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MAGNETIZATION PRECESSION OF MAGNETIC THIN FILMS STUDIED BY ALL OPTICAL PUMP-PROBE TECHNIQUE.

by

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MAGNETIZATION PRECESSION OF MAGNETIC THIN FILMS STUDIED BY ALL OPTICAL PUMP-PROBE TECHNIQUE.

Steven A. Michalski, Ph.D.

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The study of magnetization dynamics such as magnetization precession and precessional damping provides insights into the behavior of complex magnetic systems, and indeed may lead to a better understanding of the fundamental limits of magnetic reversal process. In this work, a time-resolved magneto-optic Kerr effect system (TRMOKE) was developed to study magnetization dynamics: Precession and damping. The system uses a femtosecond laser in a pump-probe experiment with direct optical excitation, very similar to the method introduced by Ganping Ju and coworkers. Also, a model based on the Landau-Lifshitz-Gilbert equation (LLG) was developed and used to interpret and analyze the experimental magnetization precession data of a single magnetic layer. The model can be used to predict the precession frequencies with and without damping, the eigenvectors of the magnetization and allows the Gilbert damping parameter (α) to be determined. The model is extended to a system of two magnetic layers coupled through a nonmagnetic spacer layer. The capabilities of the TRMOKE system and the LLG models, were demonstrated by studying the magnetization dynamics of Ni/Pt bilayers.

Static and dynamic magnetic properties of exchange-coupled magnetic layers have been investigated by magneto-optical measurements. The samples are [Pt/Co] multilayers with perpendicular magnetic anisotropy (PMA) exchange-coupled to a Co layer with in-plane magnetic anisotropy. The exchange is indirect, realized and tuned by an intervening Pt layer of varying thickness. Both the strength and the angle of an external applied magnetic field were varied and for many samples, two modes with two distinct precession frequencies were observed in the precession measurements. The frequencies of both modes depend on the strength and the angle of the applied magnetic field. The LLG model predicts two precessional modes ("acoustic" and "optic") whose behaviors depend on the strength and sign of the exchange coupling. The model is in good qualitative agreement with the data and allows us to estimate the magnitude of the exchange coupling between the two layers.

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Chapter 1: Introduction

In today's technological world magnetic devices are used in televisions, computers, cars and almost every electrical device. In the future, magnetic materials and magnetic devices will continue to play an important part in technology from computer hard drives to new spintronic sensors and actuators. Improvements in technology require an improvement in the magnetic materials used in magnetic and electronic devices. A perfect example is the improved performance of magnetic hard drives. Due to the increasing demand to store and manipulate large amounts of data, the magnetic recording industry has dramatically increased the capacity and performance of magnetic hard drives. The hard drive capacity has increased due to new and novel magnetic materials [1-8], the introduction of new techniques such as perpendicular magnetic recording [8-14], and the discovery and application of Giant Magneto Resistance [15,16] (GMR). A GMR element (read head) consists of two ferromagnetic layers separated by a nonmagnetic layer. The electrical resistance of the element depends on the relative orientation of the magnetizations in the ferromagnetic layers. Since the orientation of the magnetization can be changed by an external magnetic field, for example as created by a closely placed magnetic domain wall, the GMR read head is a very sensitive magnetic field sensor. The increased sensitivity not only improved the read performance of the magnetic read head but allowed for an increase in the storage capacity of the hard drive by reducing the bit size required to obtain a good signal to noise ratio. This continued increase in performance of magnetic materials will lead to improvements in existing technology and will give rise to new technologies in the future.

The emerging field of spintronics has led to the development of new magnetic devices such as spin valves [16-25] which include GMR elements, magnetic random access memory (MRAM) [25-29], spin transistors [30-34], and spintronic biosensors [35-37]. Spintronics devices exploit the spin of the electrons not just the electrical charge. Spintronics devices work by encoding data into the spin of electrons. For example, spin-polarized electrons can be sent down a wire as current, and another spintronic device can read the spin information transmitted. This adds an extra degree of freedom in designing and producing new technologies.

As the amount of data continues to increase, hard drives and spintronic devices will need to be able to operate at fast speeds, which in turn requires a faster way to control the magnetization in the magnetic materials in those devices. This control can be complete reversal of the magnetization for magnetic hard drives or simply reorientation of the magnetization into a new stable state. For magnetic recording, the speed of writing magnetic data depends on the switching characteristic of the magnetic material used and the method used to produce a reversal of the magnetization. In last two decades, much research focused on developing techniques to increase the speed of complete magnetic reversal. Much of this research has focused on increasing the speed of reversal by using magnetic pulses. At first, magnetic pulses were produced by a coil or strip line circuit that was mechanically or lithographically produced and powered by a bank of capacitors. These systems could produce large pulsed field in a small area but were limited to pulse widths of about a nanosecond [38-40].

Recent advances in ultrafast pulsed lasers have lead to the development of pump-probe techniques to produce and utilize fast magnetic pulses in the study of

magnetization dynamics. In pump-probe experiments, the ultrafast laser pulse is split into two parts: Pump pulse and a probe pulse, with the pump pulse being used to perturb the system and the probe pulse to measure the subsequent properties of the system. Such experiments have provided unprecedented time resolution in the study of magnetization and electronic dynamics, and they are discussed in more detail in Chapter 4. A common technique developed by Freeman and others to generate picosecond magnetic pulses is to use a photoconductive circuit[41-46]. The circuits are usually strip line or coil geometries of copper or gold lithographically patterned onto semiconducting GaAs substrates. The pump pulse strikes the GaAs, temporarily making it a conductor and thus launches a current pulse which generates a magnetic field pulse. The probe pulse arrives later and measures the change in the magnetization induced by the magnetic field pulse using Faraday or Kerr magneto-optical effect. The magnetic fields produced by these methods can have pulse widths down to picoseconds if high quality low-temperature grown GaAs is used[47].

The development of fast magnetic pulses and the need to increase the write speed of hard drives and MRAM has lead to renewed interest in precessionally assisted magnetic switching[48-52]. In conventional magnetic reversal, a sufficiently large static magnetic field is applied in the opposite direction to the magnetization. This increases the internal energy of the system making it favorable for the magnetization to reverse. In precessional switching, a magnetic field pulse is applied which changes the equilibrium orientation of the magnetization which then can precess into the reversed direction. This process depends on the intrinsic precessional dynamics of the system. The advantage of this technique is the field pulses are fast and thus switching times can be fast. The

maximum reversal rate using this method would be one half of the precessional frequency, typically in the 10-100 GHz range[53-55]. One problem with this technique is the ringing of the magnetization. During the precession, the magnetization tends to oscillate between states (ringing) until the precession is stopped by damping or some other mechanism. Recently, precessional magnetic switching in soft magnetic materials such as permalloy has been observed[49,56-59] and control of the precession ringing has been demonstrated using another magnetic pulse to stop the precession[43,46,59,60].

It would be ideal to control the magnetization without a magnetic field. Recent research has opened up the possibility of controlling the magnetization using electric fields or direct optical pulses. Electric field control of the magnetization relies on using materials that exhibit the magnetoelectric effect such as multiferroics, which are materials that have both ferromagnetic and ferroelectric properties [61,62]. The magnetoelectric (ME) effect allows for the coupling of magnetic properties to an external electric field and couples the electrical properties to a magnetic field. Using the magnetoelectric effect, a magnetic bit could be written with an electric field instead of a magnetic field which could lead to faster memory. Partial control of the magnetization by an electric field has been observed in a composite thin film of Co/Pd – $Pb(Zr_xTi_{1-x})O_3$ by Kim *et al.* [63]. Magnetic control of the electric polarization has been demonstrated [64] and also electric field control of the exchange bias field has been reported [65] using ME materials.

Optical control of the magnetization also has very promising potential. Recent experiments show the optical pulses can give a rise to a rapid demagnetization of magnetic thin films [66-75], a reduction in magnetic anisotropy[76] and changes in the exchange coupling strength and exchange bias field of magnetic multilayers[77-79] on time

scales of a few picoseconds. All of these reports relied on the ultrafast heating of the electron, lattice, and spin systems of the magnetic material produced by a direct optical excitation to change the magnetic properties. The changes were not enough to induce a coherent reversal of the magnetization but such studies give insights into the magnetization dynamics. Another method of optical control has been proposed recently which relies on the inverse Faraday Effect[80-85]. The inverse Faraday effect produces an effective magnetic field pulse when an intense pulse of circularly polarized light passes through a magnetic material. The magnetic field strength is proportional to the intensity of the light pulse and Verdet constant of the sample[86]. This technique opens the possibility of controlling the magnetization on time scales equal to the pulse width of the optical pulse. Complete magnetization reversal of $Gd_{22}Fe_{74.6}Co_{3.4}$ has been observed using circular polarized 40 fs pulses by Stanciu *et al.* in reference 85.

All the methods presented here deal with increasing the speed of the magnetization reversal. The work presented in this dissertation focuses on studying the magnetization dynamics of thin film magnetic systems. Precession frequencies and damping are measured in order to get a better understanding of the fundamental limits of magnetic reversal process. Primarily the work here focuses on studying magnetization dynamics of magnetic layers separated by a nonmagnetic material. The intervening nonmagnetic layer provides indirect exchange-coupling between the two magnetic layers. Such materials are scientifically interesting and important in various areas of nanotechnology. Similar systems are already used in spin valve devices[16] such as field sensors, and such materials could be candidates for magnetic media for use in magnetic recording. The focus here is on spin-reorientation caused by competing magnetic

anisotropies, realized by exchange-coupling a Pt/Co multilayer structure with perpendicular magnetic anisotropy to a Co layer having the easy axis of the magnetization in the film plane. The interlayer exchange *J* is tuned by the varying the thickness of an intervening Pt spacer layer. This permits the control of magnetic properties by tuning exchange strength and perpendicular magnetic anisotropy, a feature of great practical importance.

In this study, we using an all optical pump-probe technique very similar to the method introduced by Ganping Ju *et al.* [77] who investigated the $Ni_{81}Fe_{19}$/NiO exchange-biased system. Our system uses direct optical excitation, which changes the magnetic properties both electronically and thermally. Chapter 2 will give a brief introduction into the experimental techniques use to fabricate and study the samples. Chapter 3 gives a detailed description of the Landau-Lifshitz-Gilbert based theoretical models used to guide the experiments and interpret the data. Chapter 4 presents the pump-probe optical and electronic setup in great detail and gives an example of how the system works by studying Ni/Pt bilayers. Chapter 5 presents the study of the magnetization dynamics of indirect exchanged-coupled [Pt/Co]-Co thin films. Chapter 6 will summarize the results presented here and give some ideas for future study.

Chapter 2: Experimental Procedures

The thin film samples studied in this work were prepared by magnetron sputtering. The micro-structures of the samples were measured by X-Ray Diffraction (XRD) and are consistent with Transmission Electron Microscopy (TEM) measurements. The magnetic properties were measured by an Alternating Gradient Force Magnetometer (AGFM) and a Magneto-Optical Kerr Effect (MOKE) system. This chapter will describe the basic operations and procedures for each of these systems while leaving any necessary details to the following chapters as needed. The magnetization dynamics were measured by an all optical pump-probe Time Resolved Magneto-Optical Kerr Effect (TRMOKE) system which is presented in detail in Chapter 4.

2.1 Sample Deposition

The samples were fabricated in one of two homemade magnetron sputtering systems. The first system was based on equipment obtained from the Dale Corporation (Dale), which includes two DC sputtering guns and one RF gun contained in a large vacuum bell jar. A water cooled diffusion pump (Varian 6") backed by a mechanical pump is used to produce a base pressure of 2-3 x 10^{-7} Torr. The other system is based on equipment received from the 3M Corporation (3M) and also contains two DC and one RF guns. The vacuum in the 3M system is achieved by a cryo-pump backed by a mechanical pump which gives base pressures normally in the 2-4 x 10^{-7} Torr range.

In both systems, sputtering was done in a 5 mTorr argon environment. Substrates were mounted on a water cooled table which can hold 12 samples per sputtering run. The rotational position of the sample table is controlled by a stepper motor connected to a PC. The chamber is pumped down for roughly 14 hours or until the desired base pressure is reached. Multilayered films are produced by moving the substrates to positions above each target gun to sputter the specific amount of material needed. A QuickBasic program controls the time the substrate stays above each target based upon the calibrated sputtering rates. The targets (Co, Pt, and Ni) used for these study were normally purchased from the Kurt J. Lesker company with a 99.95% purity.

The sputtering rates are calibrated by cutting aluminum foil into approximately 1 inch squares. The foils are cleaned in alcohol by an ultrasound for 10 minutes. The foils are then weighed at least twice using a microbalance with a sensitivity of 0.1μg. The foils are mounted to the substrate table and the chamber is pumped down to the base pressure. Then the target materials are sputtered onto 3-5 foils at different sputtering powers and different exposure times. The foils are weighed again and the difference in mass is due to the sputtered material. The sputtering rate R at a given sputtering power is given by

$$R = \frac{T}{\Delta t} = \frac{\Delta m}{\rho A \Delta t} \qquad (2.1)$$

for each target material. In equation 2.1 Δt is the sputtering time, Δm is the change of mass of the Al foil, A is the film area, T is the thickness of the sputtered material, and ρ is the density of the sputtered material, usually taken to be bulk value. Figure 2.1 shows the sputtering rate as a function of sputtering power for Pt, Co, and Ni targets, the lines

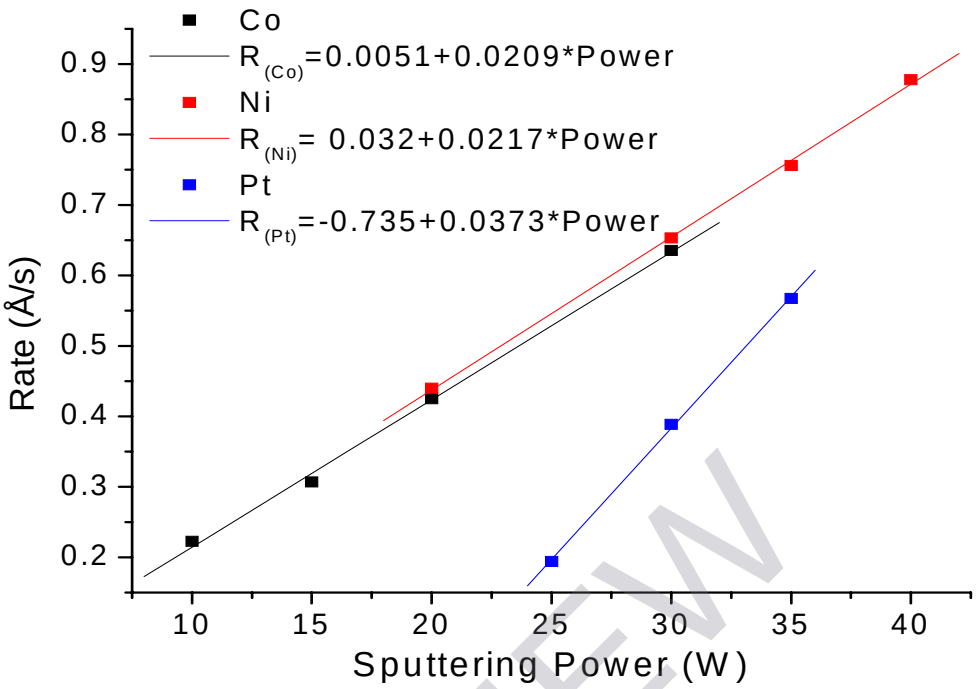

Figure 2.1 Sputtering rate as a function of the power of the sputtering gun for various targets.

represent the best linear fit to the data and the lines are used to calculate the rate at a given power.

2.2 Structural Characterization

The magnetic properties of the samples are dependent on the nanostructure of the sample; so, we need to understand the structure of the sample as much as possible. The nanostructures were measured by X-ray diffraction and transmission electron microscopy. X-ray diffraction was performed using a Rigaku DMAXB and a Bruker D8Discover