. Under these circumstances, it is clear that the resistance in the ferromagnetic and anti ferromagnetic configurations is the same, and consequently there is no magnetoresistance [34]

$$\triangle R/R = (R_{AF} - R_F)/R_F \tag{3.2}$$

where R_{AF} and R_F are the resistances corresponding to the anti ferromagnetic and ferromagnetic configurations respectivily. Another straight forward case is when the mean-free paths are long compared with the layer thicknesses in the multilayer. Then the resistivity is an average of the resistivity of the various layers in the multilayer, in proportion to the thicknesses of the corresponding layers. Note that for the ferromagnetic configuration, only two resistivities must be averaged, but in the antiferromagnetic configuration there are four resistivities to be considered. The giant magnetoresistance model figure 3.1 depends on two parameters, α/β and $M\beta/N$, Where $\alpha = \rho_F^+/\rho_s$ and $\beta = \rho_F^-/\rho_s$. This model shows, that the magnitude of $\triangle R/R$ is strongly dependent on the scattering asymmetry between the spin conduction channels in the ferromagnetic layers. Of course it is irrelevant in which spin channel the scattering is stronger, and the magnitude of the magnetoresistance depends on how much the ratio α/β differs. The highly simplified model also predicts that for a constant ratio α/β, the magnetoresistance decreases monotonically with increasing spacer layer thickness, falling off as $1/N^2$ for large thickness of the spacer N. The magnetoresistance is actually found to decrease exponentially with N for large N [34]. The reason for this discrepancy that the resistor network model is no longer applicable for N large compared to the mean-free path in the spacer layer. Such a simple

resistor network model can easily give values of magnetoresistance exceeding 100 percent for α/β ratios of $\simeq$ 8 to 10 [1, 37], and these ratios are considered reasonable. Nevertheless, they note that, as shown by the resistor network model, the magnitude of the magnetorsistance is expected to be related to the ratio of the scattering rates within the two conduction channels no matter where the spin dependent scattering takes place. The scattering asymmetries have been indirectly determined from measurements of the resistivity of magnetic ternary alloys [38]. However, no correlation between the magnitude the scattering asymmetries from studies of bulk magnetic alloys and the magnitude of the MR in magnetic multilayers has yet been found. The simple resistor network model discussed above predicts that the resistance of a magnetic multilayer will be higher for antiparallel alignment of the magnetic layers as compared with parallel alignment. This is schematically demonstrated in the upper portion of figure 3.1, where it is clear that the lower resistance for parallel alignment of the magnetic layers results from a short circuit of the current through one of the spin conduction channels. In this case, the resistance of the multilayer will be lower for the antiparallel alignment of neighboring magnetic layers, thereby leading to a positive or an inverse giant magnetoresistance effect.

3.2 Dependence of Giant Magnetoresistance on Structure

In multilayers, the magnitude of the saturation giant magnetoresistance is strongly dependent on the details of the multilayer structure. In particular, the giant magnetoresistance will depend on the thicknesses of both the magnetic and non magnetic layers and the number of bilayers, as well as on the composition and thickness of

any seed layers and capping layers [34]. In addition, the giant magnetoresistance is sensitive to the detailed morphology of the structure, which can be changed by varying deposition conditions such as the deposition temperature, the detailed method of preparation, and the substrate [33]. The giant magnetoresistance will also be decreased if the magnetic layers are not completely coupled antiferromagnetically to one another in the high resistance state. This means that it is very easy to obtain different values of giant magnetoresistance for nominally the same structure, and it is very difficult to make meaningful comparisons of results on individual samples from different groups. It is most useful to study sets of samples made under identical conditions where one aspect of the structure is systematically varied. Perhaps one of the most obvious aspects of the structure of a magnetic multilayer that can be varied is the overall thickness of the multilayer, as determined by the number of bilayers N. The magnitude of the giant magnetoresistance can be, and usually is, strongly dependent on the thickness of the spacer N. Figure 3.2 [34] shows typical resistance versus field curves for representative samples from two series of Fe/Cr multilayers with different N. The series differ only in the thicknesses of the Cr over layer t_o and the Cr under layer t_u. A minimum Cr under layer thickness of $\simeq 10\mathring{A}$ was required for the growth of well layered structures. As shown in figure 3.2 the measured giant magnetoresistance is increased with increasing N in both series of structures. However, the rate of increase of giant magnetoresistance with N is significantly different for the two series. The detailed dependence of magnetoresistance on N is displayed for the two families of structures. The magnetoresistance is observed to increase much more rapidly with N for the $[Fe/Cr]_N$ multilayers with very thin Cr under and over layers than for the structures with thicker Cr layers. The origin of this effect is similar

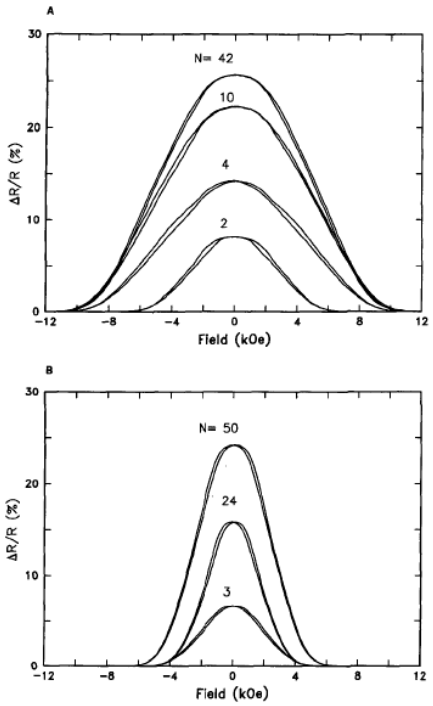

Figure 3.2: Resistance versus field curves at 4.2 K for several members of two families of Fe/Cr multilayers with different number of bilayers.(A) This corresponds to data for Fe/Cr multilayers of the form $Si/10\mathring{A}\ Cr/[18\mathring{A}\ Fe/9\mathring{A}Cr]_N/10\mathring{A}$ Cr with N $\approx$ 2, 4, 10, and 42. (b) This corresponds to data for $Si/115\mathring{A}\ Cr/[16/\mathring{A}Fe/11.5/\mathring{A}Cr]_N$ $/115\mathring{A}$ Cr with N = 3, 24, and 50.

to that described above for the dependence of giant magnetoresistance on Cu layer thickness in Co/Cu multilayers. The giant magnetoresistance in the Fe/Cr multilayers is reduced in proportion to the measuring current passing through the Cr under and over layers. The dilution of the $[Fe/Cr]_N$ portion of the multilayer contributing to the giant magnetoresistance, by the non contributing portion of the structure, will be decreased as the relative proportion of the non contributing portion decreases with increased N. The largest giant magnetoresistance values in Fe/Cr (and other multi layers) are found multilayers with large values of N [39]. The dependence on N is not

completely determined by a simple dilution effect; there are several other factors.

1. An important and very simple factor affecting the dependence of giant magnetoresistance on N is that the two magnetic layers at either end of the multilayer contribute to giant magnetoresistance only half as much as the magnetic layers with in the interior of the multilayer (assuming diffuse scattering at either extremity of the multilayer).

2. As described in the very first models of GMR [40, 41], the giant magnetoresistance will be increased if the electrons propagate across many magnetic/nonmagnetic interfaces within a conduction carrier mean free path. When N is small compared with some mean-free path within the multilayer, the giant magnetoresistance is reduced. Thus it follows that the dependence of giant magnetoresistance on N will be temperature dependent, as described by the temperature dependence of the mean-free path. This effect is much more important as the conductivity of the multilayer increases: for example, in multilayer systems containing metals with long mean-free paths such as Cu, Ag, and Au and in single crystal, defect free multilayer systems.

3. The resistance of the film will increase as the film thickness is decreased because of scattering at the film surfaces. This leads to a decreased giant magnetoresistance effect. Finally, the structure of the multilayer itself will vary with total film thickness. For poly crystalline films, the grain size often increases in proportion to the film thickness. The giant magnetoresistance is clearly sensitive to the grain size [42]. The variation in number of grain boundaries with film thickness will lead to variations in film resistivity and thus giant magnetoresistance. For single crystal films with no large angle grain boundaries, the changes in structure with film thickness

may be more subtle. For Fe/Cr, it has been proposed that increases in giant magnetoresistance with N may be attributed to an increase in the roughness of the Fe/Cr interfaces at some length scale [43].

3.3 Dependence of Giant Magnetoresistance on Magnetic Layer Thickness

A basic assumption of the resistor network model of giant magnetoresistance described in figure 3.1 is that the spin dependent scattering giving rise to the giant magnetoresistance originate purely within the interior of the magnetic layers, i.e. from bulk spin dependent scattering. This model can be readily generalized to allow the spin dependent interfacial scattering by adding additional resistors in the network representing the scattering in the interfacial regions [34]. The relative contribution of spin dependent scattering from bulk scattering and from spin dependent scattering at the interfaces between the magnetic and spacer layers is a subject of great current interest. A simple experiment to examine the role of interfacial versus bulk spin dependent scattering is vary to the interfacial content of the magnetic multilayer by varying the thickness of the magnetic layers. The magnitude of the saturation giant magnetoresistance for these samples is plotted in figure 3.3 versus Fe layer thickness [34]. These data show that maximum giant magnetoresistance values are obtained for thin Fe layers $\simeq 8\mathring{A}$ thick, which strongly suggests that interfacial scattering of predominant importance. Note, however, that the giant magnetoresistance is diluted by the presence of necessary under layers (for growth) and over layers (for protection against corrosion). This means that the Fe thickness for which maximum giant magnetoresistance is obtained will be affected by the presence of these layers and by the

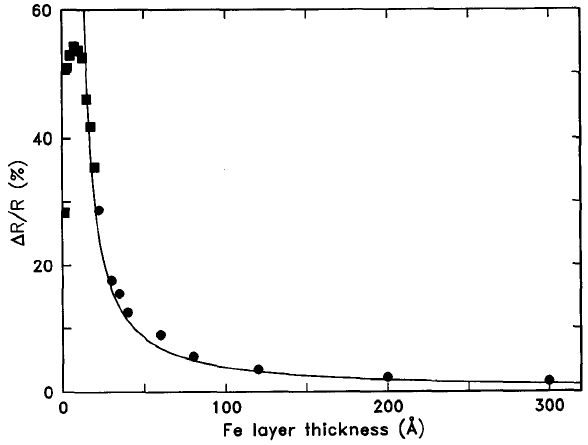

Figure 3.3: Dependence of saturation magnetoresistance at 4.2 K versus Fe layer thickness for structures, Si/9$\mathring{A}$ Cr/[Fe(t_{Fe})/9$\mathring{A}$ $Cr]_{2o}$, for Fe layer thicknesses ranging from 1.5 to 300/$\mathring{A}$ For thick Fe layers, the magnetoresistance becomes a significant fraction of the giant magnetoresistance effect.

thickness of the Cr spacer layers themselves. Increasing the thickness of these layers will increase the thickness of Fe necessary to obtain maximum giant magnetoresistance. Thus it is not straight forward to interpret such studies without appealing to detailed theoretical models. Note, however, that giant magnetoresistance models predict a maximum in the giant magnetoresistance effect for Fe layers significantly thicker than those found in Figure 3.3 for any significant spin dependent bulk scattering [44]. Finally, note that the giant magnetoresistance decreases approximately as the inverse Fe layer thickness for Fe layers, ranging in thickness from 20 to 300$\mathring{A}$ consistent with dilution of the interfacial scattering regions, and predominant interfacial spin dependent scattering. In short giant magnetoresistance is intimately related to scattering at the interfaces between the magnetic and nonmagnetic components in both magnetic layered structures. The largest giant magnetoresistance values are

usually found for structures in which the interfacial component is maximized, by reducing either the thickness of magnetic layers or the size of the magnetic particles. Similarly, the giant magnetoresistance is extremely sensitive to the detailed chemical nature of the interfaces. Modifications of these interfaces by dusting with just sub monolayer to monolayer equivalent coverages of impurity elements results in dramatic variations in giant magnetoresistance value. Indeed, giant magnetoresistance may thus be used to probe the electronic character of the magnetic/nonmagnetic interfaces, just as oscillatory interlayer coupling can be used to probe details of the Fermi surface topology of the spacer layer material and perhaps the magnetic layer material.

Chapter 4

Giant Magnetoresistance in Ferromagnetic Crystals

4.1 Inter Layer Exchange Coupling and GMR in Magnetic Multilayers

In this topic the magnetic coupling between ferromagnetic layers across a non magnetic spacer layer and the giant magnetoresistance are emphasized. Magnetic materials are formed artificially by magnetic multilayers. Multilayers consist of two materials arranged alternatively in layers of certain thicknesses. They are mostly prepared by molecular beam epitaxy under ultra high vacuum conditions. The progress in developing and refining these preparation techniques in the last decade has been possible to grow layers of very high purity and with extra ordinarily good thickness control for many materials combination. The greatest interest has been in the simplest form of the coupling,

$$\frac{E}{A} = -\mathbf{J} m_1 . m_2 \tag{4.1}$$

called bilinear because the energy per area is linear in the directions of both magnetization m_i. With this form of the interaction, positive values of the coupling constant **J** favor parallel alignment of the magnetization and negative values favor antiparallel

alignment. The discovery the coupling constant **J** and hence the preferred alignment of the magnetization oscillates as the thickness of the spacer layer is varied accelerated the interest started by the discovery of giant magnetoresistance. The fact that artificial multilayers thus prepared do not occur in nature suggests that, given the unique manipulation opportunities and unique geometry, they may be engineered to have properties which might not be attainable. Several interesting and sometimes spectacular physical phenomena have been reported [45, 46]. Among these are dimensionality effects already exhibited by single films (i.e. multilayers are not necessary). First take an example concerns the temperature dependence of the magnetization, which can be affected considerably due to the reduction in the number of magnetic neighbors. Curie temperatures which are strongly reduced with respect to the bulk metals, with reductions of an order of magnitude for monolayers. A second group of effects can be classified under interface effects, i.e. effects which occur due to the presence of a boundary between two different materials. One of the most striking phenomena in this category is the occurrence of an easy direction for the magnetization perpendicular to the plane of the magnetic layer. Since magnetic films were always expected to have their magnetization oriented parallel to the film plane as a result of the strong demagnetizing fields created when tilting the magnetization out of the film plane. A third group of effects concerns physical phenomena which only occur for systems consisting of at least two magnetic layers. One of these is the magnetic coupling between two ferromagnetic layers separated from each other by an intervening non magnetic layer. Another fascinating and for application oriented researchers perhaps the most important effect, is the so called giant magnetoresistance effect. Giant magnetoresistance was observed that the electrical resistance of several multilayered systems

decreased strongly upon applying a magnetic field. Interlayer exchange coupling is the magnetic coupling which has been discovered to exist between ferromagnetic layers across non magnetic interlayers. The term magnetic coupling between magnetic moments (or spins) usually refers to an interaction energy which depends on the relative orientation of the magnetic moments. In the present case we are interested in the dependence of the energy E on the relative orientation between macroscopic layer magnetization. It appears that this situation can be described phenomenologically by the expression $E = -J/\cos(\theta)$, where θ is the angle between the magnetization vectors of the interacting layers and J is the strength of the interaction being positive for ferromagnetic coupling and negative for anti ferromagnetic coupling. In such situations effects of this term are actually observed experimentally [47]. As they seen an important problem in these experiment is the practical difficulty in manufacturing ultra thin interlayer films without microscopic holes. The formation of such holes, through which the ferromagnetic layers can touch and form ferromagnetic bridges (so called pinholes), is disastrous, since such structures will outweighs any indirect anti ferromagnetic coupling through their very strong direct ferromagnetic coupling. Subsequently it was discovered that the phenomenon was a general feature: almost all non magnetic 3d, 4d and 5d transition metals were found to transmit an oscillatory interaction [34]. For many spacer materials about $10\mathring{A}$ was found for the oscillation period. However, it soon appeared that this rather simple experimental situation which suggested a $10\mathring{A}$ universal period was over simplified. For Cr a long period of $18\mathring{A}$ was found whereas for Os, which was not included in earlier experiments, also a significantly larger period of approximately $15\mathring{A}$ was found [48]. Moreover, further

experiments [49, 50], also inspired by theoretical predictions, showed that the oscillation periods depended on the specific growth orientation, i.e. on the orientation of the crystallographic planes with respect to the film normal. so that, even for a given element, no unique period could be defined. The situation became even more complicated after more refined experiments on samples having a considerably improved crystalline quality. From these it appeared that in addition to the above mentioned long period oscillations also oscillations were present with very short periods down to 2 monolayers (MLs) for Cr and Mn spacers. i.e.the exchange coupling displayed a so called multi periodic coupling behavior.

4.2 Giant Magnetoresistance in Ferromagnets (Organic Semiconductors)

Observation of magnetoresistance in magnetic trilayers is a common approach to study spin injection and transport. Here, the magnetic trilayer is comprised of soft and hard magnets separated by a non magnetic spacer to allow parallel *(on)* and antiparallel *(off)* alignments of the magnetic layers. The magnetoresistance defined as

$$MR = \frac{R_{AP} - R_P}{R_P} \tag{4.2}$$

relies on spin dependent scattering at the interfaces and spin polarized carrier transport in the spacer [51]. The *spintronic* applications of organic semiconductors (OSC) were motivated by long spin lifetime in organic semiconductors due to low spin-orbit coupling and weak hyperfine interaction [52]. In this project, we use the term giant magnetoresistance referring to magnetoresistance induced by the injection and transport of spin-polarized carriers through the nonmagnetic spacers instead of tunneling

through thin insulating barriers. Organic semiconductors typically have an energy gap of more than 2eV between highest occupied molecular orbital(HOMO) and lowest unoccupied molecular orbital (LUMO) levels. Thus, these materials are closer to insulators than to conventional inorganic semiconductors. The charge transport in the HOMO/LUMO levels is provided by phonon assisted hopping as the orbital overlap between the adjacent molecules is small and driven by the strong electric field in the organic electronic devices. In accordance with the previous criticisms [52, 53], concerning the observation of giant magnetorsistance, the amorphous organic semiconductors film spaced spin valve devices should have (a) extremely high junction resistance at low bias (several mV) and low temperature T due to large energy gap, (b) strong temperature dependent junction resistance due to activated carrier injection at the interface and activated carrier transport in the bulk, and (c) strong non linear current I versus voltage V curves with substantial temperature dependence due to carrier injection and space charge effect. The observation of giant magnetorsistance is still controversial and the understanding of spin injection and transport in organic semiconductors layer is still lacking due to lack of comprehensive device characteristic study. Though the organic semiconductors materials hold promise for their long spin life times, injection and transport of spin-polarized carriers in organic semiconductors films meet significant obstacles. There are typically large band effects between the Fermi level of typical ferromagnetic metals and the HOMO and LUMO levels of the organic semiconductors. The dipolar barrier at the metal/OSC interface creates defect states and may interfere with spin-polarized carrier injection [54]. Even when the efficient spin injection into the HOMO/LUMO levels of anorganic semiconductor is achieved, hopping transport in amorphous small molecule films associated

with phonon interaction may undermine efficient spin transport, especially at high temperature. Finally, there is a conductivity mismatch issue in applying highly resistive materials as the spin transporting spacer [55, 56]. However, the flexibility of organic chemistry has potential for significant improvement of efficient spin injection and transport in organic semiconductors. For intermediate thickness $d = 20nm$,the carrier injection described by thermionic field emission controls the device current. Applying high bias is needed to have viable device current as well as to observe magnetoresistance. The observed giant magnetorsistance for the devices with intermediate thickness of *rubrene* layer shows spin polarized carrier injection into, and subsequent transport through the *rubrene* layer. The responses of giant magnetorsistance in our devices to bias field and temperature show clear differences from that of tunneling magnetoresistance through the thin hybrid oxide or organic semi conductors layer.

Chapter 5

Conclusion

Giant magnetoresistance is the drastic change in electrical resistance of metallic layered systems when the magnetization of the ferromagnetic layers are reoriented relative to one another under the application of an external magnetic field. Various magnetic layered structures have been found sizable values of giant magnetoresistance. The giant magnetoresistance has been a huge impact on our life, especially for mass data storage devices. Giant magnetoresistance's application to the read head of hard discs greatly contributed to the fast rise in the density of stored information and lead to the extension of the hard disk technology to consumers' electronics. Besides in terms of further technological advances, the development of spintronics revealed many other phenomena related to the control and manipulation of spin currents. Thus basically giant magnetoresistance of the magnetic multilayers opened the way to an efficient control of the motion of the electrons by acting on their spin through the orientation of a magnetization. Several applications will be presented on the use of individual giant magnetoresistance materials. So at the beginning of this century outstanding progress had been made both in designing the magnetic properties through

atomic engineering, and in understanding and controlling the spin-dependent electrons transport. And materials exist that allow thermally stable magnetic particles to be produced down to size of a few nanometers, seemingly opening a bright future for high density spin storage.

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