Radiomeasuring Transducer of the Pressure on the Basis of Reactive Properties of Transistor Structure with Negative Resistance

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Abstract — **The opportunity of direct transformation of pressure in frequency is shown on the basis of the hybrid integrated circuit consisting of the two-collector tenzosensitive transistor and the field two-gate transistor with an active inductive element on the basis of the bipolar transistor with a phase-shifting RC chain. Analytical dependencies of transformation function and the equation of sensitivity are received. Theoretical and experimental researches have shown, that sensitivity of the transducer makes 1,55-1,10 kHz /kPa.**

Keywords— ***transducer of the pressure; frequency; negative resistance; pressure; reactive properties***

I. INTRODUCTION

The microelectronic transducers of mechanical quantities define precision and reliability of monitoring systems of processes, environmental properties, safety of operation of nuclear, thermal, chemical installations, aircrafts, sea objects, etc. In this connection to the microelectronic transducers which measure manifold mechanical quantities, in particular pressure, the strong requirements are showed. They should be economic, unjammable, provide high fast operation, sensitivity and a measurement accuracy, to have small gabarits and a weight, to be compatible with the modern PCs and will allow coding and an information communication on major distances.

One of perspective scientific directional, allowing to solve a complex of the tasks in view suggested in the given operation, use of dependence of reactive properties and a negative resistance of semiconductor devices of effect of pressure and making on this basis of a new class of the microelectronic transducers is. In devices of such type there is a transformation of pressure to the frequency signal that allows to establish transducers on integrated technology and enables to boost fast operation, precision and sensitivity, to improve reliability, noise performance in terms of error probability and long-term parameter stability. Besides integrating single-crystal the transducer of pressure with the plan of an information handling enables makings "intellectual" devices. Use as information parameter of frequency allows to avoid application of intensifying devices and analog-to-digital converters at an information handling that reduces the cost price of monitoring systems and guidances [1 - 3]. In the given operation surveyed theoretical and experimental researches of effect of pressure on parameters of the bipolar transistor and its use as tenzosensitive a device of the microelectronic transducer of pressure in the frequency signal.

II. THEORETICAL AND EXPERIMENTAL RESEARCHES

The electric circuit of the transducer of a pressure is shown on fig. 1. It represents the hybrid integrated circuit consisting of the two-collector tenzosensitive transistor, the field two-gate transistor and the bipolar transistor with phase-shifting circuit R5C1 which create the autogenerating device which generation frequency depends on the pressure.

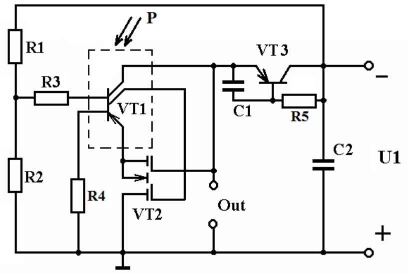

Fig. 1. The electric circuit of the frequency transducer of a pressure

On electrodes of the first collector of the tenzosensitive bipolar transistor VT1 and a drain of the field two-gate transistor VT2 there is a full resistance which an active component has negative value, and a reactive component has capacitor character. Connection of active inductance on the basis of transistor VT3 and phase-shifting circuit R5C1 to the first collector VT1 and the general line through short-circuit capacity C2 creates an oscillatory contour, losses of energy in which are compensated by a negative resistance [3]. Resistors R1–R4 provide power supply on a direct current of the researched circuit. At action of a pressure on transistor VT1 there is the change of equivalent capacity of an oscillatory contour that causes the change of a resonant frequency [4].

As in work of the device it is used an active inductive element we shall consider the physical mechanism of work of such element on the basis of bipolar transistor VT3 with phase-shifting circuit R5C1 which allows to adjust size of inductance and good quality of an element.

Consider the principle of the two collector bipolar transistor. As for the anisotropic conductive semiconductor crystals and the current direction of the electric field is not in general coincide. This determines that the movement of charge carriers between the current contacts forces act on them, which are transverse to the current direction [5]. The magnitude of this force in the case of anisotropy, which is powered by external directional influences, such as uniaxial elastic deformation of the magnetic field, the light is proportional to the magnitude of these effects. Thus, when artificial anisotropic conductivity becomes possible to control the phenomena of charge transport in a wide range. The practical use of this feature, the basis for the creation of a number of semiconductor devices such as microelectronic many collector tenzosensitive transistor [6] and magnetic sensitive transistor [5, 6], which are sensitive to mechanical stress and uniaxial magnetic field. When the injection of charge carriers in the base region (plane xy) is their longitudinal drift in the towing field base and their diffusion in the z direction to the collector junction. In the absence of mechanical deformation collector currents, which are determined by the diffusive motion in the direction of z, are equal, so the output signal that is removed from the collector load resistors is zero for the same values of resistance collectors. When a mechanical load on tenzosensitive transistor occurs uniaxial compressive strain (stretch) in the crystallographic <110> direction, so that the mobility of holes in the base becomes anisotropic. The injected holes drift in the towing database field in the x direction, due to the reduced mobility anisotropy deflected laterally further by diffusion in the z direction is achieved collectors junction. The appearance in the base region of the cross flow holes due to the anisotropy of their mobility leads to significant disbalance collector currents and the appearance of the output signal.

Consider how the mobility of holes in the semiconductor under pressure, i.e. anisotropy of mobility. In the unstrained semiconductor hole mobility is equal [6]

$$\mu_{p0} = \frac{q\tau}{m_v^{3/2}(m_L^{1/2}+m_M^{1/2})}, \qquad (1)$$

where q - the charge of the electron; m_v - the hole effective mass at the top of the valence band; m_L and m_M - the effective masses of light and heavy holes; τ - the relaxation time, the same for both types of holes. The action of the pressure hole mobility is determined by the expression [7]:

$$\mu_p(p) = \frac{p_1\mu_1 + p_2\mu_2}{p_1 + p_2}, \qquad (2)$$

where p_1 and p_2 - the concentration of holes in the upper and lower zones, which were split; μ_1 and μ_2 - appropriate mobility. Then, the deformation of the hole mobility gains will be described by the expression [7]:

$$\Delta\mu_p(p) = \frac{q\tau}{m_v^{3/2}}\left[\frac{\left(1+\left(\frac{m_M}{m_L}\right)^2 \exp\left(\frac{\Delta E_{v-}(p)-\Delta E_{v+}(p)}{kT}\right)\right)}{\left(1+\left(\frac{m_M}{m_L}\right)^{3/2} \exp\left(\frac{\Delta E_{v-}(p)-\Delta E_{v+}(p)}{kT}\right)\right)}\times \right. \qquad (3)$$

$$\left. \times m_L^{1/2} - \left(m_L^{1/2}+m_M^{1/2}\right)\right],$$

where $\Delta E_{v+}(p)$ - deformation increment position at the top of the valence band of deformation; $\Delta E_{v-}(p)$ - increase in the deformation of the lower branch of the valence band upon deformation.

The dependence of the mobility of holes and electrons in the Si-semiconductor from pressure is shown in Fig. 2.

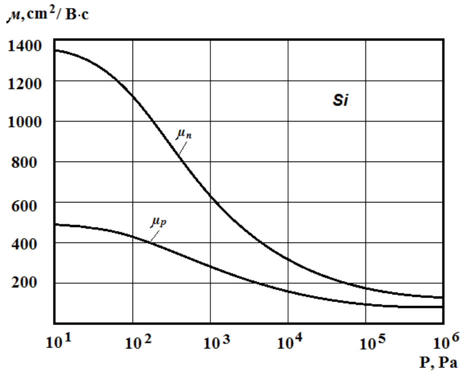

Fig. 2. The dependence of the charge carrier mobility of the pressure

The dependence of the distribution of injected charge carriers from the action of the pressure in the base tenzosensitive transistor can be determined by solving the transport equation, while considered a low level carrier injection and weak deformation field. The transfer equation of the form [5]:

$$\left[\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}+2\sigma_x\frac{\partial p}{\partial x}+2\sigma_y\frac{\partial p}{\partial y}\right]-\frac{p-p_0}{L^2}=$$

$$=-\rho(x',y')\delta(x-x')\delta(y-y')\delta(z-z') \qquad (4)$$

with the boundary conditions

$$p(0,y,z)=p(l_x,y,z)=p(x,0,z)=p(x,L_y,z)=p(x,y,l_z)=p_0 \qquad (5)$$

where L - diffuse length of the injected charge carriers in the base; p_0 - the equilibrium concentration of charge carriers in the base; $\delta(x-x')$ -Dirac function. The function $\rho(x',y')$ describes the density of the sources of nonequilibrium charge carriers. Coefficients σ_x and σ_y linked to the value of the applied field E_x in the database tenzosensitive transistor relations

$$\sigma_x = \frac{qE_x}{2kT}, \qquad \sigma_y = a\cdot\sigma_x, \qquad (6)$$

where k - the Boltzmann constant; T - temperature, a - the anisotropy parameter of mobility of charge carriers. Field base and emitter is limited coordinates, respectively,

$$0 \le x \le L_x\,, \qquad 0 \le y \le L_y\,, \qquad 0 \le z \le L_z\,,$$

$$0 \le x' \le L_x\,, \qquad 0 \le y' \le L_y\,, \qquad 0 \le z' \le L_z\,.$$

Equation (4) is solved using the Green's function, which is described by the expression [5]:

$$P(x,y,z,x',y',z') = \frac{4l_x}{D_p l_y l_z}\exp\left[a_x(x-x')\right]\sum_{m,k=1}^{\infty}\frac{sh\left[\beta_{mk}(1-\frac{x}{l_x})\right]}{\beta_{mk}sh(\beta_{mk})}\times \qquad (7)$$

$$\times sh\left(\frac{\beta_{mk}x'}{l_x}\right)\sin q_k z\sin q_m y\sin q_m y'\sin q_k z'\,,$$

where $q_m = \dfrac{\pi m}{l_y}$; $q_k = \dfrac{\pi k}{l_z}$; $\beta_{mk} = l_x^2(q_m^2 + q_k^2 + a_x^2 + a_y^2 + L^2)$; $L^2 = D_p\tau$; D_p - hole diffusion coefficient; τ -hole lifetime.

The Green's function determines the concentration of the injected holes at the base with the coordinates, which was born a source of unit intensity emitter coordinates. The density of sources that emit nonequilibrium holes in the base determined by the expression [5]:

$$\rho(x',y') = \frac{p_0}{\tau}\left[\exp\frac{U_{eb}(x',y')}{kT} - 1\right]\,. \qquad (8)$$

Thus, the distribution of injected carriers in the base region tenzotranzistora described by [5]:

$$p(x,y,z) = \int_0^{l_x}dx'\int_0^{l_y}dy'\int_0^{l_z}\rho(x',y')\,p(x,y,z,x',y',z')dz'\,. \qquad (9)$$

On the basis of the expression (9) is determined by the diffusion current collectors, which are dependent on mechanical deformation tenzosensitive transistor.

So, consider the principle of the two collector tenzosensitive transistor and its main characteristics, proceed to consider the work of the radio gage pressure sensor with a frequency output, the circuit is shown in Fig. 2 [4].

To determine the function of converting the pressure sensor, that is, Depending on the frequency of generation of the pressure from the equivalent circuit of the device which is shown in Fig. 3.

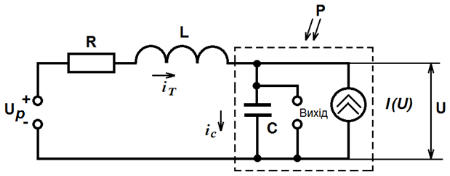

Fig. 3. The equivalent circuit of the radio gage pressure sensor

The diagram (Fig. 3), the total inductance L includes an external oscillation circuit active inductance VT3 and the inductance terminal of the circuit, the capacitance C includes an external capacitance *C1*, and the internal capacitance of transistors VT1 and VT2 at the collector electrode - drain. The resistance R includes all the resistance loss of the circuit. The current source of *I(U)* simulates the falling portion at the output voltage characteristic of the device.

The equivalent circuit of the pressure sensor (Fig. 3) is described by Kirchhoff

$$U_p = Ri_T + L\frac{di_T}{dt} + U\,, \qquad (10)$$

$$i_T = C\frac{dU}{dt} + I(U)\,. \qquad (11)$$

From the equations (10) and (11) are defined by components

$$\frac{di_T}{dt} = \frac{U_p - i_T - U}{L}\,, \qquad (12)$$

$$\frac{dU}{dt} = \frac{i_T - I(U)}{C}\,. \qquad (13)$$

At equilibrium, a DC current and voltage do not change over time, where

$$\left.\frac{di_T}{dt}\right|_{i_T = i_{T0}} = 0\,, \qquad \left.\frac{dU}{dt}\right|_{U = U_0} = 0\,. \qquad (14)$$

If you use conditions (14) from (12) and (13) define

$$U_P = i_{to}R - U_0 = 0\,, \qquad (15)$$

$$i_{T0} - I(U_0) = 0\,. \qquad (16)$$

Circuit condition in accordance with (15) and (16) can be realized at one point of the incident-sectional area and the current-voltage characteristics of the load line

$$R = \frac{U_p - U_0}{I(U_0)}\,, \qquad (17)$$

which is a state of equilibrium DC schemes investigated.

For a review of the circuit in a dynamic mode in the equation (12) and (13) introduce the variables which have the form

$$u = U - U_0\,, \qquad i = i_T - i_{T0}\,. \qquad (18)$$

Nonlinear static voltage-current characteristic of the circuit near the equilibrium point will replace the linear function

$$I(U_0 + u) = I(U_0) + u / R_g\,, \qquad (19)$$

where R_g - negative differential resistance at the point of equilibrium.

Nonlinear capacitance on electrodes first collector - drain tenzosensitive transistor FET VT1 and VT2 near the equilibrium believe constant, which is independent of voltage. Accordingly, the condition of equation (12) and (13) are converted into linear with constant coefficients

$$\frac{di}{dt} = -\frac{Ri}{L} - \frac{u}{L}\,, \qquad \frac{du}{dt} = \frac{i}{C} - \frac{u}{R_g C}\,. \qquad (20)$$

Combining equations (20) allows you to get a second order differential equation, which describes the oscillation process in autogenerating pressure sensor

$$\frac{d^2u}{dt^2}+\left(\frac{R}{L}-\frac{1}{R_gC}\right)\frac{du}{dt}+\frac{u}{LC}\left(1+\frac{R}{R_g}\right)=0\,. \tag{21}$$

The solution of equation (21) has the form

$$u(t)=A\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_gC}\right)+\sqrt{\frac{1}{4}\left(\frac{1}{R_gC}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t+ \\ +B\exp\left[-\frac{1}{2}\left(\frac{R}{L}+\frac{1}{R_gC}\right)-\sqrt{\frac{1}{4}\left(\frac{1}{R_gC}+\frac{R}{L}\right)^2-\frac{1}{LC}\left(1+\frac{R}{R_g}\right)}\right]t\,, \tag{22}$$

where A and B the coefficients are determined from initial conditions.

Two components of the equation (22) describe a batch process, the amplitude of which increases exponentially. Terms of occurrence of sinusoidal oscillations in the system described by the inequalities

$$\left(\frac{1}{R_gC}+\frac{R}{L}\right)<0\,,\qquad \frac{1}{LC}\left(\frac{R}{R_g}+1\right)>0\,. \tag{23}$$

Thus, the occurrence of fluctuations in the resonance frequency of the pressure sensor in the test will take place when the conditions (23). The resonant frequency is determined by the reactive component of the impedance at the output, which at the resonant frequency is zero (Fig. 3). The current source $I(U)$ at the operating point changes by device. Thus, the transformation function, ie, the dependence of the resonance frequency of the sensor from the effects of pressure by the expression

$$F(P)=\frac{1}{2\pi R_gC(P)}\sqrt{\frac{R_g^2C(P)}{L}-1}\,. \tag{24}$$

The sensitivity is determined on the basis of expressions (24) and has the form

$$S_P^{F_p}=-\frac{1}{2}\frac{\sqrt{\frac{R_g^2C(P)}{L}-1}\left(\frac{dC(P)}{dP}\right)}{\pi R_g^2C(P)}+\frac{1}{2}\frac{\frac{dC(P)}{dP}}{\pi L\sqrt{\frac{R_g^2C(P)}{L}-1}}\,. \tag{25}$$

Fig. 4 shows the dependence of the resonance frequency of the pressure. As can be seen from the graph, its dependence on the pressure of the non-linear, this is due to the nonlinear dependence of the equivalent capacitance of the autogenerator oscillating pressure.

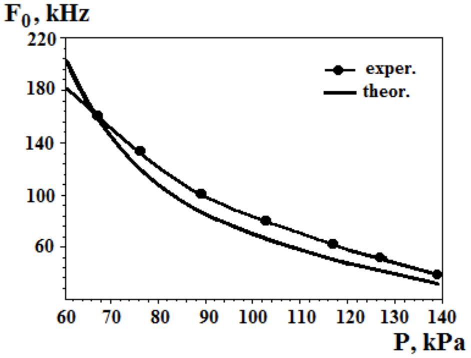

Fig. 4. Dependence of frequency of generation on an induction of a pressure

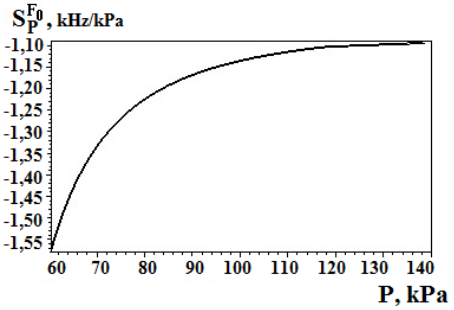

Fig. 5. Dependence of sensitivity on the induction of a pressure

The schedule of dependence of sensitivity is submitted on fig. 5. As it is seen from the schedule the greatest sensitivity of the device lays in a range from 60 up to 140 kPa and makes 1,55-1,10 kHz /kPa.

CONCLUSIONS

The opportunity of direct transformation of pressure in frequency is shown on the basis of the hybrid integrated circuit consisting of the two-collector tenzosensitive transistor and the field two-gate transistor with an active inductive element on the basis of the bipolar transistor with a phase-shifting RC chain. Analytical dependencies of transformation function and the equation of sensitivity are received. Theoretical and experimental researches have shown, that sensitivity of the transducer makes 1,55-1,10 kHz /kPa.

REFERENCES

[1] Microelectronic sensors of physical quantities. Edited Z.Yu..Hotra. In 3 volumes. - Lvov: League-Press, 2003. Vol.2. - 595 p.

[2] P.V. Novitsky, V.G. Knoring, V.S. Gutnikov. Digital devices with frequency sensors. -Leningrad: Energy, 1970. - 424 p.

[3] Osadchuk V.S. Osadchuk A.V. Reactive properties of transistors and transistor circuits. -Vinnitsa: "Universum-Vinnitsa", 1999. - 275 p.

[4] Patent №83354 Ukraine, N01R 19/00. Pressure sensor with active inductive element / Osadchyk V.S., Osadchyk A.V., Osadchyk I..A. // Application № u201300303; Applications. 09.01.2013; Publ.10.09.13 Bull. 17 - 6 p.

[5] Babichev G.G. Vertical tenzotranzistor with the dual-accelerating electric fields in the base and the emitter / G.G. Babichev, S. Kozlovsky, V.A. Romanov // Physics and tehnikapoluprovodnikov. -1999. -T.33, №3, - P. 370-379.

[6] Popovic R. S. Nall effect devices / Popovic R.S. – Bristol; Philadelphia: Institute of Physics. – 2004. – 419 p.

[7] Polyakova A.L. deformation of semiconductors and semiconductor devices / A.L. Polyakova. -M. : Energy, 1979. -168 p.