Вирішується задача побудови теплового датчика на основі технології мікроелектромеханічних систем шляхом структурного і схемотехнічного інтегрування ємніснозалежної і термомеханічної частин. Для цього запропоновано використання МОН-транзистора (ємніснозалежної частини) із заслоном у вигляді біморфної мембрани (термомеханічної частини), що здійснює циклічні коливання під впливом нагрівання від чутливого елементу і наступного охолодження. Новизною датчика, що пропронується, є забезпечення частотно-залежного вихідного сигналу без використання додаткових генераторних схем. Це дозволяє спростити суміщення датчика з цифровими системами обробки його сигналів і знизити вплив ліній передачі на точність вимірювань. Перевагою датчика є також зменшені габаритні розміри, що досягається за рахунок вертикальної інтеграції його елементів.

Проведено модельні дослідження датчика і на їх основі запропоновано схемні та програмно-апаратні рішення з реалізації визначення температури чутливого елементу. Показано, що застосування логаріфмичної залежності для апроксимації впливу температури чутливого елементу на зміну частоти вихідних імпульсів датчика дозволяє мінімізувати похибку вимірювань до 3,08 %. Визначено склад інформаційно-вимірювальної системи, яка містить тепловий датчик, схему попередньої обробки сигналів датчика і частину обробки результатів вимірювань з використанням мікроконтролера Atmega328 на платформі уніфікованого модуля ArduinoUno. Показано, що сумарна похибка визначення температури у розробленій системі не перевищує 4,18 % у діапазоні зміни температури чутливого елементу датчика від 20 °C до 47 °C.

Розроблено програмний код мікроконтролерної частини інформаційно-вимірювальної системи, який займає 12 % програмній пам'яті і 4,9 % динамічній пам'яті уніфікованого модуля.

Тепловий мікроелектромеханічний датчик, що пропонується, може бути використано для контактного вимірювання температури газоподібних та рідких середовищ, реєстрації сигналів оптичного випромінювання і НВЧ сигналів

Ключові слова: МОН-транзистор, біморфна мембрана, чутливий елемент, частота імпульсів, мікроконтролер

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THERMAL MICROELECTROMECHANICAL SENSOR CONSTRUCTION

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1. Introduction

Thermal sensors are widely used in energy, construction, industrial production and medicine. Thermocouples, bolometers and pyroelectric elements are used to convert the temperature field into an electric signal [1]. When integrating such converters into modern microelectronic devices, it is not always possible to remain within the standard integrated circuit technologies.

Today, thanks to the advances in the field of microsystem technology, an important direction of the sensor electronics, called microelectromechanical systems (MEMS) is intensively developing. This involves combining the structures resulting from the integration of sensors, actuators and special control electronic circuits with traditional integrated semiconductor circuits.

Creation of thermal MEMS sensors is aimed at overcoming limitations inherent in traditional converters, expanding the functionality and using sensor systems, reducing cost and energy consumption [2]. For thermal converters, the use of microsystem technologies allows reducing the inertia of products, the dissipation of thermal energy, increasing the reliability and repeatability of meter parameters.

Therefore, the development of new thermal MEMS sensors combining thermomechanical and capacitive measurement methods is urgent. This will simplify the information and measurement systems, increase their functionality and expand the scope of such devices.

2. Literature review and problem statement

One of the traditional ways to construct modern sensors is the conversion of external physical quantities into a proportional change in capacitance. In [3], the results of research on the development of capacitive pressure and gas flow sensors are presented. It is shown that the conversion of the capacitance of the sensitive element (SE) into voltage is possible by the use of an external measuring RC – generator and capacitance-to-voltage converter, amplitude detector and analog-to-digital converter (ADC). However, questions about the influence of communication line parameters on measurement signal parameters remain unresolved. A way to overcome such disadvantages can be an integrated version of the sensor with the signal processing circuit, presented in [4]. This solution has a comparatively high cost of implementation of these systems. As shown in [5], the option to reduce the cost of capacitive sensors and improve their accuracy is the integration of the SE into MEMS-based MOS transistors. This approach is used in [6] to construct direct conversion pressure sensors. Similarly, in [7], a tactile sensor is developed.

In [8], a capacitive thermal sensor with a capacitor having a bimetallic cover, which changes its location under the influence of heating is developed. But for the capacitance-to-voltage conversion, such sensor is connected to an external meter. This can be avoided by indirect conversion. In [9], a pyroelectric converter and MOS transistor are horizontally integrated into the thermal radiation sensor. The drawbacks of such a device include the need to modulate the intensity of recorded radiation and the relatively large length of interelement connections. In order to reduce the overall dimensions of the sensor, vertical integration of constituent elements is proposed in [10]. In this design, the converter is located on the surface of the MOS transistor gate, so that the overall dimensions of the sensor are less than in [9]. But in further information processing circuits, it is necessary to perform amplitude measurements or transformations. This requires the sensor signal normalization units to be placed next to it and increases its cost.

Thus, it is advisable to conduct a study on the vertical integration of a thermomechanical capacitive temperature converter with a microelectronic element, which changes its output signal in the deformation of the input electrode. Such solutions will allow not only contact measurements of temperature, but also the use of sensors, as shown in [11], to record thermal effects of radiation.

3. The aim and objectives of the study

The aim of the study is to develop the structure of the thermal MEMS sensor with a movable part, which cyclically changes the output signal of the integrated solid-state element.

To achieve the aim, the following objectives are formulated:

– to formulate the principles of construction of the thermal sensor with a frequency-dependent output signal;

– to analyze the sensor functioning and to develop its research methodology;

– to conduct model studies of the thermal MEMS sensor;

– to analyze the signal conversion in the information and measurement system on the basis of the developed sensor.

4. Principles of construction of thermal MEMS sensor

In classical thermal sensors, the SE directly changes its temperature upon contact with a controlled object or under the action of radiation energy. Subsequently, the conversion of the SE temperature variation into an electric signal takes place.

According to this principle, the structure of the MEMS sensor [12] is developed, shown in Fig. 1. Heating or radiation changes the temperature of the SE, modulating the capacitance of the actuating element (AE) through the action of the thermomechanical control element (CE).

For this purpose, in the design of the sensor (Fig. 2), the dielectric base with the control element and the sensitive element are arranged in series above the actuating element, and the control element is made in the form of a bimorph membrane. The SE is made in the form of a nielloed metal film in contact with the bimorph membrane consisting of two layers with different coefficients of thermal expansion. The SE and CE are secured on an insulating base. On the other side of the membrane, there is an empty area separating the CE from the silicon frame, where the AE – MES transistor is created. The surface of the transistor structure is covered with a silicon oxide film, isolating its channel, drain and source from the unfilled area under the membrane.

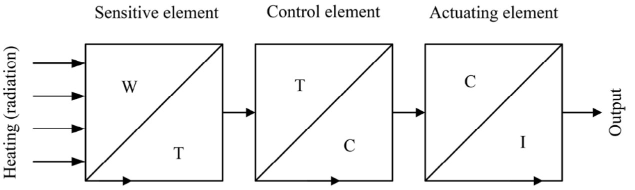


Fig. 1. Structure of thermal MEMS sensor: *W* — heating (radiation) power, *T* — temperature, *C* — capacitance, *I* — current strength

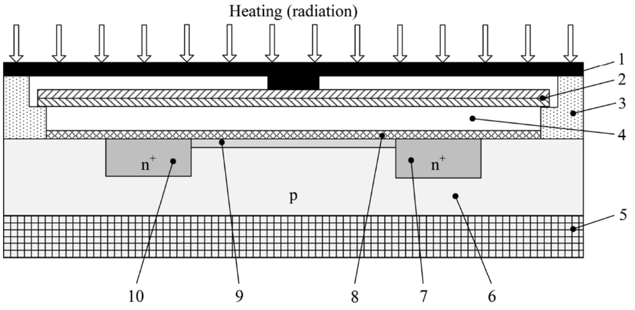


Fig. 2. Design of thermal MEMS sensor: 1 — sensitive element, 2 — bimorph membrane, 3 — insulating base, 4 — empty area, 5 — silicon frame, 6 — actuating element (MOS transistor), 7 — MOS transistor drain, 8 — silicon oxide film (undergate dielectric), 9 — MOS transistor channel, 10 — MOS transistor source

In the process of measurement, the SE is heated due to contact with the environment or by radiation. A change in the SE temperature also leads to a change in the CE temperature. As a result of the difference in temperature expansion coefficients of the layers, the bimorph membrane bends towards the AE and is disconnected from the SE, CE heating ceases and thermal energy begins to be removed from the membrane due to heat conduction. After cooling the bimorph membrane, it returns to its original position, restoring contact with the radiation absorber.

5. Performance analysis and development of research methodology of thermal MEMS sensor

Since the membrane is simultaneously the AE gate and is under direct voltage, the output current of the sensor is the leakage current of the MOS transistor and is defined as [13]:

$$I_B = -\frac{W}{2L}\mu_n C\left(U_{GS}-U_T\right)^2, \tag{1}$$

where W is the width of the transistor channel; L is the length of the transistor channel; C is the total specific capacitance of the space between the sensor membrane (gate) and the MOS transistor channel; U_{GS} is the voltage between the gate and the source of the MOS transistor; U_T is the threshold voltage of the MOS transistor; μ_n is the electron mobility in the MOS transistor channel.

The total specific capacitance of the space between the sensor membrane (gate) and the MOS transistor channel consists of the capacitance of the silicon oxide film on the transistor surface C_{OX} and the capacitance of the cavity C_C between this film and the converter membrane:

$$C = C_{OX} + C_C. \tag{2}$$

When the membrane is bent under the influence of SE heating, the total specific capacitance changes by the value of the change in the capacitance of the empty space between the membrane and the dielectric ΔC_S:

$$C = C_{OX} + C_C + \Delta C_S. \tag{3}$$

[3] shows that for capacitive sensors in case of deformation of one of the covers:

$$\Delta C_S = -\frac{\varepsilon\varepsilon_0 \Delta d}{\left(d+\Delta d\right)^2}, \tag{4}$$

where ε_0 is the dielectric constant of the vacuum, ε is the dielectric constant of the air, d and Δd are the thickness and thickness variation of the cavity.

Thus, the output current changes by a value proportional to the change in the capacitance of the empty space between the membrane and the dielectric.

However, the loss of mechanical and thermal contact of the SE with the membrane leads to its cooling by thermal conductivity. Over time, depending on the material properties of the membrane layers, its size, heating degree and conditions of thermal insulation from the base, the mechanical part returns to its original state and contact with the SE is restored. Therefore, during the long-term action of heating on the SE, alternating current flows in the output circuit of the converter, whose pulse amplitude and duration depend on the power of recorded radiation or ambient temperature.

To investigate the sensor, an approach based on the identification of cavity thickness variation in (4) by means of two-dimensional simulation of the bimorph membrane dynamics at different values of the SE temperature is proposed. The data obtained form the basis for the analytical calculation of the MOS transistor output current according to (1).

6. Model studies of the sensor

Model studies of the mechanical part of the thermal sensor are carried out in the COMSOL Multiphysics software environment [14].

The two-dimensional model uses the "HeatTransferinSolids" and "SolidMechanics" physical interfaces with adaptation to thermal expansion of elastic membrane materials. The obtained view of the spatial model of the sensor is shown in Fig. 3 using a triangular finite element grid used for sampling. The grid contains 379 elements, the dimensions of which are adapted to the geometry of the model.

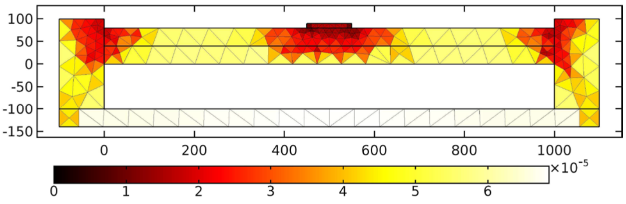
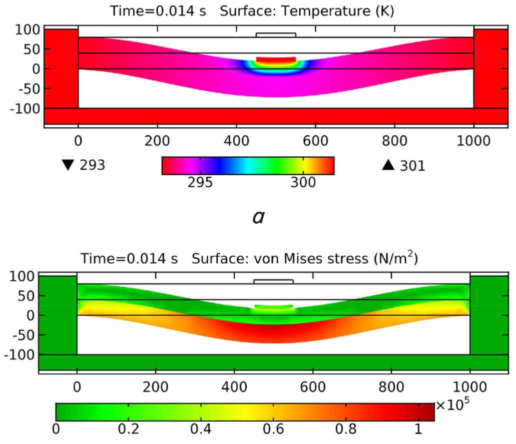


Fig. 3. Grid model of the thermal sensor

To solve non-stationary problems of thermal conductivity and deformation with a step of 1 ms, a linear MUMPS solver is chosen.

The results of the studies in the form of distributions of temperature and mechanical stresses in the membrane are shown in Fig. 4 for the SE temperature of 310 K. The spatial distribution of temperature over the sensor structure shows that the thermal field gradient is concentrated within the bimorph membrane. Therefore, even with slight temperature variations (0.5 K), considerable mechanical stresses arise, the difference of which in the membrane layers is up to $1.6\cdot10^5$ N/m^2. This causes the central part of the membrane to shift towards the surface of the MOS transistor channel.



a

b

Fig. 4. Results of sensor membrane dynamics simulation: *a* — temperature distribution, *b* — mechanical stress distribution

The calculations of the sensor membrane dynamics in the SE temperature range from 293.17 K to 320 K allow determining that the thickness of the cavity of the submembrane area Δd is changed by 15.6 nm (Fig. 5).

Using the results from Fig. 5 and (1)–(4), it is found that the pulses of the sensor output current change the amplitude from 4 μA to 12 mA. The temperature dependence of the sensor output frequency is shown in Fig. 6.

The approximation of the obtained data by the logarithmic dependence shows that the sensor output frequency f can be defined as:

$$f = -13.2\ln dT + 64.95, \tag{5}$$

where dT is the temperature gain of the SE sensor.

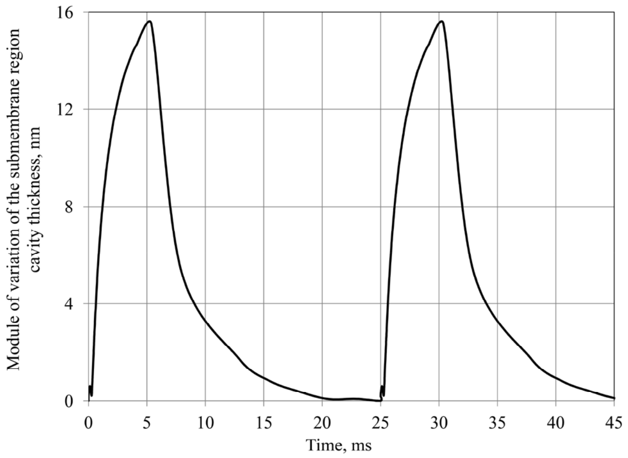


Fig. 5. Time dependence of the module of submembrane region cavity thickness variation

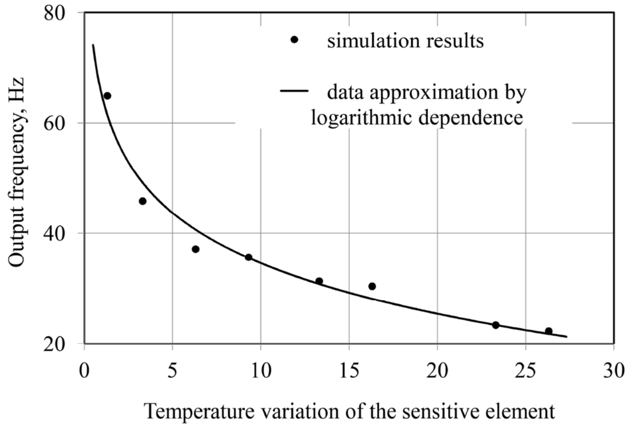


Fig. 6. Dependence of the sensor output frequency on the sensitive element temperature

Thus, the hardware or software determination of the frequency of the sensor output frequency and additional data processing according to (5) will reduce the error of SE temperature measurement by 3.08 %.

7. Analysis of processes in the signal processing system of thermal MEMS sensor

On the basis of the simulation results, a block diagram of the information and measurement system based on the thermal MEMS sensor is developed (Fig. 7).

The diagram includes:

– thermal MEMS sensor (VK1) with elements setting the operating mode, temperature stabilization (R1–R4, C2) and separation with the following DC part of the system (C1);

– sensor output pre-processing unit (R5–R7, VD1, DA1, DD1);

– unit for processing measurement results using Atmega328 microcontroller on the platform of the unified ArduinoUno module connected to a personal computer (PC) through a built-in serial asynchronous interface via a serial port.

In order to implement the measurement processing unit, it is necessary to normalize the sensor output signals, whose amplitude can vary from 0.1 V to 7 V depending on the temperature of the sensitive element. For this purpose, a pre-processing circuit is developed containing an amplifier with a Zener diode input voltage limiter connected to its input. From the amplifier output, the signal is sent to the Schmitt triggered inverter, which is a standard link for generating and limiting pulses.

Model studies of the developed sensor signal pre-processing circuit are conducted in the Multisim environment [15]. The task for the circuit simulation is shown in Fig. 8, where the controlled voltage source V2 simulates the output signal of the sensor, the parameters of which vary depending on the voltage of the source V3.

Amplification of low-level signals is performed by a non-inverting amplifier that consumes current from a unipolar VCC source. This allows changing the output signal of the operational amplifier only towards positive values of the output voltage and thus eliminating negative interference from the measuring pulses. For protection against overload, Zener diode D1 and resistor R1 voltage stabilizer is connected to the amplifier input. The Schmitt triggered inverter U1A, generates a rectangular signal of the amplified and limited pulses given to a load simulated by resistor R2.

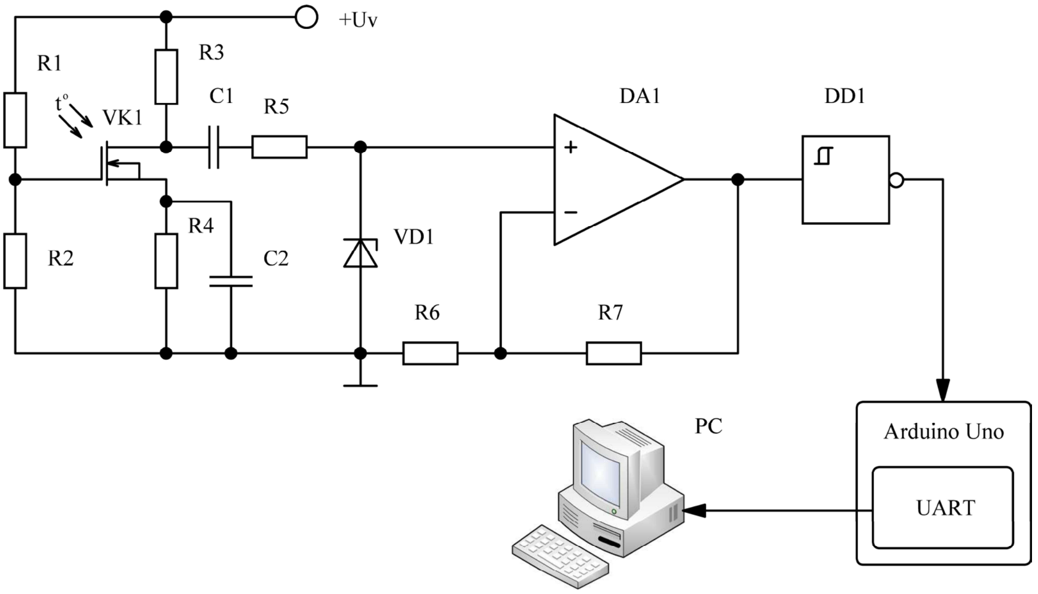


Fig. 7. Block diagram of information and measurement system based on thermal MEMS sensor

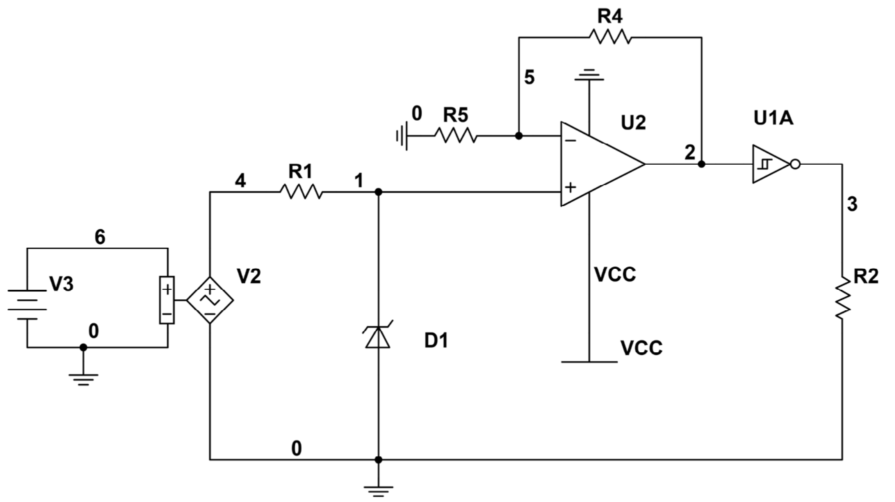


Fig. 8. Task for sensor signal pre-processing circuit simulation

The results of pre-processing circuit simulation are shown in Fig. 9 in the form of diagrams of the input and output signals. The analysis of the obtained results shows that the frequency of rectangular output signals of the circuit coincides with the frequency of output signals of the sensor, and their amplitude is limited to the level of 5.2 V.

To determine the effect of sensor temperature variation on the output signals of the pre-processing circuit, a parameter analysis is performed, the results of which are shown in Fig. 10.

The analysis of the obtained data allows concluding that the frequency of rectangular pulses at the output of the sensor signal pre-processing circuit varies from 22 Hz to 63.3 Hz when the temperature of the sensitive element increases within 2–27 K. Comparing the data in Fig. 10 with the temperature dependence of the sensor output frequency (Fig. 6), it is possible to establish that the sensor signal pre-processing circuit has a conversion error of 1.1 %. Thus, the received signals as a source of measurement information can be input into the computing environment and processed by software methods.

Determination of the frequency of measuring pulses and heating of the sensitive element of the sensor, as well as correction of conversion nonlinearity according to (5), are carried out by software in the microcontroller part of the system. For this purpose, a program code is developed in which the duration of the logical one and logical zero states of the signal coming from the Schmitt triggered inverter to the measurement processing unit is determined by applying the built-in pulseIn function. The next step is determination of the oscillation period, frequency calculation and conversion into the sensor heating value on the basis of (5). The heating temperatures are then transmitted via the serial port to the computer. The program code occupies 3,971 bytes in the Atmega328 microcontroller memory and the global variables – 96 bytes of dynamic memory.

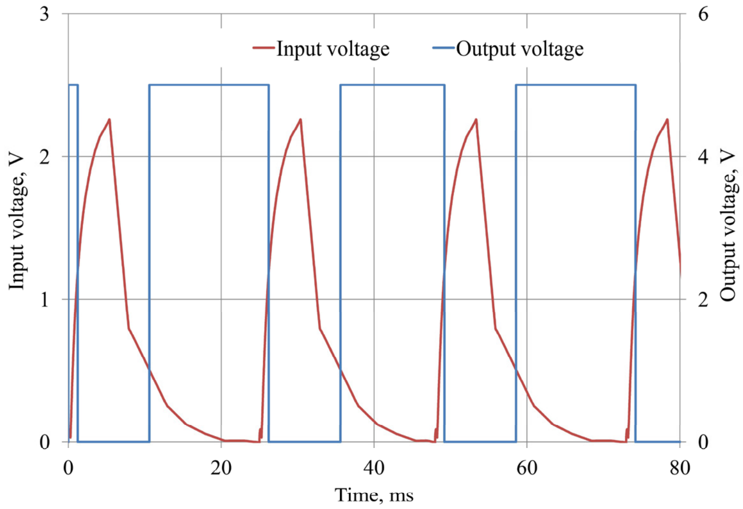


Fig. 9. Diagrams of the input and output voltage of the sensor signal pre-processing circuit

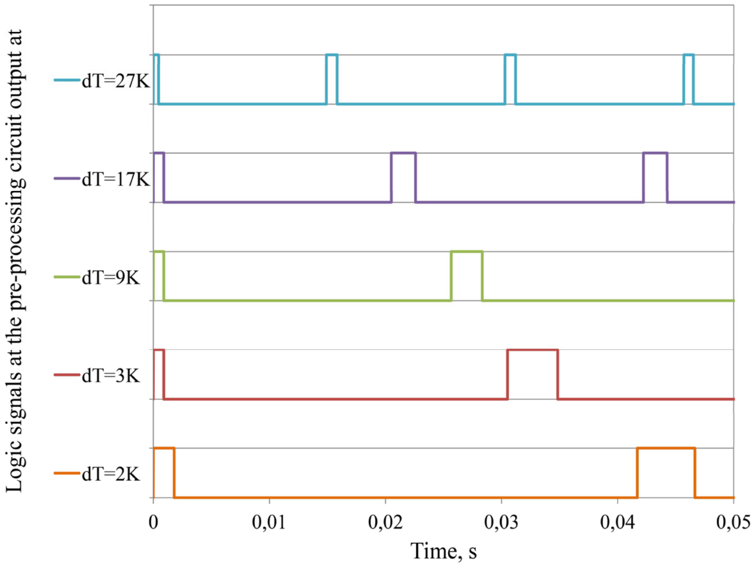


Fig. 10. Variation of the output pulse frequency from the sensor signal pre-processing circuit

8. Discussion of the results of thermal MEMS sensor studies

The structure of the vertically integrated thermal sensor, which combines a radiation absorber that heats the bimorph membrane, is developed. Upon cyclic displacement of the membrane, there is a modulation of the capacitance of the MOS transistor and oscillation of the output current of the sensor.

It is shown that in the proposed structure of the thermal MEMS sensor, in contrast to cantilever designs of heat energy harvesters [16,17], it is necessary to provide the reverse order in the sequence of bimorph membrane layers. The material of the layer in contact with the heat source must have a coefficient of thermal expansion less than the material of the second (lower) layer. As a result, the membrane is deformed towards the surface of the SE sensor. Vertical integration of the sensor elements allows combining the functions of the moving gate of the MOS transistor in the second layer of the bimorph membrane.

The advantage of the developed sensor is the absence of inter-element conducting paths, the contact between the CE and AE is made directly. Thus, the accuracy of measurements is increased by at least an order of magnitude due to the absence of spurious inductances of inter-element connections.

The cost of the thermal MEMS sensor, compared to the known samples, increases slightly, as the basic operations of integrated microelectronic technology are used in its manufacturing. The advantage of the sensor is also smaller overall dimensions, which is achieved by vertical integration of its elements.

On the basis of the sensor and the measurement processing system presented in the work, instruments for measuring the power of optical and IR radiation can be created.

The use of the proposed sensor is limited by conditions of thermal insulation of the mechanical part of the actuating element to ensure stable temperature regime of the MOS transistor. By reducing this, a silicon carbide-based semiconductor part can be developed.

Mechanical vibrations and shocks may also affect the accuracy of the sensitive element’s temperature. Such a parasitic signal is rejected by single effects or filtered out by continuous action.

Further researches of the developed structure are aimed at the geometrical optimization of the mechanical part on the basis of three-dimensional physical simulation.

9. Conclusions

1. The principles of construction of the thermal MEMS sensor are determined and the problem of structural and circuit integration of its constituent elements is solved. The novelty of the proposed sensor is the provision of a frequency-dependent output signal without the use of additional generator circuits. This makes it easier to combine the sensor with digital signal processing systems and reduce the impact of transmission lines on measurement accuracy.

2. It is shown that upon heating of the sensitive element, there is a cyclic variation in the undergate capacitance of the MOS transistor of the sensor. Therefore, the method to study it is proposed, based on the identification of variations in the geometric dimensions of the undergate part of the actuating element by means of two-dimensional multiphysical simulation of the dynamics of the bimorph membrane, with subsequent analytical calculations of the output current of the MOS transistor.

3. Model studies of the developed sensor based on the analytical model with parameter identification in the COMSOL Multiphysics environment are carried out. The frequency of the output signal is shown to decrease from 65 Hz to 23 Hz, and the amplitude increases from 4 μA to 12 mA while the absorber is heated from 293 K to 320 K. The obtained analytical dependence of the output pulse frequency on the absorber temperature is logarithmic.

4. The structure of the information and measurement system, which realizes the analytical dependence of the output pulse frequency on temperature and contains the sensor signal pre-processing circuit and the microcontroller part of measurement processing is proposed. Using the methods of simulation of electronic circuits in Multisim environment, it is shown that the total error of measuring the temperature of the sensitive element of the sensor does not exceed 4.18 %. The program code that occupies 3,971 bytes in the program memory (12 % of total capacitance) and 96 bytes in the dynamic memory (4.9 % of total capacitance) of the microcontroller is synthesized.

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