ORTHOGONAL THIN FILM MAGNETOMETER USING THE ANISOTROPIC MAGNETORESISTANCE EFFECT

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Abstract

In an orthogonal thin film magnetometer a driving field oriented in the plane of a permalloy film along its hard-axis, saturates this film periodically in positive and negative direction. On return from saturation and in absence of a magnetic field component along the easy-axis, the magnetization in 50% of the film will rotate clockwise and in the remaining 50% anticlockwise giving rise to domain formation.
With an easy-axis field component H_m, more than 50% will rotate in a sense determined by H_m and a net magnetization M_m will be present as the drive field goes through zero. H_m is measured by detecting M_m.
In previous proposals M_m is detected inductively. We propose the application of the anisotropic magnetoresistance effect by measuring either the planar Hall voltage or the resistance of the film with the dc-current at respectively 0° or 45° to the easy-axis. Expressions for the sensitivity of both the inductive and the magnetoresistive detection methods are derived, showing that the magnetoresistive method behaves better under miniaturization.
With a 1 cm square permalloy film, using phase-sensitive detection of the planar Hall voltage, synchronously with the third harmonic of the drive frequency, 3×10^{-5} V m/A sensitivity and 0.01 A/m resolution have been obtained.

Introduction

Many sensors for measuring magnetic field strength in the range $10^{-3}..100$ A/m are known. The normal Hall effect can be used if (bulky) flux-concentrators are employed [1]. Many types of fluxgate magnetometers [2] and thin film magnetometers using inductive detection [3] have been described. If these magnetometers have to be miniaturized, rather high drive field frequencies must be used. On the other hand the anisotropic magnetoresistance effect can be used. To achieve true vector-performance with this type of magnetometer however rather accurate dc-bias fields must be applied [4].
We propose the combination of a well-known orthogonal thin film magnetometer principle [5],[6] with detection by means of the anisotropic magnetoresistance effect.

In an orthogonal thin film magnetometer a driving field H_d, oriented in the plane of a permalloy film along its hard axis, saturates this film periodically in positive and negative direction. On return from saturation and in absence of a magnetic field component along the easy-axis, the magnetization in 50% of the film will rotate clockwise and in the remaining 50% anticlockwise giving rise to domain formation.
With an easy-axis field component, which is the field to be measured H_m, more than 50% will rotate in a sense determined by H_m and a net magnetization M_m will be present as the drive field goes through zero. Figure 1 shows this magnetization component as a function of H_m. The slope and range of the curve are determined by the characteristics of the magnetic anisotropy in the film (mean anisotropy field and angular dispersion).

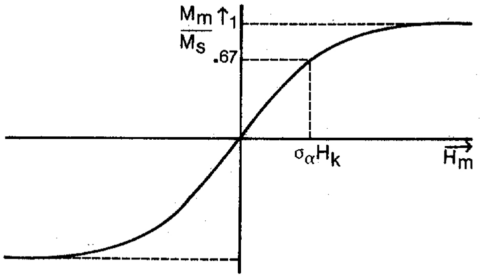

Figure 1: Easy-axis magnetization at drive-field zero-crossing versus easy-axis field.

H_m can be measured by detection of M_m. In proposals presented until now M_m is detected inductively. We propose to exploit the anisotropic magnetoresistance effect to do this.

Method of detection

When a constant current I is applied parallel to the geometrical axis (length) of a suitable ferromagnetic strip, the anisotropic magnetoresistance -mr- effect manifests itself in two ways: 1) a change in the voltage across the length of the strip (the magnetoresistance -MR- effect in a narrower sense), and 2) a voltage across the width of the strip (the planar Hall -PH- effect).
For optimum sensitivity of the device, the easy-axis of magnetization must make a 45° angle with the direction of current (strip-axis) in the MR-case and a 0° angle in the PH-case (figure 2).

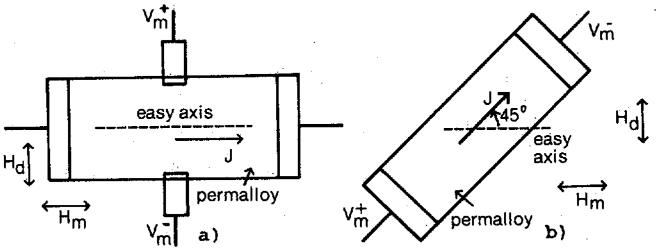

Figure 2: Sensor layout: a) planar Hall effect,
b) magnetoresistance effect.

In these configurations, "domains" rotating in opposite directions will give contributions of opposite polarity to the overall PH or MR voltage, V_m. Figure 3 displays this voltage during one period of the drive-field. As can be seen from this figure, the first and third harmonic of the drive-field frequency are prominently present in the output signal, having about equal amplitudes. The third harmonic however is preferred for detection, because a first harmonic component can be generated also by inductive coupling between drive- and output-circuit of the sensor.

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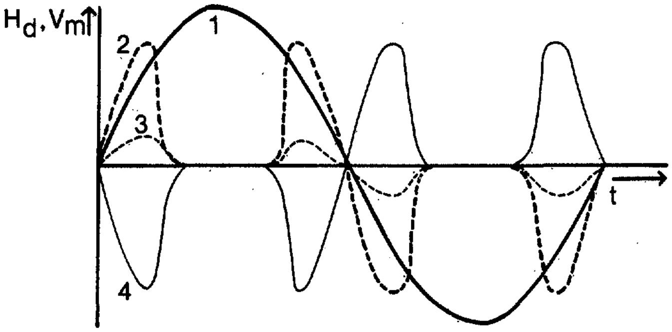

Figure 3: Drive-field and PH or MR voltage versus time; curves 1: drive-field, 2 to 4 output voltage at H_m = 2, 0.5 and -2 A/m respectively.

Phase-sensitive detection, synchronously with the third harmonic of the drive signal, is exploited resulting in a signal V_s, which is proportional to M_m.
Sensitivity is largest around the origin, so in a magnetic field measurement application, the sensor is preferably used as a zero-field detector in a feedback arrangement.

Sensitivity

The sensitivity of the device can be derived with the aid of a simple dispersion model: the anisotropy field is uniform throughout the film (no magnitude dispersion) and the angular dispersion of the easy-axis shows a normal distribution having a standard deviation σ_α.

For the magnetization component M_m can be derived[7]:

$$\frac{\partial M_m}{\partial H_m} = \frac{M_s}{H_k} \chi_1 \tag{1}$$

$$\chi_1 = \chi_{10} \exp\left(-\frac{1}{2}\left(\frac{H_m}{\sigma_\alpha H_k}\right)^2\right) \tag{2}$$

$$\chi_{10} = \frac{1}{\sigma_\alpha} \sqrt{\frac{2}{\pi}} \tag{3}$$

where: χ_1 = the normalised orthogonal susceptibility
χ_{10} = the initial value of χ_1
M_s = the saturation magnetization of the film.

For low fields H_m the sensitivity is largest and M_m can be approximated by:

$$\frac{M_m}{M_s} = \frac{1}{H_k} \chi_{10} H_m \tag{4}$$

The amplitude of V_m is proportional to M_m/M_s:

$$\hat{V}_m = \hat{V}_{sat} \frac{M_m}{M_s} \tag{5}$$

At saturation ($M_m = M_s$):

$$\hat{V}_{PH,sat} = \frac{1}{2} \Delta\rho \; w \; J \; F \tag{6a}$$

$$\hat{V}_{MR,sat} = \frac{1}{2} \Delta\rho \; l \; J \tag{6b}$$

where: $\Delta\rho$ = the absolute resistance-anisotropy of the film,
J = the current density in the strip,
w, l = width, length of the strip,
F = F(w/l) = dimensionless geometrical correctionfactor.

So finally combining (3), (4), (5) and (6) we find for low fields H_m:

$$\hat{V}_{PH} = \frac{\Delta\rho \; w \; J \; F}{\sigma_\alpha \; H_k \sqrt{2\pi}} H_m \tag{7a}$$

$$\hat{V}_{MR} = \frac{\Delta\rho \; l \; J}{\sigma_\alpha \; H_k \sqrt{2\pi}} H_m \tag{7b}$$

This result can be compared to the sensitivity in the case of inductive detection.
The voltage induced in the detection coil is:

$$V_i = \mu_o \; H^1 \; Q \frac{dM_m}{dt} \tag{8}$$

where: $H^1 = G \frac{N}{r}$ (9)
the magnetic field generated at the film-location by a unit current through the coil,
G = a dimensionless factor depending on coil-geometry,
r = a typical coil dimension,
N = the number of turns of the coil,
μ_o = the permeability of vacuum ($= 4\pi \times 10^{-7}$ Vs/Am),
Q = the volume of the film.

Combining (3), (4), (8) and (9) we find for the amplitude of the second harmonic component of the signal:

$$\hat{V}_i = \frac{8\pi\mu_o \; f \; G \; N \; Q \; M_s}{r \; \sigma_\alpha \; H_k \sqrt{2\pi}} H_m \tag{10}$$

where: f = drive-field frequency.

For a comparison of both detection methods the signal power, available to a well matched amplifier input, should be considered.
For the general magnetoresistive detection we find:

$$P_{mr} = \frac{\Delta\rho^2 \; J^2 \; Q \; F'}{8\pi \; \sigma_\alpha^2 \; H_k^2 \; \rho} H_m^2 \tag{11}$$

where: F' = F'(w/l,s/l), a dimensionless factor, depending on sensor-geometry,
F' = 1 for the MR-effect, F' < 1 for the PH-effect,
s = the width of the Hall voltage contacts,
ρ = the average resistivity of the film ($= 3 \times 10^{-7}$ Ωm).

For inductive detection:

$$P_i = \frac{8 \; \mu_0^2 \; f^2 \; G' \; Q^2 \; M_s^2}{\sigma_\alpha^2 \; H_k^2 \; r \; \rho_{Cu}} H_m^2 \tag{12}$$

where: G' = a dimensionless factor, depending on coil geometry,
ρ_{Cu} = the resistivity of the coil windings ($= 2 \times 10^{-8}$ Ωm).

The power-ratio:

$$\frac{P_{mr}}{P_i} = \frac{\Delta\rho^2 \rho_{Cu} J^2 F' r}{64\pi \mu_o^2 \rho f^2 M_s^2 G' Q} \qquad (13)$$

is proportional to r/Q, where the typical coil dimension r can be scaled with a linear film-dimension. From this dependence, we can see that the magnetoresistive detection method behaves favourably under miniaturization, compared to the inductive method.

Up till now, our experiments have concentrated (for historical reasons) on the application of the planar Hall effect. As can be seen from a comparison of (7a) and (7b), for a given permalloy film area a much larger sensitivity can be obtained by using the magnetoresistance effect, which has the additional advantage that a smaller current is required to realize a given current-density. In this case a trade-off must be made between sensitivity and drive-field requirements, as the demagnetizing field, opposing the drive-field, will increase as the width of the permalloy strip decreases. (Film thickness cannot be reduced indefinitely.)

Experimental

Permalloy ($Ni_{81}Fe_{19}$) films of 10x10 mm and 50 nm thickness have been prepared by both vacuum evaporation and sputtering. Measurements have been made using the planar Hall effect. Drive-field frequency was in the order of 100 Hz. For $J = 2\times10^8$ A/m^2, $H_k = 430$ A/m, $\sigma_\alpha = 0.038$ (2.2°), $\Delta\rho = 5.8\times10^{-9}$ Ωm, w = 10 mm, a sensitivity $V_m/H_m = 130$ μV m/A was found. From (6a) the theoretical value for the sensitivity is found to be 167 μV m/A. The discrepancy with the measured value might be explained by the angular dispersion not having a normal distribution.

By multiplying the Hall voltage V_m with a square wave with three times the drive-frequency and feeding the result to a low-pass filter having a 0.1 s time-constant, the third and related higher harmonics contained in V_m were detected, giving a final signal V_s. Figure 4 shows a recorded example.

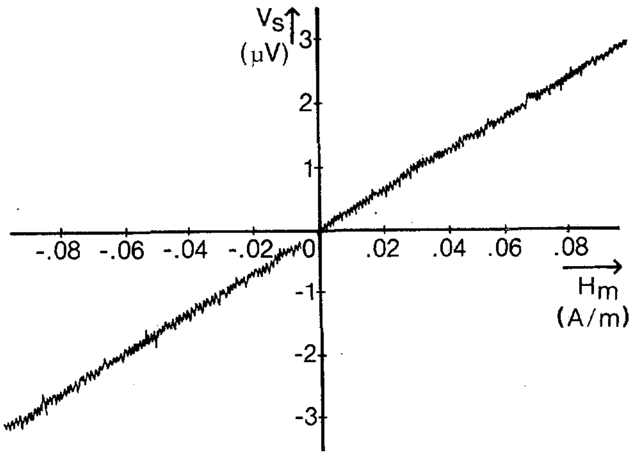

Figure 4: Final signal versus easy-axis field.

In the relation between V_m and H_s hysteresis (not visible in figure 4) has been observed which by increasing the drive-field amplitude could be reduced to less than the detection limit of about 5×10^{-3} A/m. In general for our sputtered films a drive-field amplitude of 1000 A/m was sufficient to do this; the evaporated films needed much larger drive-fields and showed large individual differences.
The occurrence of hysteresis implies that some parts of the film are not saturated by the drive-field. This could be due to large local demagnetizing fields at the film edges or to dispersion of the magnitude of anisotropy. As films with equal dimensions (and consequently equal demagnetizing fields) show large differences in their hysteresis behaviour, at least a part of the hysteresis is ascribed to magnitude dispersion. As we do not have at our disposal an independent method for measuring this dispersion, we could not yet confirm this supposition experimentally.

Conclusion

As an alternative detection method for orthogonal thin film magnetometers, use of the anisotropic magnetoresistance effect is proposed. Using this method, sensitivity is independent of drive-field frequency and the need for a detection-coil is obviated.
This detection method has been shown to behave better under miniaturization than the inductive method.
Compared to other magnetoresistive sensors, this magnetometer shows vector-sensitivity without the need for carefully adjusted bias-fields; furthermore offset-trimming is not required. However, alignment of the drive-field with the hard-axis of the film is quite critical.
Hysteresis, varying with the permalloy deposition method and decreasing with increasing drive-field amplitude, has been observed. This phenomenon is provisionally ascribed to dispersion in the magnitude of the anisotropy.

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References

[1] e.g.: H.Weiss,"Physik und Anwendung galvanomagnetischer Bauelemente", Vieweg, Braunschweig, 1969, 174.

[2] e.g.: F.Primdahl,"The fluxgate magnetometer", J. Phys. E:Sci. Instrum., 12, 241-253, (1979).

[3] e.g.: H.R. Irons and L.J. Schwee,"Magnetic Thin-Film Magnetometers for Magnetic-Field Measurement", IEEE Trans. Magn., MAG-8, 61-65, (1972).

[4] G.R. Hoffman, J.K. Birtwistle and E.W. Hill,"The performance of magnetoresistive vector magnetometers with optimised conductor and anisotropy axis angles",IEEE Trans. Magn., MAG-19, 2139-2141, (1983).

[5] W.J. Odom,Jr.,Richardson, and F.G. West,"Thin film magnetometer", US patent 3,239,754 (1966)

[6] F.G. West, W.J. Odom, J.A. Rice, T.C. Penn, "Detection of low-intensity magnetic fields by means of ferromagnetic films", J. Appl. Phys., 34, 1163-1164, (1963).

[7] F.S. Greene, R.B. Yarbrough, "Orthogonal susceptibility of permalloy films", J. Appl. Phys., 41, 4076-4082, (1970).