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OPTIMIZATION OF MICROSENSOR STRUCTURES THROUGH HALL – EFFECT MODELLING

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Abstract: In this paperwork, based on the model of dual Hall devices, it is analysed the operation, and are established the main characteristics for two magnetotransistors structures, realised in the MOS and the bipolar integrated circuits technology.
Using numerical simulation it is emphasized the way in which the choise of its geometry and material features, allow the obtaining of high performance magnetic sensors.
There are also presented and described the original electrical diagrams of the transducers which contain such sensors, proposing possible applications in naval installation.

Key Words: double-collector magnetotransistors, offset equivalent magnetic induction, noise equivalent magnetic induction, signal-to noise ratio, detection limit.

1. INTRODUCTION

In the presence of a magnetic field, the Hall effect takes place in the active region of the transistors, however their magnetic sensitivity is insignificant.
Moreover, the Hall effect may interfere with the action of a bipolar transistor in many ways which makes the analysis and optimisation of devices much more difficult.
However, there are also magnetotransistors structures in which, under appropriate operating conditions the magnetic sensitivity increases to values useful in practical work.
In this way integrated magnetic sensors can be obtained which are useful for emphasizing and measuring mechanical and geometrical quantities.

2. THE STRUCTURE AND OPERATING PRINCIPLE

Figure 1 illustrates the cross section of a mangnetotransistors operating on the current deflection principle [6].
This device has the structure of a long channel MOS transistor, but operates as a lateral bipolar transistor with a drift-aided field in base region.
The device is situated in a *p*-well, serving as the base region of the transistor. The two base contacts B^+ and B^-, allow the application of an accelerating voltage for the minority carriers injected into the base region. The two n^+ regions laterally separated by the length of base along the distance L, serve as the emitter E and primary collector C. The substrate S works as the secondary collector.

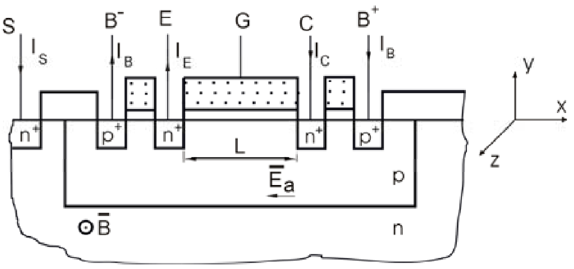

Fig. 1. Cross section through a lateral magneto-transistor in CMOS technology

In order to describe the qualitative operation of the device, let us assume that it is adequately biased for the forward active operation.
Owing to the accelerating field $\overline{E}_a$ in the base region, the most part of electrons injected into the base region drift mainly along the base length and are collected by collector C, producing collector current I_C. However, some of the which diffuse downwards, are collected by the secondary collector S, producing the substrate current I_S. The rising of ratio between the useful current I_C and the parasite current I_S is determined by the accelerating field. A magnetic

induction $\overline{B}$ perpendicular to the figure plane, modulates the distribution of the emitter current I_E among I_C and I_S. The modulation in the collector current I_C is used as the sensor signal.
If the acceleration field $\overline{E}_a$ in the base region is very small the electrons moving essentially by diffusion, the transverse Hall current will be [2]:

$$I_H = I_Y = \frac{L}{Y} I_C \mu_{Hn} B_{\perp} = \Delta I_C \tag{1}$$

where μ_{Hn} is the Hall mobility of electrons in the *p*-well, and Y is a geometrical parameter given approximately by $y_{jn} < Y < y_{jp}$. Here y_{jn} and y_{jp} denote the junction depths of the collector region and the *p*-well respectively.

3. SENSITIVITY AND NOISE EQUIVALENT MAGNETIC INDUCTION

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 $B_{\perp}$. The supply-current-related sensitivity of the device is defined by:

$$S_I = \frac{1}{I_C} \cdot \left| \frac{\Delta I_C}{B_{\perp}} \right| = \frac{L}{Y} \cdot \left| \mu_{Hn} \right| \tag{2}$$

The noise current at the output of a magnetotransistor can be interpreted as a result of an equivalent magnetic induction.
The mean square value of noise equivalent magnetic induction (NEMI) is defined by:

$$\left\langle B_N^2 \right\rangle = \frac{\int_{f_1}^{f_2} S_{NI}(f) \cdot df}{\left(S_I \cdot I_C\right)^2} \tag{3}$$

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 short noise, the noise current spectral density at frequencies over 100 Hz is given by [4]:

$$S_{NI} = 2qI \tag{4}$$

where *I* is the device current.
In a narrow frequency band around the frequency *f*, by substituting (2) and (4) into (3) it results:

$$\left\langle B_N^2 \right\rangle \le 2q \left(\frac{Y}{L} \right)^2 \frac{\Delta f}{\mu_{Hn}^2} \cdot \frac{1}{I_C} \tag{5}$$

In figure 2 there are shown NEMI 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 $\mu_{Hn} = 0.85 m^2 V^{-1} s^{-1}$

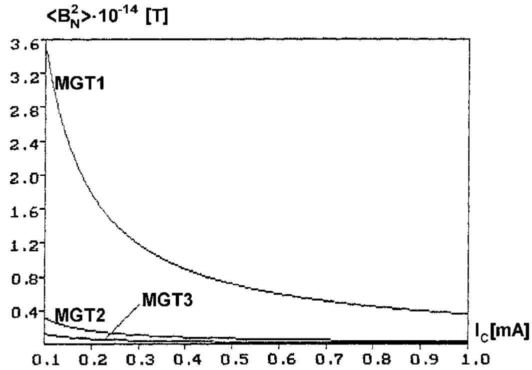

Fig. 2. NEMI depending on the collector current for three devices of different materials

For the same collector current $I_C = 0{,}2mA$ the NEMI value of the Ga As device decreases by 25.6 times as compared to that of the silicon device.
To emphasise the dependence of NEMI device geometry, there were simulated (figure 3) two magnetotransistor structures realised on silicon and having different ratios Y/L ($L = 50\,\mu m$, $MGT_1 : Y/L = 0.5$; $MGT_2 : Y/L = 0.7$).

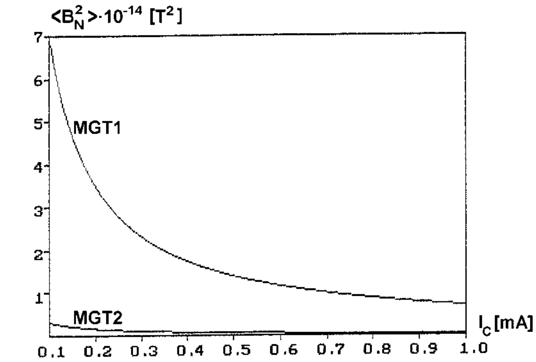

Fig. 3. NEMI depending on the collector current for two devices of different geometry

4. SIGNAL-TO-NOISE RATIO

The noise affecting the collector current of a magnetotransistors is shot noise and $1/f$ noise.
Signal-to-noise is defined by:

$$SNR(f) = \frac{\Delta I_C}{\left[S_{NI} \cdot (f) \cdot \Delta f\right]^{1/2}} \tag{6}$$

where Δf denotes a narrow frequency band around the frequency f, and S_{NI} is given by (4). In case of shot noise, by substituting (1) and (4) into (6) it results:

$$SNR(f) = \frac{1}{\sqrt{2}} \mu_{Hn} \frac{L}{Y} \cdot \frac{I_C}{(q \cdot I \cdot \Delta f)^{1/2}} \cdot B_{\perp} \leq$$

$$\leq 0{,}707 \mu_{Hn} \frac{L}{Y} \left(\frac{I_C}{q \Delta f} \right)^{1/2} \cdot B_{\perp} \tag{7}$$

In figure 4 is shown the $SNR(f)$ dependence on collector current of three magnetotransistor structures of different materials ($L/Y = 5, \Delta f = 1\,Hz, B = 0.2\,T$)

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 $\mu_{Hn} = 0.85 m^2 V^{-1} s^{-1}$

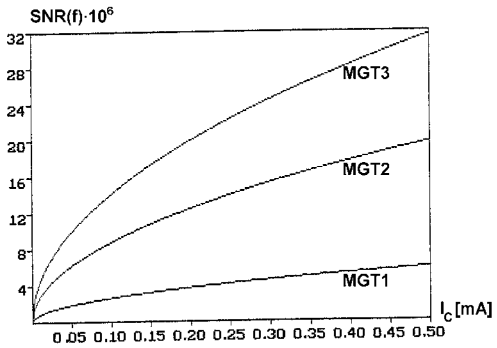

Fig. 4. *SNR(f)* depending on I_C for three devices of different materials

A high value of carrier mobility causes the increasing of $SNR(f)$. So for $I_C = 0.2\,mA$ $SNR(f)$ increases with 60% for Ga As comparative with Ga Sb.

To emphasise the dependence of $SNF(f)$ on device geometry there were simulated (figure 5) three magnetotransistor structures realised on silicon ($\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$) and having different ratios L/Y $(L = 50\,\mu m; B = 0.2\,T; \Delta f = 1 Hz)$.

$MGT_1 : L/Y = 5$; $MGT_2 : L/Y = 3$; $MGT_3 : L/Y = 2$.

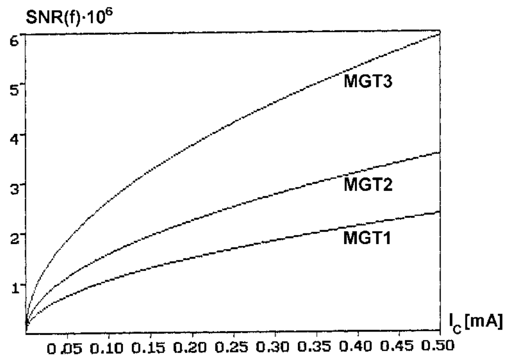

Fig. 5. *SNR(f)* depending on I_C for three devices of different geometry

In case of $1/f$ noise, the noise spectral density at the device output is given by [5]:

$$S_{NI}(f) = I^2 \frac{a}{N} \cdot \frac{1}{f^{\beta}} \tag{9}$$

To illustrate the $SNR(f)$ dependence on device geometry three lateral magnetotransistor structures realised on silicon were simulated (figure 6).

$MGT_1 : L/Y = 0.5$; $MGT_2 : L/Y = 1$; $MGT_3 : L/Y = 4$.

It is considered that $f = 1.5 Hz$, $\Delta f = 1 Hz$, $\alpha = 10^{-7}$ $n = 4.5 \cdot 10^{21} m^{-3}, d = 10^{-5} m, q = 1.6 \cdot 10^{-19} C$, the device being biased in the linear region and the magnetic field having a low level.

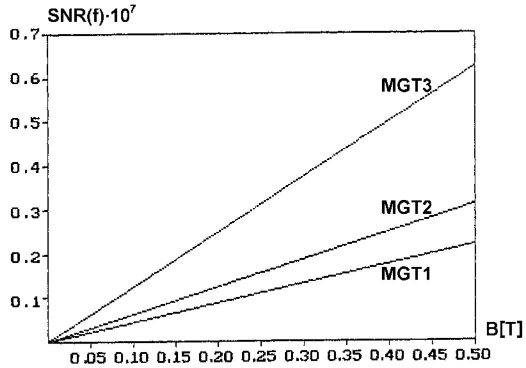

Fig. 6. *SNR(f)* depending on magnetic induction for three devices of different geometry

For the same magnetic induction $B = 0.2T$ $SNR(f)$ is maximum in case $L = 4Y$. The increasing of the geometrical parameter Y causes the decreasing of *SNT(f)* with 50% for a square structure $Y = L$ and with 63.3% for $Y = 2L$.

In figure 7 it can be seen the material influence on *SNR(f)* values for three sensors MGT_1, MGT_2, MGT_3 realised on Si ($\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$, $f = 1.2 Hz$), GaSb ($\mu_{Hn} = 0.50 m^2 V^{-1} s^{-1}$, $f = 5 Hz$) and GaAs ($\mu_{Hn} = 0.85 m^2 V^{-1} s^{-1}$, $f = 7.8 Hz$); $L = 3Y$, $Y = 20 \mu m$.

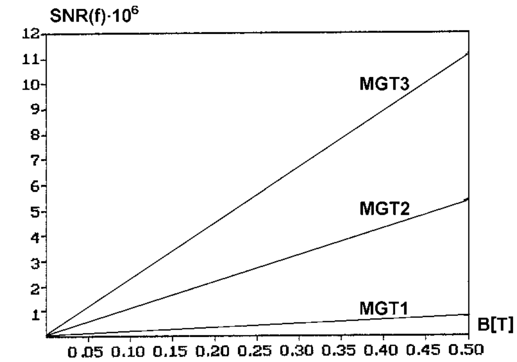

Fig. 7. *SNR(f)* depending on magnetic induction for three devices of different materials

5. THE DETECTION LIMIT OF MAGNETIC SENSORS

A convenient way of describing the noise properties of a sensor is in terms of detection limit, defined as the value of the measured corresponding to a signal-to-noise ration of one. In case of shot noise, it is obtained from expression (7):

$$B_{DL} \geq \frac{(2q\Delta f)^{1/2}}{\mu_{Hm}} \cdot \frac{Y}{L} \cdot I_C^{-1/2} \tag{10}$$

In figure 8 are shown B_{DL} values obtained for three sensors, MGT_1, MGT_2, MGT_3 realised on Si ($\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$),GaSb ($\mu_{Hn} = 0.50 m^2 V^{-1} s^{-1}$) and GaAs ($\mu_{Hn} = 0.80 m^2 V^{-1} s^{-1}$).

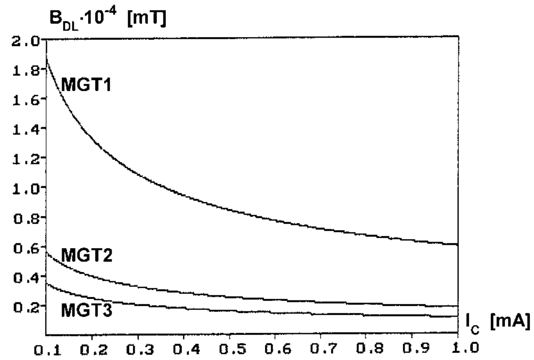

Fig. 8. B_{DL} depending on I_C for three devices of different materials

6. THE CHARACTERISATION OF THE SPLIT COLLECTOR MAGNETOTRANSISTOR.

Figure 9 illustrates the cross section of a split-collector magnetotransistor operating on the current deflection principle. This structure is compatible with bipolar integrated circuit technology [1].

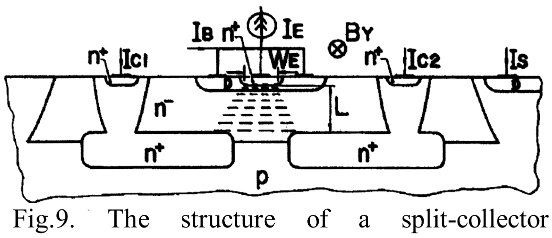

Fig.9. The structure of a split-collector magnetotransistor.

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 $^+$). L is the emitter-collector distance, and W_E is the emitter width.

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): $\Delta I_C = I_{C1} - I_{C2}$. Since the output signal of the double collector mangetotransistor 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 [3]:

$$\Delta I_C = \frac{I_H}{2} = \frac{1}{2} \mu_{Hn} \frac{L}{W_E} G \cdot I_C B_\perp \tag{11}$$

7. NOISE – EQUIVALENT MAGNETIC INDUCTION

Magnetotransistors are usually intended for sensing magnetic field.
The absolute sensitivity of a magnetotransistor is defined by:

$$S_A = \left| \frac{\Delta I_C}{B} \right| \tag{12}$$

Using (11) the supply-current related sensitivity of the device can be put in this form:

$$S_I = \frac{S_A}{I_C} = \frac{1}{I_C} \left| \frac{\Delta I_C}{B_\perp} \right| = \frac{1}{2} \mu_{Hn} \frac{L}{W_E} G \tag{13}$$

The mean square value of noise magnetic induction (NEMI) is given by (3):

$$\left\langle B_N^2 \right\rangle = \frac{\int_{f_1}^{f_2} S_{NI}(f) \cdot df}{(S_I \cdot I_C)^2} \tag{14}$$

From (14) it is obtained the noise-equivalent magnetic induction spectral density:

$$S_{NB}(f) = \frac{\partial \left\langle B_N^2 \right\rangle}{\partial f} = \frac{S_{NI}(f)}{B} \tag{15}$$

In case of shot noise by analogy with (5) it results:

$$S_{NB}(f) = 2qI \cdot 4 \left(\frac{W_E}{L} \right)^2 \cdot \frac{1}{G^2 \mu_{Hn}^2} \cdot \frac{1}{I_C^2} \leq$$

$$\leq 8q \left(\frac{W_E}{L} \right)^2 \cdot \frac{1}{G^2} \cdot \frac{1}{\mu_{Hn}^2} \cdot \frac{1}{I_C} \tag{16}$$

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

In this case:

$$< B_N^2 >_{min} \leq 14.6q \frac{1}{I_C} \cdot \frac{1}{\mu_{Hn}^2} \quad (17)$$

In figure 10 there are shown $S_{NB}(f)$ values obtained by simulation of three magnetotransistors structures from different materials.

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

MGT_2: InP with $\mu_{Hn} = 0.46 m^2 V^{-1} s^{-1}$

MGT_3: GaAs with $\mu_{Hn} = 0.85 m^2 V^{-1} s^{-1}$

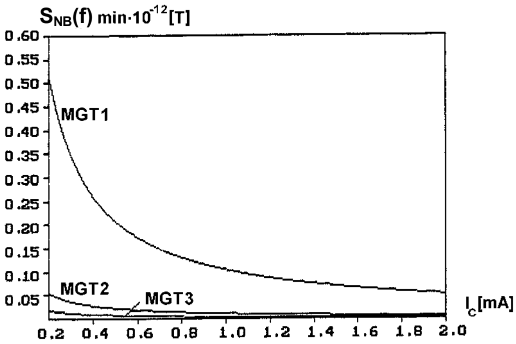

Fig. 10. S_{NB}(f) depending on the I_C for three devices of different materials

To emphasize the dependence of $S_{NB}(f)$ on device geometry there were simulated (figure 11) three double-collector magnetotransistors structures realised on silicon, $\mu_{Hn} = 0.15 m^2 V^{-1} s^{-1}$, and having different ratios W/L $(W = 50 \mu m)$. The devices were biased in the linear region and the magnetic field is low ($\mu_H^2 B^2 << 1$).

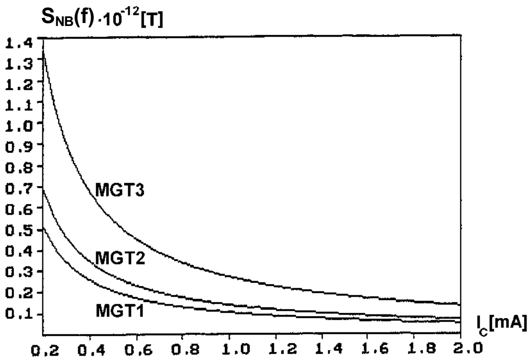

Fig. 11. S_{NB}(f) depending on the I_C for three devices of different geometry

MGT_1 with $W_E/L = 0.5$ and $(LG/W_E)^2 = 0.576$

MGT_2 with $W_E/L = 1.0$ and $(LG/W_E)^2 = 0.409$

MGT_3 with $W_E/L = 0.2$ and $(LG/W_E)^2 = 0.212$

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 $W = 2L$.

8. THE MODELING OF OFFSET EQUIVALENT MAGNETIC INDUCTION

For the split collector magnetotransistor illustrated in figure 9, the offset current is the difference between the two collector currents in the absence of magnetic field:

$$\Delta I_{Coff} = I_{C1}(0) - I_{C2}(0) \quad (18)$$

The causes of offset are essentially the same as those responsible for offset in Hall plates, which are the imperfections of manufacturing process: the material non-uniformity contacts misalignment and piezoeffects.

To charaterize the error caused by the offset, there will be determined the magnetic induction which causes an unbalance I_C equal with I_{Coff}.

The offset equivalent magnetic induction for the split collector magnetotransistor is defined by:

$$B_{off} = \frac{\Delta I_{Coff}}{S_I I_C} = \frac{2}{\mu_{Hn}} \cdot \frac{\Delta I_{C_{off}}}{I_C} \cdot \left(G \frac{L}{W_E} \right)^{-1} \quad (19)$$

For low magnetic fields ($\mu^2 B^2 << 1$) and $\Delta I_{Coff} = 10 \mu A$ there were simulated (figure 12) three magnetotransistors having $\frac{W_E}{L} = 0.5$, the materials being:

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

MGT_2: Ga Sb with $\mu = 0.46 m^2 V^{-1} s^{-1}$

MGT_3: Ga As with $\mu = 0.85 m^2 V^{-1} s^{-1}$

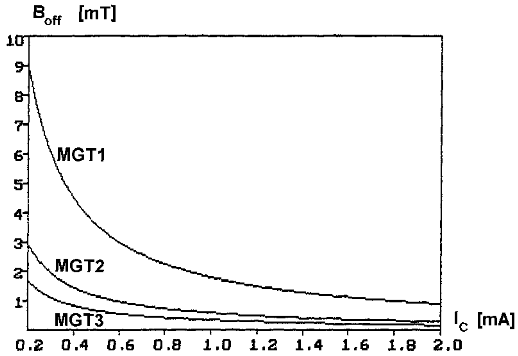

Fig. 12. B_{off} depending on the I_C for three devices of different materials

The offset equivalent induction values could be compared with the noise equivalent magnetic induction values for the same material, geometry and current I_C.

It is noticed that B_{off} is smaller than $< B_N^2 >$ with 30%.

In figure 13 there is emphasized the geometry influence on B_{of} by simulation of three magnetotransistors structures from *Si* and having the next rations W_E/L ($W_E = 50\mu m$):

MGT$_1$ with $W_E/L = 0.5$ and $LG/W_E = 0.74$

MGT$_2$: with $W_E/L = 1$ and $LG/W_E = 0.64$

MGT$_3$: with $W_E/L = 2$ and $LG/W_E = 0.46$

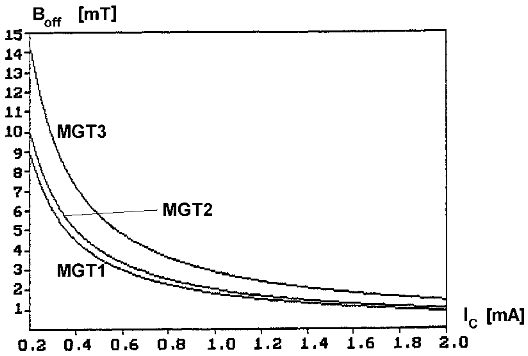

Fig. 13. B_{off} depending on the I_C for three devices of different geometry

9. CONCLUSIONS

The magnetotransistors have a lower magnetic sensitivity than the conventional Hall devices but allow very large signal-to-noise ratios, resulting a high magnetic induction resolution. The detection limit B_{DL} decreases under $10^{-5}T$ in case of GaAs at a total collector current of $1\,mA$.

The analisys of the characteristics of two magnetotreansistor structures shows that the $W/L = 0{,}5$ ratio is theoretically favourable to high performance regarding the signal-to-noise ratio, as well as the offset equivalent magnetic induction

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

The uses of magnetotransistors as magnetic sensors allows the archieving of some current-voltage conversion circuits, more efficient that conventional circuits with Hall plates.

The transducers with integrated microsensors have a high effieciency and the possibilities of using them can be extended to some measuring systems of thickness, short distance movement, level, pressure, linear and revolution speeds.

In figure 14 shown the electrical diagram of a speed of rotation transducers based on a double-collector vertical magnetotransistors.

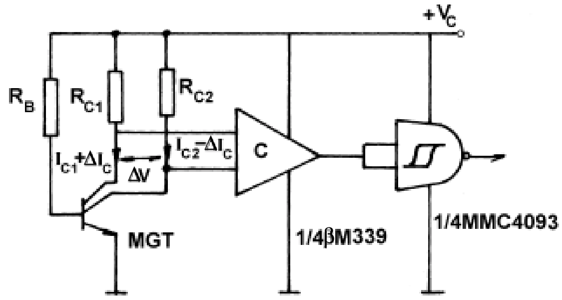

Fig. 14. The electric diagram of transducer

When a magnetic field is present there takes place an imbalance of the collector currents and the effect is potential difference between the two collectors which is proportional to the induction value B.

$$\Delta V_C = \mu_{Hn}\left(\frac{L}{W_E}G\right)R_C I_C B \qquad (19)$$

This voltage is applied to a comparator with hysteresis, which acts as a comutator. The existence of the two travel thresholds ensure the immunity at noise to the circuit. The monostable made with *MMC 4093* ensures the same duration for the transducers generated pulses.

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