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Transducer of Pressure with a Frequency Output

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Introduction

The transducers with a frequency output have a series of advantages before peak, which constitute a considerable boost of noise stability, that allows to magnify a measurement accuracy, and also in an opportunity of deriving of major output signals. It establishes premises of a refusal of amplifying devices in an after-treatment of signals. Usage of a frequency signal as information allows to discard A/D converters, that boosts profitability of the metering equipment [1].

In the given time the intensive research on learning properties of analog microelectronic transducers [2, 3] are carried on, though the investigations of frequency transducers of a pressure on the basis of reactive properties of transistors is in an incipient state. Therefore given article is devoted to investigations of function of converting and equation of sensitivity of a pressure transducer on the basis of transistor structure with negative resistance.

Theoretical and experimental research

The electric circuit of the transducer is shown in Fig. 1. It represents a hybrid integrated circuit, which consists of two bipolar and field-effect transistors, resistances R5-R10, and also of the tenzo-resistive bridge on a membrane (R1-R4), that allows to establish the auto generating device. The tuning circuit of the device is implemented on the basis of equivalent capacity of a complete resistance on electrodes of a drain of a field-effect transistor VT1 and collector of the bipolar transistor VT2 and active inductance on the basis of the transistor VT3 with a phase-shifting line-up R11C1 [4]. On the tenzosensitive bridge (R1-R4) the pressure is applied, which reduces variation of equivalent capacity of a tuning circuit, that in turn, calls variation of a resonance frequency of the self-excited oscillator. The power loss in a tuning circuit is completed at the expense of negative resistance [5-7].

Let's consider the physical mechanism of work of an active inductive element on the basis of the bipolar transistor VT3 and phase-shifting line-up R11C1, which allows to regulate value of inductance and quality factor of an element.

The originating of inductive properties in bipolar structures is coupled to terminating traveling speed of charge carriers in base area. The signal affixed on the emitter can not appear on collector junction while the charge carriers transit basis, therefore there is a delay in time, which has received a title of time of delay. Thus, the collector current lags behind in time from voltage on the emitter, which has invoked this current, so that it corresponds an inductive response on electrodes the emitter - collector of the bipolar transistor.

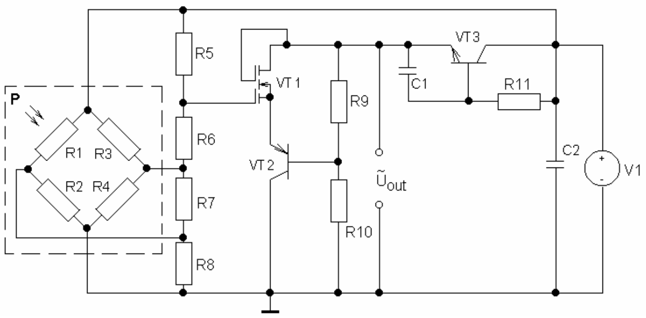

Fig. 1. An electric circuit of transducer

The value of inductance and quality factor is defined on the basis of nonlinear model of the inductive transistor on base of Ebers-Moll model, which is obtained from common mathematical model of the transistor. Output for the given model is the system of the fundamental equations, which feature behaviour of charge carriers in a semiconductor material, and also mathematical ratios, which characterize behaviour of p-n junctions. The inductance of theoretical model depends on physical properties of a semiconductor material of basis, mode of supply of the transistor on direct and alternative voltages, and also from the geometrical sizes of the transistor, that allows to drive its value from both electric, and technological paths. External parameters of the transistor, which are irrelevant to processes of a carrier charge transfer, such as transition capacitances of emitter and collector junctions, ohmic resistance of base area, inductance of lead-outs essentially influence value of inductance, which arises during a carrier charge transfer in base area. The connection external R11C1 - line-up to the transistor VT3 allows to magnify both inductance, and a quality factor of an active element on the one hand, and on the other hand – to completely implement both active inductive element, and all device using integrated technology.

The value of equivalent inductance of an active element is defined by expression

$$L = \frac{1}{\omega} \cdot \frac{A_4 A_1 - A_3 A_2}{A_1^2 + A_2^2}, \tag{1}$$

where $A_1 = \omega C_1 \left[(r_B + r_E - R_{11}\alpha_1)^2 - (R_{11}\alpha_2)^2 + \frac{1}{(\omega C_1)^2} \right]$,

$A_2 = \omega C_1 \left[2R_{11}\alpha_2 (r_B + r_E - R_{11}\alpha_1) \right]$,

$A_3 = \left[R_{11}\alpha_1 (r_B + r_E - R_{11}) + (r_B + r_E) \frac{R_{11}^2}{r_K} - \frac{2\alpha_1 R_{11}^3}{r_K} + \frac{R_{11}^2 \alpha_2^2}{(\omega C_1)^2} \right]$,

$A_4 = \left[2R_{11}^2 \alpha_1 \alpha_2 - (r_B + r_E) R_{11} \alpha_2 + \frac{2R_{11}^3}{r_K} \alpha_2 \right]$,

$\alpha_1 = \frac{\alpha_0}{1 + (f / f_\alpha)^2}$ – real part of the coefficient of the transmission ratio of a current in the common-base circuit,

$\alpha_2 = \frac{\alpha_0 f / f_\alpha}{1 + (f / f_\alpha)^2}$ – imaginary part of a transmission ratio of a current in the common-base circuit, where r_E, r_B, r_K – accordingly resistance of emitter, base and collector of the transistor VT3, f_α – cut-off frequency of the bipolar transistor in the common-base circuit, f – operating frequency, $\omega = 2\pi f$ – circular frequency.

The quality factor of an active inductive element is defined by the formula

$$Q = \frac{(A_4 A_1 - A_3 A_2)\omega C_1}{\omega C_1 (A_3 A_1 + A_4 A_2) - (A_1^2 + A_2^2)}. \tag{2}$$

Let's consider a principle of operation and some design features of the tenzosensitive bridge. The sensitive element – microsensor – represents a membrane formed in a plate from monocrystal silicon by a method of a chemical anisotropic etching. On a surface of a sensitive element, in places of the greatest mechanical stresses, by a method of introduction of boron in silicon such as n-type admittance tenzosensitive resistors are generated, which make a measuring circuit. The sensitive element is characterized by temporal stability and absence of a hysteresis. The configuration of a membrane depends on a configuration of a window of an etching and has the square shape.

The resistance strain gauges are disposed on edges of a membrane and are directional along crystallographic directions <110> in such a manner that at a strain of a membrane in two of them arise positive magnifying of a voltage ($+\Delta U_1$) Owing to a longitudinal tension resistive effect, and in two others - ($-\Delta U_2$) Owing to a transversal tension resistive effect, and $|\Delta U_1| = |\Delta U_2|$. As display measurements on breadboard samples, the nominals of resistance strain gauges can have spread up to 5 %. The spread at nominals of resistance strain gauges reduces in an initial unbalance of the bridge, and also to deterioration of temperature characteristics microsensor. Therefore to balance zero of the bridge two methods of adjustment of nominals of resistance strain gauges are applied: switch on padding resistance in bridge arms on a chip or switch on padding resistance beyond the scope of a chip (an element added).

The first method admits automation of process trimming and, besides at exact calculation of electric parameters microsensor allows to troubleshoot thermocompensation of the bridge without complication of technology of manufacture. This circumstance in business during mass production essentially reduces the cost price of sensors.

The important design stage of similar sensors is the selection and calculation of components of an electric circuit. The dependence of a resistivity and tenzosensitive coefficient on temperature is known to be more strong in semiconductor resistance strain gauges than in other resistance strain gauges (foil, wire).

It is known from [8], that with boosting of a concentration level the temperature effect on tenzosensitive of a semi-conductor is diminished. However with magnification of concentration of doped admixtures both tenzosensitive coefficient Π and nominal of the resistor are diminished. At a room temperature Π = 160 for concentration $N = 10^{17}$ (cm^{-3}) and Π = 75 at $N = 10^{20}$ (cm^{-3}).

Second parameter, which depends on temperature, is the resistance of a resistance strain gauge. As it is known from [8], the dependence of a temperature coefficient of resistance (TCR) with boosting of a concentration level from temperature is less expressed and at $N = 10^{20}$ cm^{-3} TCR of silicon equals $0{,}96 \cdot 10^{-3}$, i.e. each degree of variation of temperature answers $0{,}96 \cdot 10^{-3} \cdot 100$ % = 0,1 % of variation of resistance of a bridge arm. From here it implies, that the boosting of a concentration level ($N = 10^{20}$ cm^{-3}) is one of optimum paths of deriving sensor with a wide temperature range.

For calculation of relative variation of resistance of resistance strain gauges and sensitivity microsensor we shall consider the intense condition of a membrane. The mechanical stress of a membrane of the square shape are calculated by the formulas [9]:

$$\tau_r = \frac{3}{4} \frac{P \cdot r^2}{h^2}, \tag{3}$$

$$\tau_t = v \frac{3}{4} \frac{P \cdot r^2}{h^2}, \tag{4}$$

where τ_r - radial stress, Pa; τ_t - tangential stress, Pa; v - Poisson`s ratio; r - radius of a membrane (half of leg of the membrane), mm; h - width of a membrane, micron.

By calculating τ_r and τ_t, radiating from a given range of measurement microsensor, we transfer to calculation of relative variation of resistance [9]

$$\frac{\Delta R}{R} = S_{np}\tau_{np} + S_{nn}\tau_{nn}, \qquad (5)$$

where S_{np}, S_{nn} - longitudinal and transversal sensitivity of resistance strain gauges accordingly, mV/(V·Pa); τ_{np}, τ_{nn} - mechanical stresses in resistance strain gauges in longitudinal and transversal directions, Pa.

The relative variation of resistance of a resistance strain gauge near edges of a membrane is defined [9]:

$$\left(\frac{\Delta R}{R}\right)_r = S_{np}\tau_r + S_{nn}\tau_t = S\tau_r(1-\nu), \qquad (6)$$

$$\left(\frac{\Delta R}{R}\right)_t = S_{np}\tau_t + S_{nn}\tau_r = S\tau_r(\nu-1). \qquad (7)$$

For the bridge with four active shoulders for resistance strain gauges with identical initial resistances the relative variation of an electric voltage will be equal [9]:

$$\frac{\Delta U}{U} = 4\frac{\Delta R}{R}, \qquad (8)$$

where $R, \Delta R$ - electrical resistance and its variation accordingly, Ohm; $U, \Delta U$ - electric voltage and its variation accordingly, V.

On the basis of an equivalent circuit according to a Lapunov method of positive stability [10] the function of converting of the device is defined which represents dependence of frequency of generation on pressure. The analytical dependence of function of converting has an aspect

$$F_0 = \frac{1}{2\pi}\sqrt{\frac{B_1 + \sqrt{B_1 + 4LC_{GD}(C_B(P)R_B(P))^2}}{2LC_{GD}(R_B(P)C_B(P))^2}}, \qquad (9)$$

where $B_1 = LC_{GD} - (C_B(P)R_B(P))^2 - C_{GD}C_B(P)R_B^2(P)$, L – equivalent inductance of a active element, C_B, R_B – equivalent capacity and resistance of an impedance on electrodes drain – collector of transistors VT1 and VT2, C_{GD} – capacity of a shutter – drain of a field-effect transistor VT1.

The graphic dependence of function of converting is represented on Fig. 2. The sensitivity of a transducer with a frequency output is defined on the basis of expression (9) and is featured by the equation

$$\begin{aligned}
S_P^{F_0} = -0.0198\Bigg(& -2C_B(P)R_B^3(P)C_{GD}\left(\frac{\partial C_B(P)}{\partial P}\right)\sqrt{B_1+2B_2} - \\
& -2C_B^2(P)R_B^3(P)\left(\frac{\partial C_B(P)}{\partial P}\right) - 2C_B^3(P)R_B^2(P)\left(\frac{\partial R_B(P)}{\partial P}\right) - \\
& -3C_B(P)R_B^3(P)C_{GD}\left(\frac{\partial C_B(P)}{\partial P}\right) - 2C_{GD}C_B^2(P)R_B^2(P)\times \\
& \times\left(\frac{\partial R_B(P)}{\partial P}\right) + 8C_B^2(P)R_B^3(P)LC_{GD}\left(\frac{\partial C_B(P)}{\partial P}\right) + \\
& +8LC_{GD}C_B^2(P)R_B^2(P)\left(\frac{\partial R_B(P)}{\partial P}\right) + 4LC_{GD}R_B(P)\times
\end{aligned}$$

$$\begin{aligned}
& \times\left(\frac{\partial C_B(P)}{\partial P}\right)\sqrt{B_1+2B_2} + 4R_B(P)\left(\frac{\partial C_B(P)}{\partial P}\right)LC_{GD} + \\
& +4C_B(P)LC_{GD}\left(\frac{\partial R_B(P)}{\partial P}\right)\sqrt{B_1+2B_2} + 4LC_{GD}C_B(P)\times \\
& \times\left(\frac{\partial R_B(P)}{\partial P}\right)\Bigg)\Bigg/\Bigg(\left(2\sqrt{B_1+\sqrt{B_1+2B_2}}\Big/B_2\right)\times \\
& \times LC_{GD}C_B^3(P)R_B^3(P)\sqrt{B_1+2B_2}\Bigg), \qquad (10)
\end{aligned}$$

where $B_2 = 2LC_{GD}(C_B(P)R_B(P))^2$.

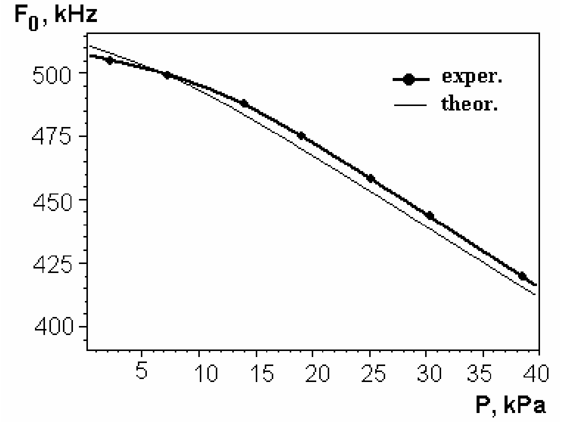

Fig.2. Dependence of theoretical and experimental curves of converting function

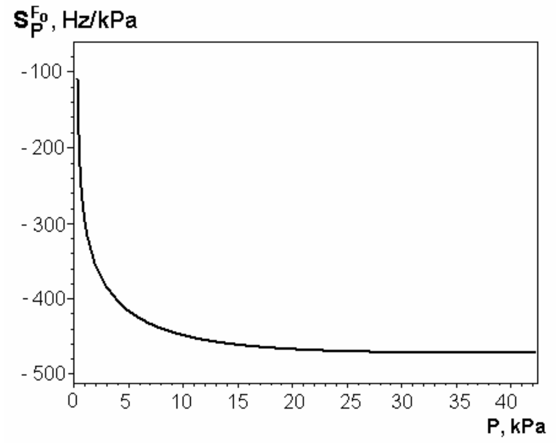

Fig.3. Sensitivity dependence on pressure

The graph of dependence of sensitivity of a pressure transducer with a frequency output is represented in Fig. 3. As it is seen from the graph, the greatest sensitivity of the device lays in a range from 10 up to 40 kPa and makes 450 Hz/kPa.

Conclusion

The opportunity of converting of pressure to frequency is shown on the basis of a hybrid integrated circuit of the auto generating device consisting of two bipolar and field transistors, and also of the tenzoresistive bridge on a membrane. The analytical dependences of transformation function and equation of sensitivity are obtained.

The theoretical and experimental research have shown, that the sensitivity of a designed transducer of pressure with a frequency output makes 450 Hz/kPa.

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In the given article operation research of a pressure transducer are presented on the basis of reactive properties of transistors. The analytical dependences of function converting and equation of sensitivity are obtained. The theoretical and experimental research have shown, that the sensitivity of a designed transducer of pressure makes 450 Hz/kPa. Ill. 3, bibl. 10 (in English; summaries in English, Russian and Lithuanian).

В.С. Осадчук, А.В. Осадчук. Радиоизмерительный преобразователь давления с частотным выходом // Электроника и электротехника. –Каунас: Технология, 2006. –№ 3(67). – С. 5 – 12.

В данной работе представлены исследования радиоизмерительного преобразователя давления на основе реактивных свойств транзисторов. Получены аналитические зависимости функции преобразования и уравнение чувствительности. Теоретические и экспериментальные исследования показали, что чувствительность разработанного радиоизмерительного преобразователя давления составляет 450 Гц/кПа. Ил. 3, библ. 10 (на английском языке; рефераты на английском, русском и литовском яз.).

V. Osadčiuk, A. Osadčiuk. Slėgio keitiklis su dažniniu išėjimu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – Nr. 3(67). – P. 5 – 12.

Pateikiami slėgio keitiklio tyrimų, atlikti remiantis reaktyviosiomis tranzistorių savybėmis, rezultatai. Gautos analitinės keitimo funkcijos priklausomybės ir jautrio lygybė. Teoriniai ir eksperimentiniai tyrimai parodė, kad nagrinėjamo slėgio keitiklio jautris sudaro 450 Hz/kPa. Il. 3, bibl. 10 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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