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Combined Semiconductor Injection Magnetic Field Sensors for Wireless Information Networks

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Abstract—The possibility of sensitivity increasing of magnetic field sensors by combining different types of sensitive elements in one sensor circuit is experimentally investigated. For this purpose, four new sensor constructions are proposed: based on bridge circuit, based on magnetotransistor in combination with magnetodiode or with second magnetotransistor and with frequency output. More thermostable and radiation-resistant sensor with 10 times greater sensitivity than in conventional two-diode bridge sensor is obtained with four polar magnetodiodes in bridge circuit, instead of two non-polar ones. Sensor constructions with two-collector magnetotransistors in combination with two polar magnetodiodes or one additional magnetotransistor are described. The sensitivity of such devices is 6 and 4 times higher compared to single-transistor sensors, while their temperature stability and radiation resistance increase. Relaxation generator circuit based on unijunction transistor is proposed as magnetic field sensor with frequency output. Inclusion of additional magnetodiode in generator circuit increases sensitivity by 2.3 times in comparison with single-transistor sensor and improves environmental stability. The described devices can be used as effective magnetic field sensors in wireless communication networks.

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1. INTRODUCTION

The world leader in standards development for radio electronics, electrical engineering and hardware for computing systems and networks, IEEE Institute of Electrical and Electronics Engineers, along with BigData, CloudComputing and Cybersecurity, set further development of Internet of things concept (IoT). It assumes the presence of ubiquitous sensor network and executive networks on intelligent objects.

This development is limited by wired and fiber-optic communications, because of their high price and implementation complexity. Therefore, researches on creation radio-controlled contactless executors and wireless autonomous sensors of physical values are relevant at present [1, 2].

Magnetosensitive devices are widely used in executive networks as hitless switches, eddy current motors and in sensor networks as electronic compasses [3, 4], systems of RAM and long-term memory [5, 6], sensors of various values (pressure, movement, shaft speed etc.), in electronic ignition systems of automobiles.

Currently ultrahigh magnetoelectric sensors allowing to register fields with induction 10^{-12} T [7] and resonator sensors with sensitivity of 92 μV/mT [8] are developed. However, rather a long magnetic circuit made of special composite material with strong piezoelectric coupling [7] is used in magnetoelectric sensor constructions, and production of multilayer microconsole of resonator sensor [8] requires jewelry accuracy.

Constructions of combined sensors with several physical phenomena for sensitivity increasing are known. For example, there are ferroprobe fluxgate principle of measurement in a sensor based on giant magnetoresistance [4], or magnetic concentrators in a highly sensitive sensor based on magnetic tunneling junction [9], or combination of an active magnetic circuit with a tunnel magnetoresistive magnetometer [10]. However, such techniques require several different technologies, which greatly complicates sensor construction, energy consumption, and dimensions.

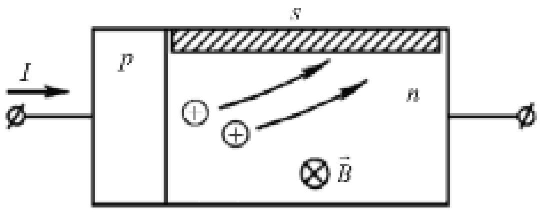

Fig. 1. MD structure.

Hall sensors still are the most common magnetic devices [11, 12]. However, they consume significant energy, and their sensitivity is small (with order of 100 V/(A·T)), which requires additional amplifiers. In addition, the indications of these devices depend on external factors, such as temperature and ionizing radiation. At the same time, a wireless sensor should have low energy consumption, high sensitivity and be environmentally stable.

The main advantage of wireless sensor networks is ability to monitor in the most inaccessible places and in extreme conditions. Therefore, much attention is paid to temperature stability and radiation resistance of designing detectors for such networks [7, 12].

Semiconductor magnetosensitive devices are widely used in modern radio controlled automation systems and sensor networks, since they are highly energy efficient, can significantly change certain electrical properties with magnetic field changes, and are easily integrated into wireless system electronic circuits.

Semiconductor resistors are widely used as various sensors (magnetoresistors, thermistors, photoresistors, etc.). Usually they are included in a bridge circuit with four elements, two of which are sensitive to the measured influence (semiconductor resistors), and two other are passive load resistors [13]. The disadvantage of these sensors is their sensitivity to other influences in addition to measured magnetic field. For example, indications of magnetoresistors are influenced by temperature and radiation. This reduces measurement accuracy of the required parameter. In semiconductor injection devices (diodes, transistors) such disadvantages can be compensated.

Improving efficiency and environmental stability of semiconductor injection magnetic field sensors by combining several magnetically sensitive elements with different sensitivity to various environments in one electrical circuit is the aim of this work. This method is applied to three magnetic field sensor constructions: bridge magnetodiode sensor, sensors based on magnetotransistor, and sensor with frequency output based on unijunction transistor.

2. BRIDGED MAGNETODIODE SENSORS

Magnetodiodes (MD) are one of the first types of magnetically sensitive semiconductor devices that have wide practical application [14, 15]. Typical MD is the p^+–n junction with long n-base. Commercially available KD301 type devices are not polar, and for planar KD303 and KD304 types MDs magnetic field direction changes reduce only sensor sensitivity in low magnetic fields.

MDs, structurally closed to industrial KD301 type devices, which has s-region on one side surface of base with high recombination rate of injected charge carriers, are proposed to obtain polar magnetic field sensor (Fig. 1). With MD switching-on in the forward direction, holes injected from the p^+–n junction are divided into two flows: one to s-region, where holes recombine with electrons, and second to the ohmic contact of n-base. MD resistance is completely determined by the concentration of holes filling the base with length equal to the hole diffusion length.

In operation as magnetic field sensor, the current I is passed through MD and the voltage drop across it is measured

$$U = I(R_0 \pm \Delta R), \tag{1}$$

where R_0 is the MD resistance with magnetic induction $B = 0$, ΔR is the resistance change in the external magnetic field perpendicular to current direction.

Lorentz force acts on the injected holes when magnetic field is directed from the observer $\otimes B$ (Fig. 1). It deflects them towards s-region, where they recombine on the surface states. Accordingly, holes concentration in base decreases and its resistance increases, which corresponds to the plus sign in (1). When

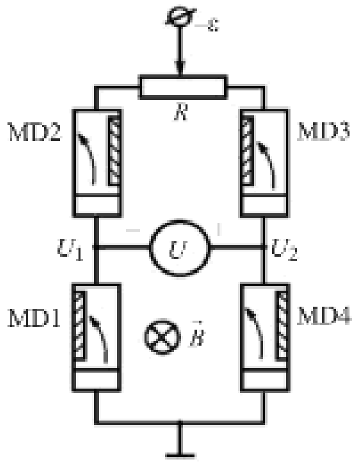

Fig. 2. Sensor bridge circuit of four polar MDs.

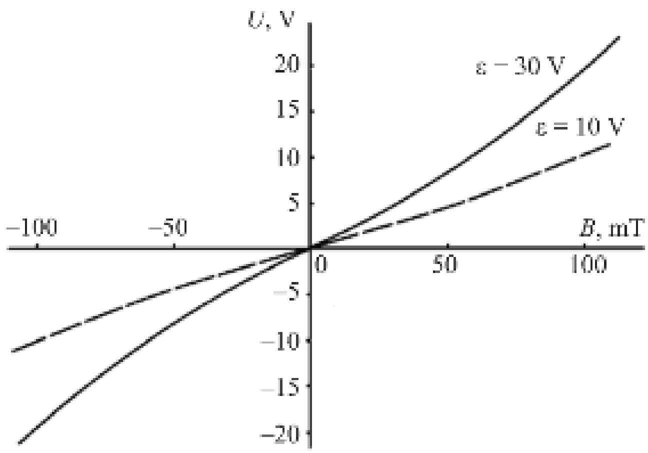

Fig. 3. Output characteristic of sensor based on bridge circuit of four polar MDs at different supply voltage.

the magnetic field polarity changes toward the observer $\odot B$, the holes flow deviates from *s*-region to ohmic contact of *n*-base, and recombination rate and base resistance decrease. In this case, in the formula (1) "plus" sign changes to "minus." Magnetosensitivity is characterized by the value $\gamma = \Delta U/\Delta B$.

As noted above, only two sensing elements are used in four-element bridge measuring circuits [13, 16]. The advantage of MDs over magnetoresistors is that measuring bridge with four sensors can be built. For this purpose, the most promising polar MD are used, which resistance grows for one polarity magnetic field, and for the opposite polarity falls down. The magnetically sensitive sensor circuit is presented in Fig. 2. This method of sensor characteristics improving by several sensor elements combining with the opposite sign of sensitivity has already been used in [17] for radiation detector.

In the absence of magnetic field, the resistances of all MDs are the same, and the voltage in diagonal of the bridge is $U = 0$. In this case, the variable resistor serves for precise zero setting.

The flux of injected holes into MD1 and MD3 bases deviates towards *s*-region, and their resistance increases when magnetic field of the indicated polarity is switched on (Fig. 2). For other pair MD2 and MD4, flux of holes deviates from *s*-region, and their resistance decreases. The current in each vertical pair of MD is practically independent of the magnetic field

$$I = \varepsilon / (2R_0). \tag{2}$$

Increase in the resistance of one MD is almost completely compensated by reduction in the resistance of second MD. Here ε means the apply voltage.

As follows from (1) $U_1 = I(R_0 + \Delta R)$, $U_2 = I(R_0 - \Delta R)$, so the voltmeter indications are

$$U = U_1 - U_2 = 2I\Delta R = \varepsilon\Delta R / R_0. \tag{3}$$

As we can see from (3), the voltage U grows with increase in MD resistance change in magnetic field ΔR. Voltage U polarity is reversed with the opposite direction of magnetic field $\odot B$.

Sensor consisted of two MD pairs with the opposite sign of magnetosensitivity has two significant advantages. Firstly, it is high stability of zero at $B = 0$, since under any external influences, the resistance R_0 of all four MDs changes in the same way. Secondly, output voltage is less affected by various types of ionizing radiation.

Their resistivity ρ changes most strongly with irradiation of semiconductors, which in this case leads to one-sided change in R_0 and ΔR of all four MDs. Therefore, their ratio, and hence output signal of the bridge sensor, is much less sensitive to irradiation than signal of the sensor based on one or pair of MDs. It is obvious, as for any bridge measurement circuits, procedure for sensitive elements selection with the same temperature coefficient is required.

In experimental studies of sensor sensitivity based on four polar MDs bridge circuit at different temperatures and after radiation exposure, the laboratory samples of polar MDs were used. They are

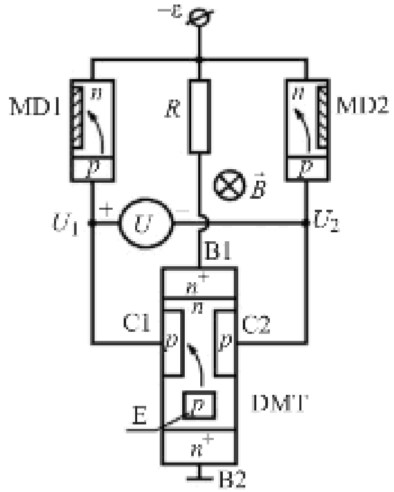

Fig. 4. Sensor circuit based on DMT with two MDs.

structurally similar to industrial KD301 type MDs [15], but with addition of increased recombination rate region. Selection of bridge elements with the same temperature coefficients was carried out.

The output characteristic of the sensor based on four polar MDs bridge circuit for various values of supply voltage is shown in Fig. 3.

The magnetic sensitivity of these bridge sensors in magnetic fields up to 0.1 T at supply voltages $\varepsilon = 10$ and 30 V are equal to 97 and 208 V/T, respectively. It is an order of magnitude higher than in sensors based on one KD301 type MD. We achieve this through four sensitive MDs and the region with high recombination rate.

Experiments have shown that impact of external influences on the sensor with four sensitive MDs is much weaker than on one MD. The magnetic sensitivity changes by no more than 1.5% in the temperature range 0–60 °C according to the experimental data. Also we experimentally established that after the irradiation of sensor samples with Co^{60} gamma quanta, the output signal does not change up to 10^7 R exposure level, in contrast to sensor with two MDs, where the output signal changes by more than 10% at the same radiation.

Thus, in the bridge measurement circuit with two pairs of polar magnetodiodes, not only increase in sensor sensitivity is achieved, but also rise in its thermal stability and radiation resistance.

3. SENSOR BASED ON DOUBLE-COLLECTOR MAGNETOTRANSISTOR

A double-collector magnetotransistor (DMT) has the widest measurement range and the highest magnetic sensitivity of all semiconductor devices [18], [19]. Its structure and connection circuit are shown in Fig. 4. Typically, resistors are used as loads in collector circuits.

Injected from emitter charge carriers are distributed equally between two collectors. Their currents are equal, and the potential difference between them is $U = 0$. With the indicated in Fig. 4 direction of magnetic field, carrier flux is deflected towards collector C1, its current increases, and potential decreases. Accordingly, collector current C2 decreases and potential increases. As a result, with the magnetic field induction B growth, the voltage U between collectors goes up.

Characteristic $U = f(B)$ is linear up to the values of magnetic induction $B \sim 0.4$ T with the sensitivity of about 60 V/T at $\varepsilon = 100$ V. In strong magnetic fields the carriers' redistribution between collectors ends, and sensor sensitivity drops.

Polar MDs oriented relative to DMT as shown in Fig. 4 are proposed as load in DMT collector circuits to expand the measurement range and increase the magnetosensitivity. In this case, MD1 resistance grows and MD2 resistance declines when magnetic polar direction is turned on. It leads to additional decrease in U_1, increase in U_2 and larger growth of the output signal U.

Two MDs introduction into DMT circuit enhances noise immunity, simultaneously with increase in sensitivity. This sensor, similar to sensor based on four MDs, can be considered as the bridge consisting of two MD and two DMT collectors resistances. The effect of temperature or radiation is appeared in decrease

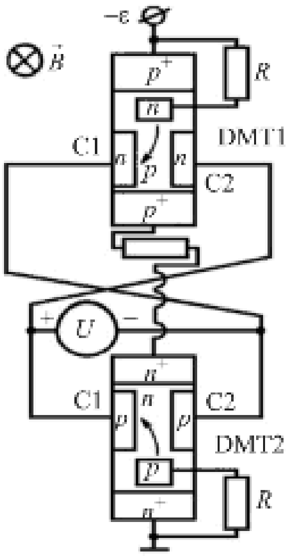

Fig. 5. Bridge circuit of two DMTs with opposite conductivity.

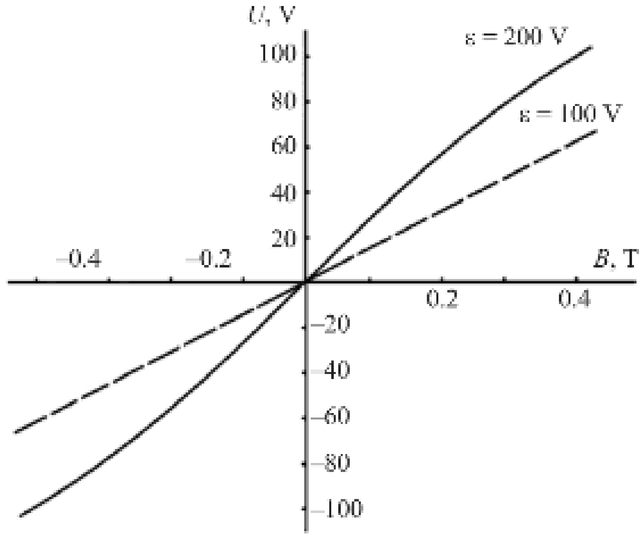

Fig. 6. Output characteristic of sensor based on two DMTs at different of supply voltage.

in diffusion movement length of injected carriers in all elements of the bridge. These changes compensate each other and noise immunity of sensor increases.

In experiments we used the planar DMT based on *n*-silicon with the resistivity ρ = 200 Ω·cm, the distance between collectors is 150 μm, and the emitter width is 30 μm. The above-described polar MDs similar to industrial KD301 type MDs, but with addition of increased recombination rate region, were used as additional sensitive elements.

The magnetic sensitivity of such sensor based on DMT and two additional MDs increases to 350 V/T at supply voltage ε = 120 V. The experiments shown that in the temperature range 0–60 °C the magnetic sensitivity varies by no more than 1.8%. Also we experimentally established that after the irradiation of sensor samples with Co^{60} gamma quanta, the output signal does not change up to 10^7 R exposure level.

In *p–n–p* DMT sensors instead of two MDs we can use second *n–p–n* DMT with emitter connected to the negative contact of power supply and collectors cross-connected with collectors of first DMT (Fig. 5). This circuit is the measurement bridge formed by four collectors of two DMTs. With the indicated direction ⊗*B* the currents of C1 and C2 collectors go up and fall down, respectively. It leads to the bridge imbalance and increase in the voltage *U*.

The experimental studies used the same DMT as in the circuit shown in Fig. 4. DMT pairs with the same temperature coefficients were selected for measurements. The output characteristic of the sensor based on two DMTs is presented in Fig. 6 for different supply voltage.

The magnetic sensitivity of this combined sensor based on two DMTs in the magnetic fields up to 0.4 T is equal to 164 and 232 V/T at ε = 100 and 200 V, respectively.

The experiments shown that in the temperature range 0–60 °C the magnetic sensitivity varies by no more than 1.2%. Also we experimentally established that after the irradiation of sensor samples with Co^{60} gamma quanta, the output signal does not change up to 10^7 R exposure level.

Thus, we achieve the gain in the detector sensitivity and also expanded measurement range, thermal stability and radiation resistance growth for DMT in combination with two polar MDs or with another DMT.

4. SENSOR BASED ON UNIJUNCTION TRANSISTOR GENERATOR WITH MD

Sensors with frequency output are of particular interest for digital wireless sensor networks [20]. These devices have number of advantages over current output converters. They can be connected directly to digital systems without ADC. They have relatively low cost, high sensitivity, ability to work in conditions of increased EMI level, as a result of noise immunity of frequency modulated signal.

For sensors based on unijunction transistor (UJT) generator, the output parameter is the frequency of generated signal as a function of measured influence [21]. UJT is a semiconductor plate with ohmic contacts

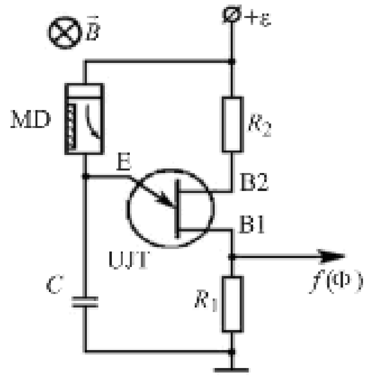

Fig. 7. Sensor circuit based on UJT with MD.

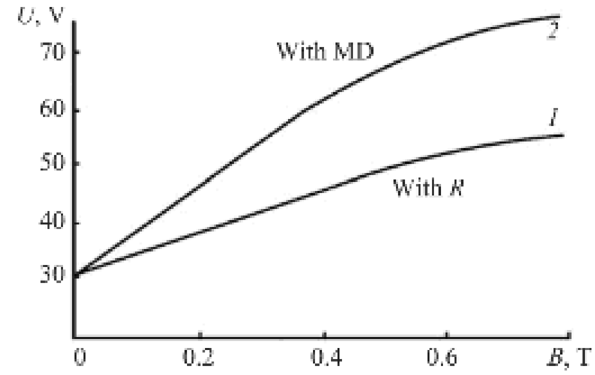

Fig. 8. Output frequency of sensor based on UJT and MD vs magnetic induction of external field.

at the ends (B1 and B2) and the emitter *p–n* junction (E) between them. The E–B1 input circuit voltage-current characteristic has the section of negative differential S-type resistance, and is characterized by the triggering voltage U_{trig} and the valley voltage U_{val}.

The relaxation generator circuit as magnetic field sensor is given in Fig. 7. The magnetic field sensor with frequency output can be assembled on single UJT transistor if a simple resistor for capacitor C charging is used as load in the emitter circuit.

In this case, the capacitor C is charged to the voltage U_{trig}, emitter junction opens, and capacitor is discharged to the voltage U_{val}, then process repeats. The oscillation frequency of the generator f is defined as follows:

$$f \approx \frac{I}{C(U_{trig} - U_{val})}, \tag{4}$$

where I is the charging current in current generator mode, U_{trig} is the triggering voltage, U_{val} is the valley voltage of UJT.

The E–B1 circuit does not differ from any long base *p–n* junction and, similarly to MD, the injected into UJT base charge carriers with switched on magnetic field are deflected to the surface by Lorentz force and recombine on the surface states. As a result, UJT base resistance rises, which means that the valley voltage U_{val} of UJT grows, it leads to increase in the oscillation frequency f of generator in accordance with (4).

The operation of single-transistor sensor is carried out on KT117 type UJT. The dependence of the output frequency vs the magnetic induction for sensor with equivalent resistance R instead of MD (Fig. 7) at C = 0.01 μF and ε = 20 V is presented in Fig. 8 (curve *1*). The magnetic sensitivity of such sensor is 34 Hz/T.

The injected into MD base charge carriers are deflected by Lorentz force from the surface to the ohmic contact of MD base when resistor R is replaced by MD (Fig. 7) with indicated magnetic field direction. As a result, the MD base resistance decreases, and the capacitor charging current I through MD increases, which, in accordance with (4), leads to additional growth in the oscillation frequency f. Thus, the magnetic sensitivity of this sensor grows.

In experimental measurements we used discussed above polar MDs. Dependence of the frequency vs the magnetic induction for sensor with MD (Fig. 7) at C = 0.01 μF, ε = 20 V is shown in Fig. 8 (curve *2*). Adding further MD to generator circuit increases its sensitivity to 78 Hz/T.

The experiments shown that in the temperature range 0–60 °C the magnetic sensitivity varies by no more than 1.9%. Also we experimentally established that after the irradiation of sensor samples with Co^{60} gamma quanta, the output signal does not change up to 10^7 R exposure level. This confirms assumptions based on the model (4) that under external influences, such as temperature or radiation, changes in UJT triggering voltage U_{trig}, valley voltage U_{val}, and current I through MD (4) mutually compensate each other, which improves frequency stability.

Thus, the replacement of resistance in UJT emitter circuit with magnetodiode provides not only magnetic sensitivity growth, but also leads to increase in the sensor noise immunity, that is often more important for practical applications of sensor.

5. CONCLUSIONS

The effectiveness of several sensitive elements combination method for the sensor magnetic sensitivity improving is experimentally confirmed by the example of four circuits of magnetic field sensors. Combination of polar magnetosensitive semiconductor injection elements with the same temperature and radiation sensitivities makes it possible to design thermostable and radiation-resistant magnetosensors without loss of energy efficiency. Slight power consumption magnification is achieved by significant increase in sensitivity of devices.

The measurement bridge circuit with four sensitive MDs instead of conventional bridge circuit with two sensitive MDs creates thermostable, radiation-resistant sensor with sensitivity 10 times higher than in two-diode sensor.

Such increase in temperature stability and resistance to irradiation of sensors is confirmed experimentally using DMT in combination with two MDs or one additional DMT, while the sensitivity of devices rises 6 and 4 times, respectively.

Dependence of the output frequency vs the magnetic induction of external field for UJT sensor in combination with MD in the relaxation generator circuit is experimentally investigated. MD use improves the magnetic sensitivity of sensor with frequency output by 2.3 times compared to conventional UJT sensor.

Described devices can be used as magnetic field sensors in wireless communication networks, since only standard element base is used in their design. They are easily integrated into digital networks, very energy efficient, and have increased thermal stability and radiation resistance.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ADDITIONAL INFORMATION

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