THE MODELLING ON HALL EFFECT IN THE BIPOLAR AND MOS STRUCTURES

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Abstract: An essential parameter in the setting up of the performance of the measurement systems that uses Hall microsensors is the detection limit of such devices. This paperwork presents the structure, the operating conditions, and the main characteristic for the MOS Hall-plates and for double-collector magnetotransistors. By using numerical simulation, the values of signal-to-noise ratio and the detection limit for the two analysed devices are compared and it is also emphasised the way in which choosing the geometry and the material features allows getting high-performance sensors.

Keywords: magnetic microsensors, signal-to-noise ratio, detection limit, Hall carriers mobility

1. INTRODUCTION

The possibility of having the sensor and the amplifier circuit on the same chip has brought about the increase of conversion efficiency and high performance transducers with large values of signal-to-noise ratio and a high resolution of magnetic induction have been made.

My research work has been focused on the analysis and improvement of a microsensors structure based on bipolar and MOS technology.

Significant expressions regarding the response, the signal-to-noise ratio and detection limit of these devices have been defined and established.

There was also emphasized the dependence of the characteristics on the material features, on the mobility of carriers as well as on the device geometry.

2. THE GENERAL CHARACTERIZATION OF THE MOS HALL PLATES

In a MOSFET structure (figure 1), an extremely thin Hall plate can be realised if the channel constitutes the active region of plate, and the source (S), and drain (D) are the biasing contacts. [1]

Two additional strongly doped (n^+) regions, made simultaneously with the source and drain regions, are used as contacts for sensing the Hall voltage. The channel length is L, its

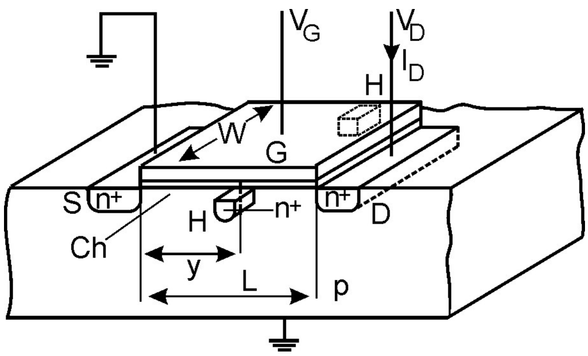

Fig. 1 Rectangular MOS-Hall plate

width is *W*.

Considering the operation in Hall voltage mode, the MOS-Hall plate working in the linear region is equivalent to a conventional Hall plate, the only difference being that the charge carriers are due to the surface field effect in a MOS-Hall plate.

In case of a conventional hall plate, the Hall voltage is [2]:

$$V_H = G\frac{r_H}{qnd} I \cdot B_\perp \tag{1}$$

where G denotes the geometrical correction factor, r_H is the Hall factor, d is the plate thickness, and n denotes the electrons density.

By substituting in (1) the qnd product by the surface density of charge carriers in the channel and i with I_D, it is obtained for the MOS-Hall plate:

$$V_H = G\frac{r_H}{Q_{Ch}} I_D \cdot B_\perp \tag{2}$$

At very low values of drain voltage V_D the carriers density in the channel is approximately constant and is given by [3]:

$$Q_{Ch} = C_{ox}(V_G - V_P) \tag{3}$$

where C_{ox} denotes the gate oxide capacitance per unit area, V_G is the gate-to-source voltage, and V_p the threshold voltage.

In the linear region of MOSFET operating:

$$I_D = (W/L)m_{Ch} \cdot C_{ox}(V_G - V_P)V_D = (W/L)m_{Ch}Q_{Ch}V_D \tag{4}$$

By substituting (3) and (4) into (2), it follows that:

$$V_H = m_{H_{Ch}}\left(\frac{W}{L}G \cdot\right)V_D \cdot B_\perp \tag{5}$$

where $m_{H_{Ch}} = r_H m_{Ch}$ denotes the Hall mobility of carriers in the channel.

The absolute sensitivity for a hall device used as a magnetic sensor is:

$$S_A = |V_H / B_\perp| \tag{6}$$

and the supply-voltage-related sensitivity is defined by:

$$S_V = \frac{S_A}{V_D} = m_{H_{Ch}}\left(\frac{W}{L}G\right) \tag{7}$$

The sensor response is given by:

$$h(B_\perp) = \frac{V_H}{V_D} = m_{H_{Ch}}\left(\frac{W}{L}G\right)B_\perp \tag{8}$$

and it is linear for magnetic induction values that satisfy the condition: $m_{H_{Ch}}^2 B_\perp << 1$

3. SIGNAL-TO-NOISE RATIO FOR MOSS-HALL PLATES

In case of a MOS-Hall plates, at high frequencies, thermal noise dominates. The voltage spectral density of thermal noise is given by [4]:

$$S_{NV} = 4kTR_{out} \tag{9}$$

where $k = 1{,}38054 \cdot 10^{-23} JK^{-1}$ is the Boltzmann constant, and R_{out} is the output resistance of device.

The output resistance of a rectangular MOS-Hall plate with very small sense contacts is given by [5]:

$$R_{out} \cong 2\frac{r_b}{pd}\ln\left(\frac{W}{s}\right) \quad (10)$$

on condition that: $s << W << L$.

The coefficient r_b denotes the effective material resistivity, and s is the small sense contacts diameter.

If the biased voltage of device is constant, r_b practical not depends of magnetic field.

By substituting (10) into (9) it results spectral density:

$$S_{NV} = \frac{8kT}{pnqm_{Ch}d}\ln\left(\frac{W}{s}\right) \quad (11)$$

For a narrow bandwidth Δf around a frequency f, ($f > 100kHz$, [6]) the signal-to-noise ratio, can be expressed as:

$$SNR(f) = \frac{V_H}{\left[S_{NV}(f)\cdot\Delta f\right]^{1/2}} \quad (12)$$

where $S_{NV}(f)$ is the noise spectral density at the device output.

By substituting (2) and (11) into (12) it results:

$$SNR(f) = \left(\frac{pm_{Ch}}{8hTqnd\Delta f\,\ln(W/s)}\right)^{1/2} r_H G I_D B_{\perp} \quad (13)$$

Since the signal-to-noise ratio increases with the drain current I_D, the maximal *SNR(f)* is limited only by maximal acceptable device power dissipation P_{max}.

From (2) and (5), we also obtain the Hall voltage as a function of the power $P = V_D I_D$ dissipated in the device.

Multiplying (2) and (5) member-by-member it results:

$$V_h = G\left(\frac{W}{L}\right)^{1/2} r_H \left(\frac{m_{Ch}}{q_{Ch}}\right)^{1/2} P^{1/2}\cdot B_{\perp} \quad (14)$$

where $P = V_D I_D$ in the power dissipated in the device.

From (13) and (14) it results:

$$SNR(f) = 1{,}11\, m_{H_{Ch}}\left[\frac{G^2(W/L)P}{kT\Delta f\,\ln(W/s)}\right]^{1/2} B_{\perp} = 9{,}7\cdot 10^9\, m_{H_{Ch}}\left[\frac{G^2(W/L)P}{\Delta f\,\ln(W/s)}\right]^{1/2} B \quad (15)$$

where $T=300\ K$ and $k = 1{,}38054\cdot 10^{-23}\ JK^{-1}$.

4. THE DETECTION LIMIT OF MOS-HALL PLATES

The value of the measurand corresponding to a signal-to-noise ratio of one, constitute the detection limit of Hall device used as magnetic sensors.

In case of thermal noise for MOS-Hall plates it is obtained from expression (15):

$$B_{DL} = \frac{2}{m_{H_{Ch}}}\cdot\sqrt{\frac{2kT}{p}}\cdot\frac{\left[\Delta f\,\ln(W/s)\right]^{1/2}}{G(W/L)^{1/2}}\cdot P^{-1/2} \quad (16)$$

The detection limit of the sensor decreases when the power dissipated in the device increases, but for the same power the limit depends on the device dimensions and the material it is made of. In figure 2 are shown B_{DL} values obtained by the simulation of three MOS-Hall plates structures realised on silicon ($m_{H_{Ch}} = 0{,}07 m^2V^{-1}s^{-1}$), having different ratios L/W ($W = 100mm$, $W/s = 50$, $\Delta f = 1Hz$).

It is asumed that the sense contacts are points and the magnetic induction is low ($m_{H_{Ch}}^2 B^2 << 1$).

MHP1 *: L/W =0,5;*
*M*HP2 *: L/W =1;*
MHP3 *: L/W =3.*

For same dissipate power *P*, the detection limit is minimum in case of square structure (MHP2).

It is noticed that B_{DL} increases with 18,4% comparative with MHP2 device, if the distance between the current contacts increases three times.

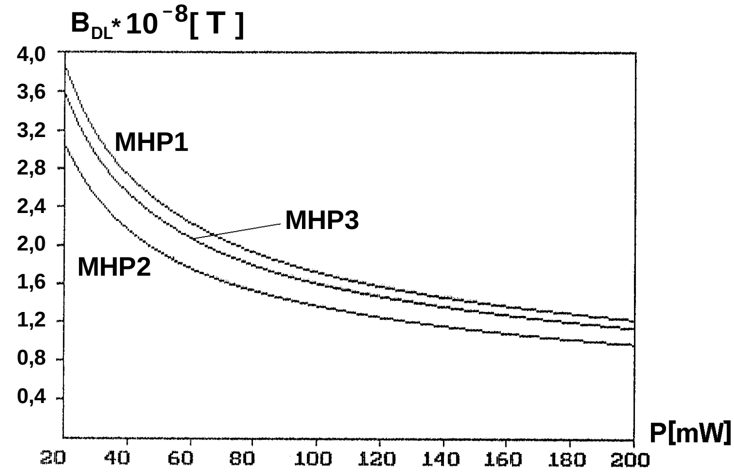

Fig. 2 B_{DL} depending on the *P* for three devices of different geometry

In figure 3 are shown the detection limit dependence on dissipated power of three MOS-Hall plates structures from different materials ($W = 200mm, L = 100mm$, $W/s = 50$).

MHP1: *Si* with $m_{H_{Ch}} = 0{,}07 m^2V^{-1}s^{-1}$;
MHP2: *GaSb* with $m_{H_{Ch}} = 0{,}25 m^2V^{-1}s^{-1}$;
MHP3: *GaAs* with $m_{H_{Ch}} = 0{,}42 m^2V^{-1}s^{-1}$.

A high value carriers mobility causes the decreasing of detection limit. B_{DL} decreases with 45% for *GaAs* comparative with *GaSb*.

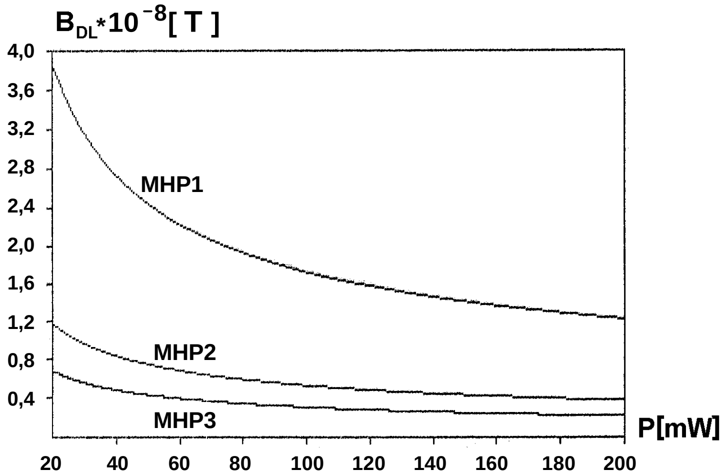

Fig. 3. BDL depending on P for three MOS-Hall plates of different materials

5. GENERAL CHARACTERISATION OF THE SPLIT-COLLECTOR MAGNETOTRANSISTOR.

Figure 4 illustrates the cross section of a split-collector magnetotransistor operating on the current deflection principle [7]. This structure is compatible with bipolar integrated circuits technology. The most part of the low-doped epitaxial layer (n^-) serves as a collector-region and it is emptied by charge carriers because of the reverse biasing of the collector-base junction. The two split-collector contacts are realised by splitting the buried layer (n^+).

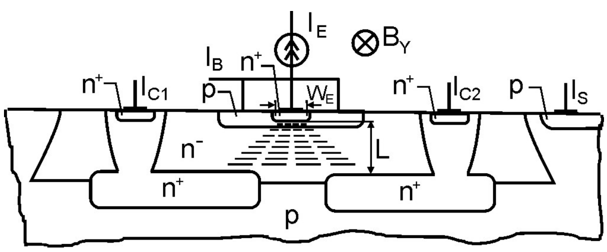

Fig.4. The structure of a split-collector magnetotransistor.

In the absence of a magnetic field the electrons tide injected from the emitter which crosses the base is symmetrical and the collector currents are equal: $I_{C1}=I_{C2}$.

In the presence of a magnetic field with induction $B_{\perp}$, the distribution of a emitter electrons current is asymmetrical and causes an imbalance in the two collector currents. This unbalance grows because of the majority carrier deflection in the collector region (the epitaxial zone):

$$\Delta I_C = I_{C1} - I_{C2} \tag{17}$$

The analysed magnetotransistor operates in the Hall current mode and ΔI_C depends on the Hall traverse current.

Assimilating the low-doped epitaxial layer of the collector region with a short Hall plate, and based on the properties of dual Hall devices it results [2]:

$$\Delta I_C = \frac{I_H}{2} = \frac{1}{2} m_{Hn} \frac{L}{W_E} G \cdot I_C B_{\perp} \tag{18}$$

where m_{Hn} denotes the carriers Hall mobility, G is the geometrical correction factor, L is the emitter-collector distance, W_E is the emitter with (see figure 4) and $I_C = I_{C1}(0) + I_{C2}(0)$.

The noise affecting the collector current of a magnetotransistor is shot noise and 1/f noise.

Signal-to-noise ratio is defined by:

$$SNR(f) = \frac{\Delta I_C}{[S_{NI}(f) \cdot \Delta f]^{1/2}} \tag{19}$$

where Δf denotes a narrow frequency band around the frequency f, and $S_{NI}(f)$ denotes the noise current spectral density in the collector current.

In case of shot noise, the current spectral density at frequencies over 100Hz is given by [4]:

$$S_{NI} = 2q \cdot I \tag{20}$$

where I is the device current.

In a narrow range f of frequency values, by subtituting (18) and (20) into (19) it results:

$$SNR(f) = \frac{1}{2\sqrt{2}} m_{Hn} (\frac{L}{W_E} G) \frac{I_C}{(q \cdot I \cdot \Delta f)^{1/2}} B_{\perp} \geq \frac{1}{2\sqrt{2}} m_{Hn} (\frac{L}{W_E} G) \frac{I_C^{1/2}}{(q\Delta f)^{1/2}} B_{\perp} \tag{21}$$

The detection limit for double-collector magnetotransistors it is obtained from expression (21):

$$B_{DL} \leq \frac{2\sqrt{2}(q\Delta f)^{1/2}}{m_{Hn}(L/W_E)G} I_C^{-1/2} \tag{22}$$

To illustrate the B_{DL} dependence on device geometry there were simulated (figure 5) three double-collector magnetotransistor structures on silicon $\left(m_{Hn} = 0.15 m^2 V^{-1} s^{-1}\right)$ and having different ratios $\left(W_E = 100 mm\right)$.

MGT1: $W_E/L = 0.5$; MGT2: $W_E/L = 1$; MGT3: $W_E/L = 2$

It is noticed that the B_{DL} is minimum for $W_E/L = 0.5$ structure.

For optimal structure B_{DL} decreases at materials of high carriers mobility.

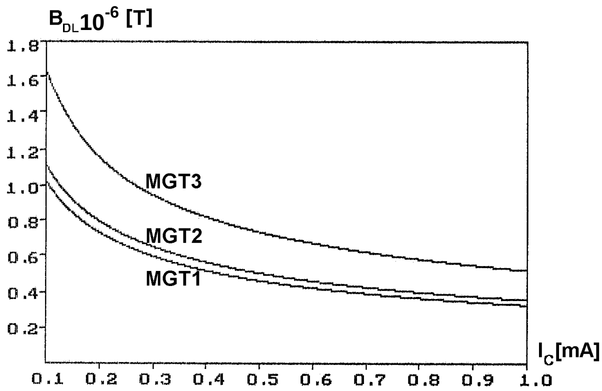

Fig. 5. B_{DL} depending on the collector total current for three devices of different geometry

In figure 6 it can be seen the material influence on B_{DL} values for three double-collector magnetotransistor structures realised from *Si*, *GaSb* and *GaAs* and having the same size: $L = 200mm$, $W_E = 100mm$.

MGT1: *Si* with $m_{Hn} = 0{,}15 m^2 V^{-1} s^{-1}$;

MGT2: *GaSb* with $m_{Hn} = 0{,}5 m^2 V^{-1} s^{-1}$;

MGT3: *GaAs* with $m_{Hn} = 0{,}8 m^2 V^{-1} s^{-1}$.

By comparing the results for the two types of Hall devices used as magnetic sensors it is recorded a lower detection limit of almost 2-order in double-colletor magnetotransistors.

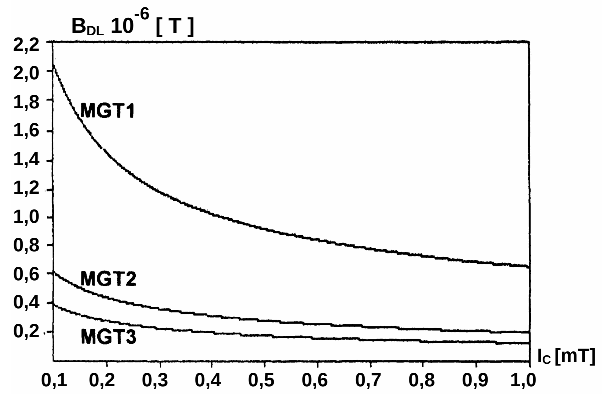

Fig. 6 B_{DL} depending on the drain current for three devices of different materials

6. CONCLUSIONS

The analysis of the main noise characteristics of the MOS-Hall plates shows that in case of thermal noise, the square structure (*W=L*) is theoretically favourable to obtain magnetic sensors of performance. From double-collector magnetotransistors, in case of shot noise, the $W/L = 0{,}5$ structure provides superior *SNR* values, and smaller detection limit values. Also substituting the silicon technology by using other materials such as *GaAs* or *InSb* with high carriers mobility allows the made of higher characteristics devices.

The using of magnetotransistors as magnetic sensors allows the achieving of same current-voltage conversion circuits, more efficient than conventional circuits with Hall plates. Although the magnetotransistors have a low magnetic sensitivity, very large signal-to-noise ratios are obtained, hence, a high magnetic induction resolution is resulting. A detection limit of about $0{,}2 \cdot 10^{-6} T$ at a total collector-current of *0,5 mA* has been obtained at double-collector magnetotransistor in case *GaSi*.

The transducers with integrated microsensors have a high efficiency and their using possibilities could be extended to some measuring systems of thickness, small displaces, level, linear speeds and revolutions.

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