COMPARISON OF A SHIELDED "ONE-SIDED" PLANAR HALL-TRANSDUCER WITH AN MR-HEAD

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ABSTRACT

The resistance anisotropy in ferromagnetic conductors gives rise to the related planar magneto-resistive and Hall-effects. The magneto-resistive effect is exploited in several field sensing transducers, while the planar Hall-effect is not. In this paper the output of direct sensing Hall-heads is compared with magneto-resistive heads for a number of situations typical for magnetic recording. The comparison is based on a computational procedure which can be executed with the help of a simple calculator. The procedure and the results are presented in such a way that known results for magneto-resistive transducers can immediately be translated into results for Hall-transducers.

1. INTRODUCTION

In the passed decade much attention has been paid to the development of magneto-resistive heads (M.R.H.'s) for reading magnetically coded information. In connection with the technological problems to be solved a number of designs has been suggested and tested to linearize the transducer, to suppress thermal and/or Barkhausen noise, to enhance the resolution and so on. The fact that all ideas consistently employ the magneto-resistive effect and not the related (planar) Hall-effect is understandable, because a direct sensing Hall-head will have a relative small output, although we do not exclude that the presence of the planar Hall-effect is occasionally overlooked. The intrinsic planar Hall- and magneto-resistivities, present in permalloy strips, obey the following laws [1]:

$$\rho_H = \Delta\rho \sin\phi \cos\phi \quad (1)$$

$$\rho_{MR} = \rho_o - \Delta\rho \sin^2\phi \quad (2)$$

with ϕ the angle of rotation of the magnetization off the strip axis. Since the intrinsic effects are equal in amplitude, it is clear that the extrinsic effects in a strip with width w and length l have an amplitude ratio roughly equal to w/l. A read head designed to sense the fields of recorded bits directly must be positioned along the edge of a substratum, having a striplike geometry with a length equal to the recording trackwidth and a width determined by a number of considerations as there are: the available field (gradient), the required output signal, reliability and heating, technological restrictions etc.

A Hall-transducer, placed along a substratum edge may have the geometry suggested in Fig. 1a [2] or a derived form like the sandwich-structure of Fig. 1b.

It is expected that in a structure as shown, with a width of, say 10 μm, only a few tenthes of a millivolt will be available. Nevertheless we think that the Hall-response in such structures is worth to be studied, not only because it is intriguing in itself or anticipates sophisticated electronics and still more reduced trackwidthes, but also because the range of applicability of the planar head is rather wide from high-density recording to low density applications such as ticket or card readers. All these applications have their own requirements and it is good to have a complete overview of possible solutions. Another possible advantage of the Hall-configuration is suggested in Fig. 1c. In this structure the Hall-voltages are generated by fields which are directly underneath the Hall-contacts, so one can have a multi-track head with current leads only at both ends. Last but not least, the Hall-effect is linear in first order and shares the range of linearity with the Barberpole head, because the latter one's behaviour is described by exactly the same formula as the planar Hall-response [3]. In the next section we describe a method to calculate Hall-potentials in a simple way. Expressions in closed form will be given which, in spite of their complex appearance, can be used with a simple (pocket) calculator at hand.

Next we present results of computed Hall- and magneto-resistive responses for a number of characteristic situations, for unshielded as well as for shielded transducers. We consistently give our results as ratios between the Hall-response and the (linearized) magneto-resistive response so that anyone, familiar with the latter, can judge for himself what the Hall-effect is worth after all.

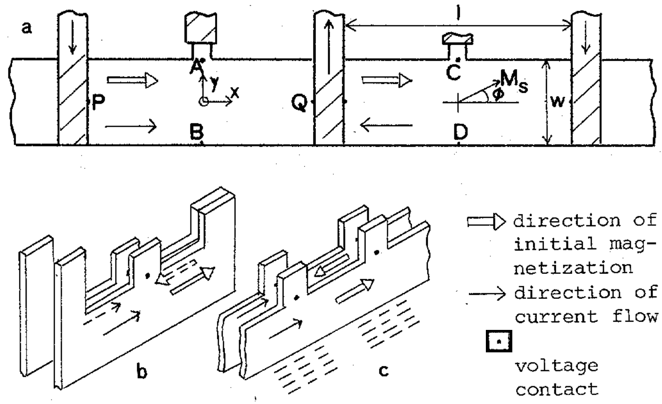

Fig. 1. Basic structures of "one-sided" Hall-transducers. With the polarities of currents and initial magnetizations as shown a linear Hall-voltage is detected from the Hall-contacts.

a. Basic geometry used in the computations. Note that the permalloy generally must extend under the current leads to prevent end domains in the effective area.
b. Sandwich structure which may be advantageous in reducing noise.
c. Multitrack Hall-head. The zero field magnetization may be the result of canted easy axes the effect of which is compensated by the bias of the drive currents. The canted easy axes may be employed to initialize the magnetization.

2. SCHEME OF COMPUTATIONS

In order to compute Hall-voltages between any two different positions on the transducer it is necessary to have the disposal of an expression which gives the

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Hall-potential at individual positions on the film. In a preceding paper [4] this expression has been derived to read:

$$V_H(\vec{r}) = \frac{\Delta\rho J}{2\pi}\int_{-w/2}^{+w/2} \sin\phi(y_o)\cos\phi(y_o)G(y_o,x,y,l,w)\,dy_o \qquad (3)$$

Here $V_H(\vec{r})$ is the Hall-potential (defined as the difference in potential with magnetic fields on and off) at a point $\vec{r}$ (x,y), somewhere on the film. J is the current density in the device. Formula (3) is valid for the case that the magnetization distribution in the strip is only inhomogeneous in the y-direction. This is expressed by the y_o-dependence of ϕ. $G(y_o,x,y,l,w)$ is a weight function which includes the short-circuiting effects of the current contacts. If we concentrate on the Hall-voltages of relevance in the configuration of Fig. 1a we need only compute the G-function at x=0, $y=\frac{1}{2}w$ (for completeness and because it simply follows from symmetry we will also give results for x=0, $y=-\frac{1}{2}w$). The G-function can only be computed using a numerical algorithm, but with trial and error we have found closed analytical expressions which form surprisingly good approximations:

$$G(y,0,w/2,l,w) = \begin{cases} \dfrac{-2\pi\,\mathrm{arctg}(\sinh a/\cosh b)}{\mathrm{arctg}(\mathrm{tgh}\ b)} & w/l \geq 1/3 \\ -2\pi y/w-\pi & w/l < 1/3 \end{cases} \qquad (4)$$

$$G(y,0,-w/2,l,w) = \begin{cases} \dfrac{-2\pi\,\mathrm{arctg}(\sinh a'/\cosh b)}{\mathrm{arctg}(\mathrm{tgh}\ b)} & w/l \geq 1/3 \\ -2\pi y/w+\pi & w/l < 1/3 \end{cases} \qquad (5)$$

with $a = \pi(w/2l + y/l)$, $a' = \pi(w/2l - y/l)$ and $b = \pi w/l$.

The error made with this formula is 1% at the most (for $w/l \simeq 1/3$) and decreases via 0.3% for $w/l = 1/2$ or 1/4 to negligible small values farther outside the region with $w/l \simeq 1/3$.
Since $V_H(0,\frac{1}{2}w)$ at the left transducerpart (Fig. 1a) is just the opposite of $V_H'(0,\frac{1}{2}w)$ at the right part we simply find that:

$$V_{AC} = 2V_H(0,\tfrac{1}{2}w) \qquad (6)$$

and $$V_{BD} = 2V_H(0,-\tfrac{1}{2}w) \qquad (7)$$

If we further concentrate on the first order (linear) response we find, with $\sin\phi = M_y/M_s$:

$$V_{AC} = \frac{2\Delta\rho J}{2\pi M_s}\int_{-\frac{1}{2}w}^{\frac{1}{2}w} M_y(y_o)G(y_o,0,\tfrac{1}{2}w,l,w)\,dy_o \qquad (8)$$

and $$V_{BD} = \frac{2\Delta\rho J}{2\pi M_s}\int_{-\frac{1}{2}w}^{+\frac{1}{2}w} M_y(y_o)G(y_o,0,-\tfrac{1}{2}w,l,w)\,dy_o \qquad (9)$$

In order to compare these results with magneto-resistive responses we have choosen the first order response for a transducer (homogeneously) biased at $\phi = \pi/4$ as a reference:

$$V_{PQ} = \frac{\sqrt{2}\Delta\rho J l}{M_s w}\int_{-\frac{1}{2}w}^{+\frac{1}{2}w} M_y(y_o)\,dy_o \qquad (10)$$

with $M_y(y_o)$ that part of the magnetization that exceeds the bias.

After some normalization eq.'s (8), (9) and (10) can be rewritten to read:

$$V_{AC} = c.w.\frac{1}{2\pi}\int_{-\frac{1}{2}}^{+\frac{1}{2}} M_y(y_o)G(y_o,0,\tfrac{1}{2},1,1)\,dy_o \qquad (11)$$

$$V_{BD} = c.w.\frac{1}{2\pi}\int_{-\frac{1}{2}}^{+\frac{1}{2}} M_y(y_o)G(y_o,0,-\tfrac{1}{2},1,1)\,dy_o \qquad (12)$$

$$V_{PQ} = c.l.\frac{1}{\sqrt{2}}\int_{-\frac{1}{2}}^{\frac{1}{2}} M_y(y_o)\,dy_o \qquad (13)$$

with $c = 2\Delta\rho\ J/M_s$.

Note that expression (13) does not contain any dimensional factor. This is because the influence of the formfactor is negligible for the case of planar magneto-resistivity [5]. The factor $1/2\pi$ in (11) and (12) is a consequence of our definition of the G-function.

3. RESULTS FOR UNSHIELDED TRANSDUCERS

For homogeneous fields and for transducers with $w/l \leq 1/4$ we simply find:

$$\frac{V_{AC}}{V_{PQ}} = \frac{V_{BD}}{V_{PQ}} = \frac{1}{\sqrt{2}}\frac{w}{l} \qquad (14)$$

For homogeneous magnetization and for transducers with $w/l > 1/4$ we have:

$$\frac{V_{AC}}{V_{PQ}} = \frac{V_{BD}}{V_{PQ}} = \frac{1}{\sqrt{2}}\frac{w}{l}F(w/l) \qquad (15)$$

with $F(w/l)$ a geometrical correction factor, directly related to our G-function and well known from literature [6]. Generally F also depends on the Hall-angle but since this angle never exceeds a few degrees F reduces to the limiting function for Hall-angle zero. Normally the fields are inhomogeneous and according to Wallace [7], decay exponentially with distance from the recording medium. Whether or not $M_y(y_o)$, in formula's (11), (12) and (13), decays exponentially as well, depends on the ratio of intrinsic to form anisotropy of the strip (material). Only when the intrinsic anisotropy field $H_k \gg tM_s/w$ we can express $M_y(y_o)$ as a simple exponential function as well, otherwise $M_y(y_o)$ can only be computed using a numerical algorithm [4]. We have computed response ratios for a number of w/l-ratios and for $H_k \gg tM_s/w$, $H_k = tM_s/w$ en $H_k \ll tM_s/w$. The results are collected in Fig. 2 giving graphs of the factor $K(w/l)$ from:

$$\frac{V_{AC}}{V_{PQ}} = \frac{1}{\sqrt{2}}\frac{w}{l}K(w/l,c) \qquad (16)$$

where K depends on w/l, the decay-constant c of the external field $H = H_o\exp(-y/cw)$ and the ratio $H_k/(tM_s/w)$. For completeness we also give K' from:

$$\frac{V_{BD}}{V_{PQ}} = \frac{1}{\sqrt{2}}\frac{w}{l}K'(w/l,c) \qquad (17)$$

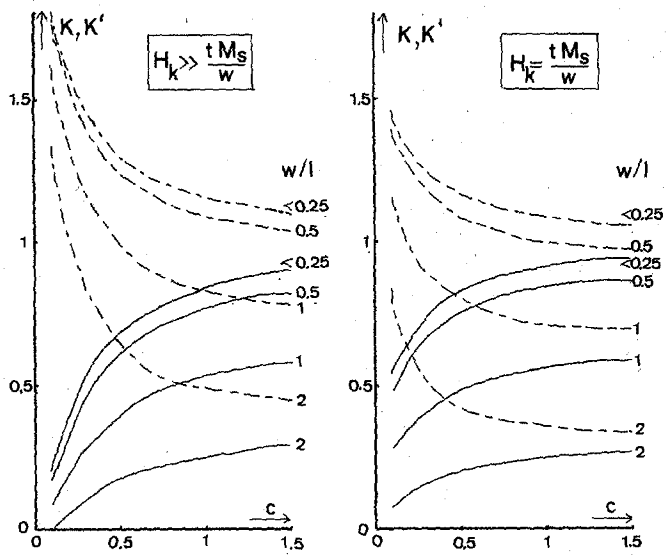
4. RESULTS FOR SHIELDED TRANSDUCERS

Surprisingly the treatment of shielded transducers can be rather simple because use can be made of an expression for $M_y(y_o)$ that is a good approximation of the real situation. Assuming $H \ll M$ in the material and accepting the transmission line model of calculating the flux through the strip [8] we have:

$$M_y(y_o) = M_o\frac{\sinh\frac{w}{\lambda}\left(\frac{1}{2}-\frac{y_o}{w}\right)}{\sinh\frac{w}{\lambda}} \qquad (18)$$

with $\lambda = \sqrt{\mu_r tg/2}$ and $\mu_r = M_s/H_k$.

With expression (18) slipped into eq's (11), (12) and (13) the computation is straightforward and if we again express our results in the form of (16) and (17) we have:



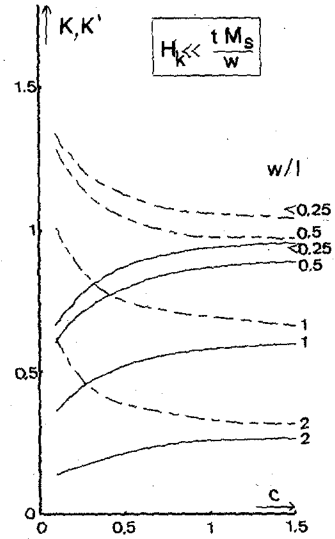
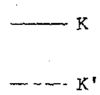


Fig. 2. Factors K and K' from (16) and (17) for several values of the ratio w/l



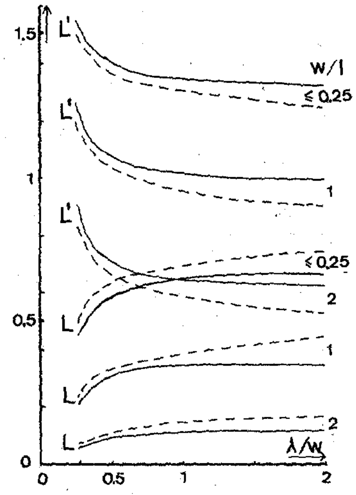


Fig. 3. Factors L and L' from (19) and (20) for several values of the ratio w/l.

$$\frac{V_{AC}}{V_{PQ}} = \frac{1}{\sqrt{2}} \frac{w}{l} L(w/l, \lambda/w) \qquad (19)$$

$$\frac{V_{BD}}{V_{PQ}} = \frac{1}{\sqrt{2}} \frac{w}{l} L'(w/l, \lambda/w) \qquad (20)$$

with L and L' not only dependent on *w/l* but also on *λ/w*, which is a measure of the penetration depth of the flux into the strip. *In Fig.* 3 we give an overview of some characteristic results. Since we after all did not feel at ease using eq. (18) we have also performed "exact" computations using the numerical procedure described by Kelley [9]. Typical results of these computations are also found in Fig. 3 (dotted curves) and we see that deviations are present indeed. The approximated values of L appear to be somewhat too small, while the approximated values of L' are somewhat too large. Nevertheless the analytical procedure is a useful tool which gives good approximations.

5. DISCUSSION AND CONCLUSIONS

We have given a computational procedure to evaluate the potential merits of Hall-detection over M.R.-detection. We have presented our result in a standard form giving the ratios of Hall-voltages to M.R.-voltages. Apart from the factor $1/\sqrt{2}$, which is a bit ambiguous and a consequence of the method of biasing the M.R output, the ratios are the product of w/l and a "formfactor" (F,K,K',L,L'). For the upper contacts two factors are responsible for K or L being smaller then the maximum attainable value (1 for K and 0.67 for L). At first the formfactor effect, starting at $l < 4w$, breaks down the Hall-effect while the magneto-resistance is hardly affected [5], at second the decaying magnetization in the strip from the medium side upwards affects V_{AC} more seriously (in a negative sense) then it does the magneto-resistivity. So generally speaking these Hall-voltages cannot compete with the M.R.-voltages. However we do not exclude that the inherent advantages of the Hall-detection (linearity, layout, noise immunity?) occasionally will turn the scale. The region of applicability is likely to be $l \simeq w$ and/or sensing of fields which do not decay too fast in the width direction of the transducer. With respect to the lower contacts the two factors mentioned above are competing, but K' and L' will have values greater than 1 generally. We have presented the K' and L' values not only because they are "costless" spin-off of our computations but also in the hope that they may inspire to possible new designs of magnetic sensors in general. We have restricted our results to the ratios mentioned, because practical values of magneto-resistive voltages are already available and the Hall-voltages can simply be derived from them. For the case of unshielded magneto-resistive transducers we can refer to the review of Collins and Jones [10] and for the case of shielded transducers there are a number of references that can be made [11-13].

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