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Mathematical Model of a Frequency Pressure Transducer Based on a Resonant Tunneling Diode

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The paper presents the design of pressure sensor with a frequency output signal that is based on the physical processes in a resonant tunnel diode under the action of pressure. The use of devices with negative differential resistance can significantly simplify the design of pressure sensors in the entire radio frequency range. Depending on the operating modes of the sensor, an output signal can be obtained in the form of harmonic oscillations. Pressure sensor characteristics researches based on complete equivalent circuit diagram resonant tunnel diode, which takes into account its capacitive and inductive properties. A mathematical model of the pressure sensor was developed, upon which the analytical dependences of the change in the elements tunnel resonance diode from pressure have been determined, as well as conversion functions and sensor sensitivity. It is shown that the main contribution to changes in the conversion function and sensor sensitivity is made by the change in the negative differential resistance with the change in pressure. This, in turn, results in different readings of the instrument's output frequency. The sensitivity of the sensor varied from 1.15 kHz/Pa$\cdot 10^5$ to 14.16 kHz/Pa$\cdot 10^5$ in the pressure range from $50\cdot 10^5$ Pa up to $350\cdot 10^5$ Pa.

Keywords: resonant tunnel diode; pressure; negative differential resistance; frequency; quantum double-barrier heterostructure.

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Introduction

The creation and development of molecular beam epitaxial technology served as the basis for the creation of new nanoelectronic devices based on quantum heterostructures. Tunneling resonant diodes are one of such devices. They have microwave properties and negative differential resistance. These properties of tunneling resonant diodes are used to construct various sensors of physical quantities, in particular, pressure sensors [1-3]. It leads to the possibility of building an autogenerating device, in which a semiconductor diode simultaneously acts as a primary pressure sensor. This greatly simplifies the sensor design. Depending on the operating modes, it is possible to implement sensors with both output sinusoidal oscillations and impulse oscillations of a special shape in the entire range of radio frequencies.

The frequency principle of operation of pressure sensors has several advantages: high measurement accuracy; high noise immunity; the simplicity of design; no influence of measuring channels on each other; the ability to transmit measurement information over a distance without wired communication; no need to use analog-to-digital converters during the subsequent processing of information signals; the ability to create “intelligent” pressure sensors. These advantages are good reason to carry out extensive studies of the properties of tunneling resonant diodes not only as pressure sensors, but also as generators, switches, logic elements, resonant amplifiers, memory devices, and others [4-6]. However, regarding pressure sensors based on resonant tunnel diodes, a mathematical model that describes the analytical dependences of all elements of the equivalent circuit on pressure has not yet been fully developed. These dependencies, in turn, determine the relationship between the output frequency and sensor pressure sensitivity [7-9]. This work is devoted to the solving of these problems.

I. Materials and Methods

The mathematical model of a pressure sensor is built regarding the physical phenomena in the diode. The operation of resonant tunnel diodes is based on quantum effects. The essence of the effects is the quantization of the energy of electrons and their tunneling through potential barriers.

Research of pressure sensors based on resonant tunneling diodes requires knowledge of physical processes, the structure of the diode, a mathematical model of the current-voltage characteristic, generators, as well as operating modes. Therefore, it is necessary to first consider these questions. Theoretical and experimental studies of tunneling-resonant diodes begin with the development of a mathematical model of the current-voltage characteristic that proceeds from the physical processes of electron tunneling through potential barriers.

Let us consider a typical quantum structure of AlAs-GaAs-AlAs, physical processes during the perpendicular motion of electrons through potential barriers, and a quantum well based on the energy diagrams of the conduction and valence bands of a resonant tunnel diode at different values of the applied voltage. Potential barriers and the quantum well between them are formed at the expense of different values of widths of the forbidden zones for semiconductive GaAs and AlAs connections which results in the breaking of energy levels of the bottom of the conductive band and the top of the valence zone [7, 11-13]. The application of an external voltage to the emitter-collector electrodes of a quantum heterostructure leads to a change in the magnitude of electrons tunneling through potential barriers and the quantum well, which causes the change in the magnitude of the current through the structure.

II. Pressure sensor mathematical model

Let's move on to considering the reactive elements of the resonant tunnel diode, based on its equivalent circuit [11]. Reactive elements include the capacitance and inductance of the device. In Figure 1 is shown the equivalent circuit of a resonant tunnel diode.

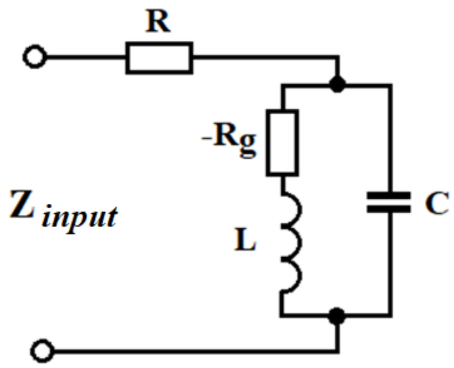

Fig. 1. Equivalent resonant tunnel diode circuit: R – resistance to losses; R_g negative.

The inductance of a resonant tunnel diode is related to the final speed of moving electrons and it always exists in the diode under any conditions. This is because the voltage at the emitter, which causes electrons to move through the device, is ahead of the current, i.e. the current always lags behind the voltage, which is equivalent to the inductive response of a resonant tunnel diode. Based on the physical laws of quantum mechanics, we calculate the inductance formula. The energy of electrons in a quantum well, on the one hand, is determined by the second component in formula [8]:

$$E(K_x, K_y, n = \frac{\hbar^2}{2m^*}\left(K_x^2 + K_y^2\right) + E_n = \frac{\hbar^2}{2m^*}\left(K_x^2 + K_y^2\right) + \frac{\pi^2\hbar^2}{2m^* a^2}n^2,\ n = (1, 2 \ldots), \quad (1)$$

and it is equal to the energy of the magnetic field, therefore:

$$\frac{\pi^2\hbar^2 n^2}{2m^* a^2} = \frac{Li^2}{2}\ , \quad (2)$$

where L – inductance of the equivalent circuit of the resonant tunnel diode, i – the diode current. From formula (2) it possible to determine the inductance value:

$$L = \frac{\pi^2\hbar^2 n^2}{m^* a^2 i^2} = \frac{h^2 n^2}{4a^2 m^* i^2} \quad (3)$$

On the other hand, the energy of electrons in the quantum well is equal to the energy of the electric field:

$$\frac{\pi^2\hbar^2 n^2}{2m^* a^2} = \frac{CU^2}{2}, \quad (4)$$

where U – voltage applied to the resonant tunnel diode. From expression (4) the capacitance can be obtained:

$$C = \frac{\pi^2\hbar^2 n^2}{m^* a^2 U^2} = \frac{h^2 n^2}{4m^* a^2 U^2} \quad (5)$$

It is possible to check the validity of formulas (3) and (5) if the equivalent capacitance and inductance are calculated from the input impedance of the equivalent circuit (Fig. 1). Thus, the value of the capacitance of the resonant tunnel diode has the form:

$$C = \frac{L}{\omega^2 L^2 + R_g^2} \quad (6)$$

Capacitance calculations C, according to formula (6) on the applied voltage are shown in Fig. 2.

As can be seen, the capacitance value is constant in the voltage range from zero to 0.3 V. In the section from 0.3 V to 0.6 V, it comes almost linearly, and then after the voltage of 0.6 V up to 0.9 V it increases. This behavior of capacitance on voltage is explained by the change in the negative differential resistance in the descending section of the current-voltage characteristic.

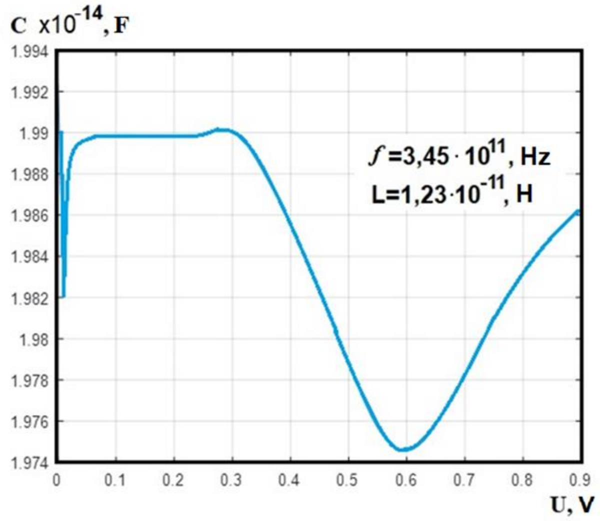

Fig. 2. Dependence of the inside capacitance of the resonant tunnel diode on the applied voltage.

Comparison of the capacitance value calculated according to the formula (5) and (6) at the applied voltage value of 0.4 V coincides with the accuracy of the second digit, that is, with the accuracy of 0.01 %.

The inductance value L of resonant tunnel diode is determined based on the expression:

$$L = \frac{\frac{1}{C} - \sqrt{\frac{1}{C^2} - 4R_g^2\omega^2}}{2\omega^2} \qquad (7)$$

Figure 3 shows the inductance calculations by formula (7).

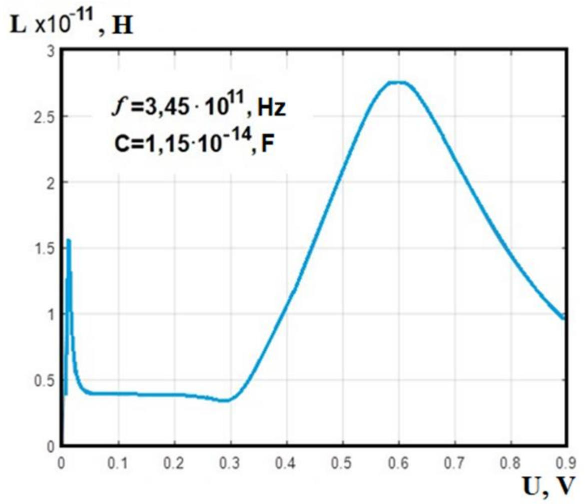

Fig. 3. Dependence of the inside inductance of the resonant tunnel diode on the applied voltage.

The change in the value of inductance from the applied voltage is also explained by its dependence on the change in the negative differential resistance on the descending section of the current-voltage characteristic. Comparison of the inductance value, which is calculated according to formulas (3) and (7), coincides with the accuracy of 0.01 % at a point with a voltage of 0.4 V. Therefore, resonant tunneling diodes can be used as adjustable capacitive and inductive elements in the terahertz frequency range, and their Q-factor can be adjusted due to a negative differential resistance in the intervals of 100 and higher.

The change in differential resistance across the entire scale of applied voltages is shown in Figure 4. The negative differential resistance is determined by the voltage range from 0.3 V to 0.6 V. Its value varies from 80 Ω to 550 Ω. Such a change in the differential resistance from the applied voltage is explained by the course of the current-voltage characteristic of the diode.

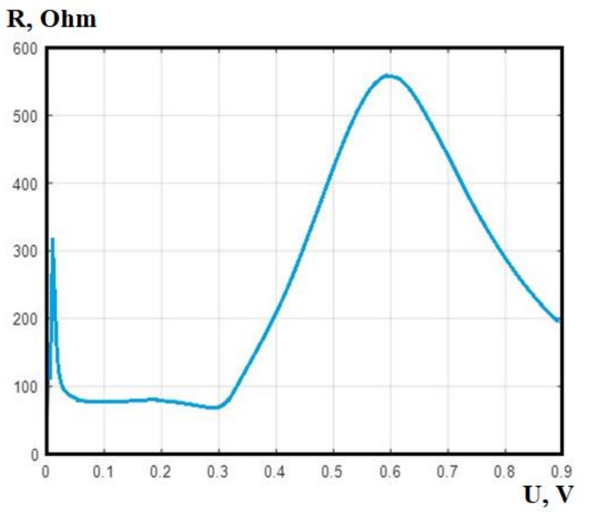

Fig. 4. Dependence of the differential resistance of the resonant tunnel diode on the applied voltage.

Figure 5 presents the dependence of the change in the natural resonant frequency of the resonant tunnel diode on the applied voltage. As can be seen from figure 5 with an increase in the supply voltage of the diode, the frequency increases, in the section from 0.05 V to 0.2 V it stabilizes somewhat, and with the further increase in voltage it approaches the maximum value, and in the section from 0.3 V to 0.6 V, where there is a negative differential resistance, it drops sharply from $5 \cdot 10^{11}$ Hz to $3.3 \cdot 10^{11}$ Hz.

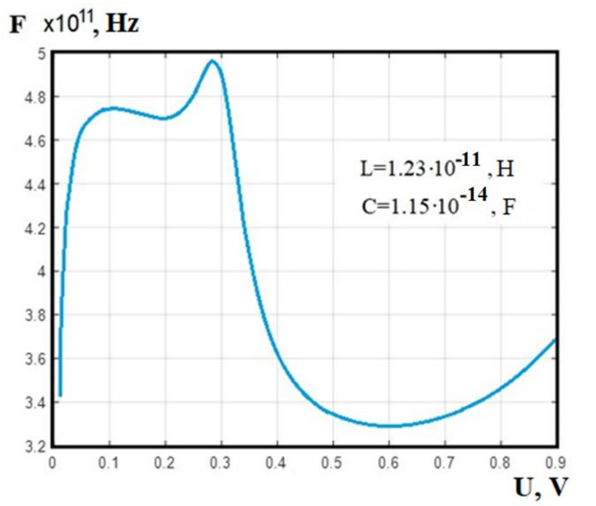

Fig. 5. Dependence of the own resonant frequency of the resonant tunnel diode on the change in the supply voltage.

This behavior of the natural resonant frequency of the diode is explained by the mutual influence of the differential negative resistance, capacitance, and inductance on the frequency due to their change from the supply voltage.

Data for the theoretical calculation of the parameters of the elements of the equivalent circuit for the real structure of the resonant tunnel diode: the spatial layer of n^+GaAs emitter – 7.6 nm, potential barrier on the side of the emitter AlAs – 5 nm, quantum well GaAs – 6 nm, potential barrier on the side of the AlAs collector – 5 nm, spatial layer n^+GaAs collector – 5 nm, structure area – 25 μm^2 [7].

Let's move on to considering the characteristics of the pressure sensor. The electrical circuit of the pressure sensor is shown in Figure 6. The circuit is powered by a constant voltage source U_p ; it consists of an active resistance R , which includes all the ohmic resistances of the circuit, external inductance L , which is serially connected to the internal inductance of the diode, and also includes the inductance of the circuit terminals, the external capacitance C , which is connected in parallel to the internal capacitance of the diode, as well as the resonant tunnel diode itself.

An equivalent sensor circuit for calculating its characteristics is shown in Figure 7.

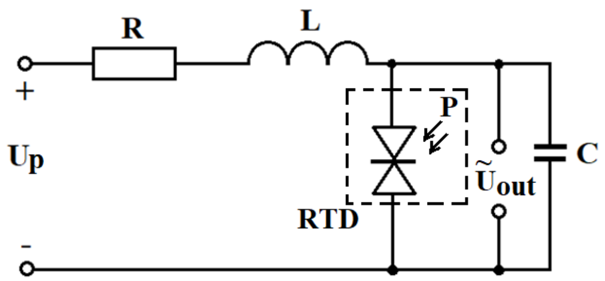

Fig. 6. The electrical circuit of a pressure sensor based on a resonant tunnel diode.

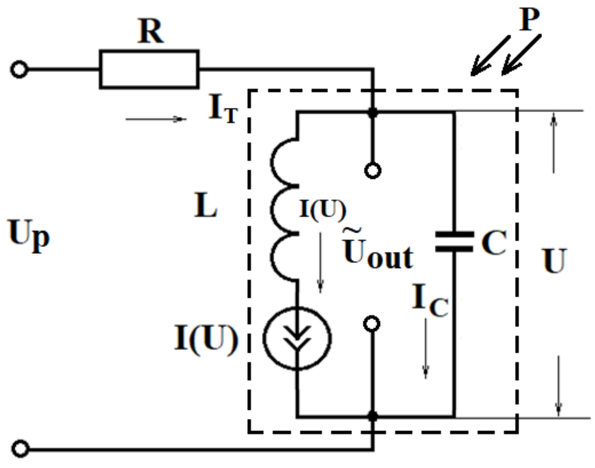

Fig. 7. Equivalent circuit of a pressure sensor with an internal current source $I(U)$.

The current source $I(U)$ at the operating point of the sensor on the falling section of the current-voltage characteristic determines the ratio $U/I(U)$, which corresponds to the negative differential resistance $-R_g$, therefore, in what follows in the equivalent circuit (Fig. 7) is replaced by R_g .

Consider the effect of pressure on characteristics of resonant tunnel diode. It should be noted that there are two pressure ranges that determine the nature of changes in the parameters of semiconductor devices. These are high pressures, at which the change in the band gap $E_g > kT$, and low pressures, when $E_g < kT$, where kT is thermal energy. At high pressures, there is a splitting of energy bands, a redistribution between the extrema of charge carriers. In this case, the main factor that changes the parameters of the resonant tunnel diode is the deformation change in the band gap. If the pressures are small, then the changes in the current shift occur due to changes in the effective masses and mobility of the charge of current carriers from pressure variations. The authors [2, 13, 15] show that the current-voltage characteristics of double-barrier resonant tunneling devices can be modified by internal polarization fields due to the piezoelectric effect caused by external uniaxial voltages. Electric polarization fields perpendicular to the interfaces arise in diodes grown on substrates with the <001> orientation at uniaxial compressive voltages parallel to the <111> crystal orientation [16, 17]. The voltages at which the peaks of the resonant tunneling current arise are sensitive to polarization fields caused by external pressures. The peak voltage can shift towards more positive or negative voltages depending on the direction of the applied pressures [16]. Under the action of external pressure on the diode, both the effective mass of electrons change and the generation of piezoelectric fields in the quantum well and potential barriers of the diode structure [2, 13]. Hydrostatic pressures cause a change in the effective mass of electrons in the quantum well. This leads to the change in the arrangement of energy levels in the quantum well. Application of uniaxial or biaxial pressures to the diode leads to a stronger change in the energies of electrons than the change of their effective masses at the expense of the influence of piezoelectric fields [2, 17]. The change in the energy of the electrons of the diode under the action of pressure changes the form of the current-voltage characteristic. This, in turn, leads to the change of the frequency of electrical oscillations in the pressure sensor [14].

Based on the equivalent circuit of the pressure sensor (Fig. 7), we calculate the changes in its parameters from pressure.

All parameters of the resonant tunnel diode sensor depend on the pressure. Their contribution to the change in the current-voltage characteristic of the sensor is different. Based on analytical formulas for ohmic resistance R , inductance L , capacity C , and differential negative resistance R_g let us determine their change from the applied pressure.

Resistance R consists of terminals resistances, ohmic contacts, and substrate spreading resistance

$$R = {}^{\rho}/_{2d}\,, \tag{8}$$

where ρ is semiconductor resistivity, d is the diameter of the diode area. The internal capacitance of diode C and inductance L are determined by expressions (3) and (5).

The negative differential resistance at the operating point of the diode has the form:

$$R_g = -\frac{U}{I}, \quad (9)$$

where U, I are voltage and current at the operating point of the current-voltage characteristic of the sensor.

Proceed from general mathematical considerations, changes in sensor parameters from pressure can be represented in the following form:

$$\Delta R(P) = \frac{\partial R}{\partial d}\Delta d(P) + \frac{\partial R}{\partial \rho}\Delta\rho(P) \quad (10)$$

$$\Delta C(P) = \frac{\partial C}{\partial m^*}\Delta m^*(P) + \frac{\partial C}{\partial a}\Delta a(P) + \\ + \frac{\partial C}{\partial U}\Delta U(P) + \frac{\partial C}{\partial n}\Delta n(P) \quad (11)$$

$$\Delta L(P) = \frac{\partial L}{\partial m^*}\Delta m^*(P) + \frac{\partial L}{\partial a}\Delta a(P) + \\ + \frac{\partial L}{\partial I}\Delta I(P) + \frac{\partial L}{\partial n}\Delta n(P) \quad (12)$$

$$\Delta R_g(P) = -\left(\frac{\partial R_g}{\partial I}\Delta I(P) + \frac{\partial R_g}{\partial U}\Delta U(P)\right) \quad (13)$$

After making the necessary transformations in the formulas (10) – (13), we get:

$$\Delta R(P) = \frac{1}{2d}\Delta\rho(P) - \frac{\rho}{2}\cdot\frac{1}{d^2}\Delta d(P) \quad (14)$$

$$\Delta C(P) = -\frac{h^2n^2}{4m^{*2}a^2U^2}\Delta m^*(P) - \frac{h^2n^2}{2m^*a^3U^2}\Delta a(P) - \\ - \frac{h^2n^2}{2m^*a^2U^3}\Delta U(P) + \frac{h^2n^2}{2m^*a^2U^2}\Delta n(P) \quad (15)$$

$$\Delta L(P) = -\frac{h^2n^2}{4m^*a^2I^2}\Delta m^*(P) - \frac{h^2n^2}{2m^*a^3I^2}\Delta a(P) - \\ - \frac{h^2n^2}{2m^*a^2I^3}\Delta I(P) + \frac{h^2n^2}{2m^*a^2I^2}\Delta n(P) \quad (16)$$

$$\Delta R_g(P) = \frac{U}{I^2}\Delta I(P) - \frac{1}{I}\Delta U(P) \quad (17)$$

Analysis of formulas (14) – (17) shows that the pressure change has the greatest influence on the differential negative resistance. As the calculations showed the change of inter capacitance has the value $0.15 \cdot 10^{-14}$ F, the inductance $0.13 \cdot 10^{-11}$ H and a negative differential resistance 12.3 Ohm from the pressure action in researched range. The values of change in an inter capacitance and inductance were on five – seven orders less than an external capacitance ($0.37 \cdot 10^{-9}$ F) and inductance ($0.3 \cdot 10^{-4}$ H) that is way they do not influence on the frequency of autogenerator pressure sensor. The negative differential resistance compensates losses the energy in a resonant circuit that is way its change causes of shift in frequency. The change of the zone parameters of structure determines experimental means by the change of volt-ampere and frequency characteristics of sensor when pressure acts on sensor.

The resonant frequency of the pressure sensor oscillator is determined based on the formula for the input impedance of the circuit (Fig. 7). The impedance formula is:

$$Z_{input} = R + \frac{-\frac{R_gL}{C} - \frac{R_g}{\omega C}\left(\omega L - \frac{1}{\omega C}\right)}{R_g^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} - \\ -j\frac{\frac{R_g^2}{\omega C} + \frac{L}{C}\left(\omega L - \frac{1}{\omega L}\right)}{R_g^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \quad (18)$$

In resonance mode, the imaginary component of expression (18) is equal to zero:

$$\frac{\frac{R_g^2}{\omega C} + \frac{L}{C}\left(\omega L - \frac{1}{\omega C}\right)}{R_g^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} = 0 \quad (19)$$

From equation (19) the resonant frequency can be determined, which is described by the expression:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R_g^2(P)}{L^2}} \quad (20)$$

In formula (20) only the differential negative resistance depends on the pressure. However, the intrinsic capacitance and inductance of a tunneling resonant diode also depend on pressure. The change in their values is five orders of magnitude smaller concerning the external values of the capacitance and inductance of the oscillatory circuit of the autogenerator of the pressure sensor, therefore, their influence is neglected.

The plot of the calculated dependence of the change in the resonance frequency on pressure is shown in Figure 8. This graph is the conversion function of the pressure sensor.

The sensitivity of the pressure sensor is determined by the first derivative of the conversion function (20) concerning pressure, i.e. equal to the ratio kHz/Pa. Figure 9 presents the calculated dependence of the sensor sensitivity function on the applied pressure. Its analytical expression is complicated and can be described by the following equation:

$$S_p = -\frac{R_g(P)\left(\frac{dR_g(P)}{dP}\right)}{2\pi L^2\sqrt{\frac{1}{LC} - \frac{R_g^2(P)}{L^2}}} \quad (21)$$

The sensor design consists of a membrane that is etched into a silicon substrate. A resonant tunnel diode is built on the membrane. Solid state capacitance, inductance and resistor are created on the substrate next to the membrane. The resistor provides DC power to the sensor. The diaphragm thickness determines the measured pressure range.

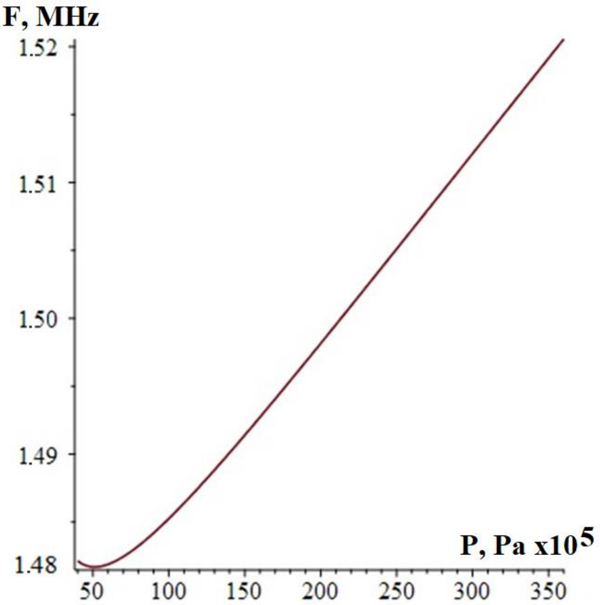

Fig. 8. The calculated dependence of the change in the resonant frequency on pressure.

As can be seen from the graph (Fig. 9), the sensitivity value varies from 1.15 kHz/Pa·10^5 to 14.16 kHz/Pa·10^5 in the pressure range from $50 \cdot 10^5$ Pa to $350 \cdot 10^5$ Pa. The complicated nature of the behavior of the sensitivity function on pressure is explained by the complicated dependence of the sensor conversion function on the changed negative differential resistance under the influence of pressure.

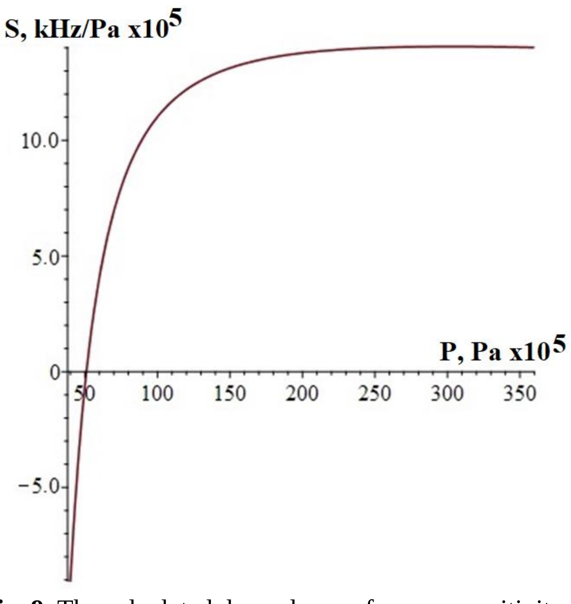

Fig. 9. The calculated dependence of sensor sensitivity on pressure.

III. Discussion

Based on the consideration of physical processes in a resonant tunnel diode under pressure, the authors proposed to design pressure sensors with a frequency output signal. The use of devices with negative differential resistance can significantly simplify the design of pressure sensors in the entire radio frequency range. Depending on the operating modes of the sensor, an output signal can be obtained both in the form of harmonic oscillations and in the form of impulse oscillations.

Pressure sensor performance studies are based on a full resonant tunnel diode equivalent circuit that takes into account its capacitive and inductive properties. The current-voltage characteristic of the sensor has a falling section, which corresponds to the appearance of a negative differential resistance in this section. The falling section arises due to a decrease in the current that passes through the double-barrier quantum heterostructure. This occurs due to a decrease in the transparency coefficient of potential barriers due to an increase in the electron energy in comparison with the energy resonance level in the quantum well.

A mathematical model of the pressure sensor was developed, based on which the analytical dependences of the change in the elements of the resonant tunnel diode on pressure, as well as the conversion function and sensor sensitivity, were determined. It is shown that the main contribution to changes in the conversion function and sensor sensitivity is made by the change in negative differential resistance with pressure change. The frequency principle of operation of pressure sensors makes it possible to increase the measurement accuracy, noise immunity, increase the amplitude of the output signal, and also allows the transmission of an informative signal over long distances, the possibility of creating "intelligent" pressure sensors.

Let us consider possible ways of using the investigated pressure sensors in various fields of science and industry. One of the key modern manufacturing challenges is the integration of sophisticated electronic and optoelectronic functions into soft and thin fibers [18]. Multifunctional fiber optic devices will be in the base of development of smart tissues, surgical sensors and instruments, robotics and prostheses, communications systems and portable energy collectors. It is obvious that in optoelectronic surgical sensors and protheses, communication systems, microelectronic pressure sensors with a frequency output will be needed.

Another area of application for pressure sensors is self-propelled nanomotors (MNM) for use in biomedicine [19]. By combining the sizes of nanomotors with the nanosize of the pressure sensor, it is possible to solve the issues of navigation and pressure measurement during the autonomous movement of the nanomotor.

Some more area of application of the pressure microsensor is its possible combination with micro- and nano-sized metal glasses to create an implantable fiber-optic probe [20].

Conclusions

A mathematical model of the pressure sensor was developed, based on which the analytical dependences of the conversion function and sensitivity were determined. It is shown that the main contribution to the conversion function is made by the change in the electron energy in the quantum heterostructure of the tunnel resonance diode under the action of pressure. This changes the negative differential resistance, which in turn changes the output frequency of the pressure sensor. The sensitivity of the pressure sensor varies from 1.15 kHz/Pa$\cdot 10^5$ to 14.16 kHz/Pa$\cdot 10^5$ in the range of pressure changes from $50\cdot 10^5$ Pa to $350\cdot 10^5$ Pa. The output frequency was varied from 1.48 MHz to 1.52 MHz.

Based on the equivalent circuit of the pressure sensor analytical expressions for the change in all circuit parameters from pressure have been determined. It is shown that pressure sensors with frequency output based on tunnel resonance diodes have significant advantages over analog sensors. Their advantages are the ability to work in the ultra-high frequency range, the pressure measurement accuracy, wireless transmission of measured information over a distance, increasing the microminiaturization of the sensor right up to nanosize, and the simplicity of the sensor design.

Considering the physical processes in a resonant tunnel diode, analytical formulas for inside capacitance and inside inductance have been determined which depend on the mode of its operation. Proceed from these formulas, their dependences on the mode of power supply with constant voltage have been calculated. It is shown that inside capacitance of the diode varies from $1.99\cdot 10^{-14}$ F to $1.97\cdot 10^{-14}$ F on the descending section of the volt-ampere characteristic, and the change of inductance lies in the range from $0{,}5\cdot 10^{-11}$H up to $2.75\cdot 10^{-11}$H.

The analytical dependence of the own resonant frequency of the diode on the modes of its operation is determined. It is shown that the own resonant frequency changes in the area of negative differential resistance from $4.8\cdot 10^{11}$ Hz to $3.28\cdot 10^{11}$ Hz. This is due to the cumulative effects of changes in capacitance, inductance, and negative differential resistance. Resonant tunneling diodes can be used as adjustable capacitive and inductive elements in the terahertz frequency range, and their Q-factor can be adjusted due to negative differential resistance in the intervals from 100 and higher.

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Математична модель частотного перетворювача тиску на основі резонансно - тунельного діода

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У роботі представлено перетворювач тиску з частотним вихідним сигналом, що базується на фізичних процесах у резонансно-тунельному діоді під дією тиску. Використання приладів з від’ємним диференціальним опором дозволяє значно спростити конструкцію сенсорів тиску у всьому радіочастотному діапазоні. Залежно від режимів роботи сенсора вихідний сигнал може бути отриманий у вигляді гармонійних коливань. Дослідження характеристик сенсора тиску базується на повній еквівалентній схемі резонансного тунельного діода, що враховує його ємнісні та індуктивні властивості. Розроблено математичну модель сенсора тиску, на основі якої визначено аналітичні залежності зміни елементів тунельно-резонансного діода від тиску, а також функції перетворення та чутливість сенсора. Показано, що основний внесок у зміни функції перетворення та чутливості сенсора вносить зміна від’ємного диференціального опору зі зміною тиску. Це, у свою чергу, приводить до різних значень вихідної частоти приладу. Чутливість сенсора змінювалася від 1,15 кГц/Па$\cdot 10^5$ до 14,16 кГц/Па$\cdot 10^5$ в діапазоні тиску від $50\cdot 10^5$ Па до $350\cdot 10^5$ Па.

Ключові слова: резонансний тунельний діод; тиск; від’ємний диференціальний опір; частота; квантова гетероструктура з подвійним бар'єром.