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SIMULATION MODEL FOR A SILICON HALL SENSOR IN AN ABSOLUTE DIGITAL POSITION DETECTION SYSTEM

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Abstract—The performance of a digital position detection system with silicon Hall sensors for the detection of coded absolute position data has been investigated. The position information is fixed in one single track as a maximum length sequence of bits by means of longitudinal saturation recording in a hard-magnetic layer. The Hall elements are positioned with their surface parallel to the hard-magnetic layer.

An efficient computer simulation model has been realized which calculates the response of a Hall element in the fringing field. The computed results are compared with experimental data on Hall elements which were realised using MOS-IC technology. The simulation model appeared to be sufficiently accurate for a first-order estimation of the performance of an absolute position detection system on the basis of silicon Hall elements. The resolution which can be realized depends strongly on the noise level in the elements and will be of the order of a few hundred μm.

NOTATION

ϕ	electric potential, V
ϕ_H	electric potential as a result of Hall effect, V
G	weight function
$x'y'$	coordinates of a point in Hall element, m
L	length of Hall element, m
W	width of Hall element, m
t	effective thickness of Hall element, m
S	width of Hall contact, m
R_h	Hall coefficient, $\Omega \cdot \mathrm{m} \cdot \mathrm{T}^{-1}$
I	input current Hall element, A
B	magnetic induction, T
μ	carrier mobility, $\mathrm{m}^2 \cdot (\mathrm{V} \cdot \mathrm{s})^{-1}$
θ	Hall angle ($= \arctan \mu B$), radian
V_H	Hall voltage, V
N_D	dopant density, m^{-3}
z_o	effective element-medium separation, m
d	thickness of hard-magnetic layer, m
k	bit period, m
V_M	detected peak voltage for single reversal, V
Δ_{50}	pulse width at $V_H = V_M/2$, m
M_r	remanent magnetization of hard-magnetic medium, A/m
V_1	"1" detection level, V
V_0	"0" detection level, V
V_{det}	detection distance ($V_1 - V_0$), V
V'_H	normalized Hall voltage ($= V_H^* t/(I^* R_H)$), T

1. INTRODUCTION

Magnetic digital position measurement devices are preferred to optical versions for applications in dirty environments containing oil, moisture, dust etc.

An absolute position detection system based on position information which is coded serially into a single track hard-magnetic layer is proposed in [1]. In this case detection of the information has been realised with the help of a magnetoresistive permalloy strip.

We make use of the same position information coding scheme in the magnetic layer but for detection of the fringing field we apply a sensor based on the Hall effect in a semiconductor. The individual elements are positioned with their surface parallel to the magnetic layer (see Fig. 1). The application of silicon Hall elements provides an opportunity to develop an integrated sensor, together with for instance multiplex circuits in order to reduce the amount of connections to the chip.

In the next section a simple simulation model is presented for the estimation of the performance of this kind of sensor. Computed results are compared with values which were found experimentally with the help of a prototype sensor head. Finally a description is given of the way the detection can be optimised using the simulation model.

2. MODELLING

In the past, much attention has been paid to methods for the calculation of the response of Hall devices, especially in inhomogeneous fields. The methods can be roughly divided into two classes.

1. Potential distribution calculation by means of numerical solution of the differential equations, resulting in the electric potential distribution $\phi(x, y)$ [2, 3].

2. Analytical deduction of weight functions from the differential equations. These weight functions $G(x', y', L/W)$ can be used to calculate the Hall potential ϕ_H of a certain point (x'_i, y'_j) (see Fig. 2), especially at the position of the Hall contacts [4, 5].

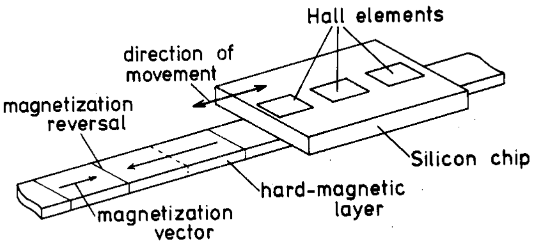


Fig. 1. Basic principle of the position detection method.

Following the second approach results in

$$\phi_H(x_i', y_j') = \frac{R_H \cdot I}{2\pi t W L} \int_{-L/2}^{L/2} \int_{-W/2}^{W/2} B_z(x, y) \cdot G(x_i', y_j', x, y, L/W)\,\mathrm{d}x\,\mathrm{d}y. \tag{1}$$

(The Hall angle θ (= arctan μB) can be taken equal to 0 in our situation with low fields.)

A simplification of (1) can be obtained assuming there is a field gradient in only one direction.

$$\frac{\partial B}{\partial y} = 0:\ \phi_H(x_i', y_j') = \frac{R_H \cdot I}{2\pi t \cdot L} \int_{-L/2}^{L/2} B_z(x) \cdot G_x(x_i', y_j', x, L/W)\,\mathrm{d}x \tag{2}$$

$$\frac{\partial B}{\partial x} = 0:\ \phi_H(x_i', y_j') = \frac{R_H \cdot I}{2\pi t \cdot W} \int_{-W/2}^{W/2} B_z(y) \cdot G_y(x_i', y_j', y, L/W)\,\mathrm{d}y. \tag{3}$$

In our application a simple simulation model resulting in a relatively short computing time rather than an accurate model is necessary.

This can be obtained by using the results of the calculations made by Hlåsnik and Kokavec[4]. The Hall voltage $V_H (= \phi_H(0, W/2) - \phi_H(0, -W/2))$ between the two Hall contacts in a rectangular element (Fig. 2) can be calculated using the values which are sketched in Fig. 3, limiting the gradient of the magnetic field to either the x- or the y-direction which is sufficient in our application. The fringing field of the magnetic layer with an arbitrary bit pattern is calculated, starting from an arctangent magnetization reversal. The total magnetic field can be calculated by the superposition of the field of the individual reversals. Some results are given in Sections 4 and 5.

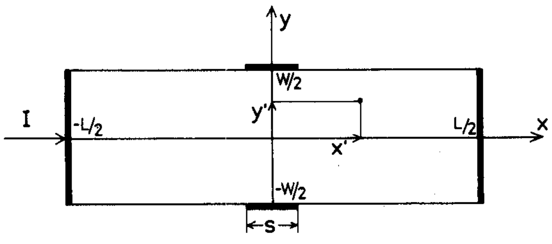


Fig. 2. Definition of parameters in a rectangular Hall element.

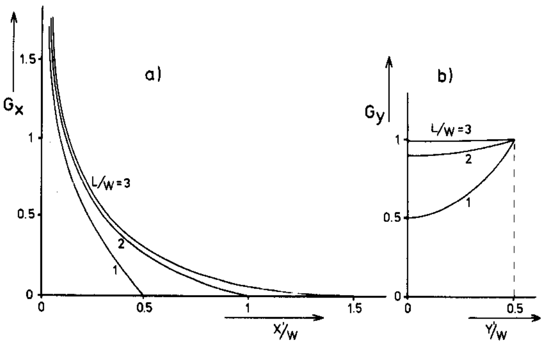


Fig. 3. Distribution of the weight functions according to [4]. B_z is only a function of x' in (a) and y' in (b).

3. EXPERIMENT

In order to obtain experimental values to verify the simulation model we realized Si Hall sensors by means of MOS-IC technology using a 500 kV ion-implantation machine. The active area is a phosphor doped n-layer with nominal thickness 1.5 μm and $N_D = 10^{17}$ cm^{-3}. The Hall element dimensions are $L = 300$ μm, $W = 100$ μm and $S = 5$ μm. The following parameters have been found experimentally:

$$t = 1.2\ \mu\text{m}, \quad N_D = 1.2\,10^{17}\ \text{cm}^{-3},$$

$$\mu = 740\ \text{cm}^2/\text{Vs and}$$

$$V_H/BI\ (\text{Hall sensitivity}) = 43\ \text{V}/AT.$$

The elements are positioned with the Hall surface parallel to the magnetic layer and the substrate side towards the magnetic layer as schematically shown in Fig. 4. Advantages of this orientation are the opportunity to create two-dimensional element configurations for the detection of the bits (surface//medium) and the possibility to connect the active area by means of ultrasonic bonding at the free surface of the device (substrate side towards magnetic layer). Reducing the substrate thickness by means of chemical isotropic etching resulted in an element-medium separation z_o of less than 100 μm. Other orientations of the sensor element with respect to the hard-magnetic layer are possible but not under discussion in this paper.

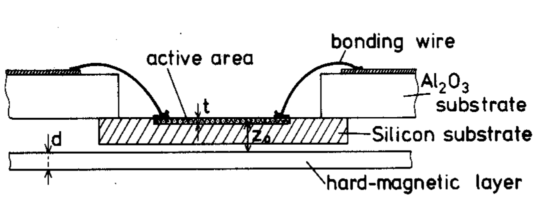


Fig. 4. Positioning of the Hall element with respect to the magnetic layer (cross-section).

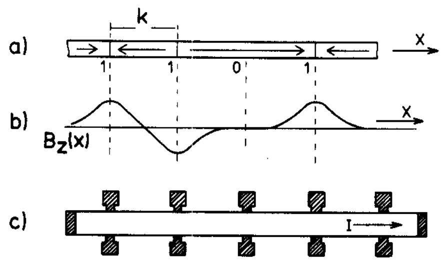


Fig. 5. Details of the position information detection. (a) Magnetic bit pattern. (b) Perpendicular component of the fringing field. (c) Hall strip, replacing five individual elements.

A $\gamma - Fe_2O_3$ layer was used as a hard-magnetic medium (thicknesses $d = 10$ µm and 14 µm). Using longitudinal saturation recording a magnetic bit pattern was written into this layer, representing "1" by a magnetization reversal and "0" by the absence of the reversal, as depicted in Fig. 5(a). The minimum distance between reversals is the bit distance k.

In our experiments the Hall element was placed with its x-axis in the longitudinal direction of the layer resulting in $B = B_z(x)$ [Fig. 5(b)].

According to our calculations this orientation principally gives a higher resolution compared with the situation with the y-axis in longitudinal direction. This can be seen directly from the distribution of the weight functions G_x and G_y (in Fig. 3) which show a relatively high "sensitivity" around the Hall contacts.

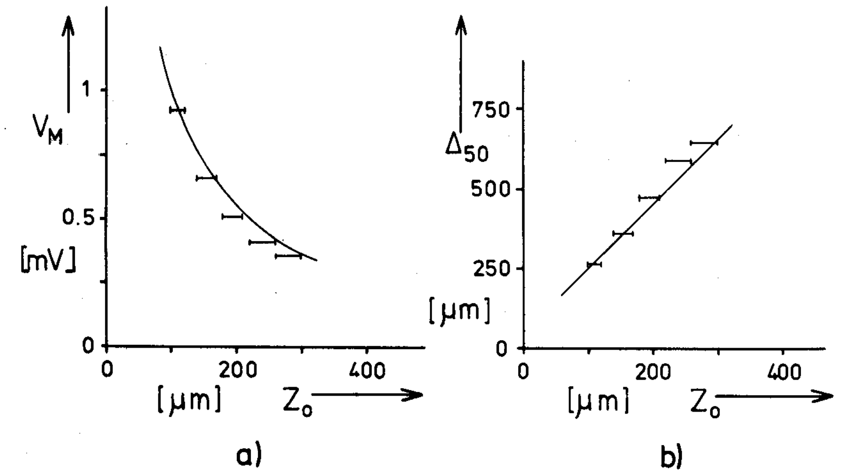
This fact means that in principle, in the chosen orientation, one single "Hall strip" can be applied for the detection of several adjacent bits [Fig. 5(c)], resulting in a decreased number of connections to the chip.

In a first experimental Hall strip the Hall sensitivity was found to be position dependent along the longitudinal axis of the strip. This effect is due to the changing thickness of the insulation region as a function of the local reverse voltage. For this reason the active area dopant density must be chosen relatively high compared with the substrate dopant density.

4. RESULTS

Experimental data were obtained using the above described sensor elements. At first the response of the element to a single isolated magnetization reversal as a function of the element–medium separation z_o was measured. ($z_0 = 100$–240 µm). Figure 6 shows the resulting values for the peak voltage V_M and the pulse width Δ_{50}, (at $V = V_H/2$) of the signals for the 10 µm thick medium with $M_r = 87500$ A/m. The values calculated with the simulation model are also given in this figure. Similar correspondence between computed and measured results was obtained for an other thickness d of the medium and for different bit patterns. In Fig. 6 the fault margin due to the uncertainty in z_o is given. Taking into account that due to the experimental method, the actual z_o-values of the experimental data will be to the right-hand side of the adjusted z_o-value, the simulation model gives a good approximation.

The model is calibrated for the response in a homogeneous field. This means that the error in the calculated value should go to zero with increasing value of z_o (small field gradient). If the data in Fig. 6(a) are fitted for $z_o = 300$ µm and the other calculated values are corrected (with a factor $c = V_{\text{exp}}/V_{\text{cal}}$ (at $z_o = 300$ µm)) an error up to 10–15% is obtained at $z_o = 100$ µm. However the calculated values will always be smaller than the experimental ones. This can be corrected by changing the distribution of the weight function or by using a smaller integration step. In our case we did not use this correction because for a rough estimation of the sensor performance the accuracy was sufficient.



a) b)

Fig. 6. Sensor response of a Hall element ($L * W = 300$ µm$*100$ µm) on an isolated magnetization reversal in a 10 µm thick medium (—— computed, — measured).

5. OPTIMIZING THE DETECTION PROCESS

The main aim of this study is to acquire knowledge of the applicability of Si Hall elements in an absolute position detection system.

With the given model it is possible to simulate the detection process while changing the different parameters of the process. The system can be optimized by maximizing the detection distance V_{det} which results from the "worst case" bit patterns as depicted in Fig. 7.

The "worst case" bit patterns are:

—A single isolated reversal, resulting in a maximum "0" level V_0.

—Three succeeding bits at minimum distance k, resulting in a minimum "1" level V_1.

Since at least two elements with a $k/2$ shift have to be applied for every bit to be detected[1] in order to avoid detection hazards, a detection interval of $k/2$ per element is employed. Using the response of the Hall element for the "worst case" patterns, an "eye pattern" can be constructed, visualizing the detection distance $V_{det}(= V_1 - V_0)$ (Fig. 7). In Fig. 8 V_1, V_0 and V_{det} are given as a function of the bit period k.

An optimal value k_{opt} for the bit period k is found due to a decrease in V_1 because of pulse crowding at small k, and a decrease in V_1 and V_0 due to a longer relative distance to the adjacent reversals at larger k.

In Fig. 8 experimental data are also presented, measured with the Hall sensor $L = 300$ μm, $W = 100$ μm, $z_o = 110$ μm, $d = 10$ μm. There is a reasonable agreement between experimental and calculated values. For small k, a strong field gradient is found in the "worst case" situations (see Fig. 7) resulting in differences, especially in V_1, up to ±30%. At the same time the experiments showed smaller values for k_{opt} with respect to the model. In spite of this it is concluded that the model can be used for a first order optimization of the detection process.

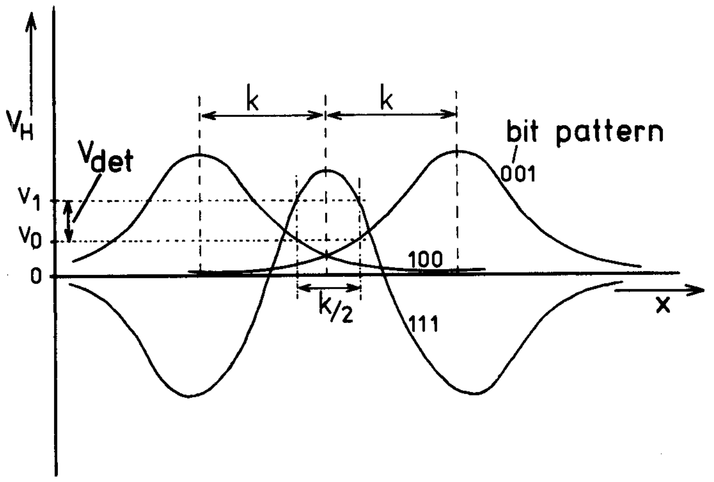


Fig. 7. Construction of the detection distance V_{det} from the sensor response on "worst case" bit patterns for a detection interval $k/2$.

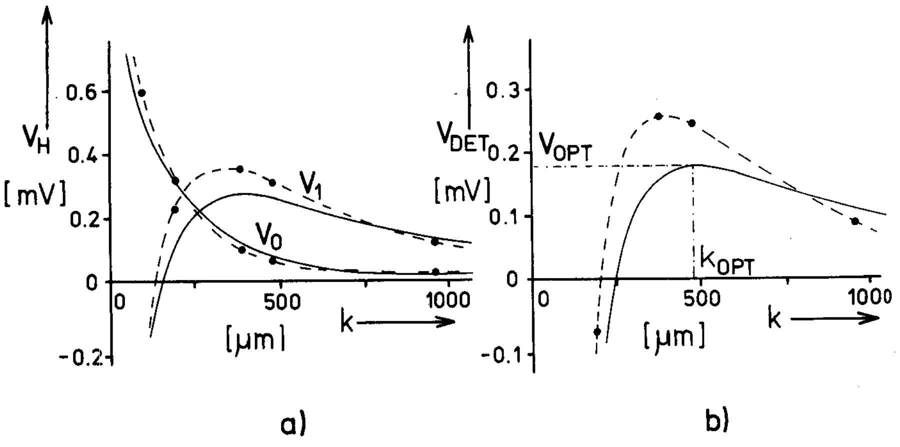


Fig. 8. Detection levels V_1 and V_0 (a) and detection distance V_{det} (b) as a function of the bit period k with sensor—medium dimensions as in Fig. 6 (—— computed, - - - measured).

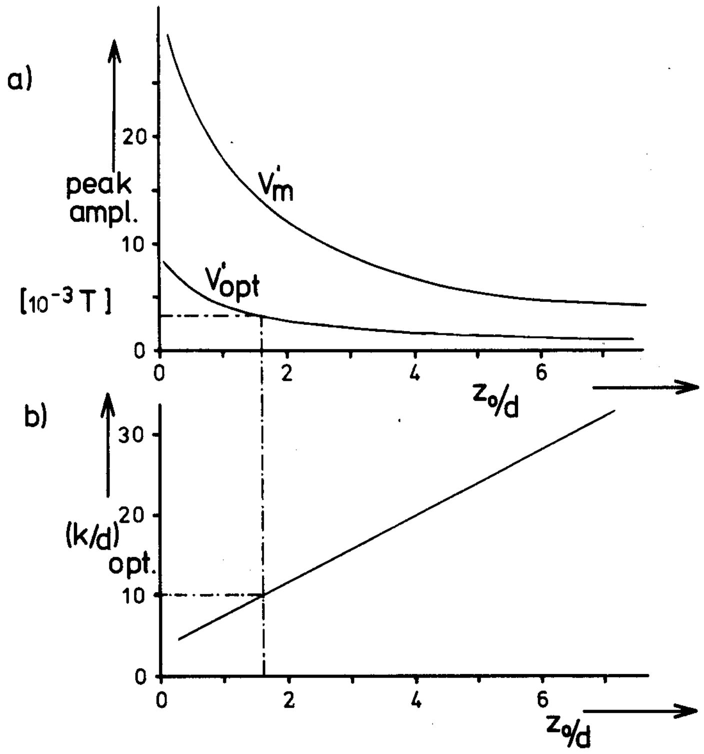


Fig. 9. Computed curves for optimization of the sensor–medium parameters ($M_r = 87500$ A/m).

Using the computer model further calculations have been made for elements with dimensions $L*W = 90*30$ μm and for $z_o > 25$ μm, obeying the condition that the field gradients in the elements are relatively small. This resulted in curves as in Fig. 9 which provided an opportunity for estimating the performance of a particular sensor–medium combination. Fig. 9(a) gives the normalized amplitude V'_M (Tesla) of the signal of one single magnetization reversal with the accompanying maximum value of the detection distance V'_{opt} which can be found for the optimal choice of the bit period k. The value of V'_{opt} appears to be about $0.25*V'_M$. The k value, which has been normalized with respect to the medium thickness d, is depicted in Fig. 9(b). The computations are performed according to the situation for the worst case patterns as given in Fig. 7.

A crucial parameter with respect to the detection performance of a sensor element is its noise level. In our case noise was mainly made up of offset fluctuations due to mechanical and thermal distortion of the chip and depends, among other things, on the choice of the applied Hall current electronics (current control or voltage control, respectively). The effect of mechanical stress depends on the angle between the direction of the electrical current and mechanical stress as well as the crystal orientation of the silicon chip[6]. It could be experimentally demonstrated that, in principle, the effect in the Hall element can be compensated with the help of a second element. In our (uncompensated) sensor elements an offset was found of the order of $0.2\ 10^{-3}$ T (50 μV) for temperature variations of 10°C (in the case of a constant input voltage of 10 V) and $3.5\ 10^{-3}$ T for a strain $\Delta l/l$ of 5.10^{-5} in the chip.

The application of the curves in Fig. 9 will be demonstrated from these noise figures. Starting from the demand that in an uncompensated element a minimal detection distance V'_{opt} of $3.5\ 10^{-3}$ T ($V'_M = 14\ 10^{-3} T$) is needed one finds $z_o/d \leqslant 1.6$ and $k/d \leqslant 10$. The minimum bit period k which can be realized (resolution of the position detection system) depends on the effective separation z_o between element and medium (in our case substrate thickness). In Table 1 data are given for some values of z_o. Also the figures resulting from a reduced noise level ($V'_{\mathrm{opt}} = 10^{-3}$ T with $z_o/d \leqslant 7$ and $k/d \leqslant 30$) are given.

It can be seen that reduction of the noise level offers the possibility to make use of a thinner hard-magnetic layer but hardly reduces the minimum bit period k. In order to obtain a smaller value of k the separation z_o between element and medium must be reduced.

Table 1. Optimal values for medium thickness d and bit period k for three values of the effective element–medium separation z_o

	$V'_{\mathrm{opt}} = 3.5 \cdot 10^{-3}$T		$V'_{\mathrm{opt}} = 10^{-3}$T	
z_o (μm)	d (μm)	k (μm)	d (μm)	k (μm)
100	62.5	625	14	420
50	31.3	313	7	210
25	15.6	156	3.5	105

6. CONCLUSION

We suggest an absolute position detection system by detecting the position information, which is written in a hard-magnetic medium, which the help of a silicon Hall sensor.

By placing the elements with the Hall surface parallel to the medium, the total chip surface can be used to realize two-dimensional arrays.

The detection process of this type of sensor has been analyzed by means of a computer simulation model. Using weight functions the output of a Hall element can be calculated. The distribution of the weight functions is given in literature. A simple and fast simulation model is obtained with this method and calculated values are in good agreement with experimental results.

It is found that the element should be positioned with its input current direction parallel to the longitudinal direction of the hard-magnetic layer for optimal resolution. This fact is favourable in view of the introduction of a Hall element array with one common input current for the detection of adjacent bits.

In view of the detection of worst case bit patterns an optimal value for the bit period k_{opt} is found. The calculated results showed increased values for k_{opt} and decreased values for the corresponding detection distance V_{opt} and can be regarded as careful approximations.

Analysis of the detection process results in two basic curves, the normalized peak amplitude V'_M (and detection distance V'_{opt}) vs the normalized element–medium separation z_o/d and the normalized optimal bit period $(k/d)_{\text{opt}}$ vs z_o/d. Starting from the noise level which was observed in our experimental Hall sensors it can be concluded that a minimum bit period of a few hundred μm is realizable. This value of the resolution of the position detection system can be decreased by decreasing the noise level in the sensor elements and, if necessary, by application of an interpolation scheme.

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REFERENCES

1. J. P. J. Groenland, *IEEE Trans. Magn.* **Mag-20**, 969 (1984).
2. A. W. Baird, *IEEE Trans. Magn.* **Mag-14**, 1138 (1979).
3. H. Leeuwis, *Sensors & Actuators* **4**, 17 (1983).
4. I. Hlâsnik and J. Kokavec, *Solid-St. Electr.* **9**, 585 (1966).
5. J. H. J. Fluitman, *Sensors & Actuators* **2**, 155 (1981).
6. Y. Kanda and M. Migitaka, *Phys. Stat. Solid(A)* **35**, K115 (1976).