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Microelectronic frequency transducers of magnetic field with Hall elements

Alexander V. Osadchuk[a], Vladimir S. Osadchuk[a], Iaroslav A. Osadchuk[a], Tomasz Zyska[b], Aizhan Zhanpeisova[c]

[a]Vinnytsia National Technical University, 95 Khmelnytsky Hwy, Vinnytsia, 21021, Ukraine; [b]Lublin University of Technology, 38D Nadbystrzycka Str., Lublin, 20618, Poland; [c]Taraz State University after M.Kh.Dulaty, 7 Suleymenov Str., Taraz, 080012, Kazakhstan

ABSTRACT

The analysis is carried out and the possibility of creation of microelectronic auto generator transducers of magnetic field on the basis of transistor structures with a negative resistance is shown. Characteristics of microelectronic auto generator transducers of magnetic field with Hall's elements with the broad range of frequencies from 10^3 to 10^7 Hz are offered and investigated, at the same time the sensitivity of devices changes from 10^3 kHz/mT up to 10^5 kHz/mT.

Keywords: frequency transducer, magnetic field, negative resistance.

1. INTRODUCTION

Sensors of magnetic field found wide use in automation and management of technological processes, in the aircraft and space equipment, in medicine, scientific research, nuclear power, in automotive industry, monitoring of the environment, etc.[1-4]. The most part of magnetic sensors is analog at which parameters of magnetic field it will be transformed to electrical output quantities of current or voltage. It leads to loss of information between an output of the transducer and an input of devices at information postprocessing, small values of a signal output, considerable measurement errors of magnetic parameters, low high-speed performance and sensitivity. These defects can be eliminated in auto generator transducers of magnetic field in which the magnetic induction will be transformed to a signal frequency output, at the same time use of analog-to-digital converters and amplifying intensifying devices is excluded that increases profitability of control and management systems[5].

It is necessary to emphasize that creation of semiconductor devices with the falling-down section of volt ampere characteristics, such as tunnel diodes, tunnel and resonant diodes, lambda diodes, four-layer diodes, unijunction transistors, lambda transistors, avalanche transistors, compound transistors, tunnel and resonant transistors and others, allowed to design auto generator devices completely in integral construction with very broad change of frequency of generation due to change of voltage output of primary transducers of physical quantities. It, in turn, to a large extent increased sensitivity and measurement accuracy of the characteristics of magnetic field transformed to a frequency signal output. Researches of transducers of magnetic field with a frequency output are at an initial stage therefore development of such devices, a research of their characteristics, operation regimes is of considerable interest. This article is devoted to a solution of these questions.

2. THE SELF-OSCILLATOR - A BASIC ELEMENT OF TRANSDUCERS OF MAGNETIC FIELD

The self-oscillator of electric oscillations is a basic element of frequency transducers therefore consideration of its work in the wide plan gives the chance to estimate dependence of parameters of transducers on action of both external, and internal factors. The scheme which implements volt ampere characteristic with the falling-down section to which corresponds negative resistance is submitted in fig. 1. It consists of bipolar and field transistors in the form of the hybrid integrated circuit.

The oscillating circuit is formed by external inductance of L_1, external capacitance C_1 of VT1 and VT2 transistors together with the negative resistance which exists on electrodes a collector and a drain of bipolar and field transistors. Work Wan der Pol[6] was one of the early studies devoted to a solution of the nonlinear equation of oscillations. In this work the equations of a oscillating circuit and nonlinear volt ampere characteristic were combined with negative resistance that allowed to receive nonlinear differential equation of the second order. It can be solved by a numerical method when using modern personal

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computers. However in practice it is necessary to have analytical expressions for oscillation amplitude, sensitivity of amplitude and frequency to change of external circuit elements, diets therefore quasilinear methods of the analysis are used. In this case the characteristic of negative resistance can be approximated by both piecewise linear function, and a polynom of different orders.

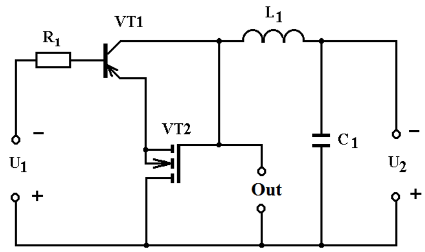

Figure 1. Electric circuit of the self-oscillator.

The analytical description of static volt ampere characteristic of transistor structure (fig. 1) is based on its approximation by elementary functions. The most reasonable is abstract approximation which is not connected with physical processes in transistor structure, and leans, first of all, on her extreme points and mathematical features of their vicinity. In fig. 2 static volt ampere characteristic of transistor structure (fig. 1) with a negative resistance is presented.

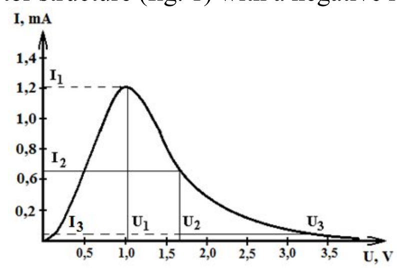

Figure 2. Direct current voltage characteristic of transistor structure.

Piecewise linear approximation of static volt ampere characteristic of semiconductor structures with a negative resistance by means of three-four segments was widely adopted [7]. In practice depending on specific conditions more simplified option of piecewise linear approximation of the falling-down section volt ampere characteristic is represented in the form of [8].

$$I = I_3 + \left(I_1 - I_3\right)\cdot\left(\frac{U_3 - U}{U_3 - U_1}\right)^n \qquad \text{at} \qquad U_1 \le U \le U_3 \ , \tag{1}$$

where $n=2\div4$. Changing n coefficient in these borders, it is possible to describe the falling-down section of a current voltage characteristic more precisely.

Let's pass to consideration of the main characteristics of the self-oscillator on the basis of quasilinear model. The scheme of the self-oscillator on the basis of transistor structure (fig. 1) on alternating current is submitted in fig. 3.

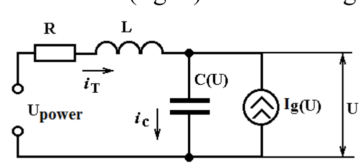

Figure 3. Electric circuit of the self-oscillator.

On the scheme total inductance $L = L_0 + L_1$ and resistance $R = r_0 + R_1$, where L_1, R_1 – inductance and resistance of an external circuit, L_0, r_0 inductance and resistance of leads of transistor structure, $C(U)$ – capacity of transistor structure which generally depends on the attached constant voltage, $I_g(U)$ – the current generator which models behavior of negative resistance. Development of processes in this scheme is connected with change of current i_T and voltage U. According to fig. 3 equations of Kirchhoff take a form

$$U_{power} = i_T R + L\frac{di_T}{dt} + U \quad , \tag{2}$$

$$i_T = i_C + I(U) = C(U)\frac{dU}{dt} + I(U) \quad . \tag{3}$$

From the equations (2) and (3) we find di_T/dt and dU/dt, therefore

$$\frac{di_T}{dt} = \frac{U_{power} - i_T R - U}{L} \tag{4}$$

$$\frac{dU}{dt} = \frac{i_T - I(U)}{C(U)} \quad . \tag{5}$$

In equilibrium state (U_0, i_{T0}) currents and voltage do not change therefore

$$\left.\frac{di_T}{dt}\right|_{i_T = i_{T0}} = 0 \quad , \qquad \left.\frac{dU}{dt}\right|_{U=U_0} = 0 \quad . \tag{6}$$

When using conditions (6), from the equations (4) and (5) we find

$$U_{power} - i_{T0} R - U_0 = 0 \tag{7}$$

$$i_{T0} - I(U_0) = 0 \quad . \tag{8}$$

The scheme state according to (7) and (8) is implemented in crosspoints of a direct current voltage characteristic and the line of a static load of the scheme

$$I(U_0) = (U_{power} - U_0)/R \, , \tag{9}$$

which is equilibrium state of the studied scheme. For the description of work of the scheme in the dynamic mode we will enter new variables into the equations (4) and (5) which have form

$$u = U - U_0 \quad , \tag{10}$$

$$i = i_T - i_{T0} \quad . \tag{11}$$

Nonlinear direct current voltage characteristic of transistor structure near equilibrium state it is replaceable linear function

$$I(U_0 + u) = I(U_0) + u / R_g \, , \tag{12}$$

where R_g – differential resistance in scheme equilibrium point.

Nonlinear capacity of transistor structure $C(U_0)$ on electrodes a collector drain near equilibrium state we consider a constant which does not depend on voltage. Taking into account these notes of the equation (4) and (5) will be transformed to linear equations with constant coefficients:

$$\frac{di}{dt} = -\frac{Ri}{L} - \frac{u}{L} \quad , \tag{13}$$

$$\frac{du}{dt} = \frac{i}{C} - \frac{u}{R_g C} \quad . \tag{14}$$

Let's carry out differentiation on time of the equation (14)

$$\frac{d^2u}{dt^2} = \frac{di}{dt}\cdot\frac{1}{C} - \frac{1}{R_g C}\cdot\frac{du}{dt} \quad . \tag{15}$$

According to the equivalent circuit of the self-oscillator (fig. 3) it is possible to write

$$i = i_c + i_g = C\frac{du}{dt} + \frac{u}{R_g} \, , \tag{16}$$

At substitution in the equation (15) expressions (13) and (16) we will receive differential equation of the second order which describes behavior of alternating voltage from time

$$\frac{d^2u}{dt^2} + \frac{du}{dt}\left(\frac{R}{L} + \frac{1}{R_g C}\right) + \frac{u}{LC}\left(\frac{R}{R_g} + 1\right) = 0 \quad . \tag{17}$$

Proceeding from the equation (17), its quadratic characteristic equation has form

$$x^2 + x\left(\frac{R}{L}+\frac{1}{R_g C}\right)+\frac{1}{LC}\left(\frac{R}{R_g}+1\right)=0 \quad . \tag{18}$$

Roots of characteristic equation (18) are defined by formulas

$$x_{1,2} = \left(-\left(\frac{R}{L}+\frac{1}{R_g C}\right) \pm \sqrt{\left(\frac{R}{L}+\frac{1}{R_g C}\right)^2 - 4\frac{1}{LC}\left(\frac{R}{R_g}+1\right)}\right)\Big/2 \quad . \tag{19}$$

According to the theory of stability of Lyapunov roots of characteristic equation (24) define equilibrium state of system. If x_1 and x_2 have real values, at $x_{1,2} < 0$ any initial deviation in system will attenuate under the exponential law, and at $x_{1,2} > 0$ – increase accrue. If $x_{1,2} = a + jb$ (complex values), in system sine wave oscillations are possible, and at $a > 0$ oscillations increase, and at $a < 0$ attenuate. The solution of the equation (17) has form

$$\begin{aligned} u(t) = {} & A\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_g C}\right)+\sqrt{\frac{1}{4}\left(\frac{1}{R_g C}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t + \\ & +B\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_g C}\right)-\sqrt{\frac{1}{4}\left(\frac{1}{R_g C}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t+\frac{U_{power}}{\left(1+R/R_g\right)}, \end{aligned} \tag{20}$$

where A and B coefficients which are defined from initial conditions. First two the working-out equations (20) describe periodic process which amplitude increases under the exponential law. The condition of emergence of sine wave oscillations in system is described by inequalities

$$\left(\frac{1}{R_g C}+\frac{R}{L}\right)<0 \ , \tag{21}$$

$$\frac{1}{LC}\left(\frac{R}{R_g}+1\right)>0 \ . \tag{22}$$

Having integrated expression (21) and (22), we will receive

$$\left(RC-\frac{L}{|R_g|}\right)^2 - 4LC < 0 \quad . \tag{23}$$

Thus, initiation of electric oscillations in the scheme (fig. 3) at a resonance frequency will take place at execution of conditions (23).

The input impedance of the scheme is defined by the equation

$$Z = R + \frac{R_g}{\left(\omega C R_g\right)^2+1} + j\left(\omega L - \frac{\omega C R_g^2}{1+\left(\omega C R_g\right)^2}\right). \tag{24}$$

At execution of a condition

$$\omega L - \frac{\omega C R_g^2}{1+\left(\omega C R_g\right)^2} = 0 \tag{25}$$

in the scheme there comes the resonance. From the equation (25) we will determine resonance frequency

$$\omega_p = \frac{1}{|R_g| C}\sqrt{\frac{R_g^2 C}{L}-1} \quad . \tag{26}$$

If at a frequency $\omega = \omega_p$ the active component of an input impedance will be less or is equal to zero

$$R + \frac{R_g}{1+(\omega C R_g)^2} \le 0, \tag{27}$$

that in the scheme there are sine wave oscillations.

Oscillation amplitude of the self-oscillator is defined on the basis of power balance: energy which is absorbed by an oscillating circuit of the self-oscillator should equal energy which is given by negative resistance. Power which is given by negative resistance, is defined by expression

$$P_{NDR} = U_p I = U_p^2 / R_{NDR} \tag{28}$$

where U_p – voltage at which loss of energy in an oscillating circuit at the expense of negative resistance is offset, $I = U_p / R_{Loss}$ – current in the parallel electric circuit made of the negative resistance and loss resistance R_{Loss}. In the stationary range at sinusoidal voltage P_{NDR} it is equal to the power of losses P_{Loss}, which is consumed by an oscillating circuit

$$P_{Loss} = \frac{1}{T}\int_0^T \frac{U^2}{R_{Loss}} dt = \frac{1}{T}\int_0^T \frac{U_m^2 \sin^2 \omega t}{R_{Loss}} dt = \frac{1}{2} \cdot \frac{U_m^2}{R_{Loss}} \ . \tag{29}$$

Having equated expression (28) and (29), we will receive

$$\frac{U_m^2}{2R_{Loss}} = \frac{U_p^2}{R_{Loss}}, \tag{30}$$

from where self-oscillator voltage amplitude

$$U_m = \sqrt{2} U_p \ . \tag{31}$$

If the operation point moves on the falling-down section to a current voltage characteristic, then to voltage of U_1 there corresponds negative resistance R_{g1} and to voltage U_2 – resistance R_{g2}, what allows to write the equation [6]

$$\frac{U_2}{U_1} = \frac{R_{g2} / R_{g1} - 1}{R_{g2} / R_{Loss} - 1} \ . \tag{32}$$

The amplitude sensitivity is defined from the equation (32) taking into account that $U_p = U_2$, then

$$S_{R_{Loss}}^{U_m} = \frac{2R_{g2}}{R_{Loss}(R_{g2} / R_{Loss} - 1)} \ . \tag{33}$$

The analysis of expression (33) shows that the amplitude sensitivity of the self-oscillator increases at approach of values R_{g2} to R_{Loss}, however, on the other hand, it reduces influence of the highest harmonic components in self-oscillator voltage. At a sinusoidal form of oscillations resonance frequency can be presented in the form[6]

$$\omega_p = \left[1 - \frac{1}{4Q^2}\left(1 - \frac{R_{Loss}}{R_{g2}}\right)^2\right]^{1/2}, \tag{34}$$

where Q – good quality of an oscillating circuit. On the basis of (34) the sensitivity of frequency relatively to change of loss resistance is defined [6]

$$S_{R_{Loss}}^{\omega_p} = \frac{1}{4Q^2}\left(1 - \frac{R_{Loss}}{R_{g2}}\right)^2 \ . \tag{35}$$

The frequency is less, the smaller different the values of the resistances R_{g2} and R_{Loss} sensitivity. On the other hand, the value of the negative resistance must be such as to provide a self-excitation mode of the self-oscillator, which means that a small frequency sensitivity has a generator that operates near the stability limit.

In fig. 4 volt ampere characteristic of the transducer, in the static and dynamic mode which is received by means of the Caltek-4810A curve tracer is presented. In fig. 5 theoretical and experimental dependences of frequency of generation of the transducer on supply variation and management are presented.

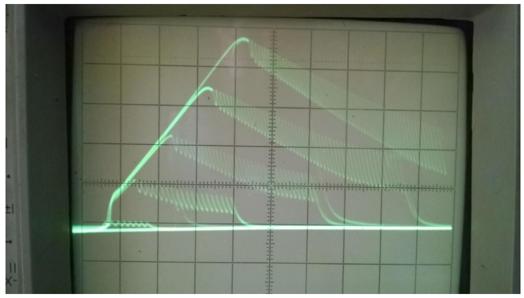

Figure 4. The volt-ampere characteristic of the transducer in static and dynamic modes.

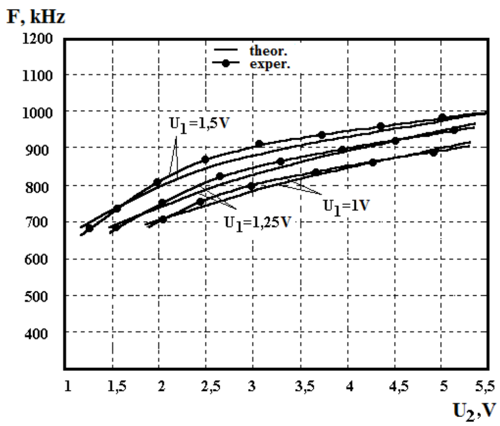

Figure 5. Theoretical and experimental dependences of frequency of generation of the transducer on voltage variations of management U1 and supply voltage of U2.

3. MICROELECTRONIC FREQUENCY TRANSDUCERS OF MAGNETIC FIELD HALL'S ELEMENTS

Briefly we will consider the physical mechanism of a Hall effect in semiconductors as Hall's element is primary transducer of magnetic field in microelectronic frequency transducers. The essence of the physical mechanism of a Hall effect lies that at action of magnetic field on the semiconductor on which there passes current with *j* density at the same time magnetic field strength of H is perpendicular to the direction of current, in the semiconductor there is electric field which direction is perpendicular both to current, and to magnetic field. Value of strength of this electric field E_H it is proportional to j current density in the semiconductor and induction of magnetic field B, in which there is a semiconductor[9]

$$E_H = R_H jB, \tag{36}$$

where R_H – proportionality coefficient (Hall's constant), $B = \mu_1 H$ – magnetic induction, μ_1 – magnetic constant of the semiconductor.

Let's consider Hall effect on the example of the semiconductor with electronic type of conductivity in which current is transferred only by electrons. At a current flow in the electronic semiconductor electrons move with a certain average speed $\vec{v}$ in a direction opposite to the direction of current. If such semiconductor places in magnetic field H, which perpendicular to current, will affect conduction electrons Lorentz force $\vec{F}_L$ which direction is perpendicular to their speed $\vec{v}_-$ and magnetic field strength $\vec{H}$ (fig. 6).

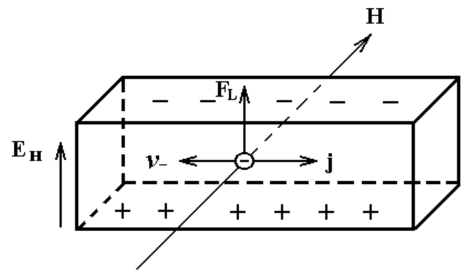

Figure 6. Formation of a field of Hall in the semiconductor with electronic type of conductivity.

As a negative charge that under the influence of Lorentz force they deviate the direction of current aside which is opposite to the direction of a vector $[\vec{v}_- \cdot \vec{B}]$ (fig. 6). Thereof electrons collect on one of semiconductor edges which is perpendicular to a vector $[\vec{v}_- \cdot \vec{B}]$. About an opposite edge of the semiconductor the uncompensated positive charge appears. Between positive and negative charges in the semiconductor electric field E_H appears, which brakes a deviation of electrons under the influence of Lorentz force. Process of accumulation of charges of different signs on opposite edges continues until strength of a Hall field does not reach values, at which force qE_H, which affects electrons, will counterbalance Lorentz force

$$qE_H = q[\vec{v}_- \cdot \vec{B}] \tag{37}$$

after that there will come stationary situation. The current density passing through the semiconductor is equal

$$j = qnv_- \tag{38}$$

where n – concentration of electrons. From expression (38) we determine the speed of electrons

$$v_- = j / qn \quad . \tag{39}$$

At substitution (39) in (37) we will receive

$$E_H = \frac{1}{qn} jB \quad . \tag{40}$$

The equation (40) corresponds to the equation (36) therefore Hall's constant is equal

$$R_H = \frac{1}{qn} \quad . \tag{41}$$

If magnetic field affects the semiconductor with hole conductivity, across there passes current, then charge carriers in it are holes which speed of the directed movement v_+ matches the direction of current, at the same time holes are affected by Lorentz force. At the selected direction of current of speed of electrons and holes $\vec{v}_-$ and $\vec{v}_+$ are opposite therefore $[\vec{v}_- \cdot \vec{B}] = [\vec{v}_+ \cdot \vec{B}]$. In this case Lorentz forces which affect electrons and holes which move in opposite directions are directed equally. Thus, in hole and electronic semiconductors at the identical directions of current and magnetic field carriers of charges deviate by Lorentz force in one and a touch the party. On this basis it is possible to draw a conclusion that at the identical directions of current and magnetic field signs of charges of the corresponding edges of electronic and hole semiconductors and, therefore, the direction of Hall fields in them will be opposite.

It is necessary to emphasize that in fact electrons and holes have not identical motion speeds along current, and their distribution on speed is uneven, it depends on the mechanism of dispersion of charges and also on extent of degeneration of electric charge. Therefore the numerator in a formula (41) has values which differ from unit therefore

$$R_H = \frac{A}{qn} \tag{42}$$

where A – is the value which depends on the nature of distribution of charge carriers on speeds and also on the mechanism of dispersion of charge carriers. From expression (40) hall voltage value is defined U_x

$$U_x = \frac{R_H}{b} \cdot I \cdot B \,, \tag{43}$$

where b – width of a rectangular sample of an element of Hall. Resistance R_x Hall's element follows from expression (43)

$$R_x = \frac{R_H}{b} \cdot B\,. \tag{44}$$

Having considered dependence of hall voltage on induction of magnetic field in Hall's elements we will pass to the description of schemes and characteristics of microelectronic frequency transducers. The scheme of the .microelectronic frequency transducer of magnetic field is submitted in fig. 7[10].

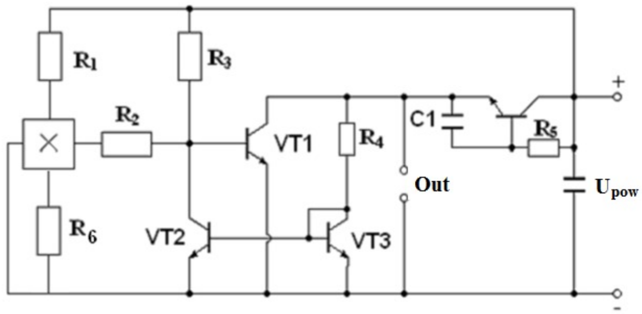

Figure 7. The electric circuit of the frequency transducer of magnetic field on bipolar transistor structure with Hall's element.

It represents the integrated circuit which consists of four bipolar transistors with identical type of conductivity. The VT4 transistor together with a phase-shifting chain of C_1R_5 implements an active inductive element of an oscillating circuit of the self-oscillator that allows to use completely microelectronic technology at production of the transducer. The magneto sensitive element of Hall is included in a chain of regenerative feedback of the self-oscillator. On electrodes of the collector emitter of VT1 and VT2 transistors there is an impedance which active component has negative value, and reactive – capacity character. The oscillating circuit is formed by extrinsic capacitance C_2, internal capacitance of VT1,VT2, VT3 transistors and active inductance on the basis of the VT4 transistor. Losses of energy in an oscillating circuit are offset by energy of negative resistance. At action of magnetic field on Hall's element there is voltage variation of Hall which changes both active, and reactive making an oscillating circuit, that result in to change of resonance frequency. For definition of output impedance of the transducer, conversion functions and sensitivity we make the equivalent circuit of the device which is presented in fig. 8. Designations on the scheme standard according to works[11, 12]. On the basis of the equivalent circuit Kirchhoff's equations according to the directions of loop currents were formed which then were solved by Gauss's method on the personal computer[13]. Values of circuit elements are taken from works[11, 12].

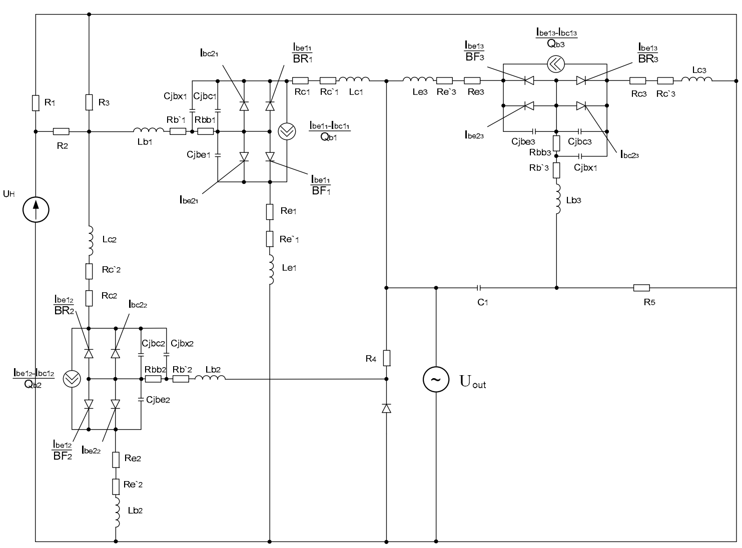

Figure 8. Equivalent circuit of the microelectronic frequency transducer of a magnetic induction.

In fig. 9 and 10 theoretical and experimental dependences of active and reactive components of output impedance of the microelectronic frequency transducer of a magnetic induction are presented.

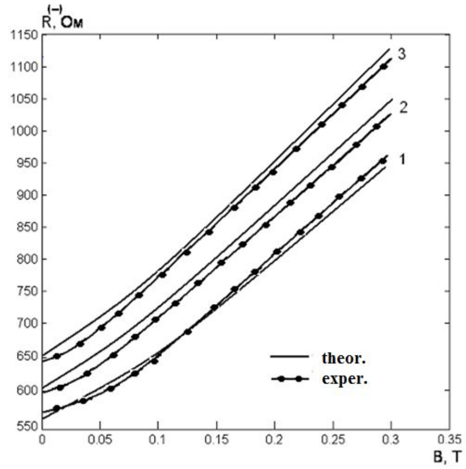

Figure 9. Theoretical and experimental dependences of an active component of output impedance of the microelectronic frequency transducer on a magnetic induction.

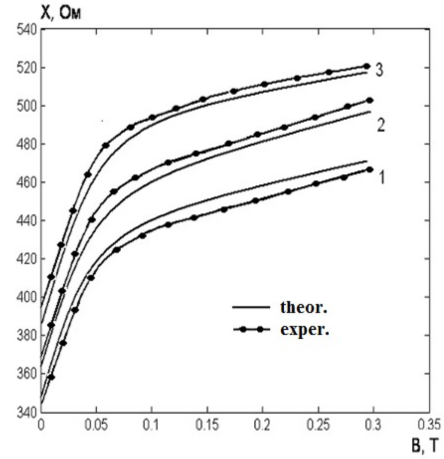

Figure 10. Theoretical and experimental dependences of a reactive component of output impedance of the microelectronic frequency transducer on a magnetic induction.

Conversion function was calculated on the basis and equalities to zero reactive component at a resonance frequency, proceeding from the equivalent circuit (fig. 8). It represents dependence of frequency of generation on a magnetic induction and is described by expression

$$F=\frac{1}{4}\frac{V_1R_H(B)+\sqrt{V_1^2R_H^2(B)-4R_H^2(B)D_1V_2}}{\pi R_H^2(B)D_1}\quad , \tag{45}$$

where $D_1=C_H^2(B)C_{be3}+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1}$; $V_1=C_{bc1}C_{be3}$; $V_2=C_{bc1}+C_{be3}$.

Dependences $R_H(B)$ and $C_H(B)$ represent active and reactive parts of output impedance of the transducer from a magnetic induction shown in fig. 9 and 10. Theoretical and experimental curve conversion functions are given in fig. 11.

The sensitivity of the transducer is defined on the basis of expression (45) and has form

$$\begin{aligned}S_B^F=&-0,5\Bigg(\Bigg(2C_H(B)C_{be3}\left(\frac{\partial C_H(B)}{\partial B}\right)+2C_H(B)C_{bc1}\left(\frac{\partial C_H(B)}{\partial B}\right)+\left(\frac{\partial C_H(B)}{\partial B}\right)\times C_{be3}C_{bc1})V_2)/(V_1^2-4(C_H^2(B)C_{be3}+\\&+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1})V_2)^{1/2}R_H(B)\pi(C_H^2(B)C_{be3}+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1}))-\frac{1}{4}((V_1^2-4(C_H^2(B)C_{be3}+\\&+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1})V_2)^{1/2})\left(\frac{\partial R_H(B)}{\partial B}\right)/(R_H^2(B)\pi(C_H^2(B)C_{be3}+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1}))-\frac{1}{4}(V_1+\\&+(V_1^2-4(C_H^2(B)C_{be3}+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1})V_2)^{1/2})\Bigg(2C_H^2(B)C_{be3}\left(\frac{\partial C_H(B)}{\partial B}\right)+2C_H(B)C_{bc1}\times\\&\times\left(\frac{\partial C_H(B)}{\partial B}\right)\Bigg)+C_{be3}C_{bc1}\left(\frac{\partial C_H(B)}{\partial B}\right)\Bigg)\Bigg)/(\pi R_H(B)(C_H^2(B)C_{be3}+C_H^2(B)C_{bc1}+C_H(B)C_{be3}C_{bc1})^2).\end{aligned} \tag{46}$$

Schedules of theoretical and experimental dependences of sensitivity of the transducer on a magnetic induction are submitted in fig. 12. Apparently from the schedule, the sensitivity of the device is 2-18 kHz/mT at change of a magnetic induction from 0 to 300 mT.

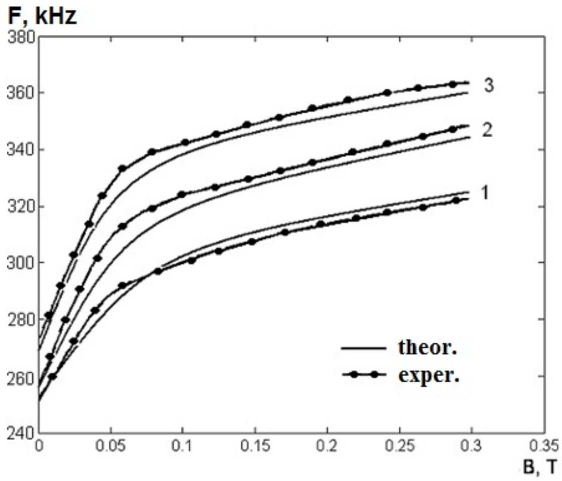

Figure 11. Dependence of frequency of generation of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1-5 V; 2-5,5V; 3-6V.

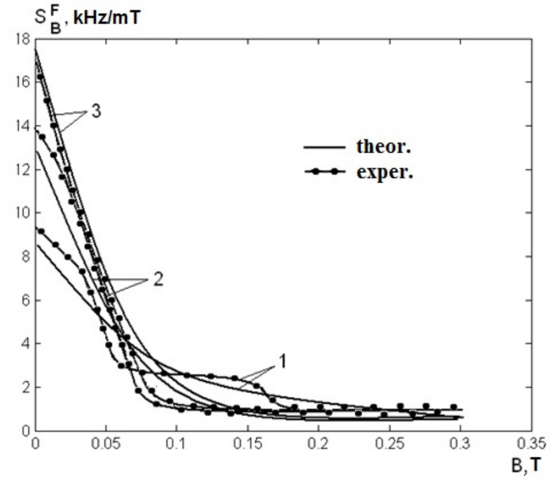

Figure 12. Dependence of sensitivity of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1–5 V; 2–5.5 V; 3–6 V.

It is possible to improve sensitivity of the frequency transducer of magnetic field with Hall's element on the basis of the scheme submitted in fig. 13[14]. It consists of the field dual gate transistor and two bipolar transistors. The bipolar transistor VT3 with a phase-shifting chain of C_2R_8 implements active inductance of an oscillating circuit, and the capacity of an oscillating circuit is internal capacitances of VT1 and VT2 transistors and also extrinsic capacitances C_1 and C_3. For definition of characteristics of the magnetic transducer it is necessary to make the equivalent circuit on the basis of fig. 13.

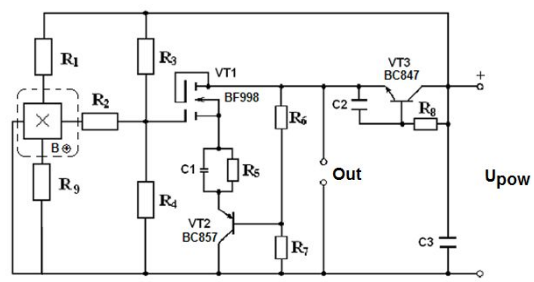

Figure 13. The electric circuit of the frequency transducer of magnetic field with Hall's element.

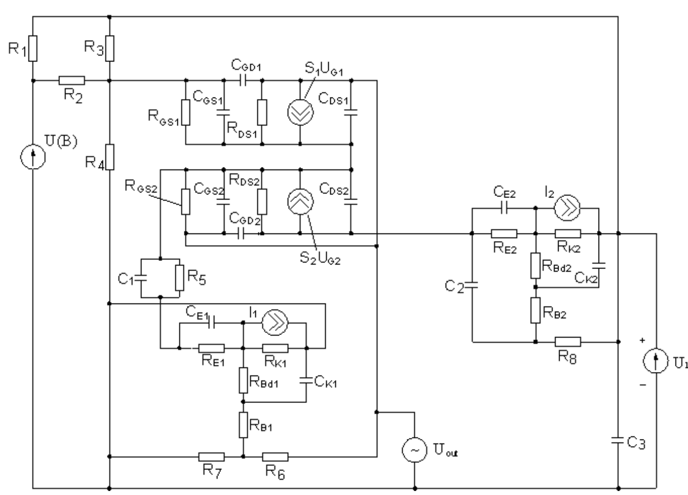

Figure 14. Equivalent circuit of the microelectronic frequency transducer of a magnetic induction.

The equivalent circuit of the frequency transducer of magnetic field is presented in fig. 14. On the basis of the equivalent circuit Kirchhoff's equations according to the directions of the selected loop currents which are solved by Gauss's method on the personal computer are worked out. The solution of a system of equations allows to define output impedance of the device. At division of an impedance into the active and imaginary parts we receive their dependence on induction magnetic which are presented in fig. 15 and 16.

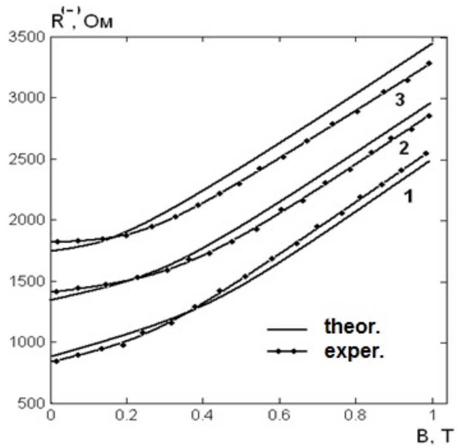

Figure 15. Theoretical and experimental dependences of an active component of output impedance of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1–5.5 V; 2–5.5 V; 3–6 V.

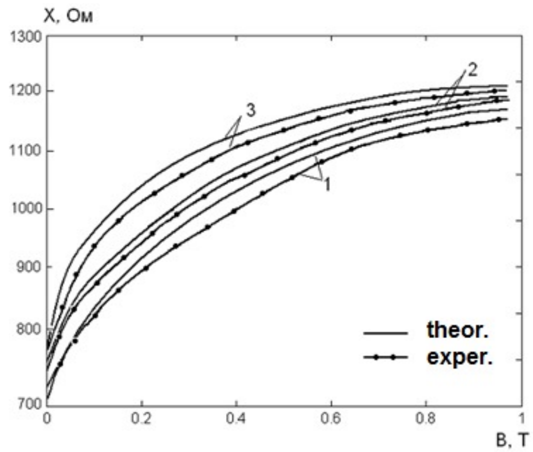

Figure 16. Theoretical and experimental dependences of a reactive component of output impedance of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1–5V; 2–5.5 ; 3–6V.

Conversion function, i.e. dependence of frequency of generation on a magnetic induction, is defined, as well as in the previous case. Its analytical formula has form

$$F = \frac{1}{2\pi}\sqrt{\frac{(C_H^2(B)R_H^2(B) + R_H^2(B)C_H(B)C_{DS2} - L_{екв}C_{DS2}) + D}{2L_{екв}C_{DS2}C_H^2(B)R_H^2(B)}}\,, \tag{47}$$

where $D = \sqrt{(C_H^2(B)R_H^2(B) + R_H^2(B)C_H(B)C_{DS2} - L_{екв}C_{DS2})^2 + 4L_{екв}C_{DS2}C_H^2(B)R_H^2(B)}$.

In fig. 17 theoretical and experimental schedules of frequency of generation from a magnetic induction are submitted. The sensitivity is defined on the basis of expression (47) and is described by the equation

$$\begin{aligned}
S_B^F = {} & \frac{1}{\sqrt{8}}\Bigl(\Bigl(\Bigl(2C_H(B)R_H^2(B)\left(\frac{\partial C_H(B)}{\partial B}\right) + 2C_H^2(B)R_H(B)\left(\frac{\partial R_H(B)}{\partial B}\right) + 2R_H(B)C_H(B)C_{DS2}\left(\frac{\partial R_H(B)}{\partial B}\right) + R_H^2(B)\left(\frac{\partial C_H(B)}{\partial B}\right)C_{DS2} + \\
& + \frac{1}{2}\Bigl(2\bigl(C_H^2(B)R_H^2(B) + C_H(B)R_H^2(B)C_{DS2} - L_{екв}C_{DS2}\bigr)\Bigl(2C_H(B)R_H^2(B)\left(\frac{\partial C_H(B)}{\partial B}\right) + 2R_H(B)C_H(B)\times 2C_H^2(B)R_H(B)\left(\frac{\partial R_H(B)}{\partial B}\right)\times \\
& \times C_{DS2}\left(\frac{\partial R_H(B)}{\partial B}\right) + R_H^2(B)\left(\frac{\partial C_H(B)}{\partial B}\right)C_{DS2}\Bigr) + 8L_{екв}C_{DS2}C_H(B)R_H^2(B)\left(\frac{\partial C_H(B)}{\partial B}\right) + 8L_{екв}C_{DS2}C_H^2(B)R_H(B)\left(\frac{\partial R_H(B)}{\partial B}\right)\Bigr)\Bigr)\Big/ \\
& /\Bigl(\Bigl(C_H^2(B)\times R_H^2(B) + C_H(B)R_H^2(B)C_{DS2} - L_{екв}C_{DS2}\Bigr)^2 + 4L_{екв}C_{DS2}C_H^2(B)R_H^2(B))^{1/2}\Bigr)\Big/\Bigl(L_{екв}C_{DS2}C_H^2(B)R_H^2(B)) - 2(C_H^2(B)R_H^2(B) + \\
& + C_{DS2}C_H(B)R_H^2(B) - L_{екв}C_{DS2} + \Bigl((C_H^2(B)R_H^2(B) + C_{DS2}C_H(B)R_H^2(B) - L_{екв}C_{DS2}\Bigr)^2 + 4L_{екв}C_{DS2}C_H^2(B)R_H^2(B))^{1/2}\Bigr)\times \\
& \times\left(\frac{\partial C_H(B)}{\partial B}\right)\Big/\Bigl(L_{екв}C_{DS2}C_H^3(B)R_H^2(B)) - 2(C_H^2(B)R_H^2(B) + C_{DS2}C_H(B)R_H^2(B) - L_{екв}C_{DS2} + 4L_{екв}C_{DS2}C_H^2(B)R_H^2(B) + \\
& + \Bigl(C_H^2(B)R_H^2(B) + C_{DS2}C_H(B)R_H^2(B) - L_{екв}C_{DS2}\Bigr)^2\Bigr)^{1/2}\Bigr)\Big/\Bigl(L_{екв}C_{DS2}C_H^2(B)R_H^3(B))\Bigr)\Big/\Bigl(\Bigl(C_H^2(B)R_H^2(B) + C_{DS2}C_H(B)\times \\
& \times R_H^2(B) - L_{екв}C_{DS2} + \Bigl(\Bigl(C_H^2(B)R_H^2(B) + C_{DS2}C_H(B)R_H^2(B) - L_{екв}C_{DS2}\Bigr)^2 + 4L_{екв}C_{DS2}C_H^2(B)R_H^2(B))^{1/2}\Bigr)\Big/\Bigl(L_{екв}C_{DS2}C_H^2(B)R_H^2(B)\Bigr)^{1/2}.
\end{aligned} \tag{48}$$

In fig. 18 theoretical and experimental dependences of sensitivity of the transducer on a magnetic induction are presented. Apparently from the schedule, the greatest sensitivity of the device lies in the range from 0 to 200 mT and 10-35 kHz/mT make.

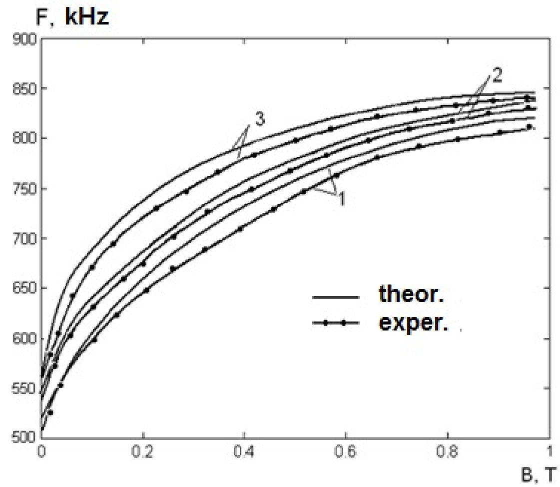

Figure 17. Theoretical and experimental dependences of frequency of generation of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1–5V; 2–5.5V; 3–6V.

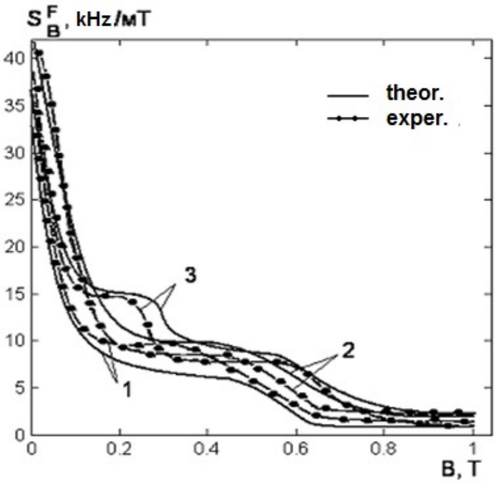

Figure 18. Theoretical and experimental dependences of sensitivity of the microelectronic frequency transducer on a magnetic induction at different supply voltages: 1–5V; 2–5.5V; 3–6V.

The scheme of the frequency transducer of magnetic field with inclusion of an element of Hall in a chain of the active inductance presented in fig. 19[15,16] is of interest. It consists of four transistors that allows to create the auto generator device on microelectronic technology. The oscillating circuit is implemented on the basis of equivalent capacity on electrodes of the collector-emitter of VT1 and VT2 transistors and active inductance on the VT4 transistor with a phase-shifting chain of R_3C_1. The VT3 transistor with the resistor R_2implements a current mirror for thermal compensation of work of the scheme. The element of Hall which is included in a chain of base and a collector of the VT4 transistor is affected by magnetic field. It leads to change of value of active inductance that, in turn, causes change of resonance frequency of the self-oscillator. Losses of energy are made up in an oscillating circuit by energy of negative resistance[17]. Experimental dependence of change of active inductance on a magnetic induction it is shown in fig. 20.

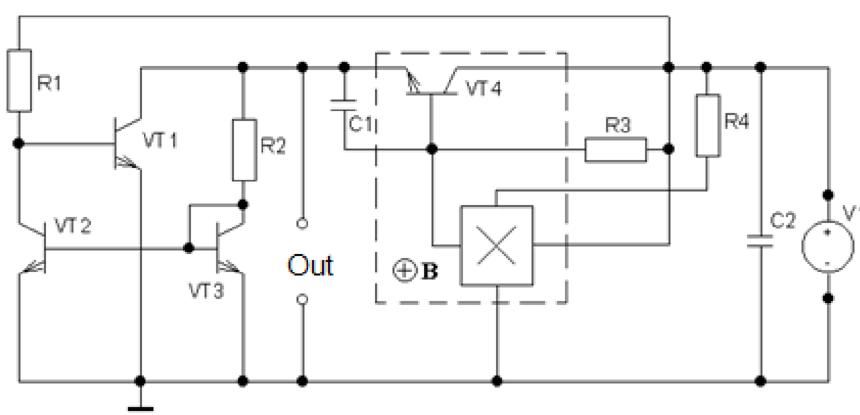

Figure 19. The electric circuit of the microelectronic transducer of magnetic field with Hall's element in an active inductive element.

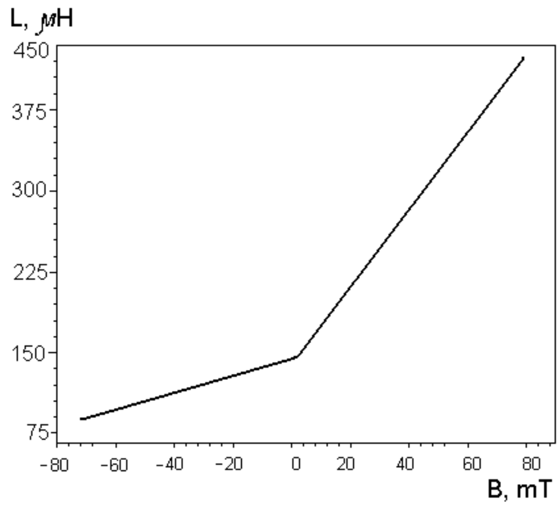

Figure 20. Experimental dependence of change of value of active inductance on a magnetic induction.

Apparently from the schedule (fig. 20) in depending on change of the direction of magnetic field the value of inductance and its corner of an inclination to a horizontal axis changes. Conversion function of the device is defined as well as in the previous schemes, its analytical expression has an appearance

$$F_0 = \frac{1}{2\pi}\sqrt{\frac{C_{BE}+C_{BC}}{L_{EKV}(B)C_{BC}C_{BE}}}\,, \tag{49}$$

where C_{BE} C_{BC} – capacity of emitter and collector junctions of VT1 and VT2 transistors, $L_{EKV}(B)$ – active inductance of the transducer.

The graphic dependence of theoretical and experimental curves of conversion function on a magnetic induction is shown in fig. 21.

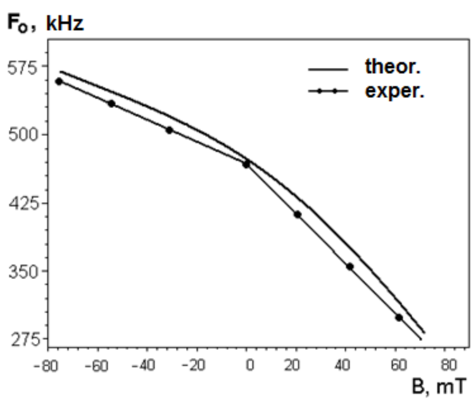

Fig. 21. Theoretical and experimental dependence of frequency of generation on a magnetic induction.

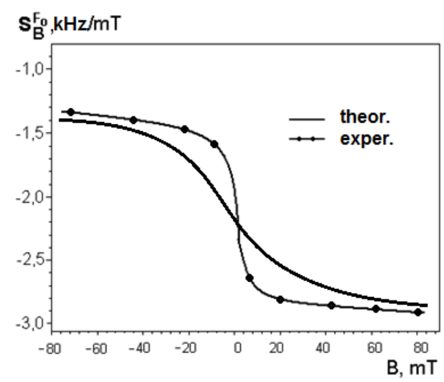

Fig. 22. Theoretical dependence of sensitivity of the microelectronic transducer on a magnetic induction.

The sensitivity of the transducer is defined on the basis of expression (49) and is described by a formula

$$S_{F_0}^{B} = -\frac{1}{4}\frac{(C_{BE}+C_{BC})\left(\dfrac{\partial L_{EKV}(B)}{\partial B}\right)}{L_{EKV}^2(B)C_{BE}C_{BC}\sqrt{\dfrac{C_{BE}+C_{BC}}{L_{EKV}(B)C_{BC}C_{BE}}}}\,. \tag{50}$$

Apparently the sensitivity of the transducer is of the schedule (fig. 22) 1.4–2.8 kHz/mT.

4. CONCLUSIONS

The analysis is carried out and the possibility of creation of microelectronic auto generator transducers of magnetic field on the basis of transistor structures with a negative resistance is shown that increases the accuracy and sensitivity of measurement of characteristics of magnetic field as a result of dependence of capacity of inductance and negative resistance of an oscillating circuit on influence of magnetic field.
Characteristics of microelectronic frequency transducers of magnetic field with Hall's elements with the broad range of frequencies from 10^3 to 10^7 Hz are offered and investigated, at the same time the sensitivity of devices changes from 10^3 kHz/mT to 10^5 kHz/mT.

The developed devices allow to refuse analog-to-digital converters and amplifying devices at postprocessing of information signals that increases profitability of the equipment of measurement of characteristics of magnetic field, at the same time information transfer about magnetic field at distance is possible.

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