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Permalloy thin-film magnetic sensors

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Abstract

An introduction to the theory of the anisotropic magnetoresistance effect in ferromagnetic thin films is given, ending in a treatment of the minimalization of the free energy which is the result of the intrinsic and extrinsic anisotropies of the thin-film structure. The anisotropic magnetoresistance effect in long strips is reviewed. Attention is given to problems like the formation of domains and measures like biasing and linearization. The paper concludes with a description of some applications which are being developed by the authors: (1) an analyser for the stray field of recording heads, (2) a sensitive magnetometer, (3) an accurate absolute angle detector, and (4) an absolute (linear) position detector.

1. Introduction

Electrically conductive magnetic materials may show the anisotropic magnetoresistance effect, which means that the electrical resistivity depends on the direction of the magnetization vector. If one considers a magnetic thin film, this effect results in resistivities which are different when measured perpendicular (ρ_{\perp}) or parallel (ρ_{\parallel}) to the local magnetization direction. If the magnetization in the film is determined by an external magnetic field, the thin-film device can act as a sensor for this field. Then, a two-step process is acting in such a sensor: a magnetic field determines the magnetization and the magnetization determines the resistivity. A sensor for magnetic fields can be applied to detect position-, angle- or time-dependent information, since magnetic fields can be given a geometrical and/or temporal structure.

In addition to the resistance anisotropy mentioned above, magnetic bodies may possess magnetic anisotropy, which can be of intrinsic (material property) or extrinsic (shape effect) nature. In a magnetic thin film, which does not have intrinsic anisotropy perpendicular to the film plane, the magnetization vector will be restricted to lie in the plane of the film to a very good approximation. This is a consequence of the demagnetizing effect, which strongly reduces the magnetization component in a direction perpendicular to the film surface. For this reason the description of the effect can be

restricted to two dimensions, with only the in-plane components of the external fields being effective in practical devices.

It must be noted that the sensitivity of anisotropic magnetoresistance devices for in-plane magnetic fields is in contrast to that of normal magnetoresistive or Hall devices, which react to perpendicular field components. In principle, the normal effect is also present in a magnetic conductor, but in the materials treated here it can be neglected with respect to the anisotropic effect.

1. The resistance anisotropy

The anisotropic magnetoresistance effect implies the electric resistivity change

$$\Delta\rho = \rho_{\parallel} - \rho_{\perp} \neq 0$$

This phenomenon is present in three-dimensional metals and alloys as a consequence of the anisotropic scattering of the conduction electrons [1, 2]. Some characteristic $\Delta\rho/\rho$ values are listed in Table 1 (we define $\rho = (\rho_{\parallel} + \rho_{\perp})/2$).

The choice of a suitable sensor material not only depends on $\Delta\rho/\rho$ values (actually in the percent regime), but also on other properties like the magnetic properties and the sensitivity for temperature or stress. These and other considerations have generally led to the choice of magnetostriction-free

TABLE I Characteristic bulk values for $\Delta\rho/\rho$ at room temperature

Material	$\Delta\rho/\rho$ (%)
$\text{Ni}_{0.70}\text{Co}_{0.30}$	6.6
$\text{Ni}_{0.82}\text{Fe}_{0.18}$	4.3
$\text{Ni}_{0.99}\text{Fe}_{0.01}$	2.7
$\text{Ni}_{0.94}\text{Mn}_{0.06}$	2.5
$\text{Ni}_{0.94}\text{Sn}_{0.06}$	1.8
$\text{Ni}_{0.83}\text{Pd}_{0.17}$	2.3
$\text{Fe}_{0.90}\text{V}_{0.10}$	1.3

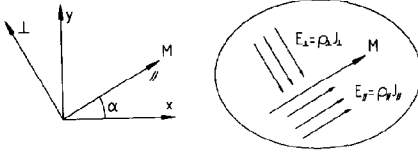


Fig 1 Magnetic thin film with magnetization vector M at an angle α with respect to the x axis. Currents are parallel or perpendicular to M (see resistivities ρ_{\parallel} and ρ_{\perp} respectively)

permalloy $\text{Ni}_{0.82}\text{Fe}_{0.18}$ and, to a much lesser extent, NiCo and NiFeCo alloys

Consider a resistance anisotropy induced by the magnetization vector, with no other anisotropy effects acting on the resistance present (the use of polycrystalline thin films eliminates the crystallographic contribution by averaging). Under the assumption of a pure anisotropic magnetoresistance effect, Ohm's law can be written in tensor form

$$\begin{pmatrix} E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} \rho_{\parallel} & 0 \\ 0 & \rho_{\perp} \end{pmatrix} \begin{pmatrix} J_{\parallel} \\ J_{\perp} \end{pmatrix} \quad (1)$$

where one of the coordinate axes is chosen along the magnetization vector (Fig 1). E is the electric field strength and J the current density. Here ρ_{\parallel} and ρ_{\perp} are uniquely determined and do not depend on direction themselves.

From a practical point of view it is more convenient to choose the x -axis of the coordinate system along J so that only a component J_x remains. Transforming eqn (1) to that system results in

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} \rho + \frac{1}{2}\Delta\rho \cos 2\alpha & \frac{1}{2}\Delta\rho \sin 2\alpha \\ \frac{1}{2}\Delta\rho \sin 2\alpha & \rho - \frac{1}{2}\Delta\rho \cos 2\alpha \end{pmatrix} \begin{pmatrix} J_x \\ 0 \end{pmatrix} \quad (2)$$

with α the angle between the magnetization vector M and the x -axis. Equation (2) can also be written as

$$E = \begin{pmatrix} \rho J_x \\ 0 \end{pmatrix} + \frac{1}{2}\Delta\rho J_x \begin{pmatrix} \cos 2\alpha \\ \sin 2\alpha \end{pmatrix} \quad (3)$$

It is easy to generalize eqn (3) and express the component E_{ζ} along a direction at an angle ζ with respect to the direction of J

$$E_{\zeta} = \rho J \cos \zeta + \frac{1}{2}\Delta\rho J \cos(2\alpha - \zeta) \quad (4)$$

3. Magnetization versus magnetic field

Permalloy films are characterized by the occurrence of an intrinsic uniaxial magnetic anisotropy [3]. This anisotropy can be specified by the energy density, which is necessary to disorient the magnetization vector M_s with respect to the anisotropy direction. The subscript s indicates that in this type of film, the magnitude of the magnetization vector has a maximum, or saturation, value. This energy term reads

$$\epsilon_a = K \sin^2 \beta \quad (5)$$

with K the constant of uniaxial anisotropy and β the angle between M_s and the anisotropy axis (also called the easy axis), which we take along the x -axis (Fig 2). The strength of the anisotropy is often represented by the anisotropy field $H_{k \text{ intr}}$ (in the remainder of this paper often denoted as H_k), defined as

$$H_{k \text{ intr}} = 2K/\mu_0 M_s \quad (6)$$

where μ_0 is the permeability of free space. The anisotropy is determined by film growth conditions and/or subsequent treatment (magnetic annealing). A characteristic value for the anisotropy field strength is 300 A/m.

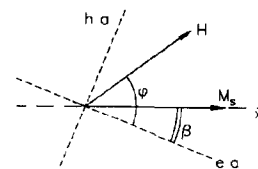


Fig 2 Definition of ϕ and β . e a is easy axis, h a is hard axis

Apart from the anisotropy, the direction of the magnetization vector M_s is determined locally by the local magnetic field H . If such a field is present, the expression for the free energy density reads

$$\varepsilon = K \sin^2 \beta - \mu_0 H \cdot M_s \quad (7)$$

The equilibrium value for the magnetization direction is determined by minimizing eqn (7) with respect to β . Taking

$$\delta \varepsilon / \delta \beta = 2K \sin \beta \cos \beta - \mu_0 M_s H \sin(\varphi - \beta) = 0$$

it follows that

$$\sin(\varphi - \beta) = H_k \sin(2\beta) / 2H \quad (8)$$

with φ the angle of H with the anisotropy axis (Fig 2). Equation (8) must be solved under the condition $\delta^2 \varepsilon / \delta \beta^2 \geq 0$. Unfortunately this can be done in only a few special cases, although it can be visualized very elegantly with the help of the so-called Stoner–Wohlfarth astroid (Fig 3). With the help of this device stable solutions can be constructed via a geometrical procedure [4]. Note that the procedure gives a single solution for an infinity of H -vectors (e.g., M_{s1} is a solution for H , H' and H'' in Fig 3), which emphasizes the need for measures to design a device with a uniquely defined output.

This Section concludes with three remarks. The first concerns the anisotropy, which always has some spread in magnitude as well as in direction. This is commonly denoted as *dispersion*.

Furthermore, the easy-axis orientation is temperature and stress dependent [5]. The second

remark concerns *exchange* interaction. A contribution from this interaction to the energy is neglected in eqn (7). This is permitted as long as we consider a single-domain model, or magnetization distributions with relatively small gradients ('almost' single-domain model). In the practical configurations, which are the subject of subsequent Sections, this condition is always fulfilled [6]. The third remark concerns the *switching time*. In principle the coherent switching of magnetic dipoles is governed by intrinsic and eddy current damping, which is greatly reduced in thin films. This makes very high switching rates (up to 1 GHz) possible [3].

4. The anisotropic magnetoresistance effect in (long) strips

This Section treats the strip depicted in Fig 4, which is considered to be very long with the current contacts far apart. This is for two reasons. First, we may expect the occurrence of domains at the end of the strip (see Section 5), while we want to confine ourselves to the 'almost' single-domain model. Secondly, the current contacts have a short-circuiting effect on the transverse voltage (which we call the *planar* Hall voltage) in the vicinity of the current contacts. This effect is extensively treated in the literature [7] for the normal Hall effect and has a comparable influence on the planar Hall effect [8]. Therefore a further treatment is omitted here. The influence of the short-circuiting effect on the (lateral) magnetoresistance is negligible in the planar case [9]. This is in contrast to the normal magnetoresistance effect.

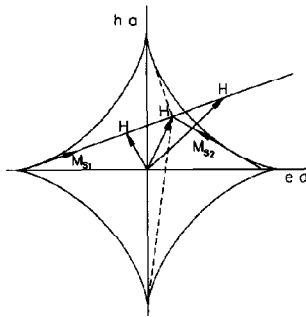


Fig 3 Stoner–Wohlfarth astroid. Magnetization directions are constructed by taking the tangents from the arrow tip of H to the astroid in the direction of the easy axis.

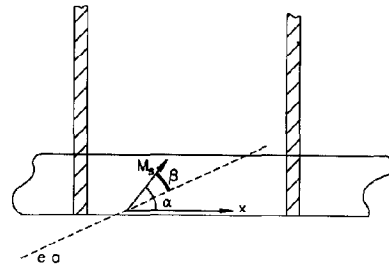


Fig 4 Long strip configuration.

The expression for the free energy of a strip, neglecting end effects, is

$$E = \int_{\text{vol}} K \sin^2 \beta - \frac{1}{2} \mu_0 \int_{\text{vol}} \mathbf{M}_s \cdot \mathbf{H}_i - \mu_0 \int_{\text{vol}} \mathbf{M}_s \cdot \mathbf{H}_a \quad (9)$$

H_a is the externally applied field, while H_i is the demagnetizing field, or (dipole-dipole) interaction field, generated by the divergence of \mathbf{M} . The factor $\frac{1}{2}$ in the second right-hand term is a consequence of the mutuality of the dipole-dipole interaction [10], where one part of the device generates the field acting on another, and vice versa. If, for mathematical convenience, a long strip with an elliptic cross section is considered, a homogeneous magnetization (single-domain film) leads to a constant value for H_i at every position of the film

$$H_i = -DM_s \sin \alpha \quad (10)$$

with α the angle between \mathbf{M}_s and the strip axis and D the demagnetizing factor, for which $D = t/(t + w)$ is valid to a good approximation in this case (t and w are the thickness and the width of the strip, respectively, with $t \ll w$, e.g., $t = 40$ nm, $w = 4000$ nm)

So we find for this case

$$\varepsilon = \frac{E}{\text{vol}} = K \sin^2 \beta + \frac{1}{2} \mu_0 DM_s^2 \sin^2 \alpha - \mu_0 \mathbf{M}_s \cdot \mathbf{H}_a \quad (11)$$

It is seen that the interaction term behaves formally as a uniaxial anisotropy along the strip axis (shape anisotropy). Although practical specimens (to which we shall return shortly) will not have an elliptical cross section, the assumption is well suited for first estimates

If $\alpha = \beta$ (coinciding anisotropy axes) an effective anisotropy K^* can be defined

$$K^* = K + \frac{1}{2} \mu_0 DM_s^2 \quad (12)$$

This leads to an 'effective' anisotropy field

$$H_k^* = H_{k \text{ intr}} + H_{k \text{ shape}} = H_{k \text{ intr}} + DM_s \quad (13)$$

Under the assumption of an elliptical cross section, the homogeneity of \mathbf{M} is justified afterwards if H_a is homogeneous as well. If H_a is directed perpendicular to the strip axis, it is convenient to introduce the normalized applied field h_a as

$$h_a = H_a / H_k^* \quad (14)$$

and the single-domain model leads to

$$\left. \begin{aligned} \sin \beta &= h_a & \text{for } h_a \leq 1 \\ \sin \beta &= 1 & \text{for } h_a > 1 \end{aligned} \right\} \quad (15)$$

Equation (15) can easily be verified by minimizing eqn (11). Introduction of eqn (15) into eqn (3) leads to

$$E_v = \rho J - \Delta \rho J h_a^2 \quad (16)$$

$$E_v = \Delta \rho J h_a (1 - h_a^2)^{\frac{1}{2}} \quad (17)$$

or, since β is constant over the strip, to

$$V_{MR} = iR - i \Delta R h_a^2 \quad (18)$$

$$\frac{l}{w} V_H = i \Delta R h_a (1 - h_a^2)^{\frac{1}{2}} \quad (19)$$

with V_{MR} and V_H the magnetoresistance and planar Hall voltages respectively, i the sensor drive current, R and ΔR the sensor resistance and maximum sensor-resistance change respectively and l the sensor-strip length. Equations (16) to (19) are valid for $|h_a| \leq 1$. For larger values of $|h_a|$, h_a should be replaced by 1 in these equations. The expressions (18) and (19) have been plotted in Fig 5 (curves numbered 1)

If $\alpha \neq \beta$ (non-coinciding anisotropy axes) an effective anisotropy can be defined in direction as well as in magnitude. The results for this situation are not derived here, but can be found in the literature [11]

Returning to the more realistic non-elliptic cross section, a form effect may be expected as well, although a shape anisotropy cannot be specified exactly. The assumption of a homogeneous

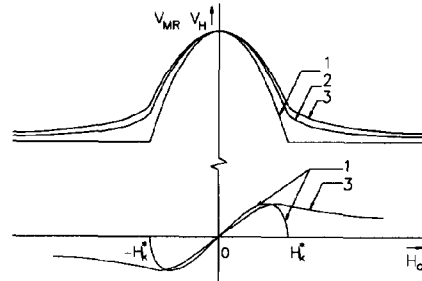


Fig 5 V_{MR} (upper curves) and V_H (lower curves) for a rectangular cross section with shape parameter $a_s = H_{k \text{ shape}} / H_k^*$. 1, Intrinsic behaviour with $a_s = 0$ (also valid for elliptic cross section), 2, $a_s = 0.5$, 3, $a_s = 1$

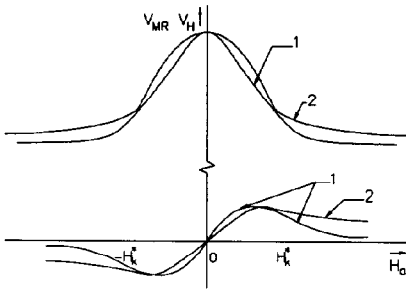


Fig 6 Influence of edge profile on magnetoresistance and planar Hall effect, curves of devices having the same shape parameter $a_s = 0.095$ 1, edge tapered over 70% of strip width, 2, rectangular profile

magnetization no longer leads to a constant value for H_x , which in turn makes the assumption of a homogeneous M no longer justified. Nevertheless, the problem can be solved with the help of numerical procedures using a computer. We shall not go into the details of such computations, which are given elsewhere [12], but only present some characteristic results of V_H and V_{MR} curves for a number of ratios $a_s = H_{k \text{ shape}}/H_k^*$ (Fig 5). Again the intrinsic anisotropy is assumed to be parallel to the strip axis while the applied field is perpendicular to it.

In contrast with the 'elliptic' case, the shape of the curves depends on the aspect ratio of the strip and it can be seen that the assumption of an elliptical cross section may lead to rather larger deviations for $a_s \approx 1$. This raises the supposition that in this limit any deviation from rectangularity may lead to a significant deviation from the results of Fig 5. This can easily be shown from a computation in which an edge-taper is assumed (Fig 6) [12]. Experimental curves on specimens with a large form effect often show deviations which can easily be ascribed to specific edge profiles, poor edge definition, edge asperities and so on.

5. Domains [3, 13]

In Section 4 only (almost) single-domain solutions were considered. No attention was paid to solutions that contain magnetic domains, which may easily occur in practice.

This can be demonstrated by the examples of Fig 7. A magnetic field in a direction perpendicular to the strip axis with a magnitude larger than

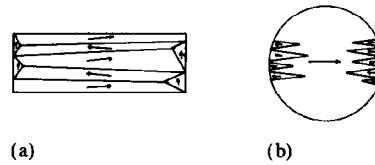


Fig 7 Possible domain configurations (a) in a short strip after relaxation from a large field perpendicular to the strip axis, (b) in a disc after relaxation from a large field pointing to the right. In both cases the easy axis is horizontal.

H_k^* pulls the magnetization perpendicular to the strip axis. If such a field decreases and becomes smaller than H_k^* again, the magnetization will start to rotate back to the easy-axis position. However, the rotation may be clockwise or anti-clockwise and, depending on the local deviations from the anisotropy direction (angular dispersion), the magnetization will rotate in opposite directions in different parts of the film. This results in a multi-domain film with (approximately) opposite magnetization directions when the external field has diminished to zero (Fig 7(a)).

A second example of domain formation can be given on the basis of the situation in discs or short strips. Starting from a decreasing but positively oriented magnetic field, the magnetization will switch from positive to negative at $H = -H_k^*$ if the Stoner–Wohlfarth (SW) model is strictly followed. In practice, however, the switching process starts at smaller (absolute) values of H as a consequence of domain formation, often starting at the film edges. So, instead of switching coherently, as predicted by the SW model, the film 'switches' by domains that grow in opposite directions throughout the film (Fig 7(b)) [3]. This gives the switch a noisy appearance, resulting in Barkhausen noise in the electrical output.

6. Biasing and linearization

Switching of the magnetization, whether or not accompanied by domain formation and growth, should generally be avoided in a working device. In practice this means that the fields to be detected must be on a trajectory outside the SW astroid. Such a requirement cannot be fulfilled if the device serves as a detector of unknown (possibly small) fields. However, in applications where permanent

magnets are part of the device (e.g., in position and angle detectors), such a requirement can be fulfilled (see applications described in Sections 7.3 and 7.4)

When small fields in a limited range should be detected (e.g., by a recording read head) a bias field may be added to shift the range outside the switching region, so that all events take place on a single branch of the magnetoresistance or planar Hall curve. Apart from this, a bias field can be used to put a small-amplitude signal around a point of maximum sensitivity [14].

In most applications the use of the magnetoresistive effect in long strips is preferred over the use of the planar Hall effect, although the latter is linear in first order. The reason for this is simple and can be derived from eqns (18) and (19). In order to make the domain influence and the short-circuiting effect at the strip ends negligible, a large l/w ratio is required, leading to a large ratio of the magnetoresistive to the planar Hall voltages.

Since in many cases the quadratic magnetoresistor response (eqn (18)) is not desirable, there is a need for linearization. Available methods have been reviewed by Tsang [15] and Kwiatkowski and Tumanski [16]. From the combination of eqns (3) and (15), it can be seen that a (first-order) linear magnetoresistive response is obtained if the direction of the current flow is oriented at 45° with respect to the easy axis (i.e., $\alpha - \beta = 45^\circ$ in Fig. 4), while still maintaining the easy axis oriented perpendicular to the magnetic field to be measured. An important variation on this theme is the so-called barberpole configuration [17], where the easy axis of a magnetoresistive strip is oriented parallel to its main geometrical axis, but where a highly conductive overlay structure deposited on the strip forces the current to flow locally at 45° to the strip axis. In a different approach to linearization, a magnetic bias field can be applied (e.g., [18–20]).

7. Applications

Anisotropic magnetoresistive devices are used to measure magnetic fields and all variables that can exploit a magnetic field as an intermediate agent, e.g., angular position, linear position, temperature, etc. Besides, they are widely used and investigated

as detectors for magnetically stored information, e.g., in disc drives or in bubble memories. In particular the application as a read head for magnetic recording (suggested by Hunt [21]) has been a subject of permanent investigation. The advantage of a magnetoresistive (MR) head over a conventional inductive head is that it scales down favourably (with respect to the latter) regarding the signal-to-noise ratio [22]. The obvious drawback of the MR head is that it must be combined with a separate write head. Nowadays the MR read head is in use in some advanced recording systems and its role in magnetic recording can hardly be circumvented. We do not go into the details of the recording MR head in this review, but refer the reader to the abundance of literature on the subject.

7.1 Field analyser

A magnetoresistive permalloy strip can be used in a measuring system for the purpose of mapping the fringing fields of recording heads (including ring-type ferrite heads, thin-film heads and single-pole-type heads for perpendicular recording) and the flux reversals in hard-magnetic layers [23, 24]. Depending on the position of the transducer with respect to the head or magnetic-layer surface, the perpendicular or tangential field component is measured (Fig. 8).

The transducer is designed such that the magnitude of the field to be measured is smaller than H_k^* , but of comparable order. This can be done by a proper choice of the aspect ratio l/w . Since the detector output is not uniquely determined by an external field (see Fig. 3), use is made of the knowledge that the nature of the fringing fields is two dimensional and the strip axis is positioned in the direction of the zero component of the magnetic-field pattern. In measuring a recording-head field, a possible disturbing field along the strip axis will generally be screened out by the soft-magnetic material of the head itself and does not influence the sensor's signal.

The magnetic-field component can be measured directly if there is a negligible field gradient along the width of the sensor strip. This is generally not the case, because the head-gap length may be of the order of one micrometer so that significant field changes occur within sub-micron distances. In that case the sensor signal has to be compared with computed values which have been derived on

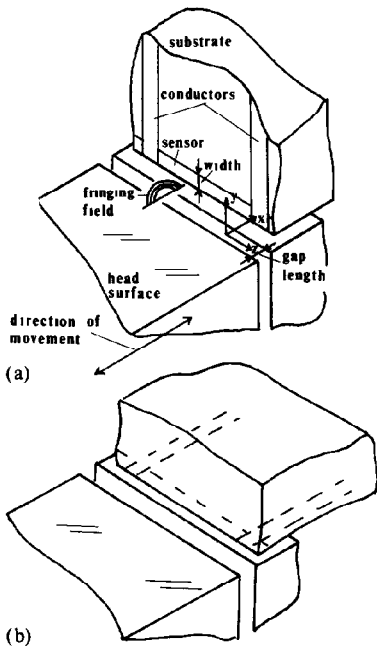


Fig 8 Orientation of the sensor substrate with respect to a ring-type head in order to determine the y component (a) or the x component (b) of the fringing field

the basis of an assumed structure of the field and a model of the behaviour of a permalloy sensor strip in a non-uniform field [25]. The character of this type of measurement requires an unbiased detector. However, if the fringing field of a flux reversal in a hard-magnetic layer is measured, a linearization of the sensor is possible by means of an externally applied homogeneous field in the width direction of the sensor strip [24].

The technology of the preparation of permalloy transducers with micron or sub-micron width dimensions on the very edge of a substrate can be found in the literature [26, 27].

7.2 Thin-film magnetometer

In most designs of magnetoresistive magnetic-field sensors, the occurrence of magnetic domains is detrimental to their operation. In the magnetometer described here, which is based on an inductive thin-film magnetometer first reported by West *et al* [28], the occurrence of magnetic domains is exploited for obtaining a sensitive magnetic-field sensor. It has been shown [29, 30] that for low operating frequencies and small film dimensions, magnetoresistive rather than inductive readout of the magnetic state of the film will in

principle lead to a better sensitivity. An alternating (e.g., sinusoidal) bias field H_{ex} is applied perpendicular to the measurand and to the easy axis of a magnetoresistive film which is shaped into a planar Hall element or a magnetoresistor having a canted current path. The bias field periodically saturates the film, and upon returning from saturation the magnetization splits into two parts (distributed over a number of magnetic domains) which rotate toward the easy axis in opposite directions. The easy-axis field component, H_s , determines the ratio of the two magnetization fractions, which in turn determines the sensor's output voltage. Using an orthogonal susceptibility model [31] and neglecting dispersion in the magnitude of anisotropy and shape effects, the peak-to-peak output voltage V_{ss} for a planar Hall configuration (shown in Fig 9) can be calculated to be [30, 32]

$$V_{ss} = \frac{2i\omega \Delta R}{\sigma_a H_k l \sqrt{2\pi}} H_s \quad (20)$$

where σ_a is the standard deviation of the distribution function of anisotropy-axis orientations (angular dispersion) and H_s is the measurand. This result is independent of the amplitude of H_{ex} , which should, of course, be larger than H_k . The waveforms occurring with a sinusoidal excitation field are shown in Fig 10.

A small hysteresis effect in the sensor can be explained by the dispersion in the magnitude of anisotropy and the inhomogeneous demagnetizing field due to the non-elliptic cross section of the permalloy film [32].

The feasibility of fabricating this type of magnetometer with an integrated drive coil using planar technology (Fig 11) has been demonstrated [33].

If appropriate driving and signal-processing electronics are employed (using a non-sinusoidal

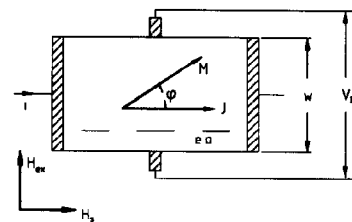


Fig 9 Magnetometer configuration, using the planar Hall effect. H_{ex} is the periodical excitation field, H_s is the magnetic field component to be measured

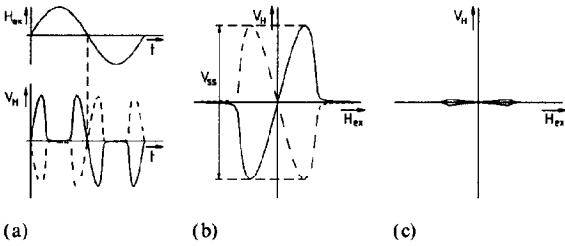


Fig 10 Magnetometer operation (a) H_{ex} and V_H vs time, (b), (c) V_H vs H_{ex} (a) and (b) solid curve, $H_s = H_{s0} \neq 0$, dashed curve $H_s = -H_{s0}$ (c) $H_s = 0$

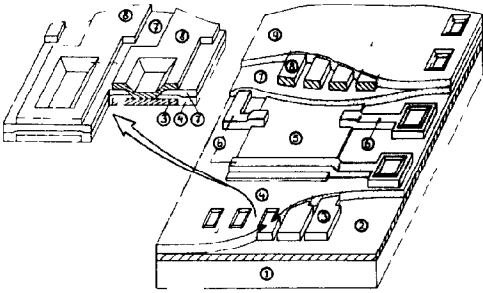


Fig 11 Magnetometer construction (1) Si substrate, (2) SiO_2 insulator, (3) Al lower half of excitation coil, (4), (7), (9) polyimide insulator, (5) permalloy, (6) Al contacts to permalloy, (8) Al upper half of coil (drawing by Rineke Groothengel)

excitation field), two magnetic-field sensors of this type can be applied in a solid-state compass, measuring both field components in the plane of the film with an accuracy of 3×10^{-2} A/m [30]. This would allow the orientation of the earth's magnetic field to be measured with an accuracy of approximately 1° .

7.3 An absolute angle detector

Whereas many applications of magnetoresistive films use relatively small magnetic fields, there are examples of magnetoresistive sensors which use very large (with respect to H_k^*), so-called 'saturating', magnetic fields. In such a sensor, all problems related to the formation of magnetic domains, to hysteresis, etc. are avoided. In homogeneous saturating fields, the performance of magnetoresistive elements can be optimized with respect to the signal-voltage level [34].

One example is an absolute angle detector [35, 36], shown schematically in Fig 12. A pair of magnetoresistive elements is used to detect the orientation of the (saturating) magnetic field of a

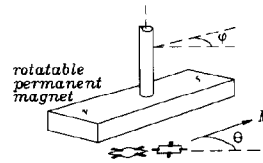


Fig 12 A contactless absolute angle detector. The orientation of the permanent magnet with respect to the magnetoresistive elements can be measured using the output signals of the elements. M represents the magnetization in the magnetoresistive elements.

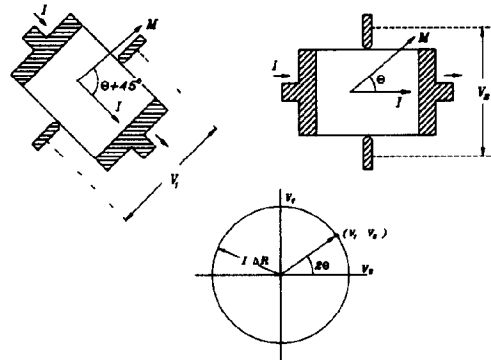


Fig 13 A pair of planar Hall elements as used in the detector of Fig 12. I represents the driving current, M the magnetization of the permalloy. A two-dimensional plot of $V_1 = I \Delta R \cos(2\theta)$ and $V_2 = I \Delta R \sin(2\theta)$ is also shown.

permanent magnet. Magnet and magnetoresistive elements do not necessarily have to be joined mechanically, as long as the orientation of the magnetic field with respect to the magnetoresistive elements represents the angle that is to be measured. This allows some freedom in the positioning of the magnet with respect to the elements, if the magnetic field is homogeneous in a certain area.

The magnetoresistive elements are planar Hall elements (Fig 13), mutually rotated over 45° . The output angle Θ can be calculated from the two signals from these elements. In Fig 13 the two signal voltages are plotted in a two-dimensional diagram for different values of Θ . It is obvious that the sensitivity of this measurement is constant in the range of the angle detector 0 to 180° . Furthermore, the measurement is intrinsically temperature independent; a change in temperature will affect $\Delta\rho$, and will cause a change in the radius of the circle in Fig 13. The measured value of Θ , however, will not be affected.

In Fig 13 the short-circuiting effect of the current terminals of the elements is neglected. This effect does not change the principle of the measurement, since it can be represented by a constant multiplication factor in V_1 and V_2 .

The magnetic anisotropy of the permalloy film causes a difference in orientation of the magnetic field and the magnetization in the film. This effect causes a systematic error in the sensor signal. Although this error can be accounted for in the electronics following the angle detector, it would be more convenient to use a permalloy film without magnetic anisotropy. This can be realized by an annealing treatment of the permalloy film [35] or by using a double layer of two permalloy films with mutually perpendicular magnetic anisotropies [37].

Several solutions for readout electronics have been tested. The signal of the detector is very similar to that of a resolver. Therefore, standard resolver electronics can be used. On the other hand, the signal processing of the angle detector is much more flexible than that of a resolver (a.c. or d.c. excitation currents, two independent elements), allowing a number of simpler solutions to be exploited.

Another angle detector that operates in a saturating magnetic field is shown in Fig 14. This figure shows a four-pole system, but the number of poles can be increased, if desired. The signal of this type of sensor has a periodicity of n if the magnet consists of n poles. Due to the symmetry of the system, the signal voltage V_{ab} is relatively insensitive to misplacement of poles on the magnet, or misplacement of the magnet from the centre of the permalloy ring pair. A possible application of

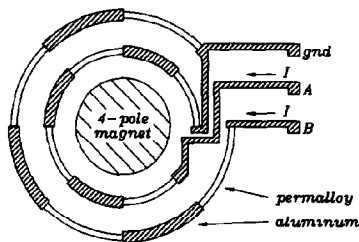


Fig 14 A four-pole detector. A pair of permalloy rings, which are partly covered with aluminium, is magnetized by the field of the magnet. The rings are driven with a current I . In this configuration, an offset-free signal V_{ab} is obtained, which is approximately sinusoidal.

this type of angle detector is to replace the collector in a d.c. motor.

Depending on the position of the rotor, the current through the driving coils in the motor can be switched with the aid of the signals from the detector. Preferably, zero-crossings of the signal are used. Different phase shifts of the signal can be obtained from extra ring pairs which are slightly rotated with respect to the ring pair shown in the figure. The signal, which is approximately sinusoidal, can easily be transformed into the switching information for the driving coils and other interesting information like the speed of the rotor can easily be obtained. A practical drive application of this sensor is currently being prepared for publication [38].

7.4 An absolute position detector

A system for the absolute detection of linear (or angular) position can be realized using a magnetoresistive permalloy strip as the position-data detector [39]. In this system the position information is not conventionally laid down in parallel tracks but is recorded in one single track of a hard-magnetic scale (see Fig 15) by means of a maximum-length sequence of $2^n - 1$ bits [40]. The position coordinate can be derived from the response of a sensor array detecting a series of n adjacent bits. Maximally $2^n - 1$ unique bit combinations can be distinguished.

The magnetoresistive sensor array is built up of a permalloy strip laid down on the edge of a substrate and is divided into separate sensor elements by means of electrical conductor strips perpendicular to the sensor strip. The magnetization distribution in the permalloy strip is determined by

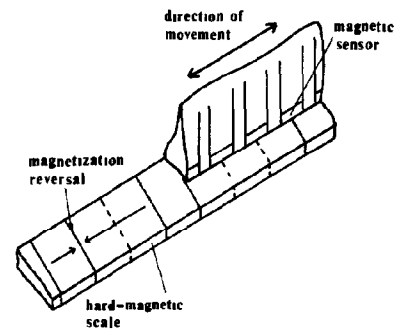


Fig 15 Detection of bits in a hard-magnetic layer by means of a magnetoresistive sensor array.

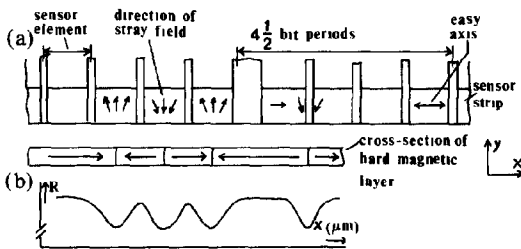


Fig 16 (a) Sensor strip, divided into two sets of sensor elements, positioned in the stray field of a hard-magnetic information layer (b) Output of a sensor element

the stray field of the hard-magnetic layer (Fig 16). The resistance of each sensor element is an indication for the presence ('1-bit') or the absence ('0-bit') of a flux reversal at that particular position in the scale. The resistance values have to be corrected for the temperature effect of the magnetoresistive material by using dummy elements. To avoid ambiguities at the boundaries of the flux-reversal positions, at least two sets of sensor elements are necessary, which should be mutually shifted over $(n + 1/2)$ bit periods (in the case of two sets). Some mechanism has to be created to decide on the choice between the two sets of sensor elements. An obvious solution is the introduction of a second (reference) track with an all-ones recording pattern. Such an additional track can also serve as the basis of an interpolation scheme for the purpose of improving the resolution of the position readout.

Prototype detection heads have been realized with strip widths in the range of 10 to 30 μm and H_k^* values of 1500 to 3600 A/m. The cross-contact leads, which must show a very low specific contact resistance to the permalloy film, were realized by patterning a Mo/Al film using a lift-off process. The response of the sensor elements with various dimensions in the stray fields of the flux reversals of magnetic scales (actually commercially available audio tapes were chosen) was evaluated. It was found that position bits can be detected with a lower bit-period limit of the order of a few hundred μm .

Based on experiments and on calculations with a simulation model, it can be concluded that the resolution of the position-detection system is of the order of 100 μm , which in principle can be improved by a factor of 10 to 100 with the

application of interpolation techniques. The performance of a system based on an alternative technique, being the semiconductor silicon Hall technology, is estimated to be of the same order as the permalloy-based version [41]. The range of the position detector depends on the position-bit period and the number of applied elements in the sensor array and in principle is not limited.

8. Concluding remarks

In the last few decades much work has been done concerning the theoretical description of anisotropic-magnetoresistance phenomena and the development of applications. The commercial feasibility of this sensor type has been shown in the field of analog magnetic sensors and magnetic-recording read heads, respectively. However, the magnetoresistive sensor has not yet emerged as a low-cost mass-product. One of the obstacles is the development of fabrication techniques for the realization of thin-film devices in large quantities, with good and reproducible properties and in a suitable package. Another aspect is the integration with electronics in order to cope with special problems like temperature effects, initialization, biasing, drive currents and communications. Multidisciplinary activities of this kind are found to form a certain barrier for the utilization of these designs.

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