УДК 621.38

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FREQUENCY TRANSDUCER OF GAS CONCENTRATION IN TRANSISTOR STRUCTURE WITH NEGATIVE RESISTANCE

I. INTRODUCTION

One of the promising scientific direction in the creation of gas transducers is the use of reactive properties of semiconductor devices with negative resistance. It allows to convert gas concentration in the frequency output providing high noise stability as well as high accuracy of gas concentration measurements.

Moreover, the transducers with frequency output have both simplicity and versatility inherent in analog devices in addition to accuracy and noise immunity intrinsic in code output transducers [1 – 3]. These transducers have high sensitivity to measuring parameters, smaller overall dimensions and weight, informational, technological and structural compatibility with microelectronic information processing devices. It provides its advantages over existing gas concentration sensors [4 – 6].

The development of a mathematical model, describing the dependence of active and reactive components of the impedance of the structure is needed to study the properties of the frequency transducer gas concentration. This model includes a transfer function, which is a basis for obtaining the sensitivity of transducer. The transfer function in turn depends on active and reactive components of the output impedance of the transducer.

The study is devoted to discussion of these problems.

II. THEORETICAL AND EXPERIMENTAL RESEARCH

The frequency transducer of the gas concentration based on self-sustained oscillator, with MEMS resistive element MiCS 6814, sensitive to concentration of combustible gases, is shown in Fig. 1.

The oscillator of the device is implemented using equivalent capacity of the impedance on such electrodes as collector and drain of bipolar and MOS field-effect transistor VT1 and VT2 respectively [7, 8]. Voltages U1 and U2 provides supply of circuit.

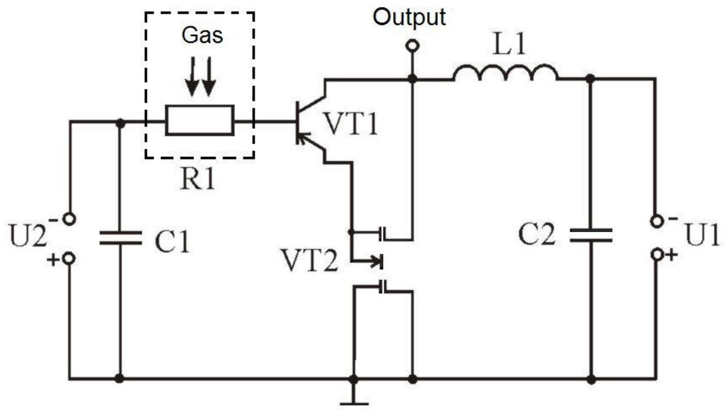

Fig. 1. An elecrtric circuit of frequency transducer of gas concentration

It is necessary that a mathematical model should be developed to study the properties of the frequency transducer of gas concentration. This model enables to obtain the dependencies of active and reactive components of the impedance of the structure on gas concentration, and the analytic expressions for the transfer function and sensitivity [15, 16]. The calculations were performed using the equivalent circuits of bipolar transistor and MOS field-effect transistor for alternating current, which create self-sustained oscillator of the frequency transducer of gas concentration (Fig. 2).

The calculation of the impedance on electrodes collector-drain of bipolar transistor VT1 and MOS field-effect transistor VT2 through equivalent circuit (Fig. 2) is needed to determine main parameters describing the frequency transducer of gas concentration operation [9].

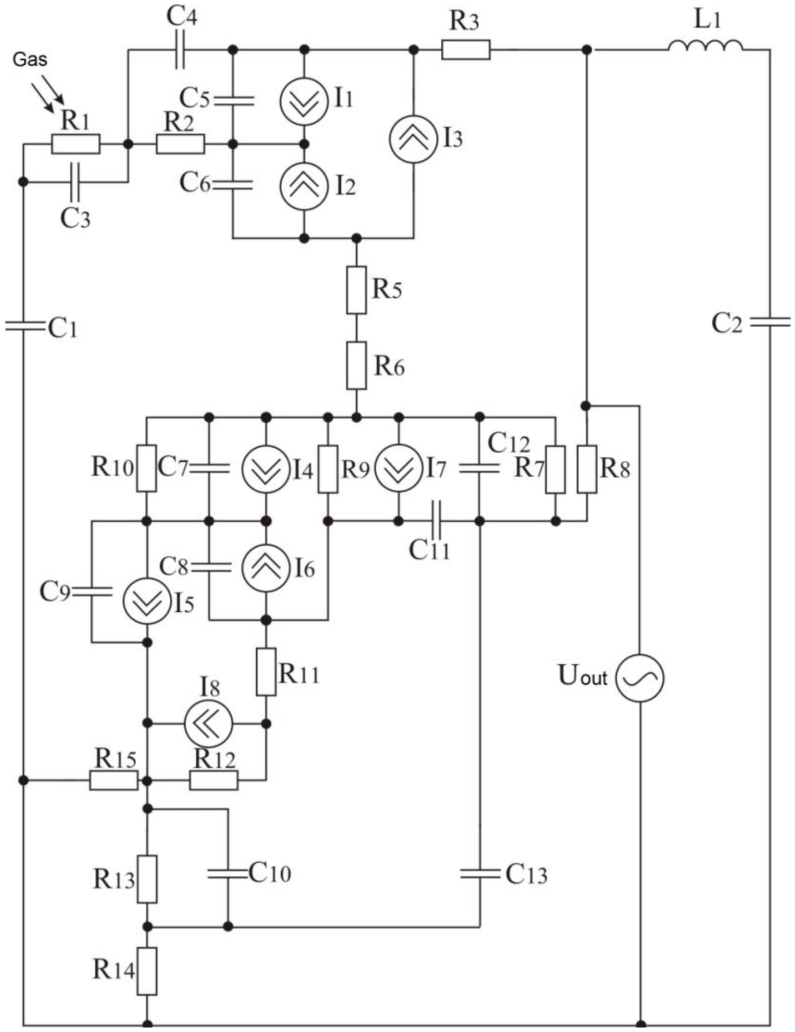

Fig. 2. Equivalent AC circuit of transducer of gas concentration

Fig. 3 shows the equivalent circuit of the frequency transducer of gas concentration for alternating current, transformed into more convenient for calculations.

The current-voltage characteristic curve of the transistor structure which is used for creation of the frequency transducer of gas concentration, has the negative resistance region. The negative resistance compensates losses in the oscillator. It is formed by the equivalent capacity of the electrodes collector-drain of bipolar transistor VT1 and MOS field-effect transistor VT2, and by the external inductance [10-12]. The equivalent circuit (Fig. 2) uses the next symbols: R_1 – resistance of MEMS resistive element MiCS 6814, sensitive to change of concentration of combustible gases; R_2, R_3, R_5 – bulk resistances of emiter, collector and base of bipolar transistor VT1 respectively; R_6, R_{15}, R_8 and R_{14}– bulk resistances of the source, drain, first and second gate of MOS transistor VT2 respectively; R_7 – bulk resistance of gate-source of MOS transistor VT2; R_8 – bulk resistance of gate of MOS transistor VT2; R_9, R_{11} and R_{12} – bulk resistances of drain-source of MOS transistor VT2; R_{10} – resistance of body of MOS transistor VT2; R_{13} – resistance of gate-drain of MOS transistor VT2; C_1 – capacity of capacitor C_1; C_2 – capacity of capacitor C_2; C_3 – capacity of MEMS resistive element MiCS 6814, sensitive to change of concentration of combustible gases; C_4 – capacity beetwen external term of base and collector of bipolar transistor VT1;

C_5, C_6 – capacities of junctions base-collector and base-emiter of transistor VT1 respectively; C_7 – capacity of body-source of MOS transistor VT2; C_8 and C_9 – capacities of body-drain of MOS transistor VT2; C_{10}, C_{11} and C_{12} – capacities of gate-drain of MOS transistor VT2; C_{13} – capacity between first and second gates MOS transistors VT2; L_1 – external inductor.

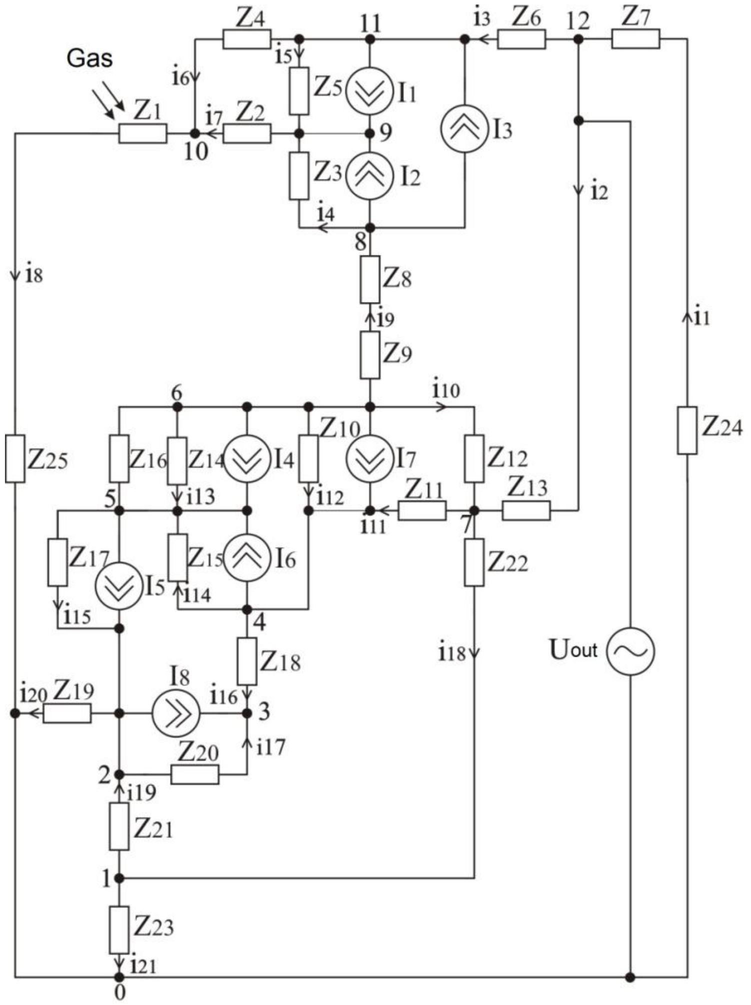

Fig. 3. Transformed equivalent AC circuit of transducer of gas concentration

The following characters are used in the transformed equivalent circuit (Fig. 3):

$$Z_1=\frac{R_1}{1+\omega^2R_1^2C_3^2}-j\frac{R_1^2\omega C_3}{1+\omega^2R_1^2C_3^2};\ Z_2=R_2;\ Z_3=-\frac{j}{\omega C_6};\ Z_4=-\frac{j}{\omega C_4};\ Z_5=-\frac{j}{\omega C_5};Z_6=R_3;$$

$$Z_7=j\omega L;\ Z_8=R_5;\ Z_9=R_6;\ Z_{10}=R_9;\ Z_{11}=-\frac{j}{\omega C_{11}};\ Z_{12}=\frac{R_7}{1+\omega^2R_7^2C_{12}^2}-j\frac{R_7^2\omega C_{12}}{1+\omega^2R_7^2C_{12}^2};$$

$$Z_{13}=R_8;\ Z_{14}=-\frac{j}{\omega C_7};\ Z_{15}=-\frac{j}{\omega C_8};\ Z_{16}=R_{10};\ Z_{17}=-\frac{j}{\omega C_9};\ Z_{18}=R_{11};\ Z_{19}=R_{15};$$

$$Z_{20}=R_{12};\ Z_{21}=\frac{R_{13}}{1+\omega^2R_{13}^2C_{10}^2}-j\frac{R_{13}^2\omega C_{10}}{1+\omega^2R_{13}^2C_{10}^2};\ Z_{22}=-\frac{j}{\omega C_{13}};\ Z_{23}=R_{14};\ Z_{24}=-\frac{j}{\omega C_2};$$

$$Z_{25}=-\frac{j}{\omega C_1}.$$

In order to receive the components of impedance, we have to solve the Kirchhoff's system of equation for AC created for the equivalent circuit shown in Fig. 3, using circuit node 0 as a basic one (1):

$$\begin{cases} 0 = -\varphi_1(y_{18} + y_{19} - y_{21}) - \varphi_2 y_{19} + \varphi_7 y_{18}; \\ I_8 - I_5 = \varphi_1 y_{19} - \varphi_2(y_{19} + y_{20} + y_{17} + y_{15}) + \varphi_3 y_{17} + \varphi_5 y_{15}; \\ -I_8 = \varphi_2 y_{17} + \varphi_3(y_{16} - y_{17}) + \varphi_4 y_{16}; \\ I_6 - I_1 = \varphi_2 y_{16} - \varphi_4(y_{16} + y_{14} + y_{12} + y_{11}) + \varphi_5 y_{14} + \varphi_6 y_{12} + \varphi_7 y_{11}; \\ I_5 - I_4 - I_6 = \varphi_2 y_{15} + \varphi_4 y_{14} - \varphi_5(y_{15} - y_{13} - y_{14}) + \varphi_6 y_{13}; \\ I_4 + I_8 = \varphi_4 y_{12} + \varphi_5 y_{13} - \varphi_6(y_{13} + y_{12} + y_{10} + y_9) + \varphi_7 y_{13} + \varphi_8 y_9; \\ 0 = \varphi_1 y_{18} + \varphi_4 y_{11} + \varphi_6 y_{13} - \varphi_7(y_{10} + y_{11} + y_2 + y_{18}) + U_{out} y_2 \\ I_2 + I_3 = \varphi_6 y_9 - \varphi_8(y_9 + y_4) + \varphi_9 y_4; \\ -(I_2 + I_1) = \varphi_8 y_4 - \varphi_9(y_4 + y_7 + y_5) + \varphi_{11} y_5 + \varphi_{10} y_7; \\ 0 = \varphi_9 y_7 + \varphi_{11} y_6 - \varphi_{10}(y_8 + y_7 + y_6); \\ I_1 - I_3 - U_{out} y_3 = \varphi_9 y_5 - \varphi_{11}(y_6 + y_5 + y_3) + \varphi_{10} y_6; \\ U_{out}(y_3 + y_2 + y_1) = \varphi_7 y_2 + \varphi_{11} y_3, \end{cases} \qquad (1)$$

The conductivity of the circuit branches are determined by the equations:

$y_1 = 1/(Z_{24} + Z_7)$; $y_2 = 1/Z_{13}$; $y_3 = 1/Z_6$; $y_4 = 1/Z_3$; $y_5 = 1/Z_5$; $y_6 = 1/Z_4$; $y_7 = 1/Z_2$; $y_8 = 1/(Z_{25} + Z_1)$; $y_9 = 1/(Z_8 + Z_9)$; $y_{10} = 1/Z_{12}$; $y_{11} = 1/Z_{11}$; $y_{12} = 1/Z_{10}$; $y_{13} = (Z_{16} + Z_{14})/(Z_{16} Z_{14})$; $y_{14} = 1/Z_{15}$; $y_{15} = 1/Z_{17}$; $Y_{16} = 1/Z_{18}$; $y_{17} = 1/Z_{20}$; $y_{18} = 1/Z_{22}$; $y_{19} = 1/Z_{21}$; $y_{20} = 1/Z_{19}$; $y_{21} = 1/Z_{23}$.

The active and reactive component of the impedance have been calculated in the software package MATLAB 8.1 using the system of equations (1). Calculated and experimental dependencies on gas concentration are shown in Fig. 4.

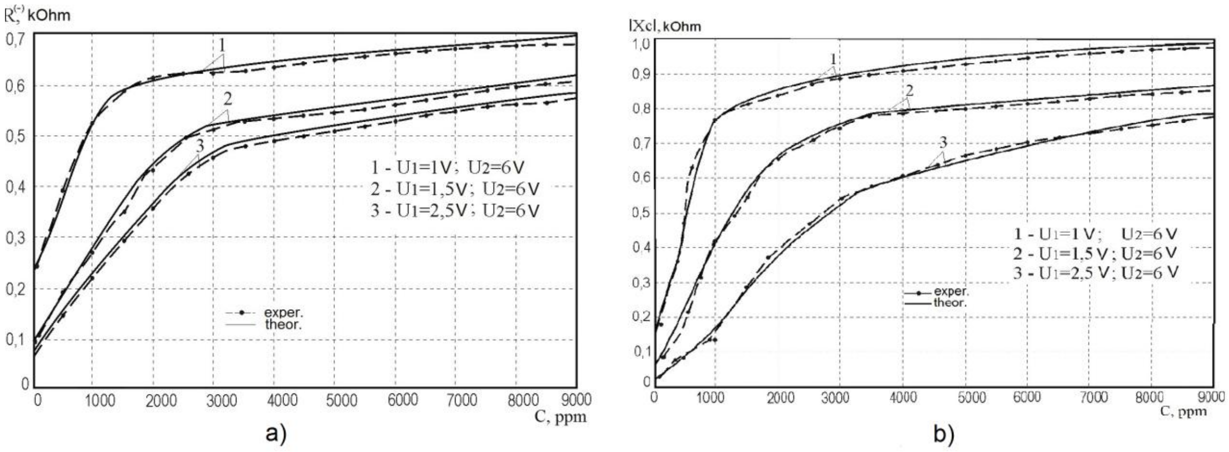

Fig. 4. Theoretical and experimental dependencies of active (a) and reactive (b) component of the impedance on gas concentration

Graphs in Fig. 4 show that active and reactive impedance components increase owing to the increased concentration of gas. Calculated and experimental dependencies of an active and reactive component of the impedance on the supply voltage U_1 are shown in Fig. 5.

The experimental dependencies of oscillation frequency of transducer of gas concentration on supply voltage U_1 and control voltage U_2 are presented in Fig. 6.

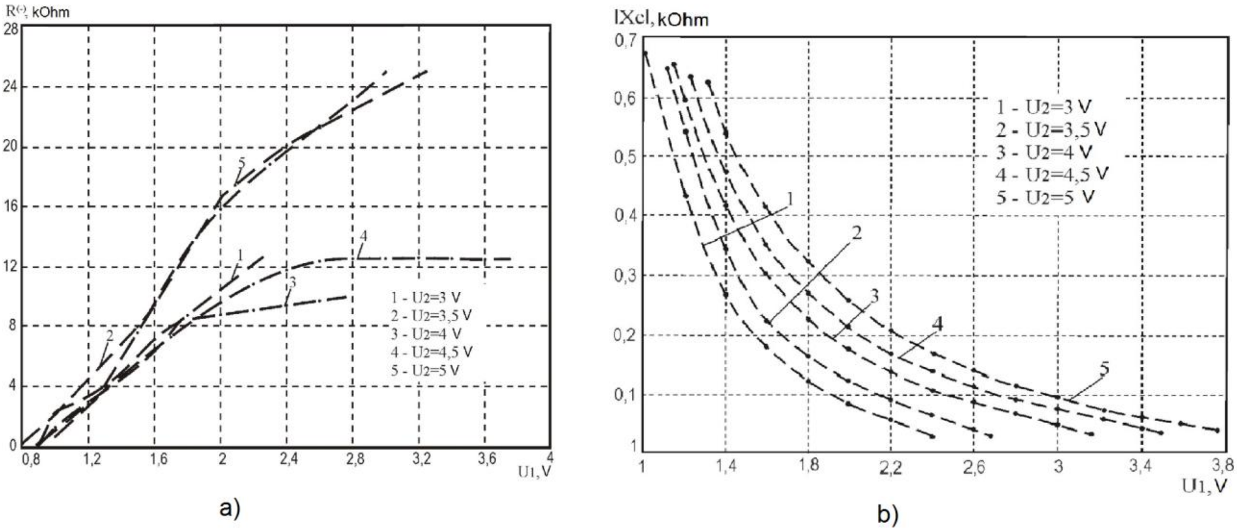

Fig. 5. Experimental dependencies of active (a) and reactive (b) component of the impedance on the supply voltage of transducer

Fig. 6 shows that an optimal mode of the transducer operation is the mode in which the oscillation frequency is linearly dependent on the supply voltage. Such mode matches the operation of transducer at the voltage control 4,5 – 5 V.

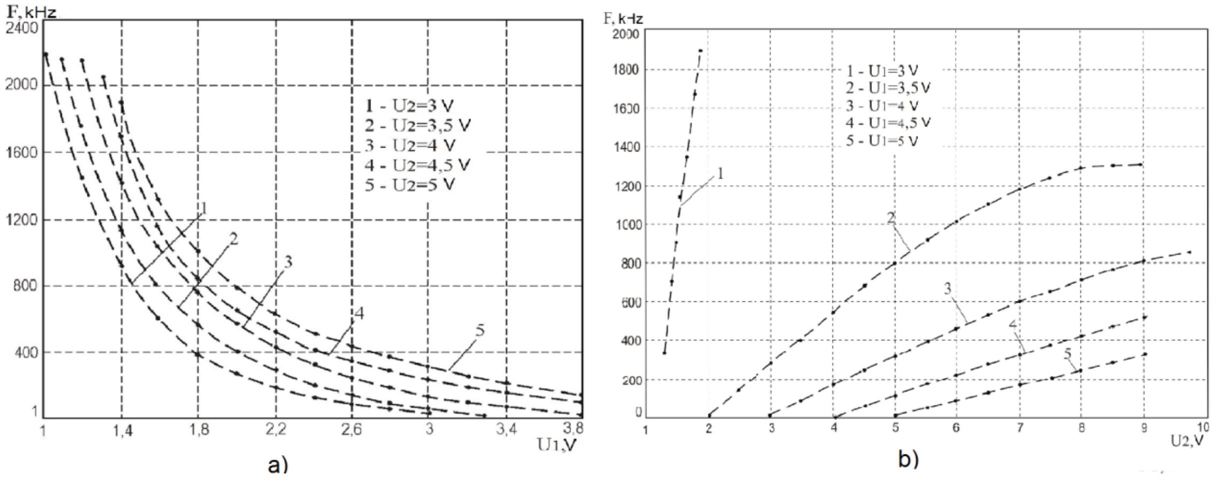

Fig. 6. Experimental dependencies of oscillation frequency on the supply (a) and control (b) voltage of transducer of gas concentration

One can show in Fig. 6 that the oscillator has a stable oscillation within the range from 5 V to 3 V and oscillation mode of the transducer of gas concentration should be selected within this range. The experimental and theoretical dependencies of oscillation frequencies of the transducer on the concentration of propane (C_3H_8) are presented in Fig. 7.

The dependence of the oscillation frequency of the gas concentration (transfer function) is determined by means of the circuit reverse current in accordance with the equivalent circuit (Fig. 3) based on Lyapunov stability theory [13]. The transfer function of radio measuring transducer is described by formula (2)

$$F = \frac{1}{2}\frac{\sqrt{2}\sqrt{L_1C_4(-L_1C_4 + R_1^2(C)C_3^2 + R_1^2(C)C_3C_{42} + A)}}{L_1C_3C_4R_1(C)}, \qquad (2)$$

where $A=\sqrt{L_1^2C_4^2+2L_1C_3^2C_4R_1^2(C)-B+R_1^4(C)C_3^2+D+R_1^4(C)C_3^2C_4^2}$; $B=2L_1C_4^2C_3R_1^2(C)$; $D=2C_3^3C_4R_1^4(C)$; C – concentration of gas (ppm).

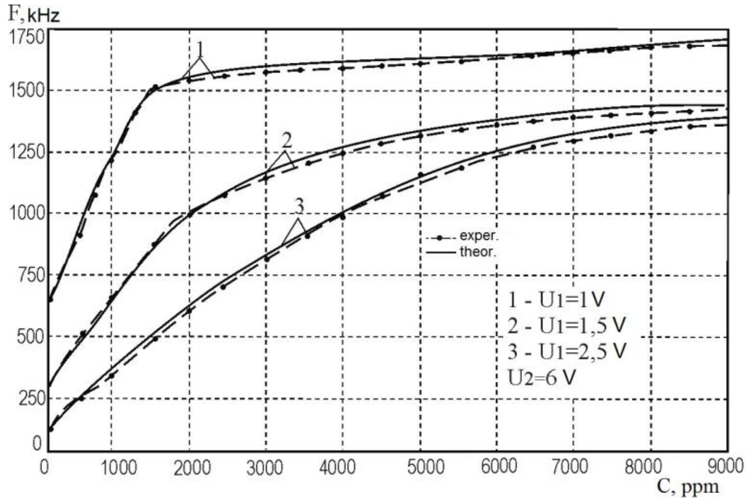

Fig. 7. Theoretical and experimental dependencies of oscillation frequency of transducer on propane (C_3H_8) concentration change

At increasing of gas concentration, the oscillation frequency raises and correlation of the oscillation frequency change and change of gas concentration is the most in the range within from 1ppm to 2000 ppm. The theoretical values agree with experimental data to within better than ± 5%.

The sensitivity of oscillation of the measuring transducer of gas concentration with MEMS resistive element MiCS 6814, sensitive to change of combustible gases concentration has been calculated having used the equation (2):

$$S_C^F=\frac{1}{4}\sqrt{2}\left(2R_1(C)C_3^2\left(\frac{\partial R_1(C)}{\partial C}\right)+2R_1(C)C_3C_4\left(\frac{\partial R_1(C)}{\partial C}\right)+\left(\frac{1}{2}\left(4L_1R_1(C)C_3^2C_4\left(\frac{\partial R_1(C)}{\partial C}\right)-\right.\right.\right.$$
$$-4L_1R_1(C)C_4^2C_3\left(\frac{\partial R_1(C)}{\partial C}\right)+4R_1^3(C)C_3^4\left(\frac{\partial R_1(C)}{\partial C}\right)+8R_1^3(C)C_3^3C_4\left(\frac{\partial R_1(C)}{\partial C}\right)+4R_1^3(C)C_3^2C_4^2\times$$
$$\left.\left.\left.\times\left(\frac{\partial R_1(C)}{\partial C}\right)\right)\Big/\sqrt{D_1}\right)\Big/\left(\sqrt{-L_1C_4(D_2+\sqrt{D_1})}\right)\right)-\frac{1}{2}\sqrt{2}\sqrt{L_1C_4(D_2+\sqrt{D_1})}\times \quad (3)$$
$$\times\left(\frac{\partial R_1(C)}{\partial C}\right)\Big/\left(L_1C_4C_3R_1^2(C)\right),$$

where

$$D_1=L_1^2C_4^2+2L_1C_4C_3^2R_1^2(C)-2L_1C_4^2C_3R_1^2(C)+R_1^4(C)C_3^4+2R_1^4(C)C_3^3C_4+R_1^4(C)C_3^2C_4^2;$$
$$D_2=-L_1C_4+R_1^2(C)C_3^2+R_1^2(C)C_4C_3.$$

Figure 8 below includes the dependence of the sensitivity of the frequency transducer of gas concentration.

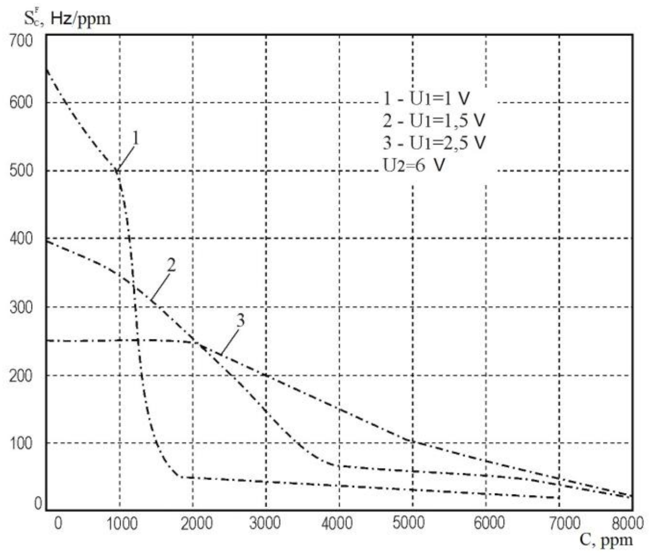

Fig. 8. The sensitivity of the transducer of gas concentration

The graphs in Fig. 8 illustrate that the transducer of gas concentration with MEMS resistive element MiCS 6814 has maximum sensitivity for supply voltage 1 V and control voltage 6 V. The sensitivity is significantly reduced by increasing the concentration of propane. It equals from 175 Hz/ppm to 48 Hz/ppm in the range 1500 ppm to 9000 ppm.

In order to test the design model for adequacy we can use the formula [14]

$$\delta_m = \frac{x_m - x_e}{x_e} \cdot 100\,\%, \tag{4}$$

where x_m – current value of the model; x_e – current experimental value of the parameter.

Fig. 9 shows the dependence of deviations of theoretical model on experimental values of gas concentration. As it is visible (Fig. 9), the divergence of experimental and theoretical data is ±5 %. The dependencies of oscillator frequency of transducer of gas concentration on temperature, are figured in fig.10. One can see that the oscillator frequency raises with increasing temperature. The optimal control voltage equals 3 V. At this voltage there is the slightest change of the oscillation frequency within the range from 20 °C to 80 °C.

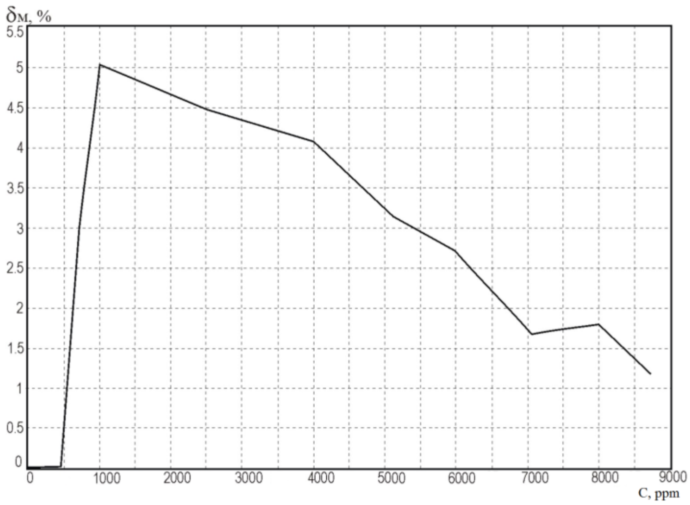

Fig. 9. Dependency of deviations of theoretical model on experimental values of gas concentration

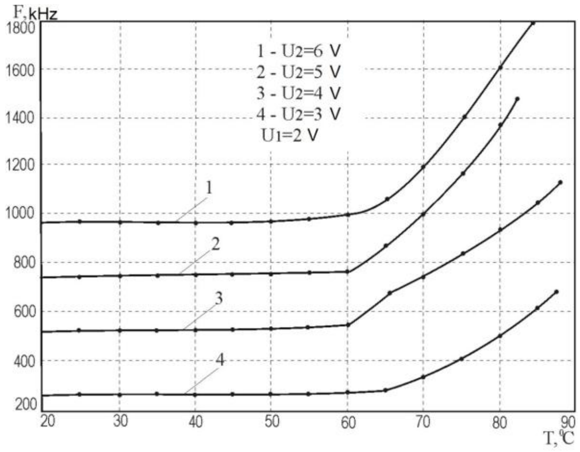

Fig. 10. Dependencies of oscillation frequency
of the transducer of gas concentration on temperature

CONCLUTIONS

The circuit of frequency transducer of gas concentration based on self-sustained oscillator was proposed. Results of the research of the frequency transducer of gas concentration with MEMS resistive element MiCS 6814, sensitive to the concentration change of combustible gases are reported. The dependencies of active and reactive components of the impedance of the frequency transducer of gas concentration on supply, control voltage and on gas concentration were calculated. Analytic expressions for transfer function and sensitivity equation were obtained.

The sensitivity of transducer of gas concentration changes from 645 Hz/ppm to 175 Hz/ppm in the range from 1 ppm to 1500 ppm. However, it substantially decreases with increasing propane concentration from 1500 ppm to 9000 ppm and changes from 175 Hz/ppm to 48 Hz/ppm within the range.

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Поступила в редколлегию 09.10.2017