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

F. A. Pronk, J. P. J. Groenland and T. S. J. Lammerink
Twente University of Technology, Department of Electrical Engineering, P.O. Box 217, 7500 AE Enschede, The Netherlands

(Received 1 April 1985; in revised form 23 August 1985)

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 a 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
φH electric potential as a result of Hall effect, V
W width, m
x, y coordinates of a point in Hall element, m
k length of Hall element, m
r effective thickness of Hall element, m
S width of Hall contact, m
R Hall coefficient, Ω · m · T−1
I input current, A
B magnetic induction, T
μ carrier mobility, m2 · (V · s)−1
θ Hall angle (= arctan μB), radian
VH Hall voltage, V
Nd dopant density, m−3
z effective element-medium separation, m
h thickness of hard-magnetic layer, m
μt bit period, μs
Vd detected peak voltage for single reversal, V
ΔVp pulse width at Vp = Vp/2, m
Mr remanent magnetization of hard-magnetic medium, A/m
V1 "1" detection level, V
V0 "0" detection level, V
Vdet detection distance (V1 − V0), V
VH normalized Hall voltage (= Vdet/(μB Rn)), V

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 φ(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 φH of a certain point (x', y') (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

$$\phi_H(x', y') = \frac{R_H \cdot I}{2 \pi \mu L} \left[ \frac{x}{W/2} - \frac{w/2}{L/2} \right] B(x, y)$$

$$\cdot G(x', y', x, y, L/W) \, dx \, dy.$$  \hspace{1cm} (1)

(The Hall angle $\theta$ (= arctan $\mu B$) 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.

$$\frac{\partial B}{\partial y} = 0: \phi_H(x', y') = \frac{R_H \cdot I}{2 \pi \mu L} \left[ \frac{x}{W/2} \right] B(x)$$

$$\cdot G(x', y', x, L/W) \, dx.$$  \hspace{1cm} (2)

$$\frac{\partial B}{\partial x} = 0: \phi_H(x', y') = \frac{R_H \cdot I}{2 \pi \mu W} \left[ \frac{w/2}{L/2} \right] B(y)$$

$$\cdot G(x', y', y, L/W) \, dy.$$  \hspace{1cm} (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 Hlánsk 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.

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 $\mu$m and $N_p = 10^{12}$ cm$^{-3}$. The Hall element dimensions are $L = 500$ $\mu$m, $W = 100$ $\mu$m and $S = 5$ $\mu$m. The following parameters have been found experimentally:

$$t = 1.2 \mu$m, $N_p = 1.2 \times 10^{17}$ cm$^{-3}$,

$$\mu = 740$ cm$^2$/Vs and

$$\displaystyle V_H/BI \text{ (Hall sensitivity)} = 43$ 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 $z_s$ of less than 100 $\mu$m. Other orientations of the sensor element with respect to the hard-magnetic layer are possible but not under discussion in this paper.

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

Fig. 3. Distribution of the weight functions according to (4), $\phi_H$ is only a function of $x'$ in (a) and $y'$ in (b).

Fig. 4. Positioning of the Hall element with respect to the magnetic layer (cross-section).
A γ-Fe₂O₃ layer was used as a hard-magnetic medium (thicknesses \(d=10 \mu m\) and 14 \(\mu m\)). 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 \(B=B(z)\) [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 insulating 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 \(z_0\) was measured. \((z_0=100–240 \mu m)\). Figure 6 shows the resulting values for the peak voltage \(V_M\) and the pulse width \(\Delta V_{50}\) at \(V=V_{in}/2\) of the signals for the 10 \(\mu m\) 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 \(z_0\) is given. Taking into account that due to the experimental method, the actual \(z_0\)-values of the experimental data will be to the right-hand side of the adjusted \(z_0\)-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 \(z_0\) (small field gradient). If the data in Fig. 6(a) are fitted for \(z_0=300 \mu m\) and the other calculated values are corrected (with a factor \(c=V_{exp}/V_{cal}\) at \(z_0=300 \mu m\)) an error up to 10–15% is obtained at \(z_0=100 \mu m\). 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.

![Graphs showing sensor response](image-url)
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 $V_{\text{det}}$ 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 $V_{\text{det}} = V_1 - V_0$ (Fig. 7). In Fig. 8 $V_1$, $V_0$, and $V_{\text{det}}$ are given as a function of the bit period $k$.

An optimal value $k_{\text{opt}}$ 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 $L = 300 \, \mu\text{m}$, $W = 100 \, \mu\text{m}$, $z_e = 110 \, \mu\text{m}$, $d = 10 \, \mu\text{m}$. 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 $\pm 30\%$. At the same time the experiments showed smaller values for $k_{\text{opt}}$ 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 $V_{\text{det}}$ 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 $V_{\text{det}}$ (b) as a function of the bit period $k$ with sensor—medium dimensions as in Fig. 6 (—– computed, - – measured).
Using the computer model further calculations have been made for elements with dimensions $L \times W = 90 \times 30 \, \mu m$ and for $z_2 > 25 \, \mu m$, 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 $V_{opt}$ (Tesla) of the signal of one single magnetization reversal with the accompanying maximum value of the detection distance $V_m$, which can be found for the optimal choice of the bit period $k$. The value of $V_{opt}$ appears to be about $0.25V_m$. 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 $0.2 \times 10^{-3} \, T$ (50 $\mu$V) for temperature variations of $10^\circ C$ (in the case of a constant input voltage of 10 V) and $3.5 \times 10^{-5} \, T$ for a strain $\Delta l/l$ of $5 \times 10^{-5}$ 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 $V_{opt}^{min}$ of $3.5 \times 10^{-3} \, T$ ($V_m^{opt} = 14 \times 10^{-3} T$) is needed one finds $z_2/d \leq 1.6$ and $k/d \leq 10$. The minimum bit period $k$ which can be realized (resolution of the position detection system) depends on the effective separation $z_2$ between element and medium (in our case substrate thickness).

In Table 1 data are given for some values of $z_2$. Also the figures resulting from a reduced noise level ($V_{opt}^{min} = 10^{-4} \, T$ with $z_2/d \leq 7$ and $k/d \leq 30$) 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 $z_2$ 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 $z_2$.

<table>
<thead>
<tr>
<th>$z_2$ (mm)</th>
<th>$V_m^{opt} = 3.5 \times 10^{-3} T$</th>
<th>$V_m^{opt} = 10^{-4} T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d$ ($\mu$m)</td>
<td>$k$ ($\mu$m)</td>
</tr>
<tr>
<td>100</td>
<td>762.5</td>
<td>625</td>
</tr>
<tr>
<td>50</td>
<td>313</td>
<td>313</td>
</tr>
<tr>
<td>25</td>
<td>15.6</td>
<td>156</td>
</tr>
</tbody>
</table>
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 $V_{opt}$ (and detection distance $V_{opt}$) vs the normalized element-medium separation $z_{opt}$ and the normalized optimal bit period $(k/d)_{opt}$ vs $z_{opt}$. 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 $\mu$m 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.

Acknowledgement—The authors like to thank J. Holleman for manufacturing the Hall devices.

REFERENCES