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Alexander V. Osadchuk, Vladimir S. Osadchuk, Serhii V. Baraban, Tomasz Zyska, Aizhan Zhanpeisova, "Temperature transducer based on metal-pyroelectric-semiconductor structure with negative differential resistance," Proc. SPIE 10808, Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018, 108085D (1 October 2018); doi: 10.1117/12.2501625

SPIE.

Event: Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018, 2018, Wilga, Poland

Temperature transducer based on metal-pyroelectric-semiconductor structure with negative differential resistance

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ABSTRACT

The paper analyses modern development status of temperature transducer on the basis of piroelectrics, represents and describes a new temperature transducer on the basis of transistor structure with negative differential resistance, simulates current-voltage and frequency characteristic of this device in the software environment Pspice.

Keywords: metal-pyroelectric-semiconductor structure, piroelectric, temperature transducer, transistor structure with negative differential resistance, emanation power transducer sensor, piroelectric detector.

1. INTRODUCTION

By estimates of world specialists technical temperature measurements make according to 40 - 50% of a total quantity of all measurements[1, 2]. It is caused by the powerful industrial and scientific and technical capacity of the countries with preferential development of such industries as metallurgy, power, mechanical engineering, the aircraft and space equipment, chemical industry, etc. which efficiency substantially depends on the accuracy of temperature measurements and heatphysical characteristics. In this regard rather important problems of modern instrument making and the measuring equipment is the choice of safe methods of temperature measurement of rather different productions, creation of measuring devices of necessary accuracy, stability and high-speed performance and also a research of influence on result of measurements of all set of the factors accompanying measuring process [3-5].

Rapid development of the semiconductor equipment caused the imperative need of comprehensive study of the physical phenomena observed in semiconductors and semiconductor devices. Researches of the dynamic modes of semiconductor structures showed that capacity properties, the inductive effect, the phenomenon of negative differential resistance can be used with success for creation of a number of original devices[6-9]. Constructive simplicity, profitability, reliability, lack of influence on adjacent nodes and elements, a possibility of production in the form of integrated microcircuits and electronic adjustment of parameters are inherent in such devices. In recent years fundamental mechanisms of the specified phenomena were intensively studied, and rather large number of works on this question is so far published[10-13].

Measurement of values of the thermal analysis occurs in a contactless manner by the primary pyrometric transducer. The thermal radiation falls on the sensing element (SE) of the primary pyrometric transducer, and then transmitted to the control element (CE). Typically, the control element is a pyroelectric, which is applied from above a film of molten metal that is thermosensitive. The third component of the primary pyrometric transducer is the actuating element (AE) - usually a transistor, or an operational amplifier. We propose to combine fine pyroelectric films with schemes of transistor structures with negative differential resistance[4, 7, 14-18]. Figure 1 presents a structural scheme for measuring the temperature transformation of sample to change the frequency of the output signal.

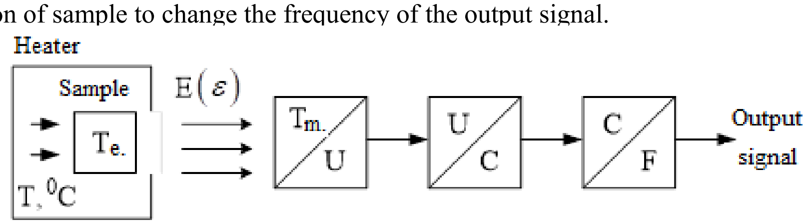

Figure 1. The block diagram of the measurement transformation.

Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments 2018, edited by Ryszard S. Romaniuk, Maciej Linczuk, Proc. of SPIE Vol. 10808, 108085D

doi: 10.1117/12.2501625

In fig. 1 the following designations are used: T - temperature of the heater; $T_{e.}$ - temperature of the test sample; E - thermal radiation flux of a sample caused by its heating; ε - integral radiative power of a sample; $T_{m.}$ - temperature of a sensitive pyroelectric element, caused by the action of a thermal radiation stream on it.
Thus, the actual value of the temperature of the non-crystalline semiconductor

$$T_{m.} = \frac{T_{e.}}{\sqrt[4]{\varepsilon}} . \qquad (1)$$

It is necessary to develop a mathematical model of the temperature transducer for finding an analytical and graphical representation of the function of the transformation *F (T).*

2. THEORETICAL AND EXPERIMENTAL RESEARCH

We suggest to include insulate gate bipolar transistor (IGBT) with plotted on baseline a film of piroelectric $PbTiO_3$ (PTO) and nielloed by gold into the schema with the bipolar device for creating structure with a negative resistance for the purpose to create self-oscillator. These device in it structure combine active integral constructions with usage of thin piroelectric film and self-oscillator on the basis of transistor structures with a negative differential resistance[4, 12].

The mathematical modeling of the frequency measuring transducer of the values of thermal analysis will be made for the scheme based on the metal-pyroelectric-semiconductor structure (Fig. 2).

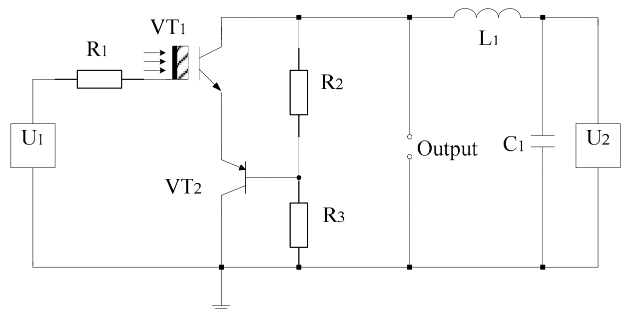

Figure 2. The transducer of temperature on the basis of the metal-pyroelectric-semiconductor structure with a negative resistance.

As is seen from fig. 2 the device contains first voltage source U_1 that is connected by one pole to the gate IGBT VT_1 with raised dust on baseline a film of piroelectric and an absorber of emanations, and the other pole to the collecting channel bipolar junction transistor (BJT) VT_2 which is connected to ground connection, emitter IGBT VT_1 is connected to emitter BJT VT_2, and collecting channel IGBT VT_1 is connected to passive inductance L_1, baseline BJT VT_2 is connected between the sequentially connected resistors R_2 and R_3 which are in bridge connected by other poles to IGBT-BJT structure, and also in bridge to transistors VT_1 and VT_2 passive inductance L_1 and capacitor S_1 and the second voltage source U_2 is connected.

Since the pyroelectric transducers are a dynamic system, analysis of the conduct of investigated structure will make during the active pulse of infrared radiation. When signal hit to the sensor, pyroelectric heated, resulting signal is occurred and charges both: the pyroelectric capacitor and the input capacitance of the transistor. The value of infrared radiation required for operation of the sensor lies in the units of microwatts. So pyroelectric film transistor has high sensitivity. At the base of the IGBT transistor filed potential of a polarity that changes the voltage of the transistor structure with the pyroelectric film is submitted

$$U = U_0 - \frac{2}{3} \cdot \theta \cdot U_{be} , \qquad (1)$$

where U_0 =2,4 B; θ – adjustment coefficient; U_{be} – base-emitter voltage.

If on one surface of the pyroelectric potential is constant and the other changes

$$\Delta U = \frac{p \cdot \delta \cdot \Delta T}{\varepsilon \cdot \varepsilon_0}, \quad (2)$$

where p – pyroelectric coefficient; δ – thickness of the pyroelectric; ΔT – temperature change; ε – pyroelectric dielectric constant; ε_0 – dielectric constant.

Substituting the expression for the temperature change in (2) we obtain

$$\Delta U = \frac{p \cdot \delta}{\varepsilon \cdot \varepsilon_0} \cdot \frac{T \cdot A \cdot \eta}{\alpha} \cdot \frac{1}{\tau^2} \cdot \exp\left(-\frac{t}{\tau}\right), \quad (3)$$

where A – absorbing layer area on the surface of the sensing element; η – emission coefficient; α – coefficient of conduction; τ – constant, independent of temperature and time; t – time; T – temperature of the radiation.

The dependence the base-emitter voltage of the IGBT transistor with pyroelectric film from the temperature is obtained, combining (1) and (3)

$$U_{be} = \frac{3T}{2\theta}\left(U_p - \frac{p \cdot \delta \cdot A \cdot \eta}{\tau^2 \cdot \varepsilon \cdot \varepsilon_0 \cdot \alpha} \cdot \exp\left(-\frac{t}{\tau}\right)\right). \quad (4)$$

Assuming that the sensor is turn on at the beginning of the radiation, equation (4) can be rewritten

$$U_{be}(T) = \frac{3T}{2\theta}\left(U_{nop} - \frac{p \cdot \delta \cdot A \cdot \eta}{\tau^2 \cdot \varepsilon \cdot \varepsilon_0 \cdot \alpha}\right). \quad (5)$$

The temperature changes affect different parameters and characteristics of the IGBT-BJT structure. These basic parameters and characteristics include: semiconductor bandgap, contact potential difference of transistor junctions and capacitance of transistor junctions [14, 15].

The dependence of the semiconductor bandgap on the temperature is described by equation

$$E_G(T) = E_{G0} - \frac{aT^2}{(T+b)}, \quad (6)$$

where T – temperature, s – area of p-n junction, E_{G0} – bandgap at normal temperature 23 ^{0}C, a, b – temperature coefficients of p-n junction.

The contact potential difference of emitter junction described by equation

$$U_{je}(T) = U_{je}\frac{T}{T_0} - 3V_t(T)\ln\left(\frac{T}{T_0}\right) - E_G\frac{T}{T_0} + E_G(T), \quad (7)$$

where T_0 – normal temperature 23 ^{0}C, $V_t = kT/q$ - temperature potential of junction, k – Boltzmann constant, q – electron charge, U_{je} – contact potential difference of emitter junction.

The dependence of the junctions voltage of the IGBT-BJT structure on the temperature was obtained, after substituting the equation (6) into (7)

$$U_{je}(T) = U_{je}\frac{T}{T_0} - 3\frac{kT}{q}\ln\left(\frac{T}{T_0}\right) - E_G\frac{T}{T_0} + E_{G0} - \frac{aT^2}{(T+b)}. \quad (8)$$

The voltage of junctions changes the capacitance of the IGBT-BJT structure junctions. The capacity of transistor junction changes the barrier capacitance of the IGBT-BJT structure and capacity of the base-emitter junction.

The dependence of the capacitance of emitter junction at zero bias on the temperature changes described by equation

$$C_{je}\left(U_{je}\right)=C_{je}\left(1+M_{je}\left(0,0004\left(T-T_{0}\right)+1-\frac{U_{je}(T)}{U_{je}}\right)\right), \tag{9}$$

where M_{je} – coefficient smoothness emitter junction, C_{je} – capacitance of emitter junction at zero bias.
Barrier capacitance described by equation [7]

$$C_{jbe}(U_{je})=\begin{cases} C_{je}(U_{je})\left(1-\dfrac{U_{be}(T)}{U_{je}(T)}\right)^{-M_{je}} \text{ at } U_{be}\le F_{\kappa}U_{je}(T); \\ C_{je}(U_{je})(1-F_{\kappa})^{-(1+M_{je})}\left(1-F_{\kappa}(1+M_{je})+M_{je}\dfrac{U_{be}}{U_{je}(T)}\right) \text{ at } U_{be}>F_{\kappa}U_{je}(T) \end{cases}, \tag{10}$$

where U_{be} – base-emitter voltage, F_K - coefficient of barrier capacitance nonlinearity.

The dependence of the IGBT-BJT structure capacity on the contact potential difference of junctions changes was obtained, after substituting the equation (9) into (10)

$$C_{jbe}(U_{je})=\begin{cases} C_{je}\left(1+M_{je}\left(0,0004\left(T-T_{0}\right)+1-\dfrac{U_{je}(T)}{U_{je}}\right)\right)\left(1-\dfrac{U_{be}(T)}{U_{je}(T)}\right)^{-M_{je}} \\ \text{at } U_{be}\le F_{\kappa}U_{je}(T); \\ C_{je}\left(1+M_{je}\left(0,0004\left(T-T_{0}\right)+1-\dfrac{U_{je}(T)}{U_{je}}\right)\right)(1-F_{\kappa})^{-(1+M_{je})}\cdot \\ \cdot\left(1-F_{\kappa}(1+M_{je})+M_{je}\dfrac{U_{be}(T)}{U_{je}(T)}\right) \text{ at } U_{be}>F_{\kappa}U_{je}(T); \end{cases} \tag{11}$$

The capacitance of the IGBT-BJT structure changes the output signal frequency of the temperature transducer, based on Thompson equation

$$F\left(C_{eql}\right)=\frac{1}{2\pi\sqrt{L_{eql}\cdot C_{eql}}}, \tag{12}$$

where L_{eql} – equivalent inductance of the frequency measuring transducer.
For the temperature transducer circuit shown in fig. 10 expression (12) will look like

$$F\left(C\right)=\frac{1}{2\pi}\sqrt{\frac{C_{jbe}(U_{je})+C_{jbc}(U_{jc})}{C_{jbe}(U_{je})\cdot C_{jbc}(U_{jc})\cdot L_{eql}}}. \tag{13}$$

Based on dependencies (5), (8), (11) the dependence of the output frequency on the temperature can be find. Values of parameters of the transistors entering the frequency transducer of temperature for theoretical calculations are received from works[18, 19]. The graphic dependence of the output frequency on the temperature is displayed in fig. 3.

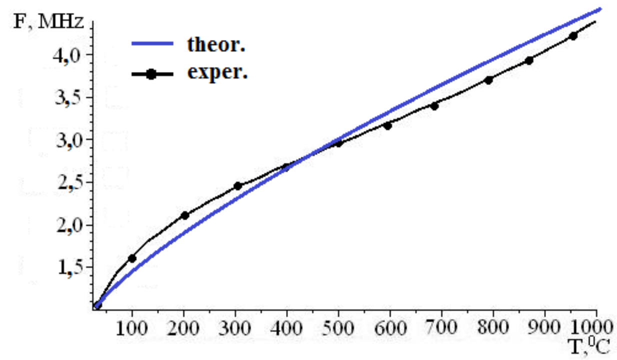

Figure 3. Theoretical and experimental dependence of transformation function of the frequency transducer temperature.

The sensitivity of the temperature transducer with negative resistance, based on the expression (14), is determined

$$S_T = \frac{\sqrt{2}\left(\dfrac{\dfrac{\partial C_{jbe}(T)}{\partial T}+\dfrac{\partial C_{jbc}(T)}{\partial T}}{C_{jbe}(T)\cdot C_{jbc}(T)\cdot L_{eql}} - \dfrac{\left(C_{jbe}(T)+C_{jbc}(T)\right)\cdot\dfrac{\partial C_{jbe}(T)}{\partial T}}{C_{jbe}(T)^2\cdot C_{jbc}(T)\cdot L_{eql}} - \dfrac{\left(C_{jbe}(T)+C_{jbc}(T)\right)\cdot\dfrac{\partial C_{jbc}(T)}{\partial T}}{C_{jbe}(T)\cdot C_{jbc}(T)^2\cdot L_{eql}}\right)}{4\pi\sqrt{\dfrac{2\left(C_{jbe}(T)+C_{jbc}(T)\right)}{C_{jbe}(T)\cdot C_{jbc}(T)\cdot L_{eql}}}}. \qquad (14)$$

The dependence of the sensitivity on the temperature changes is displayed in fig. 4.

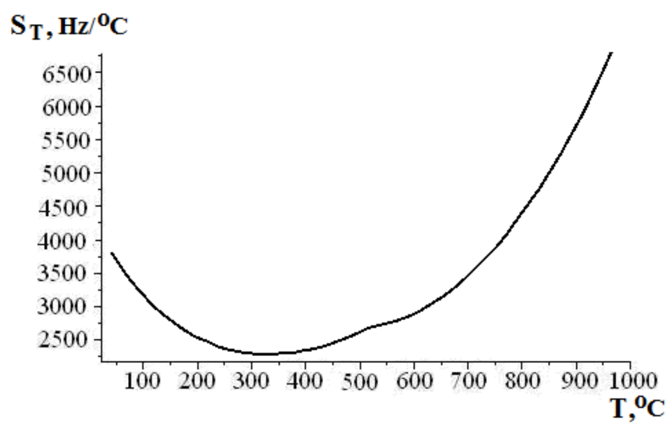

Fig. 4. The dependence of the sensitivity on the temperature changes

The developed mathematical model of measuring conversion shows that with the temperature changes from 10 ^{0}C to 1000 ^{0}C the sensitivity varies from 2500 Hz/^{0}C to 6500 Hz/^{0}C.

3. CONCLUSIONS

Having analyzed physical basis of piroelectric sensors operation, the existing methods of temperature measuring on the basis of piroelectrics, the authors suggest the new device for measuring temperature on the basis of metal-pyroelectric-semiconductor structure with negative resistance.

The dependence of reactive properties of metal-pyroelectric-semiconductor structure structure with negative resistance on the temperature is proved and conversion temperature in frequency signal happens in the the metal-pyroelectric-semiconductor structure with negative resistance, which allows create temperature transducer, which is working on a "temperature - frequency" principle.

Mathematical model of temperature transducer based on metal-pyroelectric-semiconductor structure with negative resistance is developed and the analytical dependences of conversion functions and sensitivity equations are obtained. There had been simulated the operation of device for measuring temperature on the basis of metal-pyroelectric-semiconductor structure with negative resistance in software environment Pspice, in the result of which there had been received the voltage-current characteristics and frequency characteristic.

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