# Anomalous Hall Effect Magnetometry – A Method for Studying Magnetic Processes of Thin Magnetic Films

J. R. Lindemuth[a], B. C. Dodrill[a] and N. C. Oldham[b]
[a]Lake Shore Cryotronics, Inc.
575 McCorkle Blvd, Westerville OH, 43082, USA
[b]California Institute of Technology
Caltech Mail Code 128-95, Pasadena CA, 91125, USA

## Introduction

The Hall effect is a very powerful tool for characterizing materials. In addition to the ordinary Hall effect (OHE) that is present in semiconductors and metals, there is an additional voltage proportional to the magnetization[1] called the anomalous Hall effect (AHE) in magnetic materials. The AHE has been recognized as a useful tool for measuring the magnetic hysteresis M(H) loops of perpendicular magnetic recording media (PMRM), ferromagnetic/semiconductor heterostructures (spintronic devices), and diluted-magnetic-semiconductors. The AHE technique has shown particular utility for characterizing double-layered PMRM since the loops for both the recording layer (RL) and soft under layer (SUL) may be measured simultaneously, a task not easily accomplished using conventional magnetometers because of the difficulty associated with extracting the properties of the RL and SUL individually[2,3]. We have conducted a systematic study of the magnetic properties (hysteresis loops and Henkel plots) using both a Vibrating Sample Magnetometer (VSM) and an AHE magnetometer for double-layered PMRM, and Co/Cr thin film heterostructures in an effort to correlate results and further develop the AHE technique.

## Method

To fully investigate the details of the magnetic properties, processes, and interactions magnetic measurements other than just hysteresis loop measurements are required, such as DC demagnetization (DCD), isothermal remanent magnetization (IRM), Henkel plots, Curie point measurements, minor hysteresis loops and magnetic viscosity. We have measured hysteresis loops and Henkel plots for double-layered PMRM and Co/Cr thin film heterostructure samples using both a Vibrating Sample Magnetometer (VSM) and an AHE magnetometer. In a Hall effect measurement there are three Hall voltage ($V_H$) components,

1) $$V_H = (R_H I/t)B\cos(\alpha) + (\mu_o R_s I/t)M\cos(\theta) + (kI/t)M^2\sin^2(\theta)\sin(2\phi)$$

where t = film thickness, and the angles $\alpha$, $\theta$ and $\phi$ are defined in figure 1. The first term in equation (1) is the ordinary Hall effect (OHE) and arises from the Lorentz force acting on conduction electrons. The OHE depends on the z-component of the **B** field, and produces an electric field perpendicular to $B_z$ and the current density. The second term is the anomalous Hall effect (AHE) and arises due to spin dependent scattering mechanisms. The AHE depends on the perpendicular component of **M**, and produces an electric field perpendicular to $M_z$ and the current density. The last term in (1) is the planar Hall effect (PHE), or anisotropic magneto-resistance. The PHE is proportional to the square of the planar component of **M**, and produces an electric field parallel and perpendicular to the current. The third term in (1) is the component that is perpendicular to the current. Note that all three terms in (1) are inversely proportional to the film thickness t. In a conventional magnetometer (e.g., VSM) the signal magnitude is directly proportional to t, hence as the film thickness decreases it becomes more difficult to extract the signal of interest. Just the opposite effect occurs in an AHE magnetometer rendering it ideal for measuring ultra thin magnetic films.

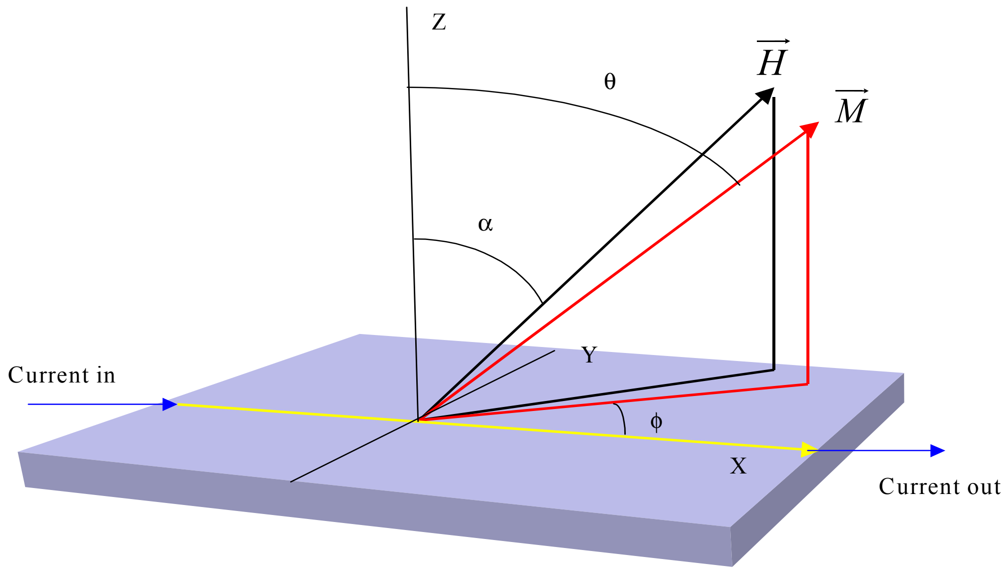


Figure 1) Geomery of the AHE measurement. α is the angle between the applied field and the normal to the sample, θ is the angle between the magnetization and the normal and ϕ is the angle between the current and the in plane component of the magnetization.

To achieve maximum sensitivity from low conductivity samples, an AC current methodology was used[4]. This technique also eliminates errors due to thermal EMF voltages. To eliminate residual resistance voltages from the Hall measurements, geometry averaging techniques commonly employed in conventional Hall effect measurements on semiconductors were used. In Hall effect measurements of semiconductors, field reversal is often used to eliminate resistance effects[5]. When a full hysteresis loop is measured, a modified form of field reversal must be used. The Hall voltage from positive fields on the descending curve are averaged with the Hall voltage at negative fields on the ascending curve. This method however is not suitable for measurements that only circumvent a portion of the hysteresis loop, such as DCD and IRM, and hence alternative methodologies are required. Geometric averaging, by measuring the hall voltage in two different directions, can be used to remove residual resistance values[5].

**Results**

Figure 2 shows results of major hysteresis loop measurements for a Au/Co-Cr/GaO/GaAlAs heterostructure thin film sample recorded using a VSM and AHE magnetometer. The data is normalized to 1. In the case of the AHE measurement the sample was measured using a van der Pauw configuration. At each field, the Hall voltage was measured across both diagonals and averaged. This removes the residual resistance from the measurements. Field reversal averaging was not used. The agreement between the two measurement methods is very good. This demonstrates that the geometrical averaging can be used in place of field averaging in an AHE magnetometer.

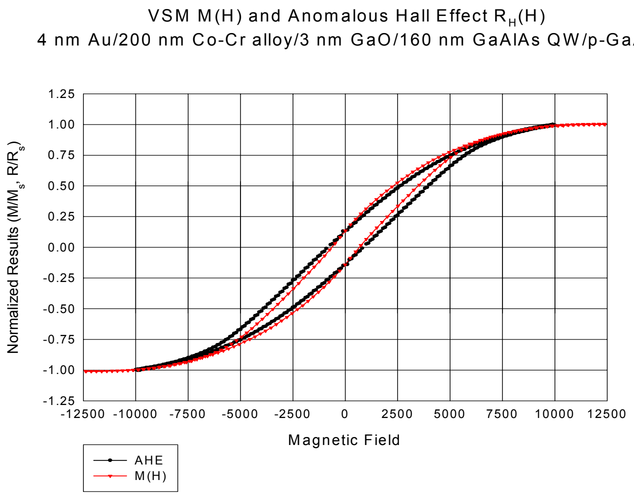


Figure 2) Measurement of a Au/Co-Cr/GaO/GaAlAs sample with VSM and AHE. This sample was measured with $\alpha$ = 90 degrees, using AC current.

In addition DC demagnetization (DCD) and irreversible remanent magnetization (IRM) measurement were conducted with both the VSM and AHE. In these experiments only portions of the Hysteresis loop are traversed. Again geometric averaging was used to remove the residual resistivity for the AHE magnetometer. Figure 3 shows a Henkel plot of the IRM and DCD data. Again the data has been normalized to one. In each case the best fit line to the data and equation are presented on the figure. In each case the slope of the lines are very close to –2, and show that the VSM and AHE results correlate quite well.

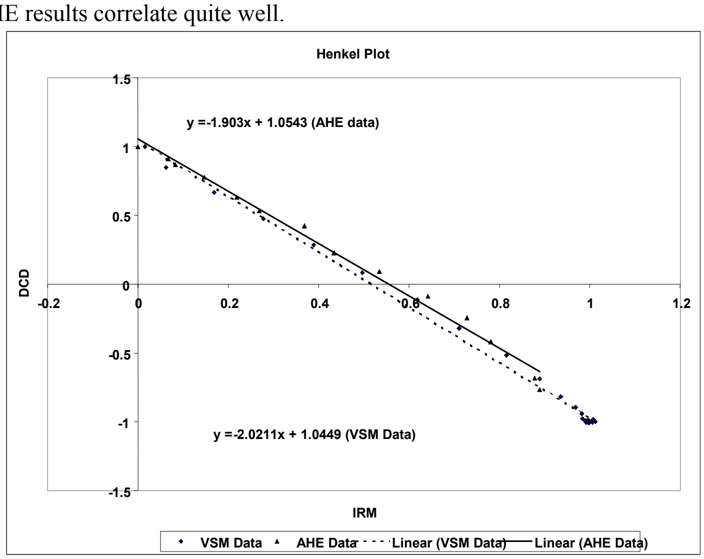


Figure 3) Henkel Plot of Au/Co-Cr/GaO/GaAlAs sample using the AHE and VSM.

Figure 4 shows results of AHE and VSM hysteresis loop measurements on a Au/Co-Cr/GaAs heterostructure thin film. The AC current methodology was employed for the AHE measurements, and the results have been normalized to 1. Here again, the agreement between the AHE and VSM measurement results is quite good.

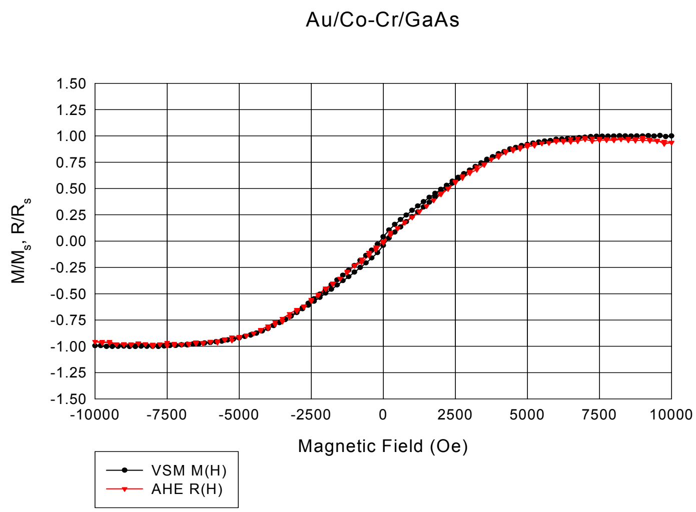


Figure 4) Measurement of a Au/Co-Cr/GaAs sample with VSM and AHE. This sample was measured with $\alpha = 90$ degrees, using AC current.

Figures 5, 6 and 7 show results of VSM and AHE measurements for a double-layered PMRM sample. Both AC and DC current methodologies were employed for the AHE measurements. Figures 5 and 6 show DC AHE and AC AHE results, respectively, superposed with the VSM results (all results normalized to 1).

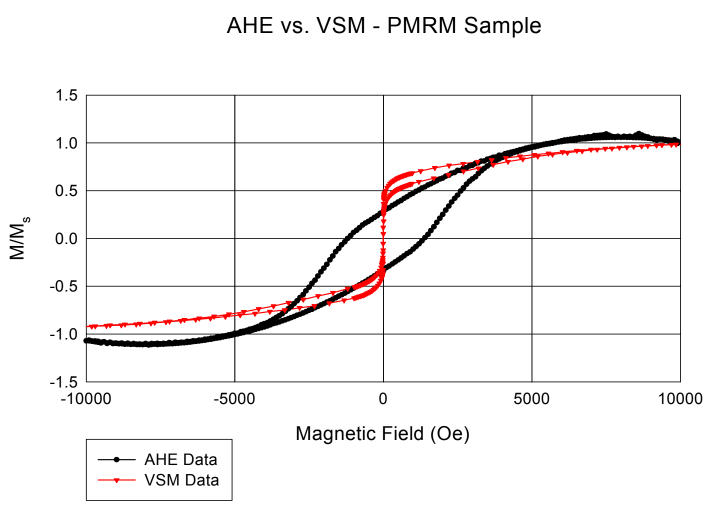


Figure 5) Measurement of double-layered PMRM sample with VSM (showing effect of SUL) and AHE showing only the hard magnetic material in the recording layer. This sample was measured with $\alpha = 35$ degrees, using DC current.

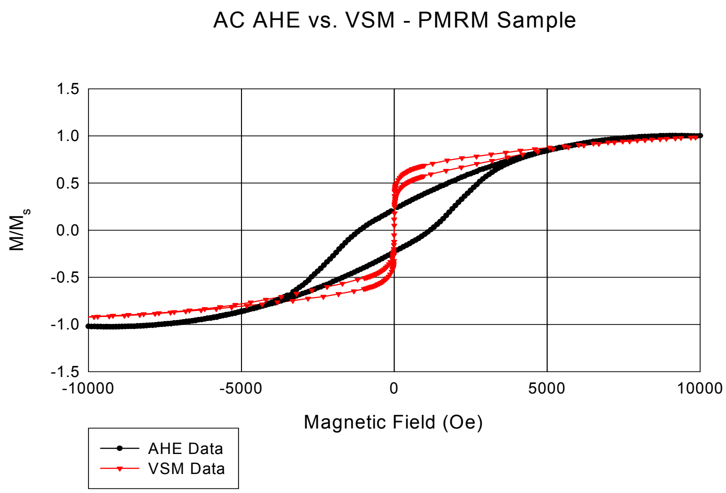


Figure 6) Measurement of the same PMRM sample with VSM (showing effect of SUL) and AHE showing only the hard magnetic material in the recording layyer. This sample was measured with $\alpha$ = 35 degrees, using AC current.

The AC and DC AHE results are shown superposed in figure 7 to illustrate the superior signal-to-noise that is achieved using the AC technique.

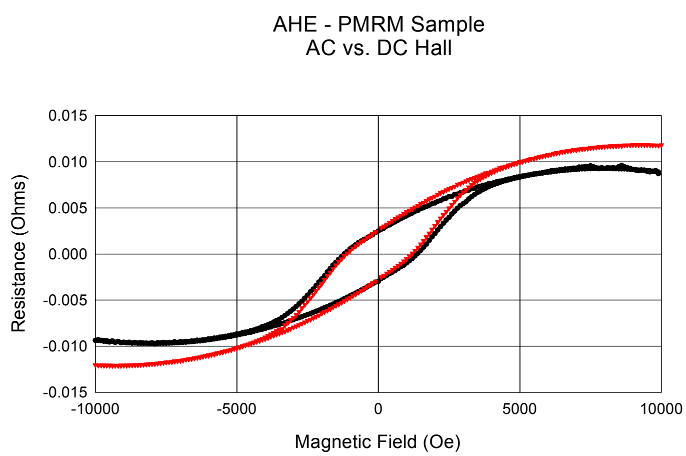


Figure 7) Comparison of AC and DC current AHE on the same PMRM sample. The AC measurement shows lower noise. The difference in resistance is due to the different contact size in the two measurements.

These figures illustrate the problems associated with using conventional magnetometry methods (e.g., VSM) to characterize double-layered PMRM. Note that the VSM M(H) loop is dominated by the magnetically soft underlayer, rendering it virtually impossible to extract the properties of the magnetically hard recording layer. In contrast, note that the AHE results clearly show the recording layer properties, and as such demonstrate the power of this technique for measuring magnetization processes in double-layered PMRM.

**Discussion**

Anomalous Hall effect magnetometry can be used to study magnetization processes in thin film materials. The AHE technique shows particular promise for those magnetic metrology applications where conventional magnetometry methodologies may be unsuited or limited in their application utility (e.g., double-layered PMRM, ultra thin magnetic films, and ferromagnetic/semiconductor heterostructures, etc.). Further, AHE magnetometry can be used to study magnetic processes using measurements other than hysteresis loops, and the results correlate well with those obtained using conventional magnetometry methodologies (i.e., VSM). Further development of this technique is warranted as it may prove to be an instrumental metrology tool for characterizing the magnetic properties of future generation recording materials and spintronics devices.

**Acknowledgments**

Financial support from ONR, monitored by Dr. Larry Cooper[b] is gratefully acknowledged.

# References

[1] Colin M. Hurd, **The Hall Effect in Metals and Alloys,** Plenum Press 1972
[2] S. Haan et al., J. Mag. Soc. Jap. 15 (1991) 349.
[3] S. Das et al., Poster presented at Joint [NA]PMRC 2003.
[4] J. R. Lindemuth and B. C. Dodrill, to be published in the proceedings of ICM03, J. of Mag. And Mag. Mat. (2003).
[5] David Look, Electrical Characterization of GaAs Materials and Device, John Whiley, 1993.