EFFECT OF 'OVERLAPPING' VOLTAGE CONTACTS IN PLANAR HALL TRANSDUCERS*

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Abstract

A mathematical model is derived to compute the output of a planar Hall transducer (PHT) with overlapping voltage contacts at arbitrary positions and of arbitrary sizes. The model is based on the finite difference representation of the integral equation $\oint \mathbf{J} \cdot \mathbf{n} \, ds = 0$. In order to verify the model, the output of five PHTs with varying overlap sizes is measured in homogeneous and inhomogeneous fields. The computed results prove to be in good agreement with the experimental ones. The model is used to predict the effect of overlapping contacts on the output and resolution for several transducer configurations. The results are given in a number of diagrams. It is shown that a PHT with lower contacts (at the medium side) can be advantageous with respect to a biased (barber-pole) magnetoresistive (MR) head having the same size.

Introduction

Normal and planar Hall transducers can be used to detect magnetic fields produced by recording heads or media. In the recent past, some authors published methods to compute the output, for instance for a cross-shaped normal Hall transducer [1] and for a hypothetical point-contacted one-sided planar Hall transducer [2]. A cross-shaped PHT or a PHT having bulge contacts may show a degraded performance because of possible domain nucleation. As a consequence, a PHT must have well-defined edges and 'overlapping' voltage contacts (Fig. 1). In order to compute the effect on the output of these overlapping contacts a new model is necessary. In addition, such a model can provide an insight into the merits of a PHT with lower voltage contact(s) of practical dimensions, for it is known that such a configuration (point-contacted) can give a higher output than an MR-head of the same size [2]. In this paper we concentrate on the one-sided PHT, although the model is also applicable to the conventional configuration.

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Fig 1 One-sided PHT with several kinds of voltage contacts A overlapping upper contact, B overlapping lower contact, C bulge contact, D point contact, $\Rightarrow$ direction of initial M_s , $\rightarrow$ direction of the current

In the next section a description of the mathematical model is given, which is generally applicable Next, the experimental verification is described and finally the results are presented in a number of diagrams

Mathematical model of the planar Hall transducer

In this description of the model we consider a configuration with only one Hall voltage contact Such a configuration may be part of the one-sided dual sensor suggested by Fluitman or may be used in the ways depicted in Fig 2 ('single' one-sided PHT) In these situations the disturbing MR component is neutralized and only in the latter (voltage-driven mode) situation is there a constant zero-field offset The voltage-driven mode is used in the computations because of better correspondence with the integral equation mentioned above, as will be shown below The change of the current by the MR effect is only a few per cent

We consider the stripe axis as the x -axis and the width direction as the y -axis The ferromagnetic resistance anisotropy can be expressed with [3]

$$E = \rho J \quad \text{or} \quad J = \sigma E \quad (1)$$

in which ρ and σ are tensors In many applications the magnetization in the stripe is inhomogeneous (demagnetizing effects, inhomogeneous fields) in the y -direction, thus σ is a function of y and has to be calculated first [4]

Fig 2 'Single' one-sided PHT and response in a homogeneous field, two possibilities are presented to neutralize the MR voltage

Figure 3 shows the rectangular permalloy stripe with two drive voltage leads and one overlapping Hall contact. In order to solve the problem, the stripe is represented by a matrix of node-points. We define the Hall voltage on the node-points as the difference between the potentials with the magnetic field on and off. The distance between the node-points in the horizontal and vertical directions can be arbitrarily chosen. Further, we know that

$$\mathbf{E} = -\nabla u \quad (2)$$

and

$$\nabla \cdot \mathbf{J} = 0 \quad (3)$$

Expression (3) is the continuity equation used by many authors to solve similar problems by deriving the differential equation. Another approach is to use the integral form of eqn. (3) that is derived by using Gauss's theorem

$$\oint \mathbf{J} \cdot \mathbf{n} \, ds = 0 \longrightarrow \oint \sigma \nabla u \cdot \mathbf{n} \, ds = 0 \quad (4)$$

We apply eqn (4) to contours around every node-point, except the ones that are part of the overlapping contact (see A, B, C and D in Fig. 3). We also apply eqn (4) to the contour around all of the overlap node-points (see E in Fig. 3). There are special boundary conditions for the node-points at the edges: a Neumann condition for the upper and lower edges (B), and a Dirichlet condition for the left and right edges (C). Both conditions apply to node-points in the corner (D). We calculate $\oint \sigma \nabla u \cdot \mathbf{n} \, ds$ by defining the potential function u in every triangle by means of the potentials on the angular points (see A in Fig. 3). In this way we get a number of finite difference equations that can be solved directly with the help of a computer, together with the set of equations that follow from the fact that all overlap node-points have an equal potential (in matrix form: $\mathbf{A}u = \mathbf{b}$). With the calculated potentials u it is possible to compute the current J_x (eqns (1) and (2)) in order to normalize the output with respect to the current of a PHT without overlap (an overlapping contact decreases the resistance and as a result increases J_x).

Fig. 3 A PHT represented by a matrix of node-points (see text)

Verification of the model

In order to verify the model, the response of five one-sided PHTs of various configurations is measured in homogeneous fields induced by a pair of Helmholtz coils and in inhomogeneous fields induced by a current conductor. The PHTs consisted of a vacuum-evaporated permalloy stripe having length $l = 11$ mm, width $w = 2$ mm and thickness $t = 50$ nm. The intrinsic properties such as magnetoresistance $\Delta\rho/\rho$ and anisotropy field H_K of the permalloy stripe are measured by standard techniques. The various configurations are defined by the aluminium contacts (thickness $t = 1$ μm). Four PHTs have a sensor length $l = 0.8$ mm of which the overlap depths vary from 0.1 to 1.5 mm. Because of the large value of w/l ($= 2.5$) the Hall voltage is built up mainly at the edges [3], so a very large degree of discretization (in the width) is necessary to obtain good accuracy. With the chosen degree of discretization (210 node-points) there is still a reasonable agreement between the computed results and the experimental ones. In order to obtain a better accuracy with the same number of node-points, a PHT is taken with a smaller value of $w/l = 1$. The computed and measured results are depicted in Fig. 4. In both cases a small bias field (40 A/m) in the x -direction is used to obtain a single-domain situation. The computed values in the homogeneous field (Fig. 4(a)) are in excellent agreement with the measured data *without* any 'fitting', i.e., by using the measured intrinsic values of $\Delta\rho/\rho$ and H_K . In order to measure the response in an inhomogeneous field, the PHT is moved from 2 mm to the left to 2 mm to the right of a current conductor, keeping distance d constant (Fig. 4(b), inset). It is easily derived that $H_y = I/[2\pi(y^2 + d^2)]$, so the form and strength of the inhomogeneous field will change along this trajectory, being a good test case of the accuracy of the model. The computed results are in good agreement with the experimental ones, although a little fitting was necessary for the absolute position y , as a consequence of the experimental procedure. In general, the computed values are too low, which can be partly ascribed to the chosen degree of discretization. Other possible origins of the deviations are (1) the small fields used because of the high sensitivity of the planar Hall-effect, so disturbing

Fig. 4 (a) Response of a PHT in a homogeneous field [$J_x = 2 \times 10^8$ A/m², $\Delta\rho = 0.6$ $\mu\Omega$ cm] (b) Response of a PHT in a field induced by a current conductor (see inset)

fields (such as the earth's magnetic field) can have a relatively large influence, (ii) the uncertainty of the intrinsic properties and the thickness of the permalloy film and (iii) the experimental procedure in the case of the inhomogeneous field verification, with the low accuracy in position y and distance d

A final verification is the comparison of the values for the form factor F with those in the literature on normal Hall transducers [5] The results appear to be in excellent agreement.

Results

The computer simulation is used to predict the effect of the size of the overlapping upper and lower voltage contacts on the output. The definition of the size of an overlap is depicted in Fig 5 In the following calculations either l or w is kept constant, so the results are not applicable for all lengths and widths (particularly, because of demagnetizing effects), but the general tendencies contain important information. Figure 6 gives the effect of overlap widening on the output for several values of w/l There is not much difference between homogeneous and inhomogeneous fields for

Fig 5 Definition of width and depth of upper and lower overlapping voltage contacts

Fig 6 Effect of overlap width b on the output for several w/l V_0 is the planar Hall voltage of a point-contacted PHT [$t = 50$ nm, $w = 40$ μ m, $d/w = 0.1$]

both upper and lower contacts. Figure 7 gives the effect of increasing overlap depth d for several w/l and field forms. Normally the output decreases for upper overlaps, the effects becoming smaller in more inhomogeneous fields. In the case of a strong inhomogeneous field and large w/l , the effect can be positive, however, this is an extreme example. The effect is always negative for lower overlaps (as expected) and becomes stronger with smaller field inhomogeneity c and higher w/l . In Fig 7(d) one can see the output decrease as a function of the inhomogeneity. Together with Fig 7 (a) - (c), the output can be calculated for many configurations knowing the output of a point-contacted PHT in a homogeneous field [2]. For instance, it can be concluded from this reference that a PHT with lower overlapping contacts can give an even higher output than an identically sized MR-head in an inhomogeneous field. The output is also computed for PHTs with varying widths (40, 80, 160 μm), while the distance between upper overlap and lower edge is kept constant ($w - d = 40 \mu\text{m}$). It appears that the PHT with the smallest width and minimal overlap depth has the highest (maximum) output and also the highest sensitivity, in spite of the higher form anisotropy tM_s/w , in both homogeneous and inhomogeneous fields.

Fig 7 (a, b, c) Effect of overlap depth (d upper, $\bar{d}$ lower) on the output for several w/l and field forms $H = H_0 \exp(-y/cw)$ [$t = 50 \text{ nm}$, $w = 100 \mu\text{m}$, $b/l = 0.2$] (d) Output as a function of field inhomogeneity c for several w/l

Finally, the resolution of four PHT configurations is computed for $w = 10, 20$ and $40 \mu\text{m}$ on the basis of the response to a line charge field [6]. The relevant component of such a field is $H_y(y, z) = Qy/(y^2 + z^2)$. The magnitude Q is chosen such that the PHT is driven in the linear region. The height $y = h$ is kept constant at $1 \mu\text{m}$ for all widths. The four types of configuration are depicted in Fig 8(c). Fig 8(a) shows the half amplitude width P_{50} as a function of the PHT width w . As expected, the resolution increases with decreasing width and increasing overlap depth, but of course the output decreases (Fig 8(b)). A PHT with small lower contacts is favourable with respect to resolution *and* output. The point-contacted two-sided PHT (type I) is depicted because of the verified fact that it has the same resolution as an MR-head with the same width.

Fig 8 Resolution and output in a line charge field for several PHT configurations as a function of width w . The output is normalized on type I with $w = 10 \mu\text{m}$ [$t = 50 \text{ nm}$, $l = 40 \mu\text{m}$, $h = 1 \mu\text{m}$]. I point contacts two-sided (hypothetical case), II small upper contact, a $d = 0 \mu\text{m}$ (hypothetical case), b $d = 2 \mu\text{m}$ (practical case), III small lower contact, a $d = 0 \mu\text{m}$, b $d = 2 \mu\text{m}$, IV upper overlap depth $d = 0.5 w$. — practical, --- hypothetical.

Conclusions

The results of the mathematical model of a PHT with overlapping voltage contacts presented above are in good agreement with the results measured for five different PHTs in homogeneous and inhomogeneous fields. The computed form factor is in excellent agreement with values in the literature concerning the normal Hall-effect. This makes it possible to predict properties such as (maximum) output and resolution of PHTs of arbitrary configuration (w/l , size of overlapping upper or lower voltage contact(s)). Generally an overlapping voltage contact lowers the output.

with respect to a point-contact at the edge. The depth of the overlapping contact has a larger influence than the width. If upper voltage contacts are chosen (for instance, because of a simpler technological procedure), a PHT can have contacts of reasonable size without losing too much output. A PHT with minimal-sized lower overlapping contacts can have a higher output and better resolution than an identically sized MR-head in strong inhomogeneous fields such as those induced by thin recording media. The resolution of a PHT with minimal-sized upper overlapping contacts is always lower than that of an MR-head. Thus if one has the technological possibility to make a PHT with lower contacts (an isolating layer with contact holes is required), this can be a good alternative to the (barber-pole) MR-head as far as output and resolution are concerned.

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