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Microelectronic Transducer of Gas Concentration based on MOSFET with an Active Inductive Element

***Abstract**. This article presents the microelectronic transducer of gas concentration. The transducer have been used in the absorption spectroscopy technique equipment for measuring concentration of combustible gases. The transducer contains photoresistor and semiconductor structure and provides converting of informative optical signal into the output frequency one. The proposed transducer is low-cost in both material and fabrication and can be used for measuring weak changes of gases. The mathematical model of the microelectronic transducer which describes the transfer function and sensitivity has been calculated. The developed transducer shows a high sensitivity up to 150 Hz/ppm*

Streszczenie.** Zaprezentowano mikroelektroniczny przetwornik koncentracji gazu (spalin) wykorzystujący spektroskopię absorpcji. W układzie przetwarzającym sygnał optyczny na częstotliwość wykorzystano fotorezystor. **Przetwornik koncentracji gazu wykorzystujący aktywny elementem indukcyjnym

Keywords: frequency transducers, negative resistance, gas concentration
Słowa kluczowe: przetwornik koncentracji gazu, fotorezystor, MOSFET

Introduction

Transducers of gas concentration are widely used in the chemical and oil and gas industry for measuring of noxious gases concentration in the production and in the systems intended for environmental monitoring. The accuracy of the determination with control over time of the gas composition in the production and technological processes provides the appropriate quality of the executed work as well as ensures safety of working environment.

The optical methods are considered as the most universal and simple methods for determination of gas concentration. The most perspective optical method is the absorption spectroscopy which has a low threshold of sensitivity (<1 μg/m3) and high selectivity. In the case of small concentrations of controlled substances, the sensitivity can be enhanced by increase in the thickness of the layer in which absorption occurs. Moreover, the advantages of this method include the multipurpose usefulness, high speed of measurements and simplicity of the implementation in the automated systems.

The absorption spectroscopy method, based on the phenomenon of selective absorption of radiation by gases, is the basis of many devices. The selective absorption is explained by the fact that the radiation frequency is resonant for molecules of a certain gas. When light is absorbed, the atoms and molecules of substances pass into a new excited state. The basic gases which concentrations can be determined by the optical method with the optimal wavelengths to occur of absorption in the different areas of the infrared range are presented in [1].

Nowadays, there is a plenty of gas analyzers for a wide variety of gases. The parameters of gas analyzers with operation based on selective absorption of infrared (IR) band radiation by gases from a hydrocarbon group with a wavelength of 2 ÷ 5 μm are given in the papers [2-6]. The parameters of gas analyzers operating on the base of selective absorption of infrared (IR) band radiation by gases which belonged to the hydrocarbon group with the wavelength of 2 ÷ 5 μm are given in the papers [2-6]. The devices operating based on measuring the rate of absorption, instead of amount of absorption are described in [7]. The drawback of analyzers described in [2-6] is the low sensitivity when combustible gases being detected. This drawback is mainly due to the small size of the monitored volume (small distance IR emitter - IR receiver). The other drawback of the analyzers is the complexity of the optical system of transmission of the working and reference IR beams, as well as availability of two IR receivers when these beams are being registered, with their noise characteristics being close but never coincide. This drawback is important when the registering of the toxic gas micro concentrations takes place. The drawback of gas analyzers with a He-Ne laser as an IR emitter is the large weight and high cost of these devices. To cope these problems of the optical frequency transducer can be applied in the circuit of the measuring device, which makes it possible to transform the intensity of radiation absorbed with the IR receiver into an output signal of the appropriate frequency. This transforming ensures a high noise immunity (and therefore accuracy) of measuring the concentrations of gases. In addition, the optical transducers with a frequency output signal, have high sensitivity to measured parameters, small weight and dimensions, constructive and technological compatibility with information technologies for perception, processing and storage of information [8]. It, in turn, proves their edge over the other available optical sensors [9-12].

It is necessary to develop a mathematical model which is going to make possible to obtain the dependences of active and reactive components of the impedance of the semiconductor structure, dependence of frequency on gas concentration as well as an equation of sensitivity.

Moreover, the experimental studies that would confirm the validity of the theory are needed.

The aim of the study is to determine the transfer function and equation of sensitivity for optical transducer of gas concentration by solving Kirchhoff's equations composed for equivalent circuit of the transducer.

Theoretical and experimental research

The optical absorbing method is in the ability of gases to absorb infrared radiation in strictly defined ranges of the spectrum due to the presence of rotational-vibrational absorption bands [13]. The magnitude of the intensity of the weakened radiation passing through the measuring cuvette with the analyzed gas can be determined according to the Bouguer-Lambert-Beer law:

(1) $$I = I_0 \exp(-k \cdot C \cdot l),$$

where: I_0 – the level of the infrared radiation flow at the entrance to the measuring cuvette; k – coefficient of absorption of the analyzed gas depending on the degree of agreement between the absorption spectra of the gas, the spectral characteristics of the source of infrared radiation, and the spectral sensitivity of the infrared receiver; C – concentration of analyzed gas; l – the length of the measuring cuvette.

The technique of measuring of gas concentration using the device shown in Fig. 1 is suggested. The change of the intensity of the light flow emitted by the infrared LED is registered by the photoresistor covered with interference filter for selecting of the control band, wavelength of which matches to the maximum intensity of the band of controlled gas (3.2 μm for methane and 3.5 μm for propane).

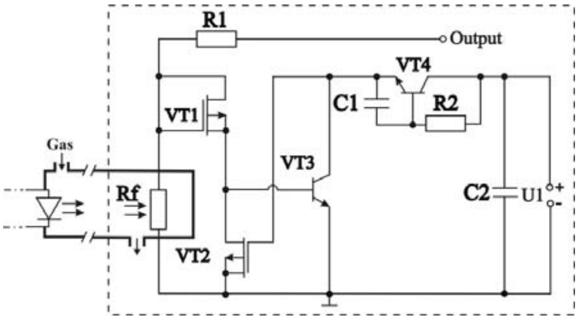

Fig.1. Circuit of frequency optical transducer of gas concentration

The transformation of the optical signal into the frequency one is performed by an oscillatory circuit. The oscillator of electric oscillations is formed by inductivity of bipolar transistor VT4 and the capacitive component of the impedance on electrodes the drain-collector of MOS transistors VT2 and bipolar transistor VT3 respectively. The inductivity based on bipolar transistor VT4 uses the shift RC-circle created with resistor R2 and capacitor C1, and has a low Q-factor. The application of this inductivity makes possible producing of the transducer on the one chip.

To determine impedance of the oscillator the equivalent circuit for alternating current have been made (Fig. 2).

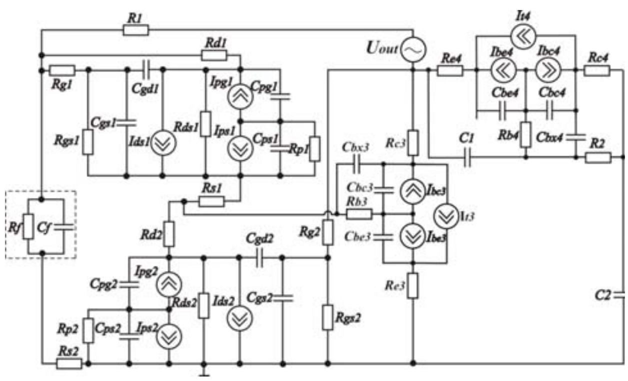

Fig.2. Equivalent AC circuit of frequency optical transducer of gas concentration

The equivalent circuit (Fig. 2) uses the following symbols: R_f – resistance of the photoresistor R_f; C_f – capacity of photoresistor R_f; $R1$ and $R2$ – resistances of the resistors $R1$ and $R2$ respectively; R_{g1}, R_{g2} – bulk resistances of the gates of MOS transistors VT1 and VT2 respectively; R_{gs1} and R_{gs2} – bulk resistances of gate-source of MOS transistors VT1 and VT2 respectively; R_{ds1} and R_{ds2} – resistances of drain- source of MOS transistors VT1 and VT2 respectively; R_{s1} and R_{s2} – bulk resistances of sources of MOS transistors VT1 and VT2 respectively; R_{d1}, R_{d2} – bulk resistances of drains of MOS transistors VT1 and VT2 respectively; R_{p1}, R_{p2} – resistances of the substrates of MOS transistors VT1 and VT2 respectively; C_{gs1} and C_{gs2} – capacities of junctions gate-source of MOS transistors VT1 and VT2 respectively; C_{gd1}, C_{gd2} – capacities of junctions gate-drain of MOS transistors VT1 and VT2 respectively; C_{ps1}, C_{ps2} – capacities of substrate - source of MOS transistors VT1 and VT2 respectively; C_{pg1}, C_{pg2} – capacities of substrate-gate of MOS transistors VT1 and VT2 respectively; C_1 and C_2 – capacities of capacitors C_1 and C_2 respectively; R_{e3} and R_{e4} – resistances of emitters of the bipolar transistors VT3 and VT4 respectively; R_{b3} and R_{b4} – resistances of bases of the bipolar transistors VT3 and VT4 respectively; R_{c3} and R_{c4} – resistances of collectors of the bipolar transistors VT3 and VT4 respectively; C_{be3} and C_{be4} – capacities of the junctions base-emitter of the bipolar transistors VT3 and VT4 respectively; C_{bc3} and C_{bc4} – capacities of the junctions base-collector of the bipolar transistors VT3 and VT4 respectively; C_{bx3} and C_{bx4} – capacities between external base terminal and collector terminal of the bipolar transistors VT3 and VT4 respectively.

The currents I_{ds1}, I_{ps1}, I_{pg1}, I_{ds2}, I_{ps2}, I_{pg2} included in the equivalent circuits of MOS transistors as well as the currents I_{be3}, I_{bc3}, I_{t3}, I_{be4}, I_{bc4}, I_{t4} included in the equivalent circuits of the bipolar transistors VT3 and VT4 are described in [14].

The equivalent circuit (Fig. 2) can be transformed into more convenient for calculations. The transformed equivalent AC circuit is presented in Fig. 3.

The conductivity of the circuit branches are determined by the equations are defined as

$$Y_1 = 1/Z_{p2};\ Y_2 = 1/Z_{pg2};$$
$$Y_3 = 1/Z_{ds2};\ Y_4 = 1/Z_{gs2};$$
$$Y_5 = 1/Z_{gd2};\ Y_6 = 1/Z_{d2};$$
$$Y_7 = 1/Z_{s1};\ Y_8 = 1/Z_f;$$
$$Y_9 = 1/Z_{g1};\ Y_{10} = 1/Z_{gs1};$$
$$Y_{11} = 1/Z_{gd1};\ Y_{12} = 1/Z_{d1};$$
$$Y_{13} = 1/Z1;\ Y_{14} = 1/Z_{ds1};$$
$$Y_{15} = 1/Z_{p1};\ Y_{16} = 1/Z_{ps1};$$
$$Y_{17} = 1/Z_{c3};\ Y_{18} = 1/(Z_1 + Z_2);$$
$$Y_{19} = 1/Z_{bx3};\ Y_{20} = 1/Z_{g2};$$
$$Y_{21} = 1/Z_{bc3};\ Y_{22} = 1/Z_{be3};$$
$$Y_{23} = 1/Z_{b3};\ Y_{24} = 1/Z_{e3}.$$

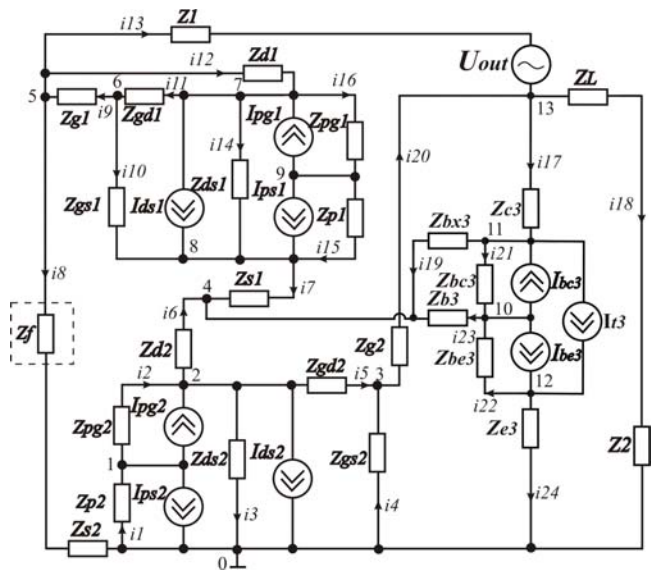

Fig.3. Transformed equivalent AC circuit of frequency optical transducer of gas concentration

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

$$
(1)\quad \begin{cases}
I_{pg2}+I_{ps2}=-\phi_1(Y_1+Y_2)+\phi_2 Y_2,\\
I_{ds2}-I_{pg2}=\phi_1 Y_2-\phi_2(Y_2+Y_3+Y_6)+\phi_4 Y_6,\\
U_{out}Y_{20}=\phi_2 Y_5-\phi_3(Y_4+Y_5+Y_{20}),\\
0=\phi_2 Y_5-\phi_4(Y_6+Y_7+Y_{19}+Y_{23})+\phi_8 Y_7+\phi_{10}Y_{23}+\phi_{11}Y_{19},\\
-U_{out}Y_{13}=-\phi_5(Y_8+Y_9+Y_{12}+Y_{13})+\phi_6 Y_9+\phi_{17}Y_{12},\\
0=\phi_5 Y_9-\phi_6(Y_9+Y_{10}+Y_{11})+\phi_7 Y_{11}+\phi_8 Y_{10},\\
I_{ds1}-I_{pg1}=\phi_5 Y_{12}+\phi_6 Y_{11}-\phi_7(Y_{11}+Y_{12}+Y_{14}+Y_{16})+\\
+\phi_8 Y_{14}+\phi_9 Y_{16},\\
-(I_{ds1}-I_{ps1})=\phi_4 Y_7+\phi_6 Y_{10}+\phi_7 Y_{14}-\phi_8(Y_7+Y_{14}+Y_{15})+\\
+\phi_9 Y_{15},\\
I_{pg1}+I_{ps1}=\phi_7 Y_{16}+\phi_8 Y_{15}-\phi_9(Y_{15}+Y_{16}),\\
I_{bc3}+I_{be3}=\phi_4 Y_{23}-\phi_{10}(Y_{21}+Y_{22}+Y_{23})+\phi_{11}Y_{21}+\phi_{12}Y_{22},\\
-U_{out}Y_{17}=\phi_{10}Y_{21}-\phi_{11}(Y_{17}+Y_{19}+Y_{21})+\phi_{14}Y_{19},\\
-(I_{be3}+I_{t3})=\phi_{10}Y_{22}-\phi_{12}(Y_{22}+Y_{24}),\\
U_{out}(Y_{13}+Y_{17}+Y_{18}+Y_{20})=\phi_3 Y_{20}+\phi_5 Y_{13}+\phi_{11}Y_{17},
\end{cases}
$$

The symbols are used in the equivalent circuit (Fig. 3) are defined as:

$$Z_f=R_f/(1+\omega^2\times R_f^2\times C_f^2)-j\omega R_f^2 C_f/(1+\omega^2 R_f^2 C_f^2)$$

$$Z_1=R1;\ Z_{g1}=R_{g1};$$

$$Z_{d1}=R_{d1};\ Z_{ds1}=R_{ds1};$$

$$Z_{s1}=R_{s1};\ Z_{d2}=R_{d2};$$

$$Z_{s2}=R_{s2};\ Z_{ds2}=R_{ds2};$$

$$Z_{g2}=R_{g2};\ Z_{c2}=-j/(\omega\cdot C_{c2});$$

$$Z_{c3}=R_{c3};\ Z_{gd1}=-j/(\omega\cdot C_{gd1});$$

$$Z_{be3}=-j/(\omega\cdot C_{be3});$$

$$Z_{pg2}=-j/(\omega\cdot C_{pg2});$$

$$Z_{gd2}=-j/(\omega\cdot C_{gd2});$$

$$Z_{e3}=R_{e3};\ Z_{b3}=R_{b3};$$

$$Z_{bx3}=-j/(\omega\cdot C_{bx3});$$

$$Z_{bc3}=-j/(\omega\cdot C_{bc3});$$

$$Z_{p1}=R_{p1}/(1+\omega^2\cdot R_{p1}^2\cdot C_{ps1}^2)-j\omega R_{p1}^2 C_{ps1}/(1+$$
$$+\omega^2 R_{p1}^2 C_{ps1}^2);$$

$$Z_{gs1}=R_{gs1}/(1+\omega^2\cdot R_{gs1}^2\cdot C_{gs1}^2)-j\omega R_{gs1}^2 C_{gs1}/(1+$$
$$+\omega^2 R_{gs1}^2 C_{gs1}^2);$$

$$Z_{p2}=R_{p2}/(1+\omega^2\cdot R_{p2}^2\cdot C_{ps2}^2)-j\omega R_{p2}^2 C_{ps2}/(1+$$
$$+\omega^2 R_{p2}^2 C_{ps2}^2);$$

$$Z_{gs2}=R_{gs2}/(1+\omega^2\cdot R_{gs2}^2\cdot C_{gs2}^2)-j\omega R_{gs2}^2 C_{gs2}/(1+$$
$$+\omega^2 R_{gs2}^2 C_{gs2}^2).$$

The relative impedance of an active inductive element Z_L is defined:

$$
(2)\quad \begin{aligned}
Z_L=U_1/(&\frac{U_1}{D_1}+\frac{A_5A_6Z_1Z_{b4}}{B_1D_1Z_{bx4}(Z_{bx4}-A_4A_6/Z_{bx4})}-\\
&-\frac{Z_{C1}A_3}{D_1B_1}+\frac{Z_{r2}A_5}{D_1(Z_{bx4}-A_4A_6/Z_{bx4})}-\\
&-\frac{A_5A_6B_2Z_{b4}}{B_1D_1Z_{bx4}(Z_{bx4}-A_4A_6/Z_{bx4})}+\frac{A_3B_2}{B_1D_1},
\end{aligned}
$$

where:

$$A_1=Z_{C1}+Z_{r2},$$

$$A_2=Z_{e4}+Z_{be4}+Z_{C1}+Z_{b4},$$

$$A_3=Z_{be4}(I_{bc4}-I_{be4}-I_{t4}),$$

$$A_4=Z_{bc4}+Z_{bx4}+Z_{b4},$$

$$A_5=Z_{bc4}(I_{be4}-I_{bc4}+I_{t4});$$

$$A_6=Z_{bx4}+Z_{c4}+Z_{r2},$$

$$Z_{c4}=R_{c4},$$

$$Z_{e4}=R_{e4},$$

$$Z_{b4}=R_{b4},$$

$$Z_{r2}=R_{r2},$$

$$Z_{be4}=-j/(\omega\cdot C_{be4}),$$

$$Z_{bc4}=-j/(\omega\cdot C_{bc4}),$$

$$Z_{bx4}=-j/(\omega\cdot C_{bx4}),$$

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

$$B_1=A_2+Z_{b4}^2A_6/\left(Z_{bx4}\left(Z_{bx4}-A_4A_6/Z_{bx4}\right)\right),$$

$$B_2=Z_{b4}Z_{r2}/\left(Z_{bx4}-A_4A_6/Z_{bx4}\right),$$

$$K_1=A_1-Z_{C1}^2/B_1+Z_{C1}Z_{b4}Z_{r2}/\left(B_1Z_{bx4}\right)+$$
$$+Z_{C1}Z_{b4}Z_{r2}A_4A_6/\left(B_1Z_{bx4}^2(Z_{bx4}-A_4A_6/Z_{bx4})\right)+$$
$$+Z_{r2}^2A_4/\left(Z_{bx4}(Z_{bx4}-A_4A_6/Z_{bx4})\right)+Z_{C1}B_2/B_1-$$
$$-Z_{b4}Z_{r2}B_2/\left(Z_{bx4}B_1\right).$$

The system of equations (1) has been solved using Gauss's method in the software package MATLAB 8.1.

The calculated and experimental dependences of the active and reactive components of the impedance on the gas are presented in Fig. 4 and 5, respectively.

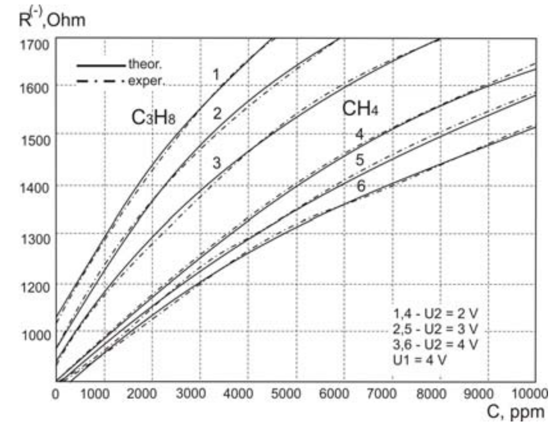

Fig.4. Theoretical and experimental dependencies of active component of the impedance on gas concentration

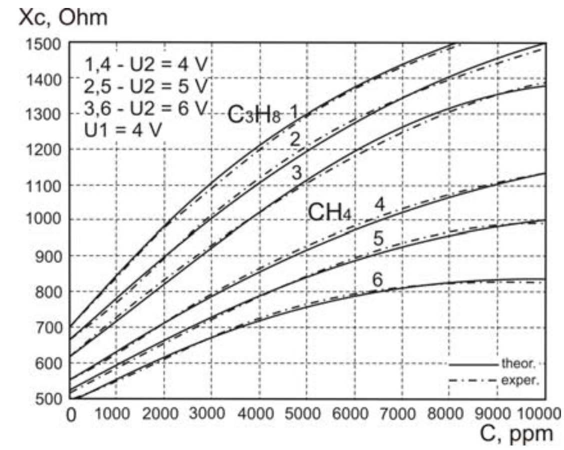

Fig.5. Theoretical and experimental dependencies of reactive component of the impedance on gas concentration

In order to determine the transfer function, it is necessary to find the dependence of the generation frequency on the gas concentration (transfer function) using the circuit reverse current in accordance with the equivalent circuit (Fig. 3) based on Lyapunov stability theory [15]. In this case the transfer function is described with the formula:

$$F=\frac{\sqrt{2}\sqrt{L_{ekv}C_{pg2}(-L_{ekv}C_{pg2}+R_f^2(C)C_f^2+R_f^2(C)C_fC_{pg2}+K_1)}}{2L_{ekv}C_fC_{pg2}R_f(C)}, \quad (3)$$

where:

$$K_1=\sqrt{\begin{aligned}&L_{ekv}^2(C_{pg2})^2+2L_{ekv}C_f^2C_{pg2}R_f^2(C)-\\&-2L_{ekv}(C_{pg2})^2C_fR_f^2(C)+K_2,\end{aligned}}$$

$$K_2=R_f^4(C)C_f^4+2R_f^4(C)C_f^3C_{pg2}+R_f^4(C)C_f^2(C_{pg2})^2.$$

The dependences of the generation frequency on the gas concentration calculated from equation (3) and determined experimentally for the converter are shown in Fig.6

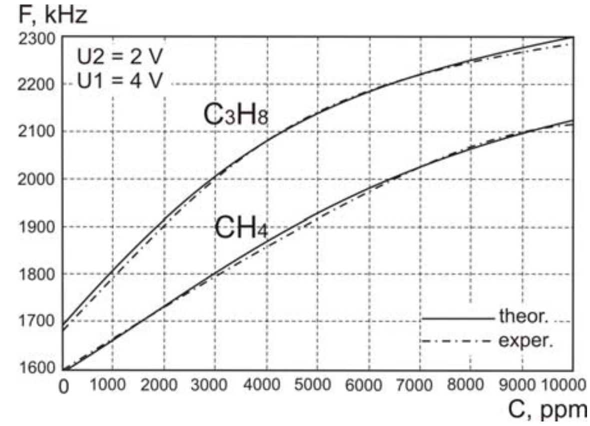

Fig.6. Theoretical and experimental dependencies of generation frequency of transducer on propane (C3H8) and methane (CH4) concentration change

$$\begin{aligned}S_C^F=&\frac{1}{4}\sqrt{2}\Big(2R_f(C)C_f^2\Big(\frac{\partial}{\partial C}R_f(C)\Big)+2R_f(C)C_fC_{pg2}\Big(\frac{\partial}{\partial C}R_f(C)\Big)+\\&+\Big(\frac{1}{2}\Big(4L_{ekv}R_f(C)C_{pg2}C_f^2\Big(\frac{\partial}{\partial C}R_f(C)\Big)-4L_{ekv}R_f(C)\big(C_{pg2}\big)^2\times\\&\times C_f\Big(\frac{\partial}{\partial C}R_f(C)\Big)+4R_f^3(C)C_f^4\Big(\frac{\partial}{\partial C}R_f(C)\Big)+8R_f^3(C)C_f^3\times\\&\times C_{pg2}\Big(\frac{\partial}{\partial C}R_f(C)\Big)+4R_f^3(C)C_f^2\big(C_{pg2}\big)^2\Big(\frac{\partial}{\partial C}R_f(C)\Big)\Big)\Big/\sqrt{M_1}\Big)\Big/\\&\Big/\Big(\sqrt{-L_{ekv}C_{pg2}(M_2+\sqrt{M_1})}\Big)\Big)-\frac{1}{2}\sqrt{2}\sqrt{L_{ekv}C_{pg2}\big(M_2+\sqrt{M_1}\big)}\times\\&\times\Big(\frac{\partial}{\partial C}R_f(C)\Big)\Big/\Big(L_{ekv}C_{pg2}C_fR_f^2(C)\Big),\end{aligned}$$

where:

$$\begin{aligned}M_1=&L_{ekv}^2\big(C_{pg2}\big)^2+2L_{ekv}C_{pg2}C_f^2R_f^2(C)-\\&-2L_{ekv}\big(C_{pg2}\big)^2C_fR_f^2(C)+R_f^4(C)C_f+2R_f^4(C)C_f^3C_{pg2}+\\&+R_f^4(C)C_f^2\big(C_{pg2}\big)^2;\end{aligned}$$

$$M_2=-L_{ekv}C_{pg2}+R_f^2(C)C_f^2+R_f^2(C)C_{pg2}C_f.$$

The dependences of the sensitivity of the optical frequency transducer on gas concentration are presented in Fig. 7.

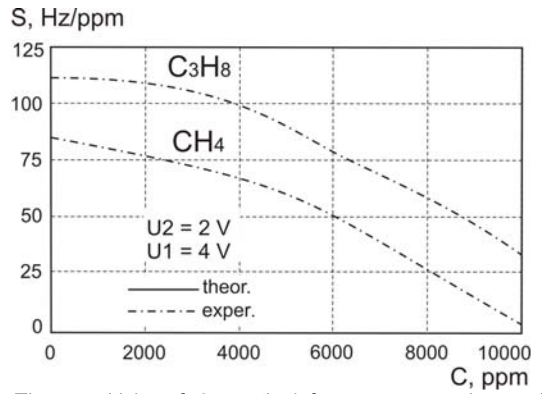

Fig.7. The sensitivity of the optical frequency transducer of gas concentration

The highest sensitivity (Fig. 7) of the transducer appeared to be within the range of gas concentration from 1 up to 4000 ppm and makes 85-10 Hz/ppm for methane and 35-110 Hz/ppm for propane. The greatest sensitivity matches the optimum mode of supply 4 V and at the control voltage 2 V.

Conclusions

The mathematical model of the optical frequency transducer of gas concentration with an active inductive element for its producing as an integrated chip, based on an self-oscillator created with MOS, and a bipolar transistors and a photoresistor as a photosensitive element is developed. The analytical expressions for the transformation and the sensitivity equation are obtained on the basis of the model. Theoretical and experimental curves have shown that the sensitivity of the developed optical transducer of gas concentration is 35-110 Hz/ppm for propane and 85-10 Hz/ppm for methane.

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