Розроблено пропозиції щодо вдосконалення обладнання для теплових випробувань сонячних колекторів. Встановлено, що в радіометрах з електричним заміщенням доцільно використовувати високочутливі напівпровідникові сенсори, зокрема досліджувані типи транзисторів. Розроблено структуру цифрового вимірювача різниці температур та методику калібрування таких термометрів у двох температурних точках. Запропоновано методику коригування нелінійної складової похибки у всьому вимірювальному діапазоні

Ключові слова: сонячний колектор, напівпровідниковий перетворювач температури, вимірювач різниці температури, калібрування термометрів

Разработаны предложения относительно усовершенствования оборудования для тепловых испытаний солнечных коллекторов. Установлено, что в радиометрах с электрическим замещением целесообразно использовать высокочувствительные полупроводниковые сенсоры, в частности исследуемые типы транзисторов. Разработана структура цифрового измерителя разности температур и методика калибровки таких термометров в двух температурных точках. Предложена методика корректировки нелинейной составляющей погрешности во всем измерительном диапазоне

Ключевые слова: солнечный коллектор, полупроводниковый преобразователь температуры, измеритель разности температур, калибровка термометров

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EXPERIMENTAL STUDIES OF TEMPERATURE CHANNEL EFFICIENCY FOR SOLAR ENERGY SYSTEMS

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1. Introduction

The natural carbon energy is significant. This type of energy is continuously increasing in the cost and has a significant negative influence on the environment during usage. Those facts lead to intensive development and extensive practical implementation of alternative energy sources. In the leading countries, exploitation of the renewable energy should be increased in the near future to several tens of percent. In Ukraine, the government approved a decree "On the National Action Plan for renewable energy for the period till 2020", which provides the achievement by 2020 of the renewable energy in the final energy consumption should be not lower than 11 % [1]. Usage of the solar radiation is particularly attractive among the alternative sources due to a virtually unlimited power and environmental clearness. Nowadays there is active development of two areas for practical implementation – solar cells and collectors. The solar cells distinct advantage are the relatively small size and weight, the ability of autonomous operation using batteries. Their disadvantages are low power density, which leads to a significant size increase of the solar energy systems compared to traditional one. The efficiency of the modern semiconductor solar cells is small and can be reached to several tens of percent. In addition, the efficiency reduction is observed after heating caused by solar radiation growth. The reason for this is through a negative temperature coefficient, which leads to a marked reduction of the solar elements output voltage. The solar photothermal converters (collectors) are widely used for power supply in the domestic sphere. Their effectiveness primarily depends on the specific density of solar radiation and completeness in its transformation into a secondary liquid temperature energy source. Therefore, an important task is to create different types of the solar installations, in which at the least cost the solar energy flow is effectively converted to the consumer-desired type of energy (heat, electricity, etc.).

Nowadays, solar panels and collectors are widely introduced at home as a clean and free energy source, which have virtually unlimited resources. The Ukrainian market offers a large number of solar panels and collectors from different manufacturers and for the correct choice of the type simple techniques and equipment for their testing are required.

In Ukraine, there is almost no test equipment for determining the thermal and operational performance of solar collectors (SC) and water heaters. As the market of hellion technique equipment requires certification of the SC, there is an obvious topicality of developing the state or harmonizing international testing regulations. This also holds back the development of the new SC and solar elements, which are produced in Ukraine. Changes and amendments to existing standards for thermal testing and the SC heating efficiency determination are only possible after testing and correction of methods. Advanced standards provide for the usage of a reliable metrological testing equipment.

2. Literature review and problem statement

The theory and researches of solar collectors are given in detail in [2]. However, the mathematical models that are presented there are quite complex for practical use. In the certification process, standardized international methods (ISO 9806-2, EN 12975) use linear [3] or quadratic approximation of the solar collector efficiency coefficient [4]. Theoretical researches and practical implementation experience show the benefits of engineering methods for the effectiveness determination of SC based on quadratic mathematical models [5]. Testing and research of solar collectors and measurement of solar energy parameters are based on a number of international standards, partly harmonized in Ukraine (SSTU – State standard of Ukraine):

– SSTU ISO 9060:2008;
– SSTU ISO 9806-1:2005;
– SSTU ISO 9806-2:2005;
– SSTU ISO 9806-3:2005;
– SSTU ISO 9846:2006;
– SSTU ISO 9847:2007;
– SSTU ISO 9459-1:2005;
– SSTU ISO/TR 9901:2006.

These standards established test methods and calculation procedures aimed at determining the SCs thermal characteristics during exploitation. The analysis shows that the requirements for test equipment are quite high under international standards. For example, the sensitivity changing of the solar radiation receivers' in the wavelength range of (0.3...3) μm should not exceed ±1 % during a calendar year in periodic calibration of the solar sensitivity (under ISO 9846 and ISO 9847). According to the standard ISO 9806-3:2005,the measurement error of the liquid coolant temperature $\Delta T_X \leq \pm 0,1$ °C; resolution ±0,02 °C; the minimum value of the measured temperature differences must not be less than $\Delta T_{Xmin} \geq 2$ °C; the temperature difference absolute error $\Delta\Delta T_X \leq \pm 0,1$ °C (preferably ±0.02 °C); relative error in this case – $\delta\Delta_T \approx \pm 5$ %. That leads to a labor-intensive and lengthy calibration procedure.

It is known that the main parameter of SC efficiency depends on the relationship between the collectors, coolants and the environments temperatures. The SC tests may be carried out both with solar simulators, and in the direct perception of solar radiation [5]. Research on the direct solar radiation perception must be executed under certain angles of incidence, which value significantly affects their thermal power [6]. This increases the requirements for measuring instruments speed after direct solar radiation, which in practice are usually dynamically changing. In addition, it is analytically and experimentally proved that the dynamic changing of SC input temperature enables to eliminate some measurement errors and to achieve test accuracy near ten percent [7]. The efficiency coefficient evaluation is based on polynomial linear regression and requires additional costs for changing the SC lighting angles. Experimental studies of various SC designs using indoor solar simulators showed that the standard methodology of the SC main characteristics could be realized with errors up to tens of percent [8]. The analysis showed [9] that the relative experimental error of the SC coefficient efficiency practically is determined by the sum of relative measurement errors of the temperature difference $\delta\Delta_T$ and the total surface radiant flux density δ_G. During the surface flux density measurement of solar radiation, it is advisable to implement laboratory methods by applying solar radiation simulators. This helps to reduce costs, to increase the accuracy of research and the number of controlled impact factors and performance of tests regardless of weather conditions [5, 10]. In practice, quasi-stationary methods are generally implemented which use dynamic models with average values of SC temperatures and heat capacity [5, 11]. It is known that the highest accuracy and simple procedure for solar radiation parameters measurement are provided by calibrated electrical substitution radiometers (calorimeters) [12]. Such radiometers alternately compare optical radiation energy and electricity using the thermal comparison method. Since in both cases the comparator is heated up to the same temperature, it can be considered that informative signal is temperature difference between the detector and the environment [13]. Traditionally, a thin metal plate is used as high-speed comparator, which temperature is measured by quick-response thermoelectric converters. Due to low sensitivity of thermoelectric converters, the plate must be strongly heated up, which reduces the overall radiometer performance. Therefore, improvement of the temperature comparator that is based on up-to-date temperature sensors should improve metrological characteristics of the whole radiometer.

In commercial solar systems, there is a need for precise metering of heat that is given to the consumers. If the minimum difference between the measured temperatures is $\Delta T_{min} \geq 1.5$ °C and the absolute error is $\Delta\Delta T \leq \pm 0.1$ °C, the relative measurement error will be $\delta\Delta_T \approx \pm 6.7$ % [9]. If to reduce both temperature difference error $\delta\Delta_T$ (or temperature) and the radiation flux density error δ_G, the total relative error of the SC efficiency coefficient may not exceed a few percent [14, 15].

3. Aims and tasks of the research

The study aim is the development of thermal measurement equipment using semiconductor sensors in electrical substitution radiometer. This will improve accuracy and simplify laboratory testing of solar collectors.

To achieve this goal, we must solve such tasks:

– theoretically prove expedience of temperature sensors choice for further implementation in electrical substitution radiometers;

– to carry out experimental researches of semiconductor transistor diodes to determine the sensor performance spread for three different measuring current values;

– to develop the digital temperature difference meter structure with the studied sensors and work out its calibration method to correct additive and multiplicative errors;

– to explore the digital thermometers calibration method in two temperature points and nonlinear error correction method.

4. Rationale for selecting the sensor type

The errors reducing ways analysis for the temperature difference measurement in electrical substitution radiometer showed that the thermal comparator mass should be as small as possible. It must be heated up to the lowest possible temperature to achieve maximum speed. Traditionally used thermoelectric converters have low sensitivity and significant instrumental error values (up to several kelvins). Therefore, they are connected in a thermopile and their signals are processed by special information-measuring systems with an optimal algorithm to find the average integral temperature [16]. This complicates the design and reduces performance and makes virtually impossible to use this type of converter in radiometers. Resistive temperature transducers (RTT) should be film, have high sensitivity and small instrumental error values and errors caused by self-heating. Modern compact film RTT are made of class A with an initial resistance value of 1000 Ohms and default power dissipation of up to 0.1 mW. The maximum value of the measuring current does not exceed I_{all}≤0.3 mA. The voltage drop value on RTT is equal to U_{TR}=0.3 V and a signal voltage sensitivity – ΔU_{TR}=1.2 mV/K. Series connection of ten film thin RTT increases their sensitivity to 12 mV/K. The main disadvantages in this case are quite large overall dimensions and cost performance [17].

Since all parameters of semiconductor pn-junction have a significant temperature dependence, immediately after developing electronic devices, in addition to adjustment methods, the methods of their use as thermometers have been developed. However, due to significant limitations, mainly technological, they were realized too slowly.

The rapid development of semiconductor technology has given rise to real microelectronic elements that allowed creating digital thermometers with high accuracy. The advantages of semiconductor temperature converters (STC) are [18]:
- high sensitivity;
- long-term stability;
- high operation speed;
- relatively small nonlinearity;
- relatively wide temperature application range;
- the possibility of spot temperature measurement;
- low cost;
- manufacture simplicity.

The variation of modern STC parameters can be adjusted using structural and technological methods during their manufacture, as well as using structural and algorithmic methods for correcting errors that are realized mainly in the secondary device [19]. The basic idea in this case is the statistical averaging of STC transmission characteristics in temperature and temperature difference meters' structures. The authors conducted preliminary studies that showed the STC technology spread reduction to several tenths of a kelvin using surface mount transistors [20]. Therefore, further analysis is aimed at limiting the possibilities of using STC during testing SC.

5. Description of experimental unit for sensors research

Fig. 1 shows a block diagram of an experimental unit for studying semiconductor temperature sensors VD_X. It contains:
- liquid thermostat;
- voltage supply source U_{PS};
- measuring current generators I_1, I_2, I_3;
- measuring currentswitches S_{12};
- exemplary resistors R_{N1}, R_{N1}, R_{N1} for controlling measuring current values;
- exemplary resistors switch S_{11};
- precision voltmeter V for voltage drop measurement over the STC and exemplary resistors.

To ensure the noise immunity and noise stability of conversion, the measurement circuit in Fig. 1 provides for several measures [18].

For a correct characteristics spread comparison, several STC are connected in series in the current generators loop and STC are placed in the digital precision liquid thermostat TCP-0105 HO (Ukraine).

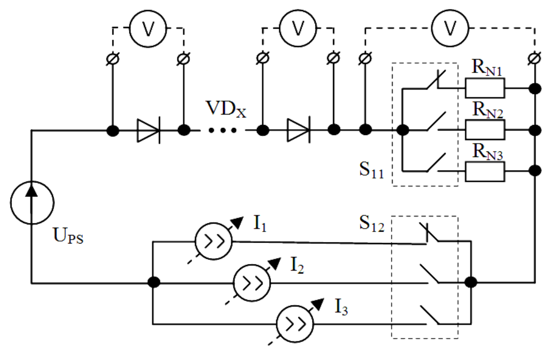

Fig. 1. A block diagram of the experimental unit for semiconductor temperature sensors studies

Thermostat specifications: temperature control range (0...+100) °C; temperature setting resolution 0.01 °C; permissible main error limit values of temperature measurement and maintenance ±0.02 °C.

Current generators are set up as current-setting two-terminal circuits, which current values can be controlled. If necessary, current values can be set within the prescribed limits, contributing to a correct comparison between the STC parameters, studied for long periods of time. Voltage drop on the STC and exemplary resistors is measured by a digital multimeter Picotest M3511A (Taiwan). Measurement ranges – 0.1 V, 1 V and 10 V, the accuracy of 0.012 % per year and unit LSB in the averaging mode 1 μV.

Structurally, the STC have five series-connected transistor diodes. Surface mount transistors BC858C, BC859V, BCW61C (p-n-p type) and BC849V, BC849S, BC850VE (n-p-n type) (Malaysia) were used as STC. To protect transistors in a liquid, the STC were covered with shrink film (Fig. 2).

Fig. 2. Appearance of transistor temperature sensors

Analyzed sensors were placed in a thermostat with the temperature from 0 °C to +80 °C and 10 °C resolution. For a correct selection of measuring currents, the following values were set: 0.1 mA, 1.9 mA and 1 mA.

6. Experimental results elaboration

The studies have shown the feasibility of using the BCW61C transistors with the lowest voltage drop variations from sample to sample: ±0.49 mV (±0.049 °C) (Malaysia) in STC (Table 1, 2). Three different measuring currents I_1=1 mA, I_2=0.1 mA and I_3=1.9 mA were serially passed through STC, and their voltage drop values were recorded by a digital multimeter.

Table 1

Experimental voltage drop values when I_1=1 mA for BCW61C transistors in the measurement range (0...+ 80) °C

No.	U_{bei}, B				
	Temp. 0 °C	Temp. 20 °C	Temp. 40 °C	Temp. 60 °C	Temp. 80 °C
1	3.42138	3.21386	3.00465	2.79343	2.58004
2	3.42091	3.21345	3.0043	2.7931	2.57965
3	3.42162	3.21428	3.00519	2.79404	2.58057
4	3.42081	3.21347	3.00456	2.79339	2.57997
5	3.42133	3.21394	3.0049	2.79378	2.58033
6	3.42122	3.21382	3.00473	2.79358	2.58004
7	3.42124	3.21382	3.00487	2.79383	2.58038
8	3.42124	3.21381	3.00469	2.79349	2.57998
9	3.42132	3.21391	3.00494	2.79361	2.58008
$U_{av.bei}$, B	3.42123	3.21382	3.00476	2.79358	2.58011

The study method was to measure the voltage drop on the STC, changing the polarity of the voltmeter and averaging the results of several converters. It is possible to reduce random and additive (caused by contact emf) error components, their value does not exceed ±0.02 °C equivalent. Experimental voltage drop variations at the STC ΔU_{bei} were determined by (1):

$$\Delta U_{bei} = U_{bei} - \Delta U_{av.bei}, \quad (1)$$

where U_{bei} – voltage drop at the p-n junctions of STC for the i-th sensor; $U_{av.bei}$ – the average voltage drops at p-n junctions of STC for the i-th sensor.

Table 2

Experimental voltage drop variations when I_1=1 mA for BCW61C transistors in the measurement range (0...+ 80) °C

No.	ΔU_{bei}									
	Temp. 0 °C		Temp. 20 °C		Temp. 40 °C		Temp. 60 °C		Temp. 80 °C	
	mV	°C	mV	°C	mV	°C	mV	°C	mV	°C
1	0.15	0.015	0.04	0.004	–0.11	–0.011	–0.16	–0.016	–0.08	–0.008
2	–0.32	–0.032	–0.37	–0.037	–0.46	–0.046	–0.48	–0.048	–0.47	–0.047
3	0.39	0.039	0.46	0.046	0.43	0.043	0.46	0.046	0.45	0.045
4	–0.42	–0.042	–0.35	–0.035	–0.20	–0.020	–0.19	–0.019	–0.14	–0.014
5	0.1	0.01	0.12	0.012	0.15	0.015	0.2	0.02	0.21	0.021
6	–0.01	–0.001	0.005	0.0005	–0.03	–0.003	0	0	–0.08	–0.008
7	0.01	0.001	0.005	0.0005	0.11	0.011	0.25	0.025	0.27	0.027
8	0.01	0.001	–0.005	–0.0005	–0.07	–0.007	–0.1	–0.01	–0.14	–0.014
9	0.09	0.009	0.09	0.009	0.18	0.018	0.03	0.003	–0.03	–0.003

6. 1. Evaluation of the exercise of temperature difference meters

Analysis of voltage drop measurements at each of nine BCW61C transistors (Malaysia) when three measuring currents (0.1 mA, 1 mA and 1.9 mA) flow across them showed, that the variations of these mean drop values are almost temperature independent. For all set measuring current values, the variation was within ±0.004 °C. Also, it was experimentally established that the STC temperature dependencies maximum variation does not exceed ±0.05 °C throughout the measuring range of 0 °C to +80 °C (Fig. 3). The variation value is independent of the measuring current values.

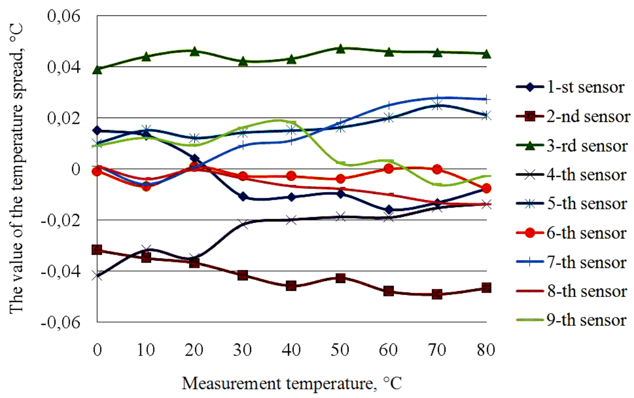

Fig. 3. The variation between the characteristics of nine BCW61C transistors (Malaysia) depending on the measurement temperature for I_1=1 mA

This provides for zero calibration in the digital temperature difference meter. For example, by placing both sensors in the environment at the same temperature, memorizing a reading and entering it as an amendment to the measurement results (Fig. 4).

After calibration of the temperature difference meter, the following errors will be adjusted:

– caused by the temperature spread of both STC;

– instrumental errors of both current-setting resistors R_{I1} and R_{I2};

– due to the bias voltage of both operational amplifiers DA1 and DA2 under the given operation conditions.

The analysis of the dependencies in Fig. 3 has shown that after calibration the temperature difference error value in the measuring temperature range (20±10) °C will not exceed ±0.05 °C.

6. 2. Correction of errors during temperature measurement

The analysis of the experimental results also showed that 1 mA current has the smallest STC interchangeability error. Throughout the measuring range of 0 °C to +80 °C its value does not exceed ±0.05 °C (Fig. 3). During the practical implementation of digital thermometers (DT), instrumental additive and multiplicative errors of used components will also exert an influence. In addition, the STC have also the nonlinearity, whose value can be estimated at several tenths of a degree [13, 17–20]. Therefore, calibration of DT with Celsius scales in a wide measuring range at minimum two temperatures is appropriate.

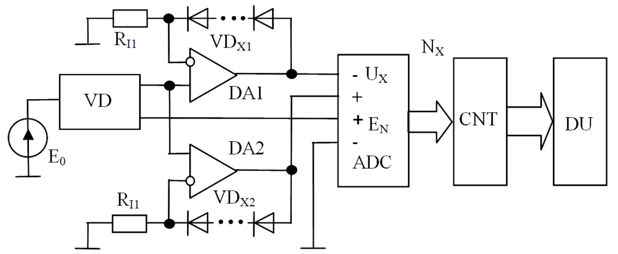

Fig. 4. A block diagram of a digital temperature difference meter: VD – voltage divider; CNT – controller; DU – display unit

Obviously, the ice melting temperature 0 °C is advisable to be taken as the first calibration value, which is rather simply and accurately implemented in practice, even in portable units for DT metrological assurance. The second calibration value is appropriate to be taken near to the maximum measured temperature value. Given the nonlinear device transformation function, it is recommended to choose the calibration value with a factor approximately equal to 0.82 of the maximum measured temperature value [18].

The authors proposed the following method of thermometers calibration. For each of the sensors and measuring currents, the voltage drops U_{i0} and U_{iclb} are determined, if the calibration temperatures θ_0=0 °C and θ_{clb}=70 °C are set in a thermostat and voltage difference is computed (2):

$$\Delta U_{iclb} = U_{i0} - U_{iclb}. \qquad (2)$$

Calibration coefficients α_{iclb} are defined as the ratio (3):

$$\alpha_{iclb} = \frac{\Delta U_{iclb}}{\theta_{clb}}. \qquad (3)$$

Experimentally defined nonlinearity error values Δ_{inl} of the conversion characteristic are represented by the ratios (4):

$$\Delta_{inl} = \frac{\Delta U_{ix}}{\alpha_{iclb}} - \theta_{jx}, \qquad (4)$$

where ΔU_{ix} – the difference between the average and i STC voltage drops at the current temperature θ_{jx} and 0 °C; θ_{jx} – the value of temperature in the thermostat.

Temperature measurement errors after the calibration of nine BCW61C transistors (Malaysia), are shown in Fig. 5. The range of measured temperatures from 0 °C to +80 °C, provided that the second calibration temperature value is +70 °C. From the analysis of submitted graphical dependence (Fig. 5), it becomes apparent that maximum nonlinearity error values are midway between the two calibration temperatures and at the measured temperature maximum value. For adjusting its value, it is proposed to approximate this relationship by such function, which character is inherent to p-n junction parameters. These function parameters are defined from experimental data and then it may be introduced into the measurement results as a correction. Since modern DT can be implemented in controllers with significant computing power, the amendment calculation is not a difficult technical challenge.

The temperature dependence of the nonlinearity error in the measurement range is proposed to be approximated by logarithmic dependence considering the conditions of equality of its values to zero for both calibration temperatures (5):

$$\Delta_{inl} = m\eta_i \left[\frac{\theta_X}{\theta_{clb}} \cdot \frac{kT_{clb}}{q} \cdot \ln\frac{T_{clb}}{T_0} - \frac{kT_X}{q} \cdot \ln\frac{T_X}{T_0} \right], \qquad (5)$$

where k, q – Boltzmann constant and electron charge, respectively; T_0=273.15 K – first calibration point temperature; T_{clb}=343.15 K – second calibration point temperature; T_X – current temperature in the thermostat; η_i – STC non-ideality factor; m – the number of transistor diodes in the STC.

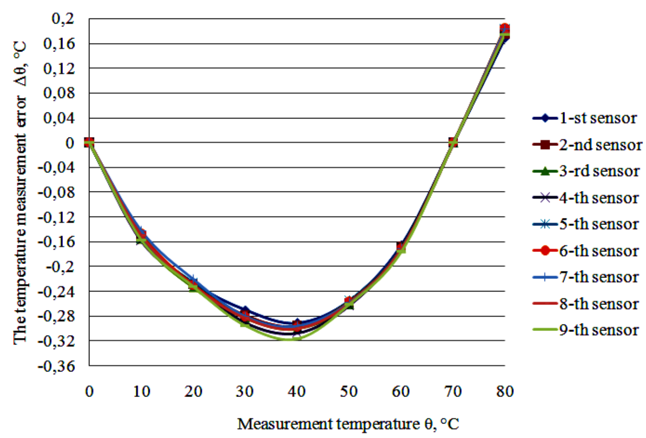

Fig. 5. The temperature measurement error dependence for nine semiconductor converters with a measuring current I_1=1 mA

From equation (5) of the approximating dependence of the nonlinearity error Δ_{inl} we find the coefficient η_i from the experimental data at 30 °C (6):

$$\eta_i = \frac{\Delta_{inl}}{5\left[\frac{\theta_X}{\theta_{clb}} \cdot \frac{kT_{clb}}{q} \cdot \ln\frac{T_{clb}}{T_0} - \frac{kT_X}{q} \cdot \ln\frac{T_X}{T_0} \right]}. \qquad (6)$$

To verify the obtained results, a difference between both the calculated and experimentally determined nonlinearity error was found. This difference proved to be zero for all the thermostat temperature values over the whole range (0...+80) °C. That indicates the correctness of the proposed method of STC nonlinearity error adjustment.

7. Discussion of experimental studies of the temperature channel efficiency

The feasibility of the series transistors connection in a temperature sensor, which provides a significant sensitivity increase was experimentally confirmed. At the same time, the sensor voltage drop does not exceed the 4 V value, which allows their easy coordination with microelectronic components for the thermometers construction. This enables the digital temperature difference meter implementation with the study sensors without precision scaling components.

The proposed methods of digital meters' calibration can be implemented in software. In terms of hardware, only a few buttons can be used to enter the gauge value information.

Our studies also provide an opportunity to implement precision digital thermometers in the measuring range from 0 °C to +100 °C. The results showed, that the calibrating digital thermometers may have better metrological characteristics, than those with measuring-current modulation. Developed digital temperature and temperature difference meters can be used as portable devices in the utilities sector, agriculture, food industry and others.

A narrow temperature range of sensors experimental studies and somewhat cumbersome method of calibrating digital thermometers can be attributed to the results shortcomings. Solving these problems is a major challenge for further research.

8. Conclusions

1. To improve the performance specifications of electrical substitution radiometers, it is proposed to use highly sensitive semiconductor sensors. Based on the experimental studies, planar transistors are chosen and sensors that can be used in temperature channels of devices for solar system studies are designed. Series connection of several transistor diodes enables an increase in sensitivity while reducing technological variations and simplifying secondary devices.

Structurally, the STC was five series-connected transistor diodes. Surface mount transistors BC858C, BC859V, BCW61C (p-n-p type) and BC849V, BC849S, BC850VE (n-p-n type) (Malaysia) were used as STC. To protect transistors in a liquid, STC were covered with shrink film.

2. It is found experimentally that the characteristics maximum variation of the nine studied transistor diodes does not exceed ±0.06 °C. In addition, throughout the measuring range of 0 °C to +80 °C this value does not depend on the measuring currents values of 0.1 to 2 mA.

3. The structure of a digital temperature difference meter with the studied sensors was designed. Its novelty is the absence of a separate precision amplifier element, which allows creating accurate, portable devices in the modern microelectronic components base. The meter calibration at an arbitrary temperature in the measurement range while ensuring the temperature uniformity of both sensors is proposed. After calibration, the estimated error value of the temperature difference meter does not exceed ±0.1 °C throughout the measuring range.

4. The digital thermometers calibration method in two temperature points is proposed. At 0 °C, the thermometer additive error is determined, which is later used as a correction to all measuring results. The multiplier factor value is suggested to be determined near the maximum measured temperature as the ratio of the nominal and the resulting values of the code that matches the calibration temperature.

5. A method for adjusting a nonlinear error component in the whole measuring range is developed. It is based on determining the parameters of sensors approximating dependencies using experimental data. The logarithmic approximation temperature dependence of semiconductor sensors, whose value is equal to zero at both calibration temperature values is proposed.

6. It is theoretically estimated that after calibration the acceptable error limit of digital thermometers in the whole measuring range from 0 °C to +100 °C does not exceed ±0.1 °C.

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