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Microtesla Sensitivity and Noise of a Triple Collector Magnetotransistor

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Abstract

The sensitivity of a bipolar magnetotransistor with the base in a well has been studied in a microtesla magnetic field. The noise was experimentally measured to compare the performance of two designs of dual-collector lateral bipolar magnetotransistor, which are formed in a uniformly doped substrate or in a diffused well. The noise decreases in a diffused well. Acquiring an adequate understanding of the mechanism underlying the operation of the device should help to improve its magnetic sensitivity. A low velocity of surface recombination and an extraction of the injected electrons using a base–well p-n junction determined the operating mode with the deviation of two charge carrier flows.

Keywords: magnetotransistor sensitivity, spectrum of noise

1. Introduction

The bipolar magnetotransistor (BMT) provides a linear output, allows complete determination of the magnetic-field direction, can be implemented as part of an integrated circuit (IC), is measured in micrometers, and has high resolution. Conceptually, there are certain peculiarities about the behavior of the BMT that are difficult to explain. It shows an extremely wide range of variation in relative sensitivity, ranging from 10^{-2} to 10^{4} T^{-1}. This range of sensitivity is difficult to associate with particular structures of the device (Roumenin, 1994).

This paper presents a study on the operation of the BMT, including an overview of the relevant literature, an experiment on BMT specimens, and a computer simulation. A comprehensive analysis should provide more accurate knowledge of the magnitude and sign of BMT sensitivity. A greater understanding of the device's operation should allow for the development of a highly sensitive BMT (Tikhonov, 2005).

2. Technique of Measurements in Weak Magnetic Fields

Earlier, with the help of device-technological modeling (Tikhonov & Kozlov, 2004), an investigation was conducted on a two-collector lateral bipolar magnetotransistor with the base in a well (BMTBW) with the common potential on a well and the base at small values of the magnetic induction B. At a well doping dose of 2 μC/sm^2 and a distance between the emitter and working collectors of 9 μm, a relative sensitivity current $S_{DR}{}^{I}$ was received on a magnetic induction B = 1 mT. High sensitivity values of $S_{DR}{}^{I} = 30\ T^{-1}$ were established from a base voltage of $U_{BE} = 0.7$ V.

The relative sensitivity current $S_{DR}{}^{I}$ of the BMTBW (Kozlov et al., 2003; Tikhonov, 2005) was investigated at a doping dose per well of 3 μC/sm^2 and a distance between the emitter and working collectors of 40 μm. At a magnetic induction of B = 3 mT in an electromagnet and at $U_{BE} = 0.7$ V, a relative sensitivity of the current reaches 7 T^{-1}. A working BMTBW in weak magnetic fields has a low noise level (Tikhonov, 2007).

Measurements in weak fields must be performed using a technique that accounts for the specificity of the working BMT. A collector current can be measured without a magnetic field and then in a magnetic field. The drift of a current over time can be comparable with the change in the current in a weak magnetic field. The common change of a collector current in this case is fixed due to the drift and influence of a magnetic field. The total change of a current, with reference to a small change in induction, causes the sensitivity to be overestimated. Measurement in solenoids and electromagnets will be performed using a current in a winding wire, which, aside from the creation of a magnetic field, heats up the windings and samples. The measurement technique in the electromagnetic sources of a magnetic field should provide the short-term inclusion of a current in a winding, excluding the contribution to the result of the time and temperature drift of the collector current.

In the two-collector transistor, the current of one collector is increased in a magnetic field and the current of the other collector decreases. The currents of two BMT collectors depend heavily on an initially imbalanced mode of operation (Tikhonov, Kozlov, & Polomoshnov, 2008). The current imbalance overestimates the value of the sensitivity.

In the BMT transducer circuit, a loading resistance is applied that determines a working point and sensitivity at a given voltage. The absolute differential sensitivity of the voltage in relation to the initial imbalance voltage of the collectors is determined by the formula:

$$S_{DA}^{V} = \{[U_{C1}(B)-U_{C1}(0)] - [(U_{C2}(B) - U_{C2}(0)]\} / B \tag{1}$$

The intrinsic sensitivity of the BMT is the relative sensitivity current S_{DR}^{I}. This value is calculated from S_{DA}^{V} at a power supply voltage Vdd and with voltages on the collectors U_{C2} and U_{C1} according to the formula:

$$S_{DR}^{I} = S_{DA}^{V}[U_{C2}(B) + U_{C1}(B) - 2Vdd]^{-1} \tag{2}$$

Formulas (1) and (2) correspond to features of the working two-collector BMT. The abstract formulas defining the sensitivity by the module of the derivative dependence of a collector current on a magnetic induction do not account for the specificity of the working BMT (Roumenin, 1994; Baltes & Popovic, 1986).

3. Experimental Results

The investigated BMTBW has a third p-n junction and is therefore known as a 3CBMTBW. This BMT is created using manufacturing techniques for devices with self-overlapping electrodes (Kozlov et al., 2012).The contact to base settles down between the emitter and collectors. The dimensions of the transistor are as follows: distance between the emitter and collectors L_{EC} = 50 µm, length of electrodes of the emitter, collectors, and contacts to base W=280 µm, width of emitter D_E = 4 µm. The doping dose per base is 3 µC/sm^2. The 3CBMTBW samples were developed with the surface of the base area covered with a thin oxide and a small speed surface recombination on a junction of silicon and silicon oxide. The 3CBMTBW uses the extraction of the base-well junction electrons injected by the emitter from the return side of the base concerning a surface of a crystal. Its structure differs from the suppressed sidewall injection magnetotransistor (SSIMT) (Ristic et al., 1987), which uses recombination on a face side of the crystal.

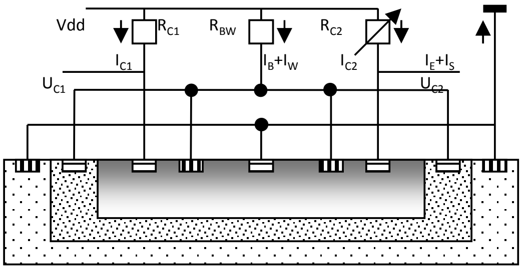

Figure 1. The electrical circuit of the 3CBMTBW: E-the emitter, B_1 and B_2 -contacts to base, C1 and C2 -two collectors, W_1 and W_2 -contacts to a well, S_1 and S_2 -contacts to a substrate

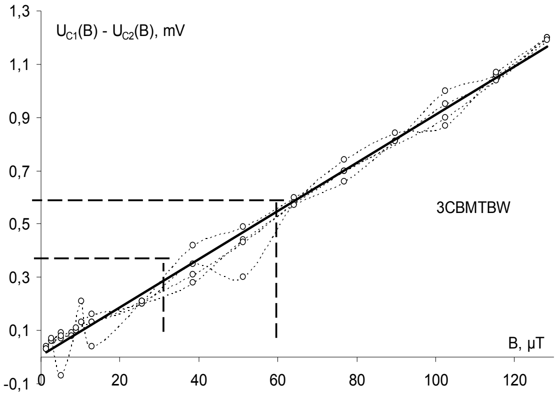

Figure 2. Dependence of the voltage difference of the collectors $U_{C1}(B)$ - $U_{C2}(B)$ on magnetic induction B = 1-130 µT for 3CBMTBW

The 3CBMTBW is measured using the circuit shown in Figure 1 at R_{C1} = 267.4 kΩ, R_{C2} = 267.4 kΩ, and R_{BW} = 1.2782 kΩ. The sensitivity was measured in the magnetic field of the solenoid. The sensitivity measurement technique provides control of all of the abovementioned features. The influence of the drift of a collector current due to changing temperatures in the solenoid was excluded by repeated consecutive measurements without a magnetic field and the short-term inclusion of the solenoid's magnetic field. For the current of the solenoid, the programmed power supply of a direct current VUPOR IPS-50804 P1 was used. The initial imbalance voltage of the collectors $U_{C1}(0)$-$U_{C2}(0)$ was excluded by adjusting the size of the resistors in loading the collectors. The voltage difference of the collectors $U_{C1}(B)$-$U_{C2}(B)$ was controlled by a digital precision multimeter DMM 4050 6-1/2.

Four cycles of measurements were performed. In Figure 2, the dependence of the voltage difference of the collectors $U_{C1}(B)$-$U_{C2}(B)$ on the magnetic induction B in a range B = 1-130 μT for the 3CBMTBW is shown. A linear dependence is observed. The differential absolute sensitivity on the voltage was determined using Formula (1) and is equal to 9 V/T.

The received values of the magnetotransistor sensitivity allow the magnetic field of Earth to be determined. Measurement of the magnetic field of Earth will be performed using a longitudinal and crosswise difference of the collector voltage U_{C1}-U_{C2}. The relationship of this difference to the sensitivity measures the magnetic field of Earth. In Figure 2, the dotted lines identify the areas of change of the magnetic field of Earth and the potential difference of the collectors.

In Figure 3, S_{DR}^{I}, the sensitivity of the 3CBMTBW versus a collector current, is given. The relative sensitivity of the current was calculated using Formula (2) to be 1.1-0.7 T^{-1}.

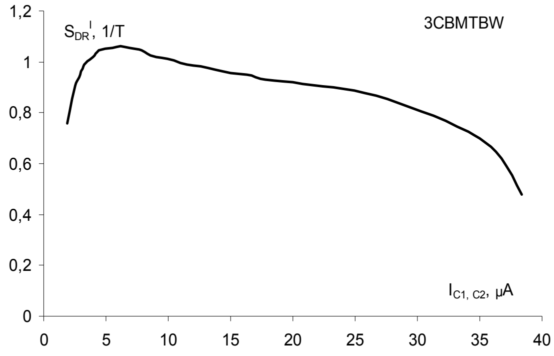

Figure 3. S_{DR}^{I} sensitivity of the 3CBMTBW versus a collector current

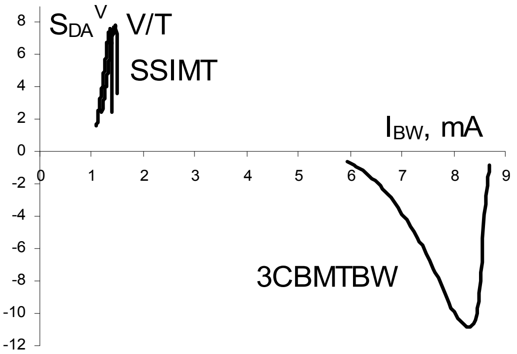

Figure 4. Sensitivity of the 3CBMTBW and SSIMT versus the base-well current, I_{BW}

Figure 4 presents the dependencies of the voltage sensitivity on the mode of bias for I_{BW} of the 3CBMTBW and SSIMT. A high surface recombination velocity of the SSIMT was obtained by surface base doping with a boron dose of 10 μC/cm^2 and the deposition of a 0.9-μm-thick silicon oxide layer in water vapor.

The 3CBMTBW has a low speed of surface recombination on a silicon-silicon dioxide junction, with carrier extraction by a base-well junction removed from a surface. This feature allows for the highly sensitive detection of the effect of a magnetic field deviation on one side of two carrier streams. The first stream proceeds from the emitter to the collectors directly through base, and the second stream proceeds through the base-well junction. The reproducibility and stability of the sensitivity are higher for the 3CBMTBW than for the SSIMT.

4. Noise

According to Roumenin (1994), the noise parameter determines the lowest value, B_{min}, of the magnetic field that can be detected by a BMT. The sensor noise will be defined (and measured) by its power spectral density, i.e., by the frequency spectrum of the mean square value of the fluctuating (noisy) quantity. The magnetic field B_{eq} equivalent to the noise in a frequency range Δf for a signal-to-noise ratio of one is defined as $B_{eq} = N/S$, where N is the noise (current or voltage) and S is the corresponding magnetosensitivity.

The noise was measured using a UNIPAN 237 nanovoltmeter. We employed the same measuring system as in (Tikhonov, 2005; Chaplygin et al., 1995). Samples of the circuits were placed in a box screened from electromagnetic interference and supplied from a 1.5- to 9-V battery. The BMTBW circuit is shown in Figure 1. The resistors had the following nominal resistances: R_{BW} = 1.8 kΩ and R_{C1}, R_{C2} = 270.3 kΩ.

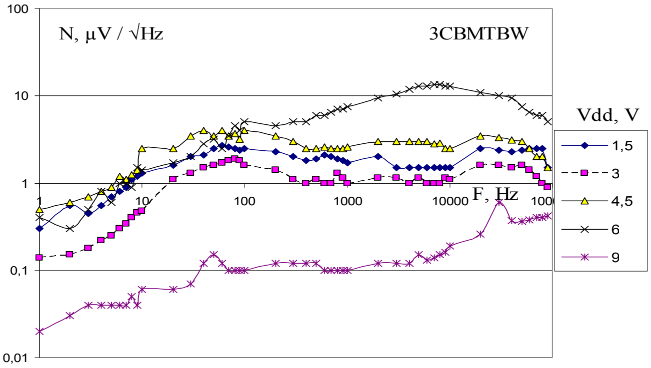

Figure 5. Spectral dependence of the voltage noise for the 3CBMTBW for different modes of operation

The measured spectrum of a noise voltage depending on the frequency of measurement is shown in Figure 5. The results of the measurement demonstrate that, in contrast to the results in Chaplygin et al. (1995), there is no low-frequency noise in the 3CBMTBW of the type 1/f. The voltage magnitudes of the noise at frequencies from 1 Hz to 100 kHz change at Vdd = 9 V from 20 nV to 300 nV, which is much lower than in Chaplygin et al. (1995).

The absence of 1/f noise will be compared to Popovic and Widmer (1986), in which a BMT generated in a well was investigated. As seen in Figure 5, the noise level for the 3CBMTBW generated in a well is reduced in comparison with the BMT (Tikhonov, 2005) generated in a substrate. In 3CBMTBW, at the connection of the contacts of the base and well, the noise decreases even more strongly. The creation of a limited area of the base with an impurity concentration that is 100 times greater than in the substrate is important for decreasing the 1/f noise. The small size of the shot noise is defined by the small magnitude of the collector current, which will be compared to (Nathan et al., 1989).

The noise voltage of the 3CBMTBW is 100 nV/Hz$^{1/2}$ at a frequency of 1 kHz at Vdd = 9 V, and the maximal sensitivity is 9 V/T. The 3CBMTBW is *Blim* = 11 nT/Hz$^{1/2}$, i.e., minimal among other types of BMTs. A nanotesla magnetotransistor (Nathan, Kung, & Manku, 1991) has an equivalent voltage noise value to a magnetic induction of 700 nT at a frequency of 1 kHz.

5. Discussion

The measured noise spectra (Figure 6) of the BMT, BMTW, and BMTBW (Tikhonov, 2005) differ from the noise spectrum of the CMOS sensor in Kozlov et al. (2012), with a small noise level at low frequencies of 1-100 Hz, which is acceptable for defining the manner in which 1/f noise relates to the influence of a silicon-silicon oxide interface.

The base of the lateral n-p-n BMT is the p-substrate. The BMTW base is the diffusion region of the p-well in the n-substrate. The BMTBW p-base diffusion layer is formed in the n-well on the p-substrate.

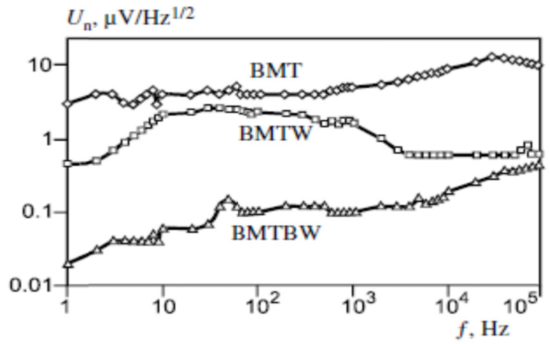

Figure 6. Spectral dependence of the noise-signal voltage

It is possible to explain a small level of noise resulting from features of the course of a current in the 3CBMTBW, as indicated by device-technological modeling and as shown in Figure 7. The high electron current is injected from the emitter and extracted by the base-well junction. The electron current deviates in a magnetic field on the same side as the current, proceeding directly through the base to the measuring collectors. It is produces a large total change of the measuring collector currents. The injected stream of emitter electrons proceeds to the collectors in the volume of the crystal. This phenomenon is similar to the junction field effect transistor, which produces very little noise (Milehin, n.d.).

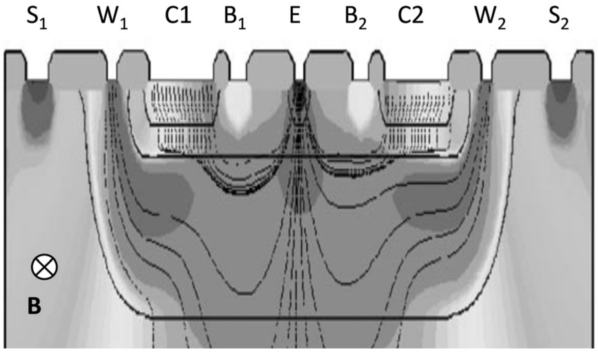

Figure 7. Distribution of electron streams and current lines in the 3CBMTBW at a voltage $U_{C1} = U_{C2} = 1.5$ V, $U_{BE} = U_{WE} = 0.8$ V at the magnetic induction B = 1 T

Hall gauges (Baltes & Popovic, 1986) and CMOS magnetotransistors (Chaplygin et al., 1995) have streams of charge carriers along a surface of the crystal and a high level of noise.

Figure 8 presents the model distribution of the electron streams between the electrodes of the 3CBMTBW, where E is the emitter; C1 and C2 are the collectors; B_1 and B_2 are contacts to the base; W_1 and W_2 are contacts to a well; and S_1 and S_2 are contacts to a substrate. The continuous lines represent the electron streams without a magnetic field. The dotted lines represent the electron streams in a magnetic field.

Effects of magnetic sensitivity:

1) A deviation of the electron streams, proceeding in the base;

2) A magnetoconcentration effect due to the surface recombination of the injected electron streams, proceeding in the base;

3) A deviation of the injected electron streams, proceeding through the base in a well and then to the collectors.

In the deviation effect (1), the injected stream of charge carriers proceeds in the base. The magnetic field, due to the effect of a deviation, shortens the current lines on one side of the emitter and extends the current lines on the other side. The resistance and volumetric recombination will change. The current of one collector grows, whereas the current of the other collector decreases.

The rapid surface recombination provides a high-sensitivity BMT due to the magnetoconcentration effect (2). In a magnetic field, if the lines of a current lie close together on a surface, the injected charge carriers recombine, and the current reduction is much greater than its growth due to the effect of the deviation on slow surface recombination, i.e., the sensitivity sign is negative.

In the course of the electron streams injected from the emitter through the base and extraction by the base-well junction (3), the overwhelming majority of the stream proceeds to the base-well junction. In a magnetic field, the deviation of the large electron streams to the measuring collectors occurs on the same side as the stream, proceeding directly through the base, which produces a large change in the measuring collectors current and provides slow surface recombination with high sensitivity and a low level of noise.

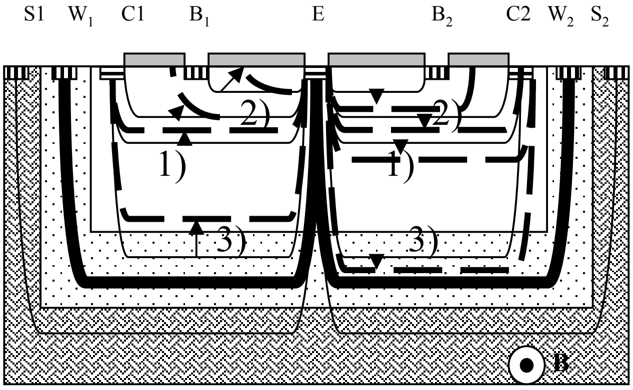

Figure 8. Electron streams between electrodes of the 3CBMTBW

6. Conclusion

In a two-collector lateral BMTBW, the charge-carrying current is injected from the emitter up to some displacement potential of the base and the well extraction by a base-well junction. In this case, the transistor has three collectors (3CBMTBW). The 3CBMTBW experimental samples are developed with a low speed of surface recombination in the base and with extraction of the charge carriers by a base-well junction that replaces surface recombination. In the 3CBMTBW, the reproducibility of the parameters increases, and high sensitivity and a low level of noise are observed. The characteristics of the device indicate a deviation under the action of the Lorentz force of a stream of charge carriers passing to the collectors through a base-well junction. The definition of the mechanism of sensitivity allows the characteristics of magnetotransistor gauges to be further improved.

Improvement of characteristics magnetotransistors can be spent as in InP/InGaAs heterojunction bipolar transistors with high mobility of carriers of a charge (Oxland, Long, & Rahman, 2009), and in the changed structures with base on the carrier recombination - deflection effect (Nagy & Trujillo, 1998; Leepattarapongpan et al., 2010). Magnetotransistors mage be used for control magnetic properties of nanostructures (Ghantous & Khater, 2013).

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