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Vikulin I. M.[1], Vikulina L. F.[2], Gorbachev V. E.[1], Litvinenko V. M.[3], Markolrnko P. Y.[1]

[1] State University of Intellectual Technologies and Communications
Ukraine, 65029. Odessa, Kuznechna st., 1, e-mail: physonat@gmail.com
[2] Odessa State Agrarian University
Ukraine, 65012. Odessa, Panteleimonovska st., 13, e-mail: lepole1@gmail.com
[3] Kherson National Technical University
Ukraine, 73008. Kherson, Berislavske road, 24, e-mail: hersonlvn@gmail.com

DETECTORS BASED ON FIELD EFFECT TRANSISTORS

The possibility of using the method of combining several sensor elements with opposite sensitivity to various external influences to obtain new designs of sensors for light, temperature and magnetic field has been experimentally investigated. Standard industrial samples of FEJT and a MOSFET in saturation mode with two-pole connection, when the gate is closed with the source, were used as sensor elements in the work. It is shown that the FEJT has a negative temperature coefficient of current change, while the MOSFET has a positive one. At the same time, the sign of the radiative action factor of the MOSFET is determined by the initial value of the drain current before irradiation. It has been experimentally confirmed that the use of four transistors in a bridge measurement circuit increases the sensitivity of the sensor tenfold compared to one transistor due to the internal mechanism of increasing the sensitivity for series-connected pairs of transistors.

1. Introduction

The employment of the IoT concept in industry, transport and everyday life has led to a rapid growth in research on new designs of various sensors that fill intelligent control and control systems with numerical information.

Light sensors occupy a special place among sensors of physical quantities, since in our life photodetectors are used everywhere from devices for automatic switching of street lighting to cameras and optical signal detectors in fiber-optic communication lines. More and more sophisticated technologies are being used to improve the performance of photodetectors.

Thus, in paper [1], a modern design of a high-speed contact photodiode with a Ge-on-Si structure with surface illumination and increased efficiency is presented. High external quantum efficiency is achieved due to the peculiarities of capturing photons by a surface with micro-holes.

In [2], a new architecture of a photodiode detector with resonant cells is proposed, in which the mirrors are replaced by lattice-patterned metasurfaces. It has been shown that structured mid-IR photodetectors less than 10 μm thick with a 75 nm HgCdTe photoabsorber can provide maximum efficiency.

Photodiodes based on mixed one-dimensional (1D) and three-dimensional (3D) *p-n*-heterostructures with synergistic properties of various dimensions have shown unique optical properties due to their large transition areas and high absorption cross-section, which provides excellent optoelectronic characteristics [3]. However, due to the complexity of designing and constructing a proper 1D-3D *p-n*-junction, their electronic properties are still unclear. As a photo detector, it covers the range from ultraviolet to visible light.

The work [4] presents the development of germanium vertical *p-i-n*-photodiodes with a matrix of holes in the shape of a pumpkin. Photodiodes were fabricated on a germanium substrate with a sensitivity of 0.74 A/W. It is estimated that the design of the pumpkin-shaped hole provides higher optical absorption compared to the cylinder-shaped hole.

In paper [5] microstructures for capturing photons were introduced into photodetectors based on GeSn and achieved highly efficient photodetection at 2 μm with a sensitivity of 0.11 A/W. The demonstration samples were implemented on the basis of a GeSn/Ge *p-i-n*-photodiode with quantum wells on the GeOI architecture.

In paper [6], designs of organic phototransistors are considered and it is argued that the practical application of inorganic photodetectors is significantly limited due to many disadvantages, including complex manufacturing processes and poor mechanical flexibility. In this scenario, organic phototransistors emerge as potential competitors with impressive performance characteristics such as high flexibility and ease of manufacture and low cost, making them suitable for next generation wearable electronic devices.

Investigations of new designs of temperature sensors are of great interest, since all industries and research without exception require temperature control of technological processes. Temperature sensors are needed to control the parameters of all electronic systems, environmental parameters, in medicine, in everyday life. They are used in most hard-to-reach places, even where other parameters cannot be measured. Often, according to their readings, other physical parameters are also evaluated (pressure, density, ignition intensity, rate of nuclear decay or chemical reaction, etc.). Therefore, in recent years, new designs of temperature sensors based on FET have been developed for narrow applications: in the aviation industry [7], for measurements in biomedicine [8], for implantation devices [9], for fire extinguishing systems [10], for monitoring the energy efficiency of buildings [11].

At the same time, magnetic field sensors are among the most common sensors. In every car, the sensor device for position and crankshaft speed sensors are magnetic field sensors; in every modern mobile phone there is an electronic compass based on a $Ni_{80}Fe_{20}$ thin-film sensor [12] a motion tracking device based on a fluxgate sensor [13], in any a computer and a processor device have magnetic storage devices based on magnetic tunnel junctions [14], systems based on Hall sensors are used for the finest research in biomedicine and neurosurgery [15], and based on magnetoelectric sensors in magnetic resonance imaging [16]. Therefore, the study of new designs of highly sensitive and low-energy magnetic field sensors is urgent.

With the development of the IoT concept, a new class of intelligent temperature sensors that built directly into the object, began to appear. Such smart sensors are found in abundance in any IoT network from computers and cars to smart homes and smart cities. It often turns out that their power consumption limits the further development of the sensor network. Therefore, new designs of ultra-low power sensors are being developed [7, 9], special energy-saving technologies are used [17, 18].

However, the use of special designs and innovative technologies requires significant costs for research and manufacture of devices, and also significantly increases the cost of finished products. In this work, we studied the possibility of using the existing element base to create cost-effective temperature and light sensors that would meet modern requirements.

In addition, sensors are often used in extreme conditions of increased level of ionized radiation, near nuclear reactors [19], in elementary particle accelerators [20], in the upper layers of atmosphere [7] and in outer space [21]. It is well known that ionizing radiation fundamentally changes the electrical properties of any sensitive structures [22, 23], and for sensors that are exposed to radiation, special methods are needed to compensate for such effects [21]. However, neither new designs of sensors, nor the latest materials and components of sensors are practically studied from the point of view of the influence of ionizing radiation.

FETs are more sensitive to external influences and consume less power than bipolar transistors. In addition, advanced CMOS technologies have allowed the development and implementation of fully integrated with digital systems, low-power intelligent sensors based on sensitive MOS elements. Therefore, in recent years, it is FETs that are increasingly used as sensing elements of various sensors.

To obtain the required properties, various designs of field-effect transistors (FETs) are used: an organic field-effect transistor (OFET) [24], a floating gate field-effect transistor (FGFET) [8], an FET based on a polymer ferroelectric [25], as well as state-of-the-art manufacturing technologies FET such as inkjet volumetric printing and chemical vapor deposition [17].

However, the use of FET-based sensors requires a special approach, since the electrical parameters of the FET are highly dependent on unwanted external influences such as ionizing radiation.

The aim of this work is to study the possibility of using standard industrial FETs as sensing elements in cost-effective temperature, magnetic field and light sensors at objects with an increased background radiation.

To fulfill the set goals, we used the method of combining several sensory elements with opposite sensitivity to various external influences.

Until now, the most preferred sensor circuit is a measuring bridge of four resistors, one of which is sensitive to the measured effect, for example, a thermoresistor [26]. The advantage of this scheme is the simplicity of establishing the zero value of the output signal at $T = 0$ °C, its further calibration and correction.

The sensitivity of the sensor is doubled if, instead of a constant resistance, a second sensor of the same type is connected to the diagonally opposite shoulder of the bridge.

However, it is also possible to further increase the sensitivity of the sensor if there will be elements sensitive to external influences in all four branches of the bridge. A feature of this combination of sensitive elements is that two pairs of sensors must have opposite resistance coefficients. Sensor elements with the same resistance coefficients should be located in diagonally opposite branches of the bridge.

In this work, it is shown that if, instead of bridge resistors, FET pairs with opposite sensitivity to the measured effect are used, then it is possible to obtain sensors with a sensitivity that is an order of magnitude higher than that of a single sensor.

2. Temperature detector

FETs can be used as temperature sensors; however, the spread of the temperature-sensitive parameter values causes certain difficulties in calibrating such sensors. The most convenient sensitive parameter for recording external influences is the saturation current of the FET at two-pole switching, when the gate of the transistor is closed with the source.

In our work [27], it was experimentally established that the temperature coefficient of the current change is negative for FEJT, and positive for MOSFETs. This difference in the properties of the two types of FETs can be used for temperature stabilization of reference current generators, as in [27], and also in our case to increase the sensitivity of the combined bridge temperature sensor.

In this way, the advantage of the bridge measurement can be maximized by connecting temperature-sensitive FETs to all four of its branches (Fig. 1).

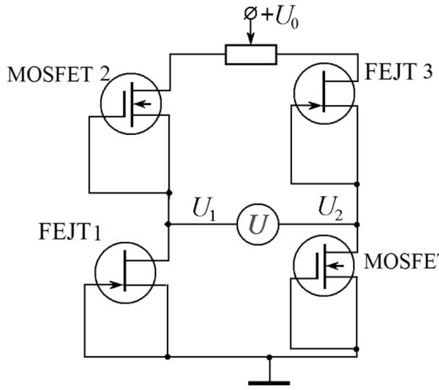

Figure 1. Schematic diagram of the bridge temperature detector

In the first pair of elements FEJT1 and FEJT3, connected in opposite branches of the bridge, the current decreases with increasing temperature, and in the other pair of MOSFET2 and MOSFET4 in other branches, it increases. The voltage of the output signal in the measuring diagonal of the bridge for such a circuit for switching on the primary converters has the form:

$$\mathrm{U}=2\frac{U_0 \cdot \Delta \mathrm{R}}{R} \tag{1}$$

where U_0 – bridge supply voltage; R – is the resistance of the transistor channel in the “source-drain” circuit; ΔR – is the change in this resistance with a change in temperature. The trimmer resistor is used to accurately set the zero value of the output signal.

As the first pair, we used FEJT type KP202 (analogs: C681 or 2N3958) with a *p-n*-junction as a gate. The experimental value of the temperature coefficient of the current of such transistors is $\beta = -3281$ ppm/°C, and the saturation current decreases with increasing temperature due to a decrease in the mobility of charge carriers in the channel [27]. A KP305 type MOSFET (analogs: MFE3002 or 2N4224) was connected as the second pair. The experimental value of the temperature coefficient of the current of such transistors is β = +14285 ppm/ºC, and the saturation current increases with increasing temperature. This happens due to an increase in the gate cutoff voltage when the charge changes on the surface states under the gate [27].

It was experimentally established that the sensitivity of a sensor with four FETs α = 1 V/ºC at a power supply voltage U_0 = 20 V in the temperature range from 0 ºC to +30 ºC, which is 10 times higher than the sensitivity of bridge sensors based on one FET. However, the linear range of the output characteristic is limited to 30 ºC.

The linear range of the output characteristics of such a temperature sensor can be expanded by connecting a stabilizing resistor into the source circuit of each FET [28].

At Fig. 2 shows the experimental dependence of the output voltage of a bridge temperature sensor with four FETs and four stabilizing resistors. Sensor sensitivity α = 0.28 V/ºC at power supply voltage U_0 = 20 V in the temperature range from –20 ºC to +190 ºC. Outside this range, the sensitivity decreases and the nonlinearity of the sensor output characteristic increases.

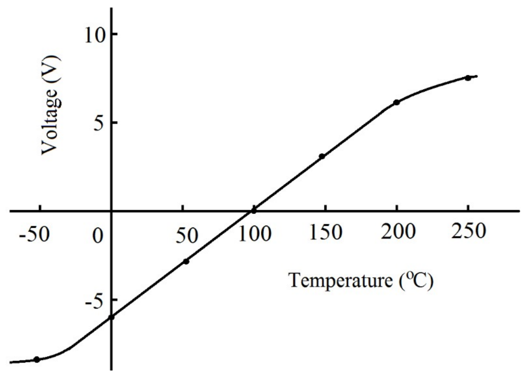

Figure 2. Temperature detector output characteristic with four FETs and four stabilizing resistors

Balancing resistors can be used instead of a trimmer to balance the bridge at any given temperature.

In our previous work [29], experimental studies of the effects of radiation on the FET were carried out. To study the effect of radiation on transistors, a batch of FEJT samples of the KP202 type and MOSFET of the KP305 type were irradiated with gamma quanta with an exposure dose of 10^4, 10^5, 10^6, 10^7 and 10^8 R. The work on irradiation was carried out within the framework of the state budget research work "Radiation effects in semiconductor sensors", which was carried out by order of the Ministry of Education and Science of Ukraine, state registration number 0115U000855. It was found that the electrical properties of different types of FETs react differently on the received dose of ionizing radiation.

Experiments have shown that the saturation current of the drain for all FEJT samples after irradiation decreases, while according to the radiation sensitivity, MOSFETs are divided into two groups depending on the initial value of the saturation current before irradiation. For all samples of the group with low saturation currents before irradiation (low concentration of electrons in the channel), the saturation current continues to increase, and for all samples from the group with high saturation currents before irradiation (high electron concentration in the channel), the saturation current decreases. Thus, it was found that all MOSFETs selected for the second group due to high saturation currents have a radiation sensitivity the same as that of a JFET. However, their temperature sensitivity remains the opposite. For the manufacture of samples of radiation-stable temperature sensors, just such MOSFET were used.

It was experimentally established that the imbalance of the bridge with four FETs at doses of 10^4 R and 10^5 R is disturbed by only 4% and 6%, respectively. Subsequent irradiation stabilized the operation of the bridge and after a dose of $5 \cdot 10^5$ R the imbalance was only 3%, but after a dose of 10^6 R it was 40 %, and after a dose of 10^7 R it was already 80 %. The sensitivity of the detector samples remained within 250-60 mV/ºC up to 10^6 R.

Thus, by combination in the opposite branches of the bridge specially selected FEJT and MOSFET pairs with opposite signs of temperature sensitivity, but with the same sign of sensitivity to ionizing radiation, it is possible to obtain a temperature sensor with high sensitivity and with a minimum number of constituent elements. It was experimentally confirmed that the temperature sensor obtained in this way consumes 49 mW of energy, with a linear output characteristic and sensitivity $\alpha = 0.28$ V/ºC in the temperature range from –20 ºC to +190 ºC, with readings deviations of no more than 6% before doses irradiation $5 \cdot 10^5$ R.

3. Magnetic field detector

When the FET operates as a primary converter of any external influence, in order to reduce the dependence of the output signal on the supply voltage, it is convenient to connect it as a two-pole, when the gate is closed with the source, and the gate voltage is absent $U_G = 0$. In this case, the saturation current of the FET is defined as

$$I_s = An^2 \mu, \qquad (2)$$

where n, μ – concentration and mobility of charge carriers in the channel; A – constant, which is determined by the geometric and electrical parameters of the channel, which depend on the supply voltage.

If the FET through which the electric current flows is situated in a magnetic field transverse to the direction of the current, then the charge carriers begin to move along spiral trajectories, a magnetoresistive effect arises, consisting in a decrease in the effective free path of the majority charge carriers in the direction of the electric field. A decrease in the mean free path of charge carriers along the direction of the electric field is equivalent to a decrease in their mobility, and hence, according to (2), the saturation current FET. The relative change in the mobility of charge carriers in weak magnetic fields, with sufficient dimensions of the sample transverse to the electric field, is described by the formula [30]:

$$\frac{\Delta\mu}{\mu} = -c\mu^2 B^2 \qquad \textbf{(3)}$$

where c – coefficient depending on the scattering mechanism and the geometric dimensions of the sample. When the semiconductor is limited in the direction transverse to the electric field, then the Lorentz force can be compensated by the force of the Hall electric field, and the flow of charge carriers will cease to be deflected by the magnetic field. What was said above fully applies to the FET channel, placed in a transverse magnetic field [30], while, for the magnetoresistive effect to appear, the transverse dimensions of the channel must be greater than its length. This condition is satisfied, for example, by an FEJT of the KP303 type (analogue of 2N5556) with an n-type channel and a p-n junction as a gate, therefore it can be used as a magnetically sensitive field-effect transistor (MFET).

After substituting expression (3) into equation (2), we obtain the dependence of the saturation current MFET Is on the transverse component of the magnetic field induction B:

$$I_s = An^2 (1 - c\mu^3 B^2). \qquad (4)$$

It can be seen from relation (4) that the saturation current of the MFET in a magnetic field will decrease. However, as experiments have shown, the change in the saturation current of FEJT type KP303 in a magnetic field up to 0.5 T is only about 3%. This is due to the fact that in the serial KP303 transistor the transverse dimensions of the channel are not large enough for the complete absence of the Hall effect in weak magnetic fields. Only in magnetic fields greater than 0.5 T the radius of the spiral trajectory of the charge carriers in the channel decreases so much that the Hall effect is absent for the standard transverse dimensions of the KP303 channel. Therefore, the use of an individual KP303 as an independent magnetic field sensor for detecting weak fields is ineffective. It is possible to use separate FETs as an independent weak magnetic field sensor if special MFET designs are made in which the transverse dimensions of the channel are much larger than its length.

However, standard industrial transistors of the KP303 type can be used to detect weak magnetic fields as sensor elements in a combined bridge sensor based on four FEJTs, because in this case, an internal mechanism of increasing the sensitivity arises in both legs of the bridge in each pair of series-connected FEJTs [30]. Fig. 3 shows a schematic diagram of a bridge magnetic field sensor with four FEJTs. Two transistors of the first pair MFEJT1 and MFEJT3 are located in opposite arms of the bridge and must be oriented so that the current in the channel flows across the magnetic field, then they play the role of sensitive elements. And two transistors of the second pair FEJT2 and FEJT3 are located in the other arms of the bridge and must be oriented so that the current in the channel flows along the magnetic field, then there is no magnetoresistive effect in them, therefore they play the role of load elements for the first pair.

With this inclusion of FEJT, an internal mechanism for increasing the sensitivity operates in each arm of the bridge for a pair of transistors [30]: a decrease in the mobility of charge carriers in a magnetic field in any of the MFEJT transistors leads to an increase in the voltage drop across it and a decrease in the voltage drop across the paired FEJT, which causes an additional an increase in the resistance of the MFEJT channel and an additional decrease in the resistance of the FEJT channel, and, hence, an additional increase in the voltage U.

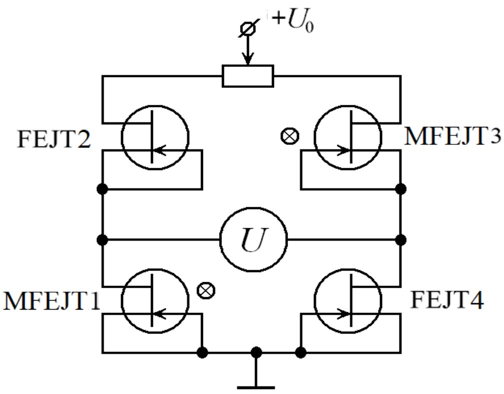

Figure 3. Magnetic field detector bridge with four FE-JTs

Resistor trimmer serves for precise zero setting (bridge balancing) in the absence of a magnetic field. As with all magnetic field sensors, a prerequisite for using such a scheme is strict adherence to the orientation of all elements.

For experimental studies of the characteristics of a bridge magnetic field sensor on four FEJTs, standard industrial FEJTs of the KP303B type were used. The experimental dependences of the bridge misbalance voltage U on the magnetic induction B of the external field are shown in Fig. 4 for supply voltage U_0 = 25 V.

Fig. 4 it is clearly seen that the output characteristic of the sensor is linear. The magnetic sensitivity of such a bridge sensor is β = 10160 V/A/T, which is two orders of magnitude higher than that of silicon Hall sensors. Experiments have shown that, unlike magnetoresistors, the magnetic sensitivity of sensors based on FEJT is maximum in the region of weak magnetic fields due to the internal mechanism of increasing the sensitivity associated with an increase in the resistance of the FEJT channel with increasing voltage at the I-V-characteristic saturation region and a corresponding increase in bridge misbalance.

In addition, such a bridge circuit eliminates the temperature drift of the output voltage zero, since all four FEJTs have the same saturation current temperature coefficient. According to the experimental data, in the temperature range from 0 to 120 °C, the relative change in the magnetic sensitivity does not exceed 0.2%.

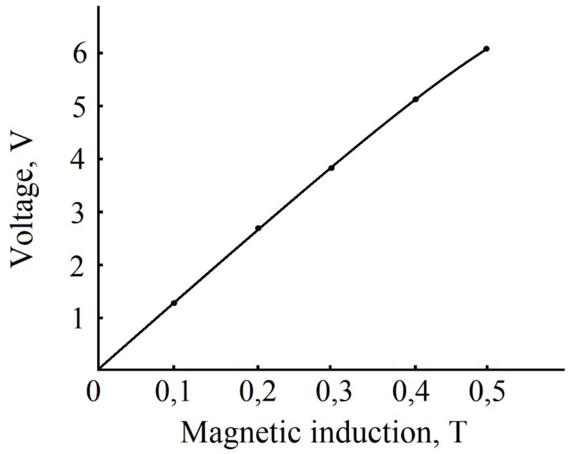

Figure 4. Output characteristic of a bridge sensor with four FEJTs

Experimental studies of the effect of ionizing radiation on the characteristics of FEJT-based sensor elements have shown that after gamma irradiation of FEJT samples doses of the order of 10^5 R, the saturation current decreases by more than 10% [29]. This fact imposes restrictions on the use of FEJT-based sensor elements in conditions of increased background radiation. However, the use of a bridge measurement circuit eliminates this drawback: since the same FEJTs are used in the bridge sensor, ionizing radiation equally affects all four bridge elements, and the balance of the bridge does not change. It was experimentally established that after irradiation of the bridge sensor elements with Co^{60} gamma quanta on a K100000 cobalt irradiator, the output signal changed by no more than

0.6% up to doses of 10^5 R.

If two sensitive elements of the bridge sensor MFEJT1 and MFEJT3 (Fig. 4) are situated at spaced points of an inhomogeneous magnetic field, then the output signal will be proportional to the difference in magnetic field induction at these points where the MFEJT channels are located. Such a sensor can be used to measure the gradient of an inhomogeneous magnetic field.

Thus, using the method of combination of several sensor elements with characteristics insufficient for use in modern sensor networks in a bridge measurement circuit, it is possible to obtain a sufficiently sensitive, thermostable, radiation-resistant magnetic field sensor, which at the same time consumes a minimum of energy. The use of four transistors in the bridge measurement circuit increases the sensitivity of the sensor tenfold due to the internal mechanism of increasing the sensitivity for series-connected pairs of transistors.

4. Photodetector

It is obvious that the method of combination several sensor elements using the advantages of the bridge measurement circuit can be applied to the creation of a photodetector (PD). To do this, it is necessary to select pairs of FETs for which the saturation current flowing through one pair increases when exposed to light, and decreases through the other.

A typical industrial MOSFET (Fig. 5, a) with a built-in channel (CH) based on an *n*-type semiconductor has a very thin oxide film (O) between the channel and a thin film of the metal gate (G). When the MOS structure is illuminated from the side of the semitransparent metal gate (G), the light passes through a thin oxide film (O) and is absorbed in the (CH) channel, the concentration of charge carriers in it increases, and the current through the MOSFET increases.

MOSFETs of the second type (Fig. 5, b) differ in that an *n*-type semiconductor layer (S) is located between the metal layer of the gate (G) and the oxide film (O). The metal-semiconductor contact is a Schottky diode (SD). Such SMOSFETs with a Schottky barrier are used in optical frequency converters [31]. When this structure is illuminated from the side of a semitransparent metal, a photo-emf appears in SD: "plus" – on the metal, "minus" – on the semiconductor. This photo-emf acts as a negative input for the SMOSFET and reduces the carrier concentration in the channel. As a consequence, the current through the SMOSFET is reduced when exposed by light. In this case, all light is absorbed in the *n*-layer of the gate and does not reach the channel.

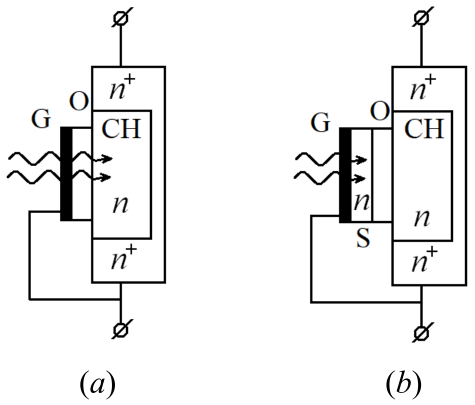

Figure 5. MOSFET with built-in channel (*a*), SMOSFET with Schottky barrier (*b*)ю

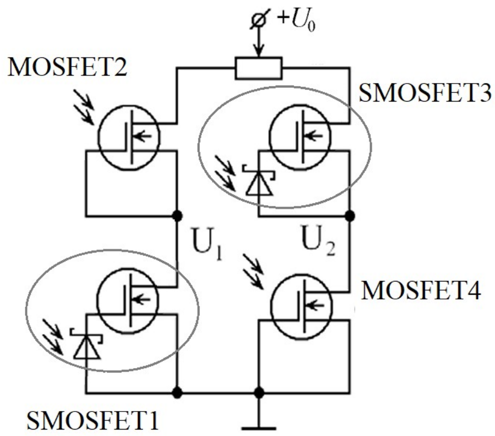

Figure 6. Equivalent bridge photodetector circuit

The operation of the bridge light sensor is explained using an equivalent circuit (Fig. 6). The first pair of sensing elements SMOSFET1 and SMOSFET3 are connected in opposite legs of the bridge, and the other pair of MOSFET2 and MOSFET4 are connected in the other legs. When there is no illumination, the resistance of all MOSFETs in the bridge legs is the same. The supply voltage U_0 is distributed equally between SMOSFET1 and MOSFET2, the potentials U_1 and U_2 in the measuring diagonal of the bridge are equal to each other and the output signal $U = U_1 - U_2 = 0$, i.e. the bridge is balanced. In reality, MOS-

FETs have some variation in parameters, therefore, using a trimming resistor, the initial balancing of the bridge is performed. Lighting causes the resistance of channels of MOSFET2 and MOSFET4 to decrease and the resistance of channels of SMOSFET1 and SMOSFET3 to increase. This leads to an imbalance in the bridge, the potential U_1 increases, the potential U_2 decreases, i.e. the output signal $U = U_1 - U_2$ increases with increasing luminous flux. In this case, the internal amplification mechanism appears in both branches of the photodetector bridge for each pair of MOSFETs, as in the bridge magnetic field sensor.

For experimental studies, we used MOSFET samples made on the basis of a standard industrial KP305 (analogs – MFE3002 or 2N4224). With a source-drain voltage U_{SD} = 10 V and a closed MOSFET gate, the channel resistance was ~ 10 kΩ. To illuminate the phototransistors, a "green" LED of the AL102DM type was used (maximum radiation at a wavelength of λ = 0.56 μm). The maximum illumination power was 0.6 mW with a 100 mA LED current. It was found that the sensitivity of the experimental samples of the photodetector at U_0 = 20 V was an order of magnitude higher than that of a bridge photodetector based on one MOSFET.

The use of a bridge measurement circuit makes it possible to stabilize the photodetector readings during temperature fluctuations, since the bridge sensor uses a MOSFET of the same type, the temperature change affects all four bridge elements equally, and the voltage on the bridge measuring diagonal does not change. According to the experimental data, in the temperature range from 0 to 120 °C, the relative change in the sensitivity of the photodetector does not exceed 0.4%.

To stabilize the readings of the photodetector when exposed to ionizing radiation, it is necessary to select the MOSFET pairs according to the initial value of the drain saturation current before the radiation exposure. As noted above, it was experimentally determined [29] that, according to the radiation sensitivity, MOSFETs are divided into two groups, depending on the initial value of the saturation current before irradiation: for all samples of the group with low saturation current values before irradiation (I_{S0} <0.1 mA), the saturation current increases upon exposure to ionizing radiation and for all samples from the group with large saturation currents before irradiation (I_{S0}> 3 mA), the saturation current decreases upon exposure to ionizing radiation. To obtain a radiation-stable photodetector, it is necessary to use in one circuit MOSFETs, either all with low or all with high saturation current values. It was experimentally determined that after irradiation of the photodetector sensor elements with Co^{60} gamma quanta on a cobalt irradiator, the output signal changed by no more than 1.8% up to doses of 10^5 R.

Thus, by combination various photosensitive elements using the advantages of a bridge measurement circuit, it is possible to obtain a sufficiently sensitive, thermostable, radiation-resistant light sensor based on existing industrial transistors with a minimum number of parts.

5. Results and conclusions

It is shown in the work that by combination specially selected FEJT and MOSFET pairs with opposite signs of temperature sensitivity, but with the same sign of sensitivity to ionizing radiation, in the opposite branches of the bridge, it is possible to obtain a high sensitivity temperature sensor with a minimum number of constituent elements. It has been experimentally confirmed that the temperature sensor obtained in this way, when exposed to radiation, retains high sensitivity and linearity of the output characteristic in the temperature range from –20 ºC to +190 ºC with deviations of readings of no more than 6% up to radiation doses of $5 \cdot 10^5$ R.

It has been experimentally confirmed that when used in a bridge measurement circuit, the method of combination of several sensor FET elements with characteristics insufficient for their use in modern sensor networks, it is possible to obtain a sufficiently sensitive, thermostable, radiation-resistant magnetic field sensor, which at the same time consumes a minimum of energy due to the minimum the number of items.

The use of four transistors in the bridge measurement circuit increases the sensitivity of the sensor tenfold compared to one transistor due to the internal mechanism of increasing the sensitivity for series-connected pairs of transistors.

It has been experimentally confirmed that by using four photosensitive MOSFETs in the bridge circuit instead of one, it is possible to obtain a photodetector with a sensitivity ten times higher than that of a single transistor. Moreover, such a photodetector has increased temperature stability, as well as radiation resistance with preliminary selection of transistors.

The described sensors can be widely used since only a standard element base is used in their design, they are very energy efficient due to the minimum number of constituent elements, they have increased thermal stability and radiation resistance.

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Vikulin I. M.[1], Vikulina L. F.[2], Gorbachev V. E.[1], Litvinenko V. M.[3], Markolrnko P. Y.[1]

DETECTORS BASED ON FIELD EFFECT TRANSISTORS

Summary. The possibility of using the method of combining several sensor elements with opposite sensitivity to various external influences to obtain new designs of sensors for light, temperature and magnetic field has been experimentally investigated. Standard industrial samples of FEJT and a MOSFET in saturation mode with two-pole connection, when the gate is closed with the source, were used as sensor elements in the work. It is shown that the FEJT has a negative temperature coefficient of current change, while the MOSFET has a positive one. At the same time, the sign of the radiative action factor of the MOSFET is determined by the initial value of the drain current before irradiation. It has been experimentally confirmed that the use of four transistors in a bridge measurement circuit increases the sensitivity of the sensor tenfold compared to one transistor due to the internal mechanism of increasing the sensitivity for series-connected pairs of transistors.

Key words: FEJT, MOSFET, temperature detector, magnetic field detector, photodetector, temperature stability, radiation resistance

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Вікулин І. М.[1], Вікулина Л. Ф.[2], Горбачов В. Е.[1], Литвиненко В. М.[3], Марколенко П. Ю.[1]

ДАТЧИКИ НА ОСНОВІ ПОЛЬОВИХ ТРАНЗИСТОРІВ

Резюме. Експериментально досліджено можливість використання методу комбінації кількох сенсорних елементів із протилежною чутливістю до різних зовнішніх впливів для отримання нових конструкцій датчиків світла, температури та магнітного поля. В якості сенсорних елементів в роботі були використані промислові зразки польових транзисторів з *p-n*-переходом в якості затвору (FEJT) і МОН ПТ (MOSFET) в режимі насичення при двополюсному включенні, коли затвор є замкнутим з витоком. Показано, що у FEJT температурний коефіцієнт зміни струму негативний, а у MOSFET – позитивний. У той же час знак коефіцієнта радіаційного впливу MOSFET визначається початковою величиною струму стоку до опромінення. Експериментально підтверджено, що використання чотирьох транзисторів у мостової схемі вимірів підвищує чутливість датчика в десятки разів у порівнянні з одним транзистором за рахунок внутрішнього механізму збільшення чутливості для послідовно з'єднаних пар транзисторів.

Ключові слова: польовий транзистор, МОП-транзистор, датчик температури, датчик магнітного поля, фотодетектор, температурна стабільність, радіаційна стійкість

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Викулин И. М.[1], Викулина Л. Ф.[2], Горбачев В. Э.[1], Литвиненко В. М.[3], Марколенко П. Ю.[1]

ДАТЧИКИ НА ОСНОВЕ ПОЛЕВЫХ ТРАНЗИСТОРОВ

Резюме. Экспериментально исследована возможность использования метода комбинации нескольких сенсорных элементов с противоположной чувствительностью к различным внешним воздействиям для получения новых конструкций датчиков света, температуры и магнитного поля. В качестве сенсорных элементов в работе были использовались промышленные образцы полевых транзисторов с *p-n*-переходом в качестве затвора (FEJT) и МОП ПТ (MOSFET) в режиме насыщения при двухполюсном включении, когда затвор замкнут с истоком. Показано, что у FEJT температурный коэффициент изменения тока отрицательный, а у MOSFET – положительный. В то же время, знак коэффициента радиаци-

онного воздействия MOSFET определяется начальной величиной тока стока до облучения. Экспериментально подтверждено, что использование четырех транзисторов в мостовой схеме измерений повышает чувствительность датчика в десятки раз по сравнению с одним транзистором за счет внутреннего механизма увеличения чувствительности для последовательно соединенных пар транзисторов.

Ключевые слова: полевой транзистор, МОП-транзистор, датчик температуры, датчик магнитного поля, фотодетектор, температурная стабильность, радиационная стойкостью

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