# Methodology for Investigating the Magnetization Process of the Storage Layer in Double-Layered Perpendicular Magnetic Recording Media Using the Anomalous Hall Effect

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***Abstract*—The Hall effect is a useful phenomenon for evaluating the magnetization processes of the storage and back layers in double-layered perpendicular magnetic recording media. Although the Hall voltage in double-layered films has two components (an anomalous Hall term arising from the perpendicular component of magnetization and a planar Hall term originating from the in-plane component of magnetization), it is possible to separate the two contributions by symmetry arguments. However, in the case where the saturation field of the recording layer (RL) is comparable to that of the soft underlayer (SUL), or when the SUL dominates the signal because of its inherently high magnetic moment, it is difficult to separate the anomalous Hall effect (AHE) contributions from the RL and SUL individually. Here we propose a methodology that overcomes this limitation and allows the extraction of the magnetization process of the RL. We assume that an average perpendicular magnetization contributes to the anomalous Hall voltage in the double-layered perpendicular media. We compare the magnetization process of the RL obtained by using this approach to that measured with a magnetooptical Kerr effect (MOKE) system. The proposed technique may be useful in those situations in which alternative tools such as the MOKE system are not suitable for measuring the magnetization process.**

***Index Terms*—Anomalous Hall effect, perpendicular magnetic recording, soft magnetic underlayers.**

## I. Introduction

A double-layered (DL) perpendicular anisotropy system incorporating a soft-magnetic keeper layer (SUL) under the hard perpendicular magnetic recording layer (RL) is a promising candidate for high-density perpendicular recording media [1]. In such double-layered systems, it is desirable to measure the magnetic properties of the RL in the presence of the SUL. However, most of the published literature has focused on the magnetic characterization of the RL without any SUL, because of the difficulty associated with extracting and evaluating the properties of the RL and the SUL individually. Conventional techniques using the vibrating sample magnetometer (VSM) fail in this regard because they sample the magnetization of all the layers of film, and often the signal from the high-moment SUL dominates over that from the RL. Moreover, in some instances, the magnetization behavior of the SUL is itself not straightforward such that the precise geometrical orientation of the sample with respect to the magnets of a VSM also needs to be taken into account [2]. In this regard, alternative techniques that make use of the Hall effect in magnetic materials have been found to be effective in separating and evaluating the magnetic properties of the RL and the SUL [3], [4].

The Hall voltage in a DL perpendicular thin film comes from three major sources—first, the anomalous Hall effect (AHE), which depends on the perpendicular (i.e., along the film normal) component of the magnetization $(M_{\perp})$ and second, the planar (or pseudo) Hall effect (PHE), which depends on the in-plane component of the magnetization $(M_{\|})$. Third, there is also a contribution from the normal Hall effect (NHE), but this is often negligible in magnetic films due to the high carrier density in metallic materials at room temperature. The AHE and the PHE contributions have different symmetries with respect to the applied magnetic field—the AHE component is proportional to $M_{\perp}$ ("odd symmetry") whereas the PHE component is proportional to $M_{\|}^2$ ("even symmetry"). This makes it possible to distinguish between the two components and extract the two parts, with the AHE component representing the magnetization process of the (mostly) perpendicular RL and the PHE component representing the magnetization of the (mostly) in-plane SUL [3]. However, the AHE output actually includes contributions from the perpendicular component of magnetization of both the RL and the SUL. In some instances, the AHE output of the SUL may be assumed linear, and hence subtracted out from the total AHE output to give the AHE output from the RL [3]. However, this approach is not always viable, especially when the saturation fields of the RL and the SUL become comparable. Moreover, the AHE output of the SUL itself may not always be a linear response. In this study, we present a methodology to overcome these limitations and extract the AHE component of the RL. Furthermore, a comparison of the magnetization process of the RL obtained using this approach with that measured using a magnetooptical Kerr effect (MOKE) system reveals good cor-

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relation. This suggests that the proposed methodology may be utilized to extract and evaluate the magnetic properties of the RL even when it is not possible to use the MOKE system, as will be the case in ultra-thin RL films wherein the incident laser penetrates into the SUL as well.

## II. Experimental Procedure

HITPERM nanocrystalline alloy was used as the SUL in this study. The preparation and properties of SUL films of this alloy is described in our earlier work [5], [6]. The SUL films of 100 nm (nominal) thickness were sputtered under radio-frequency conditions on 7059 Corning glass substrates at 4.5 W/cm$^2$ sputter power density. Fe–Pt (52–54 at % Fe) thin films of 30 nm (nominal) thickness were sputtered from a composite target and constituted the RL. Cr–Pt (<5 at % Pt) films (∼80 nm thick) were used as seed layers to promote the (002) perpendicular texture formation in the Fe–Pt RL. Previously, we have reported on the preparation of (002) textured $L1_0$ phase Fe–Pt using Cr as seed layer [7]. A thin Pt film (∼3 nm) was used as buffer layer between the Fe–Pt RL and the Cr–Pt seed layer. While the HITPERM SUL was prepared at room temperature (RT), the Cr–Pt, Pt, and Fe–Pt films were deposited *in situ* at ∼ 250 °C–280 °C. Single-layered films of Fe–Pt were also prepared for purposes of comparison. In this case, 50-nm-thick films were sputter-deposited *in situ* at ∼ 250 °C–280 °C. Measurements of the Hall voltage were made on square samples using the Van der Pauw method with an applied current of 25 mA. A VSM and a custom-built MOKE system (at Seagate Research, Pittsburgh) were both employed to evaluate and compare the magnetic properties with that obtained using the Hall technique. Structural analysis was performed using X-ray diffractometry (XRD) with Cu $K\alpha$ radiation.

## III. Evaluation Methodology

The Hall voltage $V_H$ in a magnetic thin film is given by the following expression [8], for the configuration illustrated in Fig. 1:

$$V_H = \frac{R_o I}{t} B\cos\alpha + \frac{\mu_o R_s I}{t} M\cos\theta + \frac{kI}{t} M^2 \sin^2\theta \sin 2\varphi \quad (1)$$

where $M\cos\theta$ is the perpendicular component (normal to the film-plane) of the magnetization $(M_\perp)$, $M\sin\theta$ is the in-plane component $(M_{||})$, $I$ is the applied current, and $t$ is the film thickness. $B\cos\alpha$ is the component of the applied magnetic flux density in the direction perpendicular to the current (i.e., along the film normal). Although $\varphi$ is defined in Fig. 1 to be the angle between the directions of $I$ and $M_{||}$ in the plane, in this work, we shall mention only the nominal value of $\varphi$, which is defined to be the angle between the current $I$ and the projection of the applied field $H$ onto the plane.

The first term in (1) is due to the normal Hall effect ($R_0$—normal Hall coefficient) and is related to the Lorentz force acting on moving charge carriers. The second term is the contribution from the anomalous Hall effect ($R_S$—anomalous Hall coefficient), which arises due to the asymmetric spin-orbit

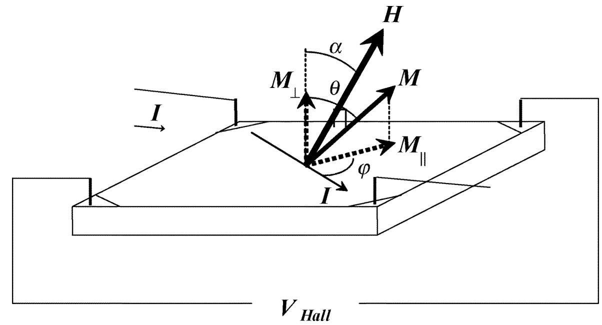


Fig. 1. Schematic of the configuration for measurement of the Hall voltage $(V_H)$ in a thin film structure.

scattering of conduction electrons from the magnetic moments in the sample. $R_S$ can be much larger than $R_0$ in magnetic metals, due to the high density of carriers at RT conditions. The third term is from the planar Hall effect, which is a pseudo Hall effect because it actually has its origin in anisotropic magnetoresistance (AMR). The constant $k$ is related to the difference in resistivity between the directions parallel to and perpendicular to the magnetization. The technique to distinguish and extract the AHE and the PHE components is based on the fact that the two have different symmetries with regard to the applied field $H$. The components with "odd" and "even" symmetries in the $V_H - H$ characteristics of a ferromagnetic thin film correspond to the perpendicular component (AHE term) and the square of the in-plane component (PHE term) of magnetization, respectively. Assuming that the NHE is negligible, this suggests that the component with even symmetry can be eliminated by subtracting the output signals of $V_H$ for the applied field $H < 0$ from those of the corresponding points for $H > 0$. The "odd" component of the Hall voltage is then obtained as

$$V_{\text{odd}}(H) = \frac{V_H(H<0) - V_H(H>0)}{2}. \quad (2)$$

In a similar manner, the component with odd symmetry can also be eliminated by adding the corresponding portions of $V_H$ for $H > 0$ and $H < 0$, to get the "even" component of the Hall voltage.

Now, the "odd" component of the Hall voltage that corresponds to the AHE output is due to the perpendicular component of magnetization in both the RL and the SUL. In such a scenario, we propose a simple model in which it is assumed that that an effective perpendicular magnetization averaged over the total thickness is the source of the AHE. In other words, we assume that the entire film-stack behaves as a single layer of magnetic thin film, at least as far as the AHE is concerned. Furthermore, in this model, we shall assume that the perpendicular magnetization behavior of the SUL does not depend on the existence of the RL. With these two assumptions, we shall derive an expression for the perpendicular (i.e., along the film-normal) magnetic hysteresis in the RL, as follows.

In any material, the Hall voltage due to the AHE can be written as

$$V_{\text{AHE}} = \frac{\mu_o R_S I}{t}\{M_\perp\}. \quad (3)$$

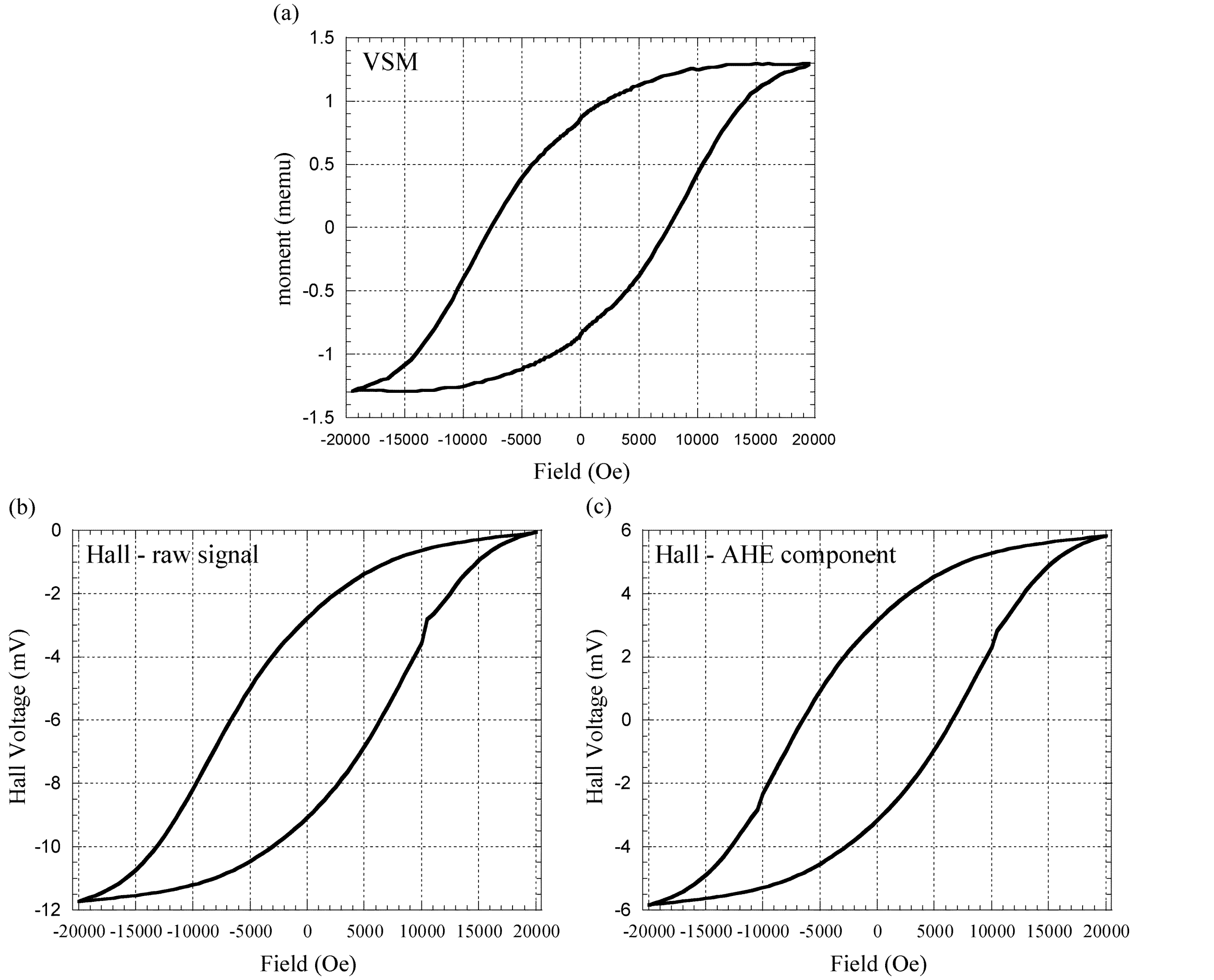


Fig. 2. (a) Perpendicular hysteresis loop from Fe–Pt (50 nm)/glass thin film, obtained using a VSM. The Fe–Pt was sputter deposited *in situ* at $\sim$ 250 °C–280 °C. (b) The raw $V_H - H$ loop for the Fe–Pt thin film at a tilt of $\alpha \sim 0°$, $\varphi \sim 0°$ (nominal). (c) The AHE component (odd symmetry) extracted from the raw loop.

Based on our model, in the case of the DL media, the "odd" component of the Hall voltage is therefore written as

$$V_{\rm odd}^{\rm COMB} = \frac{\mu_o R_S^{\rm COMB} I}{t}\left\{\frac{M_\perp^{\rm RL} t_{\rm RL} + M_\perp^{\rm SUL} t_{\rm SUL}}{t}\right\} \quad (4)$$

where $M_\perp^{\rm RL}$ and $M_\perp^{\rm SUL}$ are the perpendicular components of magnetization in the RL and the SUL, respectively, and $t_{\rm RL}$ and $t_{\rm SUL}$ are their respective thickness. $t$ is the total thickness of the film and $R_S^{\rm COMB}$ corresponds to an effective anomalous Hall coefficient of the DL medium. At fields exceeding the saturation fields of both the RL and the SUL, the saturated odd component of the Hall voltage is simply

$$\left(V_{\rm odd}^{\rm COMB}\right)_{\rm SAT} = \frac{\mu_o R_S^{\rm COMB} I}{t} \times \left\{\frac{\left(M_\perp^{\rm RL}\right)_{\rm SAT} t_{\rm RL} + \left(M_\perp^{\rm SUL}\right)_{\rm SAT} t_{\rm SUL}}{t}\right\}. \quad (5)$$

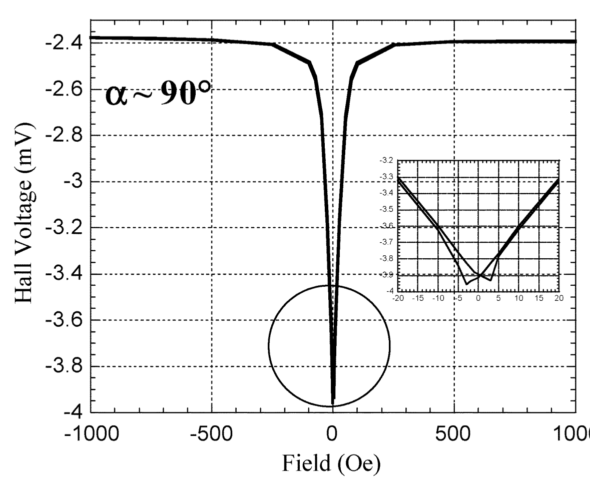


Fig. 3. $V_H$ characteristic for HITPERM (100 nm)/glass thin film obtained at $\alpha \sim 90°$; nominal value of $\varphi \sim 45°$. Inset shows an enlarged view of the encircled region.

Dividing (4) by (5), i.e., normalizing, we get that

$$\frac{V_{\rm odd}^{\rm COMB}}{\left(V_{\rm odd}^{\rm COMB}\right)_{\rm SAT}} = \frac{M_\perp^{\rm RL} t_{\rm RL} + M_\perp^{\rm SUL} t_{\rm SUL}}{\left(M_\perp^{\rm RL}\right)_{\rm SAT} t_{\rm RL} + \left(M_\perp^{\rm SUL}\right)_{\rm SAT} t_{\rm SUL}}. \quad (6)$$

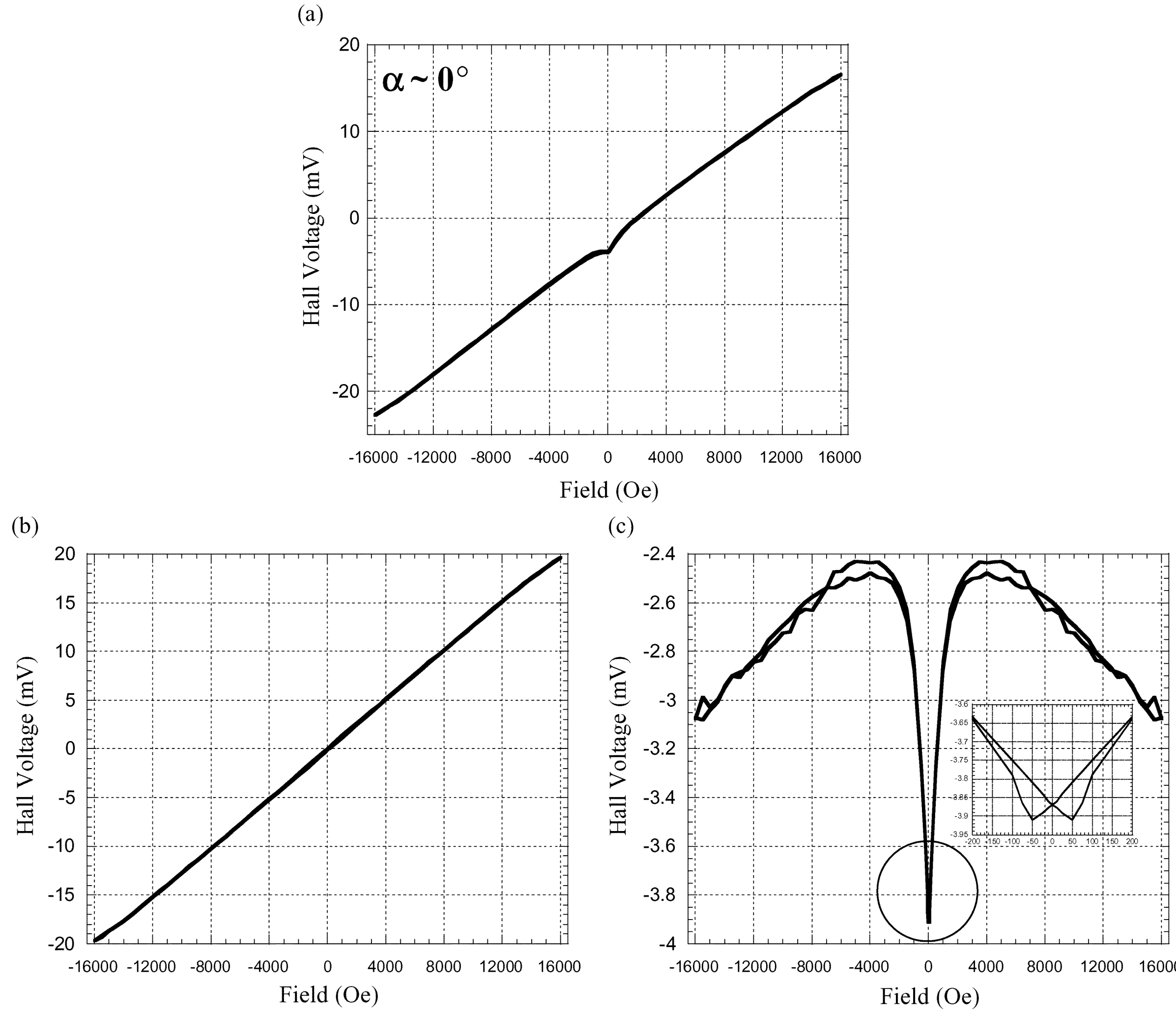


Fig. 4. $V_H$ characteristics (a) and the extracted AHE (b) and PHE (c) components showing odd and even symmetries, respectively. The sample was HITPERM (100 nm)/glass thin film; $\alpha \sim 0°$, $\varphi \sim 45°$ (nominal). Inset in (c) is enlarged view of the encircled region.

Dividing both the numerator and the denominator of the quantity on the right-hand side (RHS) of (6) by $(M_\perp^{\mathrm{SUL}})_{\mathrm{SAT}} t_{\mathrm{SUL}}$

$$\frac{V_{\mathrm{odd}}^{\mathrm{COMB}}}{\left(V_{\mathrm{odd}}^{\mathrm{COMB}}\right)_{\mathrm{SAT}}} = \frac{\frac{M_\perp^{\mathrm{RL}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + \frac{M_\perp^{\mathrm{SUL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}}}}{\frac{\left(M_\perp^{\mathrm{RL}}\right)_{\mathrm{SAT}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + 1}. \tag{7}$$

Rearranging terms

$$\frac{V_{\mathrm{odd}}^{\mathrm{COMB}}}{\left(V_{\mathrm{odd}}^{\mathrm{COMB}}\right)_{\mathrm{SAT}}} \left\{ \frac{\left(M_\perp^{\mathrm{RL}}\right)_{\mathrm{SAT}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + 1 \right\} = \frac{M_\perp^{\mathrm{RL}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + \frac{M_\perp^{\mathrm{SUL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}}}. \tag{8}$$

The second term on the RHS of (8) refers to the perpendicular magnetization process of the SUL alone. This term can be evaluated on acquiring the AHE output from the SUL thin film by itself, as follows:

$$V_{\mathrm{odd}}^{\mathrm{SUL}} = \frac{\mu_o R_S^{\mathrm{SUL}} I}{t_{\mathrm{SUL}}} M_\perp^{\mathrm{SUL}} \tag{9}$$

where $R_S^{\mathrm{SUL}}$ is the anomalous Hall coefficient of the SUL thin film. At saturation

$$\left(V_{\mathrm{odd}}^{\mathrm{SUL}}\right)_{\mathrm{SAT}} = \frac{\mu_o R_S^{\mathrm{SUL}} I}{t_{\mathrm{SUL}}} \left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}}. \tag{10}$$

Dividing (9) by (10), i.e., normalizing

$$\frac{V_{\mathrm{odd}}^{\mathrm{SUL}}}{\left(V_{\mathrm{odd}}^{\mathrm{SUL}}\right)_{\mathrm{SAT}}} = \frac{M_\perp^{\mathrm{SUL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}}}. \tag{11}$$

On subtracting (11) from (8), we get that

$$\frac{V_{\mathrm{odd}}^{\mathrm{COMB}}}{\left(V_{\mathrm{odd}}^{\mathrm{COMB}}\right)_{\mathrm{SAT}}} \left\{ \frac{\left(M_\perp^{\mathrm{RL}}\right)_{\mathrm{SAT}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + 1 \right\} - \frac{V_{\mathrm{odd}}^{\mathrm{SUL}}}{\left(V_{\mathrm{odd}}^{\mathrm{SUL}}\right)_{\mathrm{SAT}}} = \frac{M_\perp^{\mathrm{RL}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}}. \tag{12}$$

The quantity of interest is $M_\perp^{\mathrm{RL}}$ and so, rearranging terms

$$\frac{M_\perp^{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}}} = \left\{ \frac{V_{\mathrm{odd}}^{\mathrm{COMB}}}{\left(V_{\mathrm{odd}}^{\mathrm{COMB}}\right)_{\mathrm{SAT}}} \left\{ \frac{\left(M_\perp^{\mathrm{RL}}\right)_{\mathrm{SAT}} t_{\mathrm{RL}}}{\left(M_\perp^{\mathrm{SUL}}\right)_{\mathrm{SAT}} t_{\mathrm{SUL}}} + 1 \right\} - \frac{V_{\mathrm{odd}}^{\mathrm{SUL}}}{\left(V_{\mathrm{odd}}^{\mathrm{SUL}}\right)_{\mathrm{SAT}}} \right\} \frac{t_{\mathrm{SUL}}}{t_{\mathrm{RL}}}. \tag{13}$$

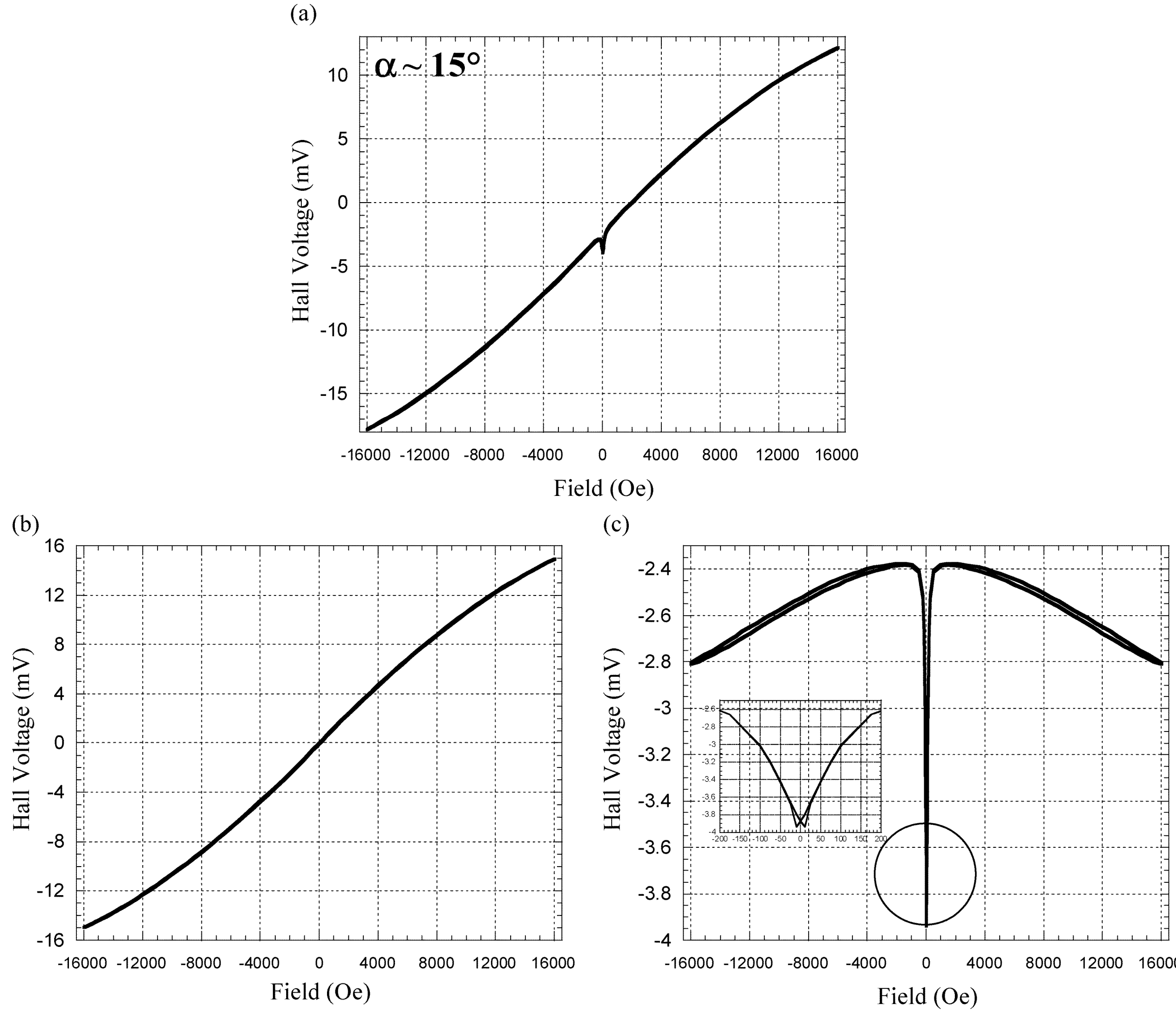


Fig. 5. $V_H$ characteristics (a) and the extracted AHE (b) and PHE (c) components showing odd and even symmetries, respectively. The sample was HITPERM (100 nm)/glass thin film; $\alpha \sim 15^\circ$, $\varphi \sim 45^\circ$ (nominal). Inset in (c) is enlarged view of the encircled region.

From knowledge of the saturation magnetization and thickness of both the RL and the SUL and on acquiring the (normalized) AHE output from both the SUL and the DL media, it is thus possible to extract the perpendicular magnetization process of the RL. It should be pointed out here that while this expression has been derived for an arbitrary direction of the applied field, the quantities $(M_\perp^{\mathrm{RL}})_{\mathrm{SAT}}$ and $(M_\perp^{\mathrm{SUL}})_{\mathrm{SAT}}$ represent only the components of the respective saturation magnetizations along the direction of the film normal. Therefore, except in the case wherein the external magnetic field is applied along the film normal $(\alpha = 0^\circ)$, the quantity $(M_\perp^{\mathrm{RL\ or\ SUL}})_{\mathrm{SAT}}$ that goes into (13) should be different (smaller) from the actual saturation value for $\alpha > 0^\circ$.

The methodology presented above hinges on the proposition made at the outset that the combined AHE output in DL media can be considered as arising from an average magnetization, as opposed to other models that consider multilayered films to act like resistors in series or parallel [9]. Second, it is implicitly assumed that the perpendicular magnetization behavior of the SUL is the same, whether in the presence or absence of the RL. While the latter of the assumptions should be reasonable, the validity of the former can best be verified by weighing the end result against that measured using other techniques that we discuss next.

## IV. Results and Discussion

Conventional and in-plane (grazing incident angle 2°) $\theta/2\theta$ XRD spectra from 50-nm-thick Fe–Pt thin film sputtered *in situ* at $\sim$ 250 °C–280 °C showed the presence of a strong (111) peak, indicative of a more or less random orientation of the magnetic easy axes. Fig. 2(a) is the perpendicular hysteresis loop for this film, obtained using a VSM. The magnetic properties are: coercivity, $H_c \sim$ 7600 Oe; $M_s \sim$ 668 emu/cm$^3$; squareness, S $(= M_r/M_s) \sim$ 0.65. The "raw" Hall output and the extracted "odd component" of the $V_H - H$ loop characteristic for the same film are illustrated in Fig. 2(b) and (c) for $\alpha \sim 0^\circ$ (i.e., along the film normal). The "raw" Hall output itself exhibits the odd symmetry. The "odd" component loop indicates $H_c \sim$ 6600 Oe, S $\sim$ 0.5 and shows a relatively weak linear section, after saturation at high fields. This linear section is due to the normal Hall effect, and given that it is relatively small compared to the contribution from the anomalous Hall effect, we shall disregard it. The "raw" and the extracted "odd" component of the $V_H - H$ loop at a different tilt of $\alpha \sim 15^\circ$ (not shown here) were identical to

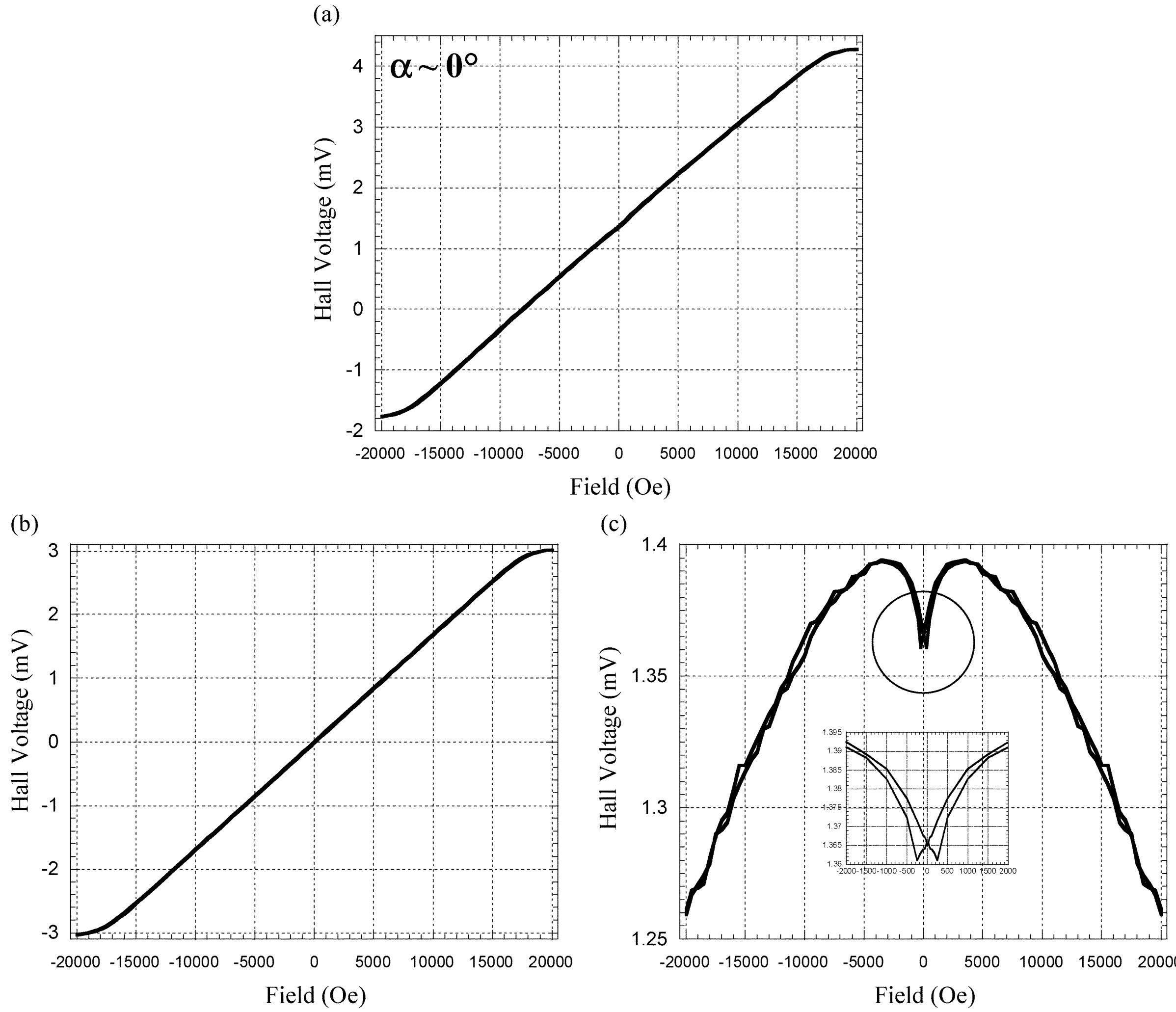


Fig. 6. $V_H$ characteristics (a) and the extracted AHE (b) and PHE (c) components showing odd and even symmetries, respectively. The sample was Cr–Pt (80 nm)/HITPERM (100 nm)/glass thin film; $\alpha \sim 0°$, $\varphi \sim 45°$ (nominal). Inset in (c) is enlarged view of the encircled region.

the measured loops at $\alpha \sim 0°$ [Fig. 2(b) and (c)], regardless of the nominal angle $\varphi$. These observations support the inference regarding the random nature of the easy-axes orientation. Thus, there is good agreement between the hysteresis measured using the VSM and the Hall technique for this single-layered Fe–Pt thin film.

Fig. 3 is the $V_H - H$ characteristic for 100-nm-thick HITPERM SUL thin film, with field applied along the plane of the film ($\alpha \sim 90°$). The coercivity, estimated from the $V_H$ measurement, is ~3 Oe. The magnetic properties of this film, measured with a VSM, were: $H_c$ ~4–5 Oe; $M_s$ ~19–20 kG (1500–1600 emu/cm$^3$) [6]. Figs. 4 and 5 are the $V_H$ characteristics for this film along the film normal ($\alpha \sim 0°$) and at an inclined angle ($\alpha \sim 15°$). The AHE (odd) and the PHE (even) components are also shown. It should be mentioned here that the HITPERM thin film exhibits an easy axis of magnetization along a preferred direction within the plane itself [2], and this makes the estimation of the angle $\varphi$, as defined in Fig. 1, more difficult and less reliable. Therefore, the value of the angle $\varphi$ reported here represents only the nominal estimate (angle between the current $I$ and the projection of the applied field $H$ onto the film plane). The PHE components however, are consistent in that the in-plane coercivity (of the HITPERM SUL) is seen to decrease from ~50 Oe at zero tilt [Fig. 4(c)] to ~10 Oe at higher tilt [Fig. 5(c)]. In any case, the AHE output is the subject of interest here and this depends only on the component of magnetization normal to the film plane ($M_\perp$) irrespective of the direction of $M_{||}$. The AHE output for $\alpha \sim 0°$ [Fig. 4(b)] shows a linear response with a slope of $\sim 1.26 \times 10^{-3}$ mV/Oe, whereas for $\alpha \sim 15°$, the AHE output [Fig. 5(b)] deviates from linearity at high fields. Nonetheless, neither of the two outputs exhibits any hysteresis, and this is consistent with the magnetization vector in the SUL being continuously pulled away from the in-plane direction toward the applied field direction. This also explains the decrease of the Hall voltage at high fields in the PHE output.

Fig. 6 depicts the $V_H$ characteristics for the Cr–Pt/HITPERM structure evaluated at $\alpha \sim 0°$. The slope of the linear part of the AHE output (before saturation) is $\sim 1.69 \times 10^{-4}$ mV/Oe. This is an order of magnitude smaller than that from the single-layered HITPERM thin film [Fig. 4(b)]. While the thicker nature of the Cr–Pt / HITPERM films can partially account for this observation, scattering of conduction electrons at the Cr–Pt-HITPERM

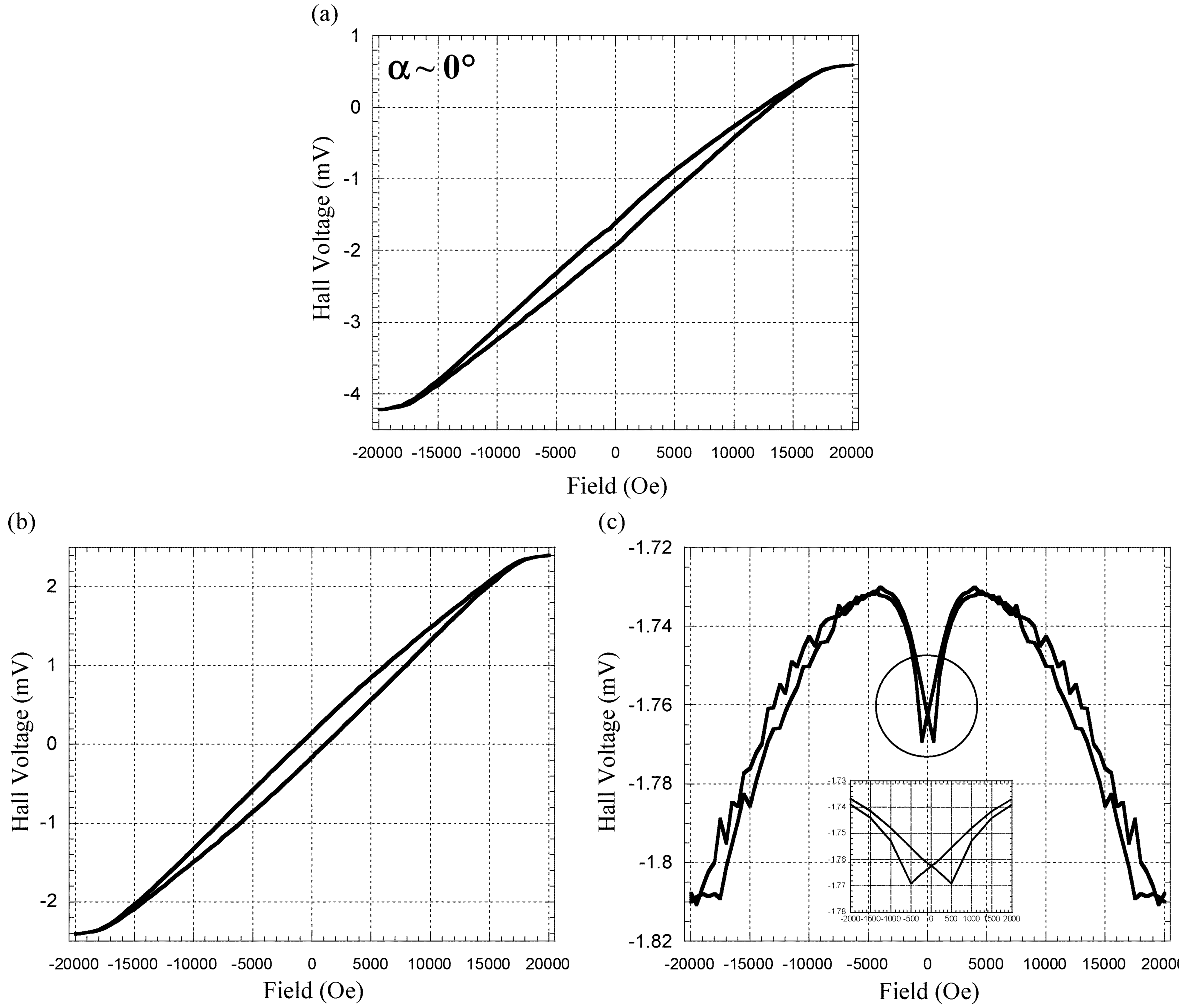


Fig. 7. $V_H$ characteristics (a) from Fe–Pt (30 nm)/Pt (3 nm)/Cr–Pt (80 nm)/HITPERM (100 nm)/glass thin film along with the extracted AHE (b) and PHE (c) components showing odd and even symmetries, respectively. The HITPERM film was prepared at RT, following which the Cr–Pt, Pt, and Fe–Pt layers were sputtered *in situ* at $\sim$ 250 °C–280 °C. Angle of measurement: $\alpha \sim 0^\circ$, $\varphi \sim 45^\circ$ (nominal). Inset in (c) is enlarged view of the encircled region.

interface is believed to play a major role as well. Interfacial scattering has commonly been postulated in magnetic multilayer systems exhibiting the giant magnetoresistance (GMR) effect. In the present circumstance, interfacial scattering affects only the magnitude of $R_S$, the anomalous Hall coefficient [10].

In conventional $\theta/2\theta$ XRD spectra obtained from the Fe–Pt/Pt/Cr–Pt/HITPERM structure (not shown here), strong Cr-(200) and Fe–Pt (200)/(002) peaks were seen. However, the presence of a weak Cr-(111) as well as Fe–Pt (111) indicated that the texture was not perfectly perpendicular. Also, the ordered (001) reflection was small, which suggested that the degree of ordering was low [7]. Fig. 7 is the $V_H - H$ output $(\alpha \sim 0^\circ)$ for this film, with the extracted "odd" and the "even" components also shown. The AHE ("odd") output includes the perpendicular magnetization behavior of both the RL and the SUL. However, it is not evident in what way each of the two layers contributes to this total AHE output. While a linear contribution of the SUL may be a suitable assumption in some cases, it is not appropriate here because of the difficulty in estimating that linear part, which arises due to the fact that the saturation fields of the RL and the SUL are in close proximity. If on the other hand, we assume that an average perpendicular magnetization is the source of the AHE, then the methodology that was developed in the last section may be used to extract the perpendicular magnetization process of the RL.

Fig. 8(a) is the hysteresis obtained using the described methodology and the normalized AHE outputs corresponding to Figs. 7(b) and 6(b). A value for $(M_{\text{Fe–Pt}})_{\text{SAT}}/(M_{\text{HITPERM}})_{\text{SAT}} \sim 0.478$ that was estimated from VSM measurements of single-layered films was used. A second hysteresis, extracted using the same method at a tilt angle $\alpha \sim 5^\circ$, is also shown [Fig. 8(b)] to corroborate the first. Although the value for $(M_{\text{Fe–Pt}})_{\text{SAT}}/(M_{\text{HITPERM}})_{\text{SAT}}$ should be different under various tilt angles, the differences are very small at small tilt angles, and therefore the same estimate ($\sim$0.478) was used in obtaining Fig. 8(b) as was used in Fig. 8(a). At higher tilt angles $(\alpha > 10^\circ)$, while the saturation fields corresponding to the SUL decreases, those for the RL conversely increase and lie beyond the maximum fields achievable with our measurement setup. Consequently, we confine our analysis to the measurements performed at the small tilt angles.

The Kerr hysteresis for the same sample, obtained using a MOKE system, is shown in Fig. 9(a). The normalized Hall hys-

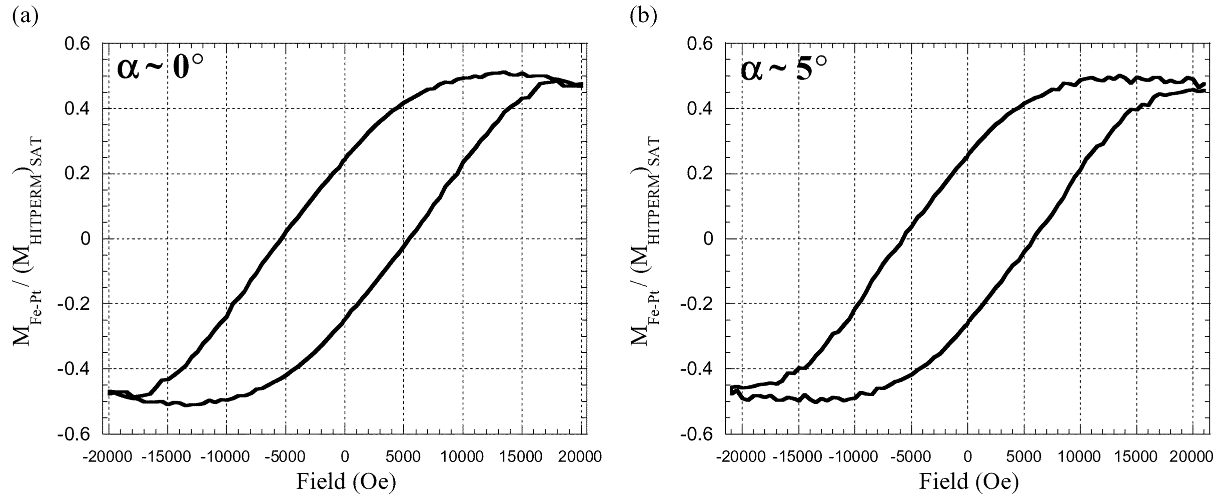


Fig. 8. Hall hysteresis loops extracted using the proposed methodology for (a) $\alpha \sim 0^\circ$ and (b) $\alpha \sim 5^\circ$. The sample was Fe–Pt (30 nm)/Pt (3 nm)/Cr–Pt (80 nm)/HITPERM (100 nm)/glass thin film.

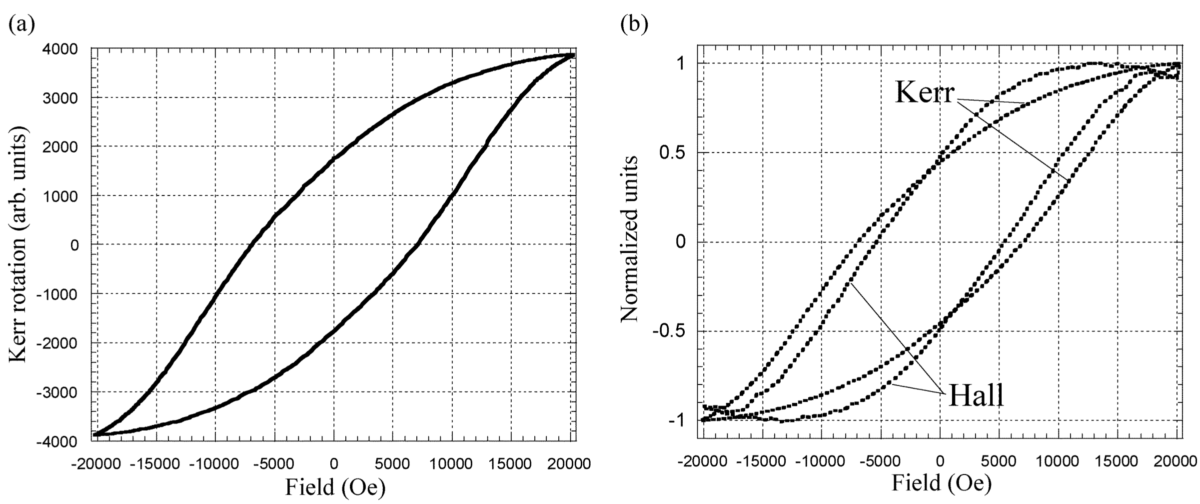


Fig. 9. Hysteresis loop obtained using a MOKE system is shown in (a). The sample was Fe–Pt (30 nm)/Pt (3 nm)/Cr–Pt (80 nm)/HITPERM (100 nm)/glass thin film. The Hall hysteresis loop for the same film is compared to the Kerr loop in (b).

teresis loop ($\alpha \sim 0^\circ$) is compared to the normalized Kerr hysteresis loop in Fig. 9(b). The coercivity values obtained are: $H_c \sim$ 5500 Oe (Hall); $H_c \sim$ 7000 Oe (Kerr). The squareness is S $\sim$ 0.48 (Hall); S $\sim$ 0.45 (Kerr). It should be pointed out here that the Kerr loop was obtained at a much higher frequency (sweep rate) compared to the $V_H$ measurement, and therefore probably overestimates the coercivity. The relatively low value for the squareness is indicative of the imperfect perpendicular orientation of the Fe–Pt RL, as was seen in the XRD scans. Errors in estimating $M_{\text{Fe–Pt}}/M_{\text{HITPERM}}$, as also in the thickness of the RL and the SUL were not seen to significantly influence the shape or other parameters of the Hall hysteresis loop.

There is strong correspondence between the two hysteresis loops. There are still differences though, especially in the high-field region and in the slope of the magnetization process. It is noted that the Hall hysteresis loop shows a decline from saturation in the high-field region, which suggests over-compensation. Some of the differences could possibly be attributed to the normal Hall effect, which we have ignored. Other factors include misalignment of the probes, and the existence of demagnetization effects, inhomogeneity, and strains in the thin film structure. Also, a major source of noise in these measurements is quite likely from the crude nature of the electrical contacts. An area of concern is that the intensities of the magnetic fields employed have only been so strong as to barely saturate the thin film specimens, which leads to some ambiguity regarding the hysteresis loops. Therefore, some fine-tuning is necessary in order to clarify on the nature of the problems and account for the differences. This should be the subject of future work. Nevertheless, the proposed methodology is seen to generate a hysteresis loop that strongly correlates to the actual. While this validates the proposition made regarding the combined AHE output in this case, further investigation is necessary to ascertain it. The possibility that the proposed method offers, in measuring the magnetic properties of the RL in ultra-thin films wherein even the MOKE system fails, is a promising one.

## V. Conclusion

A methodology has been proposed to measure the magnetization process of the recording layer in double-layered perpendicular magnetic recording media. It makes use of the Hall effect in magnetic materials and is based on the assumption that an average magnetization contributes to the Hall voltage. A comparison of hysteresis loops obtained using this method to the Kerr loop has also been made. The proposed method could potentially be useful in measuring the magnetic properties of the RL, where alternate techniques are not possible.

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