Вирішується задача функціонального інтегрування термічних та ємнісних методів досліджень, що забезпечує можливість реалізації нового покоління аналогового фронт-енду Інтернету Речей в галузях матеріалознавства, біофізики та медицини. Під функціональним інтегруванням розуміється можливість використання однієї і тієї ж структури для її керованого нагріву та вимірювання температури. Для цього замість дискретних резистивних нагрівників та сенсорів температури запропоновано використовувати транзисторні структури. Це дозволяє мінімізувати розміри вимірювальних перетворювачів, а відтак, і просторову роздільну здатність реалізованих на цих перетворювачах сенсорів термічного аналізу.

Розвинена концепція побудови функціонально інтегрованих сенсорів теплових величин на основі транзисторних структур та сигнальних перетворювачів ємнісного типу. Новизною запропонованих сенсорів термічного аналізу, крім, властиво вимірювання температури та кількості теплової енергії, що виділяється чи поглинається в об'єкті досліджень, є можливість вимірювання електричної ємності. Така можливість, зокрема, забезпечується можливість вимірювання температурної деформації досліджуваного об'єкту чи консолі, що вигинається під дією впливу цього об'єкту.

Запропоновано нове рішення схеми керування транзисторним перетворювачем, що забезпечує імпульсний керований нагрів та формування інформативного сигналу температури транзистора. За основу сигнального перетворювача ємнісного типу взято високо прецизійний 24-бітний конвертер AD7747 компанії Analog Devices.

Розроблений перетворювач забезпечує керований нагрів об'єктів дослідження, характеризується високими значеннями роздільної здатності вимірювання температури (не гірше 0,01 °С), та електричної ємності (не гірше 10-16 Ф)

Ключові слова: сенсор температури, транзисторні структури, сигнальний перетворювач ємнісного типу, функціональне інтегрування, конвертер

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DEVELOPMENT OF SIGNAL CONVERTER OF THERMAL SENSORS BASED ON COMBINATION OF THERMAL AND CAPACITY RESEARCH METHODS

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1. Introduction

The development of microelectronic devices of modern sensor technics, particularly in the concept of the Internet of Things – IoT (Internet of Things), implies the development of a new generation of means of digital-analog worlds interaction. On the one hand, the development of new digital technologies, particularly, the embedded operation systems for devices of the Internet of Things [1] and standardized IoT Platforms interworking [2] is taking place. On the other hand, the schematic knots of analog front-end, particularly, for gas sensors (Analog Gas Sensing Front End) are being developed [3]. The evolution of these means requires complex attitudes, considering all aspects of converting analog values into digital codes – amplifiers, signal transducers, adapted timers (Adaptive Clocking Techniques) [4].

Following these tendencies, new sensors are evolved with the use of different methods of measuring conversion. These methods precondition the principles of functioning and circuit technique of the knots of analog front-end. The examples are an optoelectronic sensor of organic substances [5] and a measuring front-end of the impedance type for sensors of biophysical analysis [6].

The prevailing majority of natural and technical processes are related to transformation of thermal energy. The knowledge of the processes of heat emission and absorption, and the quantity parameters of these processes allows a better understanding of a physical world, a substance structure and mechanisms of chemical and

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biochemical reactions. Information on the meaning and character of the course of thermal effects is one of the main both in the practice of scientific research and while optimizing or controlling numerous production technological processes.

Sensors of thermal quantities for physical, biophysical and electrochemical research are mainly based on the calorimetry methods. In addition to calorimetry ones, the methods of dielectric thermal analysis, thermomechanical analysis, thermooptometry and thermogravimetry are used. Using these methods, such parameters as thermocapacity, thermoimpedance, parameters of phase transitions, mechanical changes and deformations, etc. are measured.

Following the results of measurement of thermal expansion of solid bodies, we can make conclusions about electronic and phonon spectra of metals and dielectrics, the change of thermo-capacity of samples. Herewith, the possibility of combining the managed heating, measurement of temperature and amount of thermoenergy emitted or absorbed by a research object, deformation and shape measurement should be assured. The high efficiency of such research should be based on the measurement of electric capacity.

Thus, further development of functionally integrated thermal sensors, combining the thermal and capacity measurement methods, is of high topicality. The development of these sensors applies the possibility of realizing a new generation of an analog front-end in the areas of materials science, biophysics and medicine.

2. Literature review and problem statement

Recently, significant progress in sensor technology, in particular in the further expansion of functionality and precision of microelectronic sensors, has been achieved thanks to the new generation of measuring transducers of electric capacity. Such measuring transducers allow measuring mechanical properties and shapes of investigated objects, and such measurement is carried out without direct contact with the object. Capacitive measuring transducers are based on the methods of generation of the frequency-modulated oscillations [7] and sigma-delta transformation [8]. At present, the highest accuracy of the measurement conversion of capacitive sensors with sigma-delta transformation is provided by Analog Devices ADC747 24-bit capacitance-to-digital converter [9].

Thermal methods of measuring transformation and sensors of thermal quantities with a wide range of measuring transducers on the basis of thermistors and thermocouples are significant in sensory engineering [10, 11]. Modern trends in the development of sensors of thermal quantities are aimed at functionality expansion and functional integration. Functionality expansion is implemented by Differential Scanning Calorimetry (DSC) methods. Modern types of DSC are Modulated Temperature DSC (MTDSC), Flash DSC, step-by-step DSC and multi-step DSC scanning [12]. Using these methods and measuring devices on their basis allows us to create a wide range of sensors of polymeric [13] and biological [14] materials.

The unsolved problem is the functional integration of thermal research methods with other methods of measuring transformation. In accordance with the mentioned problem, in some papers the methods of functional integration are analyzed, which allows increasing the signal informativeness of sensor devices. Methods and sensors with a combination of electromagnetic [15, 16], magnetic [17], and thermal measuring transformation are examples of such integrated solutions. However, the combination of thermal and capacitive methods is not considered in the literature.

In accordance with the analysis of trends in the development of sensors and signal converters, the solution of the problem of further development of the concept of constructing functionally integrated sensors of thermal quantities is promising. It ensures the possibility of implementing a new generation of analog front-end in the fields of materials science, biophysics and medicine. In addition to the measurement of temperature and amount of heat energy emitted or absorbed in the object of research, such functionally integrated sensors should provide the ability to measure electric capacity. This allows the use of such sensors in problems of research of thermal deformation, mechanical properties and shape.

3. The aim and objectives of the study

The aim of the study is to develop a signal converter of the analog front-end of the Internet of Things sensor devices on the basis of the functional integration of thermal and capacitive research methods.

To achieve the goal, it is necessary to accomplish the following objectives:

– to formulate the problem of functional integration in the thermal sensors and to carry out the analysis of thermocycling modes in which the controlled pulsed heating of the functionally integrated transistor converters is conducted and their temperature is measured;

– to analyze the operating modes and control circuits of transistor converters of integrated thermal sensors;

– to carry out model research and practical implementation of a prototype of a functionally integrated signal converter that provides controlled heating, temperature and electric capacity measurement.

4. Functional integration and thermocycling modes in thermal sensors

Functional integration means the ability to use the same transistor structure for its controlled heating and temperature measurement. It is proposed to replace discrete resistive heaters and temperature sensors, in particular, resistance temperature detectors or thermocouples, with transistor structures. On transistors, both heating and temperature measurements are implemented, which minimizes the dimensions of the measuring transducers, and, accordingly, the spatial resolution of the sensors of thermal analysis based on these transducers.

The novelty of the proposed sensors of thermal analysis, in addition to the measurement of temperature and amount of heat energy emitted or absorbed in the research object, is the ability to measure electric capacity. This possibility, in particular, provides the ability to measure the temperature deformation of the research object or the console bending under the influence of this object. Therefore, measurement of mechanical properties, shapes, deformations, etc. allows us to expand the functionality of thermal analysis sensors. The basis of such measurements is the capacity signal transducers.

Let us consider the operating modes and control circuits of the transistor converters of integrated sensors of thermal quantities.

Generally, transistor converters of integrated thermal sensors can function in continuous and pulsed cyclic operation modes. It is evident that the implementation of the functional integration concept with the combination of controlled heating and temperature measurement in the continuous mode is problematic. Therefore, the effective realization of functionally integrated thermal sensors is possible only with the use of pulsed cyclic control modes of the transistor structures of the primary converter.

Let us consider two generalized variants of thermocycles, in which the controlled pulsed heating of transistor converters is carried out and their temperature is measured. The first of them involves the temperature regime control by modulating the current pulse amplitude of the transistors with a fixed duration of these pulses, and the second one –by modulating the pulse duration at a fixed current amplitude. Supply voltage of transistor cascades is constant.

In each of these generalized variants, certain varieties are possible. Two cases without (a) and with (b) cycles in which the transistor current is zero are considered in Fig. 1. The following symbols have been adopted: I_Q – current of the heating cycle; t_Q – duration of the heating cycle; I_T – current of the temperature measurement cycle; t_T – duration of the temperature measurement cycle; T – cycle period; t_R=T–t_T – duration of cooling; var – controlled amplitude or controlled duration of modulation of heating. The current of the heating cycle I_Q in accordance with the requirements of temperature change can be controlled in wide limits – from milliamperes to ampere units. The current of the temperature measurement cycle I_T is a constant value and typically does not exceed milliamperes. The second generalized version (for a fixed amplitude of current I_Q) is realized by modulation of the heating pulse duration t_Q at a constant period T (Fig. 2, *a*), or modulation of the period duration T with a fixed duration t_Q (Fig. 2, *b*).

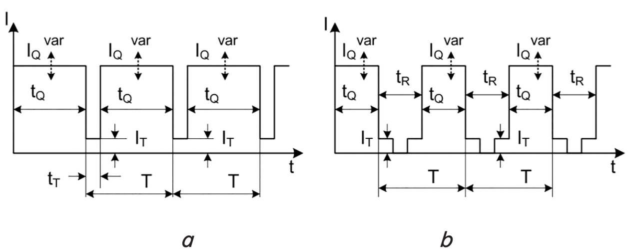


Fig. 1. Time charts of thermocycles in the modulation by the heating pulses amplitude: *a* – without the pause cycle; *b* – with the pause cycle, in which the transistor current is zero

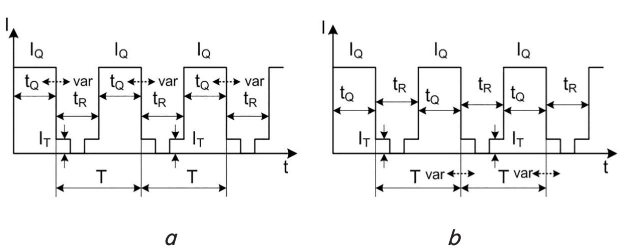


Fig. 2. Time charts of thermocycles in the modulation by the heating pulses duration: *a* – with modulation of the heating pulses duration t_Q at a constant period, *b* – with modulation of the period duration T with a fixed duration t_Q

To ensure the required rate of temperature increase, it is advisable to measure the temperature during heating. The exact measurement of temperature is carried out during the passage of a measuring current I_T through the transistor. If necessary, the heating is repeated with the subsequent refinement of temperature. The cycle period is determined by the rate of temperature increase, which is aligned with the pause cycle duration. During this time, measurements of non-thermal parameters are carried out. The presence of a the pause cycle can increase the energy efficiency of the signal converter.

To implement controlled heating, it is necessary to implement a modulation scheme of power released on a transistor structure with independent control of voltage V_{CONTR} and current I_{CONTR} of the transistor T power circuit (Fig. 3, *a*). In such scheme, the voltage drop in the power circuit of the transistor V_E is determined only by the supply voltage V_E source and, in the case of absence of voltage drop on the current source I_{CONTR}, is constant. Practical implementation of such management is given in Fig. 3, *b*. Transistor T is included in the negative feedback loop of the operating amplifier O_A, which supports the constant voltage at the emitter of this transistor.

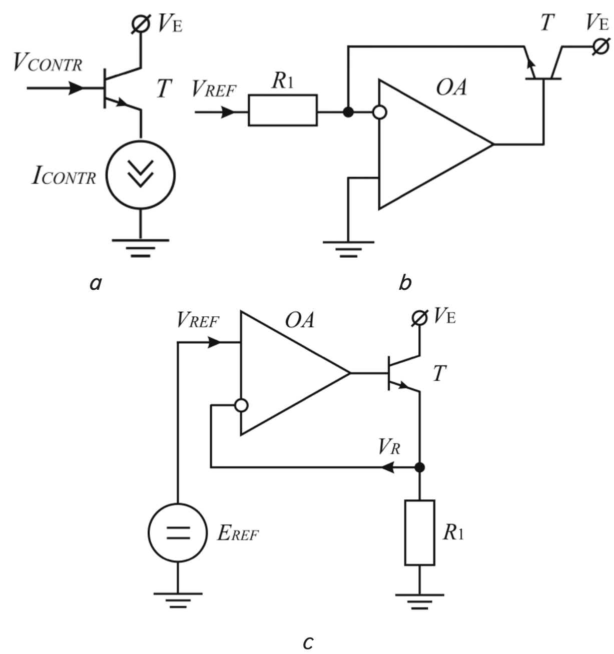


Fig. 3. Heating control scheme: *a* – elementary; *b* – on the basis of inverting; *c* – on the basis of non-inverting amplifying cascades

In turn, this voltage in the first approximation, namely – without taking into account the bias voltage of the operational amplifier (typically not more than a few millivolts), is equal to the voltage at its non-inverting input. In this case, the non-inverting input is connected to the zero bus, and therefore, the voltage on the emitter is zero. Instead, the control current I_{CONTR} is determined by the input circle $I_{CONTR}=V_{REF}/R_I$ and is constant. Thus, the thermal power released on the transistor of functionally integrated thermal sensors is determined by the elementary expression $P_Q=V_E \cdot I_{CONTR}$, where V_E – the collector supply voltage.

A more effective version of the controlled heating circuit on the transistor converter is shown in Fig. 3. The thermal power of the transistor converter is determined by the product of the control current $I_{CONTR}=V(E_{REF})/R_I$ (without errors caused by the limited values of the gain of the transistors) on and the voltage drop in the output collector-emitter circuit and is $V_{CE}(T)=V_E-V(E_{REF})$. The advantage of this solution, which is exactly chosen for the implementation of the developed functionally integrated sensor of thermal quantities, is the absence of current in the control circuit (in this case – the supply voltage source E_{REF}).

Measurement of temperature is carried out according to the known (obtained during the simulation and calibration) temperature dependence of the voltage on the emitter transition of the transistor structure. Fig. 4 shows the solution of the control circuit of the transistor converter that provides pulse controlled heating and formation of an informative temperature signal of the transistor T1. The current control of the transistor is similar to the above mentioned circuit on the operating amplifier OA_1 (Fig. 3, *b*), which transforms the voltage V_{REF} in the current I_{CONTR}= =V_{REF}/R_I. Instead, another operational amplifier OA2 with a negative feedback loop on the resistors R_2, R_3 forms a voltage V_T, the value of which is a linear function of the temperature-dependent voltage V_{EB} on a direct-displaced emitter-base p-n transition T1:

$$V_T = V_{REF} + V_{EB}\left(\frac{R_3}{R_2}+1\right).$$

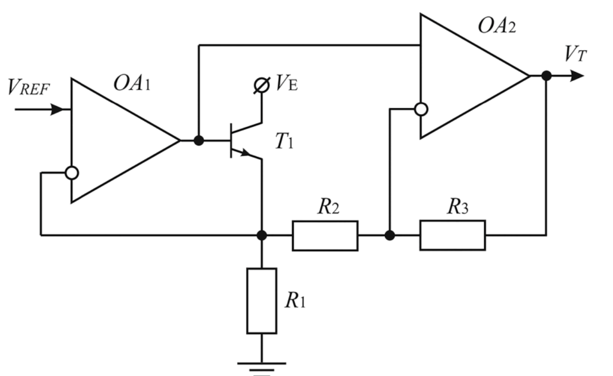


Fig. 4. Control circuit of the functionally integrated converter on the transistor structure

The advantage of this solution is:

– firstly, the possibility of using a unipolar power supply;

– secondly, the absence of a characteristic problem regarding the limitation of the range of values of the temperature-dependent signal V_T change (this signal is “raised” relative to the zero potential by the value V_{REF});

– thirdly, the ability to control the signal gain;

– fourthly, the simplicity of implementation.

5. Model research and implementation of a functionally integrated signal converter

Model studies of the signal converter of thermal quantities were performed on the basis of *S*PICE models and methods [18, 19] in the MicroCAP environment.

The results of model studies of this modified scheme (Fig. 5) are given in:

– Fig. 6 – voltage dependences when changing the reference voltage VREF;

– Fig. 7 – voltage dependences when changing the temperature *t* (°C);

– Fig. 8 – dependences of the heating power of the transistor $P(Q_1)$ and reference resistor $P(R)$ on the control voltage V_{REF}.

The numbering of the nodes in which the voltage dependencies are presented is as follows: $V(3)$ – voltage on the current-carrying resistor R_1, which in the ideal case (at zero value of the bias voltage of the operating amplifier X_1) is equal to the control (reference) voltage V_{REF}; $V(2)$ – voltage on the transistor base; $V(2)-V(3)$ – voltage drop on the emitter-base p-n transition of the transistor; $V(6)=V_T$ – output voltage (informative temperature signal). In this example, with R_2=1 kOhm, R_3=2 kOhm, the amplification factor of voltage V_{EB} is equal to (2+1) kOhm/1 kOhm=3, and hence, the coefficient of temperature dependence of the output voltage V_T is determined by the following expression

$$\frac{dV_T}{dT} = 3\frac{dV_{REF}}{dT} \approx 3\left(-1.8\frac{\text{mV}}{^\circ\text{C}}\right) \approx -5.4\frac{\text{mV}}{^\circ\text{C}}.$$

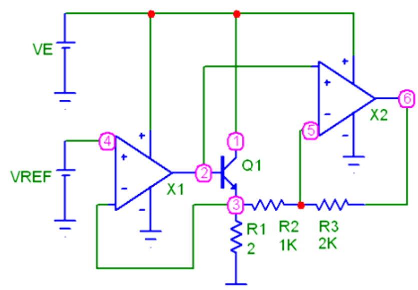


Fig. 5. Structural scheme of the signal converter of thermal quantities

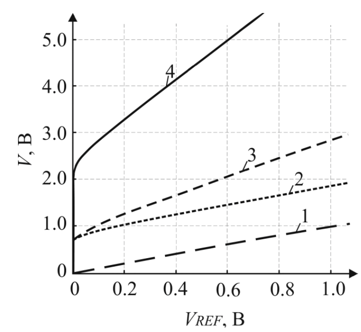


Fig. 6. Dependences of the voltage of the signal converter when changing the control voltage V_{REF} in the nodes: 1 — $V(3)$; 2 — $V(2)$ — $V(3)$; 3 — $V(3)$; 4 — $V(6)$

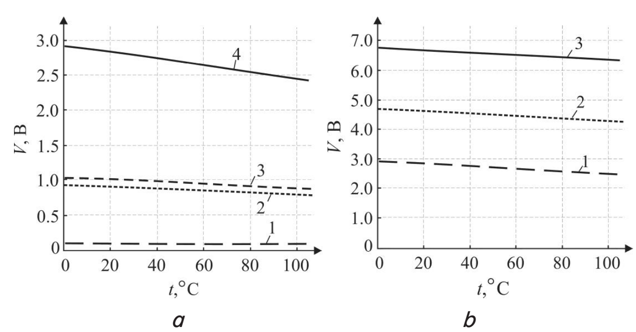
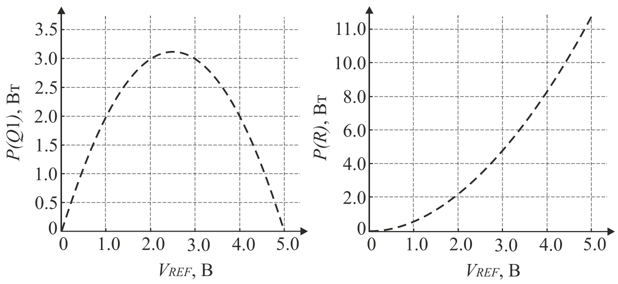


Fig. 7. Dependences of the voltage of the signal converter when changing the temperature t (°C): *a* — at V_{REF}= 0.1 V in the nodes: 1 — $V(3)$; 2 — $V(2)$ — $V(3)$; 3 — $V(3)$; 4 — $V(6)$; *b* — in the node $V(6)$ at V_{REF}=0.1 V (1); V_{REF}=0.5 V (2); V_{REF}=1.0 V (3)



a *b*

Fig. 8. Dependence of the heating power on the control voltage VREF: *a* – transistor $P(Q_1)$; *b* – reference resistor $P(R)$

The analysis of the obtained graphical dependencies (Fig. 8) allows us to carry out the parametric optimization of the scheme and modes of its functioning. In particular, it is necessary to take into account that the presence of an extremum of the dependence of the heating power of the transistor $P(Q_1)$ on the reference voltage V_{REF} with a maximum of 2.5 *V*, which corresponds to the supply voltage half.

The structural scheme of the developed functionally integrated signal converter is shown in Fig. 9, and its appearance – in Fig. 10. The scheme consists of:

– analog control node of the functionally integrated converter of thermal quantities in a transistor structure, the scheme of which was considered above (Fig. 4);

– capacitive controller on the above-mentioned AD7747 24-bit capacitor converter (the scheme shows its main functional nodes: C ADC – analog-to-digital capacitor difference converter, V ADC – analog-to-digital converter of voltage difference, I^2C – interface I^2C);

– control unit with the usage of Atmega328 microcontroller on the platform of the Arduino Nano unified module (the scheme shows its main functional nodes: UART – serial asynchronous UART interface, CPU – central processor, PWM – pulse width modulator, I^2C – interface I^2C).

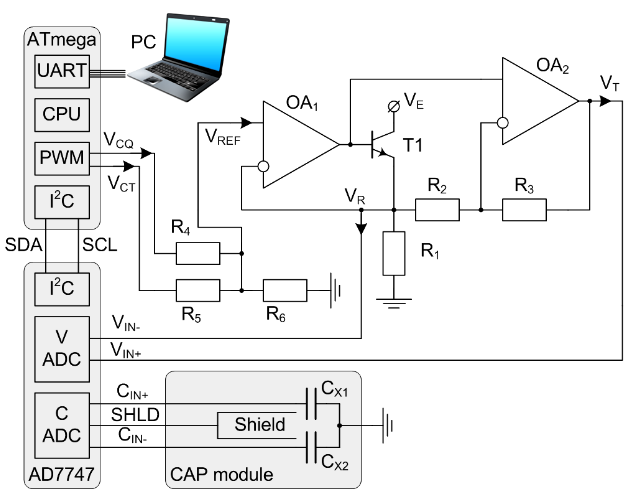
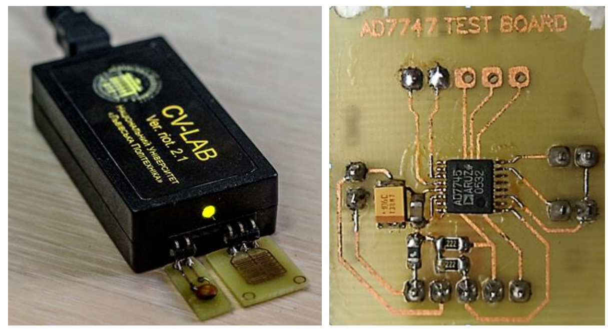


Fig. 9. Structural scheme of a functionally integrated converter of thermal quantities based on a combination of thermal and capacitive research methods

Transistor T_1 performs two functions – controlled heating of the capacitive CAP module and its temperature measuring. The signal circuit on the operating amplifier OA_1 provides control of the specified transistor T_1 current. The control is carried out by modulating the amplitude or pulse duration in accordance with the time charts of thermocycles shown in Fig. 1, 2 and implemented by the corresponding pulses at pulse width modulator PWM outputs. In particular, high current values I_Q>100 mA in the heating pulses are implemented by the control signal V_{CQ}, and low current values I_T>0.1 mA in pulses of temperature measurement by the signal V_{CT}. The duration of these pulses is determined by the period and the slit of the corresponding pulses of the pulse width modulator PWM, and amplitude values – by the resistive divider R_4, R_5, R_6. The informative value of the measured temperature is the voltage difference V_T-V_R.



a *b*

Fig. 10. Prototype of a functionally integrated signal converter: *a* – appearance; *b* – capacitor converter module based on the AD7747 converter

The measurement of electric capacity is realized on the Analog Devices AD7747 24-bit capacitance-to-digital converter. The block diagram of this capacitive converter is shown in Fig. 11, where:

– MUS – analogue multiplexer of input signals;

– 24-BIT Σ–Δ GENERATOR – sigma-delta generator (modulator);

– CLOCK GENERATOR – specifying time interval generator;

– DIGITAL FILTER – digital filter;

– EXCITATION – active shielding signal formation node;

– TEMP SENSOR – temperature sensor;

– CAP DAC1, CAP DAC2 – "digital code – capacity" converters;

– VOLTAGE REFERENCE – reference voltage source;

– CONTROL LOGIC CALIBRATION – calibration node;

– I2C SERIAL INTERFACE – serial I2C interface.

In addition to the high-precision 24-bit measurement of capacitance difference (outputs – CIN1(+), CIN1(–)), the converter provides some other important functions. First, it is active shielding (Shield) of input circuits (output – SHLD), which is extremely important during the measurement of very small capacitance changes. Such shielding is carried out by auxiliary electrodes, or shielding surfaces, on which EXCITATION pulses are formed. The amplitude of such pulses is adapted to the specific conditions of the research object. Secondly, the converter allows the synthesis of auxiliary capacities, which, being included in the measurement circuit, can compensate the parasitic capacities of this circuit. Such synthesis is carried out by CAP DAC1, CAP DAC2 "digital code – capacity" converters. And, thirdly, the converter allows measuring the voltage difference on the auxiliary outputs VIN(+), VIN(–)) with 24-bit resolution. It is precisely by using this possibility the measurements of the object temperature is performed in the developed signal converter.

Measuring conversion parameters such as noise level resolution and digital filtering duration are specified by the control bits of the AD7747 converter configuration register (the address of this register – 0x0A). During the capacitance measurement, such control bits are CAPFS0, CAPFS1, CAPFS2, and during the voltage measurement – VTFS0, VTFS1. The values of the measured transformation time (in milliseconds, 10^{-3} s), RMS (Root Mean Square) of the noise value of the measured capacitance difference (in attofarads, 10^{-18} F) and RMS of the noise value of the measured voltage difference (in microvolts, 10^{-6} V) for possible sets of control bits are shown in Tables 1, 2.

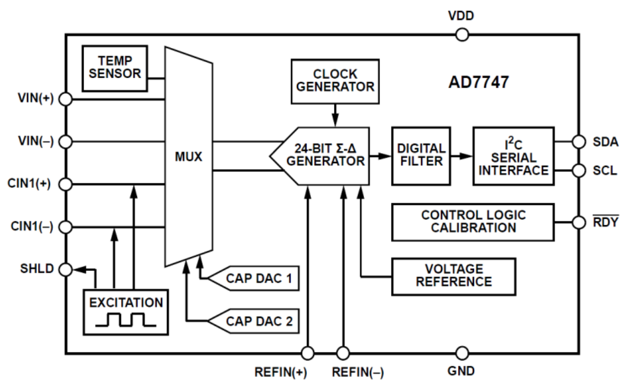


Fig. 11. Structural scheme of the AD7747 capacitance-to-digital converter

Table 1

Time and resolution parameters of capacity measurement

Values of control bits			Time of transformation, ms	RMS value of noise, $\times10^{-18}$ F
CAPFS2	CAPFS1	CAPFS0		
0	0	0	22.0	190
0	0	1	23.9	146
0	1	0	40.0	52
0	1	1	76.0	37
1	0	0	124.0	29
1	0	1	154.0	24
1	1	0	184.0	21
1	1	1	219.3	8

Table 2

Time and resolution parameters of voltage measurement

Values of control bits		Time of transformation, ms	RMS value of noise, $\times10^{-6}$ V
VTFS1	VTFS0		
0	0	20.1	11.4
0	1	32.1	7.1
1	0	62.1	4.0
1	1	122.1	3.0

The obtained results allow us to find the optimal conversion time depending on the required resolution, which is specified in each specific task. In particular: with CAPFS2=1, CAPFS1=0, CAPFS0=0, the time of the measured transformation is 124.0 ms, the RMS value of noise of the measured capacitance – 29×10-18 F; with VTFS1=1, VTFS1=0, the time of the measured transformation is equal to 124.0 ms, the RMS value of noise of the measured voltage – 3×10-6 V.

Communication between the Atmega328 microcontroller and AD7747 microconverter is carried out through I^2C serial interface with SDA data line and SCL synchronization line. Communication between the signal converter and the personal computer PC is carried out through the serial UART port.

The usage of the signal converter presented in this work allows the creation of functionally integrated thermal sensors based on a combination of thermal and capacitive research methods. The converter provides controlled heating of research object, characterized by high values of temperature measurement resolution and generated by changes in mechanical properties, shape, deformation, etc. Resolution of temperature measurement is not worse than 0.01 °C, electric capacity – not worse than 10^{-16} F. The priority of the usage of the developed signal converter is the microelectronic sensors in the concept of the Internet of Things. To implement such sensors, they incorporate wireless communication nodes, in particular on the basis of Bluetooth, Wi-Fi or ZigBee interfaces.

6. Discussion of the results of the study of functionally integrated thermal sensors

The concept of construction of signal transducers of thermal sensors, based on the functional integration of thermal and capacitive methods of research on the basis of transistor structures and signal transducers of the capacitive type, is developed in this work.

The advantage of the proposed implementation approach is the use of the same transistor structure, both for heating and for measuring temperature, which, in comparison with classical resistive heaters and temperature sensors, gives the opportunity to get a microelectronic heater with an integrated temperature sensor.

The proposed new solution for constructing a control circuit for a transistor converter, which makes it possible to use a unipolar power supply, allows you to correctly set the limits of the temperature range of the transformation, control the sensitivity of the signal converter, and differs in the simplicity of implementation.

The use of the proposed concept of constructing integrated sensors is limited only by the temperature range, which is determined by the maximum permissible temperature of the semiconductor transition of the transistor structure.

The combination of thermal and capacitive research methods makes it possible to measure the absorbed or allocated energy simultaneously to determine the change in the mechanical properties and shape of the object of research under the influence of temperature, which provides the basis for the creation of sensory devices of the new generation of analog front-end for the branches of materials science, biophysics and medicine.

7. Conclusions

1. The problem of functional integration in thermal sensors has been formulated and solved. The novelty of the

proposed sensors of thermal analysis, in addition to the measurement of temperature and amount of thermoenergy emitted or absorbed by a research object, is the possibility of measuring the electric capacity. This possibility, in particular, ensures the possibility of measuring the temperature deformation of a research object or console, bending under the influence of this object. The analysis of thermocycling modes where the managed pulse heating of functionally integrated transistor transducers and their temperature measurement is carried out, the results of which affect the development of the control scheme of heating dynamics, has been conducted.

2. The analysis of the working modes and the control scheme of transistor transducers of integrated thermal sensors has been made. The control of a temperature mode is proposed to be performed by the modulation of the amplitude of transistor current pulses or by the modulation of pulse duration at the fixed current amplitude within the range from 10 mA to 1 A. The current of the temperature measurement cycle is a constant value and typically does not exceed 1 mA. The presence of the pause cycle allows increasing the energy-efficiency of the developed signal transducer. It is shown that the maximum heating power $P(Q_1)$ of transistor is reached at the 2.5 V voltage that corresponds to the half of the supply voltage.

3. The model research of the developed scheme of the signal transducer based on SPICE models and methods within MicroCAP has been conducted. The signal transducer provides the managed heating, temperature and electric capacity measurement. The high-precision Analog Devices AD7747 24-bit capacitance-to-digital converter is taken as the basis of the signal transducer of the capacitive type. The resolution of temperature measurement of the developed signal transducer is not less than 0.01 °C, and electric capacity – 10^{-16} F.

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