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RICE UNIVERSITY

Low Frequency Noise In Spin Valve Sensors

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

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Low frequency noise in giant magnetoresistive spin valves has been studied as a means of optimizing signal to noise ratios and characterizing device performance. The devices studied were sputter deposited NiFe/Cu/NiFe/FeMn spin valves with $\Delta R/R \sim 4\%$. Static measurements demonstrated a strong dependence of the magnetic coupling and giant magnetoresistance (GMR) ratio on the thickness and quality of the Cu spacer layer and the bottom NiFe layer (free layer). These parameters were varied to determine how the noise in spin valve sensors would be affected.

Noise power spectra were measured in patterned spin valves. The noise was observed to have a 1/$f$ slope at low frequencies. The fluctuation-dissipation relation relating thermal fluctuations in magnetization to the resistance fluctuations was used to explain the origin of the 1/$f$ noise. The noise was found to be sensitive to the anisotropy and defect density of the free layer. The noise was minimized for spin valves operating with parallel anisotropy axes and an applied field aligned along the hard axis of magnetization.

Dynamic fields were used to measure the Barkhausen noise in the sense layer of the spin valve. The low frequency noise in the presence of dynamic fields was much greater than the 1/$f$ noise background. Clustering of Barkhausen jumps was used to
explain the observed dependence of the noise power on the magnitude and frequency of
the applied field. Higher frequency signals resulted in lower Barkhausen noise. The
noise was reduced when the applied field was aligned along the hard axis of
magnetization.
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Finally, I would like to thank my family. My wife Dawn has been very understanding and supportive during my graduate career. I know that it has not been easy for her and I love her very much for being there for me.
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1 Introduction

Giant magnetoresistance (GMR) has been extensively studied over the past decade because of the potential for improved sensitivity over existing magnetoresistive and Hall effect sensors. This thesis reports results of noise measurements performed on GMR devices examining the relationship between manufacturing and design issues and sensor characteristics and noise. The goal of this work is twofold: first to use noise measurements as a tool in optimizing the signal to noise ratio of GMR sensors; second to determine if noise measurements can be used in conjunction with other testing to determine sensor performance.

The remainder of this chapter reviews the GMR effect. Anisotropic magnetoresistance and GMR are introduced in relation to the magnetic recording industry. Then it reviews some of the theory of the GMR effect and provides relevant equations to describe the response of GMR materials. Chapter 2 describes the experimental details of the fabrication process and measurement of the GMR films. The fabrication process involves substrate preparation, lithographic patterning, and materials deposition. The basic quantity measured is the voltage response of the GMR device. Details of the measurement setup and data analysis procedures are given. A detailed description of the deposited films is given in Chapter 3. General characterization curves and characteristics of the films are reported. Chapter 4 reviews the mechanisms of low frequency noise and gives results of noise measurements completed on patterned GMR sensors. The implications of low frequency noise for applications and testing and the relationships between the observed low frequency noise and device parameters are discussed. Chapter 5 covers the noise observed in the spin valve due to dynamic
magnetization and domain wall effects. The Barkhausen effect is introduced and results of data analysis from the power spectra of Barkhausen jumps is presented. Finally, Chapter 6 summarizes the main points of the thesis and describes implications of the results for electrical characterization of spin valves.

1.1 Recording Industry Background

The industry driving a large share of magnetics research, especially research in GMR, is the magnetic storage industry. The density of magnetic bits stored on a medium (rigid disk or tape) has increased exponentially for decades (figure 1.1) while the cost per bit has decreased exponentially. The quest for increased storage density at a reduced cost drives much of the fundamental research into new areas of magnetism.

![Graph showing magnetic head technology progression](image)

Figure 1.1 Magnetic head technology progression.\(^1\)

The first structures used to read magnetic bits on a disk were inductive heads. The read head consisted of a ring or yoke of soft ferromagnetic material with copper coils wrapped around the core. When an inductive head passes over a magnetic transition on
the disk the core becomes magnetized. The change in magnetization in the core results in a voltage across the coil (Faraday’s law $V=-n\,\frac{d\phi}{dt}$). Inductive heads were the mainstay of magnetic recording until the early 1990’s. The problem with inductive heads is that to get a higher signal on the head coil, one needs more turns of wire. However, the inductance of the head increases with the number of turns and higher inductance limits the frequency of operation. As data rates reach the resonant frequency created by the head inductance and circuit capacitance, excessive phase shifts in the signal create read errors.

![Graph](image)

Figure 1.2 The response of an MR head to an applied field. To achieve linear operation the magnetization of the MR element is biased to 45° from the direction of current flow.

The limitations of inductive heads led to the development of heads based on the anisotropic magnetoresistance (AMR) effect (termed MR heads). Anisotropic magnetoresistance may be defined by

$$R = R_0 + \Delta R \cos^2 \theta$$  \hspace{1cm} (1.1)

where $\theta$ is the angle between the current flow and the magnetization, $R_0$ is a constant (minimum resistance), and $\Delta R$ is the change in resistance. The change in resistance, $\Delta R/R_0$ for Permalloy (Ni$_{81}$Fe$_{19}$, abbreviated Py) is 2-3%. Since AMR is a read only
effect, an MR read head is merged with an inductive write head to form a complete magnetic storage system.

In figure 1.1 there is a change in slope in the areal density versus year curve where MR heads were introduced into disk drives. This is because MR heads have several advantages over inductive heads, allowing the scaling to proceed at a faster rate. First, the signal is independent of the velocity of the read head relative to the disk. Secondly, the inductance of an MR head is very low so there is no barrier to high frequency operation. Also, the larger signal relative to inductive heads allows shrinking the head dimensions (thus increasing the number of tracks per inch). Furthermore, MR elements are ‘active’ which means increasing the current through the device will increase the signal. Finally, as already mentioned the read and write heads are now separate entities that can be optimized separately.²

The use of MR heads for magnetic recording is limited by the low change in resistance (2-3%). To continue the scaling in figure 1.1 a new material was needed to surpass the performance of MR heads. In 1988 a change in resistance approaching 80% was reported in a multilayered structure of Fe and Cr. ³ The high change in resistance observed was termed giant magnetoresistance (GMR).

1.2 Giant Magnetoresistance

1.2.1 GMR

The first structures to demonstrate GMR were single crystal magnetic multilayers grown by MBE.³ The initial structures consisted of between 30 and 60 bilayers of Fe and Cr films. The 80% change in resistance that was reported required cooling the sample to
4K and applying a field of over 2 Tesla (20 kGauss). By 1989 GMR had been observed in sputtered polycrystalline films which are easier to fabricate and therefore allowed research on the new structures to intensify.4

There are several points to be noted about the magnetic multilayers showing GMR. First, the thickness of the individual layers is an order of magnitude thinner than magnetic layers in conventional AMR materials. Also, as the nonmagnetic layer thickness increases, the GMR effect diminishes. It was found that the non-magnetic layer thickness needed to be on the order of the electron mean free path so the electrons could easily pass between the ferromagnetic layers without scattering in the non-magnetic layer. In addition, low temperature was required to achieve the highest GMR ratios. The GMR effect was observed to decrease linearly with temperature from 4K to 300K. Furthermore, very large fields are required to see large GMR, much larger than practical for applications. Finally, the shape of the GMR curve in magnetic multilayers is the same shape as AMR resistance curves and therefore needs biasing to operate in a linear range.2

![Diagram of spin valve trilayer structure](image)

Figure 1.2 Spin valve trilayer structure consists of two ferromagnetic layers separated by a non-magnetic metal spacer layer.

In 1991 a much simpler structure was discovered that also exhibited the giant magnetoresistance effect.5 The term "spin valve" was attached to the sandwich structure
in figure 1.2 because the principle of operation relies on different mean free paths of electron spins.

1.2.2 Spin Valves

The GMR effect is a clever means of exploiting spin dependent scattering in ferromagnetic materials. Electrons with spins aligned parallel to the magnetization in a ferromagnet have longer mean free paths than electrons with spins aligned antiparallel to the magnetization. The different mean free paths are due to the different density of states for the two spins. Figure 1.3 shows schematically the density of states for a transition metal where the d-bands are split by the exchange interaction. The probability of an electron scattering event is dependent on the availability of final states to scatter into. Therefore, figure 1.3 shows that while spin down electrons have states available in the 3d and 4s bands, the spin up electrons can only scatter into the 4s band. In Permalloy the mean free path of spin up electrons (aligned with the field) can be as great as 20 times the mean free path of spin down electrons.

![Diagram showing density of states schematic for a transition metal](image)

Figure 1.3 Density of states schematic for a transition metal (from White).
The easiest way to understand the spin valve is in terms of a parallel resistance model. When the magnetizations of the ferromagnetic layers are aligned parallel, one spin state has a short through both layers and the resistivity is given by

\[ \rho_p = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \]  

(1.2)

where \( \rho_p \) is the resistivity of the spin valve with layers aligned parallel, \( \rho_\uparrow \) is the resistivity of the spin up electrons, and \( \rho_\downarrow \) is the resistivity of the spin down electrons. When the ferromagnetic layers are aligned antiparallel, neither spin state has low resistance through both layers and the resistivity is given by

\[ \rho_{ap} = \frac{\rho_\uparrow + \rho_\downarrow}{4} \]  

(1.3)

where \( \rho_{ap} \) denotes the resistivity of the spin valve with layers aligned antiparallel.

Therefore the GMR ratio, defined as the maximum resistance change divided by the minimum resistance is

\[ \text{GMR ratio (\%)} = \frac{\Delta \rho}{\rho_{ap}} = \frac{(\rho_\uparrow + \rho_\downarrow)^2}{(\rho_\uparrow - \rho_\downarrow)^2} \]

(1.4)

![Resistor model of giant magnetoresistance.](image-url)
Figure 1.5 Electron trajectories through a spin valve trilayer. (a) Low resistance state, ferromagnetic layers are aligned; (b) high resistance state, ferromagnetic layers are antiparallel.

A simplified schematic of a spin valve is shown in figure 1.5. When both ferromagnetic layers are aligned one spin state is able to traverse the spin valve with very little scattering. When the layers are aligned antiparallel the “valve” is closed and both spin states are scattered strongly in one of the layers.

Experimentally, the functional form of the resistance of a spin valve depends on the relative angle between the magnetization of the two ferromagnetic layers. \(^7\)

\[
R = R_{ap} + (1/2) \Delta R \left( 1 - \cos(\theta_1 - \theta_2) \right)
\]

(1.5)

where \(\Delta R\) is the maximum change in resistance, \((\theta_1 - \theta_2)\) is the angle between the two ferromagnetic layers, and \(R_{ap}\) and \(R_p\) refer to the resistance of the spin valve when the ferromagnetic layers are aligned antiparallel and parallel respectively (\(\Delta R = R_{ap} - R_p\)).

Note that in the important case where \(\theta_2 = \pi/2\) then the resistance change is proportional to \(\sin(\theta_1)\). If the magnetic field is then oriented along the hard axis of the free layer then the response of the spin valve is linear (\(\sin \theta_1 \propto \text{field}\)). \(^8\) Taking one layer as fixed and assuming a rigidly rotating magnetization, the ferromagnetic component of magnetization can be related to the angle \(\theta\) by
\[ M = M_s \cos \theta \]  

where \( M_s \) is the saturation magnetization of the ferromagnetic layer. The resistance change due to changing magnetization in the second layer can then be written as

\[ R = R_{ap} + (1 - M/M_s) \Delta R \]  

(1.7)

While spin valves have much lower GMR ratios than magnetic multilayers (a consequence of fewer magnetic layers), spin valves have two major advantages over magnetic multilayer structures: fewer layers makes easier fabrication, and lower fields are needed to achieve the low resistance state. Further details on spin valve materials and device issues are given in chapter 3.

1.3 Applications of Spin Valves

The largest application for spin valves is in advanced read heads for magnetic storage. However, there are several other areas where GMR is replacing MR and Hall-effect sensors. Naturally there is a market for general magnetic field sensing where GMR materials give an order of magnitude improvement over AMR. GMR sensors are very sensitive to the Earth’s magnetic field and can be incorporated into navigational systems.

A variety of materials (steels, magnetic alloys) and devices (from current flow) produce magnetic fields. The largest sensing application of GMR is sensing the position or speed of ferrous materials.\(^9\) The automotive industry is a relatively large market for magnetic sensors where they are used to determine angular velocity of steel gears. In electronics applications spin valves are used to sense the presence of current through PCB traces and in power supplies.\(^{10}\) A GMR isolator (the analog to the opto-isolator) has been developed where current through a wire in one circuit produces a magnetic field sensed by a GMR element in an isolated circuit.
Several future applications are being developed for GMR materials. Magnetic random access memory (MRAM) uses the magnetization in the free layer to store bits that can then be read out nondestructively by measuring the resistance of the spin valve. MRAM chips have the potential to be faster than current memories based on silicon transistors and are inherently radiation hard. Logic devices are also being constructed out of GMR materials. The primary advantage of GMR logic is again the potential for high speed and also the small size of GMR elements.

In addition to development for the specific applications listed above there is a great deal of research into general improvements in GMR materials. For device applications the desirable qualities are high GMR, high sensitivity, low cost, small size, ability to tailor field ranges, high volume repeatability, and low magnetostriction. Examples of the type of improvements being made are the discoveries of GMR in granular materials and GMR in tunneling structures. Granular materials offer improvements in sensitivity over spin valves while spin dependent tunneling structures offer lower power and higher GMR than spin valves. As improvements are continually being made GMR materials will find increasing applications in industries which use magnetic sensors.
2 Experimental Setup

Spin valves are commonly deposited by physical vapor deposition with sputter deposition being the most used method. This chapter describes the deposition process and lithographic techniques used to fabricate spin valves. The last section of the chapter describes a low noise measurement setup used for the measurements reported in chapters 4 and 5.

2.1 Sputter Deposition Chamber

A custom UHV chamber designed for the sputter deposition of magnetic multilayers was used to deposit spin valves (Figure 2.1). The cylindrical stainless steel chamber is 30" in diameter and 18" high. The chamber has one 15" port, four 8" ports, and one 6" port (used for load lock) on the side and several 2 3/4" flanges on the side and top and bottom of the chamber. A cluster flange with five 4.5" ports can be mounted on the 15" port. The cluster flange is designed for co-deposition of layers and all five ports have a focal point on the sample stage.

The chamber is pumped by a 12" APD cryopump mounted on the bottom of the chamber. The base pressure after a bake-out is usually 1x10⁻⁸ torr or better. During sputtering, highly purified argon gas is leaked into the chamber using a precision leak valve and the pumping speed may be adjusted by closing or opening a large gate valve on the cryopump. Chamber pressure during sputtering is monitored by a capacitive transducer with a range of 0.1 through 100 millitorr.
Figure 2.1 Schematic of sputter deposition system.

The sample stage is on the end of a steel arm connected to a ferrofluid rotatable feedthrough mounted on the top central port of the chamber. A computer controlled stepper motor connected to the rotatable feedthrough moves the sample stage around the chamber with an accuracy of 0.1°. Moving the sample stage in front of the sputtering targets for determined lengths of time controls layer thickness. The thickness of the resulting layer is the sputtering rate multiplied by the sputtering time.

The deposition rate of the each target was determined by measuring the thickness of calibration samples using low angle x-ray diffraction. The Bragg reflections from the interfaces of the film create low angle peaks. The separation of the peaks gives the film thickness from the formula

\[
\frac{1}{\text{thickness}} = 2 \left( \sin \theta_2 - \sin \theta_1 \right) / \lambda
\]

(2.1)

where \( \theta_2 \) and \( \theta_1 \) are the angles of two adjacent peaks and \( \lambda \) is the wavelength of the x-rays. Additionally the peaks can be fit by a program called WinRefSim to give an estimate of the roughness of the layer. A typical x-ray scan is shown in figure 2.2.
A magnetic field was applied during growth of the spin valves to induce an easy axis of magnetization in the magnetic layers and set the direction of the pinning layer (induced anisotropy will be covered in the next chapter). A special holder was designed to apply a field of approximately 50 Oe during growth using two permanent magnets. The low magnitude of the magnetic field on the sample holder coupled with the large distance from the magnetron sputter guns (typically 6") eliminates any plasma drift from EXB.

2.2 Sputter Deposition

Sputtering is a physical process where bombardment of a target material by energetic gas atoms ejects atoms from the target. The basic sputtering theory has been known for over a century - when a high electrical discharge is placed between two electrodes, the cathode (target) slowly erodes from bombardment of the ionized gas
molecules. Argon is typically used as the sputtering gas because it is inert, has a low ionization potential, and a relatively high atomic number. When the argon ions (+ charge) strike the target they regain their lost electron and become electrically neutral again. The collision of the argon ions with the sputtering target ejects target atoms. The target atoms travel until reaching another surface (substrate) where they are deposited.

The chamber is equipped with six MiniMak magnetron sputtering guns from US Thin Films. Magnetron sputtering was developed as a way of magnetically confining the plasma discharge near the target surface to increase the sputtering rate and decrease the pressure needed to maintain the plasma. The MiniMak uses 1.3\" diameter targets and must be water-cooled. The maximum power used is 50 Watts for DC sputtering (up to 700 Volts) and 125 Watts RF power.

The typical sputtering power and rates for the layers used are listed in table 2.1. The Ar pressure during sputtering is typically 1 millitorr. Increasing the sputtering pressure decreases the deposition rate and increases surface roughness. However, low sputtering pressures also make it difficult to maintain the plasma on thicker targets or insulating targets.

<table>
<thead>
<tr>
<th>Target</th>
<th>Power (Watts)</th>
<th>Ar Pressure (millitorr)</th>
<th>Target – Substrate Separation (inches)</th>
<th>Deposition Rate (Å/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalum</td>
<td>50</td>
<td>1</td>
<td>6</td>
<td>0.77</td>
</tr>
<tr>
<td>Permalloy</td>
<td>50</td>
<td>1</td>
<td>6</td>
<td>0.72</td>
</tr>
<tr>
<td>Copper</td>
<td>30</td>
<td>1</td>
<td>6</td>
<td>1.23</td>
</tr>
<tr>
<td>Iron Manganese</td>
<td>30</td>
<td>1</td>
<td>3</td>
<td>3.63</td>
</tr>
<tr>
<td>Cobalt</td>
<td>50</td>
<td>1</td>
<td>6</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table2.1 Typical sputtering conditions for spin valve layers.
2.4 Deposition Procedures

The main considerations when depositing spin valves are smoothness and cleanliness. It is important to have a very smooth substrate since wavy substrates will increase magnetic coupling between the layers. It is also necessary to have very little contamination of the spin valves during growth since impurities in the film will act as spin independent scattering sites and degrade the GMR ratio. Bare silicon wafers are the substrate of choice since they are extremely smooth, relatively inexpensive, and can be readily obtained.

Spin valves must be deposited on an insulating substrate to eliminate current shorting through the substrate. Therefore an oxide layer is thermally grown on the silicon. The bare wafers are cleaned in dilute HF acid before oxidation to remove any surface contamination. The oxide is then grown at 1000°C in either dry oxygen or pyrogenic steam. Growth in steam doubles the growth rate of the oxide, which is about 0.15 μm/hr in dry oxygen. There was no observed correlation between wet oxidation and dry oxidation in relation to GMR properties regardless of oxide thickness. However, it has been reported that the optimum substrate preparation for spin valve growth is a wet oxidation followed by a post oxidation anneal at 1000°C in nitrogen.\textsuperscript{14}

Pattern definition of spin valves is typically performed by ion beam milling using Si$_3$N$_4$ as a hard mask.\textsuperscript{15} Ion beam milling is a physical process with high resolution very suitable for multilayer structures and magnetic layers. A second method commonly used is lift-off. The lift-off process is relatively simple. Photoresist is spun on the substrate and patterned. Then, after the metal deposition, the photoresist is dissolved — lifting off
the metal layers deposited on top of the resist and leaving behind the metal deposited in the pattern.

The problem with lift-off is that metal tends to deposit on the sidewalls of the resist even if near vertical sidewalls are achieved. This makes lift-off difficult to perform reliably and often results in unclean breaking of the film at the pattern edges. There are a few variations to the normal lift-off technique that attempt to create an overhang structure causing the film to be discontinuous (figure 2.3). The most popular methods involve using a chlorobenzene soak\textsuperscript{16}, image reversal resists\textsuperscript{17}, or double layer resists. Chlorobenzene soaks into the top portion of the resist making it less soluble in developer than the underlying resist. Image reversal resists use unique resins that invert the exposure pattern (these are essentially negative resists). The use of double layer resists in industry is popular since it gives fairly repeatable results. Two different photoresists with different sensitivities are spun on top of each other so after development an overhang always results.

![Figure 2.3](image)

The chlorobenzene soak and image reversal resist methods were evaluated for use with spin valve depositions. The image reversal process is labor intensive requiring high temperature bakes and flood UV exposures. These extra steps make it difficult to optimize the process. In contrast, the chlorobenzene soak is easy to perform and results
in a higher repeatability and better defined lines than in a conventional resist process. After spin valve deposition the resist is removed by soaking the substrates in acetone to dissolve the resist. The entire substrate preparation procedure followed for the samples in this thesis is outlined in table 2.2.

<table>
<thead>
<tr>
<th>Initial Wafer Cleaning</th>
<th>Dilute HF etch of native oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation</td>
<td>Wet oxidation at 950°C</td>
</tr>
<tr>
<td>Photoresist Application</td>
<td>Dehydration bake &gt;150°C for 30 min.</td>
</tr>
<tr>
<td></td>
<td>Spin on Shipley 1813 resist at 4000 rpm for 30 sec.</td>
</tr>
<tr>
<td></td>
<td>Softbake wafers at 90°C for 30 min.</td>
</tr>
<tr>
<td></td>
<td>Expose wafers for 2.5 minutes on lamp bed</td>
</tr>
<tr>
<td></td>
<td>Soak wafers in chlorobenzene for 15 min.</td>
</tr>
<tr>
<td></td>
<td>Bake at 80°C for 15 minutes</td>
</tr>
<tr>
<td></td>
<td>Develop photoresist for 2 minutes in Shipley MF-320 developer</td>
</tr>
</tbody>
</table>

Table 2.2 Substrate preparation for spin valve depositions.

2.4 Probe Station

A semiconductor manual probing station was modified for testing patterned spin valves. A custom electromagnet was fabricated to apply a variable magnetic field across the substrate. The magnet was machined into a 'C' shape from HyMu and copper wire was tightly wound around one leg (figure 2.4). A programmable power supply was used to generate fields up to 200 Oe (limited by the saturation magnetization in the HyMu
core). The sample spans a 0.5” gap in the magnet. A LakeShore gaussmeter was used to measure the magnetic field in the electromagnet gap. The entire probing assembly is on a vibration isolation stage and located in a shielded box (mu-metal lining).

![Diagram of Flux and Coil](image)

Figure 2.4 Electromagnet for probe station.

Resistance is normally measured in a four point probe configuration which eliminates the effect of contact resistance on measurements. For low noise or low signal measurements it is common to use six probes\(^{18}\) in an attempt to eliminate noise picked up on the probe leads (figure 2.5). Two leads are used to supply current to the sample from a battery powered current source. The remaining four leads measure the voltage across the sample. The voltage measured by the two sets of probes is amplified independently before being digitized and stored for data analysis. A cross correlation between the two captured signals (performed in Matlab) removes any spurious noise not common both signals.

The low noise amplifier designed for measuring 1/f noise uses two INA110 FET input instrumentation amplifiers. The inputs were AC coupled using an RC network. For higher bandwidth an SR560 low noise preamplifier was occasionally used. The SR560 has a bandwidth of 1 MHz while the INA110 instrumentation amplifiers have 100 kHz
bandwidth. However, the SR560 has only one channel and cannot be used for cross correlations. A National Instruments A/D card with a maximum sampling rate of 1.25 MHz (single channel) was used to store the data to disk. LabView controlled the data acquisition and data analysis was performed in Matlab. Full circuit diagrams are given in Appendix A.

![Bias Current Source
Spin Valve
12 bit A/D Card
Low Noise Instrumentation Amplifiers](image)

Figure 2.5 Spin valve measurement schematic.

The A/D card captures the measured voltage waveform to the hard drive. A Fourier transform on the captured time domain record results in a frequency spectrum of the noise. The power spectrum is defined as the magnitude squared of the Fourier transform of the time domain record (units of $V^2/Hz$).

Measurement errors are introduced from a variety of sources. First, intrinsic variation in noise will yield a slightly different measurement each time. This error is very small and sequential measurements of noise are very repeatable. A larger error is introduced from the DC bias supply. Variations in the DC bias field from run to run will
create errors, as will current fluctuations from the power supply. Additionally, the exact placement of each sample with respect to the external field will be slightly different from inaccuracies in visual alignment. The largest errors are from sample to sample variation. Sputtering rates from the targets slowly drift with time resulting in small differences between samples. Also, different chamber conditions such as base pressure or partial pressure of oxygen will result in a variation in sample quality. To minimize fabrication errors, all samples that are directly compared were sputtered on the same day to reduce variations in chamber cleanliness or target aging.
3 Simple Spin Valve Characterization

Spin valves are very sensitive to structure and deposition conditions. A complete understanding of device characteristics is necessary before noise measurements can be properly interpreted. The first portion of this chapter provides a brief review of magnetics and basic spin valve terminology. The latter sections report properties of the deposited spin valves and examines the dependence of layer thickness and processing on spin valve performance.

3.1 Magnetics Background

3.1.1 Hysteresis and Anisotropy

The magnetization ($M$) in a magnetic material is related to the applied magnetic field ($H$) by

$$M = \chi \cdot H$$

(3.1)

where $\chi$ is the magnetic susceptibility. In weakly magnetic materials $\chi$ is field independent while in strongly magnetic materials the relationship between $\chi$ and $H$ is rather complex.\(^{19}\) A plot of the magnetization as a function of the applied field is called the hysteresis loop (figure 3.1). In the demagnetized state ($H=0, M=0$) the magnetization breaks up into small regions called domains to minimize the demagnetizing energy. Each domain is a region in which all the atomic magnetic moments are pointing in the same direction. Under the influence of an applied field the domain walls move, increasing the area of favorably aligned domains. This corresponds to the region a-b of the hysteresis curve. At high fields the domains will reversibly rotate to align with the external field.
(section b-c). If the applied field is strong enough, the magnetizations will all point in the same direction and the material will reach a saturation magnetization, $M_s$ (point c). If a magnetic material is saturated by a high field and then the field is removed a certain amount of magnetization remains, called the remanence magnetization, $M_r$ (point d). A reversed field equal to the coercivity, $H_c$, is required to bring the magnetization back to zero.

![Hysteresis loop and domain configurations](image)

Figure 3.1 Hysteresis loop and domain configurations for points on the initial magnetization curve.

The magnetic field and magnetization are vector quantities and the hysteresis may be different depending on how the magnetic field is aligned with the sample. The term anisotropy refers to the fact that in the absence of an external field the magnetization will point in a certain direction referred to as the easy axis of the material. Some materials, particularly Permalloy, will develop an easy axis of magnetization along the direction of
an external field applied during growth (called field-induced anisotropy). This method is
used in the growth of spin valves to set the easy axis of magnetization. (Two other types
of anisotropy are shape anisotropy and magnetostrictive anisotropy. In the absence of
external fields or other energy interactions the magnetization will prefer to point in the
direction of the demagnetizing field to minimize the energy. In materials that have strong
magnetostriction stresses in the film will create an easy axis of magnetization relative to
the direction of the stress.)

For a material with uniaxial anisotropy, the magnetization will lie along the easy
axis in the absence of an applied field. The direction orthogonal to the easy axis in the
plane of the film is referred to as the hard axis of magnetization. Application of a
magnetic field along the hard axis will pull the magnetization towards the applied field
direction so that it makes an angle $\alpha$ with the easy axis. The energy per unit volume of
the material is then given by

$$E = K \cdot \sin^2 \alpha$$  \hspace{1cm} (3.2)

where $K$ is the anisotropy constant. The anisotropy constant can be determined from the
hard axis loop by finding the anisotropy field, $H_k$, which is the field at which saturation is
reached (see figure 3.2). The anisotropy field is related to $K$ by

$$H_k = \frac{2 \cdot K}{\mu_0 \cdot M}$$  \hspace{1cm} (3.3)

where $\mu_0$ is the permeability of free space.

The orientation of $H$ with respect to the easy and hard axis determines whether
magnetization proceeds primarily by domain wall motion or magnetization rotation. If
the magnetic field is parallel to the easy axis the magnetization is primarily by domain
wall motion. It the field is perpendicular to the easy axis the magnetization is primarily due to domain rotation. Figure 3.2 demonstrates the different hysteresis loops for easy and hard axis fields. The Permalloy film was grown in a 60 Oe magnetic field to produce the uniaxial anisotropy.

![Graphs of hysteresis loops](image)

Figure 3.2 Hysteresis loop for Permalloy film with field applied along (a) the easy axis ($H_c = 0.65$ Oe), and (b) the hard axis ($H_k = 4.4$ Oe).

### 3.1.2 Ferromagnetic and Exchange Coupling

The GMR effect was discovered in magnetic multilayer films where ferromagnetic layers are exchange coupled to each other by a quantum mechanical interaction (RKKY coupling). The sign of the coupling oscillates between ferromagnetic and antiferromagnetic depending on the thickness of the non-ferromagnetic spacer layer (Cr or Cu). When the coupling is antiferromagnetic and there is no applied field, adjacent magnetic layers are aligned antiparallel to each other. The RKKY coupling between the ferromagnetic layers is so strong that it takes a very large magnetic field to achieve a ferromagnetic alignment and the low resistance state (typically several kOe).
Two strategies may be applied in order to achieve the antiparallel alignment of the ferromagnetic layers in spin valves. If the ferromagnetic layers are of different thickness or made of different magnetic elements (or alloys) then the coercivities of the layers will be different, thereby creating a field range where one layer can be switched and the other layer not. This type of arrangement is commonly used in magnetic random access memory (MRAM) where the readout strategies often require the ability to switch both layers with fields generated from current flowing through conductors (typically a few tens of Oersteds can be generated).

The most commonly used strategy for achieving antiparallel alignment in spin valve sensors is to "pin" the magnetization direction of one of the ferromagnetic layers by depositing an antiferromagnetic layer adjacent to it. While the atomic spins in a ferromagnet tend to align to create a magnetization, the spins in an antiferromagnet align antiparallel resulting in zero net magnetization. When a ferromagnet is deposited adjacent to an antiferromagnet and the interface is clean, a quantum mechanical exchange interaction between spins in the two layers will tend to keep the magnetization in the ferromagnetic layer pointed in a constant direction, known as "pinning" the ferromagnetic layer. By growing the antiferromagnetic layer in a magnetic field the pinning direction will be set (atomic moments of the ferromagnetic atoms in the antiferromagnetic layer will align with the field during growth). The ferromagnetic layer adjacent to the antiferromagnetic layer is typically referred to as the pinned layer while the other ferromagnetic layer is called the free layer since its magnetization is free to respond to changes in applied field. A magnetic material deposited adjacent to an antiferromagnetic layer has a hysteresis loop shifted by an amount $H_{ex}$ from zero (figure
3.3). The exchange field $H_{ex}$ is a direct measure of the exchange coupling across the interface. Increasing the antiferromagnetic layer thickness or decreasing the pinned layer thickness will increase $H_{ex}$.

![Graph showing magnetization vs. field](image)

Figure 3.3 Permalloy exchange biased by an adjacent Fe$_{50}$Mn$_{50}$ antiferromagnetic layer. $H_{ex} = 360$ Oe.

In a spin valve, the free layer and pinned layer are usually very strongly ferromagnetically coupled. The offset of the free layer hysteresis loop from zero is referred to as the coupling field and denoted by $H_c$. The value of $H_c$ has a strong dependence on the spacer layer thickness. The ferromagnetic coupling is a superposition of three separate effects: ferromagnetic coupling of the layers through pinholes, Néel (or orange-peel) coupling, and oscillatory RKKY coupling. Néel coupling results from free poles created at the interfaces between the spacer layer and the ferromagnetic layers (figure 3.4). Néel coupling is typically the strongest of the three forces and determines $H_c$. Pinholes in the thin copper layer create a strictly ferromagnetic coupling that is only a factor at very low copper layer coverages. Oscillatory RKKY coupling is not as strong
as Néel coupling and can be either ferromagnetic or antiferromagnetic depending on the thickness of the copper layer.

![Diagram of ferromagnetic layers and copper spacer](image)

Figure 3.4 Néel coupling resulting from interface roughness.

### 3.2 Spin Valve Overview

The basic spin valve configuration is shown in figure 3.5. This particular layout is referred to as a simple top spin valve. Simple because there is only one spacer layer (symmetric spin valves have two), and top because the pinned layer is on top of the structure. Generally the ferromagnetic layers are either cobalt, Permalloy, or an alloy of nickel, cobalt, and iron. The choice of the free layer material is based on several considerations. First, the moment of the free layer is chosen to set the dynamic range of the sensor. Permalloy is the softest (lowest coercivity) material and is used for low field sensing (< 10 Oe). Cobalt is the harder and is used for larger dynamic range (< 50 Oe). Other considerations for the free layer are small magnetostriction, small uniaxial anisotropy, low coercivity, and large magnetoresistance (i.e. large difference in spin dependent resistivity).\(^{21}\) Permalloy spin valves achieve GMR ratios on the order of 5% while cobalt spin valves can achieve over 10%. The difference in GMR ratios primarily reflects differences in electron mean free paths between Permalloy and cobalt. It is often
common practice to ‘dust’ Permalloy based spin valves with thin (<10Å) layers of cobalt at the spacer layer interfaces. The cobalt layers serve to increase GMR ratios to near 10% while only slightly lowering the sensitivity. Also, while Permalloy and copper are miscible, cobalt and copper are immiscible and the added cobalt at the interfaces reduces interdiffusion of layers during thermal cycling.

Figure 3.5 Schematic of simple top spin valve layout.

The pinned layer is chosen to maximize GMR while setting an acceptable magnetic bias point ($H_b$). Sensor geometry has a strong influence on the desired pinned layer since size and geometry can create nonuniform coupling fields.\textsuperscript{21} Antiferromagnetic layers are chosen by the exchange field produced and the Néel temperature. The Néel temperature is the temperature above which the antiferromagnetic material loses its pinning direction. Fe$_{50}$Mn$_{50}$ is a common material for research investigations, however the low Néel temperature of 150° C makes it an unfavorable for commercial applications. The seed layer is usually tantalum since it provides a very smooth adhesion layer. Tantalum is also usually used as a capping layer for corrosion resistance. The other consideration in choosing the antiferromagnetic, seed, and capping
layer is the resistance of the layers. The lower the resistivity of a particular layer, or alternatively the larger the thickness of the layer, the more current will be shunted through the layer decreasing the GMR ratio.

The films used for this thesis are Permalloy based simple top spin valves with an iron manganese antiferromagnetic layer. Permalloy was used because the high sensitivity gives a higher noise level (discussed in the next chapter). Cobalt dusting of the Permalloy layers was not used since the effect of extra interfaces could be added noise. Iron manganese is the most studied antiferromagnetic layer for pinning applications and is the only antiferromagnetic material available as a standard sputtering target.

3.3 Free Layer Orientation

The orientation of the free layer relative to the pinned layer determines the resistance of the spin valve from equation 1.5 \( R = R_{ap} + (1/2) \Delta R [1 - \cos(\theta_1 - \theta_2)] \). If the easy axis of the free layer is parallel to the pinning direction and the applied field is applied along the easy axis of the free layer (figure 3.6a) then the switching of the free layer is very fast as \( \theta_1 \) goes from 0° to 180°. The problem with operating a spin valve in this orientation is the hysteresis present in the MR curve from the magnetization of the Permalloy (figure 3.6b). However, the low field and high field curves (figs. 3.6b,c) for this orientation yield a great deal of information about the spin valve and are often used to compare properties of different spin valves.

From the low field response, the values of the coercivity of the free layer and the coupling between the free and pinned layers can be determined. Also, the maximum GMR response, \( \Delta R/R_{ap} \), is easily measured. From the large field response (fig. 3.6c) the
properties of the pinned layer can be seen. In particular the value of the exchange coupling and the coercivity increase of the pinned layer can be measured.

Figure 3.6 (a) Geometry of spin valve with free layer easy axis parallel to pinning direction and longitudinal applied magnetic field, (b) low field MR response for Ta 50/Py 50/Cu 27/Py 65/FeMn 120/Ta 50 65x950 μm pattern, and (c) R-H loop for Ta 50/Py 50/Cu 25/Py 50/FeMn 120/Ta 50 bulk sample.

The large hysteresis in figure 3.6b makes the easy axis field configuration undesirable for device operation. If the applied field is instead aligned perpendicular to the easy axis of the free layer then the hysteresis is nearly eliminated and the cosine dependence of equation 1.5 can be more clearly seen (figure 3.7b). In this configuration the maximum resistance change is only half of that for the case of fields aligned along the easy axis since the magnetization in the free layer will be between −90° and 90° and
never reach full antiparallel alignment with the pinned layer. Although the curve in figure 3.7b is not symmetric with respect to field because of shape effects, in general a symmetric response is obtained (curling of magnetization at the edges favors one rotation direction over the other). The hard axis field configuration of figure 3.7a is commonly used in sensors because of its near hysteresis free linear output.

Figure 3.7 (a) Geometry of spin valve axes and (b) measured resistance curve for spin valve with easy axis parallel to pinned direction and transverse magnetic field (Ta 50/Py 50/Cu 27/Py 65/FeMn 120/Ta 50, 65x950 μm pattern).

The most optimum sensing configuration for a simple spin valve, referred to as the ‘crossed easy axes’ or ‘crossed anisotropy axes’ configuration, is shown in figure 3.8a. The pinning direction is perpendicular to the easy axis (θ₂ = 90°) and the external field is perpendicular to the easy axis causing a magnetization rotation from 0° to 180°. The output of the sensor in this configuration is linear with field and has very low hysteresis. The dominant mechanism in the magnetization is the reversible rotation of the magnetization of each domain (same as hard axis field case in figure 3.7). There is some hysteresis present since near saturation the domain structure is either nucleated (fields
decreasing from saturation) or destroyed (fields increasing to saturation). For single domains the crossed easy axis configuration gives zero hysteresis.

The maximum resistance change for crossed anisotropy axes is the same as in the case of an easy axis field. Also, it should be noted that unlike the hard axis field configuration of figure 3.7, the MR curve in figure 3.8b is offset from zero by \( H_r \). Because of the highly linear output and maximum GMR response the crossed easy axis configuration is used for disk drive read heads.

![Geometry of spin valve axes and measured magnetoresistance curve for spin valve with crossed easy axes](image)

Figure 3.8 (a) Geometry of spin valve axes and (b) measured magnetoresistance curve for spin valve with crossed easy axes (Ta 50/Py 50/Cu 27/Py 65/FeMn 120/Ta 50, 65x950 \( \mu \)m pattern).

There are two methods used to achieve the crossed easy axes configuration. First, the applied magnetic field used during spin valve growth can be rotated by 90° after deposition of the first ferromagnetic layer to achieve perpendicular field-induced anisotropies. Alternatively, a post-deposition field anneal above the Néel temperature of the antiferromagnetic layer will reset the pinning direction to align with the annealing field. For FeMn the Néel temperature is approximately 150°C. While Permalloy and
copper will interdiffuse at high temperatures, no problems were encountered with 10 minute anneals up to 200°C (the onset temperature for diffusion has been found experimentally to be between 200 and 250°C).  

3.4 Copper Spacer Thickness

Deposition of the copper spacer layer is possibly the most critical step in spin valve fabrication since it is very difficult to deposit such thin layers. The goal with the spacer is to have it be as thin as possible so electrons will pass through the spacer without scattering. However, there is a trade-off in the thickness of the spacer since the ferromagnetic coupling between the pinned and free layer will increase as the distance between them decreases. If the spacer layer is too thin it becomes impossible to switch the free layer independently of the pinned layer. Pinholes in very thin copper layers will add to this effect. Figure 3.9a demonstrates the dependence of the GMR ratio on the copper thickness. A copper layer below 18 Å will produce a spin valve where the layers cannot switch independently and the resulting GMR will be low. As the copper layer thickness increases there is more scattering in the copper and more current is shunted through the copper so the GMR decreases.

The coupling between ferromagnetic layers is a superposition between magnetostatic coupling and RKKY oscillatory coupling. The magnetostatic coupling decreases exponentially with copper thickness while the RKKY coupling is oscillatory with a period close to 10 Å (the RKKY coupling is proportional to \( \sin(t) / (t \cdot \sinh(t)) \) and is also affected by strain in the spin valve). The coupling field can be calculated from experimental data using the equation.\(^{24}\)
where $H$ is the mean of increasing and decreasing fields, $M_{ls}$ is the saturation moment of layer 1, and the integration is from negative to positive saturation fields. A very small local maximum can be seen in figure 3.4b around 30-33 Å, which corresponds, to a maximum in the RKKY coupling. The period of the oscillatory coupling is typically close to 9 Å. \(^{24}\)

Figure 3.9 Copper layer thickness dependence of (a) the GMR ratio and (b) the ferromagnetic coupling field for Ta 50/Py 50/Cu x/Py 50/FeMn 120/Ta 50, 120x850 μm. Both plots measured with applied field parallel to the easy axis of the free layer.
3.5 Free Layer Thickness

Spin valves are not as sensitive to small changes in the thickness of a Permalloy free layer as they are to copper thickness variations. However, the thickness of the free layer can be modified to tailor the spin valve properties. The grain size of Permalloy changes with thickness and affects the coercivity and anisotropy of the Permalloy layer.\textsuperscript{25,26} The grain size can be measuring from an x-ray diffraction scan using the Scherrer formula (ignoring strain) \textsuperscript{27}

\[
\text{FWHM} = \frac{k \cdot \lambda}{L \cdot \cos \theta}
\]  

(3.2)

where FWHM is the full width at half maximum of the x-ray peak (after correcting for instrumental broadening), \(k\) is a constant typically taken as 1.0, \(\lambda\) is the wavelength of the x-rays, \(L\) is the average grain size in the direction perpendicular to the surface, and \(\vartheta\) is the angle where the diffraction peak is located. Figure 3.10 demonstrates the dependence of grain size on Permalloy thickness.

![Graph of grain size vs. Permalloy thickness](image)

Figure 3.10 Grain size of Permalloy layers grown on 50 Å Ta buffer layer at room temperature, 1 milliTorr Ar sputtering pressure.
The coercivity and anisotropy field for the samples in figure 3.10 were determined from hysteresis loops with the field along the easy and hard anisotropy axes (figure 3.11). There is a minimum in coercivity for the 80 Å Permalloy sample (very repeatable), agreeing well with the 75 Å minimum observed by Akhter, et. al.\textsuperscript{25} The minimum in coercivity does not agree well with the observed anisotropy since the coercivity for in a film with uniaxial anisotropy is directly proportional to the anisotropy constant.\textsuperscript{19} However, very thin films are slightly discontinuous and have an increased number of defects resulting in an increased coercivity.\textsuperscript{26} The decrease in coercivity shown in figure 3.11 is due to the increased coverage and lower defect density of the thicker films.

![Graph showing Hk and Coercivity vs Permalloy thickness](image)

Figure 3.11 Anisotropy field and coercivity for Permalloy films grown on 50 Å Ta buffers.
The GMR ratio reaches a maximum for a particular value of free layer thickness (figure 3.12a). For free layers that are thinner than the electron mean free path scattering at the interfaces becomes more dominant than scattering in the bulk of the free layer and the GMR ratio drops (interface scattering is spin independent). The discontinuity of the thin Permalloy layers will also add to the interface scattering. For thick free layers the current begins to short through the layer and the GMR ratio again falls. The optimum thickness for the Permalloy free layers is between 50 and 75 Å.

The coupling between the layers (figure 3.12b) decreases as roughly 1/t for thin free layer thickness as increasing thickness increases the moment arm for rotations and the films become more continuous. For thicker free layers the coupling increases due to two effects. First, the grain size of Permalloy increases with thickness, thereby increasing the interface roughness and the Néel coupling between the layers. Secondly, the ferromagnetic coupling between the layers is directly proportional to the thickness of each ferromagnetic layer.

![Graphs showing GMR ratio and coupling field vs. Permalloy thickness](image)

Figure 3.12 Dependence of the (a) GMR ratio and (b) coupling field on the Permalloy free layer thickness in Ta 50/Pt x/Cu 27.2/Pt 50/FeMn 120/Ta 50, 120x850 μm. Both plots measured with applied field parallel to the easy axis of the free layer.
3.6 Deposition Pressure

The deposition pressure affects spin valves through the smoothness and quality of the layers. Increasing the pressure increases the scattering sputtered atoms experience while traveling to the substrate and increases the angle of impingement on the substrate. This increases the roughness of the layers and increases Néel coupling (decreasing the sensitivity of the device).

![Graph showing GMR ratio for different pressures](image)

Figure 3.13 GMR ratio (defined as (R-R_{sp})/R_{sp} * 100) plotted for spin valves grown at various pressures. Ta 50/Py 50/Cu 35/Py 50/FeMn 120/Ta 50, 120x850 μm pattern.

Figure 3.13 demonstrates how the MR curve changes for growth at different pressures. It is clear that the sensitivity and maximum GMR ratio decrease with increasing sputtering gas pressures. For the deposition done at 3 mTorr Argon pressure the coupling is too strong to achieve antiparallel alignment of the ferromagnetic layers. The resistance of the spin valve also increased fairly linearly with the deposition pressure
from near 28 ohms/□ for 1 mTorr Ar to 43 ohms/□ for the deposition at 3 mTorr (50% increase).
4 Low Frequency Noise in Spin Valves

The obvious motivation for studying low frequency noise is for optimizing the signal to noise of spin valve sensors operating in the low frequency region. Of the applications listed in chapter 1, only hard drive read heads will operate at frequencies well above the low frequency regime. However, as will be shown later in this chapter the low frequency noise in a spin valve is related to magnetic fluctuators that transition in the MHz range. These fast transitions could interfere with magnetic recording. Also, there is research looking into how low frequency noise changes with current stressing and may be indicative of early device failure.\textsuperscript{30,31}

This chapter will review two types of low frequency noise in spin valves: Johnson noise and 1/f noise. Johnson noise is present in all resistive devices and has a flat frequency spectrum. The theory of 1/f noise in spin valves will be presented in section 4.1.2. Results of noise measurements taken with the setup described in chapter 2 will be presented in section 4.2. The noise measurements were performed to see how signal to noise of devices in the low frequency range could be optimized and also to see if 1/f noise could be correlated to other device properties.

4.1 Theory of the Low Frequency Power Spectrum

4.1.1 Johnson (Nyquist) Noise

Brownian motion was originally discovered when mold spores were seen to move quickly and randomly in a drop of water. Einstein developed the theory that correctly described this random motion of particles due to thermal energy and predicted that random thermal motion of charge carriers in a resistor would lead to a fluctuating voltage
across the resistor. Johnson was the first to observe this noise voltage across a resistor and the fluctuating voltage noise was named for him. Nyquist, who analyzed the experimental data acquired by Johnson, derived the power spectrum of the noise by developing a fluctuation dissipation relation. Nyquist realized that damping (or friction) in a sample is caused by the same random thermal fluctuations that cause equilibrium fluctuations of the measured quantity (i.e. voltage). The Nyquist theorem gives the spectral density of voltage fluctuations \( S_v \) for Johnson noise as

\[
S_v(f) = 4kTR
\]

where \( k \) is Boltzmann's constant, \( T \) is the temperature of the sample, and \( R \) is the resistance of the sample. The frequency spectrum for Johnson noise is white (flat with respect to frequency).

The Nyquist theorem was generalized by Callen to apply to any linearly dissipative system. The generalized fluctuation dissipation relation (FDR) relates the equilibrium fluctuations of a system to the dissipation that arises when the system is driven by an external force:

\[
S_X(f) = \frac{h}{2\pi} \cdot \coth \left( \frac{hf}{2kT} \right) \cdot A''(\omega)
\]

where \( A''(\omega) \) is the response at the same frequency that determines the dissipated power, \( h \) is Planck's constant, \( k \) is Boltzmann's constant, and \( T \) is the sample temperature.

4.1.2 1/f Noise

An equation for the power spectrum can be directly derived using the fluctuation dissipation relation. First, the spectral density of voltage fluctuations as can be written in terms of the magnetization fluctuations as
\[ S_v = I^2 \cdot S_R = I^2 \cdot \left( \frac{dR}{dm} \right)^2 \cdot S_m \]  \hspace{1cm} (4.3)

where \( S_R \) and \( S_m \) are the spectral densities of resistance and magnetization fluctuations respectively. Then the FDR (equation 4.2) gives the magnetization fluctuations as (for \( hf \ll kT \))

\[ S_m = \frac{2}{\pi} \cdot kT \cdot \chi''_m \]  \hspace{1cm} (4.4)

where \( \chi''_m \) is the out of phase magnetic susceptibility. \(^{36,37}\) The magnetic susceptibility is defined as

\[ \chi_m = \frac{dm}{dH} = \chi'_m - i \cdot \chi''_m \]  \hspace{1cm} (4.5)

or alternatively

\[ \chi_m = |\chi_m| \cdot e^{i\phi} \]  \hspace{1cm} (4.6)

where

\[ \tan(\phi) = \frac{\chi''_m}{\chi'_m} \]  \hspace{1cm} (4.7)

Electronic measurements of spin valves do not directly measure the magnetic susceptibility, therefore a new parameter \( \chi''_R \) is defined which is the out of phase response of the resistance per unit of applied field. The two susceptibility parameters are related by

\[ \chi_R = \frac{dR}{dH} = \frac{dR}{dm} \cdot \frac{dm}{dH} = \chi'_R \cdot \frac{dR}{dm} \]  \hspace{1cm} (4.8)

Substituting the above relations into eqn. (4.3) and multiplying and dividing by \( \chi'_R \) gives
\[ S_v = I^2 \frac{dR}{dm} \frac{2kT}{\pi} \frac{\chi''}{\chi'} \frac{R}{R} \]  
(4.9)

Then using eqn. (1.7) with the substitution \( m = M V \) we find that

\[ \frac{dR}{dm} = \frac{\Delta R}{M_s \cdot V_f} \]  
(4.10)

where \( V_f \) is the volume of the free layer and \( \Delta R \) is the maximum change in resistance.

For small \( \phi \), \( \chi' \approx dR/dH \). So the final expression for the voltage fluctuations is then

\[ S_v = I^2 \frac{2kT}{\pi} \tan(\phi) \frac{\Delta R}{M_s \cdot V_f} \frac{dR}{dH} \]  
(4.11)

The general model for the source of 1/f noise in magnetic films can be explained by a two state system (Figure 4.1).\(^{38,39}\) The two state system is characterized by two energies: \( \Delta E \) is the energy between the two energy levels and \( E_a \) is the activation energy for making the transition. The transition rate then has an Arrhenius form, \( f_0 e^{(E_a + \Delta E/2)/kT} \), and the resulting spectral density of the fluctuations between the sites has a Lorentzian spectrum. If the energy barrier \( E_a \) is uniformly distributed and the separation energy is distributed up to a maximum \( \Delta E_{\text{max}} \) then the susceptibility can be given as \(^{40}\)

\[ \chi'' = \frac{\mu \cdot (M_s)^2 \cdot V}{\Delta E_{\text{max}}} \frac{kT}{<E_a>} \]  
(4.12)

where \( <E_a> \) is the mean value of the barrier energy. For magnetization rotation the barrier energy is proportional to the anisotropy constant \( K \). For domain wall displacement the barrier energy is proportional to the strength of the domain wall pinning.
The Lorentzian spectrum of individual magnetic fluctuators has been experimentally observed in spin valves\textsuperscript{30,31}, granular GMR films\textsuperscript{41,42}, and colossal GMR films\textsuperscript{43}. The key in experimentally observing noise due to a single fluctuator is to have a very small sample size (below 1 \( \mu m^2 \)) or to cool the sample in order to freeze out the other fluctuations. Figure 4.2 shows an illustration of the time domain record of a single fluctuator. It is obvious from the time domain record why the noise due to a single fluctuator is referred to as random telegraph noise (RTN). Xiao, et. al.\textsuperscript{30} were able to correlate lifetimes of the two states with external fields to prove that the states were magnetic in origin. Magnetic random telegraph noise has also been observed in ferromagnetic tunneling.\textsuperscript{44,45,46} However, in the case of tunneling charge traps in the insulating layer are primarily responsible for the noise although some noise features can be correlated with magnetic effects. The superposition of several individual fluctuators with a broad distribution of switching times results in a 1/f power spectrum.\textsuperscript{38,39}

Measuring the magnitude of the voltage fluctuations in random telegraph noise from spin valves will give an estimate of the size of the magnetic fluctuation. Using a spin tunneling film, Ingvarsson, et. al.\textsuperscript{45} estimated that a domain of 100 nm\(^2\) would have to be completely reversed to account for the voltage fluctuations. Kirschenbaum, et. al.\textsuperscript{47} used an alternative approach where the slope of the 1/f noise was used to estimate the
magnetic moment of the fluctuating area as $2 \times 10^4$ Bohr magnetons (slightly larger than 100 nm$^2$). It is very unlikely that such a small area would be able to flip since a very large increase in magnetostatic energy would result. Therefore, it is believed that small rotations of larger domains are responsible for the noise.

![Image](image.png)

Figure 4.2 Example of random telegraph time domain record.

A similar effect to RTN in spin valves can be caused by inhomogeneous current flow through the magnetic multilayer stack.\textsuperscript{31} In this case defects or grain boundaries create regions of high current flow which creates a non-uniform self field in the spin valve. The non-uniform field creates regions that are biased differently and that switch at different fields than the rest of the spin valve. The resulting time domain record for the unstable fluctuating regions resembles very closely that of purely magnetic noise. The only way to determine if current is playing a role in the RTN is to look for a current dependence of the noise. A purely magnetic RTN will scale with the square of the current (equation 4.11 — to be verified later in the chapter) and have a strong dependence on field.
4.2 Results

Figure 4.3 1/f noise spectrum of spin valve.

Low frequency noise measurements were made on the simple spin valves described in chapter 3. The structure of the spin valves and the measurement conditions were altered in order to determine which parameters affected the signal to noise of spin valves operating in the acoustic regime. As previously noted, extreme care was taken during measurements to ensure spurious noise contributions were eliminated. The typical noise power spectrum of a spin valve is shown in figure 4.3. A 1/f sloped line and a line corresponding to the Johnson noise background has been superimposed on the plot for comparison purposes. The term '1/f noise' is applied here to describe the general 1/f character of the low frequency noise. The actual power law follows $1/f^\alpha$ where $0.8 < \alpha < 1.2$ for most devices.

4.2.1 Verification of magnetization fluctuations
To insure that the spin valve was not just reproducing noise in the external magnetic field, the coherence function was taken between a deposited spin valve and a commercially available spin valve sensor. The coherence function, \( \gamma \), between two signals is defined as

\[
(\gamma_{xy})^2 = \frac{\left| S_{xy} \right|^2}{S_{xx} \cdot S_{yy}}
\]

where \( S_{xy} \) is the cross spectrum of the two signals while \( S_{xx} \) and \( S_{yy} \) are the autopower spectra of the two signals. If the \( x \) and \( y \) signals are correlated then \( \gamma = 1 \), if the signals are completely uncorrelated then \( \gamma = 0 \). The coherence estimate in figure 4.4 shows that the output from the two sensors is not correlated (except at interference peaks), therefore the spin valve is not detecting \( 1/f \) noise from the external environment.

![Figure 4.4](image)

Figure 4.4 (a) Coherence estimate and (b) power spectra for NVE GMR bridge sensor and sputtered spin valve.

Several spikes in the noise power are evident in figure 4.3 and in the coherence estimate of figure 4.4. While a cross correlation was performed and shielded leads were used, some spurious noise was still introduced into the measurements. The most prominent spikes are from 60 Hz power lines and their 2\(^{nd}\) and 3\(^{rd}\) harmonics. It should
be noted that while 60 Hz interference was present from the magnet power supply, an additional source of 60 Hz noise was from the power bus on the National Instruments A/D card in the computer.

To facilitate comparing noise from several samples, the noise power per octave (i.e., $f_i = 2f_2$) was calculated in Matlab. The octave used was 200 Hz – 400 Hz which avoided interference from the 60 Hz power lines and its first few harmonics. For pure 1/f noise the integrated power becomes

$$\int_a^b \frac{1}{f} \, df = \log(b) - \log(a) = \log\left(\frac{b}{a}\right)$$

(4.14)

The actual octave (or decade) chosen does not impact the power per octave since it is only the ratio of the integration limits that matters.

The FDR (equation 4.11) predicts that the magnitude of 1/f noise increases as the current squared. The power is plotted vs. the current in figure 4.5 where the power is shown to increase as the square of the current over the range investigated. The verification of the current scaling proves that the 1/f noise is purely a resistance fluctuation and not caused by current density effects. (It should be noted that at higher current densities a non-field dependent 1/f noise was observed that was attributed to contact noise and current density noise in the thin probe tips).
Figure 4.5 Power increases as current squared.

The theory presented in section 4.1.2 explains the presence of 1/f noise as due to thermal fluctuations in magnetization sensed by the spin valve. To prove the theory a spin valve with crossed anisotropy axes was subjected to an AC magnetic field. The phase lag, $\phi$, between the excitation field and the spin valve response was measured as a function of the DC bias field. The noise power can be calculated from the measured phase shift using equation 4.11. The calculated power is plotted with the experimentally measured power per octave in figure 4.6. The agreement is exceptionally good except near the peak. It was found that decreasing the amplitude of the AC field would bring the values at the peak into better agreement, but then the reduced signal to noise would create more scatter in the lower parts of the graph. A similar measurement was performed by Hardner, et. al. in 1993 to verify the FDR in Co/Cu GMR multilayers.\textsuperscript{37}
Figure 4.6 Comparison of noise power calculated from phase shift (equation 4.11) and experimentally measured for Ta 50/Py 65/Cu 35/Py 50/FeMn 120/Ta 50 spin valve.

4.2.2 Free layer orientation

There are two variable parameters in equation 4.11 (assuming a given $M_s$): the sensitivity $dR/dH$ ($\chi'$), and the irreversible susceptibility ($\chi''$). The sensitivity is determined by the interlayer coupling, the free layer material, and other factors discussed in chapter 3. The irreversible susceptibility is determined primarily by the $1/E_a$ dependence of equation 4.12. The activation energy for domain rotation is typically much less than the energy required for domain wall displacement. Therefore one would predict that the major noise contributor would be small regions with a fluctuating magnetization angle. The distribution of fluctuators should then be a Gaussian centered around zero effective coupling field ($H_{\text{applied}} - H_i$).\textsuperscript{36,48} A Gaussian distribution is an indicator of a large number of independent and identically distributed random fluctuations. Figure 4.7a shows the measured power / octave of the $1/f$ noise in a spin
valve with crossed easy axis. The out of phase magnetic susceptibility, $\chi''$, was calculated using equations 4.8 and 4.9. The Gaussian fit is very good, although it should be noted that the sensitivity $dR/dH$ also has a slightly Gaussian form that convolutes the true susceptibility distribution.

![Figure 4.7](image1.png)  
Figure 4.7 (a) Power per octave versus applied field for crossed easy axis. (b) Gaussian fit to out of phase magnetic susceptibility.

![Figure 4.8](image2.png)  
Figure 4.8 Power per octave for spin valve with (a) applied field along easy axis of free layer and (b) applied field along hard axis of free layer.
The measured noise for spin valves in the easy or hard axis configuration is proportional to the sensitivity dR/dH of the spin valve from equation 4.11 (figure 4.8). In these two cases the spin valve is not sensitive at zero coupling field and therefore the measured noise is lower than for a spin valve with crossed easy axis. The spin valve in the easy axis configuration is only sensitive to fluctuations occurring at $H_f \pm H_c$. The cos $\theta$ dependence of the hard axis configuration yields a broad minimum around zero coupling field.

The out of phase susceptibility is affected by demagnetizing effects through the equation \(^{49}\)

$$\chi''_{\text{effective}} = \frac{\chi''}{(1 - N \cdot \chi')^2} \quad (4.15)$$

where $N$ is the demagnetizing factor. The noise was measured on a 65 x 930 $\mu$m pattern for the cases where the easy axis of the free layer was along the long axis and the short axis of the pattern. While the sensitivity of the spin valve was different for the two cases, the noise was the same after normalizing by dR/dH.

### 4.3.3 Free Layer Thickness

Increasing the thickness of the Permalloy free layer changes both the coercivity and the anisotropy of the layer. The noise dependence on the thickness of the free layer is shown in figure 4.9. Interestingly, the noise seems to peak at a free layer thickness of 70 Å which is where the maximum in GMR occurs (figure 3.7a), a minimum in coupling occurs (figure 3.7b), and the thickness at which Permalloy films have a minimum in coercivity (figure 3.6). In chapter 3 these effects were ascribed to the discontinuity of
Permalloy films below 50 Å. The defects in a discontinuous Permalloy layer will raise the energy barriers required for magnetization. Since the susceptibility is inversely proportional to the barrier energy (equation 4.12), the discontinuous films will have lower 1/f. As the films become continuous, the noise will increases as observed in figure 4.9 for the 65 Å free layer. For thicker films the noise becomes inversely proportional to the anisotropy and decreases with increasing thickness.

![Graph](image)

Figure 4.9 Dependence of 1/f noise on Permalloy free layer thickness, measured on a sample with crossed anisotropy axes. The noise is normalized by dividing by dR/dH. Ta 50/Py x/Cu 27/Py 50/FeMn 120/Ta 50, 65 x 930 μm pattern.

### 4.3.4 Copper spacer layer thickness

There is not an expected correlation between the imaginary susceptibility and the copper thickness from equation 4.11. However, copper thickness determines the magnetic coupling between the free and pinned layer and defects in the copper layer may change the local susceptibility. Figure 4.10 shows that there is very little correlation between the copper thickness and the measured power. Interestingly, a small dip is seen
in the noise power in the 30 – 35 Å range which is where the peak in RKKY coupling was found (figure 3.4b). It is possible that the extra RKKY coupling reduced slightly the number of magnetization fluctuations occurring. Normalizing by dR/dH has the same effect as normalizing by the copper thickness since the sensitivity is related to spacer layer thickness.

![Graph](image)

Figure 4.10 Power per octave (normalized by dR/dH) vs. copper thickness for Ta 50/Py 50/Cu t/Py 50/FeMn 120/Ta 50. Measured for crossed anisotropy axes.

4.4 Conclusions

The experiments presented in this chapter demonstrate a low frequency 1/f noise due to magnetization fluctuations in the free layer. The FDR was verified by directly measuring the phase lag of the spin valve response. The crossed easy axis configuration is most sensitive to the noise but also has the most desirable characteristics for magnetic sensing (high sensitivity, linear output). While the hard axis configuration has an order of magnitude lower sensitivity than the crossed easy axis (0.2 %/Oe vs. 2.0 %/Oe), the noise is a factor of 10 lower than the crossed easy axis case after normalization by dR/dH. Our results therefore indicate that the hard axis configuration may be beneficial
for measuring very low level signals that would be buried in the noise of a crossed easy axis spin valve.

We were able to show that l/f noise was sensitive to the level of defects in the free layer. A small variation in l/f noise was observed for changes in magnetic coupling, but the variation is too small to be statistically significant. Smaller devices should be much more sensitive to defect density than the large devices measured in this thesis. Our results indicate that low frequency noise may become an important tool for free layer quality control.
5 Barkhausen Noise

Static measurements of low frequency noise show a 1/f character since thermally induced magnetization fluctuations are sensed by the spin valve. Using a time varying field to create a changing magnetization also creates low frequency noise that may be useful in characterizing device performance. This chapter describes the behavior of the low frequency noise when the spin valve is being dynamically excited. Dynamic measurements of the spin valve are more applications oriented and give insight into the complex domain behavior of the spin valve.

5.1 The Magnetization Process

When a ferromagnetic material is placed in an increasing magnetic field the magnetization increases until saturation is reached. During the initial stage of magnetization, there is a field range where the magnetization changes reversibly through the reversible displacement and nucleation of domains. If the magnetic field is further increased the magnetization increases more rapidly and is no longer reversible. This range is of magnetization is termed the irreversible magnetization range. In this range the magnetization change of the material is occurring through irreversible displacements of domain walls. The domain wall movement is not reversible because of the presence of defects in the material which serve to trap the domain walls.

The energy of a domain wall is not a smooth function of position because of inclusions, impurities, strains, grain boundaries, and other defects in the film. Defects in ferromagnetic films have dipole moments associated with them that have high magnetostatic energy. When a domain wall is centered on the defect the magnetostatic
energy of the defect is lowered and the wall is in a potential energy minimum. The
imperfections in ferromagnetic films are known as pinning centers and create a potential
energy diagram of local energy minima and saddle points through which the domain wall
moves. With zero applied field the wall will sit at the position labeled A in figure 5.1.
As energy is applied to the system in the form of an external magnetic field the domain
wall will move reversibly in the well until it reaches B at which point it will snap to
position C. From position C the wall will move to its new equilibrium point at position
D. If the field is lowered, the wall will move reversibly in its new potential well. These
jumps between potential wells are referred to as Barkhausen jumps and are accompanied
by rapid changes in the magnetization. The magnitude of the field required create a
Barkhausen jump depends on the energy required to release the domain wall from its
pinning center.

If the magnetic field is increased beyond the irreversible range the magnetization
increases less rapidly and becomes reversible again. In this range the domain wall
displacements have already occurred and magnetization takes place by rotation of domain
orientation towards the applied field.

Figure 5.1 Potential well model for pinning site (after Klaassen).
5.2 Barkhausen Noise Measurement Procedures

A quasi-static field is used to measure Barkhausen noise. The external field is very slowly ramped from negative saturation to positive saturation. Figure 5.3 shows a setup used to test for noise in thin film inductive heads. When a domain wall in the shields of the read head jumps, a voltage spike is produced in the inductive coil of the thin film head. The rise time of the measured voltage is typically a few tens of nanoseconds to a few microseconds depending on the inductance of the head. The magnitude (voltage) of the jump can be used to determine the domain displacement during the jump.

The dynamics of a moving domain wall were first described by Döring using the equation: \(^{19}\)

\[
m \cdot x'' + \beta \cdot x' + \alpha \cdot x = 2 \cdot M_s \cdot H
\]  

(5.1)

where \(m\) is the wall mass (inertial mass), \(\beta\) is the eddy current damping per unit area, and \(\alpha\) is the wall restoring force (the second derivative of the wall energy with respect to
position). The inertial mass of the wall is related to energy stored in the spins in a domain wall.\textsuperscript{19} If there were no wall damping, a wall in motion would continue to move even without an external field because of the energy in the spins of the domain wall. Solving equation 5.1 for velocity gives \( v \sim e^{-\alpha t} \) where the ratio \( \beta/\alpha \) is typically denoted by \( \tau_0 \). In inductive measurements of Barkhausen noise the voltage measured is proportional to the wall velocity and therefore has an exponential form (figure 5.4a). In a spin valve, the resistance is proportional to the magnetization, which in turn is proportional to the domain wall displacement (figure 5.4b).

![Diagram of Poles of Electromagnet, Inductive Read Head, and Read/Write Gap]

Figure 5.3 Schematic of Barkhausen noise measurement setup for inductive heads (after Klaassen\textsuperscript{50}).

The time constant \( \tau_0 \) is related to the decay of magnetostatic fields and is given by

\[
\tau_0 = \sigma \cdot G \cdot S \cdot \mu
\]  

(5.2)

where \( \sigma \) is the conductivity of the metallic film, \( G \) is a constant equal to 0.1356, \( S \) is the cross sectional area of the wall, and \( \mu \) is the permeability of the material.\textsuperscript{51} For a 50 \( \text{Å} \) thick Permalloy free layer 50 \( \mu \text{m} \) wide \( \tau_0 \sim 2 \times 10^{-9} \) seconds. Experimental values for \( \tau_0 \) often deviate from predicted values since the permeability is difficult to define on the scale of single domains.\textsuperscript{52}
Figure 5.4 (a) Exponential decay of domain wall velocity during Barkhausen jump and (b) corresponding domain wall position.

5.3 Modeling the Barkhausen Effect

As a first step towards a formula for the power spectrum of Barkhausen noise, Campbell’s theorem can be used to relate the spectrum of one pulse to that of a train of pulses\(^{53}\)

\[
V(f)^2 = 2 \cdot k \cdot S(\omega)
\]  

(5.3)

where \(V(f)^2\) is the spectral density in \(V^2/\text{Hz}\), \(k\) is the number of pulses per unit time, and \(S(\omega)\) is the power spectrum of a single pulse. Strictly speaking, equation 5.3 is only valid for identical pulses; however the differences from pulse to pulse in Barkhausen noise are often not too large and it has been shown that equation 5.3 can be used to describe Barkhausen power spectra.\(^{53}\)

It was argued in the previous section that the Barkhausen pulse could be described well by a dying exponential \(e^{-\omega T_0}\). Then

\[
S(\omega) = \frac{1}{4 \cdot \pi^2 \cdot \left(\frac{\omega}{\omega_0} - 2\right)}
\]

(5.4)

The expression for \(k\) is given as:\(^{53}\)
where \( f_0 \) is the frequency of the external magnetizing field, \( V_p \) is the sample volume, and \( V_B \) is the volume involved in a Barkhausen jump. Solving for \( V_B \) one obtains \(^5^3\)

\[
V_B = \frac{V(0)^2}{16 \cdot (M_s \cdot V_s)^2 \cdot f_0}
\]

(5.6)

Where \( V(0)^2 \) is the spectral density in the low frequency range where \( S(\omega) \) is constant. Therefore it is possible to estimate the domain size from the observed power spectrum.

The behavior of the Barkhausen jumps in response to an AC field depends on the frequency and magnitude of the applied field. As a domain wall moves, it encounters pinning sites that serve to trap the wall. The wall must then acquire some energy in order to free itself from the pinning site. The energy required to release the wall may be from an externally applied field, or in some instances may be supplied by thermal energy.\(^{1^9,5^4}\)

\(^{5^5,5^6}\) For slowly varying fields there is a relatively long time during which thermal energy can trigger a jump. For high frequency (kHz range) dynamic fields, the dwell time is too short for thermal triggering and the wall jumps are caused by the external field. The energy in an AC field is given by \(^5^6\)

\[
E_{ac} = c \cdot f^2
\]

(5.7)

where \( f \) is the frequency of the field and \( c \) is the magnitude of the field. In the frequency range where the external field is providing the energy, the power should be proportional to the square of the drive frequency.
5.4 Barkhausen Results

Using a wide bandwidth amplifier (SR560, 1 MHz bandwidth) the form of the power spectrum under dynamic excitation is observed (figure 5.5). The power spectrum in figure 5.5 is roughly constant at low frequency. At higher frequencies the spectrum drops off as $1/f^2$.

The predicted relaxation time of an individual pulse is nanoseconds whereas the observed time constant is on the order of milliseconds (figure 5.5). The discrepancy is the result of three effects. First, the sampling rate is not high enough to sample individual Barkhausen pulses. Second, at high drive frequencies the jumps are forced by the applied field and no longer caused by thermal processes. Finally, the clustering of individual Barkhausen pulses in high permeability materials alters the spectrum.$^{57,58}$

![Power spectrum image](image_url)

Figure 5.5 Power spectrum of spin valve with 1 kHz AC excitation 1.6 Oe pk-pk. The decay time from a Lorentzian fit gives $\tau = 3 \times 10^{-4}$. 

Figure 5.6 Comparison of 1/f noise spectrum with Barkhausen power spectrum.

The power spectrum give by equation 5.4 is only strictly correct when the Barkhausen pulses do not overlap each other. In soft ferromagnetic materials Barkhausen jumps occur in clusters of jumps initiated by a single domain. The 'avalanching' behavior is caused by repulsive interactions between domain walls and a spatially rough coercive force from defects. Even for a very low sweep rate individual pulses could not be observed. Figure 5.7 demonstrates a time record taken at a very slow sweep rate. Each peak in the figure is a cluster of several pulses.

Figure 5.7 (a) A string of Barkhausen pulses taken while sweeping the field at a rate of 1 Oe/minute. The decay time of the pulses is electronics limited by a high pass filter. (b) The power spectrum of the clusters in (a). A power law fit gives to the sloping region gives $f^{-2.3}$, roughly characteristic of Barkhausen noise.
The avalanching of individual Barkhausen pulses changes the expected power spectrum. Mazzetti and Montalini developed a theoretical expression for the power spectrum \(^{59}\)

\[
\Phi = \phi \left[ 1 - \frac{2 \cdot \rho}{(2 \cdot \pi \cdot \tau \cdot \rho \cdot f)^2 + 1} \right] \tag{5.8}
\]

where \(\Phi\) is the power spectrum of the clustered Barkhausen noise, \(\phi\) is the power spectrum of individual Barkhausen pulses, \(\rho\) is the average number of Barkhausen pulses per cluster, and \(\tau\) is the average time between successive pulses in a cluster. The cut-off frequency is then given by

\[
f_c = (2 \cdot \pi \cdot \tau \cdot \rho)^{-1} = (2 \cdot \pi \cdot <\tau_{av}>)^{-1} \tag{5.9}
\]

where \(<\tau_{av}>\) is the average duration of a Barkhausen avalanche.\(^{60}\) Equation 5.8 predicts three distinct regions of the power spectrum. At low frequencies, \(f << f_c\), the power spectrum is constant. For \((\tau f) \rightarrow 0\) the low frequency portion of the power spectrum will be proportional to \(2 \rho\). At intermediate frequencies, \(f_c < f < (2 \cdot \pi \cdot \tau_0)^{-1}\), the power spectrum decreases as \(f^{-2}\). At high frequencies, \((2 \cdot \pi \cdot \tau_0)^{-1} < f\), the power spectrum decreases as \(f^{-4}\). From the predicted individual pulse decay time of 2 nanoseconds the power spectrum will begin to decay as \(f^{-4}\) above 80 MHz.

The magnitude of the frequency independent part of the Barkhausen spectrum was examined to determine the scaling of the noise with the magnitude and frequency of the applied AC field (figure 5.8). An increase in noise is seen for increasing magnitude of the AC field at fixed frequency (figure 5.8a). The measured power increases exponentially with field magnitude up to an amplitude of 0.8 Oe, which is close to the coercivity of the permalloy free layer. The discrepancy is largely due to the increased
number of wall jumps per cluster (ρ) caused by the increased field magnitude. If the amplitude of the AC field is not large enough to cause a wall jump, it just shakes the wall within its potential well.\(^{56}\)

![Graphs](image)

(a) Power / Octave vs. Amplitude of 1 kHz AC field (Oe)  
(b) Power / Octave vs. Frequency of 0.5 Oe AC field

Figure 5.8 Dependence of low frequency noise on (a) magnitude and (b) frequency of the applied AC field. Applied field is along the easy axis of the free layer, Ta 50/Py 50/Cu 30/Py 50/FeMn 120/Ta 50.

Figure 5.8b demonstrates the dramatic reduction of noise as the excitation frequency is increased to a few kHz (for pk-pk magnitude close to \(H_c\)). The frequency dependence of the noise scales as approximately \(f^{-1.5}\). As the magnetizing frequency increases, the Barkhausen pulses will increasingly overlap each other. The same number of jumps occur in each hysteretic cycle, therefore the total number of individually observable pulses per cluster (ρ) decreases with frequency.\(^{61}\)

The inability to observe individual Barkhausen pulses coupled with the avalanching of pulses makes the magnitude of the power spectrum unfit for comparison between different samples. Another approach to evaluating Barkhausen noise is to use
harmonic analysis. The linearity (or deviations from linearity) of the spin valve response is measured by the total harmonic distortion, defined as

\[ THD = \sqrt{\sum_{i=1}^{5} \left( \frac{V_i}{V_1} \right)^2} \]  

(5.10)

where \( V_i \) is the signal height of the \( i \)th harmonic (\( V_1 \) is the output voltage at the signal frequency). The THD is plotted in figure 5.9 as a function of Permalloy free layer thickness for a 1 kHz and 5 kHz 0.5 Oe field. There is considerable scatter in the plot from process variations. During annealing of the samples any deviation of the field from exactly 0° or 90° will cause nonlinearity. However, it can be noted that the crossed axis configuration is more linear for low values of Permalloy thickness while the crossed axis is less linear for higher thickness. The THD for parallel anisotropy axes with the field applied along the hard axis (not shown in figure) is an order of magnitude lower.

![Graph showing THD as a function of Permalloy thickness](image)

**Figure 5.9** Total harmonic distortion as a function of Permalloy free layer thickness. Ta 50/Pt 50/Cu 35/Pt 50/FeMn 120/Ta 50.
Since increasing the Permalloy thickness increases the coupling field, one would expect that thicker Permalloy layers would be more non-linear. This is what is observed for the crossed axes configuration. For the parallel easy axes the hysteresis loop becomes more square with increasing thickness and thus enhances the linearity, as demonstrated in figure 5.9.

Barkhausen noise can be quantified by the differential high-band noise (dhbn) given by \( \text{dhbn} = 20 \cdot \log \left( \sum_{i=6}^{20} \frac{(V_i)^2}{(V_i')^2} \right) \) (5.11)

where \( V_i \) is the signal height of the \( i \)th harmonic. The dhbn measures the higher harmonics that result from domain wall jumps. As was the case for the low frequency power in figure 5.8b, the dhbn decreases for increased drive frequency (figure 5.10). Again this is primarily due to increased clustering of pulses at higher magnetization frequencies. It is also evident that for the crossed axis configuration the dhbn increases with increasing Permalloy thickness. This is a direct result of the measured increase in anisotropy with Permalloy thickness. The restoring force, \( \alpha \), in equation 5.1 decreases with increasing anisotropy.\(^{19}\) Therefore the increase in anisotropy with thickness translates into a decreased restoring force and makes it easier for domain wall jumps to occur.
Figure 5.10 Differential high-band noise as a function of Permalloy free layer thickness. Ta 50/Py 50/Cu 35/Py 50/FeMn 120/Ta 50.

The crossed axis configuration has the lowest dhbn for higher frequency signals. In a smaller sensor there should be very little Barkhausen noise since domain processes would be greatly reduced. The dhbn for parallel anisotropy axes with the field along the hard axis is comparable to the crossed axes case. It is surprising that the Barkhausen noise is not higher for the thinner Permalloy free layers since the coercivity measurements and 1/f noise measurements indicated the thin layers were defect laden. The THD measurement for a 5 kHz signal along the easy axis does show a dip in the distortion for the 80 Å layer corresponding to the dip in coercivity.

The observed clustering of pulses greatly hinders the capability of Barkhausen noise measurements to give physical insight into material properties. The development of more sophisticated models to explain the clustering of Barkhausen jumps may improve the usefulness of this method of characterization. On the other hand, the clustering serves
to decrease observed noise levels for signals above a few kHz, improving the signal to noise.
6 Summary and Conclusions

This thesis has studied low frequency noise measurements as a means of characterizing spin valve devices and as a tool in understanding fundamental properties of the spin valve layers. Each of the layers in a spin valve is critical to the device performance. Small deviations from a layer’s optimum thickness or increases in the defect density will adversely affect the spin valve’s performance.

Static measurements of spin valve resistance and magnetization were used to determine the device dependence on layer thickness and quality. Néel coupling and RKKY coupling were observed in the measured magnetic coupling between the free and pinned layers with a ferromagnetic peak near a copper layer thickness of 30 Å. The Néel coupling increased with sputtering pressure, reflecting the increasing roughness of the layers. The GMR ratio of the spin valves fell dramatically for copper layers below 20 Å indicating a discontinuous copper layer. Hysteresis loops of Permalloy layers deposited on tantalum indicated discontinuities and increased defects for Permalloy thickness less than 60 Å. The GMR ratio and magnetic coupling were strongly dependent on the thickness of the Permalloy free layer. The GMR ratio showed a maximum at 65 Å while the magnetic coupling had a minimum at 65 Å. Noise measurements were performed on spin valves in order to determine how the low frequency noise characteristics varied with free layer quality and copper spacer thickness.

The low frequency noise of the spin valves had a 1/f character. The fluctuation dissipation relation was demonstrated for these spin valves. This means that at least at low current densities, the current did not induce excess noise. Demonstrating that the observed noise is from magnetic fluctuations also reduces the chance that noise
characteristics are artifacts of the measurement setup or device processing. Devices with parallel easy axis and the applied field along the hard axis demonstrated the lowest 1/f noise. The observed 1/f noise, being of magnetic origin, showed no dependence on the copper layer thickness after normalizing by the sensitivity of the devices. The noise was very sensitive to the free layer thickness, decreasing with increasing thickness of the Permalloy layers. Permalloy layers thinner than 50 Å had increased defects and lower total noise.

Barkhausen noise was measured using a dynamic field to excite domain wall motion in the free layer. Individual Barkhausen jumps could not be detected because of the short duration of the domain wall shift and the clustering of several jumps. The clustering was dependent on the frequency and amplitude of the external drive field. The Barkhausen noise increased with increasing free layer thickness corresponding to the increasing anisotropy in the layer. The Barkhausen noise was lower for dynamic fields along the hard axis of magnetization. The Barkhausen jumps increased the low frequency noise by several orders of magnitude. Devices operated in the hard axis configuration offer advantages in low frequency sensing because of a reduced 1/f background and reduced Barkhausen noise.

The results in this thesis indicate that low frequency noise may be a useful diagnostic tool for spin valves. The 1/f noise was shown to be sensitive to defects in the free layer. Smaller devices would be expected to be even more sensitive to magnetic defects. Harmonic analysis of Barkhausen noise tracked the anisotropy in the free layers. The results indicate several areas for future work. Smaller devices enable measurement of individual magnetic fluctuations that may lead to increased understanding of thermal
effects in thin ferromagnetic films. Also, the multiple fluctuators measured in large devices may average out interesting behavior of the individual fluctuations. Furthermore, the understanding of the effects of surface roughness, which was not a controllable parameter in this work, could lead to ways of decreasing noise. Additionally, other devices demonstrating the GMR effect may be better for probing the properties of thin ferromagnetic layers. Ferromagnetic tunnel junctions have increased sensitivity over spin valve devices and should be able to detect smaller magnetization fluctuations.
References


Appendix A