Influence of demagnetization in remanence curves of magnetic thin films

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Remanent magnetization curves of perpendicular magnetic thin films are simulated and measured. The simulations are used to investigate the theoretical influence of the strong demagnetizing field present in these films. Conclusions are drawn from this on how remanence curves should be measured and how they should be corrected for the demagnetizing influence. The experimental part consists of measurements on Fe-Alumite, Co-Pt-based multilayers, and Co-Cr. In addition the latter material is also artificially patterned into microstrips in order to investigate the influence of demagnetization on remanence curves experimentally. © 1995 American Institute of Physics.

I. INTRODUCTION

Remanence measurements are becoming increasingly popular in characterizing magnetic media for high-bit-density purposes. Especially for particulate in-plane materials they are found to be suitable in characterizing magnetic media for high-bit-density purposes. It is therefore not surprising that this measurement technique is also becoming increasingly popular for the investigation of perpendicular magnetic materials. However, a point of concern here is how to correct for the strong demagnetizing field present in perpendicular media, and therefore how to interpret the results. In this article we contribute to this discussion by presenting simulated and experimentally obtained remanence curves of various types of thin films having perpendicular anisotropy.

For the simulated remanence curves use is made of a mean-field model as proposed by Maro and Kitakami. For the experimental remanence curves three types of perpendicular media are investigated, e.g., Fe-Alumite, Co-Cr, and Co-Pt-based multilayers. The experimental part consists of measurements on Fe-Alumite, Co-Pt-based multilayers, and Co-Cr. In addition the latter material is also artificially patterned into microstrips in order to investigate the influence of demagnetization on remanence curves experimentally.

II. REMANENCE CURVES AND THE CORRECTION FOR DEMAGNETIZATION

Remanence measurements were originally designed to characterize magnetic reversal and interactions between magnetic particles in (in-plane) recording tapes. These measurements, which are well established in literature, are referred to as the "conventional" obtained remanence curve measurements. Note that here the word conventional applies to the measurement routine and not to a specific type of material. When this conventional measurement method is applied to magnetic materials with a nonzero demagnetization factor the problem arises of how to correct for the demagnetizing field. Samwel and co-workers therefore proposed a new measurement routine that takes the demagnetizing character into account. This modification on the conventional measurement routine is referred to as "unconventional" remanence curves. Both measurement routines are reviewed in this section, where we start with a description of the conventional measurement routine.

There are two types of remanence curves defined in literature, i.e., the isothermal remanence magnetization (IRM) and the dc demagnetization (DCD) measurement. The IRM curve starts off with the sample in an initially demagnetized state. Remanence curves are then recorded by measuring the remanence at zero applied field $M_r$, after applying (and removing) a positive field $H'$. This procedure is repeated for a subsequent increasing field $H''$, up to positive saturation. The IRM curve is then characterized by plotting the remanence values as a function of the corresponding applied field values $M_r(H'')$. The DCD curve measurement is comparable to the IRM method, except for that its starting condition is the negative saturated state. In the DCD measurements described here the negative saturated state is chosen in order to circumvent offset errors in the Gauss-meter of a vibrating sample magnetometer (VSM) (measurement is performed in the same $MH$ quadrant). In the following we refer to the mea-
asurements described above as the conventional obtained remanence curve measurements. This means that the field is swept between an (increasing) applied field \( H' \) and a zero applied field.

For in-plane materials this conventional measurement technique results in information on irreversible magnetization changes and interaction effects. The latter are often expressed in Henkel plots where the DCD curve is plotted against the IRM curve. For a theoretical system of noninteracting particles the Henkel plot results in a straight line. The equation for this line was originally derived by Wohlfarth, and is given by DCD \( (H) = 1 \) IRM \( (H) \). Data that are below this line are known to exhibit (negative) interactions that aid to a demagnetized state. For data above that line the (positive) interactions are supposed to favor a magnetized state.

The magnitude of the interactions, however, is not quantified. Therefore, Harrell, Richards, and Parke proposed a more direct interpretation of interaction fields by \( \delta H \) plots. In these plots the remanent susceptibility is differentiated horizontally, rather than vertically as in the \( \delta M \) plot. The equation for the \( \delta H \) at a certain magnetization \( M' \) is given by

\[
\delta H(M') = H_{\text{DCD}}(M') - H_{\text{IRM}}(M'), \tag{1}
\]

where the first and second term on the right-hand side represent the field at which this magnetization \( M' \) is obtained in the DCD and IRM curves, respectively. In this way interaction fields may be plotted explicitly as a function of magnetization.

In this study magnetic materials are investigated with a nonzero demagnetization factor. The remanent measurement technique in this case is thought not to be appropriate to measure exclusively irreversible magnetization reversals. The internal field, as experienced inside the material, can become negative and thus a reversal of some low-coercivity regions may take place. Remanent values obtained in this conventional way are therefore due to both reversible and irreversible processes, and information on interactions is hard to derive. This problem is acknowledged by several authors, and led to a modification on measuring remanence curves, as proposed by Samwel and co-workers. In this modified measurement technique the remanence is measured at zero internal field, so that only irreversible magnetization changes are measured. Information on interaction effects is again obtained from Henkel plots but showed limited success. This was concluded from their experimental study on Alumite where the residual interaction appeared to be strongly dependent on the value of the used demagnetization factor and value of saturation magnetization. In the following we refer to these modified measurements described above as the unconventional obtained remanence curves.

In the following section the influence of demagnetization on the conventional and unconventional remanence measurements is simulated by a mean-field model. The influence of demagnetization and correction for demagnetization are investigated. This serves the purpose of investigating the possible errors made in both techniques, and the purpose of a more theoretical confirmation of the modified technique, proposed in Ref. 2.

### III. INFLUENCE OF DEMAGNETIZATION ON SIMULATED REMANENCE CURVES OF PARTICULATE MEDIA

The simulations presented in this section are based on the self-reorientation model of Maro and Kitakami. This model calculates the magnetization from an assumed switching field distribution \( g \). In the following this distribution is characterized by a normal Gaussian function of the internal field, i.e.,

\[
g(h_i) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(h_i-\mu)^2}{2\sigma^2}\right), \tag{2}\]

where \( h_i \) is the internal field normalized on \( M_s \) and \( \mu \) and \( \sigma \) are a measure for the mean coercivity and distribution, respectively. It is noted here that the choice of distribution function type can be of considerable influence on the results, especially for broad distributions. Here a Gaussian distribution function is chosen because it fits better than a log-normal function, which is often used in the literature on coercivity distributions. For the mean coercivity parameter \( \mu \) and distribution \( \sigma \) values of around 0.6 and 0.1 are chosen, respectively. These values agree reasonably well with the experimental results of the hereinvestigated Fe-Alumite samples (see Table 1).

In contrast to the calculations performed by Maro and Kitakami we normalize both field and magnetization on the saturation magnetization \( M_s \), i.e., \( h = H/M_s \) and \( m = M/M_s \). The description of perpendicular magnetized materials is incorporated in the model by the mean-field theory, i.e.,

\[
h_i = h_n - N_cm, \tag{3}\]

where \( h_i \) denotes the internal field, \( h_n \) the applied field, and \( N_c \), the demagnetization factor in the perpendicular direction.

The virgin curve \( m_v \) and hysteresis curve \( m_h \) (i.e., upwards) can then be calculated from

\[
m_v = \int_0^{h_n-N_cm_v} g(h)dh, \tag{4}\]

\[
m_h = -1 + 2 \int_0^{h_n-N_cm_v} g(h)dh. \tag{5}\]

In order to obtain the conventional IRM \( (m_{\text{IRM}}) \) and DCD remanence \( (m_{\text{DCD}}) \) curves, the applied field is reduced to zero. For media with a nonzero demagnetization factor this can result in a negative internal field \( h_i = -N_cm(h_i) \), and thus magnetic moments are reversed to the negative direction again. This effects is the so-called self-orientation effect, and is described by

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pore diameter (nm)</th>
<th>Cell diameter (nm)</th>
<th>( M_s ) (kA/m)</th>
<th>( H_{\text{IRM}} ) (kA/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B11</td>
<td>30.0</td>
<td>74.5</td>
<td>240</td>
<td>147</td>
</tr>
<tr>
<td>B21</td>
<td>37.5</td>
<td>74.5</td>
<td>362</td>
<td>105</td>
</tr>
<tr>
<td>B33</td>
<td>45.0</td>
<td>74.5</td>
<td>325</td>
<td>73</td>
</tr>
</tbody>
</table>

### TABLE I. Magnetic and structural properties of the Fe-Alumite samples.

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FIG. 1. Recoil lines obtained from simulating remanence curves, i.e., IRM (top) and DCD (bottom). Parameters: $\mu=0.61$; $\sigma=0.1$; $N_z=1$.

$$m_{\text{IRM}} = m_0 - \int_0^{N_z m_{\text{IRM}}} g(h) \, dh.$$  

$$m_{\text{DCD}} = m_h - \int_0^{N_z m_{\text{DCD}}} g(h) \, dh.$$  

In Fig. 1 an example is given of how this self-reorientation effect results in recoil lines that decrease with decreasing field.

It can be concluded from Fig. 1 that the conventional IRM and DCD curves are lower than the virgin and hysteresis curves, respectively. This is not due to a reversible component, as this component is zero in the model, but it is due to a nonzero demagnetization factor that can result in negative internal fields, and thus irreversible switching of the magnetization. Due to this effect, measuring remanence curves for perpendicular media, by sweeping back to zero applied field, can indeed result in false information on reversibility and interaction effects.

In Fig. 2 an example is shown of a Henkel plot from which general the information on interaction effects is derived. Note that in Henkel plots the remanence curves are normalized on the remanent magnetization of the major loop.

From Fig. 2 it can be seen that the DCD curve does not start at zero internal field. This is to be expected because in this case $H_{\text{int}}=-N_z M_r$, i.e., already a part of the switching field distribution (SFD) is reversed. The corresponding Henkel plot is shown in Fig. 4.

From Fig. 4 can be seen that plotting the IRM and DCD curves, for corresponding internal fields, results in a line that below the Wohlfarth relation. The curves, however, only differ slightly, although the demagnetization factor is changed considerably. This makes it questionable how Henkel plots, obtained from measuring remanence curves by sweeping back to zero applied field, result in information on interaction effects.

In Ref. 3 information on this interaction is derived by correcting the data for the demagnetizing field. This means that the remanence curves are measured in the conventional way but represented as a function of internal field. This internal field is calculated from Eq. (3) where for the magnetization the following value is chosen. The field is cycled between zero applied field and an increasing applied field, say $h^+_a$ (thus, a conventional measurement routine). The correction for the demagnetizing field is such that the magnetization in the presence of that magnetizing field $h^+_a$ is the appropriate quantity to use for $m$ in Eq. (3). With this correction Fig. 1 results in Fig. 3.

From Fig. 3 it can be seen that the DCD curve does not start at zero internal field. This is to be expected because in this case $H_{\text{int}}=-N_z M_r$, i.e., already a part of the switching field distribution (SFD) is reversed. The corresponding Henkel plot is shown in Fig. 4.

From Fig. 4 can be seen that plotting the IRM and DCD curves, for corresponding internal fields, results in a line that...
starts for \( \text{IRM}>0 \). Another striking point is that the Henkel plot, corrected for the demagnetizing field, does not result in a straight line. This implies that this correction can lead to false information, and should therefore not be applied.

Another example of how remanence curves, measured in the conventional way, can result in false information is shown in Fig. 5, where a Henkel plot is given as a function of the coercivity parameter \( \mu \). Although the interaction is set at a constant value of minus one, i.e., \( N_z = 1 \), the remanence results in very different curves. This is due to the fact that the coercivity determines the value of the remanence and, therefore, the internal field. Similar conclusions can be drawn by varying the coercivity distribution function \( \sigma \).

From the above it can be concluded that Henkel plots for perpendicular media, measured and represented in the conventional way, do not result in meaningful information. In the following the modification as proposed by Samwel and co-workers\(^2\) is investigated. In the modified remanence measurements the remanence is measured at zero internal field. This results in IRM and DCD curves that resemble the virgin curve and hysteresis curve, respectively. This is due to the fact that there is no switching of magnetization (\( H_{\text{int}}=0 \)), and to the fact that this model has no reversible component. The recoil lines are therefore horizontal lines.

The resulting Henkel plot, as a function of demagnetization factor, is shown in Fig. 6, from which it can be seen that the influence of demagnetization on the Henkel plot is more pronounced than was seen in the conventional remanence measurements (cf. Fig. 2). The introduction of a negative interaction, i.e., \( 0<N_z=1 \), again results in a bending of the curves below the Wohlfarth relation. Here, however, a larger interaction coincides also with larger bending.

To investigate this interaction more quantitatively in Fig. 7 a \( \delta H \) plot is constructed. From Fig. 7 it can be seen that the introduction of negative interactions result in lines with a negative slope that agrees with the value of the interaction. This is in agreement with Ref. 9 and indicates that interactions can directly be quantized from \( \delta H \). Note that \( \delta H \) is zero for zero interaction.

When the curves of Figs. 6 and 7 are corrected for the demagnetizing field, as described above, they all result in the Wohlfarth relation or \( \delta H \) is zero, respectively. This indicates that the modified remanence measurement, together with a correction for the demagnetizing field, results in proper information on residual interactions present in the material. Also when the equivalent from Fig. 5 is simulated for the modified remanence method, all lines coincide. This agrees with the expectation that when the interaction is set at a
constant value, the Henkel plot or $\delta H$ should not result in different curves.

To summarize this section it can be concluded that remanence curves of perpendicular materials measured in the conventional way, i.e., by sweeping the field back to zero applied field, can result in both reversible and irreversible rotation of magnetization. In order to obtain information on irreversible behavior and/or interaction effects only, the measurements should be performed with sweeping the field back to zero internal field (unconventional). In Sec. V this is examined experimentally. Note, however, that the simulations in this section are not fitted on the experimental results of Sec. V. The aim of this section is more to visualize the different measurement routines and demagnetization corrections and, thus, to obtain a qualitative insight in demagnetization trends.

Two remarks should be made to these theoretical conclusions. From the experimental point of view it was noted in Ref. 2 that the correction for the demagnetizing field is strongly dependent on the chosen value of the demagnetization factor and saturation magnetization (magnetic volume). This makes conclusions on interaction effects therefore very difficult. The second point is that the simulated remanence curves represent a particulate medium because a certain switching field distribution is assumed. This implies that remanence curves display a successive switching of particles with increasing coercivity. For materials inhibiting a negative interaction this will always result in IRM and DCD curves that cannot coincide because of their relative shift in internal field, $[H_{\text{IRM}}(h')<H_{\text{DCD}}(h')]$. For perpendicular materials that reverse their magnetization by domain-wall motion, however, the hysteresis curve is determined by a pinning distribution in combination with a domain structure. Whereas the domain structure is magnetostatically driven to reach a (metastable) equilibrium for a certain applied field, this means that the IRM and DCD in principle can coincide. This behavior is further investigated in Sec. V.

IV. EXPERIMENT

In this study three types of perpendicular magnetic media are investigated, i.e., Fe-Alumite, Co-Cr thin films, and Co-Pt-based multilayers. The Fe-Alumite films consist of 1-μm-long small iron needles and are varied in diameter and interparticle distances. The Co-Cr films are rf sputtered from alloyed targets under optimized conditions and varied in thickness, saturation magnetization, and magnetic anisotropy. The artificially patterned Co-Cr exhibits a bit-shaped structure. The strip width and length are in the order of 1-5 μm and also "bit period" and "track pitch" were varied. Photolithography was performed using a positive resist (Shipley S-1400-31), and ion-beam milling ($V_{\text{sec}}=500$ V, $I_{\text{cat}}=12.5$ mA, Ar flow: 200 sccm) which caused no annealing effects on the Co-Cr. The CoNi-Pt multilayer consists of alternating CoNi and Pt layers (17 stacks) and the Co-Pt multilayer of alternating Co and Pt layers (25 stacks). The most interesting parameters for this study are listed in Tables I, II, and III. For a more extensive description of these films the reader is referred to the literature.

V. RESULTS AND DISCUSSION

In this section experimentally obtained remanence measurements of perpendicular media are discussed. First Fe-Alumite is presented, then multilayers and as-sputtered Co-Cr films. This section ends with measurements on patterned Co-Cr to experimentally investigate remanence curves as a function of demagnetization factor.

A. Fe-Alumite

Fe-Alumite is a particulate medium and is therefore regarded as a model medium to experimentally verify the simulated trends of Sec. III. In Fig. 8 a typical example is shown of the IRM and DCD measurement, as obtained in the conventional way.

As can be seen the IRM curve stays almost horizontal until an applied field of about 100 kA/m is reached and then gradually increases to saturation. This behavior reflects a coercivity distribution with a very small number of particles exhibiting a coercivity less than 100 kA/m. The DCD curve equals minus one for zero applied field and immediately increases with a steep slope up to plus one. As stated previously in Sec. III this curve does not reflect the complete coercivity distribution. For zero applied field already a considerable part of the particles has been switched which makes its meaning unclear.

In Fig. 9 an example is shown of an unconventional remanence measurement on the same sample. As can be seen both the IRM and DCD curves reflect the coercivity distribution, i.e., the curves start off slowly almost horizontally.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr content (at. %Cr)</th>
<th>Thickness (nm)</th>
<th>$M_s$ (kA/m)</th>
<th>$H_{\text{IRM}}$ (kA/m)</th>
<th>$N_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>140391-2</td>
<td>21</td>
<td>470</td>
<td>463</td>
<td>72</td>
<td>0.72</td>
</tr>
<tr>
<td>140391-5</td>
<td>21</td>
<td>475</td>
<td>469</td>
<td>75</td>
<td>0.82</td>
</tr>
<tr>
<td>140391-8</td>
<td>21</td>
<td>485</td>
<td>470</td>
<td>77</td>
<td>1.00</td>
</tr>
<tr>
<td>140391-9</td>
<td>21</td>
<td>485</td>
<td>475</td>
<td>100</td>
<td>0.79</td>
</tr>
</tbody>
</table>

TABLE II. Magnetic and structural properties of the as-sputtered Co-Cr and multilayer samples.

TABLE III. Magnetic and structural properties of patterned Co-Cr samples.
and then gradually increase until saturation is reached. Note that both curves do not overlap until positive saturation is reached. This was already contributed in the end of Sec. III to indicate the particulate reversal mechanism. In the description of the multilayers and Co-Cr samples this is further discussed.

From Fig. 9 no direct information on interaction effects can be deduced; therefore, in Fig. 10 the corresponding Henkel plot is given together with the curves of the two other Fe-Alumite samples listed in Table I.

The three curves bend below the Wohlfarth line indicating a strong negative interaction (compare Fig. 6). Their relative positions are determined by their interactions but also coercivity distribution and the value of remanence and susceptibility of the major loop.

Because an interpretation of the magnitude of interaction is difficult, in Fig. 11 the corresponding $\Delta H$ plots are shown. In this figure all curves exhibit a negative slope of approximately $-0.9$ which indicates an interaction of equal value. It appears that sample B11 has the lowest interaction whereas sample B33 has the largest interaction. This seems to be in accordance with the pore diameter of the needles as given in Table I. If the interparticle distance is kept constant and the pore diameter increases then the demagnetization factor will increase to one.

Summarizing the measurements on Fe-Alumite it can be concluded that remanent measurements resemble the simulations of Sec. III quite well. Note, however, that no effort was made to fit the simulations to the experimental results because of the uncertainties in distribution function, magnetization value, and demagnetization factor. This latter factor is uncertain because of the inhomogeneous character of the material (not all pores are filled) and the magnetization dependence of the demagnetization factor.

When investigating the interaction $\Delta H$ plots are preferred above Henkel plots because they offer a direct determination of this interaction.

### B. Multilayers

Multilayers are at present extensively researched because of their (possible) application in MO recording. In this section we discuss two examples of conventional remanence measurements on multilayers and show their inability to conclude the interaction present in the materials.

The first type of multilayer investigated here is an example of a multilayer that exhibits a highly squared hysteresis loop. Its remanence curves are shown in Fig. 12. As can be seen the IRM curve resembles the behavior as previously
seen in Figs. 8 and 10. The DCD curve, however, shows an anomalous behavior. In the IRM curve parts of the sample have already reversed their magnetization where the DCD curve stays saturated (−1) up to approximately 100 kA/m. For a particle medium this would be a striking result because of the fact that the internal field of the DCD curve in this region is larger than that of the IRM curve. This type of multilayer, however, exhibits a reversal by domain-wall motion and the feature that it is very difficult to nucleate and/or stripe out domains. Therefore, the DCD curves lags behind with respect to the IRM curve because this curve starts off from the demagnetized state where a domain structure is already present.

This behavior is reflected in its corresponding Henkel plot (see Fig. 13) where this lagging behind is translated into a positive interaction. Once a domain structure is created the line quickly transforms into a negative interaction, confirming that these perpendicular materials exhibit negative interaction. One may question the significance of positive interactions when the reversal behavior of a domain structure in the IRM curve is compared to the saturated state of the DCD curve. It, of course, clearly shows the presence of a domain-wall-type material with nucleation and/or stripe-out field, but this information can also be deduced directly by comparing the virgin curve to the major loop.

This comparison of different domain structures at identical applied fields of both IRM and DCD curve becomes very apparent in Fig. 14. Here an example is shown of a nonsquare multilayer that exhibits a maximum normalized remanent value larger than one. This means that by sweeping the applied field a domain structure can be created which exhibits a larger domain-wall coercivity than the coercivity present in the major loop. As a result larger remanence values occur. The phenomenon of an increase in coercivity with decreasing domain period was reported by several authors who investigated the coercivity of minor loops in comparison with the corresponding major loop. The fact that it can also occur in remanence measurements again leads to the conclusion that information on interaction effects can be very unambiguous. As an example the Henkel plot of Fig. 14 is shown in Fig. 15, showing the unexpected behavior of the maximum remanent values larger than one (note the scale on the x and y axis).

Summarizing the two examples given of multilayers it can be concluded that for domain-wall-type reversal materials the information on the interaction effects can be very decisive. This is due to the fact that a domain structure can

![FIG. 12. Remanence curves obtained from conventional remanence measurement of ML Pt710.](image)

![FIG. 14. Remanence curves obtained from conventional remanence measurement of ML 921105.](image)

![FIG. 13. Henkel plot obtained from conventional remanence measurement of ML Pt710.](image)

![FIG. 15. Henkel plot obtained from conventional remanence measurement of ML 921105.](image)
not be translated into the concept of a fixed coercivity distribution. Although domain walls should interact with the same density and distribution of pinning sites, the domain structure itself also contributes to the coercive force.\textsuperscript{17} And whereas the domain structure of the IRM curve starts off in a (forced) demagnetized state and the DCD curve in the saturated state, very different domain structures can be present for similar internal fields. The coercivity distribution (SFD) extracted from IRM and DCD curves differs therefore not only because of interactions but also because of the measurement routine and history of the sample.

C. Co-Cr

In this subsection we discuss Co-Cr media which were investigated for perpendicular recording applications (see also Table II). The samples were all prepared under equal conditions\textsuperscript{15} except for their thickness, which ranged from 46 to 982 nm. The reversal mechanism for this type of material is generally classified neither as typically particulate nor as typically by domain-wall motion. Unconventional remanence measurements for the thicker films, however, resulted in curves that exhibited a maximum remanence larger than one. This maximum remanance was largest for the thickest film (max $\approx 1.2$) and decreased with decreasing thickness to a normal maximum of 1.0 for the 46 nm film. This indicates, at least partly, domain-wall-type reversal for the thicker films.

Another feature of these Co-Cr films is shown in Fig. 16, e.g., the IRM and DCD curves seem to coincide for applied fields larger than 100 kA/m. This behavior is different from that observed for the Fe-Alumite samples (Fig. 9) and would also imply reversal by domain-wall motion (see remark at end of Sec. III).

This overlap of IRM and DCD curves at higher applied fields is reflected in the Henkel plot as is given in Fig. 17. In this figure all lines coincide with a curve that is characterized by the relation $\text{DCD}(H') = -\text{IRM}(H')$. As already mentioned in Sec. III this can only be attained for films exhibiting non-particulate behavior.

From Fig. 17 it can be concluded that from such Henkel plots no quantitative information on (negative) interactions can be deduced. Therefore, in Fig. 18 an example is given of the corresponding $\delta H$ plot of Fig. 17, revealing clearly different behavior for the different films. It can be seen that the value of interaction decreases with film thickness, a behavior that can be understood from the reversal by domain-wall motion.

In the case of domain-wall-type reversal the domain structure (geometry and size) is magnetostatically driven and dependent on film thickness. For low-coercivity materials this behavior is known to be adequately described by the Kooy and Enz model,\textsuperscript{20} where a lowest-energy solution for the domain period and resultant magnetization is calculated as a function of applied field. Its solution scheme can be regarded as finding a tradeoff between minimizing the demagnetizing influence of the (oppositely) perpendicular magnetized domains and minimizing the domain-wall energy. It appears that the resulting demagnetizing influence of the domains, in this thickness regime, is lowest for the thinner films. This means that the shearing of the hysteresis curve increases with increasing thickness. Around coercivity this behavior can be approximated by\textsuperscript{21}

$$\chi^{-1} = 1 - 1.20 \sqrt{\lambda / T},$$

where $\chi$ stands for the susceptibility, $T$ for the thickness, and $\lambda$ for the characteristic length ($\lambda = \sigma \mu_0 M^2_z$), with $\sigma$ the
domain-wall energy. The demagnetizing influence can be deduced, in first approximation, by considering the relation $\chi \sim 1/N_z$.

When applied to these films a good agreement is obtained, even though these films cannot be considered as low coercive. For example, the 982 nm sample exhibits an average (theoretical) slope of 0.88 and the 46 nm sample exhibits an average slope of 0.55. This coincides with the slope of the $\delta H$ curves in Fig. 18.

Summarizing the investigated perpendicular Co-Cr samples it can be concluded that unconventional remanence curves can result in information on (negative) interactions. It should, however, be noted that quantitative information can only be obtained from $\delta H$ plots and not from Henkel plots. This is due to the fact that the IRM and DCD curve, for the samples investigated here, overlap at applied fields higher than approximately two times the coercivity.

D. Patterned Co-Cr

In the previous subsection four Co-Cr samples were considered that should exhibit a $-1$ (demagnetizing) interaction because their shape can be regarded as an infinite plate. The $\delta H$ plot, however, resulted in different interactions and a possible explanation was found in the Kooy and Enz model. The drawback in this approach is that it assumes the intrinsic properties of the Co-Cr samples to be equal. This is not true, although the samples were prepared under equal conditions. The thickness was varied, as was, therefore, sputter time. In order to circumvent this drawback we patterned a Co-Cr wafer into differently shaped samples. In this way the demagnetizing influence (shape anisotropy) was varied but the intrinsic properties were not changed. The demagnetizing influence was determined from torque measurements by comparing the effective anisotropy to an as-sputtered sample ($N_z = 1$).

In Fig. 19 the resulting Henkel plot is shown for unconventional remanence measurements. As can be seen all curves overlap. This is in disagreement with Fig. 6 from which an increase in bending below the Wohlfarth line is to be expected with increasing demagnetization factor. It consequently points to nonparticulate reversal behavior as is also seen in Fig. 17.

In Fig. 20 a $\delta H$ plot is constructed in order to extract information on the demagnetizing interaction. The demagnetizing influence can be seen clearly and a qualitative agreement is attained, e.g., the lower the demagnetization factor, the lower the slope of the $\delta H$ curve. The value of the slope of this curve, however, is approximately 0.2 below the value of the demagnetization factor. This can probably be explained by the fact that these films also exhibit a domain structure that increases their susceptibility and therefore looks like a lower effective demagnetizing influence. Note in that respect the influence of a domain structure on the slope of the $\delta H$ curves in Fig. 18.

Summarizing this section it can be said that a change in demagnetization of the Co-Cr samples investigated here does not have any effect on the Henkel plot. It does, however, have an effect on the $\delta H$ plot and shows qualitative agreement with the demagnetization factor.

VI. SUMMARY AND CONCLUSIONS

In this article remanent measurements of perpendicular magnetic thin films were simulated and experimentally measured. It follows that the results differ from those obtained for in-plane magnetic media and are difficult to interpret.

The simulations served the purpose of attaining a better understanding of the impact of a mean demagnetizing field on particulate reversal behavior. These simulations confirmed the inability of deriving information on irreversible behavior and/or interaction by measuring remanence curves of materials with a nonzero demagnetization factor in the conventional way. Therefore, an unconventional method, as proposed by Samwel and co-workers, was investigated and visualized. From this can be concluded that information on irreversible behavior and/or interaction effects can be derived. However, this information is very hard to quantify because corrections for the demagnetizing field are very sensitive to the chosen value of demagnetization factor and saturation magnetization (magnetic volume). The $\delta H$ plot was shown to circumvent this problem.
In Sec. V the experimentally obtained results were discussed. In this section several examples were given of perpendicular media, which seem to exhibit anomalous behavior in comparison to in-plane materials. Four types of perpendicular media were investigated: Fe-Alumite, Co-Pt–based multilayers, Co-Cr, and patterned Co-Cr.

Fe-Alumite is a particulate medium and resembles the features of the simulations quite well. It was shown that the conventionally obtained DCD curve cannot exhibit information on the complete coercivity distribution (SFD). The unconventional remanent measurements lead to Henkel plots from which no information on interactions can be derived directly. The $SH$ plot showed a negative interaction of approximately 0.9 and showed agreement with the packing density of the columns.

The multilayers investigated here served the purpose of showing that for domain-wall-type reversal materials the information on interaction effects can be very indecisive. Anomalous behavior of remanent values, which exceeded the value of the saturation remanence, was present. The influence of a nucleation field also shows that the concept of a coercivity distribution (SFD) cannot be transferred to multilayers. The nonparticulate reversal behavior is held responsible for this and shows that IRM and DCD curves depend not only on interactions but also on the measurement routine and history of the sample.

Some of the Co-Cr samples, measured in the conventional way, also showed remanent values that exceeded the value of the saturation remanence. This behavior indicates, at least partly, reversal by domain-wall motion. Furthermore, the unconventional obtained IRM and DCD curves showed an overlap at applied fields higher than approximately two times the coercivity. This result could not be confirmed by the simulations and is also an unexpected result for particulate media because in general the internal fields of the IRM and DCD curves must differ. Quantitative information, obtained from $SH$ plots, showed a close connection to the slope of the hysteresis curve.

Artificially patterned Co-Cr was investigated in order to study the influence of demagnetization on remanence curves. It can be said that a change in demagnetization of the Co-Cr samples investigated here did not have any effect on the Henkel plot. It did, however, on the $SH$ plot showing qualitative agreement with the demagnetization factor of the samples.

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