The offset and the noise of magnetic microsensors

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In this paperwork based on the adequateHall effect models it is analysed the operating conditions, and are established the main characteristics for three magnetic microsensor structures, realised in the bipolar and the MOS integrated circuits technology. By using the numerical simulation the values of the offset-equivalent magnetic induction and the noise-equivalent magnetic induction spectral density for different structure devices are compared and it is also emphasized the way in which choosing the geometry and the material features allows getting high-performance sensors.

1. General characterization of the hall semiconductor plates

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

$$V_H = (R_H / \delta) \cdot I \cdot B_\perp \quad (1)$$

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

In the case of a Hall device with finite contacts, at low magnetic inductions, $\widetilde{B} \cong 0$, for an extrinsic semiconductor, V_H is [1]:

$$V_H = G \frac{r_H}{qn\delta} IB_\perp \quad (2)$$

G being the geometrical correction factor, and r_H is the Hall factor. The Hall voltage can be expressed in terms of the bias voltage V, as follows:

$$V_H = \mu_H \frac{w}{l} \cdot GVB_\perp \quad (3)$$

where μ_H is the Hall mobility of the charge carriers. The absolute sensitivity of a Hall magnetic sensor is its transduction ratio for large signals:

$$S_A = \left| \frac{V_H}{B_\perp} \right| = G \frac{r_H}{qn\delta} I \quad (4)$$

Supply-voltage related sensitivity is defined by:

$$S_V = \frac{S_A}{V} = \mu_H \cdot \left(\frac{w}{l} \right) G \quad (5)$$

2. The offset voltage and the offset equivalent magnetic induction

Because of misalignment of contacts and non-uniformity of material resistivity and thickness, an offset voltage is generated in the absence of the magnetic field at the output of the Hall device. Also, a mechanical stress may produce offset by the piezo-resistive effect.

In the case of the misalignment of the sensing contacts, for a tolerance Δl (figure 1) the assimetrical output voltage or the offset voltage is expressed by:

$$V_{off} = \int_P^N \rho_b \overline{J} d\overline{s} = \rho_b \int_P^N \frac{I}{w\delta} ds = \rho_b \frac{I}{w\delta} \Delta l \quad (6)$$

The coefficient ρ_b denotes the effective material resistivity in the direction of the current density.
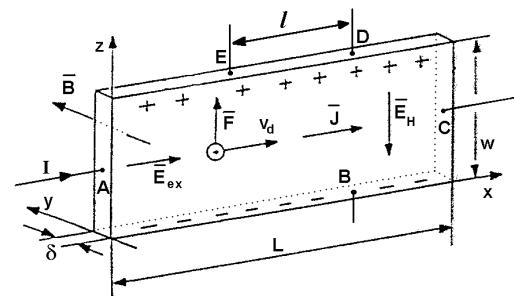
Fig. 1. Rectangular Hall plate.

The value of the magnetic induction coresponding to a Hall voltage equal with V_{off} represents offset equivalent magnetic induction. Using the equations (6) and (3) the B_{off} can also be put in this form:

$$B_{off} = \frac{V_{off}}{S_A} = \rho_b \frac{\Delta l}{w} \frac{qn}{Gr_H} \qquad (7)$$

At low magnetic field, the resistivity ρ_b is reduced to the usual resistivity:

$$\rho_b = \frac{1}{qn\mu} \qquad (8)$$

By substituting (8) into (7) it results:

$$B_{off} = \frac{1}{\mu_H} \cdot \frac{\Delta l}{l}\left(\frac{l}{wG}\right) \qquad (9)$$

where $\mu_H = r_H \mu$ is the Hall mobility of carriers.

Fig. 3. B_{off} depending on $\Delta l / l$ for three devices of different materials

The carrier mobility influence on B_{off} values for three Hall plates made from different materials are illustrated in figure 3 ($w = 200\,\mu m$, $l = 100\,\mu m$).

$$PH1: Si\ (\mu_H = 0.15\ m^2 V^{-1} s^{-1})$$
$$PH2: InP\ (\mu_H = 0.46\ m^2 V^{-1} s^{-1})$$
$$PH3: GaAs\ (\mu_H = 0.85\ m^2 V^{-1} s^{-1})$$

3. The noise of the hall plates

At the output of a Hall device the noise voltage is due to the generation-recombination noise, thermal noise, and $1/f$ noise. Because the generation-recombination noise is negligible in comparison with the $1/f$ noise, the noise voltage spectral density at the sense contacts of the Hall device is given by:

$$S_{NV}(f) = S_{V\alpha}(f) + S_{VT} \qquad (10)$$

Here $S_{V\alpha}(f)$ is the noise voltage spectral density of the noise of the $1/f$ noise and S_{VT} denotes the noise voltage spectral density due to thermal noise.

The noise voltage spectral density of thermal noise is given by [2]:

$$S_{NV} = 4kTR_{out} \qquad (11)$$

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 Hall plate with very small sense contacts is given by:

Fig. 2. B_{off} depending on $\Delta l / l$ for three devices of different geometry

In figure 2 are represeted the B_{off} values for three devices made from silicon ($\mu_H = 0,15 m^2 V^{-1} s^{-1}$), and having different ratios l/w ($l = 200\,\mu m$). It is assumed that the sense contacts (S_1, S_2) are points, and the magnetic field is low ($\mu_H^2 B^2 << 1$).

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

It is noticed that the B_{off} is minimum for $l/w = 0.5$ and for smaller values of this ratio.

$$R_{out} \approx 2\frac{\rho_b}{\pi\delta}\ln\left(\frac{w}{s}\right) \qquad (12)$$

on condition that: $s \ll w \ll l$

The coefficient ρ_b denotes the effective material resistivity, and s is the small sense contacts diameter. If the biased voltage of device is constant, ρ_b practically it does not depend on the magnetic field. By substituting (15) into (11) it results the spectral density:

$$S_{NV} \cong 8kT\frac{\rho_b}{\delta}\ln\left(\frac{w}{s}\right) \qquad (13)$$

The current spectral density of $1/f$ noise can be described by expression [2]:

$$S_{NI} = I^2\frac{\alpha}{N}\cdot\frac{1}{f^\beta} \qquad (14)$$

where I is the device current, N is the total number of charge carriers in the device, α is a non-dimensional parameter called the Hooge parameter and β is a constant $(\beta \cong 1 \pm 0.1)$. For semiconductors α values of 10^{-9} to 10^{-7} were reported. The $S_{V\alpha}(f)$ for a conventional rectangular Hall plate is given by [3]:

$$S_{V\alpha}(f) \cong \alpha\left(\frac{V}{l}\right)^2(2\pi \cdot n \cdot \delta \cdot f)^{-1}\cdot\ln\left(\frac{w}{s}\right) \qquad (15)$$

4. The noise-equivalent magnetic induction spectral density

The noise voltage at the output of a Hall magnetic sensor can be interpreted as a result of an equivalent magnetic induction, acting on a noiseless Hall device. Replacing the Hall voltage in (4) by the mean square noise voltage:

$$v_n = \left(\int_{f_1}^{f_2} S_{NV}(f)\right)^{1/2} \qquad (16)$$

it is obtained:

$$\langle B_N^2 \rangle = \left(\int_{f_1}^{f_2} S_{NV}(f)\right)\cdot S_A^{-2} \qquad (17)$$

Here $\langle B_N^2 \rangle$ is the mean square noise-equivalent magnetic induction in a frequency range (f_1, f_2), and $S_{NV}(f)$ is the noise voltage spectral density at the sensor output. At high frequencies, thermal noise dominates. For a narrow bandwidth Δf around a frequency f by substituting (5) and (13) into (17) it results:

$$\langle B_N^2 \rangle = \frac{8kT\Delta f}{\pi}\cdot\frac{\rho_b V^{-2}\ln(w/s)}{\delta\mu_H^2}\left(G\frac{w}{l}\right)^{-2} \qquad (18)$$

From (17) it is obtained the noise-equivalent magnetic induction spectral density:

$$S_{NB}(f) = \frac{\partial < B_N^2 >}{\partial f} = \frac{S_{NV}(f)}{S_A^2} \qquad (19)$$

By analogy with (18) it is deduced:

$$S_{NB}(f) = \frac{8kT\rho_b \ln(w/s)}{\pi\delta\mu_{H_{Ch}}^2}\left(G\frac{w}{l}\right)^{-2} V^{-2} \qquad (20)$$

To emphasize the geometry influence on $S_{NB}(f)$ there were simulated (figure 5) three Hall semiconductor plates structures made on silicon

$$\mu_H = 0.15m^2V^{-1}s^{-1}, \rho_b = 10^{-2}\,\Omega m$$

HP 1: $l/w = 2$; HP 2: $l/w = 1$;
HP3: $l/w = 0.5$;
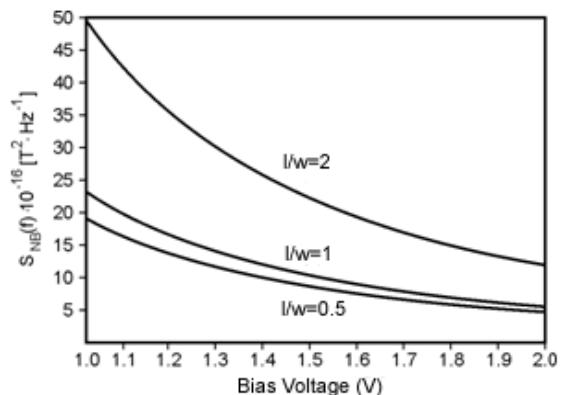
Fig. 5. The $S_{NB}(f)$ depending on bias voltage
for three devices of different geometry

The increasing of the device length causes the decreasing of device performances.
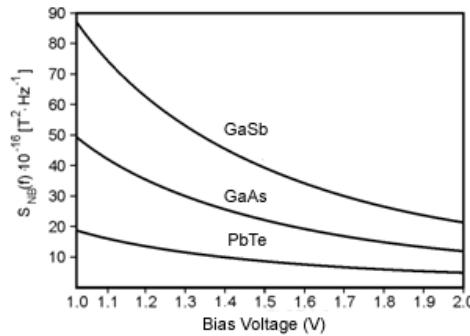
Fig. 6. The $S_{NB}(f)$ depending on bias voltage for three devices from different materials

If the length increases twice, the noise-equivalent magnetic induction spectral density increases with 18% and if the same distance increases four times (PH1), $S_{NB}(f)$ increases with 148%. In figure 6 it can be seen the material influence on $S_{NB}(f)$ values for three devices made from GaSb, GaAs and PbTe and having the same sizes: $l = 50\mu m$, $w = 100\mu m$, $\delta = 10^{-7}\mu m$, $w/s = 50$.

PH1 (GaSb): $\mu_H = 0.5 m^2 V^{-2} s^{-1}$; $\rho_b = 0.27\Omega m$

PH2 (GaAs): $\mu_H = 0.85 m^2 V^{-2} s^{-1}$; $\rho_b = 0.16\Omega m$;

PH3 (PbTe): $\mu_H = 0.6 m^2 V^{-2} s^{-1}$; $\rho_b = 0.23\Omega m$.

At low frequencies, 1/f noise dominates. By substituting (5) and (15) into (19) it is obtained:

$$S_{NB}(f) = \frac{\alpha}{2\pi} \cdot \frac{1}{f} \cdot \frac{\ln(w/s)}{n\delta L^2 \mu_{H_{Ch}}^2} \cdot \left(G \frac{w}{l}\right)^{-2} \quad (21)$$

The numerical values of the $S_{NB}(f)$ for Hall semiconductor plates made of different materials and having different geometry are listed in table 1.

($\alpha = 10^{-7}$, $f = 4Hz$, $\Delta f = 1Hz$, $\delta = 5 \cdot 10^{-7}\mu m$, $w/s = 50$, $n = 4.5 \cdot 10^{21} m^{-3}$, $w = 100\mu m$)

Table 1. The $S_{NB}(f)$ numerical values for different devices

Device	Material	μ_H $[m^2 V^{-1} s^{-1}]$	w/l	$S_{NB}(f)$ $[10^{-16} T^2 \cdot Hz]$
HP1	Si	0.15	2	2900
HP2	Si	0.15	1	3400
HP3	Si	0.15	0.5	7300
HP4	GaAs	0.85	2	10.2
HP5	GaSb	0.50	2	26
HP6	InAs	3.30	2	0.59

5. The general characterisation of the lateral bipolar magnetotransistors

Figure 7 illustrates the cross section of a lateral bipolar magnetotransistor structure, operating on the current deflection principle, realized in MOS integrated circuits technology.
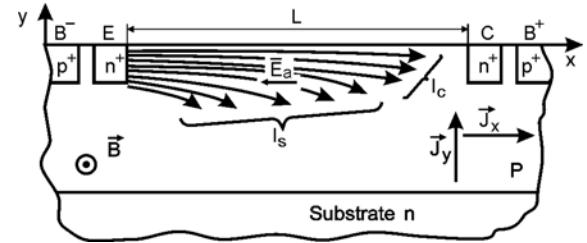
Fig. 7. Cross section of lateral magnetotransistor

The n^+ regions of emitter E and primary collector C are laterally separated on an L distance from base which is a type p region. The two p^+ base contacts, allow the application of the drift-aided field $\overline{E}_a$. On its action the most part of the minority carriers injected into the base drift to primary collector, producing collector current I_C. However, some of the electrons diffuse downwards to the n type substrate (the secondary collector) and thus produce the substrate parasitic current I_S.

In the presence of a magnetic induction $B_\perp$, perpendicular to the plane of the section, the ratio between I_C and I_S, changes because of the current deflection.

The area from base region, between the emitter contact and collector contact, operates as a short Hall plate, and an induction field $\overline{B}$ causes the deflection of current lines. The Hall transverse current will be[4]:

$$I_H = I_Y = (L/Y)I_C \mu_{Hn} B_\perp = \Delta I_C \quad (22)$$

where μ_{Hn} is the Hall mobility of electrons in the base region.

A magnetotransistor may be regarded as a modulation transducer that converts the magnetic induction signal into an electric current signal. This current signal or output signal is the variation of collector current, caused by induction $\overline{B}_\perp$.

The absolute sensitivity of a magnetotransistor is defined by:

$$S_A = |\Delta I_C / B| \quad (23)$$

The supply-current-related sensitivity of the device is expressed as:

$$S_I = \frac{S_A}{I_C} = \frac{1}{I_C} \cdot \left| \frac{\Delta I_C}{B_\perp} \right| = \frac{L}{Y} \cdot |\mu_{Hn}| \quad (24)$$

For a given induction $(B = 0.4T)$ and at given collector current ($I_C = 1mA$), the sensitivity depends on the device geometry and the material properties. In table 2 are presented the values obtained for five magnetotransistors structures.

Table 2. The numerical values of the supply-current related sensitivity

MGT	L/Y	μ_{Hn} $(m^2V^{-1}s^{-1})$	$S_I(T^{-1})$
MGT$_1$ (Si)	3	0.15	0.45
MGT$_2$ (Si)	1	0.15	0.15
MGT$_3$ (Si)	0.5	0.15	0.075
MGT$_4$ (GaAs)	3	0.80	2.40
MGT$_5$ (GaSb)	3	0.50	1.50

6. The offset equivalent magnetic induction

For bipolar lateral magnetotransistor presented in figure 8 the offset current consists of the flow of minority carriers which, injected into the base region in absence of magnetic field diffuse downwards and are collected by the secondary collector S. The main causes of the offset are due to the misalignment of contacts to non-uniformity of the thickness and of the epitaxial layer doping.

Also a mechanical stress combined with the piezo-effect, may produce offset.

To describe the error due to the offset it is determined the magnetic induction, which produces the imbalance $\Delta I_C = \Delta I_{Coff}$. The offset equivalent magnetic induction is expressed by considering the relation (24):
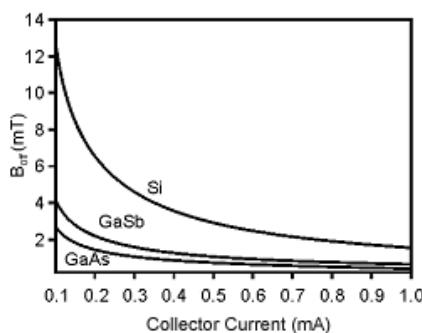
Fig. 8. The B_{off} depending on the I_C for three devices of different materials

$$B_{off} = \frac{\Delta I_{C_{off}}}{S_I I_C} = \frac{1}{\mu_{Hn}} \cdot \frac{\Delta I_{C_{off}}}{I_C} \quad (25)$$

Considering $\Delta I_{Coff} = 0.10 \mu A$ and assuming that the low magnetic field condition is achieved, in figure 8 is presented the dependence of B_{off} on I_C for three magnetotransistors with the same geometry $L/Y = 0.5$ made from different materials:

MGT1: Si with $\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$;

MGT2: GaSb with $\mu_{Hn} = 0.50 m^2 V^{-1} s^{-1}$;

MGT3: GaAs with $\mu_{Hn} = 0.85 m^2 V^{-1} s^{-1}$

The offset-equivalent magnetic induction lowers with the increase of carriers' mobility.

So for the same collector current $I_C = 0.10 mA$ the B_{off} value of the GaAs device decreases by 70% as compared to that of the silicon device.

7. The noise equivalent magnetic induction for lateral bipolar magnetotransistors

The mean square value of noise magnetic induction (NEMI) is defined by :

$$\langle B_N^2 \rangle = \frac{\int_{f_1}^{f_2} S_{NI}(f) \cdot df}{(S_I \cdot I_C)^2} \quad (26)$$

Here S_{NI} is the noise current spectral density in the collector current, and (f_1, f_2) is the frequency range. In case of shot noise, the noise current spectral density at frequencies over 100 Hz is given by [2]:

$$S_{NI} = 2qI \quad (27)$$

where I is the device current.

From (26) it is obtained the noise-equivalent magnetic induction spectral density:

$$S_{NB}(f) = \frac{\partial \langle B_N^2 \rangle}{\partial f} = \frac{S_{NI}(f)}{S_A^2} \quad (28)$$

In a narrow frequency band around the frequency f, by substituting (24) and (27) into (28) it results:

$$S_{NB}(f) \le 2q \left(\frac{Y}{L} \right)^2 \frac{1}{\mu_{Hn}^2 I_C} \quad (29)$$

In Fig. 9 there are shown S_{NB} (f) values for three magnetotransistor structures made of different materials ($Y/L = 0.5; \Delta f = 1\,Hz$)

MGT_1: Si,with $\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$

MGT_2: Ga Sb, with $\mu_{Hn} = 0.50 m^2 V^{-1} s^{-1}$

MGT_3: Ga As, with $\mu_{Hn} = 0.80 m^2 V^{-1} s^{-1}$
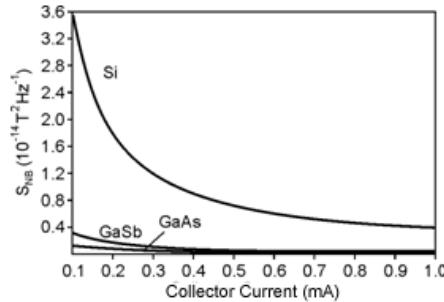
Fig 9. The S_{NB} (f) depending on the I_C for
three devices of different materials

The noise-equivalent magnetic induction spectral density lowers with the increase of carriers mobility, this increase being significant for collector currents of relatively low values. So for the collector current $I_C = 0.1 mA$, the offset equivalent magnetic induction value of the GaSb device decreases by 91.5% as compared to that of the silicon device.

8. The structure and operating conditions of the double-drain magnetotransistor

The double – drain MOS device (figure 10) is a MOSFET with two adjacent drain regions replacing the conventional single drain region, the total channel current being shared between these regions [5].
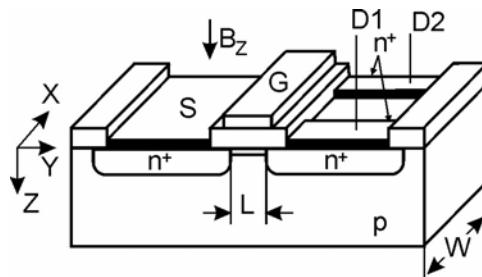
Fig. 9. Double-drain magnetic – sensitive MOSFET structure

As the result of the bias in the linear region is obtained a continuous channel of approximately constant thickness, which can be assimilated with a Hall plate.The deflection of current lines appears under the action of a

magnetic field $B_\perp$, perpendicular to the device surface. Since the output signal of the double-drain MOS magnetotransistors consists of the current variation between its terminals, this device operates in the Hall current mode. Using the features of dual Hall devices, and the Hall current expression, it results:

$$\Delta I_D = \frac{I_H}{2} = \frac{1}{2}\mu_{H_{Ch}} \cdot \frac{L}{W} \cdot G \cdot I_D \cdot B_\perp \qquad (30)$$

where $\mu_{H_{Ch}}$ is the carriers Hall mobility in the channel, and G denotes the geometrical correction factor. The magnetic sensitivity related to the devices current is defined as follows:

$$S_I = \frac{1}{I_D} \cdot \left| \frac{\Delta I_D}{B_\perp} \right| = \frac{1}{2}\mu_{H_{Ch}} \cdot \frac{L}{W} G \qquad (31)$$

For a given induction and at given drain current, the sensitivity depends on the device geometry and the material properties.

9. The offset equivalent magnetic induction of the double-drain magnetotransistor

The difference between the two drain currents in the absence of the magnetic field is the offset collector current:

$$\Delta I_{D_{off}} = I_{D1}(0) - I_{D2}(0) \qquad (32)$$

This is due to imperfections specific to the manufacturing process: the contact misaligment, the non-uniformity of the thickness and of the epitaxial layer doping, the presence of some mechanical stresses combined with the piezo-effect.

To describe the error caused by the offset it is determined the magnetic induction, which produces the imbalance $\Delta I_D = \Delta I_{D_{off}}$. The offset equivalent magnetic induction is expressed by considering the relation (31):

$$B_{off} = \frac{\Delta I_{D_{off}}}{S_I I_D} = \frac{2}{\mu_{Hn}} \cdot \frac{\Delta I_{D_{off}}}{I_D} \cdot \left(G \frac{L}{W_E} \right)^{-1} \qquad (33)$$

Considering $\Delta I_{D_{off}} = 0.10 \mu A$ and assuming that the low magnetic field condition is achieved, in figure 10 is presented the dependence of B_{off} on I_D for three magnetotransistors with the same geometry $W/L = 0.5$ made from different materials:

MDD1: Si with $\mu_{H_{Ch}} = 0.07 m^2 V^{-1} s^{-1}$;

MDD2: InP with $\mu_{H_{Ch}} = 0.23 m^2 V^{-1} s^{-1}$;

MDD3: GaAs with $\mu_{H_{Ch}} = 0.43 m^2 V^{-1} s^{-1}$.
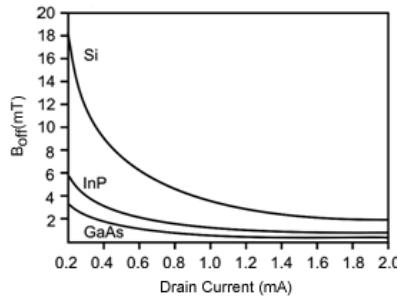
Fig. 10 - The B_{off} depending on the drain current
for three devices of different materials

The geometry influence upon B_{off} is shown in figure 11 by simulating three magnetotransistors structures made from silicon and having different $\dfrac{W}{L}$ ratios.

MDD1: $W/L = 0,5$; $G(L/W) = 0.73$;
MDD2: $W/L = 1$; $G(L/W) = 0.67$;
MDD3: $W/L = 2$; $G(L/W) = 0.46$;
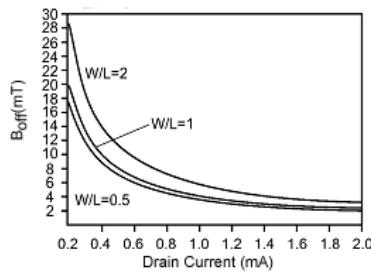
Fig.11 -The B_{off} depending on the drain current
for three devices of different geometry

If the width of the channel is kept constant, B_{off} increases as the channel length decreases. Thus minimum values for the offset equivalent induction are obtained with the device which has $L = 2W$, and in the MDD3 device these values are 53.5% bigger.

The noise current at the output of a magnetotransistors can be interpreted as a result of an equivalent magnetic induction.

The mean square value of noise magnetic induction (*NEMI*) for double-drain magnetotransistor is defined by:

$$\left\langle B_N^2 \right\rangle = \frac{\int_{f_1}^{f_2} S_{NI}(f) \cdot df}{(S_I \cdot I_D)^2} \qquad (34)$$

Here S_{NI} is the noise current spectral density in the drain current, and (f_1, f_2) is the frequency range.

From (34) is obtained the noise-equivalent magnetic induction spectral density:

$$S_{NB}(f) = \frac{\partial <B_N^2>}{\partial f} = \frac{S_{NI}(f)}{S_A^2} \qquad (35)$$

In case of shot noise, by analogy with (29) it results:

$$S_{NB}(f) = 2qI \cdot 4\left(\frac{W}{L}\right)^2 \cdot \frac{1}{G^2 \mu_{H_{Ch}}^2} \cdot \frac{1}{I_D^2} \le 8q\left(\frac{W}{L}\right)^2 \cdot \frac{1}{G^2} \cdot \frac{1}{\mu_{H_{Ch}}^2} \cdot \frac{1}{I_D} \qquad (36)$$

Considering the condition of low value magnetic field fulfilled ($\mu_H^2 B^2 << 1$), it is obtained a maximum value for $(L/W)G = 0.74$, if $W/L < 0.5$. [1]

In this case:

$$(S_{NB}(f))_{min} \le 14.6q \frac{1}{I_D \mu_{H_{Ch}}^2} \qquad (37)$$

In figure 12 are shown $S_{NB}(f)$ values obtained by simulation of three double-drain MOS magnetotransistors structures from different materials.

MGT1: *Si*, $\mu_{H_{Ch}} = 0.07 m^2 V^{-1} s^{-1}$
MGT2: *InP*, $\mu_{H_{Ch}} = 0.23 m^2 V^{-1} s^{-1}$
MGT3: *GaAs*, $\mu_{H_{Ch}} = 0.04 m^2 V^{-1} s^{-1}$
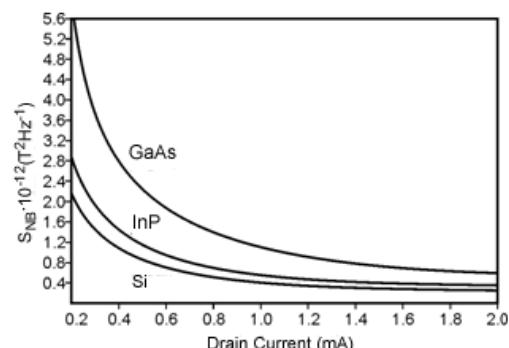

Fig. 12. The S_{NB} depending on drain current,
for three devices of different materials

To emphasize the dependence of $S_{NB}(f)$ on device geometry there were simulated (figure 13) three double-drain magnetotransistors structures made from silicon, $\mu_{H_{Ch}} = 0,07 m^2 V^{-1} s^{-1}$, and having different ratios W/L ($W = 50\mu m$). The devices were biased in the linear region and magnetic field has a low level $\left(\mu_H^2 B^2 << 1\right)$.

$$\text{MGT1:} \quad \frac{W}{L} = 0.5 \text{ and } \left(\frac{L}{W} G\right) = 0.56$$

$$\text{MGT2:} \quad \frac{W}{L} = 1 \text{ and } \left(\frac{L}{W} G\right) = 0.409$$

$$\text{MGT3:} \quad \frac{W}{L} = 2 \text{ and } \left(\frac{L}{W} G\right) = 0.212$$
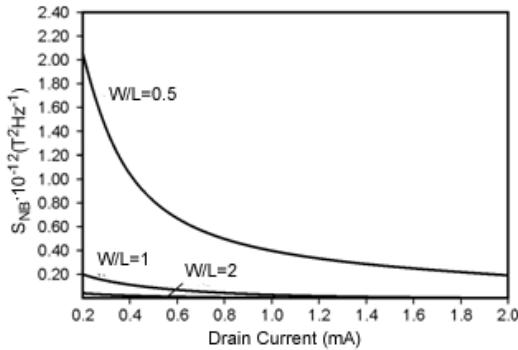

Fig.13. The S_{NB} depending on the drain current for three devices of different geometry

It is noticed that the $S_{NB}(f)$ is minimum for $W/L = 0.5$, and for smaller values of this ratio. The decreasing of the channel length causes the increasing of $S_{NB}(f)$ with 40.8% for a square structure $W = L$, and with 173% for $W = 2L$.

7. Conclusions

The analysis of the offset-equivalent magnetic induction and the noise-equivalent magnetic induction of the Hall plates shows that the $l/w = 0.5$ structure is theoretically favourable to obtaining magnetic sensors of performance. From double-drain MOSFET magnetotransistors, in case of shot noise, the $W/L = 0.5$ structure provides superior *SNR* values, and smaller S_{NB} values. In both Hall plates and MOS Hall devices by substituting the silicon technology with materials of high

carriers mobility such as GaAs, GaSb, InSb or InP allows the achievement of higher characteristics sensors.

The research work emphasizes the fact that the noise equivalent magnetic induction and the offset equivalent magnetic induction   lowers with the increase of carriers mobility, this increase being significant for drain currents of relatively low values.

So for the drain current $I_D = 0.2mA$, the offset equivalent magnetic induction value of the GaAs device decreases by 81.8% as compared to that of the silicon device.

Similar findings are outlined in this paper for bipolar lateral magnetotransistor too.

The use of magnetotransistors as magnetic sensors allows the achieving of some current-voltage conversion circuits, more efficient than conventional circuit with Hall plates.

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