Alexander V. OSADCHUK[1], Vladimir S. OSADCHUK[1], Iaroslav A. OSADCHUK[1], Piotr KISAŁA[2], Tomasz ZYSKA[2], Azamat ANNABAEV[2], Kanat MUSSABEKOV[2]

Vinnytsia National Technical University (1), Lublin University of Technology, Faculty of Electrical Engineering and Computer Science (2)

doi:10.15199/48.2017.03.26

Radiomeasuring pressure transducer with sensitive MEMS capacitor

***Abstract**. In the article the pressure transducer with frequency output based on the structure of the bipolar-field transistors with negative resistance and tenso sensitive MEMS capacitor has been considered. A mathematical model of the radiomeasuring pressure transducer in dynamic regime has been developed that allowed to determine the voltage or current in the circuit at any given moment in time when acting this pressure. Analytical expressions of the conversion function and sensitivity equation has been received. The sensitivity of the developed device is between 0.98 kHz/kPa to 1.67 kHz/kPa.*

***Streszczenie.** W artykule przedstawiony został przetwornik ciśnienia z wyjściem częstotliwościowym oparty o strukturę podwójnego tranzystora unipolarnego z ujemną rezystancją. Celę pomiarową stanowił kondensator MEMS wrażliwy na siłę. Model matematyczny przetwornika ciśnienia uwzględnia stany dynamiczne i pozwala wyznaczyć napięcie i prąd w obwodzie w dowolnym momencie pracy przetwornika. Przedstawione zostały również zależności analityczne funkcji konwersji i czułości. Czułość przetwornika zawierała się w przedziale 0,98 kHz/kPa do 1,67 kHz/kPa. (**Przetwornik pomiarowy ciśnienia z pojemnościową celą pomiarową MEMS**).*

Keywords: frequency pressure transducer, MEMS capacitor, negative resistance.
Słowa kluczowe: przetwornik częstotliwość ciśnienie, kondensator MEMS, ujemna rezystancja.

Introduction

Currently microelectronic pressure transducers are widely used in different applications, and their advantages over traditional due primarily to using them as sensitive elements of semiconductor materials, methods of group formation and processing them into measuring circuits' amplification and signal processing techniques of microelectronic technology.

Radiomeasuring transducers with a frequency output have a number of advantages over the current amplitude, which are to a significant increase in noise immunity, thus increasing the accuracy of measurement, as well as the ability to produce large output signals without pre-amplifying devices. Using frequency signal as an informative eliminates the analog-to-digital converters, increases efficiency measuring apparatus [1, 8]. Currently intensive research on the properties of analog microelectronic pressure transducers is carrying out [2, 3], although the study the frequency of pressure transducers based on the reactive properties of bipolar and field-effect transistors is in an initial stage [4–7]. Therefore, this paper is dedicated to the study of the function of transformation and equation of sensitivity of the radiomeasuring pressure transducer on the basis of transistor structure with negative resistance.

Theoretical and experimental research

Schematic diagram of the transducer is shown in Fig.1. It is a hybrid integrated circuit, which consists of bipolar and field effect transistors, R1 resistance and tenzo sensitive MEMS capacitor that creates an autogenerating device. Oscillating circuit device is implemented on the basis of the equivalent capacitance of the impedance at the collector electrode of the bipolar transistor VT1 and the drain of the field-effect transistor VT2, and inductance L. On tenzo sensitive MEMS capacitor acting pressure, which leads to a change in the equivalent capacitance of the oscillatory circuit, which in turn, causes a change in the resonant frequency of the oscillator [5].

Energy losses in the resonant circuit offset by the negative resistance [6]. To select the optimal operation of the radiomeasuring pressure transducer circuit uses two power supplies DC voltages U_1 and U_2, but to reduce the cost of the radiomeasuring pressure transducer in the future, only one power supply is used.

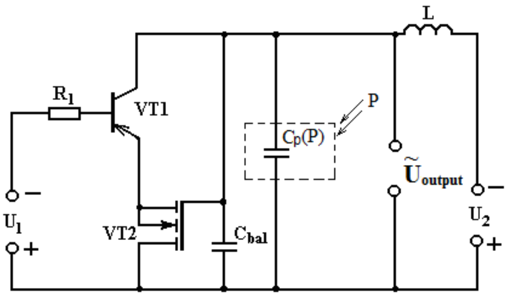

Fig.1. Schematic diagram of the radiomeasuring pressure transducer with sensitive MEMS capacitor

To determine the conversion and the sensitivity function Fig.2 shows the equivalent circuit of the radiomeasuring pressure transducer with a sensitive MEMS capacitor, which implements the dependence of oscillation frequency of the pressure change.

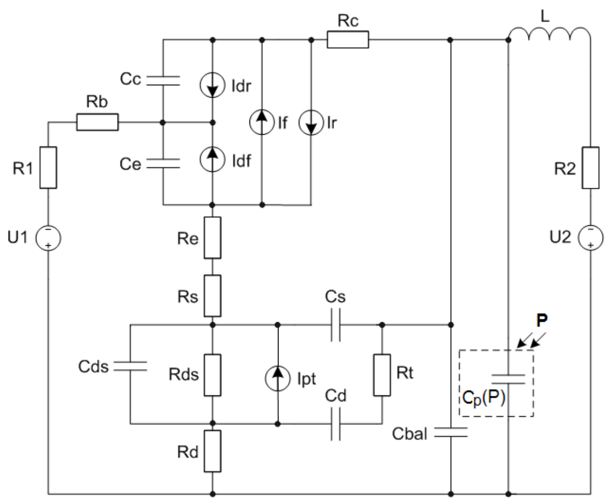

Fig.2. The equivalent circuit of the radiomeasuring pressure transducer

For convenience of calculations by combining the parallel capacitance $C_p(P)$ and C_{bal} in $C_p(P,t) = C_p(P) + C_{pbal}$ and currents I_f and I_r in $I_{bt} = (I_f - I_r)/QB$, as well as by using the method of state variables in Fig. 3 is presented a converted equivalent circuit of the radiomeasuring pressure transducer.

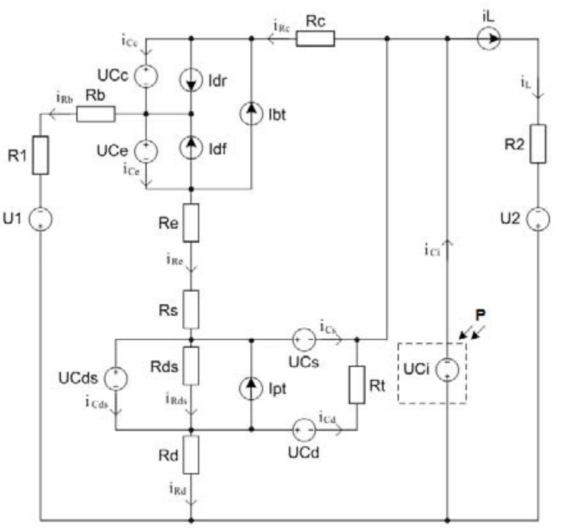

Fig.3. The transformed radio equivalent circuit of the pressure transmitter

On the Kirchhoff equation system the expression (1) was drawn up on the basis of the chosen directions of currents. The system (1) is non-linear because it contains a non-linear elements, namely the current sources I_{pt}, I_{dr}, I_{df}, $I_{bt} = (I_f - I_r)/QB$, and capacity C_c, C_e. The system (1) is a dynamic mathematical model of the radiomeasuring pressure transducer that allows to determine the value of the voltage or current at any point scheme at a given time.

$$
(1)\quad
\begin{cases}
L\dfrac{di_L(t)}{dt} = U_2 - \left(U_{C_i}(P,t) + i_L(t)\cdot R_2\right); \\
C_d\dfrac{dU_{C_d}(t)}{dt} = \dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_d}(t)}{R_t}; \\
C_{ds}\dfrac{dU_{C_{ds}}(t)}{dt} = \dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_i}(P,t)}{R_d} - \dfrac{U_{C_{ds}}(t)}{R_{ds}} + I_{pt} \\
+\dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_d}(t)}{R_t}; \\
C_s\dfrac{dU_{C_s}(t)}{dt} = -\dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_i}(P,t)}{R_d} - \dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_d}(t)}{R_t} \\
-\dfrac{U_1 - U_{C_c}(t) - U_{C_i}(P,t) + A_5R_c}{A_1} - A_5; \\
C_i\dfrac{dU_{C_i}(P,t)}{dt} = i_L(t) + 2A_5 + \dfrac{U_1 - U_{C_c}(t) - U_{C_i}(P,t) + A_4R_c/3}{A_1} \\
+\dfrac{U_{C_s}(t) - U_{C_{ds}}(t) - U_{C_i}(P,t)}{R_d}; \\
C_c\dfrac{dU_{C_c}(t)}{dt} = A_5 + I_{bt} - I_{dr}; \\
C_e\dfrac{dU_{C_e}(t)}{dt} = A_5 - \dfrac{U_1 - U_{C_c}(t) - U_{C_i}(P,t) + A_5R_c}{A_1} + I_{bt} + I_{df}.
\end{cases}
$$

where R_1 – load resistance; R_b, R_e, R_c, R_d, R_s – resistance base, emitter, collector, drain and source; R_{ds} – resistance drain – source; C_e, C_c – capacity emitter and collector junctions; C_d, C_s, C_{ds} – gate-drain, drain – source and drain-source capacitance; C_{bal} – ballast capacitance; $C_p(P,t)$ – capacitance tenso-sensing MEMS capacitor; L – inductance; U_1, U_2 – DC power supply; I_{pt} – current field effect transistor; I_{dr}, I_{df} – current internal conversion base-collector and base – emitter; I_f, I_r – direct and reverse current bipolar transistor;

$$A_1 = R_b + R_1,\ A_2 = R_e + R_t,\ A_3 = A_2A_1 + R_c\left(A_2 + A_1\right),$$

$$A_4 = A_1\left(U_{C_c} + U_{C_e} + U_{C_s}\right) + A_2\left(U_{C_e} - U_2 + U_{C_i}(P,t)\right),\ A_5 = \frac{A_4}{A_3}.$$

To test the adequacy of the model the program for calculating the parameters of the scheme among the «Maple» was written. The calculation shows that the output signal of pressure transducers really will be periodic oscillations, which frequency will vary with the changing capacitance strain-sensing MEMS capacitor (Fig. 4).

So when $C_p(P,t)$ = 52 pF frequency f = 1490 kHz, at $C_p(P,t)$ = 67 pF frequency f = 1441 kHz, at $C_p(P,t)$ = 82 pF frequency f = 1385 kHz, at $C_p(P,t)$ = 100 pF frequency f = 1343 kHz, and when $C_p(P,t)$ = 115 pF frequency f = 1295 kHz, with $U_1 = U_2$ = 2.5 V.

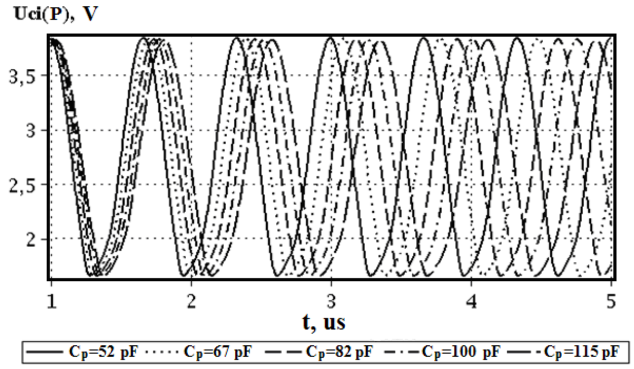

Fig.4. Change the output voltage versus time for different values of capacitance tenso sensitive MEMS capacitor

Fig. 5 shows the change in output voltage versus time for various pressures. From these characteristics can be clearly seen that if the pressure increases the output frequency will decrease. Knowing the value of the output signal frequency F for different values of strain sensitivity MEMS capacity $C_p(P,t)$ can be obtained for the transformation function of the radiomeasuring pressure transducer in a general way (as instead of pressures the values capacitance gauge MEMS capacity), while U_2 = 2.5 V. For example, Fig. 6 shows radiomeasuring pressure transducer, in which the conversion function is depended on the capacity of the tenso-sensitive element MEMS capacitor, for different values of the control voltage U_1.

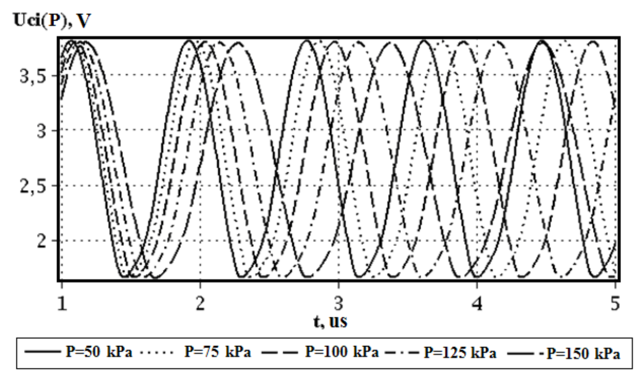

Fig.5. Changing the voltage output from the time at different values of pressure

For experimental research in the scheme shown in Fig.1 were used transistors UKT3101 and KP313 and tenso-sensitive MEMS capacitor made in scientific laboratories Institute of Micro System Technology TUHH (Hamburg, Germany) (Fig. 7).

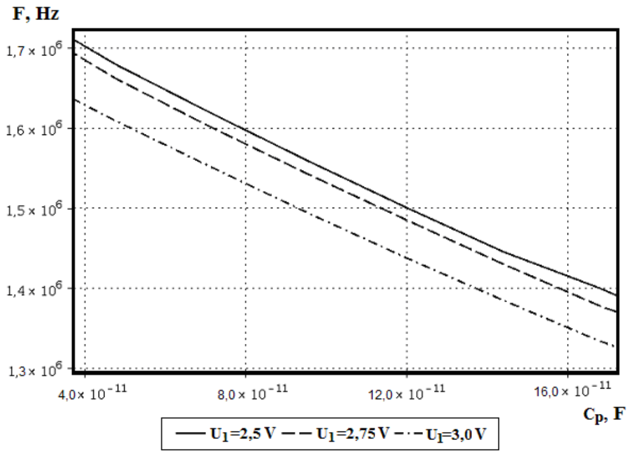

Fig.6. The theoretical transfer function for different values of strain-sensing MEMS capacity

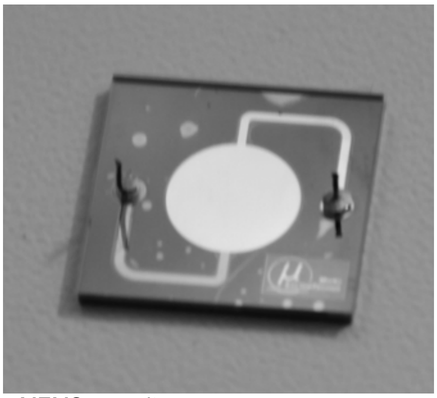

Fig.7. Photo MEMS capacitor

To prove the existence of negative resistance area and to choose working point in Fig. 8 is presented experimental VAC investigated autogenerating measuring device. Fig. 8 shows that at the control voltage U_1 = 2.5 V the area of negative resistance by U_2 is changed from 2.3 to 3.1 V.

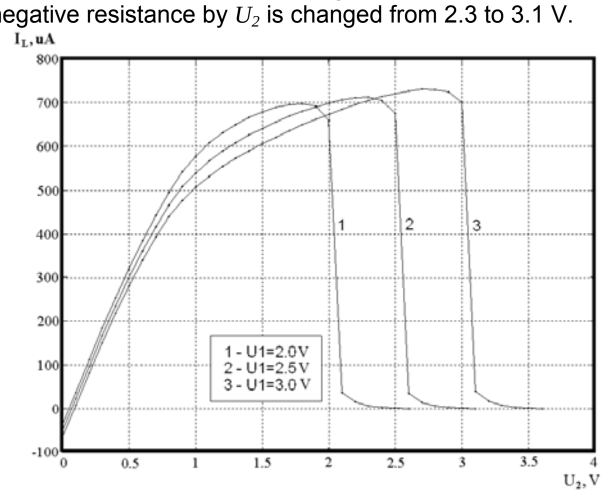

Fig.8. Experimental VAC radiomeasuring pressure transducer

The frequency of generation from the pressure is determined by the reverse current loop according to the equivalent circuit (Fig. 2) based on Lyapunov stability theory. At first, the reactive component is determined by the impedance at the drain electrode-collector transistors structure, and then from the reactive impedance component is determined by the equivalent capacitance, which depends on the pressure variation. Changing the equivalent capacitance determines the frequency dependence of the pressure generation. Conversion function radiomeasuring pressure transducer based on the structure of the bipolar and field-effect transistors with tenso-sensitive MEMS capacitor is described by expression (2)

(2)

$$F=\frac{\sqrt{2}\sqrt{LC_i(P,t)\left(R_{ds}^2C_{ds}C_i(P,t)+R_{ds}^2C_{ds}^2-LC_i(P,t)+\sqrt{A}\right)}}{4\pi LC_i(P,t)R_{ds}C_{ds}},$$

where $A=R_{ds}^4C_{ds}^2C_i^2(P,t)+2R_{ds}^4C_{ds}^3C_i(P,t)-2LR_{ds}^2C_{ds}C_i^2(P,t)$
$+R_{ds}^4C_{ds}^4+2LR_{ds}^2C_{ds}^2C_i(P,t)+L^2C_i^2(P,t).$

Numerical calculations on the PC allow obtaining a frequency conversion function for pressure transducer in the form of a graph (Fig. 9). On the basis of the expression (2) is defined the sensitivity of the radiomeasuring pressure transducer conversion based on the structure of the bipolar and field-effect transistors

(3)

$$S_P^F=\frac{\sqrt{2}\left(L(B_2+B_1)\frac{\partial C_i(P,t)}{\partial P}+LC_i(P,t)\left(B_3\frac{\partial C_i(P,t)}{\partial P}+\frac{B_4\frac{\partial C_i(P,t)}{\partial P}}{B_2}\right)\right)}{8\cdot\left(\pi LR_{ds}C_{ds}C_i(P,t)\sqrt{LC_i(P,t)(B_2+B_1)}-\frac{\sqrt{2}\sqrt{L(B_2+B_1)C_i(P,t)}\frac{\partial C_i(P,t)}{\partial P}}{4\pi LR_{ds}C_{ds}C_i(P,t)C_i(P,t)}\right)},$$

where $B_1=R_{ds}^2C_{ds}C_i(P,t)+R_{ds}^2C_{ds}^2-LC_i(P,t);$

$$B_2=\sqrt{\begin{array}{l}R_{ds}^4C_{ds}^2C_i^2(P,t)+2R_{ds}^4C_{ds}^3C_i(P,t)-\\2LR_{ds}^2C_{ds}C_i^2(P,t)+R_{ds}^4C_{ds}^4+2LR_{ds}^2C_{ds}^2C_i(P,t)+L^2C_i^2(P,t)\end{array}};$$

$$B_3=R_{ds}^2C_{ds}-L;$$

$$B_4=R_{ds}^4C_{ds}^2\left(C_i(P,t)+C_{ds}\right)+LR_{ds}^2C_{ds}\left(C_{ds}-2C_i(P,t)\right)+L^2C_i(P,t).$$

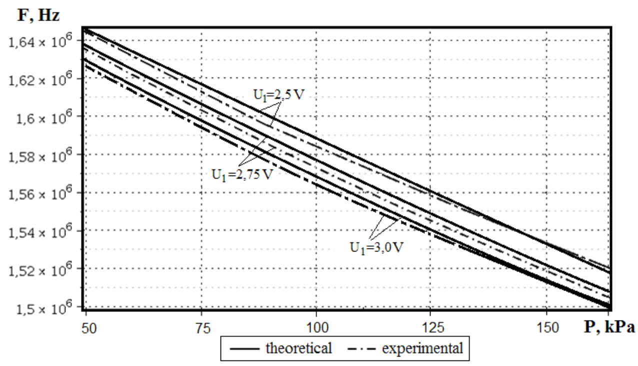

Fig.9. Theoretical and experimental radio conversion function of the radiomeasuring pressure transducer

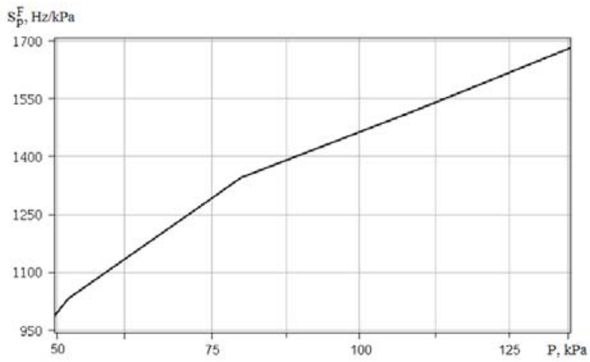

Fig.10. Dependence of the sensitivity of the radiomeasuring pressure transducer from the pressure change

As can be seen from Fig.9, the function of converting the radiomeasuring pressure transducer is almost linear. Graph of the sensitivity of the pressure change is shown in Fig. 10. The sensitivity of the radiomeasuring pressure transducer with a tenso-sensitive MEMS capacitor to pressure changes range from 50 kPa to 150 kPa is from 985.2 to 1664.4 Hz/kPa.

Adequacy of the developed model in comparing with the experiment is defined as the relative error not exceeding ±1.5%.

Conclusions

Radiomeasuring pressure transducer on the basis of the bipolar and field-effect transistors structure with negative resistance and strain sensitivity MEMS capacitor has been proposed and investigated. A mathematical model of the radiomeasuring pressure transducer in dynamic regime has been developed that allowed to determine the voltage or current at any point scheme at a predetermined time under the influence of pressure. Adequacy of the developed model in comparing with the experiment is defined as the relative error not exceeding ±1.5%. Analytical expressions of conversion function and sensitivity equation are obtained. Therefore, this paper is dedicated to the study of characteristics of the developed radiomeasuring pressure transducer on the base of transistors structure with tenso-sensitive MEMS capacitor. The sensitivity of the developed device is between 0.98 kHz/kPa to 1.67 kHz/kPa.

***Authors**: Alexander V. Osadchuk, Vladimir S. Osadchuk, Iaroslav A. Osadchuk, Vinnytsia National Technical University, Khmel'nyts'ke Hwy, 95, 21000 Vinnytsia, Ukraine; prof. Piotr Kisała, Ph.D. Tomasz Zyska, M.Sc. Azamat Annabaev, M.Sc. Kanat Mussabekov, Lublin University of Technology, Faculty of Electrical Engineering and Computer Science, Nadbystrzycka 38a, 20618 Lublin, Poland, E-mail: t.zyska@pollub.pl*

REFERENCES

[1] Novitsky P.V., Knoring V.G., Gutnikov V.S., Digital devices with frequency sensors, *Leningrad: Energy*, (1970), 424–428
[2] Vikulina L.F., Glauberman M.A., The physics of temperature and magnetic field sensors, *Odessa: Beacon*, (2000), 156–163
[3] Osadchuk V.S., Osadchuk O.V., Pressure sensors and magnetic field, *Universum, Vinnitsa*, (2005), 207–212
[4] Osadchyk O.V., Microelectronic frequency transducers based on the transistor structures with negative resistance, *Universum, Vinnitsa*, (2000), 303–307
[5] Osadchuk V.S., Osadchuk A.V., The Microelectronic Transducers of Pressure with the Frequency Output, *Electronics and Electrical Engineering. Kaunas: Technologija*, 121 (2012), n.5, 105–108
[6] Osadchuk A.V., Osadchuk V.S., Radiomeasuring Microelectronic Transducers of Physical Quantities, *Proceedings of the International Siberian Conference on Control and Communications (SIBCON)*, (2015), 67–72
[7] Osadchuk A.V., Osadchuk I.A., Frequency Transducer of the Pressure on the Basis of Reactive Properties of Transistor Structure with Negative Resistance, *Proceedings of the International Siberian Conference on Control and Communications (SIBCON)*, (2015), 21–23
[8] Kasiński K., Kłeczek R., Low power prototype of the integrated circuit with dual stage pulse processing for time and amplitude measurement, *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska*, 2014(1), 72–75