CONTACTLESS ANGLE DETECTION USING PERMALLOY

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Abstract

An overview will be given of measurements on angle
detectors. The detectors consist of a pair of planar-
Hall elements opposite to a rotatable magnet. The
measurements are performed on a number of planar-Hall
elements of different shape and size, and show very
good agreement with a previously described theoretical
model. To increase the accuracy of the angle detector,
three modifications of the original concept of the
planar-Hall elements are treated:
a: A ring-shaped element having increased output
   voltage.
b: An optimized configuration of a pair of planar-Hall
   elements and a permanent magnet, to cancel out the
   effects of magnetic anisotropy in the permalloy on
   the accuracy of the angle detector.
c: An annealing step at 500°C applied to the permalloy
   to create a magnetically isotropic film.
The results of measurements on planar-Hall elements as
suggested in a, b and c are presented and show good
agreement with theory. Magnetization behavior in a ring
structure, combining magnetic anisotropy and magnetic
form effects, is not yet properly understood.

Introduction

An angle detector consisting of a pair of planar-Hall
elements opposite to a rotatable magnet has been
proposed [1,2]. In this paper, measurements, carried
out to determine the achievable accuracy of the
detector, are described. The term "detector error" will
be used for the difference between the angle to be
measured and the angle derived from the detector output
signal. The measurements have been performed on single
planar-Hall elements of different shape and size. In a
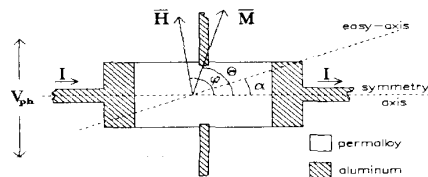planar-Hall element we have (figure 1):

Fig 1: A planar Hall element.

$$V_{ph} = \frac{1}{2} I \frac{\Delta\rho}{t} \sin(2\Theta) \qquad (1)$$

with I the exciting current, t the film thickness and
$\Delta\rho$ the magnetoresistive effect. Other parameters are
explained in figure 1. The current density at a point
in the film is considered constant over the film thick-
ness, while the shape of the element may be arbitrary.
$\bar{H}$ is the external field and $\bar{M}$ the magnetization in the
film. Permalloy thin films show a uniaxial anisotropy.
The angle between the easy-axis and the symmetry axis
of the device is called α. When the permalloy film
follows the Stoner-Wohlfarth single domain model [3],
the direction of $\bar{H}$ and $\bar{M}$ will follow (2), with H_k the
anisotropy field of the permalloy film.

$$\sin(\varphi-\Theta) = \frac{H_k}{2H} \sin2(\Theta-\alpha) \qquad (2)$$

The angle detector measures the magnetization angle Θ.
Therefore, the uniaxial anisotropy will introduce a
systematic detector error $\varphi-\Theta$.

Planar-Hall elements were created on thermally oxidized
(0.5 μm SiO_2) silicon wafers. First an aluminum elec-
trode pattern was realised by deposition of 0.5 μm
aluminum by evaporation followed by wet chemical
etching. The permalloy thin film (50 nm) was sputtered
in an Ar atmosphere using a bias field of 2000 A/m to
direct the uniaxial anisotropy. After wet chemical
etching of the permalloy, the planar-Hall elements were
fixed onto epoxy substrates.
The planar-Hall elements were mounted on a rotation
stage in a pair of Helmholtz coils which produce a
homogeneous external field of up to 6000 A/m. The
rotation stage was used to rotate the element with
respect to the field in 180 steps of 1°. The signal
voltage V_{ph} was measured for each step and stored by a
computer. The computer analysis uses (1) to calculate
the magnetization direction as a function of field
direction, deriving parameters A (offset of V_{ph}) and B
(amplitude of V_{ph}). The results are compared with the
single domain model, fitting the parameters α and H_k/H.
Finally the RMS value Δ of the deviation between
theoretical and measured magnetization direction is
calculated.
To characterize the element, the offset to signal
voltage ratio A/B is calculated as well as B/I, indi-
cating the yield of the element. Details on measurement
equipment and analysis are given elsewhere [4].

Modifications

To increase the accuracy of the angle detector in its
basic configuration, three modifications are
considered:
a: By changing the form of the planar-Hall element, the
   output voltage is increased.
b: A system of two planar-Hall elements and a permanent
   magnet is optimized to cancel out errors in the
   detector output caused by the magnetic anisotropy of
   the permalloy.
c: Annealing the permalloy at 500°C, a magnetically
   isotropic film is obtained.

Ring-shaped elements

The output voltage of a planar-Hall element is directly
proportional to the current I through the element and
inversely proportional to the film thickness t. Very
wide planar-Hall elements should be used to get a sig-
nificant increase in V_{ph} without exceeding the maximum
current density, giving rise to design problems. A
Wheatstone bridge as in figure 2a, consisting of four
magnetoresistors, has an output signal V_b which is
equivalent to the output of a planar-Hall element:

$$V_b = \frac{1}{2} I \frac{l}{wt} \frac{\Delta\rho}{} \sin(\gamma) \sin(2\varphi) \qquad (3)$$

with l and w the length and width of each magneto-
resistor and γ as in figure 2a. V_b has a maximum for
$\gamma = 90°$. In this calculation, no anisotropy effects are
considered. V_b can be increased by changing l, w and t.
In an angle detector using these elements, magnetic
form effects in the magnetoresistors will introduce a
detector error, increasing with decreasing thickness to
width ratio t/w. A ring shape (figure 2b) reduces this
error considerably. Figure 3 shows the result of a
computer simulation for given thickness to width ratio
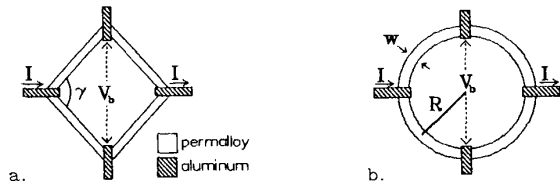and increasing field.

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Fig 2a: A Wheatstone bridge of magnetoresistors.
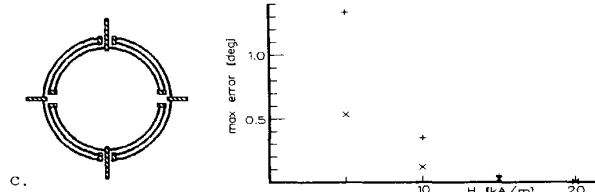*Fig 2b: A ring-shaped element.*

Fig 2c: A three times folded element.
Fig 3 : Maximum detector error for a rectangular bridge
(+) and a ring-shaped element (×), t/w=0.0025.

One can derive the output voltage for a ring-shaped
element:

$$V_b = \frac{1}{2} I \frac{\Delta\rho}{t} \sin(2\Theta) \frac{1}{\ln\left[\dfrac{R + w/2}{R - w/2}\right]} \qquad (4)$$

R is the radius to the half-width of the ring and w is
the width of the ring. To further increase the output
voltage without consuming too much space, the ring can
be folded into a structure as in figure 2c.

Using an inhomogeneous field

A way to reduce the detector error caused by the
magnetic anisotropy of the film material, is to exploit
the field inhomogeneity of a permanent magnet [1]. The
success of this method depends on the value of several
adjustable parameters.
The field strength of the magnet determines the
influence of the anisotropy. On the other hand, the
influence of the field inhomogeneity depends on the
shape of the magnet, the relation between the
dimensions of the magnet and the sensor (= planar-Hall
pair), and the distance between them.
A model of a magnet-sensor system has been made. The
magnetic charge is assumed to be homogeneously distri-
buted on two opposite faces of the magnet. The Stoner-
Wohlfarth single domain model is used and the current
distribution in the circular films is approximated with
an ellipsoidal pattern. In a computer simulation, this
model was used to optimize all parameters.
A configuration, consisting of a permanent magnet
($50\times50\times8$ mm^3, magnetization 480 kA/m) and a sensor
comprising two circular planar-Hall elements ($\varnothing$ 6.7 mm,
distance between centres 8 mm) at 16 mm beneath the
magnet surface, was found appropriate.

Isotropic permalloy films

Another way to suppress the effects of magnetic
anisotropy on the detector output is to modify the
permalloy itself. Isotropic permalloy films can be
produced by disarranging the easy-axis orientation in
different parts of the film. When the film consists of
a great number of small areas A^x, each with its own
randomly oriented uniaxial anisotropy and anisotropy
field strength H_k^x ($0 < H_k^x < H_k^{max}$), the film as a whole
will not have an easy-axis. When a homogeneous external
field $\bar{H}$ is switched on ($H > H_k^{max}$), the distribution of
magnetization directions in the areas A^x will be
symmetrical with respect to the field direction.

Therefore, the total magnetization M in the film will
have the same direction as $\bar{H}$ but will be smaller than
M_s, the saturation magnetization. The anisotropy-
induced detector error will be completely canceled out
in this way. We tried an annealing treatment at 500°C
and zero field to disarrange the easy-axis orientation.

Measurements and discussion

The result of a typical measurement on a planar-Hall
element is depicted in figure 4. The element has a
circular shape ($\varnothing$ 10 mm) and four contacts around the
circumference, overlapping 100×100 μm^2 with the film.
The difference φ-Θ between field direction and magnet-
ization direction in the film, caused by the magnetic
anisotropy, is plotted against the position of the
rotation stage over the complete range of the angle
detector. The crosses represent the measured values and
are derived using (1). For clarity of the plot, not all
180 measurement points are shown. With (2), represent-
ing the single domain model, α and H_k are calculated
from these results. A theoretical curve for φ-Θ is
determined, represented by the solid line in figure 4.
The RMS value Δ of the deviation between the measured
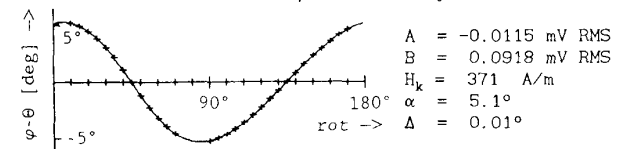and theoretical values of φ-Θ is finally derived.

A = -0.0115 mV RMS
B = 0.0918 mV RMS
H_k = 371 A/m
α = 5.1°
Δ = 0.01°

Fig 4: φ-Θ vs rotation stage position for a circular
element ($\varnothing$ 10 mm), H = 2000 A/m, I = 1.5 mA RMS.

no	H [A/m]	B/I [Ω]	A/B	H_k [A/m]	α [°]	Δ [°]	permalloy geometry
1	2000	0.0612	-0.125	371	5.1	0.01	$\varnothing$ 10 mm
2	2000	0.0936	-0.818	474	130.2	0.02	$\varnothing$ 1 mm
3	2000	0.0526	0.025	409	96.0	0.01	$\square$ 3 mm
4	2000	0.0604	0.083	386	82.4	0.09	$\diamondsuit$

Table 1: Measurement results for planar-Hall elements,
showing field strength H, yield B/I, offset ratio A/B,
anisotropy parameters H_k and α, RMS value of the
deviation from the model Δ and the geometry of the
element.

In table 1, the results are given for four different
geometries. It should be noted, that smaller size does
not affect the magnetic behavior of the element. The
fourth measurement shows a significant deviation from
the model, caused by magnetic form effects. The
permalloy in this element has circular shape ($\varnothing$ 1 mm),
with extensions of 250 μm length leading to the
contacts. These extensions are 100 μm and 250 μm wide
for the voltage and current contacts respectively.

Measurements on ring-shaped elements are shown in
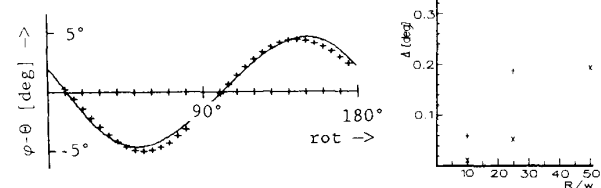figure 5a and table 2 for different radius to ring-
width ratio R/w.

Fig 5a: φ-Θ vs rotation stage position for a ring with
R/w=50, H = 2000 A/m.
Fig 5b: Measured (+) and theoretical (×) values for Δ
for different R/w at H=2000 A/m.

no	H [A/m]	B/I [Ω] exp	B/I [Ω] theory	A/B	Δ [°]	R/w
1	2000	0.451	0.428	0.681	0.06	10
2	2000	1.107	1.106	1.138	0.19	25
3	2000	11.17	11.17	-0.247	0.32	*50

*Table 2: Measurement results for ring-shaped elements. Anisotropy parameters have been left out, because the single domain model is not valid. The theoretical yield B/I of the elements is calculated from (4), with the factor Δρ/t derived from the third measurement.
: This element is a five times folded type.

The periodic deviation from the model in 5a is caused by the ring shape, but is larger than expected.
In the previous discussion, only magnetic form effects were considered. Therefore the combination of intrinsic and form anisotropy [5] in a ring-shaped element was simulated. The results are depicted in figure 5b, together with the measured results. It is clear that the extended model is not sufficient. In the model, the amplitude of the deviations is directly proportional to the square of the ratio of R/w to H. In the measurements a linear dependence is found.

To verify the model for inhomogeneous fields, a magnet-sensor system as described in the introduction was realised. The magnet was mounted on a rotation stage, rotating over 360 steps of 1°. The position of the magnet and the sensor with respect to the rotation axis of the stage could be changed. Also the distance between the magnet and the sensor could be adjusted. For all 360 positions of the magnet, the signal voltage of a single planar-Hall element was measured. In a complete angle detector, the output signal consists of a pair of planar-Hall voltages. With the measured voltage and a planar-Hall voltage calculated for an ideal element ($\varphi \equiv \Theta$), a complete angle detector was simulated, and the detector error was determined for the total measurement range (see figure 6). The detector error was minimized by adapting the adjustable geometric parameters in the magnet-sensor system.
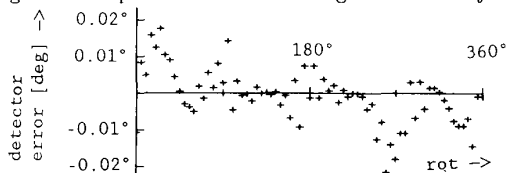

Fig 6: Detector error of a magnet-sensor system.

For a real angle detector the detector error can be calculated by simply adding the results of similar measurements, performed separately on the two planar-Hall elements of the detector.
The distance between the surface of the magnet and the sensor is 14 mm. The field of the magnet was found to be smaller than expected, explaining this lower optimum distance. The field strength in the sensor plane is 18 kA/m. The maximum detector error is less than 0.03°. It should be noted that after minimizing the detector error for one planar-Hall element, the other element may not be in its optimum position. In our case, a measurement on the other element at the same sensor position showed an error with a maximum of 0.3°. The error could be limited to 0.1° for both elements. Applying this method to increase the accuracy of an angle detector, one has to take into account that symmetry of the field of the magnet as well as accurate positioning of magnet and detector with respect to the rotation axis is of high importance. The sensitivity of the detector error for deviations in these positions is about 0.3°/mm in our magnet-sensor system.

Figure 7 shows the results of measurements on two planar-Hall elements with permalloy that had been annealed at 500°C. Anisotropy parameters can not be derived because the single domain model is not valid.
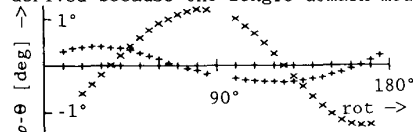

Fig 7: φ-Θ vs rotation stage position for permalloy annealed at 500°C for 0.5 hour (×) and 1.5 hour (+). H = 2000 A/m.

It is clear that the maximum error in the (average) magnetization direction decreases with increasing annealing time. A measurement, using the Crowther method [6], showed a very high angular dispersion in these films. α_{90} was estimated to be more than 80° and 100° for the films annealed for 0.5 hour and 1.5 hour respectively. Measurements at H = 6000 A/m on a planar-Hall element with permalloy annealed for 1.5 hour at 500°C shows a maximum value for φ-Θ of 0.1°. An angle detector consisting of a pair of these elements and using a magnetic field of 10 kA/m or more will show a total error of well below 0.1° for the total range, when offset voltages are not considered.

Conclusions

Measurements have been performed on a number of planar-Hall elements. A theoretical model, combining the Stoner-Wohlfarth single domain model and the planar-Hall effect in the structure, accurately describes the measurement results.
Ring-shaped elements show an increased output voltage. Magnetization behavior in a ring structure, combining magnetic anisotropy and magnetic form effects, is not yet properly understood.
Errors in the output of an angle detector, caused by magnetic anisotropy, may be reduced considerably by exploiting the inhomogeneity of the field of a permanent magnet.
Annealing at 500°C increases angular dispersion in easy-axis orientation in a permalloy film, reducing the errors caused by magnetic anisotropy in an angle detector.

Acknowledgments

References

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