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The Mathematical Model of Radio-measuring Frequency Transducer of Optical Radiation Based on MOS Transistor Structures with Negative Differential Resistance

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The article deals with results of theoretical and experimental studies of a radio-measuring frequency transducer of optical radiation based on MOS transistor structures with negative differential resistance and an active inductive element. Analytical expressions of the transfer function and sensitivity equations are obtained on the basis of the solution of a system of non-linear equations. Experimental studies of the current-voltage dependences of the proposed transistor structure of the frequency converter of optical radiation in static and dynamic modes confirm the presence of a section with negative differential resistance on the *I-V* characteristic, which compensates for the losses in the oscillatory circuit. The theoretical and experimental dependences of the frequency of generation on the power of optical radiation are presented. The dependence of sensitivity of the developed transducer on the power of optical radiation varies from 9.7 kHz/μW/cm² to 24.5 kHz/μW/cm². A mathematical model of the thermal conditions of a radio-measuring frequency transducer of optical radiation has been developed. The calculation of non-stationary thermal conditions of the frequency transducer allowed to obtain the temperature field of the transducer integrated circuit. The time to achieve the steady state does not exceed $5.8 \cdot 10^{-4}$ s. Moreover, the maximum temperature of overheating for the elements of the integrated circuit of the transducer does not exceed 2.49 °C.

Keywords: Mathematical model, Thermal modes, Optical radiation, MOS transistor, Negative resistance.

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1. INTRODUCTION

In recent years optical microelectronic frequency transducers have been widely used [1-3]. They operate using an oscillator with electronic tuning of a generation frequency in a wide frequency band. Transistor structures having negative differential resistance can be used as primary converters of physical quantities; in this case, their sensitivity and measurement accuracy are significantly increased [4-6]. Structurally, they are made in the form of a semiconductor structure consisting of two MOS transistors and an active inductive element based on a MOS transistor which is connected with a phase shifting branch of resistor and capacitor. Furthermore, sensitive elements can be included in the electrical circuit of this structure in accordance with physical quantities, which extends the measurement range of the informative parameter [7-9].

The dependence of the parameters of the MOS transistors on the effect of the informative parameter in the dynamic mode allows the designing of radio-measuring frequency transducers of optical radiation with much better characteristics than similar devices. On the other hand, the use of field-effect transistor structures with negative differential resistance allows to design a self-generating transducer, in which both the capacitance and the inductance based on the field-effect transistors depend on the information parameter, that improves the accuracy and sensitivity of the transducer [10-12].

To study the properties of radio-frequency transducers, it is necessary to develop mathematical models, which we can use for calculating the dependence of the generation frequency on the influence of optical radiation, temperature, supply modes, as well as to carry out experimental studies that confirm the validity of the theoretical principles. This article is devoted to considering these issues.

2. THE RADIO-MEASURING FREQUENCY TRANSDUCER OF OPTICAL RADIATION BASED ON MOS TRANSISTOR STRUCTURES

Fig. 1 shows the electrical diagram of the radio-measuring frequency optical radiation transducer based on MOS transistor structures with negative differential resistance.

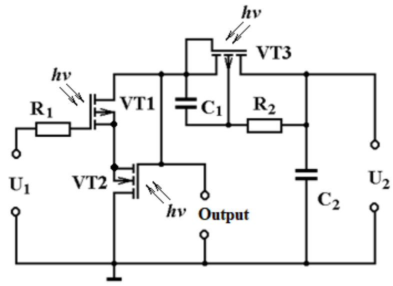

Fig. 1 – Electrical diagram of the radio-measuring frequency transducer of optical radiation with an active inductive element

The active element on the basis of two MOS transistors (VT1, VT2) has a slope of a static current-voltage curve with negative differential resistance. An operating point position is chosen on a drooping part of the current-voltage curve, using ratings of DC voltage sources. Capacitance of the oscillatory circuit of the self-generator is realized by the capacitive component of the impedance on the drain-drain electrodes of field transistors VT1 and VT2, and the inductance is realized by the inductive component of the impedance on the drain-source electrodes of the transistor VT3. Elec-

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trical oscillations appear in a self-oscillatory system. This oscillatory circuit of the self-oscillatory system is made of the capacity component of the transistor structure's complex impedance on the source electrodes of the MOS transistor structure VT1-VT2 and of active inductivity on the basis of the MOS transistor VT3 and the phase-shift circuit R2, C1.

Optical radiation falls on the MOS transistors VT1-VT3. The value of resistors of their channels depends on intensity of an optical flow *hν*. With change of the optical radiation intensity *hν*, the operating point position on the drooping part of the transistor structure current-voltage curve changes. That leads to a change of an equivalent capacity of the oscillatory circuit and to effective generation frequency tuning. A power of oscillations depends on the value of negative differential resistance.

3. THE CALCULATION OF TRANSFER FUNCTION AND EQUATION SENSITIVITY OF A RADIO-MEASURING FREQUENCY OPTICAL RADIATION TRANSDUCER BASED ON MOS TRANSISTOR STRUCTURES WITH NEGATIVE DIFFERENTIAL RESISTANCE

Calculations of the transfer function, which reproduces the dependence of the frequency of generation on the optical radiation power, can be obtained by solving the system of equations according to the converted equivalent circuit (Fig. 2).

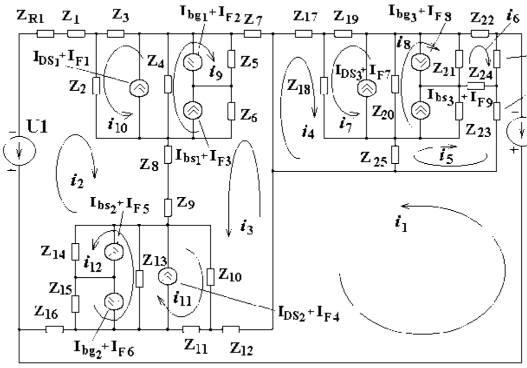

Fig. 2 – Equivalent circuit of a radio-measuring transducer

$$Z_{R1} = R1\,,\ Z_1 = R_{G1}\,,\ Z_3 = -j/(\omega C_{GD1})\,,$$

$$Z_4 = Z_K\,, Z_5 = -j/(\omega C_{BD1})\,,\ Z_7 = R_{D1}\,,\ Z_8 = R_{S1} + j\omega L_{S1}\,,$$

$$Z_{12} = R_{G2}\,,\ Z_{11} = -j/(\omega C_{GD2})\,,\ Z_{13} = Z_K\,,$$

$$Z_{15} = -j/(\omega C_{BD2})\,,$$

$$Z_2 = \frac{R_{GS1}}{1+\omega^2 R_{GS1}^2 C_{GS1}^2} - j\frac{R_{GS1}^2 \omega C_{GS1}}{1+\omega^2 R_{GS1}^2 C_{GS1}^2}\,,$$

$$Z_6 = \frac{R_{B1}}{1+\omega^2 R_{B1}^2 C_{BS1}^2} - j\frac{R_{B1}^2 \omega C_{BS1}}{1+\omega^2 R_{B1}^2 C_{BS1}^2}\,,\ Z_{16} = R_{D2}\,,$$

$$Z_9 = R_{S2} + j\omega L_{S2}\,,\ Z_{17} = R_{G3}\,,\ Z_{19} = -j/(\omega C_{GD3})\,,$$

$$Z_{20} = Z_K\,,\ Z_{21} = -j/(\omega C_{BD3})\,,$$

$$Z_{10} = \frac{R_{GS2}}{1+\omega^2 R_{GS2}^2 C_{GS2}^2} - j\frac{R_{GS2}^2 \omega C_{GS2}}{1+\omega^2 R_{GS2}^2 C_{GS2}^2}\,,\ Z_{22} = R_{D3}\,,$$

$$Z_{14} = \frac{R_{B2}}{1+\omega^2 R_{B2}^2 C_{BS2}^2} - j\frac{R_{B2}^2 \omega C_{BS2}}{1+\omega^2 R_{B2}^2 C_{BS2}^2}\,,$$

$$Z_{25} = R_{S3} + j\omega L_{S3}\,,\ Z_{R2} = R2\,,$$

$$Z_{C1} = -j/(\omega C_{C1})\,,$$

$$Z_{18} = \frac{R_{GS3}}{1+\omega^2 R_{GS3}^2 C_{GS3}^2} - j\frac{R_{GS3}^2 \omega C_{GS3}}{1+\omega^2 R_{GS3}^2 C_{GS3}^2}\,,$$

$$Z_{23} = \frac{R_{B3}}{1+\omega^2 R_{B3}^2 C_{BS3}^2} - j\frac{R_{B3}^2 \omega C_{BS3}}{1+\omega^2 R_{B3}^2 C_{BS3}^2}\,.$$

The solution of the system of equations based on Kirchhoff's laws was obtained using numerical methods in the software package «Matlab 9.3» [12, 13]. The transfer function is described by the equation:

$$F_0 = \frac{1}{2}\frac{\sqrt{\dfrac{C_d^3(P)R_d^4(P) + C_d^4(P)R_d^4(P) - A_1 + B_1}{L_{ekv}C_d^5(P)R_d^6(P)}}}{\pi}\,, \qquad (1)$$

where

$A_1 = L_{ekv}C_d^3(P)R_d^4(P)$, $B_1 = \sqrt{R_d^8(P)(C_d(P)-1)^2 C_d^6(P)}$,

L_{ekv} is the equivalent inductance of the oscillating circuit. The sensitivity of the radio-measuring frequency transducer of optical radiation is estimated based on the expression (1).

$$\begin{aligned} S_P = -\frac{1}{4}\Bigg(& 2R_d(P)\left(\frac{\partial C_d(P)}{\partial P}\right)B_1 + 2C_d(P)\left(\frac{\partial R_d(P)}{\partial P}\right)B_1 + \\ & +2C_d^2(P)\left(\frac{\partial R_d(P)}{\partial P}\right)B_1 + R_d(P)C_d(P)\left(\frac{\partial C_d(P)}{\partial P}\right)B_1 - \\ & -2L_{ekv}R_d(P)\left(\frac{\partial C_d(P)}{\partial P}\right)B_1 - 2L_{ekv}C_d(P)\left(\frac{\partial R_d(P)}{\partial P}\right)B_1 + \\ & +2R_d^5(P)C_d^3(P)\left(\frac{\partial C_d(P)}{\partial P}\right) + 2R_d^4(P)C_d^4(P)\left(\frac{\partial R_d(P)}{\partial P}\right) + \\ & +4R_d^4(P)C_d^5(P)\left(\frac{\partial R_d(P)}{\partial P}\right) + 3R_d^5(P)C_d^4(P)\left(\frac{\partial C_d(P)}{\partial P}\right) + \\ & +2R_d^4(P)C_d^6(P)\left(\frac{\partial R_d(P)}{\partial P}\right) + R_d^5(P)C_d^5(P)\times \\ & \times\left(\frac{\partial C_d(P)}{\partial P}\right)\Bigg)\Bigg/\Bigg(-C_d^3(P)\,R_d^3(P)\pi L_{ekv}B_1 \times \\ & \times\sqrt{\frac{R_d^4(P)C_d^3(P) + R_d^4(P)C_d^6(P) - A_1 + B_1}{L_{ekv}R_d^6(P)C_d^5(P)}}\Bigg). \end{aligned} \qquad (2)$$

The theoretical and experimental dependences of the frequency of generation on the power of optical radiation are shown in Fig. 3. The frequency was measured using an ATTEN F2700C frequency meter. The frequency of generation increased due to decreasing inductance of the oscillating circuit of the self-oscillator, which is related with the photo-generation of non-equilibrium charge carriers both in the channel region and in the region of *p-n* junctions of the drain and source of the MOS transistors. The dependence of the sensitivity of the transducer on the optical radiation power was calculated according to (2) and varies from 9.7 kHz/μW/cm² to 24.5 kHz/μW/cm² (Fig. 4).

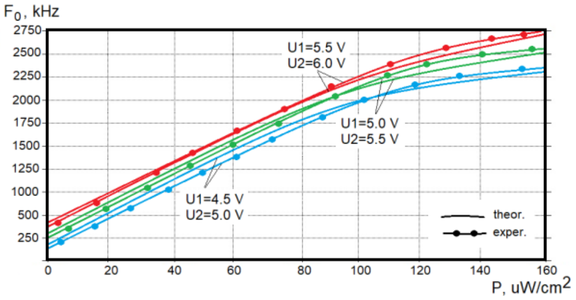

Fig. 3 – Theoretical and experimental dependences of the generation frequency on the optical radiation power

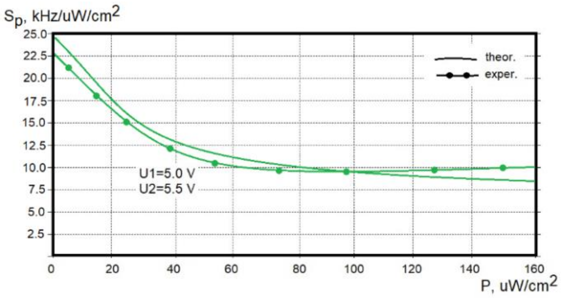

Fig. 4 – Theoretical dependence of the transducer sensitivity on the optical radiation power

4. THE MATHEMATICAL MODEL OF THERMAL MODES OF RADIO-MEASURING FREQUENCY TRANSDUCERS OF OPTICAL RADIATION BASED ON MOS TRANSISTOR STRUCTURES WITH NEGATIVE DIFFERENTIAL RESISTANCE

The integrated circuit of the radio-measuring frequency transducer of optical radiation consists of a solid-state semiconductor crystal, the atoms of which are connected by elastic forces. Therefore, the thermal vibrations of an atom are transferred to another, and thus elastic waves propagate in all directions of the volume. These waves differ from each other not only in the direction of propagation, but in their length as well: the shortest ones have a length equal to the double length between adjacent atoms, and the longest ones have a length equal to the length of the crystal. In ideal crystals, atoms are connected to each other by forces F, which are described by Hooke's law [14]:

$$F = -f\frac{x - x_0}{x_0} = -f\frac{\Delta x}{x_0},$$

where f is the spring constant, x_0 is the normalized distance between atoms in the quiescent state (i.e., lattice constant), Δx is the change of this distance.

In real crystals, the interaction force of atoms F is determined by means of Δx in an infinite series [15-17]

$$F = -f\frac{\Delta x}{x_0} + g\left(\frac{\Delta x}{x_0}\right)^2 + \dots, \qquad (3)$$

and the larger the change in the distance (amplitude of oscillations) Δx, the greater the weight of the following expansion terms.

Considering thermal fluctuations, it is necessary to take into account the second component in the expansion (3). In addition, its value the greater, the larger the coefficient g, which is called the anharmonicity coefficient, and the greater the amplitude of oscillations (i.e., the higher the temperature).

The presence of this component leads to the following consequences:

- an average distance between atoms in a real crystal increases with increasing temperature, besides, the coefficient of thermal expansion is proportional to the coefficient g;
- atomic fluctuations cease to be strictly harmonious and as a result, they cannot propagate independently, conversely, when they meet, they disperse, i.e., change their motion direction and exchange energy.

There are always defects (impurities, empty sites, atoms in interstitials, dislocations, grain boundaries) in real semiconductor materials, on which elastic waves are also scattered. Therefore, the thermal conductivity of real crystals has a certain value, which depends on the degree to which the above factors (anharmonicity and defects) prevent the propagation of thermal waves. Electrical modes of operation of frequency measuring transducers significantly affect their parameters. The current flowing through transistors, resistances and other elements of the integrated circuit leads to an increase in temperature due to power dissipation. Analysis of the thermal state of the integrated circuit is a complex task, the solution of which can be made on the basis of mathematical modeling, taking into account the physical processes and design features of the integrated circuit. Using the results of mathematical modeling, it is possible to optimize the parameters of microelectronic transducers [18-20]. In this paper, in contrast to the studies mentioned above, an attempt is made to simulate the thermal mode for radio-measuring frequency transducers of physical quantities [20].

The thermal model of the transducer consists of a thin silicon wafer with certain sizes, in the surface layer of which two complementary MOS transistors and an active inductance based MOS transistor are formed. They are combined using current-carrying tracks into a measuring circuit. MOS transistors heat up when current flows through them, which breaks the thermal mode of the radio-frequency transducer and affects the accuracy of its operation. The thickness of the source, drain, and channels of a MOS transistor is within a few micrometers, and the thickness of the silicon substrate is several hundred micrometers. Assume that the semiconductor substrate has a constant temperature and is an isothermal surface.

The temperature distribution in space and time in the microelectronic circuit of the frequency transducer is described by the heat equation, which has the form [14]:

$$c\rho\frac{\partial T}{\partial t} = F(x,y,z) + \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \qquad (4)$$

where ρ is the material density, λ is the thermal conductivity of the material, x, y, z are coordinates of MOS transistors, T is the temperature, $F(x, y, z)$ is the heat dissipation density, c is the specific heat of silicon, and t is the time.

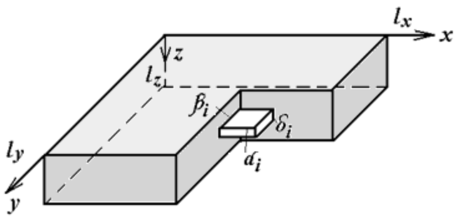

Fig. 5 – Thermal model of a radio-frequency transducer

The stationary thermal field in the volume and on the surface of the studied thermal model of the radio-frequency transducer (Fig. 5), based on formula (4), is described by the expression

$$\frac{\partial^2 T(x,y,z)}{\partial x^2}+\frac{\partial^2 T(x,y,z)}{\partial y^2}+\frac{\partial^2 T(x,y,z)}{\partial z^2}=-\frac{1}{\lambda}F(x,y,z), \quad (5)$$

where $T(x, y, z)$ is the overheating temperature in thermal models with coordinates x, y, z regarding the temperature of the transducer housing.

In equation (5), the function $F(x, y, z)$ determines the power density of heat generation, which depends on the geometric dimensions of the element, the location and power of heat sources

$$F(x,y,z)=\sum_{i=1}^{I}\frac{f_i}{V_i}q_i(x)q_i(y)q_i(z),$$

where $V_i=\alpha_i\beta_i\delta_i$ is the volume of the heat source number i; $q_i(x), q_i(y), q_i(z)$ are the coordinate functions that take a value of 1 in the region of the source number i and value 0 outside it.

Equation (5) can be solved using the Fourier transform method [18, 19] with finite limits and applying the assumption of superposition of temperature fields.

Supposing that

$$\tilde{T}(n,m,k)=\int_0^{l_x}\int_0^{l_y}\int_0^{l_z}T(x,y,z)\cos\frac{n\pi x}{l_x}\cos\frac{m\pi y}{l_y}\times$$
$$\times\left[\gamma_k l_z\cos\gamma_k z+hl_z\sin\gamma_k z\right]dxdydz, \quad (6)$$

where $\tilde{T}(n,m,k)$ is the expression of temperature $T(x, y, z)$, γ_k are the positive roots of the equation

$$\mathrm{ctg}\gamma_k l_z=\frac{\gamma_k^2-h^2}{2\gamma_k h}\,(k=0,1,2...).$$

Equation (5) is transformed into the space of Fourier images. For this transformation, both parts of expression (5) are multiplied by the core of transformations (6) and integrated over x from 0 to l_x, over y from 0 to l_y, over z from 0 to l_z.

The formula for estimating the temperature at any point in the volume of the frequency measuring transducer takes the form

$$T(x,y,z)=T_c+\frac{2}{\lambda\gamma_0^3 l_x l_y \upsilon_0}\sum_{i=1}^{I}\frac{f_i}{\delta_i}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\sin\gamma_0\frac{\delta_i}{2}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)+\frac{4}{\lambda\gamma_0\pi l_y\upsilon_0}\sum_{n=1}^{\infty}\frac{1}{n\left[\left(n\pi/l_x\right)^2+\gamma_0^2\right]}\times$$
$$\times\sum_{i=1}^{I}\frac{f_i}{\alpha_i\delta_i}\cos\frac{n\pi x_i}{l_x}\sin\frac{n\pi\alpha_i}{2l_x}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\sin\gamma_0\frac{\delta_i}{2}\cos\frac{n\pi x}{l_x}(\gamma_0\cos\gamma_0 z+h\sin\gamma_0 z)+\frac{4}{\lambda\gamma_0\pi l_x\upsilon_0}\sum_{m=1}^{\infty}\frac{1}{m\left[\left(m\pi/l_y\right)^2+\gamma_0^2\right]}\times$$
$$\times\sum_{i=1}^{I}\frac{f_i}{\beta_i\delta_i}\cos\frac{m\pi y}{l_y}\sin\frac{m\pi\beta_i}{2l_y}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\sin\gamma_0\frac{\delta_i}{2}\cos\frac{m\pi y}{l_y}(\gamma_0\cos\gamma_0 z+h\sin\gamma_0 z)+\frac{2}{\lambda l_x l_y}\sum_{k=1}^{\infty}\frac{1}{\gamma_k^2\upsilon_k^2}\times \quad (7)$$
$$\times\sum_{i=1}^{I}\frac{f_i}{\delta_i}(\gamma_k\cos\gamma_k z_i+h\sin\gamma_k z_i)\sin\gamma_k\frac{\delta_i}{2}(\gamma_k\cos\gamma_k z+h\sin\gamma_k z)+\frac{64}{\lambda\pi^2}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{k=1}^{\infty}\frac{\cos\frac{n\pi x}{l_x}\cos\frac{m\pi y}{l_y}(\gamma_k\cos\gamma_k z+h\sin\gamma_k z)}{nm\gamma_k\left[\left(n\pi/l_x\right)^2+\left(m\pi/l_y\right)^2+\gamma_k^2\right]}\times$$
$$\times\sum_{i=1}^{I}\frac{f_i}{\upsilon_i}\cos\frac{n\pi x_i}{l_x}\sin\frac{n\pi\alpha_i}{2l_x}\cos\frac{m\pi y_i}{l_y}\sin\frac{m\pi\beta_i}{2l_y}(\gamma_k\cos\gamma_k z_i+h\sin\gamma_k z_i)\sin\gamma_k\frac{\delta_i}{2}.$$

In (7), T_c is the ambient temperature. Expression (7) is a trigonometric series that converges fast, therefore, in its calculations, the number of members of the series is limited by the numbers $N=2^r$, $M=2^d$, $K=2^e$, where r, d, e are the integers that are selected based on the accuracy of calculations. Such selection N, M, K allows to use fast Fourier transforms in temperature calculations. The geometric dimensions of the controlled integrated circuit of the radio-frequency transducer, the values of the thermal conductivity of the material and the heat transfer coefficients from its surface, the number of active elements and the coordinates of their centers are determined from the design of the transducer. To determine the number of unknown heat generation capacities f_i ($i=1, \ldots, I$, where I is the number of heat sources), discrete temperature values are substituted into the left side of formula (7), while being limited to a finite number of series components on the right side of expression (7). As a result, we obtain a system of linear algebraic equations for unknown heat generation capacities. The temperature on the surface of the active elements of the measuring frequency transducer is determined by the equation

$$T(x_p,y_p,0)=T_c+\frac{2}{\lambda\gamma_0^3 l_x l_y \upsilon_0}\sum_{i=1}^{I}\frac{f_i\gamma_0}{\delta_i}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\sin\gamma_0\frac{\delta_i}{2}+\frac{4}{\lambda\gamma_0\pi l_y\upsilon_0}\sum_{n=1}^{N}\frac{\cos\left(n\pi x_p/l_x\right)}{n\left[\left(n\pi/l_x\right)^2+\gamma_0^2\right]}\sum_{i=1}^{I}\frac{f_i\gamma_0}{\alpha_i\delta_i}\cos\frac{n\pi x_i}{l_x}\times$$
$$\times\sin\frac{n\pi\alpha_i}{2l_x}(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\sin\gamma_0\frac{\delta_i}{2}+\frac{4}{\lambda\gamma_0\pi l_x\upsilon_0}\sum_{m=1}^{\infty}\frac{\cos\left(n\pi y_p/l_y\right)}{m\left[\left(m\pi/l_y\right)^2+\gamma_0^2\right]}\sum_{i=1}^{I}\frac{f_i\gamma_0}{\beta_i\delta_i}\cos\frac{m\pi y_i}{l_y}\sin\frac{m\pi\beta_i}{2l_y}\sin\gamma_0\frac{\delta_i}{2}+$$
$$+(\gamma_0\cos\gamma_0 z_i+h\sin\gamma_0 z_i)\frac{2}{\lambda l_x l_y}\sum_{k=1}^{K}\frac{\gamma_k}{\gamma_k^2\upsilon_k^2}\sum_{i=1}^{I}\frac{f_i}{\delta_i}(\gamma_k\cos\gamma_k z_i+h\sin\gamma_k z_i)\sin\gamma_k\frac{\delta_i}{2}+\sum_{i=1}^{I}\frac{f_i}{\upsilon_i}\cos\frac{n\pi x_i}{l_x}\sin\frac{n\pi\alpha_i}{2l_x}\cos\frac{m\pi y_i}{l_y}\sin\frac{m\pi\beta_i}{2l_y}\times \tag{8}$$
$$\times\frac{64}{\lambda\pi^2}\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}\frac{\gamma_k\cos\left(n\pi x_p/l_x\right)\cos\left(m\pi y_p/l_y\right)}{nm\upsilon_k\left[\left(n\pi/l_x\right)^2+\left(m\pi/l_y\right)^2+\gamma_k^2\right]}(\gamma_k\cos\gamma_k z_i+h\sin\gamma_k z_i)\sin\gamma_k\frac{\delta_i}{2},\quad (p=1,2,3\ldots p),$$

where p is the number of active elements of the measuring frequency transducer.

The thermal model of the radio-frequency transducer under stationary thermal conditions is described by expressions (7), (8). Using the developed mathematical model, the temperature field of the radio-frequency inverter has been calculated. It has the form of curves with identical temperature variation over the area of the integrated circuit (Fig. 6). The curves demonstrate an overheating temperature in degrees Celsius. The design parameters of the transducer have the following values: the size of the integrated circuit is 800×600 microns, the maximum power dissipated by transistors is 55 mW. As can be seen in Fig. 7, the areas of transistors beside the drains, that impede heat dissipation to the transducer housing, have maximum overheating.

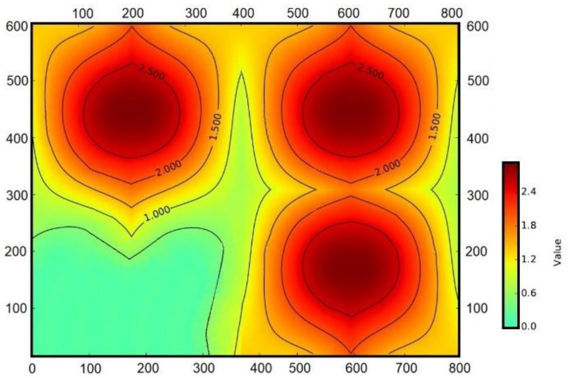

Fig. 6 – The temperature field of the frequency transducer

The solution of the two-dimensional unsteady equation of heat conduction allows one to determine the parameters of the transient process, which reproduces the dependence of temperature on time for different parts of the surface of the integrated circuit of the transducer

$$T(x,y,t)=T_C(x,y)+\frac{2}{\sqrt{l_x l_y}}\times$$
$$\times\left[\sum_{n,m=1}^{\infty}\frac{2}{\sqrt{l_x l_y}}\int_0^{l_x}\int_0^{l_y}T_C(x,y)\sin\frac{n\pi x}{l_x}\sin\frac{m\pi y}{l_y}dxdy\right]\times \tag{9}$$
$$\times\exp\left(^{-\pi^2 a^2(n^2/l_x^2+m^2/l_y^2)t}\right)\sin\frac{n\pi x}{l_x}\sin\frac{m\pi y}{l_y},$$

where $a = c\rho/\lambda$, t is the time.

Fig. 7 presents the calculations of the unsteady thermal mode according to (9) of the microelectronic transducer. The time to reach steady state does not exceed $5.8\cdot10^{-4}$ s. In this case, the maximum temperature of overheating for the elements of the integrated circuit of the transducer does not exceed 2.49 °C. Calculations of the temperature field and transition state are performed in a software environment "Matlab 9.3" [13].

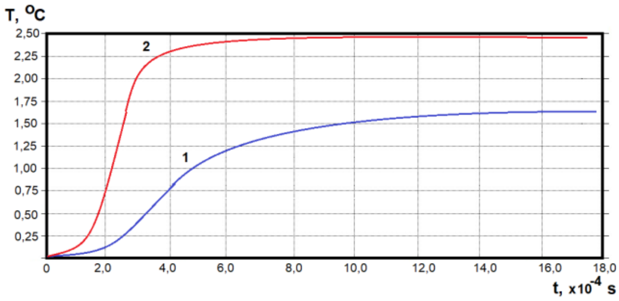

Fig. 7 – Transient state of thermal conditions of various parts of the measuring transducer: 1 – the central zone of the transducer; 2 – elements oriented parallel to the side of the substrate

5. CONCLUSIONS

The study of the radio-frequency transducer of optical radiation based on the MOS transistor structure with the active inductive element has been performed and the analytical expressions of the transfer function and sensitivity equations have been obtained based on the solution of the system of non-linear equations. Theoretical and experimental dependences of the frequency of generation on the power of optical radiation are presented. The increase in the frequency of generation is associated with a decrease in the inductance of the oscillating circuit of the self-oscillator, which is due to the photo-generation of non-equilibrium charge carriers in the channel region and also in *p-n* junctions of the drains and sources of MOS transistors. The dependence of the sensitivity of the transducer on the optical radiation power varies in the range from 9.7 kHz/μW/cm² to 24.5 kHz/μW/cm². The mathematical model of thermal modes of the radio-measuring frequency transducer of optical radiation has been developed. The calculations of the non-stationary thermal mode of the frequency converter have been performed according to these results. The temperature field of the integrated circuit of the transducer has been obtained. The time to reach steady state does not exceed $5.8\cdot10^{-4}$ s. The maximum temperature of the overheating for the elements of the integrated circuit of the transducer does not exceed 2.49 °C.

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Математична модель радіовимірювального частотного перетворювача оптичного випромінювання на основі МДН-транзисторної структури з від'ємним диференційним опором

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У статті розглядаються результати теоретичних та експериментальних досліджень радіовимірювального частотного перетворювача оптичного випромінювання на основі МДН транзисторної структури з від'ємним диференційним опором та активним індуктивним елементом. Представлено аналітичні вирази функції перетворення та рівняння чутливості, які отримано на основі розв'язку системи нелінійних рівнянь. Експериментальні дослідження вольт-амперних характеристик запропонованої транзисторної структури частотного перетворювача оптичного випромінювання в статичному та динамічному режимах підтверджують наявність ділянки з від'ємним диференційним опором на ВАХ, який компенсує втрати в коливальному колі. Представлені теоретичні та експериментальні залежності частоти генерації від потужності оптичного випромінювання. Залежність чутливості розробленого перетворювача від потужності оптичного випромінювання коливається від 9,7 кГц/мкВт/см² до 24,5 кГц/мкВт/см². Розроблено математичну модель теплових умов радіовимірювального частотного перетворювача оптичного випромінювання. Розрахунок нестаціонарних теплових умов частотного перетворювача дозволив отримати температурне поле інтегральної схеми пристрою. Час досягнення стійкого стану не перевищує $5,8 \cdot 10^{-4}$ с. Більше того, максимальна температура перегріву для елементів інтегральної схеми перетворювача не перевищує 2,49 °C.

Ключові слова: Математична модель, Теплові режими, Оптичне випромінювання, МДН-транзистор, Від'ємний диференційний опір.