The Stability and the Detection Limit for Hall Microsensors

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Abstract — In a system of measuring in which the Hall device is used as input transducer, its stability is essential for transfer constant of system.

In this work is analyzed the variation effect of the charge carriers density on the stability of magnetic sensors realized on the semiconductors Hall plates.

At the same time it is emphasized the way in which the adequate choice of material and geometry of the device allow an increase in its stability.

An essential parameter in the setting up of the performance of the measurement systems that use Hall microsensors is the detection limit of these devices. In the paper is defined the detection limit for Hall plates; it is also emphasized the way this characteristic is influenced by the geometry and material properties.

I. General characterization of the Hall semiconductor plate

If the Hall device is a homogenous plate of length l, width w and thickness δ, having point contacts, the voltage generated by the magnetic field $B_\perp$, perpendicularly to the plate surface, is given by:

$$V_H = \frac{R_H}{\delta} \cdot I \cdot B_\perp \quad (1)$$

where R_H denotes the Hall coefficient, and I the total biasing current.

In the case of a Hall device with finite contacts V_H is given by [1]:

$$V_H = G\frac{R_H}{\delta} \cdot I \cdot B_\perp \quad (2)$$

G being the geometrical correction factor.

At low magnetic inductions, $\overline{B} \approx 0$, for an extrinsic semiconductor, the Hall voltage can be expressed in terms of the bias voltage $V = R_{in} I = \rho \frac{l}{w\delta} I$, as follows :

$$V_H = \mu_H \frac{w}{l} G V B_\perp \quad (3)$$

where μ_H is the Hall mobility of the charge carriers.

From (2) and (3) we also obtain the Hall voltage as a function of the power $P = V \cdot I$ dissipated in the device.

$$V_H = G r_H B_\perp \left(\frac{w}{l}\right)^{1/2} \cdot \left(\frac{\mu}{qn\delta}\right)^{1/2} \cdot P^{1/2} = \mu_H \left(\frac{\rho_b}{\delta}\right)^{1/2} \cdot G\left(\frac{w}{l}\right)^{1/2} \cdot P^{1/2} B_\perp \quad (4)$$

The absolute sensitivity of a Hall device used as a magnetic sensor is:

$$S_A = \left(\frac{V_H}{B_\perp}\right)_c = \mu_H \frac{w}{l} G V \quad (5)$$

where c denotes a set of operating conditions.

Supply-current-related sensitivity is defined by:

$$S_I = \frac{S_A}{I} = \left|\frac{1}{I} \cdot \frac{V_H}{B_\perp}\right|; V_H = I S_I B_\perp \quad (6)$$

By substituting the Hall voltage V_H in (6) it is obtained:

$$S_I = G\frac{|R_H|}{\delta} \quad (7)$$

If the plate is strongly extrinsic, R_H is given by: $R_H = \frac{r_H}{qn} sign[e]$, and (7) attains the form:

$$S_I = \frac{S_A}{I} = G\frac{r_H}{qn\delta} \quad (8)$$

In low doped, small doping gradient layers, the $n\delta$ product should be replaced by the surface charge carrier density N_S.

Then, S_I reduces to:

$$S_I = G\frac{r_H}{qN_S} \quad (9)$$

where the product qN_S equals the charge carrier by free electrons per unit area.

II. The influence of surface instability in the Hall devices

In a system of measuring in which the Hall device is used as input transducers, its stability is essential for transfer constant of systems.

As relative sensitivity S_I depends on the surface density of charge carriers in the plate, any variation in the carrier density may cause an instability in sensor sensitivity.

If in the oxide layer or at the oxide-n-type epitaxial layer interface of a Hall sensor, a variation ΔQ_S of the

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charge occurs, it will cause a variation $-\Delta Q_S$ in the surface density in the Hall plate. Assuming that at the n-layer surface the inversion phenomenon does not occur, the corresponding variations of ΔQ_S will be ΔS_I.

By substituting into (9) $qN_S = Q_{SH}$, where Q_{SH} denotes the total surface charge of the plate, it is obtained:

$$S_I = \frac{Gr_H}{Q_{SH}} \tag{10}$$

From (10) it results that:

$$\begin{aligned}\Delta S_I &= \frac{\partial S_I}{\partial Q_{SH}}\Delta Q_{SH} = -\frac{Gr_H}{Q_{SH}^2}\Delta Q_{SH} = \\ &= \frac{Gr_H}{Q_{SH}}\cdot\frac{\Delta Q_S}{Q_{SH}} = S_I\frac{\Delta Q_S}{Q_{SH}}\end{aligned} \tag{11}$$

Or:

$$\frac{\Delta S_I}{S_I} = \frac{\Delta Q_S}{Q_{SH}} = \frac{S_I}{Gr_H}\Delta Q_S \tag{12}$$

Assuming that $G \cdot r_H = 1$, which is true in many practical situations:

$$\frac{\Delta S_I}{S_I} \cong S_I \cdot \Delta Q_S \tag{13}$$

Therefore, the surface instability influence on the device sensitivity is proportional to the sensitivity itself.

Uncorrelated variations in interface charge may also bring about asymmetry in Hall plate resistivity. At low magnetic fields, if the biased voltage of device is constant the active device layer sheet resistance can be expressed by:

$$R_S = \frac{\rho}{\delta} = \frac{1}{\mu q n \delta} = \frac{1}{\mu Q_{SH}} \tag{14}$$

The absolute charge in the layer resistance is then:

$$\Delta R_S = \frac{\delta R_S}{\delta Q_{SH}}\cdot\Delta Q_{SH} = -\frac{\Delta Q_{SH}}{\mu Q_{SH}^2} = \frac{R_S}{Q_{SH}}\Delta Q_S \tag{15}$$

From (15) it result:

$$\frac{\Delta R_S}{R_S} = \frac{\Delta Q_S}{Q_{SH}} \tag{16}$$

III. THE OFFSET EQUIVALENT MAGNETIC INDUCTION

The main causes of the offset in the case of Hall plates realised in the bipolar integrated circuits technology are due to misalignment of contacts, to non-uniformity of both material resistivity and thickness.

The existence of mechanical stress, of the fluctuations in the oxide layer charge as well as of the variation in the oxide-semiconductor interface charge can also produce offset.

The asymmetries produced by the above causes can be represented by using for the Hall plate the Wheatstone bridge circuit model (figure 1)

Ideally all the resistors should be equal. Any of the causes above mentioned can bring about bridge resistance variation ΔR consequently between the sense contacts appears the offset voltage:

$$V_{off} = \frac{\Delta R}{R}V \tag{17}$$

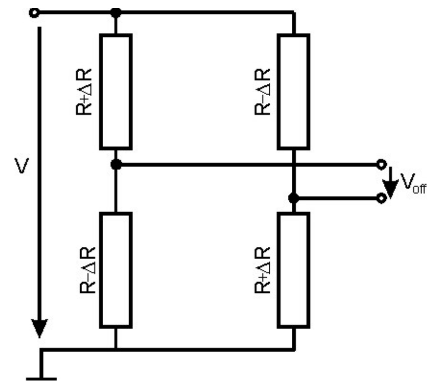

Fig. 1. The bridge circuit for the Hall-plate

At low magnetic field ($\overline{B} \cong 0$) in a Hall device biased by a constant voltage the dependence of $R(B_\perp)$ is neglected.

To characterize the measurement error caused by offset is defined the offset-equivalent magnetic induction.

From S_A expression is found:

$$B_{off} = \frac{V_{off}}{S_A} = \frac{\Delta R}{R}\cdot\frac{l}{\mu_H wG} \tag{18}$$

The offset-equivalent magnetic induction due to fluctuation in surface charges is obtained by substituting (16) into (18):

$$\begin{aligned}B_{off} &= \frac{l}{\mu_H wG}\cdot\frac{\Delta Q_S}{qn\delta} = \frac{Gr_H}{qn\delta}\cdot\frac{l}{\mu_H wG}\cdot\frac{\Delta Q_S}{Gr_H} = \\ &= S_I\frac{1}{\mu_H}\left(G\frac{w}{l}\right)^{-1}\cdot\frac{\Delta Q_S}{Gr_H}\end{aligned} \tag{19}$$

For the practical situations when $Gr_H \cong 1$, relation (19) becomes:

$$B_{off} \cong S_I\frac{\Delta Q_S}{\mu_H}\left(G\frac{w}{l}\right)^{-1} \tag{20}$$

The product $G(w/l)$ is maximum for $(l/w) < 0.5$, namely: $[G(w/l)]_{max} = 0.74$[1]

Therefore:

$$(B_{off})_{max} \cong S_I\frac{\Delta Q_S}{\mu_H}\cdot\frac{1}{0.74} = 1.35\frac{\Delta Q_S}{\mu_H}S_I \tag{21}$$

In more sensitive devices the B_{off} is higher.

This inconvenience can be removed by isolating the active region by a reverse-biased pn junction as in the case of buried structures [5].

For a silicon rectangular device homogenously doped: $n \approx N_D = 4.5 \cdot 10^{21} m^{-3}$ with $\rho = 10^{-2} \Omega \cdot m$, at 300 K, having $l = 300 \mu m$, $w = 100 \mu m$, $\delta = 10 \mu m$ and being biased at $V = 10V$ for $B = 1T$, is obtained successively:

$$R_H = \frac{r_H}{qn} = 1.6 \cdot 10^{-3} C^{-1} m^3$$

$$S_I = G \frac{R_H}{\delta} = 78.88 VA^{-1} T^{-1}$$

$$Q_H = qnd = 14.4 \cdot 10^{-1} C$$

Considering a fluctuation in the surface charge density:

$\Delta Q_S = 1.6 \cdot 10^{-5} Cm^{-2}$, one can calculate:

$$B_{off} = S_I \frac{1}{\mu_H} \cdot \frac{\Delta Q_S}{G(w/l)} = 0.067T$$

In the case of a ratio $(l/w) = 0.5$, it results:

$$\left(B_{off}\right)_{\max} = 1.35 \frac{\Delta Q_S}{\mu_H} S_I = 0.011T$$

In figure 2 are shown B_{off} values of three silicon Hall devices $\left(\mu_H = 0.15 m^2 V^{-1} s^{-1}\right)$ with the sensitivity $S_I = 100 VA^{-1} T^{-1}$ which have different ratios: $l/w(w = 100 \mu m)$

HP1: $l/w = 0.5; G(w/l) = 0.73$

HP2: $l/w = 1; G(w/l) = 0.67$

HP3: $l/w = 2; G(w/l) = 0.46$

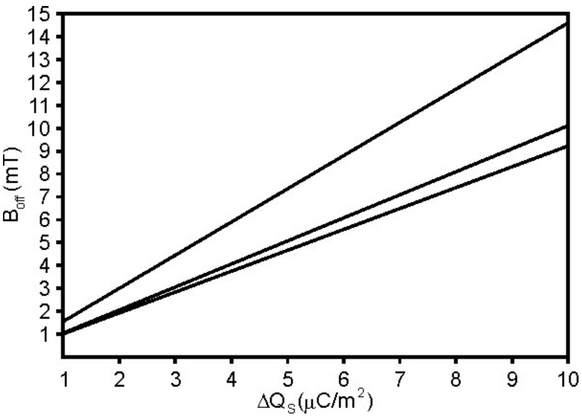

Fig. 2. B_{off} depending on the surface charge density variation

The minimum values for B_{off} induction are obtained for the structures of $(1/w) \leq 0.5(HP1)$. If the device length increases twice, it causes a 9% B_{off} increase, and in the case of $l = 2w$ we obtain a 45% increase.

To emphasize the material influence on the B_{off} induction there were simulated (figure 3) three Hall devices, made of different materials:

HP1: $GaSb$, $\mu_H = 0.5 m^5 V^{-1} s^{-1}$

HP2: $GaAs$, $\mu_H = 0.85 m^5 V^{-1} s^{-1}$

HP3: $GaSb$, $\mu_H = 3.3 m^5 V^{-1} s^{-1}$

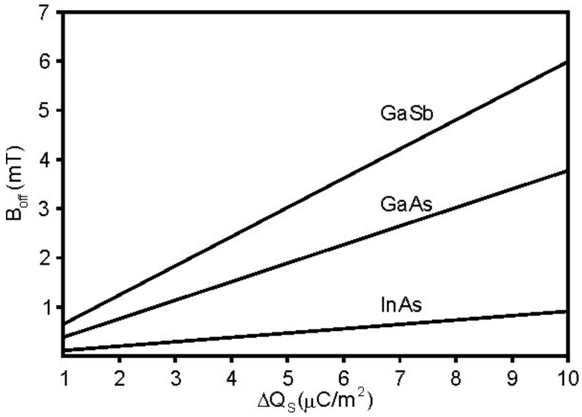

Fig. 3. B_{off} depending on ΔQ_S for three devices of different materials

These have $: l = 3w \cdot (w = 100 \mu m)$, and sensitivity $S_I = 300 VA^{-1} T^{-1}$.

We can see that the sensors made of high mobility materials have a superior stability, the offset magnetic induction being inversely proportional to the mobility for the same fluctuation of the surface charge density. At the InAs device, B_{off} decreases 4.25 times compared to the value for the GaAs, but due the compatibility with the main microelectronics technologies, the latter is preferred.

IV. Signal-to-noise ration for Hall plates

In case of a Hall Plates, at high frequencies, thermal noise dominates.

The voltage spectral density of thermal noise is given by [3]:

$$S_{NV} = 4kTR_{out} \tag{22}$$

where $k = 1.38054 \cdot 10^{-23} JK^{-1}$ is the Boltzmann constant, and R_{out} is the output resistance of the device.

The output resistance of a rectangular Hall plate with very small sense contacts is given by [4]:

$$R_{out} \cong 2 \frac{\rho_b}{\pi \delta} \ln\left(\frac{w}{s}\right) \tag{23}$$

on condition that: $s << w << l$.

The coefficient ρ_b denotes the effective material resistivity, and s is the small sense contact diameter.

If the biased voltage of device is constant, ρ_b practical not depends of magnetic field. By substituting (23) into (22) it results spectral density:

$$S_{NV} = \frac{8kT}{\pi n q \mu_H \delta} \ln\left(\frac{w}{s}\right) \tag{24}$$

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

$$SNR(f) = V_H\left[S_{NV}(f)\cdot \Delta f\right]^{-1/2} \quad (25)$$

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

By substituting (4) and (24) into (25) it results:

$$SNR(f) = 9.7\cdot 10^9 \mu_{H_{Ch}}\left(G\frac{w}{l}\right)^{\frac{1}{2}}\left[\frac{P}{\Delta f\cdot \ln(w/s)}\right]^{\frac{1}{2}} B_{\perp} \quad (26)$$

where $T = 300K$ $k = 1.38054\cdot 10^{-23} JK^{-1}$

V. THE DETECTION LIMIT OF 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 Hall plates it is obtained from expression (26):

$$B_{DL} = \frac{2}{\mu_H}\sqrt{\frac{2kT}{\pi}}\cdot\frac{1}{G}\left(\frac{l}{w}\right)^{1/2}\cdot\frac{\left[\Delta f\cdot \ln(w/s)\right]^{1/2}}{P^{1/2}} \quad (27)$$

The detection limit of the sensor decreases when the dissipated power increases, while at the same power the B_{DL} depends on the dimensions of the device and the material it is made of.

In figure 4 are shown B_{DL} values obtained by the simulation of three Hall plate structures realised on silicon $\left(\mu_{Hn} = 0.15 m^2V^{-1}s^{-1}\right)$, having different ratios *w/l* $\left(w = 100\mu m;\ w/s = 50;\ \Delta f = 1Hz\right)$.

It is assumed that the sense contacts are points and the magnetic induction is low $(\mu_H^2 B^2 << 1)$.

PH1: $l/w = 0.5$; PH2: $l/w = 1$; PH3: $l/w = 3$.

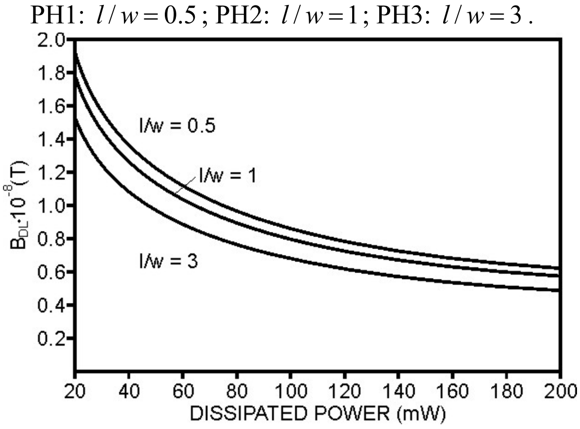

Fig. 4. B_{DL} depending on the P for three devices of different geometry

For the same dissipate power P, the detection limit is minimum in case of square structure (PH2).

It is noticed that B_{DL} increases with 18.4% comparative with PH2 device, if the distance between the current contacts increases three times.

To emphasize the material influence on B_{DL} there were simulated three Hall plate structures with some dimensions, $\left(w = 200\mu m;\ l = 100\mu m;\ w/s = 50\right)$, realised from different materials (figure 5)

$Si, \mu_H = 0.15 m^2V^{-1}s^{-1}$; $GaSb, \mu_H = 0.5 m^2V^{-1}s^{-1}$; $GaAs, \mu_H = 0.85 m^2V^{-1}s^{-1}$;

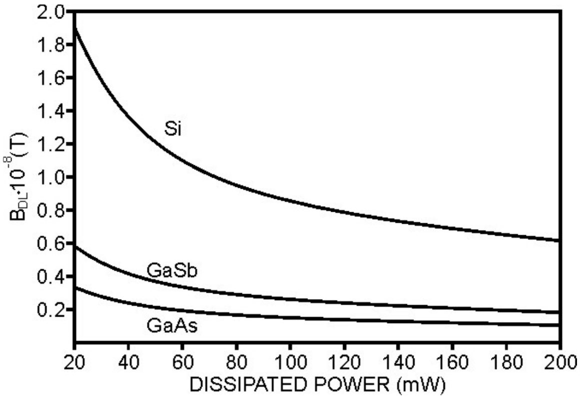

Fig. 5. B_{DL} depending on P for three devices of different materials

A high value carrier mobility causes the decreasing of B_{DL}. So the detection limit decrease with 40% for GaAs comparative with GaSb

VI. CONCLUSIONS

The analysis of the characteristics of the rectangular semiconductor plates shows that the $w/l = 0.5$ structure is theoretically favorable to high performance regarding the offset-equivalent magnetic induction due to the fluctuation in surface charges.

The analysis of the main noise characteristic of the Hall plates shows that in case of thermal noise the square structure $w/l = 1$ is theoretically favorable to obtain magnetic sensors of performance.

Also substituting the silicon technology by using other materials such as GaAs or InSb with high carrier mobility values, assure higher characteristics of the sensors.

The B_{off} lowers with the increase of carriers mobility. So for the same variation in the surface charges density $\Delta Q_S = 5\cdot 10^{-6} Cm^{-2}$, the B_{off} value of the GaAs device decreases by 82% as compared to that of the silicon device.

Also, the increase in the plate length brings about higher values for B_{off}.

A detection limit of about $0.8\cdot 10^{-8} T$ at a 100mW device dissipated power has been obtained at rectangular Hall plate in case of GaAs.

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