Techniques for measuring small changes in the orientation of the easy axis in permalloy films

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It is well known that the orientation of the easy axis in permalloy can be affected by annealing. The need in our research for detailed information of the behavior of the easy-axis orientation in the temperature range from room temperature to 100 °C and the absence of measurement techniques to derive this information, led to the development of two new measurement techniques: (1) an adapted version of the Crowther method for measuring dispersion in easy-axis orientation combined with the optical Kerr technique and (2) a new measurement technique for determining the orientation of the easy axis combined with a galvanomagnetic method for determining magnetization direction. Both methods give detailed information on the behavior of the easy-axis orientation as a function of temperature. The resolution of both methods is 0.01° and may be increased, especially for the optical method. The optical method imposes few restrictions on film geometry and may be used, e.g., during a fabrication process. The easy-axis behavior can be observed locally. The galvanomagnetic technique requires four electrical contacts on the film. The easy-axis behavior is averaged over the total current-carrying area. This method can be used for observing the behavior of the easy axis in encapsulated devices.

INTRODUCTION

In our research on magnetic sensors^{1,2} using the anisotropic magnetoresistance effect³ in permalloy (82 at. % Ni, 18 at. % Fe), we experienced the need for measuring small changes in the orientation of the easy axis of magnetization in permalloy films. It has been known for a long time that the orientation of the easy axis of permalloy films can be modified by annealing at temperatures below 100 °C in a 4 kA/m magnetic field.^{4,5} Besides this irreversible annealing effect, we found a reversible temperature dependence of the easy-axis orientation, showing a few tenths of a degree rotation over a 50 °C temperature range. Details on this phenomenon will be given elsewhere.⁶

The orientation of the easy axis may be determined in a number of ways. For ferromagnetic thin films having in-plane anisotropy, only in-plane magnetic field and magnetization components have to be considered. In the measurement methods to be mentioned below, an alternating magnetic field $H \sim$ is applied at an angle φ (to be determined) to the mean easy axis. Furthermore, static magnetic field components parallel ($H_{\parallel}$) and perpendicular ($H_{\perp}$) to $H \sim$ may be present. Magnetization components parallel ($M_{\parallel}$) or perpendicular ($M_{\perp}$) to $H \sim$ can be measured while slowly rotating the film. When a certain condition is met, φ has reached a known value as indicated in the following. Among the methods available:

(A) Observation of the M vs $H \sim$ hysteresis loop. When the curve is most linear around the origin, φ equals 90°.

(B) Measuring the anisotropy field H_k using the Kobellev⁷ or improved Kobellev⁸ method. The maximum (and true) value of H_k is found when $\varphi = 45^\circ$.

(C) Measuring the amplitude of $M_{\perp}$ when only a large field $H \sim$ is present. A zero amplitude will be measured for $\varphi = 0^\circ$ or $\varphi = 90^\circ$.

(D) Measuring the amplitude of $M_{\parallel}$ when a large $H_{\parallel}$ is superimposed on $H \sim$. Again, a zero amplitude will be measured for $\varphi = 0^\circ$ or $\varphi = 90^\circ$.

Method (A) is most frequently used in practice, but it is not very accurate, and in some cases an unambiguous position of maximum linearity is difficult to find. The methods under (B) are indirect and time consuming. The other methods (C) and (D), which will be discussed in more detail, may seem to be quite similar, but the magnetic processes in the film are rather different and they differ in sensitivity as well. Both methods are well suited to monitoring small changes in easy-axis orientation.

In all methods previously mentioned, some magnetization component must be measured, which can be done in different ways, e.g., (for permalloy), (a) inductively, (b) using the magneto-optical Kerr effect, or (c) galvanomagnetically using the anisotropic magnetoresistance effect. The inductive method is most general, but its implementation often poses heavy constraints on film thickness and substrate dimensions. The magneto-optical method generally offers a large freedom in film and substrate dimensions while having the additional advantage of position-dependent measurement. The galvanomagnetic method requires electrical contact to be made with the film and it is not as flexible as (a) and (b) in selecting a particular M component for measurement, but it has the advantage that completed and encapsulated galvanomagnetic devices can be tested.

Each of the methods (A) through (D) can, in principle, be combined with each of (a) through (c). We have chosen to develop two measurement systems: (I) combination Cb and (II) combination Dc. Both methods (I) and (II) can be made very sensitive and accurate. In our implementation however, the magneto-optical method (I) was less accurate due to the use of an existing magneto-optical curve tracer incorporating low-precision positioning equipment and an

improvised heating device. We used the magneto-optical method for fast qualitative measurements to check the influence of various processing steps during manufacture of our sensor devices.

I. MAGNETO-OPTICAL MEASUREMENT METHOD

Using the longitudinal Kerr magneto-optical effect, the local state of magnetization in a thin permalloy film can be determined. In the arrangement, shown in Fig. 1, where linearly (*s*-)polarized light is incident on a permalloy film, the reflected light will, in general, be elliptically polarized with the major axis rotated by a small⁹ amount, proportional to the magnetization component in the plane of incidence.

Light from He-Ne laser L_1 is passed through optics O_1 and polarizer P_1 to the permalloy film F . O_1 allows the diameter of the light spot on F to be adjusted from 0.1 to 10 mm. The reflected light passes through analyzer P_2 and optics O_2 which images F on photodetector D . The film F is located in the *x-y* plane; the plane of incidence is the *x-z* plane. Polarizer P_1 is oriented in such a way, that only the E_y component of the light is transmitted.

Analyzer P_2 is oriented with its polarizing axis at approximately 45° to the *y* axis. The light-intensity variations produced at D are approximately proportional to the magnetization component M_x in F . The film can be rotated about the *z* axis by a rotation stage R ; the film is located at the center of two orthogonal Helmholtz pairs (not shown), respectively, producing magnetic field components in *x* and *y* directions. Finally, the film F can be heated by the incandescent lamp L_2 , which is imaged on F by optics O_3 .

The magnetic measurement setup is equivalent to Crowthers method I for measuring angular dispersion of anisotropy.¹⁰ The mean easy axis of the permalloy film is oriented at a (small) angle φ to the *x* axis. H_y is an alternating magnetic field with amplitude larger than the anisotropy field H_k , saturating the film periodically; H_x is adjusted to

zero by compensating for the Earth's magnetic field. For the purpose of qualitative measurements, the ac component of the photodetector signal is fed to the vertical channel of an oscilloscope, while a signal proportional to H_y is applied to the horizontal channel.

The film splits up into two sets of magnetic domains in which the magnetization vectors rotate (in the *x-y* plane) synchronously with the alternating field H_y . The sense of rotation is opposite for both sets. When the easy axis is parallel to the *x* axis ($\varphi = 0$), each set comprises one half of the film area, so that the M_x components of both sets cancel out for all values of H_y . In this case the oscilloscope will show a single horizontal trace. If $\varphi \neq 0$, the two sets will not cancel out completely and a resulting M_x component will remain as shown in Fig. 2(a), extrema occurring at the zero crossings of H_y . As φ increases, the maximum M_x difference ΔM_x will increase until for a certain value φ_s one set of domains disappears completely, so that the magnetization in the film rotates coherently. Then ΔM_x will have the maximum value $2M_s$, where M_s is the saturation magnetization of the film. When $\Delta M_x/2M_s$ is plotted vs φ , the distribution function of angular dispersion is obtained (Fig. 3). In permalloy films, φ_s usually is of the order 1° . ΔM_x can be measured accurately using a lock-in amplifier, locking in quadrature to H_y .

The same measurement setup can be used for measuring the stability of the easy-axis orientation of the permalloy film. At room temperature φ is adjusted to be 0° ($\Delta M_x = 0$). Then the lamp L_2 is switched on, heating the film. If ΔM_x changes to a value $\neq 0$, this must be due to φ becoming $\neq 0$. Measurements have shown that no mechanical rotation of the film with respect to the rest of the structure occurs, so that any change of φ must be caused by a rotation of the easy axis with respect to the film itself. Two methods can be employed for measuring φ :

(1) If the ΔM_x vs φ curve has been measured before, it can be used as a calibration curve for ΔM_x as a measure for φ ;

(2) The rotation stage R can be continuously adjusted to keep $\Delta M_x = 0$, so that the rotation angle of R is always kept equal to φ . Method (1) can be easily used when $\varphi \ll \varphi_s$. However, some uncertainty is introduced as the calibration curve might be temperature dependent. The second method is preferred for accurate measurements (and necessary for measuring large rotations of the easy axis), but then the addition of a control system for automatically adjusting the rotation stage is highly desirable for ease of measurement.

FIG. 1. The Kerr measurement arrangement. A light beam from laser L_1 is polarized by P_1 and reflected by a permalloy film F . With optics O_1 , the diameter of the light spot on the film surface can be adjusted. The reflected beam passes through the analyzer P_2 and optics O_2 . The intensity of the beam is then measured by detector D . Changes in the Kerr rotation can thus be observed as changes in the signal from D . The orientation of the easy axis in F can be adjusted with rotation stage R . The film F can be heated by the incandescent lamp L_2 , which is imaged on F by optics O_3 .

FIG. 2. Magnetization M_x vs magnetic field H_y . (a) $H_x = 0$; $\varphi \neq 0$, (b) $H_x \neq 0$; $\varphi = 0$.

FIG. 3. Distribution function of angular dispersion. ΔM_x is the peak-to-peak change in magnetization component M_x observed in the measurement. M_s is the saturation magnetization and φ is the angle between the x axis and the easy axis in the permalloy. For $\varphi = 0$, the alternating magnetic field is perpendicular to the easy axis. $\Delta M_x/2M_s$ increases monotonically with φ until it reaches a value of 1 at $\varphi = \varphi_s$.

In our provisional implementation of the measurement system, we had to use a manually operated rotation stage exhibiting 0.2° accuracy and resolution. Using method (1), a measurement resolution of 0.01° was obtained.

II. GALVANOMAGNETIC MEASUREMENT METHOD

A second way to detect changes in the easy-axis orientation is proposed. The technique resembles the improved Kobelev method for measuring the anisotropy field.⁸ Consider a thin permalloy film in a homogeneous magnetic field $\vec{H}(t)$. The easy axis of the film is oriented at an angle α to the x axis, as shown in Fig. 4; as a consequence of ambient conditions, α may show a deviation $\Delta\alpha$ from the initial orientation angle α_0 : $\alpha = \alpha_0 + \Delta\alpha$. $\vec{H}(t)$ is directed at an angle φ to the x axis, and its magnitude is chosen to be

$$|\vec{H}(t)| = H_0 + H_1 \sin(\omega t), \quad H_0 - H_1 > H_k, \quad (1)$$

where H_k is the anisotropy field of the permalloy film. $\vec{H}(t)$ varies in strength, not in direction, and should be carefully aligned with the Earth's magnetic field. The condition on H_0 and H_1 in (1) must be fulfilled in order to prevent switching in the film and to ensure coherent rotation of the magnetization. For permalloy, H_k is usually smaller than 500 A/m.

The following calculation is based on the assumption that the Stoner-Wohlfarth single domain model¹¹ is valid and that demagnetizing fields in the film are homogeneous. The direction of the saturation magnetization $\vec{M}_s$ in the film (see Fig. 4) will oscillate between two extrema (Θ_1 and Θ_2), while the magnetization itself will remain homogeneous

FIG. 4. Field and magnetization in a permalloy film. $\vec{H}(t)$ is the sum of an alternating magnetic field and a large constant field. The angle between the field and x axis is called φ . The angle between the easy axis and the x axis at room temperature is called α . The magnetization vector $\vec{M}_s$, oriented at an angle Θ with the x axis, will oscillate between the extrema Θ_1 and Θ_2 .

throughout this process. The amplitude of the oscillation, $\Theta_1 - \Theta_2$, will be zero when $\vec{H}(t)$ is parallel or perpendicular to the easy axis. From Ref. 11 we know that

$$\sin(\varphi - \Theta) = (H_k/2H) \sin 2(\Theta - \alpha). \quad (2)$$

When $\vec{H}(t)$ is parallel to the initial easy axis ($\varphi = \alpha_0$), (2) can be approximated by

$$\Theta(t) = \alpha_0 + \left(\frac{H_k/H(t)}{1 + H_k/H(t)} \right) \Delta\alpha, \quad |\Delta\alpha| < 1^\circ. \quad (3)$$

When $\vec{H}(t)$ is perpendicular to the initial easy axis ($\varphi = \alpha_0 + 90^\circ$), (2) can be approximated by

$$\Theta(t) = \alpha_0 + 90^\circ + \left(\frac{H_k/H(t)}{1 - H_k/H(t)} \right) \Delta\alpha, \quad |\Delta\alpha| < 1^\circ. \quad (4)$$

The amplitude of the oscillation in Θ is zero for $\Delta\alpha = 0$ and is linearly dependent on $\Delta\alpha$.

The changes in magnetization direction can be detected using the galvanomagnetic properties of permalloy. A current I flows through the film in a direction parallel to the x axis (Fig. 5). A voltage can be measured parallel to the current flow (V_{mr} , magnetoresistance effect) or perpendicular to the current flow (V_{ph} , planar Hall effect). The dependence of these voltages upon the direction of magnetization is described by¹²

$$\begin{aligned} V_{mr} &= Ik_1[\rho - \Delta\rho \sin^2(\Theta)], \\ V_{ph} &= Ik_2(\Delta\rho/2) \sin(2\Theta), \end{aligned} \quad (5)$$

where ρ and $\Delta\rho$ are the resistivity and magnetoresistive effect of the permalloy film, respectively, k_1 and k_2 are geometric factors, and Θ is the angle between the magnetization and the current direction. The current density at any point in the film is assumed to be constant over the film thickness. When (5) is used for measuring the direction of the magnetization, we find an averaged value over the film area. Different parts of the film will contribute to the measured voltage in a different way, depending on film and contact geometry. Therefore, it is desirable to have a homogeneous magnetization in the film.

Both the planar Hall effect and the magnetoresistance effect can be used to detect the changes in magnetization direction. The following calculations are restricted to the planar Hall effect. The calculations for the magnetoresistance effect are identical, but one should take care to use a current flow at an angle of approximately 45° to the easy axis of the permalloy.

FIG. 5. A planar Hall configuration. A driving current I flows through the film. Two voltages, V_{mr} and V_{ph} , can be measured, which depend on the magnetization direction in the permalloy.

The signal voltage derived from the voltage contacts of the film will be 90° out of phase with inductive voltages from the connecting wires, caused by $\bar{H}(t)$. The inductive voltages can be canceled out using a lock-in amplifier. An offset voltage, arising from misalignment of the planar Hall configuration, consists of a small fraction of the magnetoresistance signal V_{mr} . Simulation shows that offset voltages have minor influence on signal amplitude and measurement accuracy.

Highest sensitivity for small changes in magnetization direction is achieved when the current flow is parallel or perpendicular to the field direction. We take care to position the current contacts along the easy axis ($\alpha_0 \approx 0$). Deviations of up to 20° from the desired current direction only cause a small decrease in signal amplitude and linearity in the measurement as will be demonstrated below.

Figure 6 shows the complete measurement configuration. A rotation stage R is used to position the easy axis of the film with respect to the magnetic field, $H(t) = H_0 + H_1 \sin(\omega t)$, which is generated with sine generator G and power amplifier A, supplying current to a Helmholtz pair. The permalloy film is driven with a current I from current source C and the planar Hall signal from the film is connected to the input of the lock-in amplifier (LIA). The output from G is used as reference signal. To adjust the phase shift of the LIA, the current I is made zero. The phase of the LIA reference input is adjusted to give zero output signal. Only signal voltages from the permalloy film are now detected when the current through the film is reestablished.

The permalloy is heated with hot air from a blower B. Temperatures of up to 80°C can be reached. The voltage across the current contacts on the film is used as an indication for the temperature of the permalloy. This voltage is directly proportional to the resistance R of the element. We measured resistivity versus temperature for our permalloy films (Fig. 7) and found that temperature may be derived as a linear function from resistivity within an error of 1°C . Temperature indication and output voltage of the LIA were fed to the X and Y channel of an XY plotter. In this way, direct plots of easy-axis orientation versus temperature were derived.

FIG. 6. The galvanomagnetic measurement configuration. A generator G and amplifier A are used to drive a pair of Helmholtz coils. The permalloy film is positioned in the field of the coils and driven with a constant current from a current source C. The signal from the film is amplified by an operational amplifier followed by a lock-in amplifier (LIA). The output of the LIA is plotted on a X-Y recorder together with a temperature signal derived directly from the film. A rotation stage R is used to rotate the film. The film can be heated with hot air from a blower B.

FIG. 7. Resistance vs temperature for a permalloy strip.

The output signal of the LIA will be

$$V_{\text{out}} = A \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T I k_2 \frac{\Delta \rho}{2} \sin[2\Theta(t)] \sin(\omega t) dt, \quad (6)$$

with $\Theta(t)$ as in (3) or (4) when $\bar{H}(t)$ is parallel or perpendicular to the easy axis, respectively. A is the gain of the LIA and preamplifier (see Fig. 6).

Computer simulations of V_{out} have been performed. When $|\alpha_0| < 20^\circ$, $|\Delta\alpha| < 1^\circ$, and $H_0 - H_1 > 2H_k$, we find that the nonlinearity of V_{out} as a function of $\Delta\alpha$ is less than 0.2% of full scale range when $\varphi = \alpha_0$ (easy axis parallel to the field) and less than 0.5% when $\varphi = \alpha_0 + 90^\circ$ (easy axis perpendicular to the field). For these conditions of α_0 , $\Delta\alpha$, H_0 , and H_1 , (6) may be approximated by

$$V_{\text{out}} = F A I k_2 (\Delta \rho / 2) 2 \cos(\alpha_0) \Delta \alpha, \quad (7)$$

with

$$F = \frac{H_k}{H_1} \left(1 - \frac{H_0^*}{\sqrt{(H_0^*)^2 - (H_1)^2}} \right),$$

where $H_0^* = H_0 + H_k$ for the field parallel to the easy axis and $H_0^* = H_0 - H_k$ for the field perpendicular to the easy axis.

A calibration measurement of V_{out} vs φ is depicted in Fig. 8. The behavior of V_{out} is identical for small changes in φ

FIG. 8. A calibration curve of V_{out} vs φ . The field is parallel to the easy axis. The solid line was calculated with Eq. (7). $H_0 = 1200$ A/m, $H_1 = 400$ A/m.

Fig. 9. Easy-axis rotation vs temperature for a typical film.

and α . Rotation stage R was used to increase φ . No significant deviations from a straight line are apparent. The solid line in Fig. 8 was calculated with (7).

High dispersion in easy-axis orientation in the permalloy will slightly decrease the measurement sensitivity. The measurement linearity will not be affected.

Magnetic form effects due to the geometry of the planar Hall element will reduce the measured rotation of the intrinsic easy axis. In fact, the measured rotation is the rotation of the averaged effective anisotropy, combining intrinsic anisotropy with magnetic form effects.¹³

A typical result of a measurement is shown in Fig. 9. A permalloy film was heated and cooled down to room temperature after 15 min. A reversible and an irreversible change of easy-axis orientation are apparent.⁶

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