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MATHEMATICAL SIMULATION OF A MICROELECTRONIC TRANSDUCER WITH FREQUENCY OUTPUT FOR MEASURING THE INDUCTION OF THE MAGNETIC FIELD

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Abstract. *A new magnetically sensitive element based on the synthesized semiconductor material has been developed. A method for the synthesis of a complex compound has been developed tetrakis-μ_3-(methoxo) (methanol)-pentakis (acetylacetonate) (tricuprum (II), neodymium (III)) methanol (I). Conducted properties have been studied complex compound in compressed form in the temperature range 273 - 493 K. In the developed magnetoresistor when changing the induction of the magnetic field from 10^{-3} to 200 mT, the resistivity varies from $3.12\cdot10^{-5}$ Ohm to $1.25\cdot10^{-2}$ Ohm·m. On the basis of the developed magnetically sensitive resistive element the circuit solution of the frequency transducer of a magnetic field is offered. The frequency transducer of the magnetic field is a hybrid integrated circuit consisting of a bipolar transistor and a gate transistor. The frequency of generation of the developed transducer increases the most in the range from 10^{-3} T to 0.2 T, and at a supply voltage of 5.0 V varies from 250 kHz to 600 kHz, and in the whole range of changes in magnetic field induction varies from 250 kHz to 750 kHz. The sensitivity of the developed device with frequency output for measuring the induction of the magnetic field is from 400 Hz/mT to 800 Hz/mT.*

Keywords: microelectronic transducer, complex compound, magnetic field, conductivity, generation frequency, negative differential resistance

SYMULACJA MATEMATYCZNA PRZETWORNIKA MIKROELEKTRONICZNEGO Z WYJŚCIEM CZĘSTOTLIWOŚCIOWYM DO POMIARU INDUKCJI POLA MAGNETYCZNEGO

Abstrakt. *Opracowano nowy element czuły magnetycznie oparty na zsyntetyzowanym materiale półprzewodnikowym. Opracowano metodę syntezy związku złożonego tetrakis-μ3-(methoxo)(metanol)-pentakis(acetyloacetonian)(tricuprum (II), neodym (III)) metanol (I). Badano właściwości przewodzące związku złożonego w postaci sprasowanej, w zakresie temperatur 273–493 K. W opracowanym magnetooporniku przy zmianie indukcji pola magnetycznego od 10^{-3} do 200 mT rezystywność zmienia się od $3{,}12\cdot10^{-5}$ Ohm do $1{,}25\cdot10^{-2}$ Ohm·m. Na podstawie opracowanego magnetycznie czułego elementu rezystancyjnego zaproponowano rozwiązanie układu przetwornika pola magnetycznego na częstotliwość. Przetwornik ten jest hybrydowym układem scalonym składającym się z tranzystora bipolarnego i tranzystora bramkowego. Częstotliwość generacji opracowanego przetwornika wzrasta najbardziej w zakresie od 10-3 T do 0,2 T i przy napięciu zasilania 5,0 V zmienia się od 250 kHz do 600 kHz, zaś w całym zakresie zmian indukcji pola magnetycznego zmienia się od 250 kHz do 750 kHz. Czułość opracowanego urządzenia z wyjściem częstotliwościowym do pomiaru indukcji pola magnetycznego wynosi od 400 Hz/mT do 800 Hz/mT.*

Słowa kluczowe: przetwornik mikroelektroniczny, związek złożony, pole magnetyczne, przewodność, częstotliwość generacji, ujemna rezystancja różnicowa

Introduction

Leading specialists of the world are currently developing and creating primary transducers of physical quantities (humidity, temperature, pressure, magnetic field induction), because their measurement in a gas mixture (air) significantly affects both human well-being and the quality of technological processes in microelectronics technology and in various industries [3, 5, 20].

An important role in the development of new functional materials belongs to complex compounds in which β-diketone is a chelating and in some cases a bridging ligand. Nowadays, the field of practical use of functional materials containing β-diketonates of metals is constantly expanding. In particular, they are used in gas sensors, molecular thermometers, in the production of optical fiber and light-converting materials are the starting materials for materials with valuable electrical, optical, catalytic and other properties [2, 6–8, 19, 24]. Of particular interest among this class of complex compounds are heterometallic β-diketonates, which have semiconductor properties [12, 13, 21, 22].

A promising scientific direction in this field is the creation of frequency measuring devices for magnetic field induction based on semiconductor structures with negative resistance, in the development of the theory of which significant achievements have been made by domestic and foreign scientists. The use of the principle of "magnetic induction – frequency" based on transistor structures with negative resistance eliminates the use of analog-to-digital transducers in signal processing, which reduces the cost of control and management systems. In addition, microelectronic frequency magnetic transducers combine both simplicity and versatility, which are inherent in analog devices, as well as accuracy and noise immunity characteristic of transducers with code output, have high sensitivity to measurement parameters, low weight, size, information and design technology. microelectronic means of information processing. Which is their advantage over existing magnetic induction transducers [10, 11, 15]. Therefore, the development and practical application of such devices based on new nanocomposite materials is an urgent task.

1. Technological aspects

It is established that the technical level of sensory systems of physical quantities depends primarily on the technical development of the transducer, namely its sensitive elements, design solution, principle of operation and manufacturing technology [1, 9, 14, 17]. This motivates for the implementation of further research.

The purpose of the study is to develop devices with frequency output for measuring the induction of a magnetic field based on semiconductor structures with negative resistance (Fig. 1). The magnetically sensitive resistive element served as an experimental sample. This element was made from a complex compound – tetrakis-μ_3-(methoxo) (methanol)-pentakis (acetylacetonate) (tricuprum (II), neodymium (III)) methanol (I), of the following composition:

$$[Cu_3Nd(AA)_5(OCH_3)_4CH_3OH]\cdot CH_3OH$$

where HAA = H_3C–C(O)–CH_2–C(O)–CH_3.

This chemical structure was obtained by the following method: samples of salts 3.62 g (15 mmol) of copper (II) nitrate trihydrate and 2.19 g (5 mmol) of neodymium (III) nitrate hexahydrate were dissolved in 130 ml of absolute methyl alcohol containing 40 ml of orthomut ether, kept for 2 hours at room temperature in a hermetically sealed conical flask. Then 2.7 ml (25 mmol) of acetylacetone was added to the reaction mixture, the conical flask was closed with a reversible water cooler and placed on a heated magnetic stirrer. Then, with continuous stirring and heating (~ 50ºC), the piperidine was gradually introduced into the reaction mixture to pH = 8 and continued to heat and stir for one hour. After cooling, a homogeneous fine blue crystalline precipitate precipitated from the solution, which was filtered on a glass filter, washed with a small amount of absolute methanol, diethyl ether and dried in a vacuum desiccator over silica gel. The practical yield is 4.07 g, which is 80% of theoretical. The isolated complex compound (I) is a fine crystalline powder, which is poorly soluble in dimethylformamide, preferably in dimethyl sulfoxide, practically insoluble in alcohols, chloroform, benzene, acetone, decomposes in water.

For the synthesized complex compound (I) in the dry powder state, elemental analysis was performed and it was found that it contains:

Cu – 18.65%; Nd – 14.25%; C – 36.68%; H – 5.24%

As can be seen from the above data, the ratio of metals in the compound(I) Cu:Nd = 1:3, and its composition corresponds to the following gross formula: $Cu_3NdO_{16}C_{31}H_{55}$. In addition, magnetochemical, IR spectroscopic and thermogravimetric studies were performed for the isolated heterometallic compound (I) [18]. A detailed analysis of the obtained experimental data of physicochemical research methods allows us to propose the following scheme of placement of chemical bonds for complex compound (I) (Fig. 1) [18]:

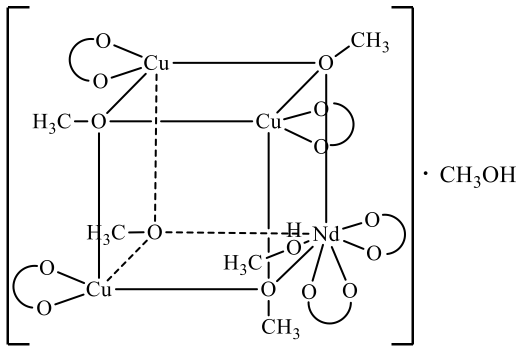


Fig. 1. Scheme of arrangement of chemical bonds in tetrakis-μ_3-(metokso) (methanol) pentakis (acetylacetonate) (tricuprum (II), neodymium (III)) methanol (I)

For the complex compound $[Cu_3Nd(AA)_5(OCH_3)_4CH_3OH]$ (I), a molar mass of 985.5 g/mol and the number of valence electrons in one molecule of 270 was calculated. The density of this material was also calculated as $\rho = 7.046 \cdot 10^3$ kg/m^3 and the band gap $\Delta E = 1.6125$ eV. The dependence of the conductivity of this material on temperature is shown in Fig. 2.

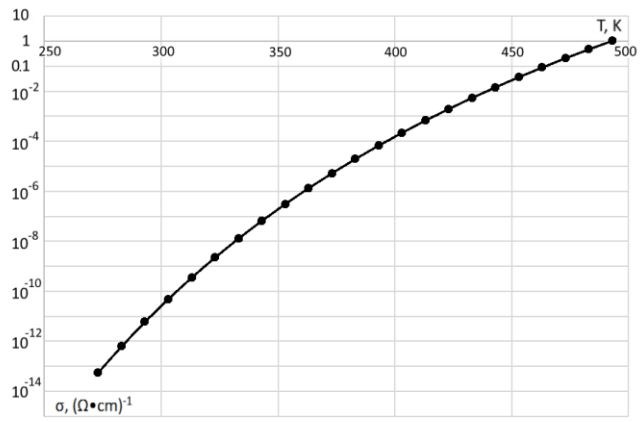


Fig. 2. Logarithmic dependence of the conductivity of heterometallic compound (I) on temperature

As can be seen from the graph, the conductivity varies from $5.67 \cdot 10^{-14}$ (Ohm·m)$^{-1}$ at a temperature of 273 K to 1.06 (Ohm·m)$^{-1}$ at a temperature of 493 K. The experiment showed that in the temperature range of 303–423 K, the specific resistancef the pressed sample of the studied material of compound (I) decreases from $2 \cdot 10^{10}$ Ohm·m to $5 \cdot 10^2$ Ohm·m, that is, the isolated compound is a semiconductor.

To use this complex compound (I) as a magnetically sensitive resistor, a device was created, by analogy with magnetoresistors of the MR-1, MR-2, MR-3 and CM1-1 types, the appearance of which is shown in Fig. 3., with the thickness of the active layer area $7 \cdot 10^{-4}$ m.

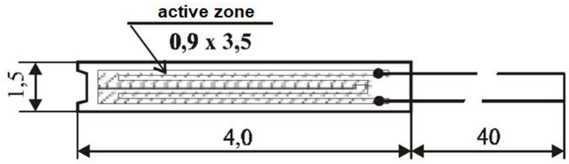


Fig. 3. Appearance and overall dimensions of the magnetically sensitive resistor

The dependence of the resistance of the magnetoresistor on temperature is shown in Fig. 4.

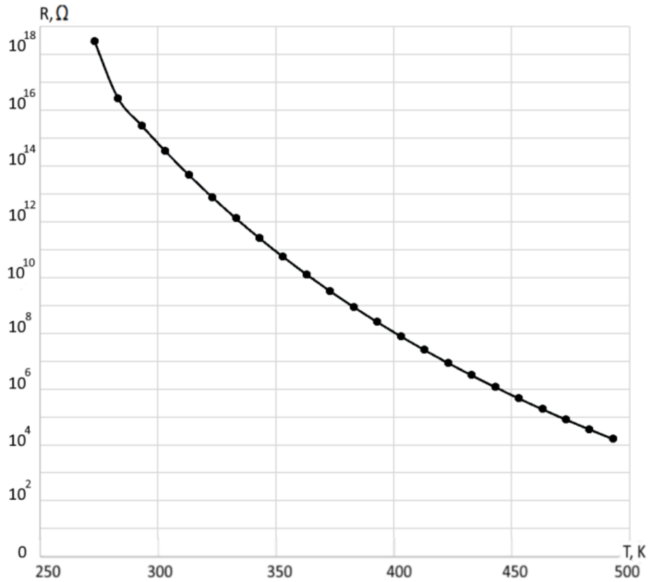


Fig. 4. Logarithmic dependence of the resistance of heterometallic compound (I) on temperature

As can be seen from the graph, the resistance of this material varies from $3.14 \cdot 10^{18}$ Ohm to 16799.2 Ohm when the temperature changes from 273 K to 493 K. The dependence of the concentration of charge carriers on temperature is shown in Fig. 5.

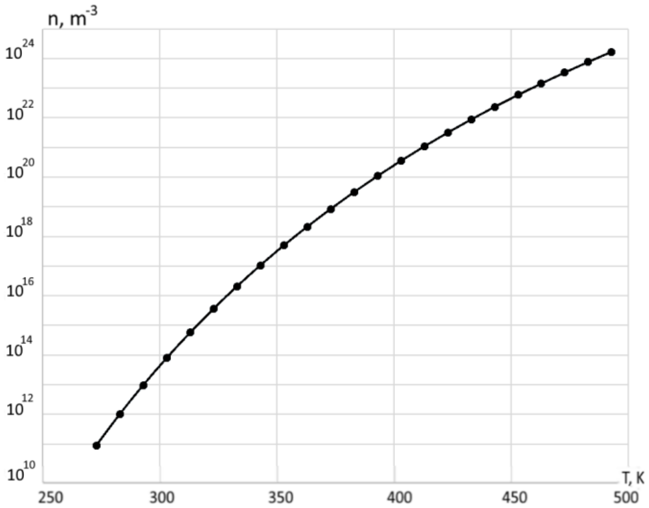


Fig. 5. Logarithmic dependence of charge carrier concentration on temperature

As can be seen from the graph, the concentration of charge carriers increases from $9.02 \cdot 10^{10}$ m^{-3} to $1.68 \cdot 10^{24}$ m^{-3}, in the temperature range from 273 K to 493 K.

The dependence of the change in resistivity of the magnetoresistor on the induction of the magnetic field at a temperature of 393 K is shown in Fig. 6.

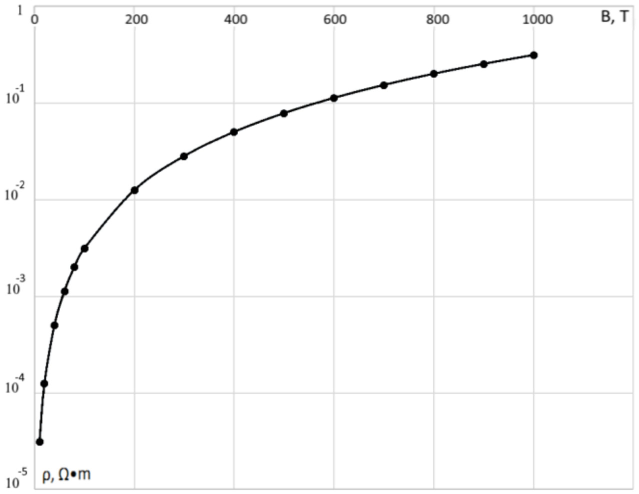


Fig. 6. Logarithmic dependence of the change in resistivity on the induction of the magnetic field

As can be seen from the graph, when changing the induction of the magnetic field from 10^{-3} to 200 mT, the resistivity varies from $3.12{\cdot}10^{-5}$ Ohm to m$1.25{\cdot}10^{-2}$ Ohm · m, and from 200 mT to 1 T, the resistivity varies from$1.25{\cdot}10^{-2}$ Ohm to 0.3 Ohm.

2. Mathematical modeling

The autogenerator transducer is designed as an integrated circuit based on a field-effect double-gate transistor VT1 and a bipolar transistor VT2. The negative differential resistance formed by the parallel connection of the impedance with the capacitive component on the emitter-collector electrodes of the bipolar transistor VT2 and the drain of the field-effect transistor VT1 and inductance L1 leads to the occurrence of electrical oscillations in the circuit. Two resistors R2 and R3 form a voltage divider to power the autogenerator transducer. The capacitor C1 and the resistance of the magnetically sensitive resistor R1 form a phase-shifting circuit [16]. To select the resonant frequency of the oscillatory circuit, capacitor C2 is connected in parallel to the equivalent capacitance of the transistor structure. The passage of alternating current through the DC voltage source is prevented by clamping capacitor C1. Under the action of a magnetic field on the magnetically sensitive resistive element R1, the capacitive component of the impedance on the electrodes of the transistor structure changes, which causes an effective change in the frequency of the oscillatory circuit. An experimental circuit of a microelectronic converter with a frequency output for measuring the magnetic field induction (Fig. 7) was assembled on a BC547 bipolar transistor and a BF998 field-effect double-gate transistor. The mode of transistors VT1 and VT2 for direct current was as follows: the current in the collector circuit of the transistor VT2 is 1.75 mA, and the voltage on the collector is 1.1 V. The circuit resistances have the following values R1 = 2.5 kOhm; R2 = 10 kOhm; R3 = 1.4 kOhm. The self-oscillator inductance is 100 μH. This regime at a magnetic field induction of 1 T corresponded to a generation frequency of 750.470 kHz. The described generator circuit allows you to get an output voltage of up to 1.6 V in a wide frequency range. The frequency instability is $1.17{\cdot}10^{-4}$ Hz.

Without knowing the parameters of the transducers, it is impossible to create, so the task was to develop a mathematical model, based on the solution of which the transformation function and sensitivity equations will be determined. Based on the electrical circuit of the device with a frequency output for measuring the magnetic field induction (Fig. 7), a converted nonlinear equivalent circuit of a microelectronic converter with a frequency output for measuring the magnetic field induction was developed (Fig. 8).

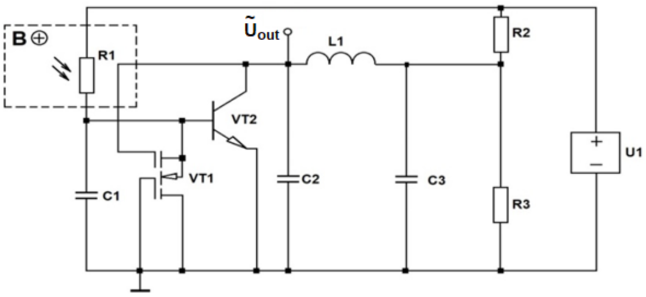


Fig. 7. Electrical circuit of a microelectronic transducer with frequency output for measuring the induction of a magnetic field

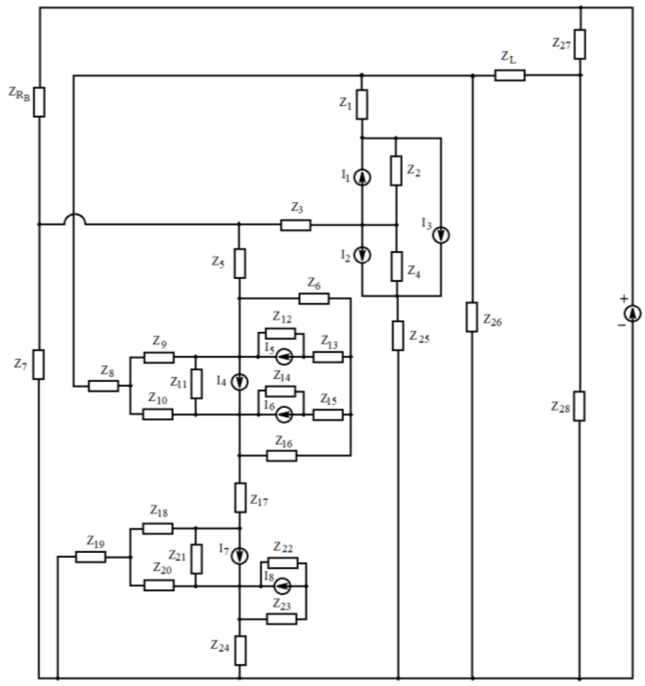


Fig. 8. Transformed equivalent circuit microelectronic transducer with frequency output for measuring magnetic field induction

Elements of the transformed equivalent circuit (Fig. 8) are described by the following values:

$$Z_{R_B} = R_1,\ Z_L = j\omega L,\ Z_1 = R_c + R'_c + j\omega L_c,\ Z_2 = \frac{1}{j\omega C_c},$$

$$Z_3 = R_{bb} + R'_{bb} + j\omega L_{bb},\ Z_4 = \frac{1}{j\omega C_e},$$

$$Z_5 = R_{s2} + R'_{s2} + j\omega L_{s2},$$

$$Z_6 = \frac{R_{b2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2} - j\frac{R_{b2}^2 \omega C_{bs2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2},\ Z_7 = \frac{1}{j\omega C_1},$$

$$Z_8 = R_{g2} + R'_{g2} + j\omega L_{g2},\ Z_9 = \frac{1}{j\omega C_{gs2}},\ Z_{10} = \frac{1}{j\omega C_{gd2}},$$

$$Z_{11} = R_{ds2},\ Z_{12} = \frac{1}{j\omega C_s},\ Z_{13} = R_{bs3},\ Z_{14} = \frac{1}{j\omega C'_d},$$

$$Z_{15} = R_{bd2},\ Z_{16} = \frac{1}{j\omega C_{bd2}},\ Z_{17} = R_{ds1},\ Z_{18} = \frac{1}{j\omega C_{gs1}},$$

$$Z_{19} = R_{g1} + R'_{g1} + j\omega L_{g1},\ Z_{20} = \frac{1}{j\omega C_{gd1}},\ Z_{21} = R_{ds1},$$

$$Z_{22} = \frac{1}{j\omega C_d},\ Z_{23} = R_{bd1} - j\frac{1}{\omega C_{bd1}},$$

$Z_{24} = R_{d1} + R'_{d1} + j\omega L_{d1}$, $Z_{25} = R_e + R'_e + j\omega L_e$,

$Z_{26} = \dfrac{1}{j\omega C_2}$, $Z_{27} = R_2$, $Z_{28} = R_3$.

where R_1 – magnetically sensitive resistor; L – inductance of the oscillating circuit; R_c – the resistance of the collector junction of the bipolar transistor; R'_c – ohmic resistance of the collector electrode of the bipolar transistor; L_c – collector electrode inductance; C_c – capacitance of the collector junction of the bipolar transistor; R_{bb} – base resistance; R'_{bb} – ohmic resistance of the base electrode; L_{bb} – inductance of the base electrode; C_e – emitter junction capacity; R_s – leakage resistance of the field-effect transistor; R'_s – ohmic leakage resistance; L_s – leakage electrode inductance; R_b – resistance of the substrate of the field-effect transistor; C_{bs} – capacitance substrate-leakage of the field-effect transistor; C_1, C_2 – capacitance capacitors C_1, C_2; R_g – resistance of the gate electrode; R'_g – ohmic resistance of the gate electrode of the field-effect transistor; L_g – inductance of the gate electrode; C_{gs} – shutter-leak capacity; C_{gd} – shutter-drain capacity; R_{ds} – drain-leakage resistance; C_s – leakage transition p-n capacitance; R_{bs3} – volumetric resistance p-n of the substrate-leakage transition; C_d, C'_d – capacity p-n runoff transition; R_{bd1}, R_{bd2} – three-dimensional supports p-n transition substrate-drain; C_{bd} – capacity substrate-drain; R_d – drain resistance; R'_d – ohmic drain resistance; L_d – inductance of the drain electrode; R_e – emitter transition resistance; R'_e – ohmic resistance of the emitter electrode; L_e – emitter electrode inductance; R_2, R_3 – divider supports; I_1 – collector-base current of transistor VT2; I_2 – emitter-base current of transistor VT2; I_3 – current emitter-collector of transistor VT2; I_4, I_7 – leakage currents of transistor VT1; I_5 – the substrate-source transition current of the transistor VT1; I_6 – substrate-drain-source transition current of transistor VT1; I_8 – the substrate-drain transition current of the transistor VT1.

The equation on the basis of which the analytical expression of the transformation function is obtained is determined from the circle of positive feedback of the nonlinear equivalent circuit (Fig. 8):

$$F_0 = \frac{2C_{ds}C_{bbe} \pm \sqrt{A_1 + A_2 + A_3 + A_4}}{2\pi(AA_1 + AA_2 + AA_3)} \tag{1}$$

where:

$$A_1 = C_{ds}^2 C_{bbe}^2 - 4R_B^2(B)C_{R_B}(B)C_{ds}C_{bbe}^2 - 4R_B^2(B)\times \times C_{R_B}(B)C_{ds}^2 C_{bbe}$$

$$A_2 = -4C_{bbe}^2 R_B^2(B)C_{R_B}(B)C_{cbb} - 8C_{bbe}R_B^2(B)C_{R_B}(B)\times \times C_{cbb}C_{ds} + 4C_{bbe}^2 LC_{cbb}$$

$$A_3 = 8C_{bbe}LC_{cbb}C_{ds} - 4C_{bbe}^2 R_B^2(B)C_{R_B}^2(B) - -8C_{bbe}R_B^2(B)C_{R_B}^2(B)C_{ds}$$

$$A_4 = -4C_{ds}^2 R_B^2(B)C_{R_B}(B)C_{cbb} + 4C_{ds}^2 LC_{cbb} - -4C_{ds}^2 R_B^2(B)C_{R_B}^2(B)$$

$$AA_1 = -4R_B^2(B)C_{R_B}(B)C_{ds}C_{bbe} - 4C_{bbe}R_B^2(B)C_{R_B}(B)C_{cbb}$$

$$AA_2 = 4C_{bbe}LC_{cbb} - 4C_{bbe}R_B^2(B)C_{R_B}^2(B) - -4C_{ds}R_B^2(B)C_{R_B}(B)C_{cbb}$$

$$AA_3 = 4C_{ds}LC_{cbb} - 4C_{ds}R_B^2(B)C_{R_B}^2(B)$$

Based on expression (1), the function of transforming a device with frequency output for measuring the induction of a magnetic field with a magnetically sensitive resistive element is theoretically calculated and experimentally investigated (Fig. 9).

Based on equation (1), the analytical expression of the sensitivity equation (2) of the developed device is determined:

$$S_B^{F_0} = -\frac{2C_{ds}C_{bbe} \pm 2\sqrt{A_1 + A_2 + A_3 + A_4}\cdot(D_1)}{2\pi(AA_1 + AA_2 + AA_3)} \pm \pm \frac{D_2}{\left(2\pi(AA_1 + AA_2 + AA_3)\sqrt{A_1 + A_2 + A_3 + A_4}\right)}, \tag{2}$$

where

$$D_1 = -8R_B(B)C_{R_B}(B)C_{ds}C_{bbe}\left(\frac{\partial R_B(B)}{\partial B}\right) - 4R_B^2(B)\times \times\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{ds}C_{bbe} - 8C_{bbe}R_B(B)C_{R_B}(B)C_{cbb}\times \times\left(\frac{\partial R_B(B)}{\partial B}\right) - 4C_{bbe}R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{cbb} - 8C_{bbe}\times \times R_B(B)C_{R_B}^2(B)\left(\frac{\partial R_B(B)}{\partial B}\right) - 8C_{bbe}R_B^2(B)C_{R_B}(B)\times \times\left(\frac{\partial C_{R_B}(B)}{\partial B}\right) - 8C_{ds}R_B(B)C_{R_B}(B)C_{cbb}\left(\frac{\partial R_B(B)}{\partial B}\right) - -4C_{ds}R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{cbb} - 8C_{ds}R_B(B)C_{R_B}^2(B)\times \times\left(\frac{\partial R_B(B)}{\partial B}\right) - 8C_{ds}R_B^2(B)C_{R_B}(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)$$

$$D_2 = -8R_B(B)C_{R_B}(B)C_{ds}C_{bbe}^2\left(\frac{\partial R_B(B)}{\partial B}\right) - 4R_B^2(B)\times \times\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{ds}C_{bbe}^2 - 8R_B(B)C_{R_B}(B)C_{ds}^2 C_{bbe}\times \times\left(\frac{\partial R_B(B)}{\partial B}\right) - 4R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{ds}^2 C_{bbe} - 8C_{bbe}^2\times \times R_B(B)C_{R_B}(B)C_{cbb}\left(\frac{\partial R_B(B)}{\partial B}\right) - 4C_{bbe}^2 R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)\times \times C_{cbb} - 16C_{bbe}R_B(B)C_{R_B}(B)C_{cbb}C_{ds}\left(\frac{\partial R_B(B)}{\partial B}\right) - 8C_{bbe}\times \times R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{cbb}C_{ds} - 8C_{bbe}^2 R_B(B)C_{R_B}^2(B)\times \times\left(\frac{\partial R_B(B)}{\partial B}\right) - 8C_{bbe}^2 R_B^2(B)C_{R_B}(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right) - 16C_{bbe}\times$$

$$\times R_B(B)C_{R_B}^2(B)C_{ds}\left(\frac{\partial R_B(B)}{\partial B}\right)-16C_{bbe}R_B^2(B)C_{R_B}(B)C_{ds}\times$$
$$\times\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)-8C_{ds}^2R_B(B)C_{R_B}(B)C_{cbb}\left(\frac{\partial R_B(B)}{\partial B}\right)-4C_{ds}^2\times$$
$$\times R_B^2(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)C_{cbb}-8C_{ds}^2R_B(B)C_{R_B}^2(B)\left(\frac{\partial R_B(B)}{\partial B}\right)-$$
$$-8C_{ds}^2R_B^2(B)C_{R_B}(B)\left(\frac{\partial C_{R_B}(B)}{\partial B}\right)$$

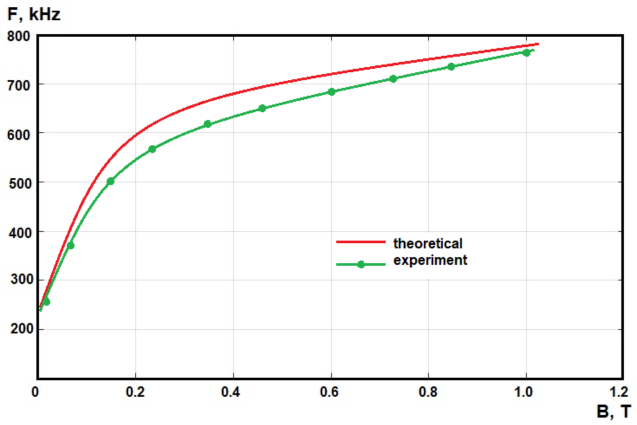


Fig. 9. Experimental and theoretical dependences of generation frequency on the influence of magnetic field induction

The experimental and theoretical dependences of the sensitivity on changes in the magnetic field induction of the developed device with a frequency output for measuring the magnetic field induction with a magnetically sensitive resistive element are shown in Fig. 10.

The sensitivity of the developed device with frequency output for measuring the induction of the magnetic field is from 400 Hz/mT to 800 Hz/mT.

3. Computer experiment

To confirm the existence of a section of negative resistance on the volt-ampere characteristic, an electric circuit microelectronic frequency transducer of the magnetic field with a magnetically sensitive resistive element and two power supplies (power supply and control source) was investigated in the circuit modeling environment LTSpice XVII [4] (Fig. 11).

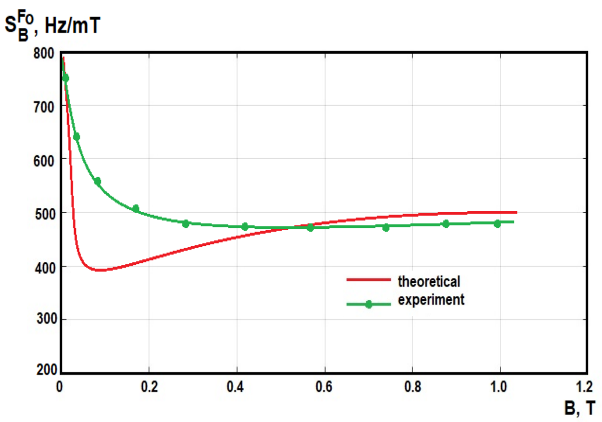


Fig. 10. Experimental and theoretical dependences of sensitivity on changes in magnetic field induction

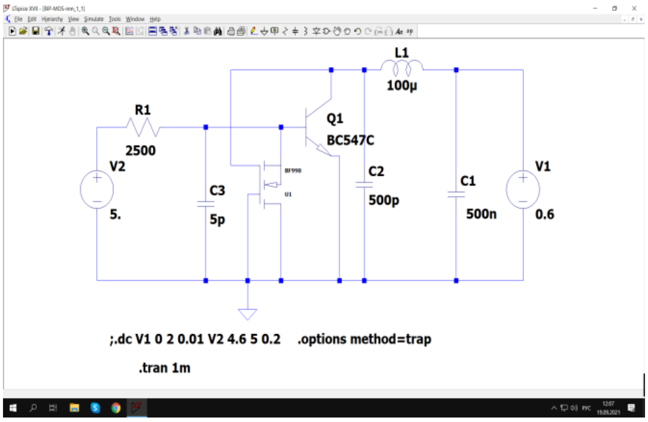


Fig. 11. Electrical circuit microelectronic transducer with frequency output for measuring magnetic field induction in the LTSpice environment

In Fig. 12 shows the volt-ampere characteristic a device with a frequency output for measuring the induction of the magnetic field obtained in the LTSpice environment [23]. From Fig. 12 shows that with increasing control voltage U_2 the area of negative resistance increases. Thus, at a current of 0.61 mA, the area of negative differential resistance U_1 lies from 0.05 to 0.4 V, at a current of 1.1 mA – from 0.07 to 0.6 V, at a current of 1.75 mA – from 1.1 to 0.8 V.

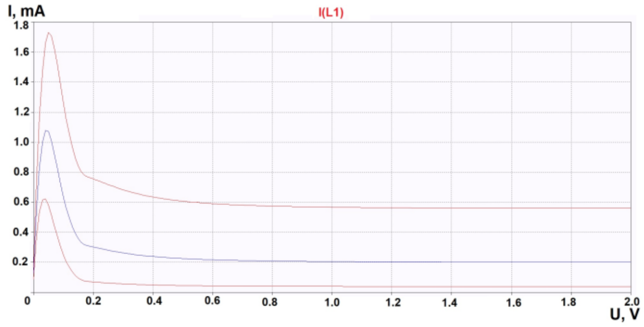


Fig. 12. Volt-ampere characteristic device with frequency output for measurement magnetic field induction

Figure 13 shows a diagram of a microelectronic transducer with frequency output for measuring the induction of a magnetic field with one power supply.

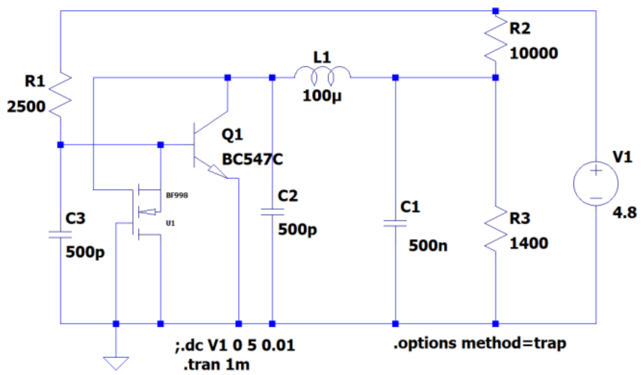
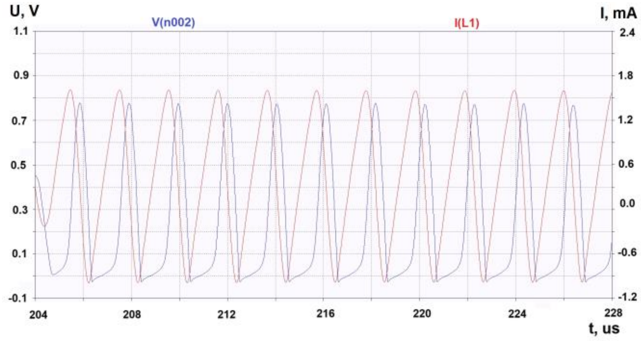
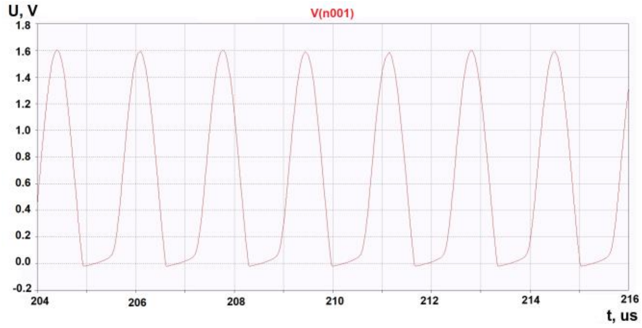


Fig. 13. Electrical circuit microelectronic transducer with frequency output for measuring magnetic field induction in the LTSpice environment with one power supply

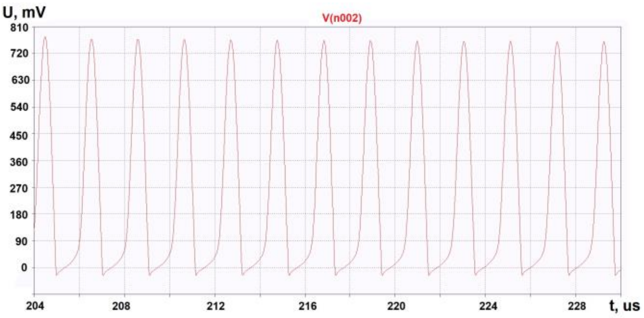
The generation frequency of the developed microelectronic converter with a frequency output for measuring the magnetic field induction without the action of the magnetic field induction is 250 kHz. The generation frequency was tuned in the range from 250 kHz to 750 kHz with a voltage change from 4.6 V to 5 V, which corresponds to a change in the magnetic field induction from 0 to 1 T. Figure 14 shows the changes in the output signal with time for different values of induction magnetic field: a) change in output voltage and current over time; b) change in the output voltage from time to time without the action of a magnetic field; c) change in the output voltage with time under the action of a magnetic field of 1 T.



a)



b)



c)

Fig. 14. Variation of the output signal with time for different values of the magnetic field induction

Based on the results of theoretical and experimental studies, it is easy to see that at the output of the microelectronic frequency transducer of the magnetic field, there will indeed be periodic oscillations, the frequency of which will increase with an increase in the value of the magnetic field induction. Comparing the obtained theoretical and experimental values of the output signal frequency, it was found that the relative error does not exceed 2.5%.

4. Conclusions

1) A new magnetically sensitive element based on the synthesized semiconductor material has been developed and investigated. A scheme for the placement of chemical bonds for this complex compound is proposed. Conducted studies of the electrically conductive properties of tetrakis-μ_3-(methoxo)(methanol)-pentakis (acetylacetonato) (tricuprum(II), neodymium(III)) methanol (I) in a compressed form in the temperature range 273–493 K showed that the conductivity changes $5.67 \cdot 10^{-14}$ $(Ohm \cdot m)^{-1}$ to 1.06 $(Ohm \cdot m)^{-1}$ when the temperature changes from 273 K to 493 K. In the developed magnetoresistor, when the magnetic field induction changes from 10^{-3} to 200 mT, the resistivity varies from $3.12 \cdot 10^{-5}$ Ohm·m to $1.25 \cdot 10^{-2}$ Ohm·m, and from 200 mT to 1 T, resistivity changes from $1.25 \cdot 10^{-2}$ Ohm·m to 0.3 Ohm·m.
2) On the basis of the developed magnetically sensitive resistive element, a circuit solution for a frequency converter of the magnetic field is proposed. The magnetic field frequency converter is a hybrid integrated circuit consisting of a bipolar transistor and a double-gate field-effect transistor, which creates the prerequisites for the creation of a self-oscillating device, the positive feedback circuit of which includes a magnetically sensitive resistor based on tetrakis-μ_3-(methoxo)(methanol)-pentakis(acetylacetonato) (tricuprum(II), neodymium(III)) methanol (I). Analytical expressions for the conversion function and sensitivity equations for a microelectronic transducer are obtained. The computer simulation of the developed converter was carried out in the LTSpice XVII circuit simulation environment. The generation frequency of the developed converter increases more in the range from 10^{-3} T to 0.2 T, and at a supply voltage of 5.0 V it changes from 250 kHz to 600 kHz, and over the entire range of magnetic field induction it changes from 250 kHz to 750 kHz. The sensitivity of the developed device with a frequency output for measuring the magnetic field induction is from 400 to 800 Hz/mT. The experimental studies carried out confirmed the theoretical calculations and showed that the values of the output signal frequency are described with a relative error not exceeding 2.5%.

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