Microstrip Resonators for Microwave Spectroscopy of Ferromagnetic & Paramagnetic Spin Systems

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ABSTRACT

The primary objective of this project was to conduct spectroscopy in the microwave frequency range (~10 GHz) of ultra-thin films of cobalt (~5 nm thick films) and Diphenylpicryl-Hydrazyl (DPPH). A second objective was to evaluate the capacity of microstrip resonators for this application, including their sensitivity and quality factor. From such spectroscopy, one can determine the total spin of the samples and get insight into their atomic or molecular structure, magnetic interactions and energy level structure.

The microstrip resonators were lithographically patterned thin film structures of mm dimensions, with an unevenly split strip of gold. At resonance, the length of the smaller strip is half the radiation wavelength. Using these microstrips is advantageous because this AC magnetic field is concentrated near the smaller strip, where the sample materials are placed, and their resonance frequencies can be designed to be in the range of many magnetic materials.

Magnetic resonance was successfully observed on cobalt films. The dependence on thickness of cobalt was studied. Paramagnetic DPPH was also examined. In addition, information on feasibility and limitations of the use of microstrips for FMR on magnetic materials was investigated. Initial data demonstrate that microstrip resonators do have the desired capacity, but are sensitive to factors such as background dielectrics and position of sample.

BACKGROUND AND SIGNIFICANCE

The applications of my research are toward a new field known as spintronics. Electronics uses a fundamental property of electrons, their charge. The aim of spintronics is to also make use of another intrinsic characteristic of the electron--the fact that it has a magnetic moment or spin. Presently, we store data by the direction of the magnetic moment of small magnets in layers: the magnetic moment in these layers can be parallel or anti-parallel, which represent the binary system. We currently write data by applying a magnetic field. There are advantages to using a spin polarized current, instead, to produce the spin torque effect for writing data [1]. The first advantage is increased packing density (how many and how closely the magnets can be layered) and the second is that the devices would be more solid state (fewer moving parts, resulting in a longer life.) They would also be faster than devices that use magnetic fields. To make an efficient (low current density required) spin polarized current, we use ultra-thin magnetic
films. Therefore, we want to understand the fundamental physics of ultra-thin magnetic films.

Characteristics of interest in ultra-thin magnetic films are magnetization, (magnetic moment per unit volume), and magnetic anisotropy, both bulk and surface. Bulk anisotropy is related to the concentration of the magnetic moments per unit volume. Surface anisotropy is related to the amount of surface relative to the volume of the sample. A ferromagnet has a large number of ordered electron spins. Each spin has a magnetic moment given by \( m = -g\mu_B S \), where \( S \) is the spin, \(-g\) is the spectroscopic splitting factor, which is a constant that depends on the ordering (\( g = 2 \) for free electrons), and \( \mu_B \) is the Bohr magneton, which in terms of fundamental constants is \( \frac{e\hbar}{2\pi m} \).

The primary objective was to conduct spectroscopy in the microwave frequency range (~10 GHz) of ultra-thin films of cobalt (~10 nm thick films) and Diphenylpicryl-Hydrazyl (DPPH). The second objective was to evaluate the capacity of microstrip resonators for primary objective, including their sensitivity and quality factor. From this spectroscopy, one can get insight into the atomic or molecular structure of a sample, magnetic interactions, and its energy level structure. Our samples include ultra-thin magnetic films.

MATERIALS AND METHODS

FMR (Ferromagnetic Resonance) is the phenomenon that I used to carry out spectroscopy of ultra-thin films of cobalt. ESR (Electron Spin Resonance) was used to perform spectroscopy of the paramagnetic DPPH. FMR is similar to the more well known NMR (nuclear magnetic resonance) used in MRI machines. In NMR, a static magnetic field is applied to align the nuclear spins of the atoms. A perpendicular oscillating magnetic field is absorbed strongly when its frequency is at resonance. In FMR (or ESR), the analogy of nuclear spin is the magnetic moment, \( m \), (or electron spin).

For FMR, if a sample is in the static magnetic field, all the magnetic moments behave alike. Therefore, one can consider a single equivalent magnetic moment. In this static magnetic field, the equivalent magnetic moment has states of lower energy and of higher energy.

There are two applied fields: the static field, and the oscillating field, which is at a frequency \( \omega \). The static field aligns and determines the energy level separation, (this could be represented on an Energy Level Diagram with \( E = 2g\mu_B S\hbar = 2\gamma \hbar BS \), where \( \gamma \) = gyro-magnetic ratio). The oscillating field provides energy \( (E = \hbar \omega) \) to cause transitions between these energy levels. The separation in energy, and the energy provided, need to be the same in order to be absorbed. The frequency of the oscillating magnetic field, \( \omega \), when there is absorption, is called the resonance frequency.

The experimental setup consisted of a magnet, microstrip, and PNA (Network Analyzer). The magnet applies the static magnetic field of different strengths. The PNA sends an oscillating current through the microstrip. All currents have a magnetic field around them. Hence, the PNA applies the oscillating magnetic field. The PNA also measures the absorption of the oscillating magnetic field. The strength (frequency) of the applied static magnetic field was swept, while the applied oscillating magnetic field was...
held constant near the resonance frequency of the microstrip, until the absorption was found. The frequency of the static magnetic field when there is absorption, is $B_{res}$.

Microstrip resonators have advantages for high frequency spectroscopy, as compared to a standard cavity. They have a better filling factor (volume of sample divided by the volume of the fields), and the size of the resonator is smaller than the size of the needed cavity (at low frequencies). Also, the same resonator can be used for different harmonics of the resonance frequency [2].

We designed two microstrips to have a resonance frequency of about ten and fifteen GHz. The microstrips consisted of five layers (from bottom to top): surfaces of gold (200nm), platinum (1.5nm), gallium arsenide (.5mm), platinum (1.5nm), and an unevenly split strip of gold. The microstrip was placed in a rectangular brass cavity. There was an outside wire connection to the longer of the split strips, which was soldered. This device produced an electromagnetic wave at its resonance frequency, a function predominantly of the length of the smaller strip. The length of the smaller strip is about half the frequency of the field emitted. Using these microstrips is advantageous because their resonance frequencies are in the range of many magnetic materials.

Two types of samples were investigated: ultra-thin magnetic films of ferromagnetic cobalt, and a paramagnetic powder of DPPH (a molecular system of spin $\frac{1}{2}$). The thicknesses of the cobalt layers for the five samples were: 50, 30, 10, 8, and 6 nm. Three of out of the five cobalt samples had dimensions of: platinum (5nm), copper (30nm), cobalt (X nm), copper (30nm), platinum (5nm), where X was 10, 8, and 6 nm. They were on a gallium arsenide substrate. The two other cobalt tri-layers samples had dimensions of: platinum (2.5nm), copper (30nm), cobalt (X nm), copper (30nm), platinum (2.5nm), where X was 50 and 30 nm, and were on sapphire substrate (Al2O3) about 500µm thick. The DPPH sample is an organic compound which has an unpaired valence electron at one of the nitrogen bridges. This is the source of the paramagnetism.

The fabrication of the microstrips was accomplished in our lab using evaporation in an ultra-high vacuum thin film deposition system. The lift-off process used a single photoresist, a light sensitive polymer.

Characterizations of microstrips with different configurations were done. The microstrips used had resonance frequencies close to the expected values. The resonance frequency coming from the smaller strip, “resonator,” was found by placing a cobalt film and, separately, a gallium arsenide wafer, which shifted only the emission from the resonator, distinguishing this from background emission. Possible causes of the background emission were from the longer strip, and from the soldered connection point. (See Figure 1 in the appendix.)

RESULTS

My results show that microstrip resonators are sensitive enough to conduct spectroscopy in the microwave frequency range on ultra-thin films. This was deduced from the spectroscopic results achieved on the aforementioned cobalt samples with the ~10GHz and ~15GHz microstrips. (See Figure 2 for one of these results.) It should be noted that the magnitude, real, and imaginary portions of the absorption, is graphed because most of the results for the magnitude absorbed did not give a Lorentzian or a differential, but a combination of both. For these cases, the real and imaginary
components would give a Lorentzian and a differential, (or vice-versa), demonstrating $\chi'$ and $\chi''$ components of the susceptibility.

In addition, my results suggest that microstrip resonators are sensitive enough to conduct spectroscopy in the microwave frequency range on paramagnetic materials similar to DPPH. This was deduced from the spectroscopic results achieved on the aforementioned DPPH sample with the $\sim$10GHz microstrip. (See Figure 3 for one of these results.)

From the spectroscopy that was conducted on the cobalt samples, a thickness dependence of the frequency of the static magnetic field, $B_{\text{res}}$, was found (see Figure 4.)

**DISCUSSION**

We can interpret the thickness dependence in Figure 4 with the following equation [3, Chapter 16]:

$$f = \left(\frac{\gamma}{2\pi}\right)\left[B_{\text{res}}(B_{\text{res}} + 4\pi M_{\text{eff}})\right]^{1/2}$$

This equation applies for a thin film with the static field in the plane of the film, where $B_{\text{res}}$ is the resonance frequency of the applied static magnetic field, $f$ is the frequency of the applied oscillating magnetic field (i.e. the magnetic moments precess at this frequency), and $\gamma$ is the gyroscopic ratio for a specific structure and sample. Therefore, $f$, $\gamma$, and $2\pi$ are at constant values. Note that $M_{\text{eff}}$ decreases as $B_{\text{res}}$ increases only for small $B_{\text{res}}$. Figure 5 shows $M_{\text{eff}}$ vs. thickness. This shows a general decrease in $M_{\text{eff}}$ as the thickness decreases.

$M_{\text{eff}}$ is the “Effective Magnetization,” and is the difference between $M_s$ and $B_u$. (The exact equation is $4\pi M_{\text{eff}} = 4\pi M_s - B_u$.) $M_s$ is the “Saturation Magnetization,” and is related to the concentration of the magnetic moments per unit volume. $B_u$ is the “Uniaxial Anisotropic Field,” and is related to the amount of surface anisotropy relative to the volume. Therefore, the thickness dependence of the effective magnetization is probably caused by $M_s$ or $B_u$.

If it was caused by $M_s$ the saturation magnetization (the magnetic moment per unit volume of a uniformly magnetized material), one may expect it to be the result of a mixing of cobalt and copper at the interfaces, causing the density of magnetic moments, the magnetization, to decrease near the interfaces. It then makes sense that the relation shown should be that $M_s$ is decreasing as the thickness decreases; this general relation was seen.

If the thickness dependence of $M_{\text{eff}}$ was caused by $B_u$, (known as “Surface Anisotropy”), one may expect it to be because the thinner the film, the greater the ratio of the surface to the volume, causing $B_u$ to increase as the thickness decreases; this general relation was seen.

A more accurate relation for the thickness dependence of $M_{\text{eff}}$ is found from the equation:

$$4\pi M_{\text{eff}} = 4\pi M_s - B_u = 4\pi M_s - (2K_u/M_s)(1/t)$$

This equation describes how surface anisotropy would change the effective magnetization, $M_{\text{eff}}$. If $K_u > 0$ ($< 0$) then the sample has uni-axial in-plane (out-plane) anisotropy. From the equation, the graph of $4\pi M_{\text{eff}}$ vs. $1/$thickness gives a roughly linear
dependence, where $4\pi M_s$ is the y-intercept and $2K_u/M_s$ is the slope. The experimental results imply this (see Figure 6).

CONCLUSIONS

Surface Anisotropy is a possible cause of $M_{\text{eff}}$ decreasing as the thickness decreases, but it is not a unique solution; a bulk contribution is possible.

Microstrip resonators are sensitive enough to conduct spectroscopy in the microwave frequency range on ferromagnetic ultra-thin films and the paramagnetic samples.

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REFERENCES


APPENDIX

Figure 1: Characterization of a ~10GHz microstrip with and without a cobalt load, used to find the resonance frequency of the resonator.
Figure 2: Results from spectroscopy of an 8nm Co sample with ~10GHz microstrip.
Figure 3: Results from spectroscopy of the DPPH sample with ~10GHz microstrip.
Figure 4: Thickness dependence of $B_{\text{res}}$ for cobalt samples.
Figure 5: Thickness dependence of $M_{\text{eff}}$ for cobalt samples.
Figure 6: A linear 1/thickness dependence of $M_{\text{eff}}$ is visible for cobalt samples. $4\pi M_s = 17$ kGauss; $K_u = -0.7877 \text{ erg/cm}^2$; perpendicular (out-plane) anisotropy is observed.

The following is an explanation of the unit converting from $[\text{G}^2 \cdot \text{cm}]$ to $[\text{erg/cm}^2]$, which is involved in calculating $K_u$. The equation of the linearly fitted line is:

$$4\pi M_{\text{eff}} = 4\pi M_s - \left(\frac{2K_u}{M_s}\right)(1/t)$$

$$4\pi M_{\text{eff}} = 17443 \text{ Gauss} - (11350 \text{ Gauss nm})(1/t)$$

Then $M_s$ is found to be:

$$4\pi = 12.57$$

$$M_s = \frac{17443 \text{ Gauss}}{4\pi} = 1388 \text{ emu/cm}^3 = 1.388 \times 10^3 \text{ emu/cm}^3$$

Next $K_u$ is found to be:

$$2K_u/M_s = 1.1350 \times 10^4 \text{ Gauss nm}$$

$$K_u = 1.1350 \times 10^4 \text{ Gauss nm} \left(\frac{1.388 \times 10^3 \text{ emu/cm}^3}{1/2}\right)$$

$$K_u = 7.9 \times 10^6 (\text{G*nm*emu})/\text{cm}^3 = 7.9 \times 10^6 (\text{G*10}^{-7}\text{cm*emu})/\text{cm}^3$$

$$K_u = 0.79 (\text{G*emu/cm}^2)$$

Note that because:

Energy/Volume = Magnetization Density * Magnetic Field (i.e. $E = \mu \cdot H$--$E/\text{Vol.} = M \cdot H$)

Therefore, it is a given that: $1 \text{ G} = 1 \text{ emu/cm}^3$

It is also given that $1 \text{ emu} = 1 \text{ erg/G}$:

$$K_u = 0.79 \text{ erg/cm}^2$$

This corresponds to perpendicular anisotropy.