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High Frequency Giant Magnetoresistance
in
Evaporated Co/Cu Multilayers Deposited on
Si(111) and Si(100)

By
Tim Rausch

A Thesis
Submitted to the College of Graduate Studies and Research
through the Department of Physics in the Partial
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Abstract

We report Giant Magnetoresistance (GMR) in Co/Cu multilayers deposited using high vacuum electron beam evaporation on Si(111) and Si(100). Samples grown on Si(111) show enhanced magnetoresistance and coercivity, which may be attributed to ill-defined interfacial boundaries between successive layers. Previous work exploring the frequency dependency of GMR has been done using microwave techniques to indirectly determine GMR. Our magnetoresistance data was obtained by replacing one side of a square loop antenna with a Co/Cu multilayer and measuring the impedance. No effect on the magnitude of the GMR, due to high frequency test signals, was observed for a frequency range from DC to 5.5 GHz.

Dedication

This Thesis is dedicated to my beautiful fiancée Allison, who I love dearly.

In addition I would like to thank her parents, Don and Carolyn Mabley and my parents, Siegfried and Mary-Lou Rausch, for their continued encouragement and support.

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Chapter I

Introduction

1.1.0 Introduction

During the last two decades, the growth of interest in metallic multilayer films has been enormous. This growth rate has been attributed to simultaneous developments, which converged during the late 1980s, in ultra high vacuum techniques, spin polarized electron techniques and computational physics [1]. Because of their unique properties, which seem to have unlimited industrial applications, artificially synthesized metallic multilayers continue to be of great importance in the area of late-20th century technology. This is due in part to the observation that metallic multilayers exhibit enhanced hardness [2], enhanced wear resistance [3], unique optical properties [1], and unique magnetic properties [4], all of which differ from their bulk characteristics. The magnetic properties of these films, specifically giant magnetoresistance (GMR), are the topic of this thesis.

Many devices have been proposed and fabricated which take advantage of the magnetoresistive effect. For example, thin film permalloy sensors have been used as detectors in magnetic bubble memories [5], magnetoresistive read heads [6] and magnetic memory devices [6]. Recently, in January of 1998 IBM was the first company to retail GMR based magnetic read/write heads in a family of disk drive products, designated Deskstar 16GP [7]. The use of GMR read/write heads allows for the reading and writing of extremely small magnetic

Figure 1 Schematic diagram of a multilayer comprised of alternating magnetic (Co) and non-magnetic (Cu) layers.

bits of information, which facilitates high-density storage. Using current technology, they were able to store 3.2 gigabytes of data on a single 95-mm diameter disk. Researchers predict that they will be able to increase the storage density on these disks to a remarkable 10 gigabytes per square inch by 2001 [7].

A simple magnetic multilayer consists of alternating thin films of a magnetic and non-magnetic metal, as shown on Figure 1. Subjecting this construct to a weak magnetic field may cause the resistance to drop by up to 60% in some systems [8]. The magnetoresistance (MR) in this case, is called 'giant' because it is much larger than the normal anisotropic magnetoresistance (AMR) observed in bulk materials [1]. In order to observe the GMR effect, the metal layers in the film have to be very thin, typically less than 50Å. Depositing such thin, smooth layers, with well defined boundaries, requires special deposition techniques, some of which did not exist prior to the mid eighties.

Currently four principle methods exist for the fabrication of multilayers, molecular beam epitaxy (MBE) [9], dc magnetron sputtering [8], electrodeposition [10] and electron beam evaporation (EBE) [11]. Of the four, MBE and sputtering are the most accepted since they seem to give reliable results with good GMR. Until recently, little work had been published that used EBE as a deposition method [11]. EBE is advantages over MBE and sputtering since it is a less technologically complicated process and is far less expensive. These facts make EBE an attractive alternative for industry since EBE systems are easily adapted to large-scale production methods. In order to facilitate the distinction between these methods, the following is a brief description of each technique.

DC magnetron sputtering involves the momentum transfer from a sputtering gas, usually Ar, to the deposition metal. Ar gas is ionized and accelerated to the target, which consists of the material to be deposited. Through the momentum transfer, atoms from the target metal are released into the evaporation chamber. The liberated components condense on surrounding areas and consequently on the substrate placed at the anode. The two species of metal are sputtered simultaneously and a computer controlled shutter system is used to control which metal is deposited. Deposition rates are typically 5-10Å/s which is by far the highest deposition rate for the vacuum techniques [8]. Results from sputtering deposited films are usually polycrystalline in nature and seem to show good GMR.

Electrodeposition has been used to fabricate Ni/Cu [10], Co/Cu [10], Co-Ni/Cu [12] multilayers as well as a few other combinations [12]. In electrodeposition, the two different species of metals, which

form the multilayer are dissolved in a single solution. One metal, say copper, is deposited at a lower potential than the other, such as cobalt. The cobalt is dissolved at a much higher concentration than copper, typically 99% by mass, while copper is dissolved at a much lower concentration, typically 1% by mass and as a result deposits at a slower rate. A potential is first applied that is sufficient to deposit copper but not cobalt. When an adequate amount of copper has been deposited, the potential is switched to a higher value to deposit cobalt. Since the higher potential is able to deposit both copper and cobalt, an alloy is deposited. However, since the relative concentration of cobalt is much higher, the layer is relatively pure. The double pulse is again repeated and in this manner multilayers are deposited. Deposition rates are different for the two species due to the large difference in concentrations of the two metals. Copper, which deposits at a much the lower potential, has a deposition rate of about $.5\text{\AA}/\text{s}$ while cobalt, with the larger potential, is deposited at a much higher rate (typically $60\text{\AA}/\text{s}$ to ensure the purity of the layer). With this technique it is possible to deposit very thick multilayers that can have over 5000 layers [10]. These thick layers make electrodeposition very practical when multilayers are needed for their unique wear [2] and/or hardness [3] properties. The magnetoresistance data seems to vary from group to group. Reports of GMR in Co/Cu multilayers have varied from 6% [13] up to 60% [10]. Furthermore, the quality of the multilayer is highly dependent on the small variations in the growth techniques used by each group and the choice of substrate. These facts make it difficult to compare results from different groups.

MBE is closely related to EBE in that they are both pure evaporation techniques. The metal to be deposited is heated until it begins to evaporate. The substrate is not heated, and as a result the hot metal gas condenses on the much cooler substrate facilitating film growth. The main differences between the two methods are the technique used to heat the deposition metals, the deposition rate, and the vacuum pressure prior to deposition. MBE usually requires a base pressure of 10^{-11} to 10^{-10} torr, which requires specialized vacuum techniques. The deposition metals are heated thermally by a Knudsen Cell [14] which allows for a steady, well-controlled molecular beam. The sources are controlled by a pair of computer operated shutters that determine which metal is deposited. Typical deposition rates are $.1\text{-}.3\text{ \AA}/\text{s}$ [11]. The thickness of the deposit is determined by a mass spectrometer calibrated for high accuracy measurement. MBE is used when epitaxial samples of extreme purity and with almost ideal crystal structure are needed. By far the

sharpest interfaces are obtained from MBE systems. MBE deposits are typically single crystal deposits and are thought to closely resemble the near perfect constructs used in theory [11].

Very few results have been published in the literature for samples grown using EBE technique. Recently, Oepts *et al.* [11] examined the dependence of GMR on the deposition method for samples grown by EBE and MBE. They deposited multilayers on V-grooved substrates, which allows for the determination of GMR in both the current perpendicular to the plane (CPP) and current in the plane (CIP) geometry [11]. The authors reported a slightly higher GMR for sample grown by MBE than for samples grown by EBE in the CPP geometry. However, the GMR was higher for the EBE samples when measurements were performed in the CIP geometry. The differences were attributed to the more granular growth of the EBE samples [11]. EBE systems are more practical than MBE systems in that they are simpler to maintain and operate, which as pointed out earlier, make them attractive to industry [11]. The major difference between the two systems is the base pressure prior to deposition. EBE systems use a vacuum pressure on the order of 10^{-8} torr, which is considerably higher than those used by MBE systems. To maintain the low pressures of a MBE system, expensive cryo-pumps are often required. The ultra low pressures used in MBE make it impractical for large-scale deposition of multilayers while the higher-pressure EBE technique is much more viable. Unlike MBE, EBE systems do not heat the deposition metal thermally. An electron beam is used to melt the deposition metal until it begins to evaporate. This is different from sputtering systems in that the electrons heat the metal causing it to evaporate rather than liberating metal atoms through a momentum transfer process. EBE systems typically deposit at a rate of .5 – 2 Å/s, which is higher than MBE systems but less than those used in sputtering. As a consequence of the higher deposition rate, EBE samples tend to be more granular than the near perfect crystals deposited by MBE systems [11].

As stated earlier, subjecting a magnetic multilayer to a magnetic field causes that resistivity of the sample to decrease. The mechanism by which the reduction in the resistance occurs can be understood qualitatively by spin dependent scattering [15]. The transport properties of the itinerant electrons in the conduction band can be expressed as separate contributions from spin-up (majority) and spin-down (minority) electrons [15]. Furthermore, individual magnetic moments of the atoms in each magnetic layer are assumed to point in the same direction in space. As such, each magnetic layer is given a net magnetic

moment. An interaction between neighboring net magnetic moments can occur via the magnetic susceptibility of the conduction electrons. This interaction between magnetic layers causes the net moments to align themselves in a particular orientation in space, which is depended on the non-magnetic layer thickness; this phenomenon will be discussed in detail in section 2.1.2. In the absence of an external magnetic field, the net magnetic moments between successive magnetic layers will align themselves in an antiferromagnetic (AFM) orientation. If an external magnetic field of sufficient strength is applied, the net magnetic moments of the multilayer can be forced to align in a ferromagnetic (FM) orientation. As such,

Figure 2 Origin of giant magnetoresistance (GMR) depicted in terms of spin dependent scattering. (a) and (b) shows the multilayer in the ferromagnetic (FM) and antiferromagnetic (AFM) orientation respectively. (c) and (d) shows the equivalent circuits for (a) and (b). R represents a higher resistivity due to spin dependent scattering for a particular channel and $R > r$. If suitable conditions exist, the multilayer in the absence of an external magnetic field will be orientated in the AFM arrangement as in (b). Both spin channels are equally scattered and the equivalent resistance can be found from (d). If an external magnetic field, of sufficient strength, is used to align the moments in each layer, the multilayer can be forced into the FM arrangement as in (a). In this orientation, one spin channel (spin up) is not scattered and represents a lower resistance spin channel for the conduction electrons. The equivalent resistance can be found from (c).

two different magnetic orientations exist for the multilayers, AFM and FM. If an itinerant electron passes through a magnetic layer it will be more scattered if its spin is opposite that of the magnetic layer than if the spin is aligned to the net moment of the layer [15]. Each magnetic layer acts as a spin-selective valve since its magnetization determines whether it transmits predominantly spin-up or spin-down electrons. When the multilayer is in the AFM orientation, both spin channels are scattered equally since every second magnetic layer is aligned opposite to the one before it. When the orientation of each magnetic layer is forced, by an external magnetic field, in the FM orientation, one spin channel is not scattered. This un-scattered spin channel represents a lower resistance alternative for the electrons, which reduces the overall resistance of the multilayer. The effect is illustrated schematically in Figure 2, where R and r represent the resistance when an electron is scattered and when it passes through unaffected respectively.

From Figure 2c and 2d, the resistance of the ferromagnetic orientation, R_F , and the antiferromagnetic orientation, R_{AF} , can be obtained. Clearly, R_F is indicative of a much lower resistance orientation than R_{AF} and is the origin of GMR.

$$R_F = \frac{2rR}{r + R} \quad R_{AF} = \frac{r + R}{2} \quad (1)$$

Currently in the literature, two definitions are in use for reporting GMR. The most common and the one used in this thesis, is the “inflationary” definition given by,

$$GMR = \frac{R_{AF} - R_F}{R_F} = \frac{(R - r)^2}{4rR} \quad (2)$$

A less common, “conservative” definition is also in use and is defined as,

$$GMR = \frac{R_{AF} - R_F}{R_{AF}} = \frac{(R - r)^2}{(R + r)^2} \quad (3)$$

The difference between these two definitions, is the term in the denominator. The inflationary definition defines the GMR with respect to R_F , which is lower than R_{AF} . The effect of using the lower R_F rather than R_{AF} in the definition is to increase the reported magnitude of the GMR.

GMR as defined in equations 2 and 3 is modified somewhat in order to reveal the shape of the magnetoresistance curve as it evolves from zero applied field to full applied field. This is accomplished by defining the magnetoresistance as a function of the applied magnetic field, H . Rather than using the fixed resistance R_{AF} we substitute a variable resistance R_H , which is dependent on the magnetic field. In addition, since in experiments the magnetic field is often increased well beyond what is required to obtain the FM orientation, GMR will be defined in terms of the saturation (or maximum) magnetic field resistance, R_{SAT}

$$GMR(H) = \frac{R_H - R_{SAT}}{R_{SAT}} \quad (4)$$

Considering that most multilayers are less than 300 layers thick and that the largest GMR values are obtain when the layer thickness' are less than 50Å, it is evident that the films are too thin to practically measure the resistance in the CPP geometry as shown in figure 2. However, CPP magnetoresistance has been reported in the literature where the authors used very sensitive equipment [16] or specialized growth techniques [11]. Typically, the length of the multilayer is sufficient enough to allow for the measurement of the film resistance without using specialized equipment. In this arrangement the current runs in the plane (CIP) of the film, as seen in figure 3. A physical consequence of the CIP geometry is that the measured GMR is somewhat less than that observed in the CPP configuration [11]. This can be understood in terms of the momentum distribution of the itinerant electrons. In a metal, the conduction electrons are in random motion but the overall distribution of the momentum is such that the net current is zero. Applying a potential difference across the film superimposes a net current onto the random motion of the electrons. If the potential is applied perpendicular to the plane, a net current will flow in the CPP geometry as shown in figure 2. The effect is to force the net current to sample all the magnetic layers causing electrons in the appropriate spin channel to be scattered. If the potential is applied parallel to the plane of the film, the net current will not sample the magnetic layers. However, GMR is still observed since scattering due to the

Figure 3 Schematic representation of GMR for the net current running parallel to the plane (CIP) geometry. In the absence of an external magnetic field, the magnetic layers are aligned anti-ferromagnetically as in (a). When a magnetic field of sufficient strength is applied, the magnetic layers are forced to align ferromagnetically as in (b). Within the multilayer, the itinerant (conduction) electrons are in random motion in the absence of an external potential difference. Applying a potential superimposes a net current onto this random motion. The random motion of the electrons leads to sampling of the magnetic layers, and therefore scattering still occurs even though the net current runs parallel to the magnetic layers.

magnetic layers will occur through the random motion of the itinerant electrons. This is depicted schematically in figure 3.

Clearly, if effect of the potential is to force the net current across the magnetic layers, it is expected that the GMR would be greater than if the effect of the potential was to force electrons to travel parallel to the layers. Regardless of whether or not the CIP or CPP geometries are used, the theory of spin dependent scattering still applies. Most theories assume the CPP geometry in their construction since it often simplifies the immense computational aspects typical of modern theories. Nevertheless, the major effects that each theory predicts apply to both orientations. The original theory to explain GMR, as outlined above, assumes that the spin dependent scattering originates in the interior of the magnetic layers.

This theory, although useful since it gives a simple working model, lacks in that it fails to explain some observed properties such as the exponential decrease of GMR with respect to the magnetic field [17]. More advanced theory [17], which will be derived in section 2.1.3, assume an interface contribution as well as an interior contribution, account better for the observed GMR. This large contribution of interfacial scattering has received some recent experimental support in the literature [18]. Interfacial doping [18], which involves depositing a very thin Co layer between the magnetic and non-magnetic layers in a permalloy/Cu multilayer, has lead to an increase in the measured GMR. The effect of the thin Co layer ($>4\text{\AA}$) was assumed to introduce a purely interfacial scattering component since the film was too thin to contribute interior scattering. Even though new theoretical models are being developed which seem to better account for the observed data, a coherent theoretical framework is still lacking.

The current models, which best account for the GMR data, indicate that the magnetic properties of the film should be independent of the frequency of the itinerant electrons. The purpose of the work presented here is to verify this using a direct contact method to measure the magnetoresistance. Thus providing further support for the successful GMR models

GMR measurements are usually performed using the four-point probe method developed by L. J. van der Pauw [19]. The sample is loaded into the probe and placed in an external magnetic field. The resistance of the sample is measured as a function of the changing magnetic field. To the best of the author's knowledge, all GMR reported which uses this technique, has used a DC current to test the magnetoresistance of multilayers (DC-GMR). Little work has been done which examines the effect, if any, of using high frequency signals rather than a DC signal to measure the magnetoresistance of multilayers (HF-GMR). Some of the high frequency work that has been done [19,20,21] involves using non-contact methods, which indirectly measures the GMR. To appreciate the scope of the work in this thesis, a brief review of the HF-GMR data that currently resides in the literature will be discusses.

Krebs *et al.* [19] and Kuanr *et al* [20] used similar techniques to determine HF-GMR from observed ferromagnetic resonance (FMR) data. It has been shown that in magnetic multilayers, a non-resonant absorption of microwaves is present, and its magnetic field dependence is related to the GMR effect [22]. Experiments were performed by placing a Fe/Cr/Fe trilayer at the end of a rectangular waveguide operating in the TE_{001} mode [19]. The wave-guide is used to generate an oscillating

electromagnetic field in the microwave region, which causes precessional motion of the magnetic moments in the trilayer. A static magnetic field is applied parallel to the film and perpendicular to the magnetic component of the electromagnetic field in order to align all the magnetic moments. The output of the signal, is proportional to the magnetic-field derivative of the microwave power absorbed, dP/dH , and is detected using field modulation and a lock in amplifier [19]. The magnetoresistance contribution to dP/dH is given by [19],

$$\frac{dP}{dH} \propto \left(\frac{E^2 d}{R(0)} \right) \left(\frac{dGMR}{dH} \right). \quad (5)$$

where E is the microwave electric field, d is the sample length, $R(0)$ is the sample resistance at zero applied field and GMR is defined by the “conservative” definition of equation 3. From equation 5, the digitally calculated values of the HF-GMR may be calculated. By changing the location of the sample in the waveguide, Kuanr *et al.* were able to determine the HF-GMR in the field-in-plane (FIP) and field-perpendicular-plane (FPP) geometry. The FIP and FPP geometries are considered to be analogous to the CIP and CPP geometries of normal DC-GMR [20]. Using this method, Krebs *et al.* and Kunar *et al.* were able to obtain HF-GMR results up to 35 GHz and 12 GHz respectively.

Rather than measure the magnetic-field derivative of the power absorbed, dP/dH , Ustinov *et al.* [22] defined a ratio similar to the “conservative” GMR. Transmission giant magnetoresistance (TGMR), is given in terms of the microwave transmission coefficient, $D = P_{out}/P_{in}$,

$$TGMR = \frac{D(H) - D(0)}{D(0)}. \quad (6)$$

A sample consisting of 14 repeats of a Fe/Cr multilayer was placed in the center of a rectangular waveguide operating in the TE_{01} mode as shown in figure 4. An external magnetic field is applied perpendicular to the electric field E , and the direction of propagation k , to force the film from the AFM into the FM orientation. The transmission coefficient of electromagnetic waves and its magnetic field dependence $D(H)$, are measured instrumentally based on the reflectometer scheme [22]. The results are

Figure 4 Diagram of the experimental set up for the measurement of transmission giant magnetoresistance (TGMR) [22]. A waveguide is set to operate in the TE_{01} mode with the electric field, E , and the propagation direction, k , as shown. The sample is placed at the center of the waveguide and the input power, P_{in} , and the output power, P_{out} , are measured as a function of the external magnetic field B . Using electromagnetic wave transmission theory, the output power can be shown to be dependent on the resistivity of the sample. By applying an external magnetic field the resistivity of the sample can be reduced through the GMR effect, this in turn causes a reduction in the measured output power.

similar to magnetoresistive measurements reported in the literature since the transmitted power is proportional to the resistance of the sample. Using the theory of electromagnetic wave transmission through a metal plate, the authors were able to derive an expression for the transmission coefficient D .

$$D = \frac{c^2}{2\pi\sigma d} \quad (7)$$

Here σ is the DC conductivity, which is dependent on the external magnetic field through the GMR effect, and d is the thickness of the sample. The authors reported a direct correlation between DC-GMR and TGMR up to an external magnetic field strength of 85% of saturation and for a frequency range of 5.6 GHz to 9 GHz [22].

It should be emphasized that both methods outlined above do not measure the impedance or resistance of a magnetic multilayer. Both techniques demonstrate how applying an external magnetic field

effect electromagnetic wave propagation through a thin multilayer. The authors attribute their observed results to a manifestation of the GMR effect within the confines of electromagnetic wave propagation theory.

For the purposes of this work, 32 samples were fabricated using the EBE method. In each case, 40 repeats of a Co/Cu multilayer were grown between a 50Å Fe seed layer and cap. The magnetic cobalt layer was maintained at constant thickness of 10Å while the copper layers varied in thickness from 8 to 32Å. A direct contact method similar to DC-GMR measurement was developed to measure HF-GMR by observing the impedance of the sample. To the best of the author's knowledge, this work is the first to report a change in the impedance of a magnetic multilayer due to an external magnetic field. We attribute this change to the HF-GMR effect. At the frequencies under consideration, the results had to be interpreted through advanced antenna theory since the test fixture tended to behave more like an antenna than a resistor. We report HF-GMR data from DC up to 5.5 GHz. The effect was observed to remain unchanged in magnitude for the frequency range under consideration. In the course of this study, probes and techniques had to be designed and developed for DC as well as for HF measurement. In addition, computer programs had to be written to perform the GMR measurements and interpret high frequency data.

The importance of this work is evident in that it verifies that a change in impedance due to the GMR effect can be observed at high frequencies as well as at DC. Many new technologies, especially in the area of communication and micro-sensors, are operating at higher and higher frequencies. Novel devices, such as high frequency attenuates [23] may be constructed which take advantage of HF-GMR effect. This work is not only important in terms of potential application but also in the strengthening of existing theory, which indicates that GMR should be independent of measurement current frequency. In addition, we have shown that EBE is a viable alternative to MBE, sputtering and electrodeposition since they demonstrate similar magnetoresistive properties.

Chapter II

Theoretical Considerations

2.1.0 Electromagnetic Characteristics

In the introduction, a simplified model of spin dependent scattering was shown to adequately account for the GMR effect. Although this model is useful since it provides a pictorial representation of spin dependent scattering, it is somewhat incomplete. Many of the important details concerning coupling between successive magnetic layers and the spin dependent scattering mechanisms were omitted. In addition, more complete models [24, 25] have been proposed which better account for the observed magnetoresistive data.

In this section we will discuss:

- a) Spin dependent scattering mechanisms.
- b) The model proposed for the coupling of successive magnetic layers via the conduction electrons.
- c) Semi-classical magnetoresistive models.

In order to formulate a clear picture, a brief review of the conduction of electrons in a metal will be discussed. It should be emphasized that many of the theories covered in this section are quite complex and often only the results will be quoted.

2.1.1 Spin Dependent Scattering Mechanisms

We begin this section by considering the butadiene atom of figure 5a, which is a prototype metallic system [26]. When the molecule is formed, each carbon atom contributes 4 electrons and each hydrogen atom 1. Of the 16 carbon electrons, 12 participate in the covalent C—C and C—H bonds known as the σ bonds, which hold the atom together. Since each carbon atom contributes one more electron than is required for covalent bonding, the extra electrons become delocalized from the carbon atom. These delocalized electrons occupy a region in space both above and below the plane of the atom as shown in figure 5 [26]. The electrons are free to range over the linear dimension, l , spanned by the carbon atoms and

Figure 5 (a) The ball and stick view of a butadiene molecule, which is a prototype metallic system. Each carbon molecule (large black circle) contributes four electrons from the valance shell and each hydrogen atom (small white circle) one. Three of the carbon electrons and the single hydrogen electron contribute to the C—C and C—H bonding (black line) and constitute the σ bonds. The remaining valence electrons on each carbon molecule form the π bonds, which are localized within the shaded area. The π bond electrons are free to traverse the entire length of the molecule, l . (b) A representation of the allowed energies for the π bond electrons. As a consequence of the Pauli exclusion principle, only two electrons per energy level are allowed. The electrons can be excited into the higher energy states which is typical of a metallic system.

form what are known as π bonds. The π bond electrons, may be considered to be confined to a one-dimensional potential well, whose energy is given by the familiar result [26],

$$E_n = n^2 \left(\frac{h^2}{8ml^2} \right). \quad (8)$$

Here n , m and l are the quantum number, mass of the electron, and range over which the π bond electrons are free to roam, respectively. The first five energy levels of such a configuration are shown schematically in figure 5b. In the figure, electrons are placed in the potential well according to the ground state specifications of the system. As a result of the Pauli exclusion principle, only two electrons per energy

Figure 6 The band structure for a single copper atom and for a metal consisting of N copper atoms. There are 2 electrons in the 3s state of the copper atom and therefore $2N$ electrons in the 3s band. In copper the 4s and 4p levels form a s/p band that in a sample that contains N atoms accommodates N electrons. This band is isolated from other energy levels and the itinerant electrons behave largely as free particles. Within the s/p band resides a narrow filled band from the 3d energy level. The fact that the s/p and d states interact with one another often complicates calculations involving copper [27].

level are allowed. The existence of the vacant, higher energy states, available to the delocalized π bonds is typical of the metallic state. These states can only become populated if electrons from lower lying levels are excited by the application of an external agent. If we imagine adding more atoms on to this molecule, the length of l would increase bringing the energy levels closer together as seen by equation 8. Eventually, the energy levels become so close together, they are assumed to form a continuous energy band throughout which the delocalized electrons are distributed [26]. This is depicted in figure 6 for copper where we show the structure for a single copper atom and metallic copper consisting of N atoms. In the latter case, the well-defined energy levels of a single copper atom form bands of energy. The delocalized electrons in a metallic crystal are known as the itinerant (or conduction) electrons and they reside in the higher energy bands of the system known as the conduction band. This is the elementary view of a metal known as the Sommerfeld model.

The itinerant electrons are in constant random motion in such away as to ensure the net current of a metal is zero. In a typical metal, these electrons on average are approximately $2\text{\AA}$ apart and move in all directions with an average velocity of $\sim 2 \times 10^6$ m/s [26]. Applying a potential to the metal superimposes a net velocity onto these electrons thereby generating a current. In copper, for example, a potential of 100 Volt/m adds about .5 m/s to the electron's velocity in the direction of the applied field [26]. The electrons are not free to move without collision. Although they do not collide with the periodic atoms in the lattice, they do collide with impurities or dislocations in the crystal. The typical mean free path (MFP), or average length between collisions in a metal is approximately $500\text{ \AA}$ at room temperature [28].

The electrons in the conduction band have an equal mix of both spin up and

Figure 7 Three types of scattering process. If the electron is moving too fast its motion is changed little. If the electron is moving too slow, it is scattered due to the Coulomb repulsion of the outer most electrons in the ion. Electrons with energy comparable to that of the outer orbital of the ion may temporarily be captured. These electrons are strongly effected by the presence of the atom since collisions may be inelastic or the spin orientation of the electron may be changed.

spin down electrons providing that the metal is non-magnetic. As such, copper for example, has the net current divided into two equal spin channels of up and down electrons. In the absence of spin dependent scattering, both these channels are scattered equally by phonons [29], impurities [30] or by Bragg refraction [31]. At room temperature, phonon scattering dominates the electrical resistivity of a metal, while, at liquid helium temperatures, impurity scattering dominates [32]. If spin dependent scattering is introduced, in addition to the before mention scattering mechanism, magnon scattering and spin dependent impurity scattering do occur. Current explanations for the GMR effect assume that the contribution from phonon, magnon or Bragg scattering mechanisms are the same for both channels and are ignored. This is not to say that they do not exist, but rather that they are assumed to remain unchanged in the presence of an external magnetic field. As such, only impurity scattering will be considered.

When an itinerant electron passes near an impurity there are 3 possibilities [33] depending on the energy and momentum of the incident electron. The fastest moving electrons are effected little by the presence of the impurity; they pass quickly through the region and do not spend sufficient time there to either make any contribution or feel any significant effects. Slow moving electrons are effected by the repulsive Coulomb force of the electrons localized in the outer shells and are strongly scattered. These electrons are not able to penetrate close to the ion or stay within its vicinity for any long period of time [33]. Electrons having energies comparable to the outer orbital of the ion may temporarily be captured by the ion, contributing to and feeling the effects of the ion, before being released back into the conduction band. This is known as resonant scattering and is shown schematically in figure 7 along with the fast and slow scattering mechanisms. When an itinerant electron is resonantly scattered by an impurity and experiences no change in energy it is said to be elastic; otherwise it is said to be inelastic. If the scattering process changes the electrons spin between initial and final states, it is called a spin-flip event; otherwise it is a nonspin-flip event. Since the fast and slow moving electrons cannot interact with the impurity they are elastic nonspin-flip processes.

Resonantly scattered itinerant electrons are said to be in a virtually bound state of the impurity [34]. Electrons in a virtual state can be regarded as an intermediate state since it is atomic like in that it is localized around a particular ion but yet it is free to interact with the itinerant electrons. In other words, virtual levels are regions of space and energy around an impurity where itinerant electrons linger and

Figure 8 In a and b a single atomic level in a non-magnetic impurity atom gives rise to a virtual level buried deep within the conduction band and one near the edge respectively. In c and d a single atomic level in a magnetic impurity is split which results in two virtual levels for each spin orientation

temporarily assume the atomic features of the impurities atomic states [34]. The physical origin of the virtual level is the hybridization between the energy levels of the foreign ion and those of the host conduction band that have comparable energies. Depending on the impurity, the virtual level can be deep within the conduction band or at the boundaries as shown in figures 8a and 8b respectively. If the virtual level is buried deep within the conduction band it, its effects on the itinerant electrons and consequently the metals electrical properties may not be felt. The reason for this is that only those electrons whose energy is close to the Fermi level determine the transport properties of the metal [34].

The virtual level can be split as shown in figure 8c and 8d. There are four potential causes for this splitting namely, crystal field splitting where; the electrostatic effects of the crystal cause the energy levels to split [35], interatomic coulomb repulsion; where electrons within a shell produce the virtual level [35], spin-orbit coupling; where the orbital and spin momenta couple and split the field [35], and finally, interatomic exchange potentials which we now turn our attention to.

The direct intraatomic exchange coupling between electrons in a given shell can split an atomic level into two spin states as shown on figure 8c and 8d [35]. In a single atom, the electrons with a given orbital arrange themselves in such a manner to have all the spins parallel [36]. When all the electrons in the atom are aligned in one direction, the system is in its lowest energy configuration. This is a consequence of Hund's rules. Friedel proposed that if these characteristics of an atom survived the alloying process, the split atomic levels would manifest themselves in the form of split virtual levels as seen in figure 8c and 8d. The electrons arrange themselves in the virtual energy levels to give rise to the lowest possible allowed energy for the system and any scattering event which may occur, can not decrease the energy of the system any further.

In the usually classic analogy, the spin S , of the atom is defines as the sum of the unpaired electron

Figure 9 Un-split virtual level scattering. Since the energy of the impurity $2E$, is already in its lowest possible state, any scattering event must either increase the energy of the impurity or leave it unaffected. Since the energy in the virtual level is independent of spin, the level is degenerate. As such, the scattering events are elastic. In a and c the scattering is non spin-flip while in b and d the process is spin flip. Are four process are considered equally likely from conservation of energy arguments.

spins in the level. There are $2S + 1$ different allowed alternatives or orientations with respect to some fixed direction, usually taken as the z direction. The spin projection quantum number, M_S , thus has $2S + 1$ allowed alternatives. In the absence of an external field, the $2S + 1$ levels are degenerate in energy and all have equal probability of being occupied. Applying a magnetic field causes the levels to become Zeeman split and the degeneracy is gradually lifted [35]. As such, the electrons preferentially occupy the lower energy Zeeman levels. These split virtual levels, are the cause of spin dependent scattering.

From the electron's point of view, in terms of its spin, there are two possibilities when it is scattered; either the scattering is a spin-flip process or a nonspin-flip process. Since electrons are either spin up or spin down, there are four processes that must be considered.

1. $k\uparrow \rightarrow k'\uparrow$
2. $k\uparrow \rightarrow k'\downarrow$
3. $k\downarrow \rightarrow k'\downarrow$
4. $k\downarrow \rightarrow k'\uparrow$

If the itinerant electron is captured in a non-split virtual level such as in figure 8b, the interaction is clearly spin independent. The reason being that there is no difference in energy due to the spin of the electron. Since the energy of the impurity cannot be lowered, the scattering must be elastic. That is to say that if a spin up electron is captured, escaping spin up or spin down electron must have the same energy. Since the virtual level is not split, all four possibilities may be considered to be equally probable from a conservation of energy viewpoint. The possible spin dependent scattering events for an un-split virtual level is illustrated in figure 9. The impurity is considered to have two electrons of opposite spin in the virtual level of energy E . In actuality, the number of electrons in the virtual level may be much greater. The electrons in the impurity are assumed to be in the lowest energy state with an energy $E_p = E + E = 2E$. An impinging electron of either up or down spin is scattered by the impurity as shown in figures 9a through 9d. Since the impurity is in its lowest energy state, the only condition on the scattering mechanism is that the energy of the impurity either stays the same or increases. As such, the scattering must be elastic and the electron has the same energy both before and after scattering. Figures a and c and figures b and d are non-spin flip and spin flip scattering events respectively. The effect of the spin flip events is to permanently increase or decrease the total spin, S , of the impurity.

Figure 10 illustrates the scattering mechanisms when the virtual levels are split due to an applied magnetic field. The energy of the up and down spin virtual levels are $E_{\uparrow}$ and $E_{\downarrow}$ respectively where $E_{\uparrow} < E_{\downarrow}$. As in elastic un-split virtual level scattering, the energy of the impurity can only remain the same or be increased. In figures 10a and 10c the non-spin flip scattering mechanism are shown where the energy of the impurity and of the scattered electron remain the same. The effect of splitting the virtual level is to allow for inelastic scattering mechanisms to occur as illustrated in figure 10b and 10d. In figure 10d, a spin down electron is incident on the impurity. Since this is a spin flip process, the spin up electron is liberated from the up spin virtual level, while the incident electron remains in the down spin virtual level. Since an electron in the down spin virtual level has a higher energy than one in the up spin virtual level, the impurity's energy increases as a result of the scattering event. The increase in the impurity's energy results

Figure 10 Split virtual level scattering mechanisms. a and c are indicative of elastic non-spin flip scattering and are similar to those described in figure 9. d is an example of an inelastic scattering mechanism since the impurities energy increases by an amount $\Delta E = E_{\downarrow} - E_{\uparrow}$ while the liberated electrons energy decreases by the same amount. b is an example of a forbidden scattering mechanism. Since the impurity is already in its lowest energy state, any process, which requires the energy of the impurity to be reduced further, is forbidden.

in a decrease in the kinetic energy of the liberated up spin electron. Figure 10b is an example of a forbidden scattering mechanism. An incident up spin electron enters the spin up virtual level. If a spin flip process is to occur, the down spin electron must be liberated. However, once the down spin electron leaves the virtual level, the energy of the impurity will be reduced since $E_{\uparrow} < E_{\downarrow}$. The impurity is already in its lowest energy state and its energy cannot be reduced further, therefore this mechanism is forbidden. In this manner, applying a magnetic field may lead to a reduction in the resistivity as a result of spin dependent scattering. In the absence of an external magnetic field, all four spin scattering mechanisms are allowed and all are equally probable. Applying a magnetic field causes the energy levels of the impurity to be Zeeman split. The Zeeman splitting causes the impurity to rearrange the virtual levels into its lowest possible energy configuration. The result of this reconfiguration is to introduce forbidden scattering mechanisms, which in turn reduce the resistance of the sample.

The scattering mechanisms presented here are simplified process in that they do not take into account what happens while the electron is in the virtual level. In addition, from the standpoint of quantum mechanics, it is incorrect to imagine what happens to individual electrons. The same processes mentioned above are still valid, but it is more correct to think of the scattering as an itinerant electron being annihilated and a different itinerant electron being created. This is an example of a one step process. Two step processes involve the consideration of a middle step, which may strongly effect the probability of a scattering mechanism occurring. Typically in a two step process an itinerant electron is annihilated and created in a localized state within the virtual level, this electron is subsequently annihilated and a new itinerant electron is created. The two step process leads to a further reduction in the allowed scattering mechanisms because of the introduction of the Fermi factor [37] whenever a spin flip process occurs in the presence of an external field. This effectively causes a further decrease in the resistance of the sample [37].

2.1.2 Exchange Coupling in Magnetic Multilayers

In the previous section, spin dependent scattering mechanisms were discussed from a conservation of energy viewpoint, without mention of the cause of exchange splitting. To understand how magnetic layers in a multilayer interact with one another it is necessary to explore the origins of exchange coupling between two electrons. The total wave function of an electron can be expressed as the product of its spatial wave function, $\Psi(\mathbf{r})$, and a spin dependent component $\chi(\sigma)$. In this notation, $\Psi_u(\mathbf{r})$ denotes a wave function for an electron with an energy E_u while $\chi_\alpha(\sigma)$ and $\chi_\beta(\sigma)$ are spin wave functions for electrons with up and down spin respectively such that if σ is a spin up electron, then $\chi_\alpha(\sigma)$ and $\chi_\beta(\sigma)$ are one and zero, respectively.

Suppose we have two electrons in two different virtual levels around an ion. For a given electron there are four possible wave functions that arise due to two different energy levels and spin possibilities that are available, $\Psi_u(\mathbf{r})\chi_\alpha(\sigma)$, $\Psi_u(\mathbf{r})\chi_\beta(\sigma)$, $\Psi_v(\mathbf{r})\chi_\alpha(\sigma)$, and $\Psi_v(\mathbf{r})\chi_\beta(\sigma)$. Since electrons are fermions, if we construct a total wave function for two electrons it must be anti-symmetric [38]. This condition gives us four available total wave functions in the absence of any external force [39],

$$\begin{aligned}\Psi_I &= \frac{1}{\sqrt{2}} \left(\psi_u(r_1)\chi_\alpha(\sigma_1)\psi_v(r_2)\chi_\beta(\sigma_2) - \psi_v(r_1)\chi_\beta(\sigma_1)\psi_u(r_2)\chi_\alpha(\sigma_2) \right) \\ \Psi_{II} &= \frac{1}{\sqrt{2}} \left(\psi_u(r_1)\chi_\beta(\sigma_1)\psi_v(r_2)\chi_\beta(\sigma_2) - \psi_v(r_1)\chi_\beta(\sigma_1)\psi_u(r_2)\chi_\beta(\sigma_2) \right) \\ \Psi_{III} &= \frac{1}{\sqrt{2}} \left(\psi_u(r_1)\chi_\alpha(\sigma_1)\psi_v(r_2)\chi_\alpha(\sigma_2) - \psi_v(r_1)\chi_\alpha(\sigma_1)\psi_u(r_2)\chi_\alpha(\sigma_2) \right) \\ \Psi_{IV} &= \frac{1}{\sqrt{2}} \left(\psi_u(r_1)\chi_\beta(\sigma_1)\psi_v(r_2)\chi_\alpha(\sigma_2) - \psi_v(r_1)\chi_\alpha(\sigma_1)\psi_u(r_2)\chi_\beta(\sigma_2) \right)\end{aligned}\quad (9)$$

If we ignore the coulomb repulsion between electrons, all of the states in equation 9 have the same energy $E_u + E_v$. If we now include the Coulomb force between electrons the energy of the system will change. If we assume that turning on the coulomb repulsion will only slightly perturb the system, the resulting perturbed states will be described by linear combinations of the original states in equation 9 [39]. In principle there are an infinite number of these states but the best linear combinations are the following perturbed states [39],

$$\Psi_{\text{III}}, \Psi_{\text{II}}, \frac{1}{\sqrt{2}}(\Psi_{\text{I}} + \Psi_{\text{IV}}), \frac{1}{\sqrt{2}}(\Psi_{\text{I}} - \Psi_{\text{IV}}). \quad (10)$$

Written out explicitly, these states are,

$$\begin{aligned} \Psi_{\text{I}}' &= \frac{1}{\sqrt{2}}(\psi_u(r_1)\psi_v(r_2) - \psi_u(r_2)\psi_v(r_1))(\chi_a(\sigma_1)\chi_a(\sigma_2)) \\ \Psi_{\text{II}}' &= \frac{1}{\sqrt{2}}(\psi_u(r_1)\psi_v(r_2) - \psi_u(r_2)\psi_v(r_1))(\chi_\beta(\sigma_1)\chi_\beta(\sigma_2)) \\ \Psi_{\text{III}}' &= \frac{1}{\sqrt{2}}(\psi_u(r_1)\psi_v(r_2) - \psi_u(r_2)\psi_v(r_1))(\chi_a(\sigma_1)\chi_\beta(\sigma_2) + \chi_a(\sigma_2)\chi_\beta(\sigma_1)) \\ \Psi_{\text{IV}}' &= \frac{1}{\sqrt{2}}(\psi_u(r_1)\psi_v(r_2) + \psi_u(r_2)\psi_v(r_1))(\chi_a(\sigma_1)\chi_\beta(\sigma_2) - \chi_a(\sigma_2)\chi_\beta(\sigma_1)) \end{aligned} \quad (11)$$

Once we know the total wave functions for a particular system, the coulomb repulsion can be worked out in the usual fashion. For the first total wave function, Ψ_{I}' , the coulomb repulsion is,

$$U = \iint \Psi_{\text{I}}'^* \frac{e^2}{r_{12}} \Psi_{\text{I}}' dr_1 dr_2. \quad (12)$$

Substituting for Ψ_{I}' of equation 11,

$$U = \frac{1}{2} \chi_a(\sigma_1)\chi_a(\sigma_2) \iint (\psi_u^*(r_1)\psi_v^*(r_2) - \psi_u^*(r_2)\psi_v^*(r_1)) \frac{e^2}{r_{12}} \times (\psi_u(r_1)\psi_v(r_2) - \psi_u(r_2)\psi_v(r_1)) dr_1 dr_2, \quad (13)$$

and expanding the brackets,

$$\begin{aligned} U &= \frac{1}{2} \chi_a(\sigma_1)\chi_a(\sigma_2) (\iint (\psi_u^*(r_1)\psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_1)\psi_v(r_2)) \\ &\quad - \iint (\psi_u^*(r_1)\psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_2)\psi_v(r_1)) \\ &\quad - \iint (\psi_u^*(r_2)\psi_v^*(r_1)) \frac{e^2}{r_{12}} (\psi_u(r_1)\psi_v(r_2)) \\ &\quad + \iint (\psi_u^*(r_2)\psi_v^*(r_1)) \frac{e^2}{r_{12}} (\psi_u(r_2)\psi_v(r_1))) \end{aligned} \quad (14)$$

Since electrons are fermions, the interchange of coordinates under the 3rd and 4th integrals of equation 14 does not change the sign of the integral [40]. Thus the energy due to the coulomb repulsion is given by.

$$U = \iint (\psi_u^*(r_1) \psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_1) \psi_v(r_2)) dr_1 dr_2 - \iint (\psi_u^*(r_1) \psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_2) \psi_v(r_1)) dr_1 dr_2 \quad (15)$$

Performing similar calculations for the remaining 3 total wave functions of equation 11 we obtain the result.

$$U = \iint (\psi_u^*(r_1) \psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_1) \psi_v(r_2)) dr_1 dr_2 \pm \iint (\psi_u^*(r_1) \psi_v^*(r_2)) \frac{e^2}{r_{12}} (\psi_u(r_2) \psi_v(r_1)) dr_1 dr_2 \quad (16)$$

When the electron spins are parallel, the coulomb repulsion energy is obtained by taking the negative sign and when the spins are ant-parallel, the coulomb repulsion energy is obtained by taking the positive sign. The first term in expression 16 is known as the coulomb energy U_0 , while the second term is known as the exchange energy, J_0 . J_0 represents half of the difference between the energies of the two electrons in the state $\psi_u(\mathbf{r})$ and $\psi_v(\mathbf{r})$ on the same atom if their spins change from parallel to anti-parallel alignment. Thus the energy of the system with the coulomb term is given by $E_u + E_v + U_0 \pm J_0$.

The fact that the energy depends on the vector spin of the two electrons, s_1 and s_2 , leads to the suggestion that the exchange energy could be expressed as the inner product of the two spins [41],

$$J_0 = -2J \frac{\bar{s}_1 \cdot \bar{s}_2}{\hbar^2} = -J \bar{\sigma}_1 \cdot \bar{\sigma}_2 \quad (17)$$

Where in the usual manner we substituted $\sigma = 2s/\hbar$.

The definition above may be extended beyond simple electron-electron interactions to include the interaction between an impurity with a net moment and the conduction electrons. In this instance, the term J in the exchange energy is not always a constant and its sign and/or magnitude may vary depending on the system. A qualitative explanation of this effect can be understood in terms of electron interference. Suppose that we have an impurity in a copper metal lattice with a net charge. The conduction electrons will redistribute themselves around the impurity in an attempt to screen out the excessive charge. The electrons that participate in the screening are not static since all the electrons in the conduction band are in constant

motion. As a result of this motion some electrons are scattered by the non-spin dependent scattering mechanism outlined in the previous section and some are not. In a manner similar to optical scattering by an object, the scattered electrons will form an interference pattern with the non-scattered electrons. The net result is that the itinerant electrons participating in the screening of the impurity form halos of charge distribution. The magnitude of the charge distribution falls off as $1/r^2$ and alternates from increased to

Regions of Decreased Electron Density

Regions of Increased Electron Density

Figure 11 A schematic view of the screening charge built up by the itinerant electrons around an impurity with a net charge less than that of the surrounding electron density (below) Graphical representation of the same situation (above).

Figure 12 Instead of using the smooth electron density functions of figure 11 to illustrate how the spin polarized halos are formed, square waves are used. In figure (a) the spin up electrons (dotted line) are displaced further away in space than the spin down electrons (solid line). If we consider zone 1 in figure (a) we have more spin up electrons than spin down, therefore the net spin of the conduction electrons is up as shown in (b) (Note: The diagram is incomplete in that presumes that the electrons at the impurity are spin up which is false. In the region very close to the impurity all the electrons are spin down. The problem arises in the asymptotic behavior of the induced charge distribution) In region 2 there is again more spin up than spin down electrons while in regions 3 and 4 we have more spin down electrons than spin up so the net spin of the conduction electrons is down. (c) and (d) show the analogous situation when the true induced electron density is used rather than square waves.

decreased charge density zones with a period on the order of the Fermi wavelength [42] These oscillations are known as Friedel oscillations and are illustrated in figure 11. If we allow for spin dependent scattering mechanisms to occur in the above-mentioned process, we have in addition to halos of charge density, halos of spin polarization. These halos of spin polarization occur because each spin channel (up and down) form their own halos of charge distribution [43]. These halos are slightly mismatched in space because of the presence of exchange effects. If in a region of space a higher spin up charge density occurs than a spin down charge density, that region will have a net moment of spin up. This is illustrated graphically in figure 12.

We can generalize equation 17 to include the interaction between a magnetic impurity of spin S_{α} , and the conduction electrons to facilitate a quantitative explanation of the above effect. The exchange

energy term between the impurity with spin S_α located at $r = 0$ and the conduction electrons s_i located at r is,

$$J_0 = -2J \sum_i \frac{\bar{S}_\alpha \cdot \bar{S}_i}{\hbar^2}. \quad (18)$$

Since an electron has an intrinsic magnetic moment it senses the effects of an external magnetic field $\mathbf{H}$. In the usual manner the energy of this interaction can be expressed as,

$$U' = -\mathbf{u} \cdot \mathbf{H} = g u_b \bar{\mathbf{S}} \cdot \bar{\mathbf{H}}, \quad (19)$$

where g and u_b are the gyrometric g -factor and Bohr magneton respectively. By comparison of equations 18 and 19, we can consider the electrons to be under the influence of an effective external magnetic field, H_{eff} , caused by the spin of the impurity,

$$H_{\text{eff}} = \frac{-2J}{g u_b \hbar^2} \bar{S}_\alpha. \quad (20)$$

Assuming a free-electron gas model for the conduction electrons, the magnetization of the conduction electrons due to the effective field, H_{eff} , is given by,

$$\bar{M} = \chi \bar{H} = \frac{-2J}{g u_b \hbar^2} \chi \bar{S}_\alpha. \quad (21)$$

Using the susceptibility for a free electron gas [44],

$$\chi = \frac{1}{V} \sum_q \frac{3g^2 u_b^2 \rho}{8\varepsilon_F} \left(\frac{1}{2} + \frac{k_F}{2q} \left(1 - \frac{q^2}{4k_F^2} \right) \ln \left| \frac{2k_F + q}{2k_F - q} \right| \right) e^{iq \cdot \bar{r}}, \quad (22)$$

where V is the volume, ρ is the electron number density, k_F is the Fermi wave vector, E_F is the Fermi energy and q is the scattering vector. Using equation 22 and the relation between the magnetization, $\mathbf{M}$, and the electron spin density $\mathbf{s}(\mathbf{r})$,

$$\bar{M} = \frac{\sum_i \bar{u}_i}{V} = \frac{\sum_i -u_b g \bar{s}_i}{V} = -u_b g \bar{s}(\bar{r}) \quad (23)$$

we obtain.

$$\bar{s}(\mathbf{r}) = \frac{1}{V} \sum_q \frac{6\rho J}{8\varepsilon_F \hbar^2} \left(\frac{1}{2} + \frac{k_F}{2q} \left(1 - \frac{q^2}{4k_F^2} \right) \ln \left| \frac{2k_F + q}{2k_F - q} \right| \right) e^{i\bar{q} \cdot \bar{r}} \bar{S}_\alpha. \quad (24)$$

Equation 24 can be evaluated by converting the sum to an integral and integrating [44],

$$\bar{s}(\mathbf{r}) = \frac{3\rho J k_F^3}{52\pi\varepsilon_F \hbar^2} \left[\frac{\sin 2k_F r - 2k_F r \cos 2k_F r}{(k_F r)^4} \right] \bar{S}_\alpha. \quad (24)$$

Equation 24 is the response of an electron gas's spin to the net spin of an impurity and is sketched in figure 12d.

If another magnetic impurity S_b , is introduced into the host metal, it will interact with S_a via the conduction electrons. The interaction between S_b and the conduction electrons is given in analogy to equation 18 by,

$$J_0 = -2J \sum_i \frac{\bar{S}_\beta \cdot \bar{s}_i}{\hbar^2} = \frac{-2J}{\hbar^2} \bar{S}_\beta \cdot \bar{s}(r). \quad (25)$$

were we used the electron spin density $\mathbf{s}(r)$ in place of the discrete electron spin sum. Using equation 24 for the electron spin density induced by S_α the interaction between the two impurities is given by,

$$J_0 = \frac{-3\rho J^2 k_F^3}{26\pi\epsilon_F \hbar^4} \left[\frac{\sin 2k_F r - 2k_F r \cos 2k_F r}{(k_F r)^4} \right] \bar{S}_\alpha \cdot \bar{S}_\beta \equiv \frac{-2J(r)}{\hbar^2} \bar{S}_\alpha \cdot \bar{S}_\beta. \quad (26)$$

$J(r)$ is known as the Ruderman-Kittel-Kasuya-Yosida (RKKY) range function in honor of the four people who lead to its development. If S_β is introduced in a region where the primary spin polarization of the itinerant electrons due to S_α is spin up, S_β will be spin down. If S_β is introduced in a region where the primary spin polarization of the itinerant electrons due to S_α is spin down, S_β will be spin up. In this manner, the impurities will be aligned ferromagnetically or anti-ferromagnetically depending on the distance between them. In a similar manner, the RKKY interaction is believed to be responsible for the oscillatory coupling between magnetic layers in a multilayer film.

Equation 26 represents the exchange interaction between two magnetic impurities in a conducting medium. To extend these ideas into the multilayer framework, rather than assuming discrete magnetic ions in the magnetic layer, a continuous sheet of constant spin density is used. The multilayer is modeled as continuous spin sheets separated by a layer of a free electron gas [45]. The RKKY range function, rather than falling off as $1/(k_F r)^4$ as in the previous case, falls off as $1/(k_F r)^3$ [45],

$$J(r) \equiv \frac{\sin 2k_F r - 2k_F r \cos 2k_F r}{(k_F r)^3}. \quad (27)$$

Depending on the thickness of the conduction layer, the magnetic layers will be either aligned ferromagnetically or anti-ferromagnetically in a similar manner to two impurities. From observed GMR

Figure 13 RKKY oscillation exchange coupling due to a single magnetic layer (solid line) showing the longer period oscillation (dashed line) obtained by sampling the function only at integer values of spacing, x , between atomic planes.

data, the period of the exchange oscillation is close to $10\text{\AA}$ for most systems [7, 10] while that predicted by the RKKY interaction is between $1\text{-}3\text{\AA}$ depending on the system. To explain the apparent discrepancy between observed and calculated data aliasing was introduced simultaneously by a number of authors [46,47]. The free electron calculation shown above assumed a uniform spin density sheet for the magnetic layers. If the lattice periodicity is introduced into the calculations, the oscillation period is increased. As an example of this effect imagine two magnetic layers A and B only one atom thick separated by layers of copper atoms also only one atom thick. Furthermore, the separation between atomic layers of copper/copper and copper/cobalt will be assumed to be x . If the spacing of the magnetic layers is increased by successive addition of copper layers the separation of the magnetic layers increases in integer amounts of x . As such, the magnetic layer B will only be able to sample the exchange field of magnetic layer A at these integer amounts. This is illustrated schematically in figure 13. The result of aliasing is to increase the period of the exchange field and thus better account for the observed data.

2.1.3 Giant Magneto Resistance

Giant Magnetoresistance, as defined in the introduction, is the change in the resistance of a magnetic multilayer subject to an external magnetic field. The principle cause of this effect is the spin dependent scattering of the conduction electrons as they pass from the non-magnetic to the magnetic layer. The spin scattering mechanism believed to be

Figure 14 Geometry of magnetic/non magnetic/magnetic metal trilayer including the mixing regions B and E. An electric field is applied along the x-axis as shown.

responsible for these effects were described in detail in section 2.1.1. Recently, experimental work has shown that the majority of the spin dependent scattering occurs at the interface between the magnetic and nonmagnetic layers rather than evenly throughout the magnetic layer. A theoretical framework to explain this phenomenon is still lacking and as of yet only phenomenological models exist to explain the observed magnetoresistive data. Nevertheless, most authors do believe that the spin dependent mechanisms for interfacial scattering are similar to those discussed earlier in section 2.1.1[48]

The most accepted model for GMR is the one proposed by R.E Camley and J. Barnas [49]. The authors constructed a trilayer consisting of a non-magnetic metal sandwiched between two magnetic metals as shown in figure 14. The theory utilizes the Boltzman transport equation to model the two spin channels of the conduction electrons as they pass through the multilayer. Spin dependent scattering coefficients are introduced at the interfaces and within the magnetic layer for each spin channel, which depend on the relative orientation of the moments of the magnetic layer. This model has been extensively used in numerical calculations of the magnetoresistance of trilayer and multilayers [50,51] because it predicts the following features, which are observed in magnetic multilayers [52].

1. The magnetoresistance ratio decreases as the ratio of the non-magnetic layer to the MFP increases. This is a result of the conduction electrons not being able to retain their spin information as they sample different magnetic layers.
2. The magnetoresistance ratio increases, as the number of magnetic layers is increases up to the MFP. This is a result of the electron being able to sample more magnetic layers while retaining its spin information.
3. The magnetoresistance ratio becomes independent of the number of bilayers when the thickness of the film exceeds the MFP, which is a direct consequence of the effect described in 2.

Minor improvements have been made to this model to introduce the anisotropy of the MFP in terms of the different in plane and perpendicular MFP [53] and changing the way the interfacial scattering contribution is described [54]. The basic model starts with the steady state Boltzman transport equation in the relaxation time approximation [55],

$$\bar{a} \cdot \nabla_r f + \bar{v} \cdot \nabla_r f = -\frac{f - f_0}{\tau}, \quad (28)$$

where f , $\bar{a}$, $\bar{v}$ and τ are the classic distribution function, particle acceleration, particle velocity and the relaxation time respectively. If the electrons are under the influence of an externally applied electric field, equation 28 becomes,

$$-\frac{e}{m} \bar{E} \cdot \nabla_r f + \bar{v} \cdot \nabla_r f = -\frac{f - f_0}{\tau}. \quad (29)$$

For high frequency measurement, the electric field $\bar{E}$ is time dependent, however, since the period at the frequencies under consideration are much longer than the spin relaxation time, the steady state approximation is still valid. If we assume the electron distribution function depends only on position and

velocity and that it can be written in terms of a Fermi-Dirac distribution, $f_0(\mathbf{v})$, plus a correction term, $g(z, \mathbf{v})$, due to local scattering from surfaces and interfaces [48, 49].

$$f^{\uparrow(\downarrow)}(z, \bar{\mathbf{v}}) = f_0^{\uparrow(\downarrow)}(\bar{\mathbf{v}}) + g^{\uparrow(\downarrow)}(z, \bar{\mathbf{v}}). \quad (30)$$

Here and in what follows, the arrows refer to spin up and spin down electrons since we assume the current is carried in two separate spin channels. In addition the functional dependence of equation 30 will be suppressed. Subbing equation 30 into equation 29 and expanding we obtain,

$$\begin{aligned} -\left(\frac{e}{m}\right)\bar{E} & \left(\left(\frac{\partial f_0^{\uparrow(\downarrow)}}{\partial v_x} + \frac{\partial g^{\uparrow(\downarrow)}}{\partial v_x} \right) \hat{x} + \left(\frac{\partial f_0^{\uparrow(\downarrow)}}{\partial v_y} + \frac{\partial g^{\uparrow(\downarrow)}}{\partial v_y} \right) \hat{y} + \left(\frac{\partial f_0^{\uparrow(\downarrow)}}{\partial v_z} + \frac{\partial g^{\uparrow(\downarrow)}}{\partial v_z} \right) \hat{z} \right) \\ & + \bar{\mathbf{v}} \cdot \left(\left(\frac{\partial g^{\uparrow(\downarrow)}}{\partial x} \right) \hat{x} + \left(\frac{\partial g^{\uparrow(\downarrow)}}{\partial y} \right) \hat{y} + \left(\frac{\partial g^{\uparrow(\downarrow)}}{\partial z} \right) \hat{z} \right) = \frac{-\left(f_0^{\uparrow(\downarrow)} + g^{\uparrow(\downarrow)} - f_0^{\uparrow(\downarrow)}\right)}{\tau^{\uparrow(\downarrow)}}. \end{aligned} \quad (31)$$

In light of equation 30 and retaining only the linear terms in equation 31 we obtain,

$$\frac{\partial g^{\uparrow(\downarrow)}}{\partial z} + \frac{g^{\uparrow(\downarrow)}}{v_z \tau^{\uparrow(\downarrow)}} = \left(\frac{eE}{mv_z} \right) \frac{\partial f_0}{\partial v_x}. \quad (32)$$

It is convenient to separate g into two parts, g_+ for electrons with positive v_z and g_- for electrons with negative v_z . The solutions of equation 32 are different in each region of figure 14, however they are of the same form. For example in region A one finds [48],

$$g_{A\pm}^{\uparrow(\downarrow)} = \left(\frac{eE\tau^{\uparrow(\downarrow)}}{m} \right) \left(\frac{\partial f_0}{\partial v_x} \right) \left[1 + F_{A\pm}^{\uparrow(\downarrow)} \exp\left(\frac{-z}{\tau^{\uparrow(\downarrow)} v_z} \right) \right]. \quad (33)$$

The parameter F is determined in each case by the boundary conditions at each interface. For example, in region A at $z=-c$ the electron distribution travelling to the left must be equal to the electron distribution travelling to the right since electrons cannot escape the trilayer. Therefore,

$$\begin{aligned} g_{A+}^{\uparrow(\downarrow)} &= g_{A-}^{\uparrow(\downarrow)} & \text{at } z = -c \\ g_{F-}^{\uparrow(\downarrow)} &= g_{F+}^{\uparrow(\downarrow)} & \text{at } z = +c \end{aligned} \quad (34)$$

The interior boundary conditions are found in the same manner. The electron distribution function leaving the interface at $z=b$ and traveling to the right, depends on the probability of electrons in F traveling to the left being reflected and electrons in E traveling to the right being transmitted. If the transmission and reflection coefficients are given by $T^{\uparrow(\downarrow)}$ and $R^{\uparrow(\downarrow)}$, we obtain the boundary condition,

$$g_{F+}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{E+}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{F-}^{\uparrow(\downarrow)} \quad \text{at } z = +b. \quad (35)$$

In a similar manner the boundary condition for each interface may be obtained.

$$g_{E-}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{F+}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{E+}^{\uparrow(\downarrow)} \quad \text{at } z = +b. \quad (36)$$

$$g_{E+}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{D+}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{E-}^{\uparrow(\downarrow)} \quad \text{at } z = +a. \quad (37)$$

$$g_{D-}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{E-}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{D+}^{\uparrow(\downarrow)} \quad \text{at } z = +a. \quad (38)$$

$$g_{C+}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{B+}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{C-}^{\uparrow(\downarrow)} \quad \text{at } z = -a. \quad (39)$$

$$g_{B-}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{C-}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{B+}^{\uparrow(\downarrow)} \quad \text{at } z = -a. \quad (40)$$

$$g_{B+}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{A+}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{B-}^{\uparrow(\downarrow)} \quad \text{at } z = -b. \quad (41)$$

$$g_{A-}^{\uparrow(\downarrow)} = T^{\uparrow(\downarrow)} g_{B-}^{\uparrow(\downarrow)} + R^{\uparrow(\downarrow)} g_{A+}^{\uparrow(\downarrow)} \quad \text{at } z = -b. \quad (42)$$

The artificial boundary we defined at $z=0$ is used to change the quantization axis for the electron distribution. This is done to take into account whether or not the magnetic layer is aligned or not. If we define the angle θ to be the angle between the magnetization of the layers, the boundary conditions at $z=0$ become [48],

$$\begin{aligned} g_{D+}^{\uparrow(\downarrow)} &= \cos^2(\theta/2) g_{C+}^{\uparrow(\downarrow)} + \sin^2(\theta/2) g_{C+}^{\downarrow(\uparrow)} & \text{at } z = 0 \\ g_{C-}^{\uparrow(\downarrow)} &= \cos^2(\theta/2) g_{D-}^{\uparrow(\downarrow)} + \sin^2(\theta/2) g_{D-}^{\downarrow(\uparrow)} & \text{at } z = 0 \end{aligned} \quad (43)$$

When $\theta=0$, the layers are ferromagnetically aligned and when $\theta=180$ the layers are antiferromagnetically aligned.

Equations 34-43 give 24 equations to solve for the 24 different values of F in each section, which may be obtained by numerical calculation, and making certain assumptions about T and R [48]. Once all the F are known the value for g in each region can be evaluated and the current density in each region is given by [49],

$$J(z) = \int v_x g(v_z, z) d^3v. \quad (44)$$

This model can easily be extended to multilayers by moving the boundaries at $-c$ and c to $\pm(c+b)/2$ and assuming that no scattering occurs between the interface of neighboring trilayers. It is difficult to

calculate the current density and often many unphysical assumptions are made to simplify the calculation.

The results of Camely *et al* [48] are shown in figure 15 were the author's assumed that:

1. The two metals have the same Fermi energy and MFP.
2. Only transmission occurs at the interfaces so $R^{\uparrow} = R^{\downarrow} = 0$.
3. The mixing region can be ignored

The above model is incomplete in that it fails to accurately predict both the resistivity of the sample and the GMR [48]. The authors pointed out that for various systems, if the magnetoresistance was correct the resistivity was 20-30% too high. Including the mixing region and taking into account scattering from grain boundaries has shown to improve the model somewhat [48].

The main feature of figure 15 is that the GMR ratio decreases with an increase in the external magnetic field. This effect is the result of the moments in adjacent magnetic layers becoming aligned as the strength of the magnetic field is increased. This is not to say that when the angle between the magnetic layers is 90° , that the moments of the layers are perpendicular, but rather that there is an equal amount of moments within the layer parallel

and anti-parallel to the field. The effect of having an equal mixing of moments parallel and anti-parallel is to have a net moment in the layer of zero. At a certain applied field, the magnetic layers are in a FM alignment and there is no change in resistance due to the GMR effect.

The additional decrease in the magnetoresistive curve in figure 15 is due solely to anisotropic magnetization [48].

Figure 15 Percentage change in resistance as a function of the applied field for a magnetic trilayer. Courtesy of R.E. Camley and R.L Stamps, J. Phys.: Condens. Matter 5, 3727 (1993)

2.2.0 High Frequency Measurement

For high frequency measurements the test fixture was modeled as a radiating antenna to facilitate proper interpretation of the results. The test fixture consisted of a half loop square antenna above a finite ground plane being driven by a coaxial transmission line. It can be shown, by using the method of images, that the impedance of such a construct can be calculated by taking half the value of the impedance assuming a full loop antenna of similar dimension being driven by a parallel wire

transmission line [56]. In addition, loop antennas of circular geometry have similar electrical properties as square loops of the same dimension [56]. Therefore the sample holder will be modeled as a circular loop rather than a half-square loop antenna above a ground plane to simplify the mathematics.

The equivalent circuit representing the test fixture is shown in figure 16. Here R_r , L and R represent the radiation resistance, self-inductance and the resistance of the sample respectively. Often, a capacitor is used in series or in parallel with the circuit of figure 16 to model loop antennas [56], however, for the frequencies under consideration, the self capacitance may be ignored [56]. Since the GMR effect is a purely resistive phenomenon, only the real part of the impedance needs to be considered. As such we define the “apparent GMR”, the term introduced for the purpose of this work, which reflects the situation during high frequency measurements when the radiation energy loss cannot be neglected.

Figure 16 Equivalent circuit for a loop antenna. R_r , L and R represent the radiation resistance, self-inductance and the sample resistance respectively

$$GMR(H, f) = \left\{ \frac{[\text{Re}(Z_H) - \text{Re}(Z_{\text{sur}})]}{\text{Re}(Z_{\text{sur}})} \right\} \times 100\% \quad (45)$$

Consideration of figure 16 yields $\text{Re}(Z) = R + R_r$, and consequently leads to the formula,

$$GMR(H, f) = \left[\frac{(R_H - R_{sur})}{(R_{sur} - R_r(f))} \right] \times 100\% \quad (46)$$

At low frequencies the radiation resistance is zero and equation 46 reduces to equation 4, the classical GMR equation.

2.2.1 Radiation Resistance

In general, the vector potential for a point (x, y, z) , a distance R away from a current carrying element at the point (x', y', z') is [56],

$$\bar{A}(x, y, z) = \frac{\mu}{4\pi c} \int \bar{I}(x', y', z') \frac{e^{-ikR}}{R} dl' . \quad (47)$$

where $k = \omega/c$ is the wave propagation constant for the emitted radiation. If the current source is a loop of constant current, as shown in figure 17, the geometry of the situation lends itself to spherical coordinates. The generalized current source for a loop with current flowing in the ϕ direction in spherical coordinates is,

Figure 17 Geometrical arrangement for a loop antenna system.

$$\vec{I} = I_\phi \sin \theta \sin \phi \hat{r} + I_\phi \cos \theta \sin \phi \hat{\theta} + I_\phi \cos \phi \hat{\phi} \quad (48)$$

and the distance between the observer and the source becomes,

$$R = \sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}. \quad (49)$$

The components of $\mathbf{A}$ in spherical coordinates can then be written as,

$$\begin{aligned} A_\phi &= \frac{\mu a I_\phi}{4\pi} \int_0^{2\pi} \cos \phi \frac{e^{-ik\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}}}{\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}} d\phi \\ A_\theta &= \frac{\mu a I_\phi \cos \theta}{4\pi} \int_0^{2\pi} \sin \phi \frac{e^{-ik\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}}}{\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}} d\phi. \\ A_r &= \frac{\mu a I_\phi \sin \theta}{4\pi} \int_0^{2\pi} \sin \phi \frac{e^{-ik\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}}}{\sqrt{r^2 + a^2 - 2ar \sin \theta \cos \phi}} d\phi \end{aligned} \quad (50)$$

Since we are interested in the total radiated power of the loop, the far field approximation ($r \gg a$), can be used to simplify the components of $\mathbf{A}$ in equation 50. In addition, it can be shown that within this approximation, $A_\theta = A_r = 0$. Therefore the equations in 50 reduce to,

$$A_\phi = \frac{a\mu I_\phi e^{-ikr}}{4\pi r} \int_0^{2\pi} \cos \phi e^{ika \sin \theta \cos \phi} d\phi \quad (51)$$

The above integral can be solved in terms of a first order Bessel function J_1 , thus,

$$A_\phi = i \frac{a\mu I_\phi e^{-ikr}}{2r} J_1(ka \sin \theta). \quad (52)$$

Using the vector potential of equation 52, the electric and magnetic fields may be calculated to be,

$$\begin{aligned}
 E_r &= E_\theta = 0 \\
 H_r &= H_\phi = 0 \\
 E_\phi &= \frac{a\omega\mu I_\phi e^{-ikr}}{2r} J_1(ka \sin \theta) \quad . \\
 H_\theta &= -\frac{a\omega\mu I_\phi e^{-ikr}}{2\eta r} J_1(ka \sin \theta)
 \end{aligned} \tag{53}$$

where η is the impedance of free space.

Given that the time averaged power density $\bar{W}_{av}$ and the radiated power P_{rad} are given by,

$$\bar{W}_{av} = \frac{1}{2} \text{Re}[\bar{E} \times \bar{H}^*] = \frac{1}{2\eta} |E_\phi|^2 \hat{r} \quad P_{rad} = \iint \bar{W}_{av} \cdot d\bar{s} \tag{54}$$

the total radiated power for the loop of figure 17 is,

$$P_{rad} = \frac{\pi(a\omega\mu)^2 |I_\phi|^2}{4\eta} \int_0^\pi J_1^2(ka \sin \theta) \sin \theta d\theta \quad . \tag{55}$$

If we equate the total power radiated in equation 55 to the power lost due to a resistor, $P = \frac{1}{2}I^2R$.

the radiation resistance for the full loop of figure 17, R'_{rad} , may be obtained. As mentioned above, the radiation resistance calculated for a full loop, R'_{rad} , being driven by a transmission line is equivalent to twice the radiation resistance calculated for a half loop, R_{rad} , above a ground plane i.e. $R'_{rad} = 2 R_{rad}$. Therefore the radiation resistance for the half loop above the ground plane is,

$$R_{rad} = \frac{\pi(a\omega\mu)^2}{4\eta} \int_0^\pi J_1^2(ka \sin \theta) \sin \theta d\theta \tag{56}$$

Using the properties of Bessel functions, and rearranging some terms, the radiation resistance may be expressed as,

$$R_{rad}(f) = \frac{c\pi\kappa f\mu^2}{2\eta} \int_0^{\frac{4\kappa f}{c}} J_2(x) dx. \quad (57)$$

Equation 57 is the expression for the radiation resistance used in equation 46. The integral in equation 57 cannot be calculated exactly and numerical methods must be used.

Chapter III

Experimental

3.1.0 Experimental

In this section the experimental procedures for the growth of the samples, DC GMR and HF GMR are outlined. The samples were characterized by x-ray diffraction and the details of this procedure may be found elsewhere [57].

3.2.0 Deposition of Multilayers

The samples used for the experimental work in this thesis were prepared by an electron beam evaporation (EBE) system as shown in figure 18. The two metals to be deposited, copper and cobalt, were placed in separate crucibles, A and B respectively. Attached to each crucible is a small filament that when heated is the source of electrons. The electrons are guided onto the deposition metal by small magnets located directly under the crucible. The electrons heat the metal until it begins to melt and evaporate. An external computer controls a shutter system located directly above each crucible. The computer monitors the thickness of each sample by means of the quartz crystal thickness monitor and when the correct thickness is obtained, the shutter is closed. Only one shutter at a time is open to ensure the purity of the layer being deposited. The evaporated metal rises to the sample and condenses on the surface of the substrate forming the metal deposit.

Cobalt/copper multilayers were deposited simultaneously on $\approx 6 \text{ cm}^2$ pieces of Si(111) and Si(100) substrates. Prior to deposition, the silicon substrates were rinsed for 15 minutes in acetone and for an additional 15 minutes in methanol. A 10% hydrofluoric acid solution was used to etch the oxide layer off of the silicon and any remaining droplets were removed with Kim Wipes. The two orientations of silicon were affixed side by side in the sample holder with metal clips to ensure identical conditions during growth.

Figure 18 Schematic representation of the electron beam evaporation (EBE) system. An electron gun located under the crucible release electrons that are guided to the evaporation material by small magnets. The electrons heat the material until it begins to evaporate. The evaporated metal proceeds to the substrate where it condenses and forms a metal. The computer controlled shutters determine which metal is being deposited by blocking the evaporated metal from the substrate.

The sample was introduced into the main chamber via the load lock system of figure 18. Samples are loaded into the loading chamber and affixed to the service rod. A roughing vacuum pump was used to reduce the pressure in the loading chamber to approximately 4×10^{-4} Torr. Once the pressure in the loading chamber was reduced, gate 1 was open and the system was pumped down for approximately 1 hr to a vacuum pressure of 4.5×10^{-6} Torr. To load the sample into the main chamber, gate 2 was opened and the sample was slid into position with the service rod. The vacuum pressure of the system prior to deposition was on the order of 10^{-8} Torr.

Crucible A, in addition to copper, has a separate boat that contained the iron metal. Using this boat a 50 Å iron seed layer was manually deposited before deposition of the multilayer began. The deposition rate for the iron seed layer was .5 Å/s and 200 Å of iron was pre-evaporated before opening the

shutter to ensure steady state conditions had been achieved. Once the iron seed layer had been deposited the computer deposited the cobalt/copper multilayer. Both cobalt and copper were deposited at the same rate of .5 Å/s and at least 50 Å of each material was pre-evaporated. Once the deposition of the multilayer was complete, a 50 Å iron cap, similar to the seed layer, was deposited. The sample was removed from the main chamber via the service rod and the loading chamber was brought up to room pressure by nitrogen gas.

In each sample the thickness of the cobalt layer was 10 Å while the thickness of the copper layer varied. In total 28 samples were grown with copper thickness of 8, 10, 12, 14, 16, 18, 20, 22, 23, 24, 25, 26, 30 and 32 Å on both orientations of silicon.

3.3.0 DC Giant Magnetoresistance Measurements

Figure 19 (a) Schematic view GMR measurement system. (b) Diagram of sample holder.

Prior to magnetoresistance measurement, the larger sample was cut using a diamond stylus into a thin strip approximately 2 mm x 12 mm. DC GMR measurements were performed using the inline geometry of the van der Pauw method [58] for determining the resistance of thin films. The sample holder was built in house and is shown in figure 19 along with the schematic setup of the measurement apparatus. The sample holder was placed between the poles of a Magnion Inc./Harvey Wells electromagnet, which was driven by a 60 amp Hewlett Packard 6673A Power Supply outfitted with a Hewlett Packard 59511A Relay. A Hewlett Packard 34401A Multimeter operating in the 4 point probe resistance mode measured the resistance of the sample.

A computer program was written using Labview, which automatically perform the magnetoresistance measurements. The sample was first polarized by reversing the relay and increasing the current in the electromagnet to 60 A and then reducing back to zero before switching the relay back into its normal setting. The current was then slowly increased in increments of .2 A until 5 A was reached at which point the current was increase in increments of 1 A to a final current of 60 Å. Between each incremental increase and resistance measurement, a 10 second time delay was programmed to allow for steady state conditions to be obtained. All magnetoresistance measurements were performed in the CIP geometry with the magnetic field running parallel to the current (longitudinal) and perpendicular to the current (transverse).

3.4.0 High Frequency Giant Magnetoresistance Measurement

Prior to magnetoresistance measurement, the larger sample was cut using a diamond stylus into a thin strip approximately 0.3 mm x 5 mm. HF GMR measurements were performed using a two point contact method. The sample holder was built in house and is shown in figure 20b along with the schematic setup of the measurement apparatus, figure 20a. The sample holder was placed between the poles of a transformer modified into an electromagnet as shown in figure 20a. A 60 amp Hewlett Packard 6673A Power Supply drove the electromagnet. The impedance was measured using a Hewlett Packard 8753D Network Analyzer that was connected to the sample holder by a 1m SMA cable. The amount of power reflected from the sample holder is directly related to the impedances of both the sample holder and the Network analyzer. The reflection coefficient Γ , is defined as the ration of the reflected voltage to the incident voltage: $\Gamma = 0$ only occurs when the impedance of the sample holder and network analyzer exactly match. Every other value of Γ corresponds uniquely to complex sample holder impedance, according to the equation,

$$Z_{\text{Sample Holder}} = \frac{1 + \Gamma}{1 - \Gamma} Z_{\text{Network analyser}} \quad (58)$$

where $Z_{\text{Network Analyser}}$ is the impedance of the network analyzer and by default is 50 Ω . The Network Analyzer uses the above formula to convert the reflection coefficient measurement data to impedance data. A Smith chart overlay on the polar display allows for the reading of both the real and imaginary component of the impedance. The impedance data measured represents the impedance of not only the multilayer but also the entire sample holder. The electrical circuit used to describe the sample holder was outlined in section 2.2.1.

Measurements were performed over a narrow bandwidth of 100 MHz for frequencies of .1, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 GHz. Each time the measurement range was changed the Network Analyzer was recalibrated using a 3-point calibration cycle were the end of the SMA cable was shorted, open and loaded with a 50 Ω load. Measurements were performed in the CIP geometry with the current

Figure 20 (a) Schematic representation of the system used to measure HF GMR data. The electromagnet was a modified transformer where the iron core was opened and the sample holder was inserted in the resulting gap. (b) Diagram of the high frequency sample holder. The contact pins are connected to the inside of the SMA cable jack and the ground plane respectively. The sample holder was constructed from circuit board to reduce the capacitive effects of the test fixture.

running perpendicular to the magnetic field (longitudinal). Prior to recording magnetoresistive data, the sample was polarized in a similar manner to that described in the DC GMR procedure.

Chapter IV

Results

4.1.0 X-Ray Diffraction

Of the 32 samples grown, 10 samples were selected for x-ray diffraction studies with a Rigaku Spectrometer. The samples tested were grown on both the Si(111) and Si(100) substrates with a copper thickness of 23, 24, 25, 26 and 30 Å. For brevity, typical results are presented in figures 21 through 24. Since the samples tested are small, in some cases a large Al(100) peak is observed which is due to the aluminum clip used to hold the samples in place.

For low angle X-ray diffraction, .6 mm slits were used in order to increase the accuracy of the results by filtering out obscure reflections. The scanning range was from 0.4 degrees to 10 degrees in 0.02-degree increments per step using a scanning rate of 2 seconds per 0.02-degree increment.

High angle X-ray diffraction data was taken with a wider aperture and a longer scan rate. 2 mm slits and a scan rate of 10 seconds per 0.04 degree increment were used. The 2θ scanning range for all samples was 35 degrees to 55 degrees, which would reveal any cobalt copper multilayers of the (111) or (100) orientation.

Figure 21 X-Ray Diffraction for sample 50Fe/40x(10Co/25Cu)/50Fe/Si(111)

Figure 22 X-Ray Diffraction for sample 50Fe/40x(10Co/25Cu)/50Fe/Si(100)

Figure 23 X-Ray Diffraction for sample 50Fe/40x(10Co/26Cu)/50Fe/Si(111)

Figure 24 X-Ray Diffraction for sample 50Fe/40x(10Co/26Cu)/50Fe/Si(100)

4.2.0 DC Giant Magnetoresistance Data

All samples grown by EBE had a shiny, smooth, silver finish and were subjected to DC electromagnetic studies at room temperature. Figure 25 shows the experimental curve used to convert the electromagnet current into magnetic field data. Figure 26 to figure 46 are graphs of DC GMR verses magnetic field strength. The GMR was calculated by means of equation 4, which was derived in the introduction. Typical samples had a resistance of 3-4 ohms depending on the size of the sample.

Figure 25 Calibration curve for Magnion Inc. Electromagnet. Field strength verses electromagnet current.

Figure 26 DC GMR for sample 50Fe/40x(10Co/8Cu)/50Fe/Si(111) and 50Fe/40x(10Co/8Cu)/50Fe/Si(100)

Figure 27 DC GMR for sample 50Fe/40x(10Co/10Cu)/50Fe/Si(111) and 50Fe/40x(10Co/10Cu)/50Fe/Si(100)

Figure 28 DC GMR for sample 50Fe/40x(10Co/12Cu)/50Fe/Si(111) and 50Fe/40x(10Co/12Cu)/50Fe/Si(100)

Figure 29 DC GMR for sample 50Fe/40x(10Co/14Cu)/50Fe/Si(111) and 50Fe/40x(10Co/14Cu)/50Fe/Si(100)

Figure 30 DC GMR for sample 50Fe/40x(10Co/16Cu)/50Fe/Si(111) and 50Fe/40x(10Co/16Cu)/50Fe/Si(100)

Figure 31 DC GMR for sample 50Fe/40x(10Co/18Cu)/50Fe/Si(111) and 50Fe/40x(10Co/18Cu)/50Fe/Si(100)

Figure 32 DC GMR for sample 50Fe/40x(10Co/20Cu)/50Fe/Si(111) and 50Fe/40x(10Co/20Cu)/50Fe/Si(100)

Figure 33 DC GMR for sample 50Fe/40x(10Co/22Cu)/50Fe/Si(111) and 50Fe/40x(10Co/22Cu)/50Fe/Si(100)

Figure 34 DC GMR for sample 50Fe/40x(10Co/23Cu)/50Fe/Si(111) and 50Fe/40x(10Co/23Cu)/50Fe/Si(100)

Figure 35 DC GMR for sample 50Fe/40x(10Co/24Cu)/50Fe/Si(111) and 50Fe/40x(10Co/24Cu)/50Fe/Si(100)

Figure 36 DC GMR for sample 50Fe/40x(10Co/25Cu)/50Fe/Si(111) and 50Fe/40x(10Co/25Cu)/50Fe/Si(100)

Figure 37 DC GMR for sample 50Fe/40x(10Co/26Cu)/50Fe/Si(111) and 50Fe/40x(10Co/26Cu)/50Fe/Si(100)

Figure 38 DC GMR for sample 50Fe/40x(10Co/30Cu)/50Fe/Si(111) and 50Fe/40x(10Co/30Cu)/50Fe/Si(100)

Figure 39 DC GMR for sample 50Fe/40x(10Co/32Cu)/50Fe/Si(111) and 50Fe/40x(10Co/32Cu)/50Fe/Si(100)

4.3.0 High Frequency GMR

High frequency measurements were performed manually using a Hewlett Packard 8753D Network Analyzer. Since it was difficult to make accurate readings when the change in resistance was very small, only those samples with large DC GMR were tested. The transverse high frequency GMR data for these samples at integer frequencies is presented in figures 41 through 45. The complete set of data is summarized in the discussion in figures 47, 48, and 49. High frequency measurements were performed using a different electromagnet than that used for DC studies and the calibration curve is shown in figure 46. The inductance of the test fixture was measured to be $\approx 5 \times 10^{-9}$ H, which is in agreement with the theoretical value obtained from first principle calculations.

Figure 40 Calibration curve for electromagnet used for high frequency GMR measurement.

figure 41 HF-GMR for the sample 50Fe/40x(10Co/23Cu)/50Fe/Si(111) and 50Fe/40x(10Co/23Cu)/50Fe/Si(111)

figure 42 HF-GMR for the sample 50Fe/40x(10Co/24Cu)/50Fe/Si(111) and 50Fe/40x(10Co/24Cu)/50Fe/Si(111)

figure 43 HF-GMR for the sample 50Fe/40x(10Co/25Cu)/50Fe/Si(111) and 50Fe/40x(10Co/25Cu)/50Fe/Si(111)

figure 44 HF-GMR for the sample 50Fe/40x(10Co/26Cu)/50Fe/Si(111) and 50Fe/40x(10Co/26Cu)/50Fe/Si(111)

figure 45 HF-GMR for the sample 50Fe/40x(10Co/30Cu)/50Fe/Si(111) and 50Fe/40x(10Co/30Cu)/50Fe/Si(111)

Chapter V

Discussion

5.1.0 X-Ray Diffraction

Figures 21 through 24 show the X-ray diffraction results for a select group of samples. Satellites, which are usually observed in the high angle x-ray diffraction studies of multilayers [57,59], were not seen in any of the samples tested. The reason is that with only 40 repeats of the multilayer, the intensity of the reflected beam, due to the periodic nature of the multilayer, is not strong enough to be observed above the background noise. It is clear from the high angle studies, that when the multilayer is deposited on the Si(111) substrate only a (111)-orientated film is present while multilayers deposited on Si(100) seem to show a dual orientation. Since the samples are so thin (roughly a tenth of a micron) it is difficult to determine the relative amount of crystallites in each orientation, but it appears that multilayers grown on Si(100) prefer the (111) orientation. This may be due in part, to the fact that the lattice spacing between the basal plane of the hcp phase of Co, and the (111) orientation of fcc copper are closely matched. A more detailed study on the preferential orientation of these multilayers would be helpful in clarifying the matter.

Low angle X-ray diffraction confirmed that the multilayer is layered periodically [59] by the presence of low angle peaks. These peaks are a direct consequence of Bragg's law and represent the reflection from the periodic interfaces of the multilayer [59]. If the interfaces are smooth and sharp, multi-order peaks may be observed [60]. For our samples, mostly first order peaks and in some cases second order peaks were observed indicating a smoother interface in those sample. In general, the observation of only second order peaks in our low angle x-ray diffraction studies, indicate that our samples have rough interfacial regions between the copper cobalt boundaries. In some samples other low angle peaks were observed but it is unclear exactly what they represent.

5.2.0 DC Giant Magnetoresistance

The results of the DC GMR studies are presented in figures 32 through 46 and a compilation of GMR data as a function of copper thickness is presented in figure 67. For both orientations there appears to be a broad maximum around a copper thickness of 23 Å. This phenomenon is indicative of an RKKY type interaction often observed between successive cobalt layers in Co/Cu multilayers [7, 8, 9]. The first peak around 10 Å, which is typical of an RKKY type interaction, was not observed. The explanation is that one is not able to deposit, using EBE, uniform copper layers of such a low thickness, without forming pinholes that bridge adjacent cobalt layers. The bridging destroys the AFM coupling between successive

Figure 46 GMR as a function of copper thickness as determined from the deposition rate. Shown are the samples 50Fe/40x(10Co/XCu)/50Fe/Si(111) and 50Fe/40x(10Co/XCu)/50Fe/Si(100). The first AFM maximum, at a copper thickness of 10 Å, which is typical of an RKKY interaction was not observed. The solid line is a guide for the eye and is not representative of any type of fit.

magnetic layers and only a small GMR effect is observed. This reasoning is supported by low angle x-ray diffraction data, which indicates that our samples lack high definition at the interfaces. The lack of sharp interfaces is the cause of the bridging between magnetic layers when the copper layer is thin.

In almost all cases the GMR of the samples grown on Si(111) is much greater than that for samples grown on Si(100). This result is surprising since multilayers grown by MBE and dc magnetron sputtering, on substrates of different orientations, seem to show an enhanced GMR when some (100) oriented grains are present [62]. The dependence of GMR on the orientation of the substrate and probable explanations has been reported in many systems and for a wide variety of growth techniques [61, 62, 63]. It is believed that a small amount of (100) oriented material is responsible for the GMR in magnetic multilayers [62, 63]. This is supported by Pollard *et al.* who found that when their sputtered deposited samples changed from a polycrystalline to single crystal (111) orientation, the GMR was drastically reduced [62]. However, this explanation is contrary to our results since we observed that when no (100)-orientated grains are present, the GMR is larger. A possible explanation may lie in the fact that multilayers with a rougher interface have been shown to have larger GMR than when the interface is smooth [64]. If the multilayers grown on Si(111) consistently have a rougher interface than those grown on Si(100), this argument may be plausible and may explain why we observe a larger GMR for samples with a predominant (111) orientation. Some support for the enhanced roughness of (111) multilayers may be found in the work of T. Kingetsu *et al.*. The authors reported that for Co/Cu multilayers grown by dc magnetron sputtering on MgO(111) and MgO(100), a poorer interface definition was observed for multilayers grown on MgO(111) than for ones deposited on MgO(100) [63].

The coercive field, H_c , is the displacement of the maximum GMR percentage from the zero applied field and is attributed to randomly arranged domains in adjacent magnetic layers [8, 65]. From figures 26 through 39 it is clear that the coercive field is only observed for samples with a copper layer thickness greater than 20 Å. This is most likely due to the fact that pinholes destroy any AFM coupling between neighboring magnetic layers and as such no coercive field exists. In addition, the coercive field is much larger for samples grown on Si(111) than for samples grown on Si(100). This phenomenon may be explained by the observation that for Co/Cu multilayers, in which the interlayering coupling is weak, it is likely that domains in adjacent magnetic layers will have their magnetization axes aligned non-parallel to

one another [7, 8]. The configuration with the highest degree of AFM coupling arises when the net magnetic moment of the multilayer is zero or at a field strength of H_c . Oepts *et al.*, who compared samples grown by EBE and MBE, found that samples prepared by EBE had a much higher coercive field than those grown by MBE [16]. This effect was attributed to the more granular character of the EBE samples compared to the more coherent growth of the samples prepared by MBE. It is plausible, that a similar argument may be applied with regards to samples grown on silicon of different orientations providing that samples grown on Si(111) are more granular than those grown on Si(100). Support for this can again be found in the work T. Kingetsu *et al.*, since granular growth may result in the formation of the observed rougher interfaces in MgO(111). If this is the case, the more granular Si(111) samples will have a higher degree of magnetic domain misalignment, which will give rise to a larger coercive, field. Further investigation into the character of the growth of these films is required in order to clarify the matter.

Even though the first AFM maximum was not observed, EBE seems to give good GMR at the second AFM peak. The simplicity of the deposition method and its easy scalability, make EBE an attractive alternative to MBE, dc magnetron sputtering and electrodeposition for the fabrication of multilayers with good GMR values. In principle, this method can quit easily be adapted to deposit multilayers of different metals, besides cobalt and copper, onto a wide variety of substrates.

5.3.0 High Frequency Giant Magnetoresistance.

As stated previously, little experimental work has been published which examines the high frequency behavior of the GMR effect. The reported work involves examining the reflection, transmission, or absorption of microwaves with a multilayered structure. Ustinov *et al.* [22] determined the correlation between microwave (5.6 –9 GHz) transmission and GMR in (14xFe/CR)/MgO multilayers deposited by MBE. They defined a magnetotransmission ratio similar to the usual magnetoresistive ratio to compare their results. The authors reported a correlation existed between the two effects up to a field strength of 85% of saturation. Similarly, Kunar *et al.* [21] observed microwave GMR and AMR derived from microwave surface impedance data in Fe/Cr/Fe trilayers deposited by MBE. They reported results for the X band of the microwave spectrum. The methods described in these articles demonstrate the non-contact method for determining high frequency GMR. The GMR is derived as a secondary effect from the transmission coefficient, surface impedance data, or the microwave absorption spectrum.

In figures 41 through 45 the high frequency GMR data is presented. It is seen that the overall shape of the GMR curve is very similar to the DC GMR results in that the magnitude and strength of the coercive field are similar. For higher frequencies, the GMR appears to be slightly reduced which we attribute to radiation broadcasting from our test fixture as discussed in section 2.2.1. HF GMR data as a function of frequency is presented in figures 68 through 71. The observed results and the apparent GMR calculated from equation 45, assuming that R_H and R_{sat} are identical to their DC equivalent, are in excellent agreement with one another. Clearly GMR, as calculated from impedance measurement data, is independent of frequency up to 5.5 GHz.

At frequencies greater than ~4 GHz the constant current approximation used in calculating the radiation resistance in section 2.2.2 is no longer valid. The loop can no longer be considered as electrically small, and the current phase and amplitude distributions cannot be assumed constant. A complete analysis of the radiation resistance of the loop with a non-uniform current is somewhat complex and is not necessary for the purposes of this thesis. The result of performing such a calculation [66] would be a somewhat larger radiation resistance at frequencies greater than 4 GHz providing an even better fit to the data.

In principle this technique can be used to explore higher frequencies providing one either performs the complex radiation resistance calculations or reduces the area of the loop further. At higher frequencies, the skin effect of the sample begins to become a factor in determining the resistance of the sample. These results would be interesting since the magnetic properties of the film would depend on the entire multilayer, while the resistance would only depend on the layers within the skin effect zone. For example, suppose we had a Co/Cu multilayer consisting of 100 layers. The 50 magnetic cobalt layers would all interact with each other via the RKKY interaction discussed in section 2.1.2. However, if we tested for GMR at a sufficiently high enough frequency, so the skin effect layer was only as thick as the first 25 copper layers, it would be interesting to see what effect, if any, this has on the GMR. All the layers in the film would determine the magnetic properties of the multilayer, while the electrical properties would only be determined by a fraction of the layers. The skin effect phenomenon in the multilayer would allow for some unique experimental observations, which have not yet been performed. Comparing samples of 100 repeats and 50 repeats would be especially interesting under the above conditions since the only difference in the samples is the strength of the magnetic coupling due to the extra magnetic layers. These extra magnetic layers, which do not contribute to the electrical properties of the film, do however contribute to the magnetic properties. These results may help to explain or verify our current understanding of the process since they could reveal the long range coupling between cobalt layers. Using the experimental setup in this thesis, one could perform the described experiment by simply growing samples with a thickness greater than the skin effect layer of $\sim 2 \mu\text{m}$ which is observed at 5 GHz. This would require samples of about 500 repeats of a multilayer.

Figure 47 High frequency GMR verses frequency. The solid line represents the apparent GMR as described in the theory.

Figure 48 High frequency GMR verses frequency. The solid line represents the apparent GMR as described in the theory.

Figure 49 High frequency GMR versus frequency. The solid line represents the apparent GMR as described in the theory.

Chapter VI

Conclusion

6.1.0 Conclusion

One of two noteworthy results presented in this thesis is that EBE is a viable alternative to MBE, dc magnetron sputtering and electrodeposition for the fabrication of multilayers. The samples prepared by EBE showed good GMR around the second AFM maximum typical of an RKKY interaction but the first maximum around 10 Å was not observed. This may be attributed to the poor quality of the multilayers which is probably due to the simplicity of the growth technique. The multilayers deposited on Si(111) seemed to be more granular than those deposited on Si(100). This observation was inferred from the larger coercive field and GMR for the multilayers deposited on Si(111).

In addition, this work demonstrated the existence of GMR for frequencies between dc up to 5.5 GHz, by directly measuring the resistance of the samples using the contact method. We observed that the GMR remains unaffected and appears to have no frequency dependence at these frequencies as predicted by the model of Cameley and Barns. Using this technique, we believe that it is possible to explore higher frequencies providing one modifies either the physical characteristics of the test fixture and/or performs a more mathematically rigorous analysis of the radiation resistance.

In summary, the methodology and the results presented here, both seem ideally suited to integration into leading edge technologies such as devices based on electromagnetic wave propagation and high frequency GMR transistors [67].

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