AC Susceptibility and Anisotropic Magnetoresistance: A Study of Thin Magnetic Films

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BY

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Abstract

The differential ac magnetic susceptibility of thin magnetic films was determined using the anisotropic magnetoresistance (AMR) to measure the response of the magnetization to an applied ac magnetic field. The ac susceptibility was measured as a function of an applied dc magnetic field. The frequency of the applied ac field was varied between 5Hz to 5000Hz. The ferromagnetic films investigated were permalloy, cobalt, nickel, and nickel with an antiferromagnetic nickel oxide layer on one surface. For all the samples investigated, the differential susceptibility magnitude was a function of the dc field magnitude and was frequency dependent, decreasing with increasing frequency.

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Foreword

This thesis details research into using the anisotropic magneto-resistance (AMR) of thin metal films to measure the ac susceptibility of these films; part of the work has been submitted for publication. A version of the submitted paper with small edits is included here as the main body of this work. The appendices contain additional experiments and data with some discussion. We will now present the submitted work.

Determining the AC Susceptibility of Thin Metal Films Using AMR

Synopsis

The differential ac magnetic susceptibility of thin magnetic films was determined using the anisotropic magnetoresistance (AMR) to measure the response of the magnetization to an applied ac magnetic field. The ac susceptibility was measured as functions of both the magnitude of a dc field and the frequency of the applied ac field from 5Hz to 5000Hz. The ferromagnetic films investigated were permalloy, cobalt, nickel, and nickel with an antiferromagnetic nickel oxide layer on one surface. For all the samples investigated, the differential susceptibility magnitude was a function of the dc field magnitude and was frequency dependent, decreasing with increasing frequency.

Researchers have used the anisotropic magnetoresistance (AMR) to determine the magnetic susceptibility of ferromagnetic films [1, 2, 3] to model magnetic noise with the fluctuation dissipation theorem. These studies were limited in the applied field magnitudes and the frequencies of the applied ac magnetic fields. The question arises as to the sensitivity of the susceptibility to both the frequency and magnitude of the applied field. To answer this question, we measured the resistance at room temperature of thin ferromagnetic films with a relatively small ac magnetic field applied while sweeping the dc magnetic field as a function of the ac field frequency. From these AMR data we have determined the real and imaginary components of the ac magnetic susceptibility. We investigated permalloy, cobalt, nickel, and nickel oxide coated nickel films. The ac field frequencies ranged from 5Hz to 5kHz with a field magnitude of 1 Oe. As expected, we found the magnetic susceptibility varied significantly over the range of dc magnetic fields less than the saturation field. We also found the susceptibility at any given field was frequency dependent with the real part of the susceptibility decreasing with increasing frequency and the imaginary part increasing. We will first discuss the sample preparation, measurement process and the analysis model. This will be followed by our results and discussion and end with a brief summary.

For the sample construction a simple deposition mask was made by coating silicon nitride surfaced silicon wafer squares, 1 cm on a side, with nitrocellulose. A four terminal transport layout was carefully scribed in the nitrocellulose coating creating a deposition mask. In general, the films were approximately 2 mm long and 500 microns wide with four extensions for the four-terminal measurements of the resistance. The four different ferromagnets, permalloy, cobalt, nickel, and nickel with a thin nickel oxide layer, were dc sputtered onto the substrates and the excess film removed by dissolving the nitrocellulose in acetone. The thickness of the films was on the order 100 nm thick except for cobalt, which was about 40 nm thick. The film deposition included a 5 nm seed layer of tantalum to improve adhesion and a 5 nm capping layer of ruthenium to prevent oxidation. The sample with the antiferromagnetic nickel oxide layer was created by omitting the ruthenium capping layer and allowing the nickel surface to oxidize. A total of 10 films were made and measured.

For the susceptibility measurements a dc current, *I*, was passed through the sample and external colinear ac and dc magnetic fields were applied both perpendicular and parallel to the length of a given sample. The results for the two field configurations were similar and only the results for the dc and ac fields perpendicular to the film length, i.e perpendicular to the current, are discussed here.

For an analysis of the results, we consider a sample with the magnetization along the length of the film and the ac and dc magnetic fields perpendicular to the length; the magnetization process is by rotation.

For the perpendicular geometry we have chosen for illustration, the perpendicular differential ac magnetic susceptibility, $\chi_\perp$, is defined as

$$\chi_\perp = \frac{dM_\perp}{dH} \approx \frac{\Delta M_\perp}{H_{ac}} \qquad (1)$$

where $\Delta M_\perp$ is the change in magnetization in the perpendicular direction and H_{ac} is the magnitude of the external ac magnetic field. A rotation of the magnetization from parallel to perpendicular to the current produces a change *dR* in the sample resistance via the AMR. We can relate the AMR induced *dR* to $M_\perp$ quantitatively by starting with an expression for the AMR [4] given by

$$R = R_{\perp} + \delta R cos^2\theta \tag{2}$$

where *R* is the measured resistance, $\delta R = R_{\parallel} - R_{\perp}$, $R_{\perp}$ and $R_{/\!/}$ are the measured resistances when the magnetization is saturated perpendicular and parallel to the current respectively, and θ is the angle between the net magnetization and the current. Under the influence of the ac magnetic field, the magnetization, *M,* oscillates by an angle $\Delta\theta$ and this gives a ΔR which we approximate as

$$\Delta R = \delta R(cos^2(\theta + \Delta\theta) - cos^2(\theta - \Delta\theta))$$

$$= -4\delta R cos\theta sin\theta sin\Delta\theta \tag{3}$$

where, given $\Delta\theta$ is small, we set a term $cos\Delta\theta = 1$ in this expression.

Similarly, with $M_{\perp}$= Msinθ for the same θ as for the AMR, for a $\Delta\theta$, we have

$$\Delta M_{\perp} = M(sin(\theta + \Delta\theta) - sin(\theta - \Delta\theta)) = 2M cos\theta sin\Delta\theta. \tag{4}$$

If the ac field oscillates at a frequency ω with a dc current, *I*, in the sample, then the oscillating voltage due to the ac field, V_{ω}, is

$$V_{\omega} = I\Delta R. \tag{5}$$

By combining Eqns 1, 3, 4, and 5, we find χ is given by

$$\chi = -\frac{V_{\omega}M}{2I\delta R H_{ac} sin\theta}. \tag{6}$$

Of course for the determination of the real part of the susceptibility, χ', one uses the in-phase component of the V_ω and for the imaginary part, χ'', the out-of-phase component.

Each sample was mounted in a solenoid for the ac field and a larger Helmholtz pair for the dc field. For all the differential susceptibility measurements, the ac field was held at 1 Oe and the dc field was swept in the range of -60 to +60 Oe. To determine the value of θ during a measurement, the dc voltage of the sample was measured during the field sweeps and θ determined using the expression for the AMR, Eqn 2. A comparison to a significantly less noisy method of measuring of the field-dependent resistance, using a standard ac bridge technique with a frequency of about 500Hz during a field sweep, produced consistent results. Given this, the lower noise ac measurement was used to calculate θ. A two-phase lock-in amplifier (Stanford Research 830) was used to measure the components of V_ω that were in-phase and out-of-phase with the ac magnetic field, which were V_ω' and V_ω'', respectively. From these measurements and our calculated θ, the real and imaginary components of the susceptibility, χ' and χ'', were determined using Eqn 6.

Due to the large size of our samples, the films are not single domain in zero applied dc magnetic field [5] and as a consequence, the total AMR of the sample is not observed, but rather about 60%.[6] In spite of this, the above analysis is sufficient to evaluate a differential susceptibility just as it would in other measures.

For the presentation of our results we will provide the data for the Ni films as it is representative of all data taken except where noted.

As stated earlier, the differential susceptibility measurements were taken by applying a dc current, I, and measuring the ac voltage, V_ω, at the frequency of the applied ac magnetic field. Typical results of this measured V_ω from a dc field sweep from -60 Oe to +60 Oe are shown in Figure 1 for two frequencies. Although not shown, measurements in the opposite field sweep direction, +60 Oe to -60 Oe, are a mirror image of the data in Figures 1a and 1b, as expected. By comparing the data for the two frequencies in Figures 1a and 1b, it can be seen that V_ω' is much larger than V_ω'' and both of these components are frequency dependent. Figure 1c shows a more extensive exploration of the frequency dependence for the two components of the susceptibility for zero applied dc field.

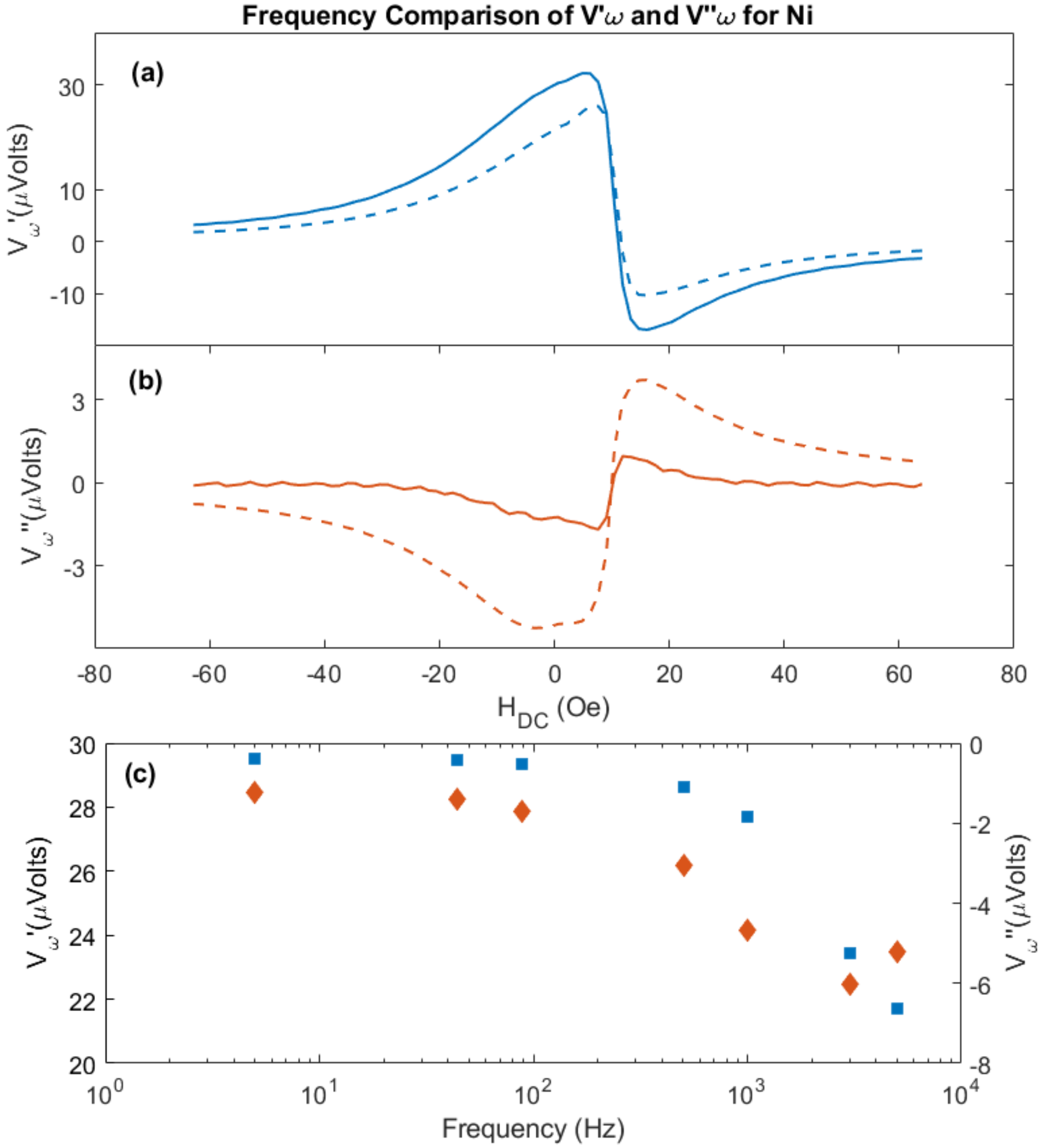

Figure 1: The magnetic field dependence of V_{ω}’ (a) and V_{ω}’’ (b) are shown. The quadrature components, V_{ω}’ and V_{ω}’’, are related to χ’ and χ’’ by Eqn 6. For these measurements, the applied ac field frequency was 5Hz(solid curve) and 5kHz(dashed curve). The dc field was swept from -60 to +60 Oe. In (c) is shown the frequency dependence of V_{ω}’(squares) and V_{ω}’’(diamonds) for zero dc field; note the negative y-axis scale for V_{ω}’’ indicating V_{ω}’’ increases in magnitude while V_{ω}’ decreases with increasing frequency. For all measurements, the applied ac field was 1 Oe.

The higher frequencies would be expected to have reduced values of V_ω'.[7] On the other hand. since χ'' is a measurement of the energy losses, it is expected that χ'' (and thus V_ω'') should increase in magnitude as frequency increases. Both expectations are corroborated by our measurements, as shown in Figure 1c. The general shape of the measured field dependent voltages for Py, Ni, and Ni capped with NiO was the same. The Co sample had a response with more structure in it, which we attribute to a more complex domain structure as a function of the dc field.

Figure 2 shows the results of the field dependence of the resistance of the Ni sample with an ac current and no applied ac magnetic field. In otherwords, this is a usual AMR measurement. As expected for Ni from Eqn 2, a resistance minimum occurs at high dc fields ($\theta \approx \pi/2$) and a maximum occurs at low dc fields($\theta \approx 0$); the data were corrected for a small drift in the signal over a hysteresis cycle. For the minimum fields shown,a θ angle of 0 is not obtained and a comparison to the expected value indicates the minimum angle is about 8° less than 0. From these data θ was determined.

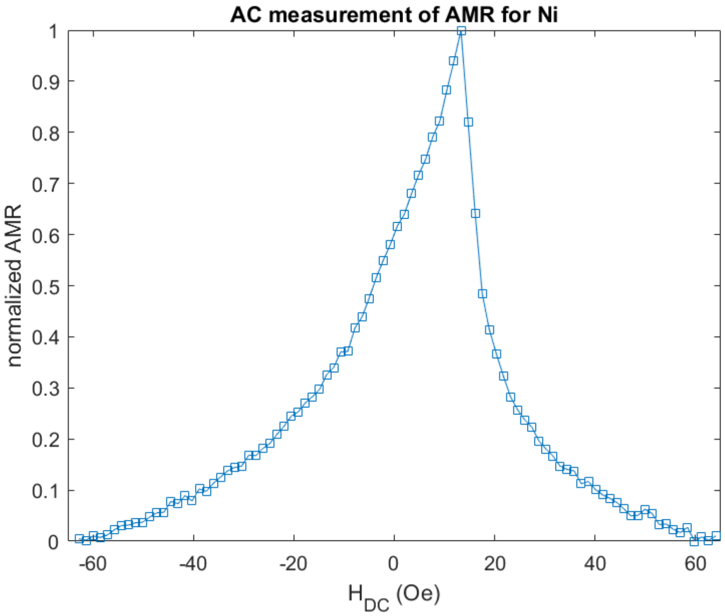

Figure 2: The AMR of nickel for an ac current applied to the sample at a frequency of about 500Hz is shown above by the percent change of ac voltage as a function dc magnetic field. The smallest percent change occurs when the magnetic domains align perpendicular to the sample current and the largest percent change occurs when the magnetic domains align parallel to the sample current. The dc field was swept from -60 Oe to +60 Oe.

Having determined θ, χ' and χ'' for the nickel sample were calculated using the measured field dependencies of V_ω' and V_ω'' in Figure 1 and Eqn. 6. The results of these calculations are shown in Figure 3.

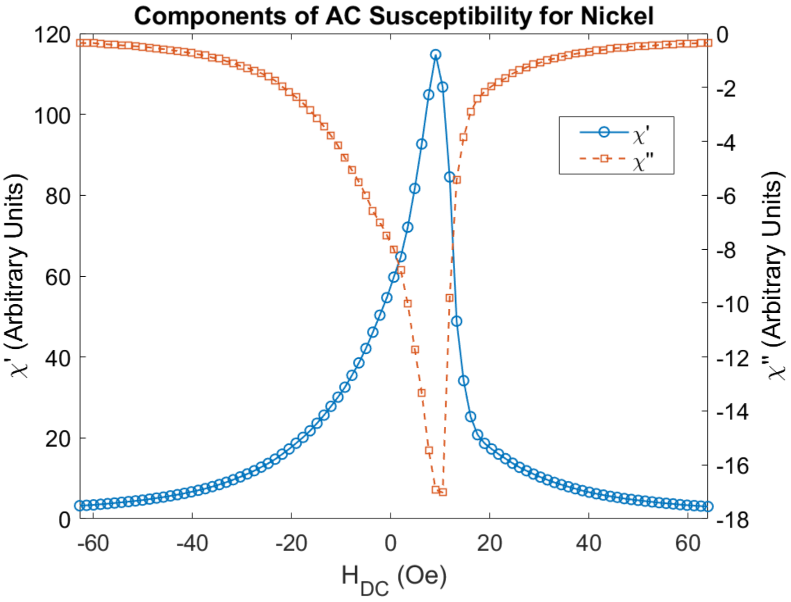

Figure 3: Plot of the dc field dependence of χ′(solid line) and χ′′ (dashed line) for the nickel sample. The scale for the χ′ data is to the left and the scale for the χ′′ is to the right. For these measurements, the applied ac field was 1 Oe at about 500Hz and the dc field was swept from -60 Oe to +60 Oe. Although measured in arbitrary units, the relative values of χ′ and χ′′ are correct.

Examining Eqn 6 indicates caution must be taken evaluating χ' at $\Delta\theta = 0$ due to the $sin\theta$ term in the denominator. In a single domain structure, this discontinuity is expected to disappear because V_ω should also be zero at $\theta = 0$. In our case with the complex domain structures in the films, an offset to θ was introduced to remove a divergence. For the data shown in Figure 3, this offset was 8°.

We have expanded our understanding of the use of AMR to measure χ' and χ'' in thin magnetic films. Our results indicate caution should be exercised in using the AMR for complex susceptibility measurements, such as for use with the fluctuation dissipation theorem. In general, measurements of χ' and χ'' must consider the field and frequency dependence.

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6. This was determined by comparing the resistances with a saturating field colinear and perpendicular to the sample current.

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Appendices

Introduction

We performed several experiments that were not included in the paper we submitted for publication. These additional experiments followed the central theme of our research. The results of these experiments are included in these appendices. We first discuss results related to the AMR of our samples and then later discuss results related to the ac susceptibility.

Appendix 1: AMR

Similar to the results shown in Figure 2, we performed AMR measurements for all four metal samples (Py, Co, Ni, and Ni with a NiO layer) under various conditions. For the measurements presented here, the dc field and ac field were both perpendicular to the sample current and a dc current through the sample was 10mA was flowing through the sample. The ac field had a frequency of 1kHz and a magnitude of 1 Oe. The dc field was swept between ±60 Oe (±38 Oe for Py). In addition, the field dependent AMR was measured by recording the dc voltage across the sample with a DVM as a function of dc field. As stated previously, the resistance will have a minimum when a saturating field is applied perpendicular to the current. Figure A1 shows the results of these measurements as the dc field was swept from positive saturation to negative saturation.

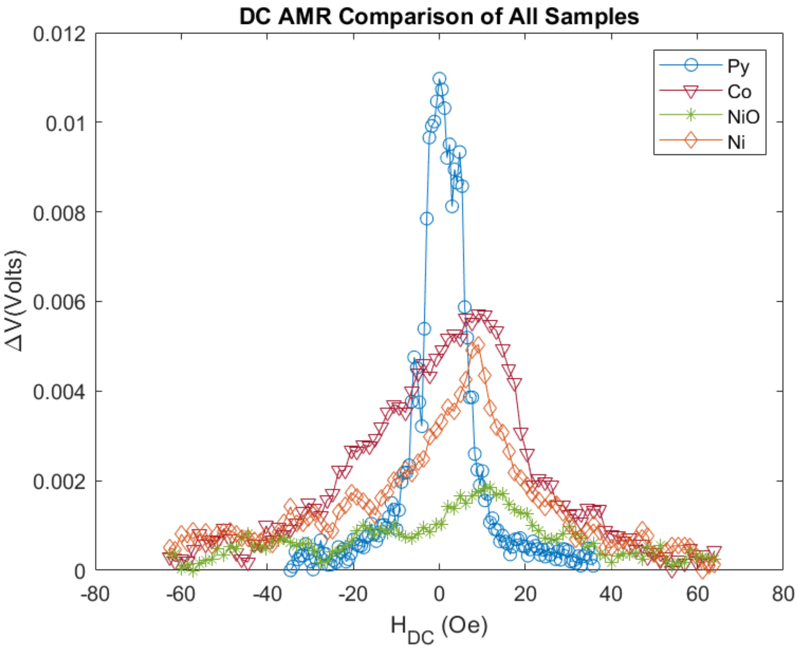

Figure A1: Plot of DC measurement of AMR for all four films studied. For these measurements, the magnitude of the applied ac field had a frequency of 1kHz and a magnitude of 1 Oe.

The four metals exhibited similar AMR behavior, with Py showing the strongest response and NiO showing the weakest. The peaks occur roughly at the coercive field for each metal and are offset from zero dc field as expected for a M-H loop. The hysteresis for Ni is demonstrated directly in Figure A2 that has data for both dc sweep directions. As shown, the location of maximum ΔV switches from about +/- 13 Oe depending on the direction the dc field is swept.

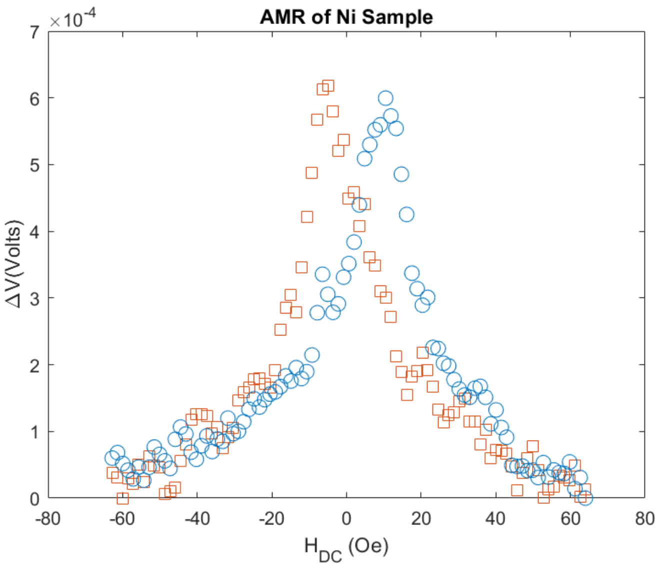

Figure A2: Hysteresis of the Ni sample. The AMR response for when the dc field is swept from +60Oe to – 60Oe(red squares) is a mirror image of the response for when the dc field is swept from -60Oe to +60Oe (blue circles).

The effect of the sample current was also examined. Although not presented here, data was taken for different magnitudes of sample current with no differences in the field dependent responses. Additionally, we took data when putting an ac sample current of 10mA across the sample. For those measurements, we read a sample's voltage using a lock-in amplifier. A comparison of the ac current and dc current data is shown in Figure A3.

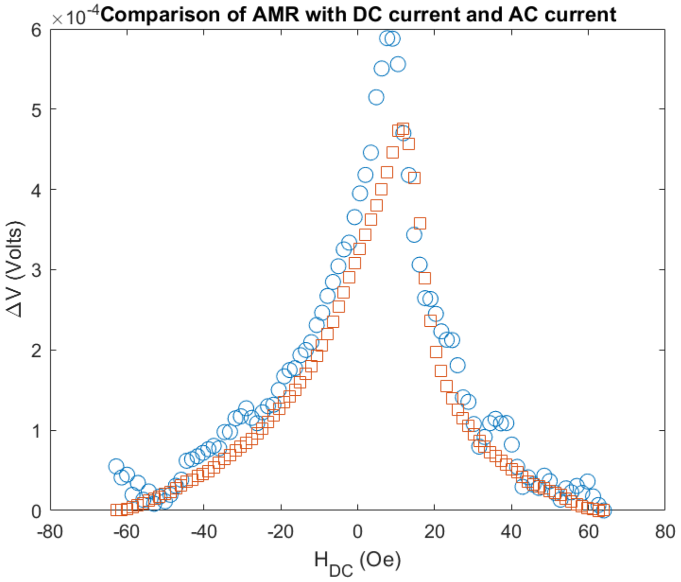

Figure A3: A comparison of the AMR response of Ni when a dc current (blue circles) and an ac current (red squares) is running through the sample.

The ac current and dc current exhibited very similar behavior, though the former was less noisy and was thus chosen when determining θ for the χ’ and χ’’ calculations.

To compare our results to traditional M vs. H data, the ac AMR data for Ni was integrated in order to determine the magnetization of the sample, with both increasing and decreasing magnetic field; Figure A4 shows the results of this integration for the Ni data.

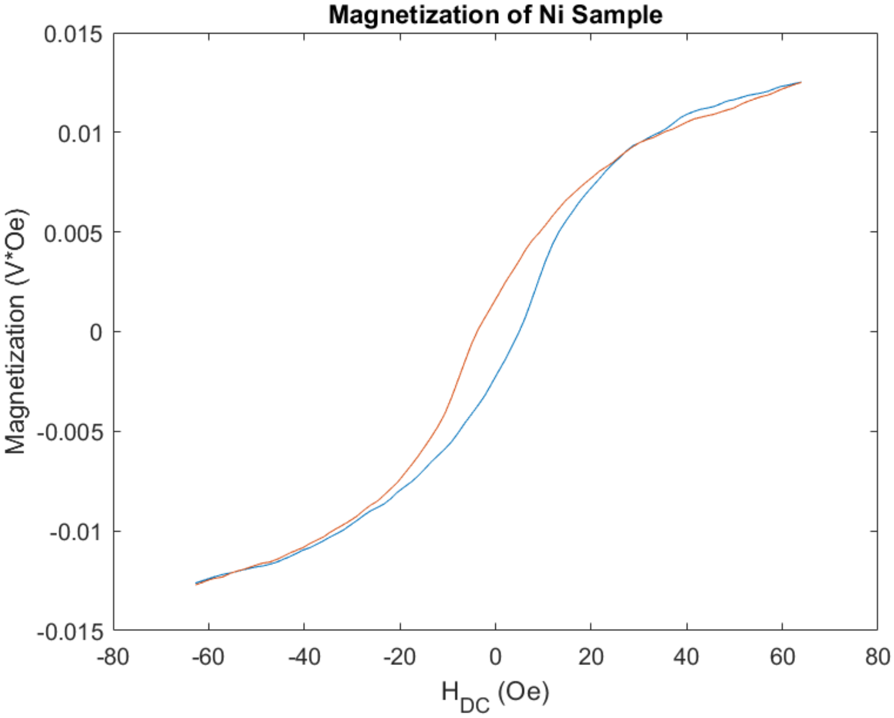

Figure A4: Plot of the calculated hysteresis curves for the Ni sample based on the ac AMR measurements. The negative dc sweep (blue line) and positive dc sweep (red line) should form a closed loop.

Appendix 2: AC susceptibility

To calculate χ' and χ'', the components of the voltage across the sample oscillating at the frequency of the applied ac field, V'_ω and V''_ω, were measured using a lock-in amplifier. The magnetic field configuration and the dc sample current for these measurements were the same as the AMR measurements. Though the main text showcases the data for the Ni, the other three samples (Py, Co, and Ni with NiO capping layer) were also heavily studied and a comparison of these sample is shown below.

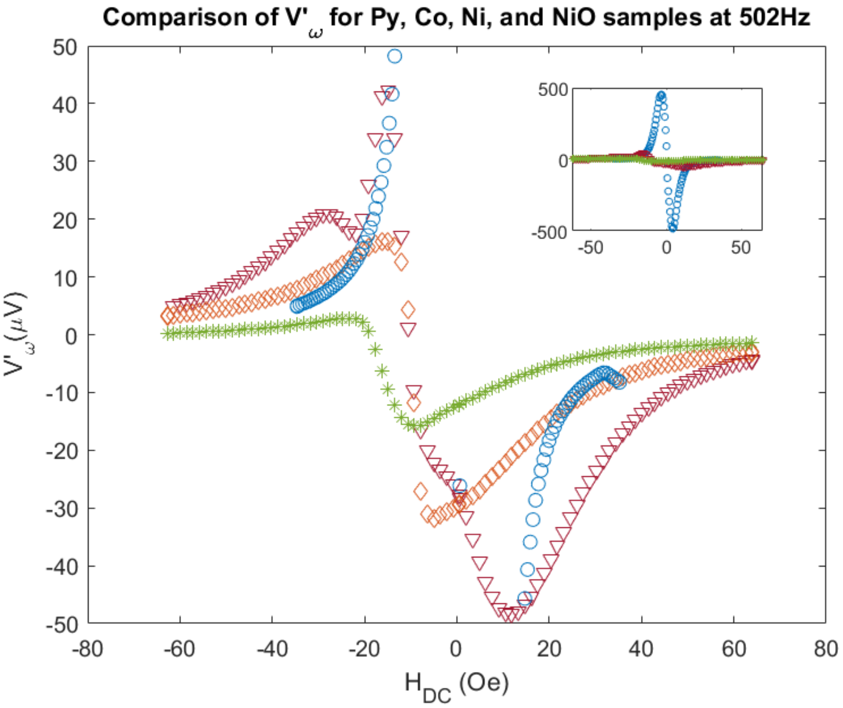

Figure A5: Comparison of Vω' for all samples. Py(blue circles) had the largest response, followed by Co(red triangles), Ni(orange diamonds), and NiO(green starbursts). For readability, the full range of the Py response was placed in the subplot.

Figure A5 shows a comparison of V'$_\omega$ for all the metals studied. Since the ac field was very small, the shape of these data is proportional to the derivative of the AMR data.