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Vasyl Stefanyk Precarpathian National University

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B.S. Dzundza[1], O.B. Kostyuk[1,2], U.M. Pysklynets[2], Z.M. Dashevsky[3]

Development of high-precision hardware and software tools for automated determination of the characteristics of thermoelectric devices

[1]*Vasyl Stefanyk Precarpathian National University, Ivano-Frankivsk, Ukraine,* bdzundza@gmail.com
[2]*Ivano-Frankivsk National Medical University, Ivano-Frankivsk, Ukraine,* oksanakostuk@gmail.com
[3]*Ben-Gurion University of the Negev, Beer-Sheva, Israel,* zdashev@bgu.ac.il

In this work, a high-accuracy setup was developed for the characterization of thermoelectric devices in the temperature range of 300-900 K. The output parameters of the thermoelectric devices, including the thermoelectric efficiency Z, Seebeck coefficient S, and internal resistance r, were measured. A technique, block diagram, and computer tools for automated measurement and preliminary processing of experimental data were developed for automated studies of the properties of semiconductor materials and thermoelectric power conversion modules. The developed tools were shown to have high efficiency. The complexity of the process of measuring the main electrical parameters of semiconductor materials was significantly reduced, and the accuracy of the obtained results was increased.

Keywords: thermoelectricity, thermoelectric materials, thermoelectric efficiency, measurement techniques, high-accuracy automated measurement.

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Introduction

Due to the increase in energy demand and depletion of natural resources, the development of energy harvesting technologies has become tremendously important [1]. The application of thermoelectric devices, which convert heat directly into electrical energy, has led to significant progress in the development of cost-effective, environmentally-friendly, and fuel-saving energy sources for power generation, refrigeration, temperature sensors, and thermal management [2–10]. The high reliability and long operational lifespan of thermoelectric (TE) energy converters make them ideal for use in the space industry, gas pipeline systems, medical devices, and consumer electronics [4,5,11,12].

The efficiency of such TE converter is determined by the following equation [4,12,13]:

$$\eta_{max} = \frac{\Delta T}{T_h} \frac{\sqrt{1+(ZT)_{av}}-1}{\sqrt{1+(ZT)_{av}}+\frac{T_c}{T_h}}, \tag{1}$$

where T_h and T_c are the hot and cold sides temperatures at the ends of TE converter, respectively, $\Delta T = T_h - T_c$, and $(ZT)_{av}$ is the average dimensionless TE figure of merit, which is determined as:

$$(ZT)_{av} = \frac{1}{T_h - T_c} \int_{T_c}^{T_h} ZT \cdot dT \tag{2}$$

$$ZT = \frac{S^2 \sigma}{\kappa} T, \tag{3}$$

where S is the Seebeck coefficient, σ and κ are electrical and thermal conductivity.

Theoretical studies have shown that the most accurate ZT value can be obtained using the Harman method [14]. There are many modifications of this method [15,16] that allow for the direct estimation of the TE figure of merit on a single sample. However, the use of measurements based on the Harman method, especially at high temperatures, has certain disadvantages [27]:

1. The effect of parasitic heat transfer between the

sample and its environment has been determined to be critical to the measurement accuracy.

2. This effect of parasitic thermal phenomena increases rapidly with increasing measurement temperature.

3. To determine thermoelectric parameters, it is necessary to use correction factors of up to 80% of the measured *ZT* value, which cannot be reliably estimated for arbitrary temperatures and sample sizes.

To measure parameters of the thermoelectric devices, direct methods were chosen, in which a heat flux is passed through the thermoelement due to a certain temperature gradient created between the heater and the cooler. Direct methods require a gradient heater, precise temperature gradient maintenance and measurement, and the accounting of heat fluxes and losses, which may introduce considerable errors in the estimate of the thermoelectric figure of merit. The design and analysis issues of devices concerning these problems are discussed in [18,19]. The use of general tools for studying thermoelectric properties poses several difficulties, primarily with regards to adapting measurement techniques and integrating such tools into pre-existing laboratory complexes [20].

The peculiarity of the developed method is the use of two identical samples placed on both sides of the heater and cooled by the same water radiators.

Due to the properties of semiconductors, n-type and p-type materials have Seebeck coefficients of opposite signs, respectively [21]. Consequently, thermoelectric modules are composed of two distinct semiconductor materials that are interconnected electrically in series and thermally in parallel [21], as shown in Fig. 1.

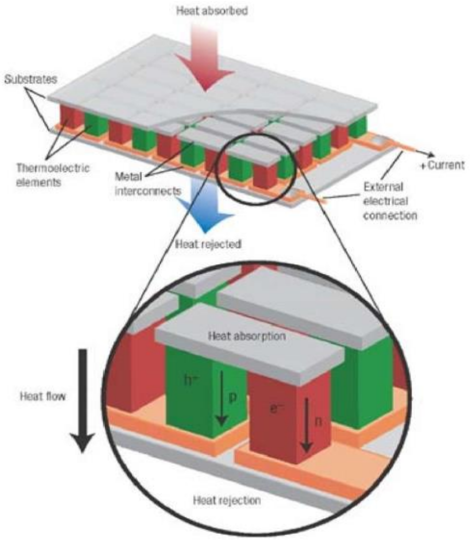


Fig 1. Thermoelectric module [21].

Thermoelectric devices available in the market typically comprise a series of thermocouples sandwiched between hot and cold plates that conduct heat. In order to maximize their efficiency, modern modules are sometimes segmented or cascaded, wherein a single leg can incorporate several materials consecutively. The rationale behind this approach lies in the fact that thermoelectric modules frequently experience temperature gradients of several hundred degrees, and given that the figure of merit of a given material may vary considerably across a range of temperatures, using more than one material becomes advantageous [21]. Additionally, the metal-semiconductor junctions present in a thermoelectric module are ohmic contacts, thereby rendering the device essentially symmetrical and enabling it to pump heat or current in either direction.

I. Development of setup

The development and widespread use of thermoelectric generation as a user-friendly technology for direct energy conversion is mainly limited by a small efficiency factor. Presently, scientists in the field of thermoelectricity are primarily focusing on increasing the thermoelectric efficiency Z across a wide range of operating temperatures (300-900 K). The quality of a thermoelectric material is determined by a set of key parameters, including the Seebeck coefficient, electrical conductivity, and thermal conductivity. Moreover, for a thermoelectric converter to be fully functional, it must also possess a range of electrical and operational characteristics, such as internal resistance, generated current and voltage, thermoelectric power, heat capacity, and other performance metrics.

For the purpose of measuring all the aforementioned parameters, direct methods have been selected, whereby a heat flow is directed through a thermoelement in response to a temperature gradient generated between the heating and cooling elements. A noteworthy aspect of the developed methodology lies in the use of two identical samples positioned on either side of the heating element, and subsequently cooled by identical water radiators. The measuring cell is shown schematically in Fig. 2.

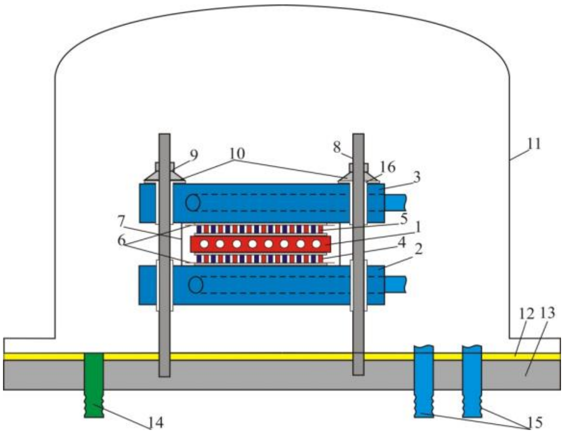


Fig. 2. Schematic representation of the measuring cell. 1 – copper electric heater with thermocouple, 2, 3 – copper water radiator with thermocouple, 4, 5 – thermocouples or single samples of thermoelectric material, 6 – electrical contacts, 7 – heat shield, 8 – clamping pins, 9 – nuts, 10 – spring washers, 11 – vacuum cap, 12 – vacuum gasket, 13 – base, 14 – fitting for pumping, 15 – fittings for water supply and drainage, 16 – fluoroplastic insulation.

The use of a water-based cooling system allowed to maintene the stable temperature of cold junction. To achieve uniform heating of cylindrical or rectangular samples, a miniature copper heater with low power output was designed and coupled with a tubular heat shield made of tantalum. This configuration was effective in in reducing the impact of parasitic heat loss, which is often challenging to accurately account for in thermoelectric measurements.

To diagnose ready-made thermoelectric energy conversion modules with a size of 40x40 mm, a rectangular copper heater with a size of 40x40x8 mm is made, which contacts the hot surfaces of the thermocouple through the thermal interface. The general view of the measuring cell is shown in Fig. 3.

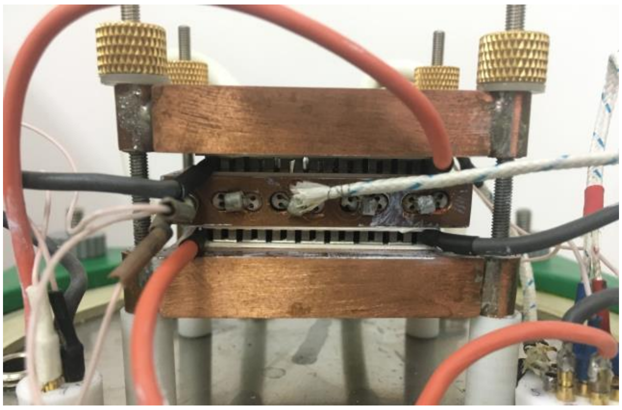


Fig. 3. General view of the measuring cell with installed thermoelectric elements.

The design further allows for the installation of an extra heater on two threaded racks, positioned at the interface level of the two radiators. This feature enables the investigation of film thermomodules, wherein the cold junction is secured between two radiators while the hot junction is pressed against an additional copper plate that is heated by the extra heater.

All electrical contacts are routed through two sealed connectors located in the base. The setup supports up to 5 thermocouples, with one placed in the heater, another in the radiators, and two more that can be drilled into the sample for additional control of heat fluxes. When investigating the electrical properties of semiconductors, fundamental parameters such as electrical conductivity, thermoelectric power, and thermoelectric EMF are measured.

The principle of determining the coefficient of thermal conductivity of stationary methods is based on the measurement of heat flux and temperature difference according to [22]

$$k = \frac{qd}{T_2 - T_1} = \frac{Pd}{S(T_2 - T_1)}$$

Here q is the heat flux; P - measured power of the electric heater; S is the area of the sample; T_2-T_1 is the temperature difference between two opposite surfaces of the sample; d is the thickness of the sample. Usually, the geometry of the sample and the configuration of the measuring system have the strongest effect on the value of the thermal conductivity. It is possible to implement comparative methods in which the amount of heat that has passed through the test sample is determined from the known parameters of the reference sample, which is in similar conditions. The method is quite well developed for different materials in a wide range of temperatures: from a few degrees to ~ 1000 K.

II. Design of software and hardware for automated studies of the properties of thermoelectric energy conversion modules

The computer system designed for measuring electrical parameters was developed with special attention given to the versatility of solutions, which allows for the study of both massive and film thermocouples, as well as the diagnosis of thermoelectric modules. The block diagram of the measuring system can be found in Fig. 4.

Cold water is running through two copper radiators, it can be both flowing tap water and water cooled by means of the cooling thermostat. The cooling thermostat is constructed on the basis of 12 V Peltier elements. The set temperature of the hot side is maintained by the microcontroller by means of a precision PID thermostat, the power of which is accurately measured and can be kept constant, regardless of changes in external conditions or the resistance of the heater. Feedback is carried out using chromel-alumel thermocouples. The thermostat maintains the set temperature with an accuracy of 0.1 K. It is also possible to connect additional thermocouples drilled in the sample, to accurately measure small temperature gradients.

The measuring system is based on the UNI-T UTM1805A digital multimeter, which supports data output to a computer and provides a resolution of 1 μV with an accuracy of 0.015% in the DC voltmeter mode and has an automatic range selection function. The control device for the system is a STM32F303 microcontroller, programmed in C language, and communication with the computer is enabled through the USB-UART converter, coupled with a text command interpreter that facilitates two-way data exchange between the device microcontroller and control programs on the computer.

The thermo-EMF recording process on the samples is executed sequentially with the aid of a switching unit integrated with a reed microrelay. The system allows for the measurement of voltage from each differential thermocouple individually, or to take an average of the readings. Furthermore, thermocouples can be connected in series to obtain the sum of the thermo-EMF of both thermocouples. The Seebeck coefficient is then automatically calculated.

The measurement of thermoelectric power is enhanced by the implementation of a load block, which enables the determination of the operational parameters of thermoelements. Additionally, studying the Peltier effect under load presents further opportunities for analyzing heat transfer parameters, particularly in determining thermal conductivity.

The computer program provides automated control of the measurement process, registration of data from a digital voltmeter, pre-processing and visualization of data. The program is developed in Delphi programming language. The measurement results of each sample are recorded in separate MS Excel-compatible files with the possibility of further continuation of the experiment. The setup exhibits high reliability, stability, and precision of results during prolonged and regular operation.

III. Experimental research and discussion of the obtained results

Let us examine the operational capabilities of the computerized measuring system through a concrete illustration, where a series of industrial thermoelectric elements of the TEKB-1-1-(15.4-6.0-51.4)-40-71 type were studied. Experimental data on the thermoelectric power, maximum power, and efficiency concerning the temperature difference applied to the module for the studied modules are shown in Fig. 5.

In Table. 1. comparison of measured and passport data for two thermoelectric modules TECB-1-1-(15.4-6.0-51.4)-40-71 is presented. The relative measurement error does not exceed 2%.

Upon analysis of the results and comparison of the calculation results with experimental measurements, it was observed that the measurement methods selected, and their hardware and software implementation, despite the relative simplicity of the implemented algorithms, demonstrated high efficiency. The implementation of the

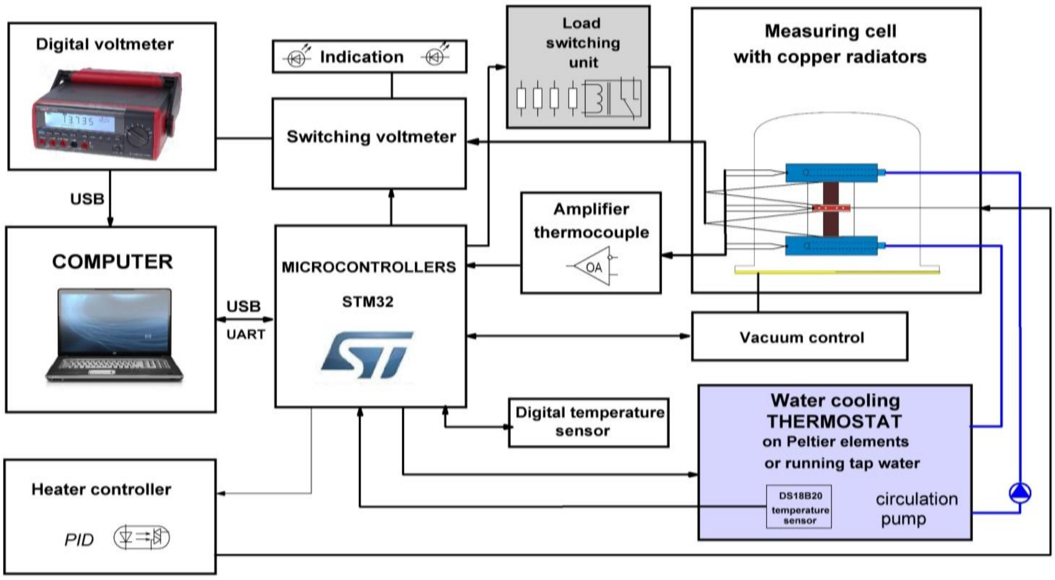
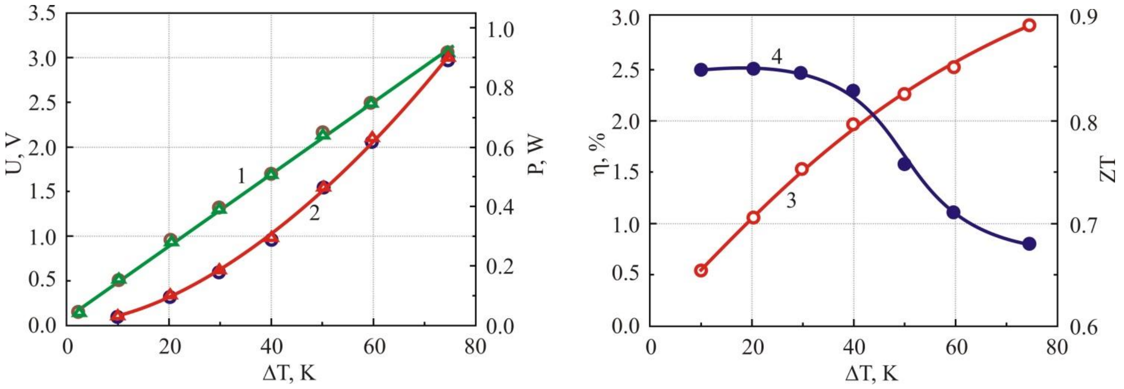


Fig. 4. Block diagram of a computer system for automated diagnostics of thermoelectric modules.



a *b*

Fig. 5. Dependences of thermoelectric power (curve 1), maximum thermoelectric power (curve 2), efficiency (curve 3) and *ZT* (curve 4) on the temperature difference applied to the module. Δ – corresponds to sample №3 placed at the bottom of heater, ○ – sample №4 placed at the top of the heater.

Table 1.

Measured and passport electrical parameters of industrial modules.

Sample	*s*, 1/Ω cm		*S*, μV/K		*r*, Ω (25 °C)		*r*, Ω (50 °C)		*Z* x10^{-3}, K^{-1}	
	Measured (M)	Passport (P)	M	P	M	P	M	P	M	P
3	1006	1000-1020	222.3	220-225	2.13	2.12	2.32	2.30	2.85	2.88
4	1005	1000-1020	222.8	220-225	2.17	2.17	2.34	2.34	2.85	2.84

computerized measuring system significantly reduced time and labor costs for experimental measurements, and facilitated automated diagnostics and fault detection of thermoelectric modules.

The advantage of the implemented research method is the automation of both the measurement process and the pre-processing of the result during the experiment, depending on the material under study. Furthermore, the representation of the acquired data through graphical dependencies makes it possible to visually detect errors, defective samples, even during the measurement process. In contrast to general-purpose tools and mathematical software packages, which offer much broader data processing capabilities, the development of specialized tools, despite the limited set of models, integrates well into the developed measuring system and provides information on electrical properties of the material with minimal effort and reduces time required. for measurement and processing.

Conclusions

1. A high-accuracy setup has been developed for the characterization of thermoelectric devices.
2. The method, flowchart, and computer tools for automated measurement and pre-processing of experimental data for automated studies of the properties of semiconductor materials and thermoelectric modules of energy conversion have been presented.
3. The developed tools were used for experimental research of thermoelectric modules with known characteristics, and their high efficiency was demonstrated. The use of these tools significantly reduced the complexity of the process of measuring the basic electrical parameters of semiconductor materials and increased the accuracy of the obtained results.

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Kostyuk O. – PhD, Senior Researcher;
Dzundza B. – PhD, Associate Professor;
Pysklynets U. – PhD, Associate Professor;
Dashevsky Z. – Doctor of Sciences, Professor.

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Б. С. Дзундза[1], О. Б. Костюк [1,2], У.М. Писклинець,[2] З. М. Дашевський[3]

Розробка високоточних програмно-апаратних засобів для автоматизованого визначення характеристик термоелектричних пристроїв

[1]Прикарпатський національний університет імені Василя Стефаника, Івано-Франківськ, Україна, bdzundza@gmail.com
[2]Івано-Франківський національний медичний університет, Івано-Франківськ, Україна, oksanakostuk@gmail.com
[3]Університет Бен-Гуріона в негеві, Беер-Шева, Ізраїль, zdashev@bgu.ac.il

У роботі розроблено високоточну установку для визначення характеристик термоелектричних приладів в діапазоні температур 350-600 K. Були виміряні вихідні параметри термоелектричних приладів, включаючи термоелектричну добротність Z, коефіцієнт Зеєбека S і внутрішній опір r. Розроблено методику, структурну схему та комп’ютерні засоби автоматизованого вимірювання та попередньої обробки експериментальних даних для автоматизованих досліджень властивостей напівпровідникових матеріалів і модулів термоелектричного перетворення енергії. Показано високу ефективність розроблених засобів. Значно зменшено трудомісткість процесу вимірювання основних електричних параметрів напівпровідникових матеріалів, а також підвищено точність отриманих результатів.

Ключові слова: термоелектрика, термоелектричні матеріали, термоелектрична ефективність, вимірювальна техніка, високоточні автоматизовані вимірювання