https://doi.org/10.15407/scine16.04.044

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THERMOELECTRIC COOLERS FOR X-RAY DETECTORS

Introduction. *X-ray methods are widely used for the nondestructive microanalytic studies of the structure and composition of materials with a high spatial resolution. Further increase in their resolution depends substantially on improving the analytical characteristics of semiconductor detectors, as well as on the application of novel types of wide-aperture position-sensitive radiation detectors.*

Problem Statement. *The resolution of X-ray detectors is essentially dependent on their operating temperature mode, provided by the use of thermoelectric coolers. Single-stage thermoelectric coolers (TEC) are used for superficial cooling (down to 250 K); to cool sensors to an operating temperature of 230 K two-stage TECs are used and three-stage TECs are used for temperatures down to 210 K, whereas four- and five-stage ones are meant for cooling below 190 K.*

Purpose. *Design and structural optimization of a thermoelectric multi-stage cooler of X-ray radiation detector.*

Materials and Methods. *Computer-based object-oriented design methods and optimal control theory methods adapted for thermoelectric energy conversion applications.*

To develop thermoelectric cooling modules, bismuth telluride-based materials (Bi_2Te_3) of n- and p-types of conductivity have been used.

Results. *Calculations of the design of the thermoelectric cooler as a part of the X-ray detector showed optimum electric power of the thermoelectric converter $W = 2.85$ W, which, with a refrigeration coefficient $\varepsilon = 0.02$, provides the detector base temperature $T_c = -70$ °C and $\Delta T = 90$ K. These temperature conditions are optimal for the operation of X-ray detectors and can significantly increase their resolution with minimal electricity consumption.*

Conclusions. *A comprehensive study and optimization has been performed, and the design of a thermoelectric multistage cooler has been calculated, which ensures optimal operating conditions for the X-ray detector. The obtained results can be used to create X-ray detectors with high resolution.*

Keywords: *computer simulation, thermoelectric cooling, and X-ray detector.*

The X-ray methods are widely used for non-destructive microanalytical studies of the structure and composition of materials with a high spatial resolution [1]. The current nuclear microanalysis methods that use focused ion beams having a MeV-order energy and a high energy homogeneity ($\Delta E/E = 10^{-5}$)) allow a spatial resolution of up to 100 nm,

Citation: Anatychuk, L.I. and Prybyla, A.V. Thermoelectric Coolers for X-Ray Detectors. *Sci. innov.* 2020. V. 16, no. 4. P. 44—49. https://doi.org/10.15407/scine16.04.044

on the surface, and up to 10 nm, in the depth of the samples. A further increase in the resolution significantly depends on the improvement of the analytical characteristics of semiconductor detectors, as well as on the use of wide-aperture position-sensitive radiation detectors of new types [2].

To increase the resolution of X-ray detectors, it is important to solve the problem of keeping the optimal temperature of their operation [3—9]. It can be solved by using semiconductor thermoelectric coolers (TECs) [5—9], which allows the required depth of cooling in the minimum operating volume of the detector. Thus, single-stage thermoelectric modules are used for shallow cooling (up to 250 K), two-stage TECs for cooling sensors to an operating temperature of 230 K, three-stage TECs for cooling down to 210 K and four- and five-stage ones for cooling below 190 K [10].

Below, there is an analysis of the capacity of thermoelectricity in terms of cooling X-ray detectors and the development of a multi-stage thermoelectric cooler for X-ray detectors.

PHYSICAL MODEL OF THERMOELECTRIC COOLER OF X-RAY DETECTOR

For calculations, a physical model of a thermoelectric cooler as part of an X-ray detector is used (Fig. 1). It consists of detector's case (*2*) with a beryllium window (*1*), through which the radiation enters the X-ray detector (*3*). The required temperature and thermal conditions are kept by means of a thermoelectric cooler (*8*) having an electric power W and consisting of branches of thermoelectric material of n- and p-type conductivity (*9*), electro-conductive switching plates (*10*) and thermo-conductive electrical insulating plates (*11*). To reduce heat loss, the detector case is filled with inert gas (*5*), and radiation shields (4) are additionally installed. The heat flow from the thermoelectric cooler is transferred through the frame of the detector case (6) and the detector holder (7).

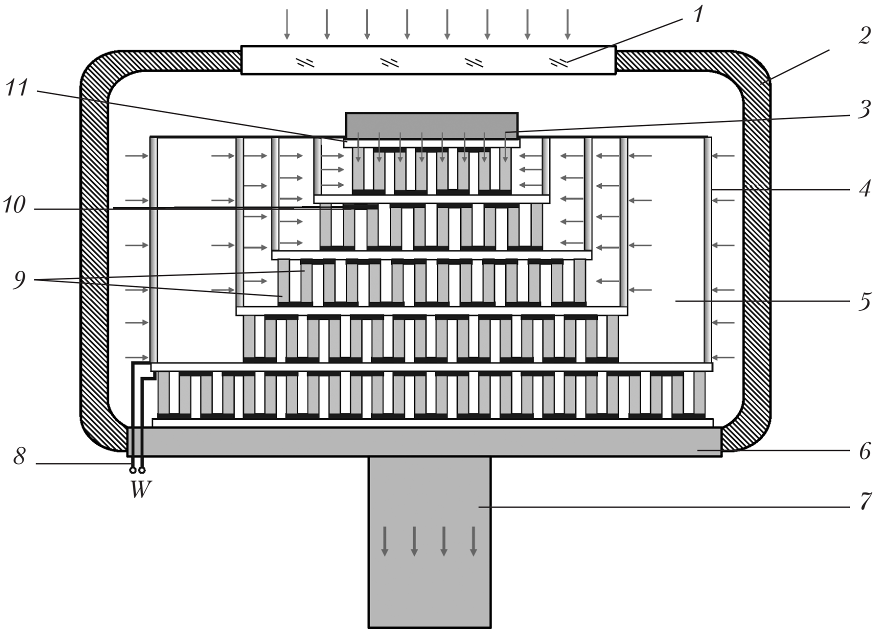

Fig. 1. Schematic model of thermoelectric cooler as part of the X-ray detector: *1* — beryllium window; *2* — detector's case; *3* — X-ray detector; *4* — radiation screens; *5* — inert gas; *6* — frame of the detector case; *7* — detector holder; *8* — thermoelectric cooler; *9* — branches of thermoelectric material of *n*- and *p*-type conductivity; *10* — switching plates; *11* — electrical insulating plates

Table 1. **Requirements for Thermoelectric Cooler of X-Ray Detectors**

Parameters	Value
Dimensions of detector's cooling plate, mm	10 × 10
Total thickness of the module, mm	7 ± 5
Heat accumulation, mW	3
Operating temperature range, °C	from –70 to +20
Supply voltage, V	5
Supply current, A	0.7

Table 1 shows the conditions that shall be met by the thermoelectric cooler to be designed.

MATHEMATICAL AND COMPUTER DESCRIPTION OF PHYSICAL MODEL

The system of equations for description of cooling coefficient of thermoelectric cooler depending on the parameters of physical model elements is determined based on the heat equilibrium equations:

$$Q_c = \chi_1 (T_c^{(1)} - T_c), \tag{1}$$

$$\begin{cases} Q_h = \chi_2 (T_h^{(2)} - T_h^{(1)}), \\ Q_h = \chi_3 (T_h^{(1)} - T_h), \end{cases} \tag{2}$$

$$Q_h = Q_c + W_{TE}, \tag{3}$$

where $T_c^{(1)}$ is detector surface temperature, T_c is temperature of the cool side of the thermoelectric module, χ_1 is heat interface resistance 4, $T_h^{(2)}$ is the hot side of the thermoelectric module, $T_h^{(1)}$ is temperature of detector's case framework, T_h is temperature of surface to which heat is transferred, χ_2 is heat interface resistance 5, χ_3 is heat resistance of the heat exchanger on the hot side of the thermoelectric cooler, Q_c is cold generation capacity of the thermoelectric module, Q_h is heat generation capacity, W_{TE} is wattage of the thermoelectric cooler.

Given expressions (1)—(3), the general formula for determining the cooling efficiency ratio of the thermoelectric cooler is as follows:

$$\varepsilon_r = \frac{Q_c}{W_{TE} + W_1} = \tag{4}$$

$$= \frac{\alpha I (T_c + Q_c N_1) - 0{,}5 I^2 R - \lambda (T_h - T_c - (Q_h + Q_c N_1))}{W_{TE} + W_1}$$

where α is Seebeck differential coefficient of the material, I is electric current, R is resistance of the thermoelectric module, λ is mean specific heat conductivity coefficient of thermoelectric module branches, W_1 is power consumption for heat exchange, N_1 is value that simplifies the expression for the cooling efficiency ratio and is calculated by the formula:

$$N_1 = \frac{(\chi_1 + \chi_2)}{\chi_1 \chi_2} \, . \tag{5}$$

The configuration of thermoelectric module is designed using the *COMSOL Multiphysics* [11] application package. For computation purposes, the equations of the physical models shall be presented in the clearly defined form, as shown below.

The heat and electric fluxes are described using the energy conservation law

$$div\vec{E} = 0 \tag{6}$$

and the electric charge conservation law

$$div\vec{j} = 0, \tag{7}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{8}$$

$$\vec{q} = \kappa \nabla T + \alpha T \vec{j}, \tag{9}$$

$$\vec{j} = -\acute{o} \nabla U - \acute{o} \alpha \nabla T. \tag{10}$$

In the above equations $\vec{E}$ is energy flux density, $\vec{q}$ is heat flux density, $\vec{j}$ is electric current density, U is electric potential, T is temperature, α, σ, κ are thermo-EMF (thermo- electromotive force), electric conductivity, and heat conductivity coefficients.

Given (9)—(10), the heat energy flux $\vec{E}$ can be calculated by the formula:

$$\vec{E} = -(\kappa + \alpha^2 \sigma T + \alpha U \sigma) \nabla T - \\ -(\alpha \sigma T + U \sigma) \nabla U. \tag{11}$$

In this case, the energy conservation laws (5), (6) are written as follows:

$$-\nabla[(\kappa + \alpha^2 \sigma T + \alpha U \sigma) \nabla T] - \\ - \nabla[(\alpha \sigma T + U \sigma) \nabla U] = 0, \tag{12}$$

$$-\nabla(\sigma \alpha \nabla T) - \nabla(\sigma \nabla U) = 0. \tag{13}$$

Second-order nonlinear differential equations in partial derivatives (12) and (13) determine the

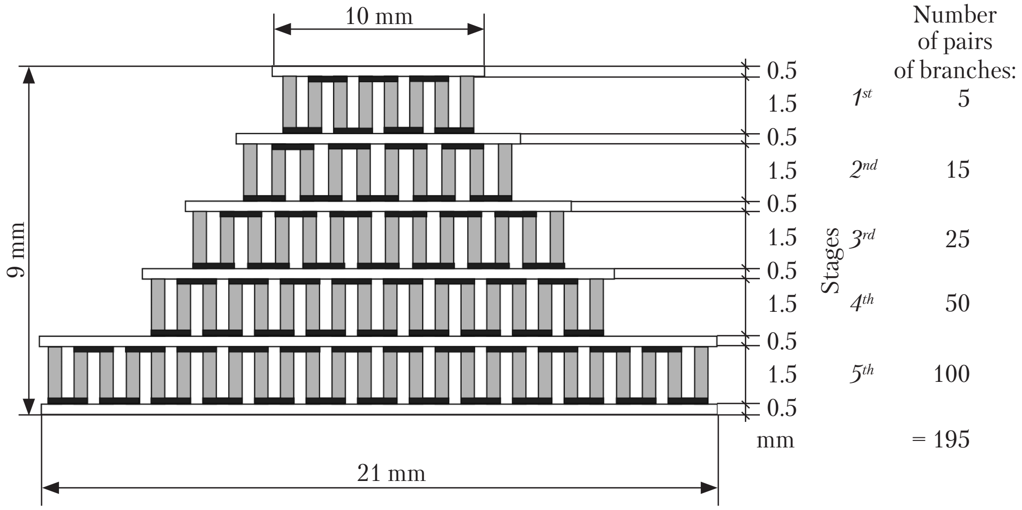

Fig. 2. Structural diagram of the designed thermoelectric cooler for the X-ray detector

temperature T and potential U distributions in the thermoelectric cooler.

The solution of these equations using the method of object-oriented computer modeling [11] and the optimal control theory [12] enables finding the optimal configuration of the thermoelectric converter and the dependence of its characteristics.

THE RESULTS OF COMPUTER MODELLING

The design of thermoelectric multi-stage module has been calculated by the method of computer modeling (Fig. 2), which provides the possibility of its use to ensure the temperature conditions of the X-ray detector (Table 2).

Based on the results of calculations, the thermoelectric cooler has 5 stages consisting of 5, 15, 25, 50 and 100 pairs of branches of thermoelectric material, its dimensions are 21 × 21 × 9 mm to provide a cooled area of 10 × 10 mm. The dimensions of the branches of thermoelectric material based on bismuth telluride (Bi_2Te_3) of n- and p-conductivity types are 1.1 × 1.1 ×1.3 mm. The electrical insulating plates shall be made of alumina oxide (Al_2O_3) and have a thickness of 0.5 mm; the copper (Cu) electrical switch shall have a 0.1 mm thick anti-diffusion layer of nickel (Ni).

Table 2. **Parameters of the Designed Thermoelectric Cooler of X-Ray Detectors**

Parameter	Value
Cold generation capacity, Q_0, mW	57
Temperature of detector’s frame, $T_c^{(1)}$, °C	–70
Temperature difference, ΔT, K	90
Cooling efficiency ratio, ε	0.02
Wattage, W, W	2.85

The estimated cold generation capacity of the thermoelectric converter is Q_0 = 57 mW (3 mW heat load from the detector and 54 mW accumulation from radiation). At a temperature on the detector $T_c^{(1)}$ = –70 °C and a heat removal temperature of T_h = +20 °C the cool efficiency ratio of the thermoelectric cooler is ε = 0.02. Respectively, power consumption of this converter is W = 2.85 W.

The obtained results have confirmed the usability of thermoelectric coolers to ensure the temperature and thermal conditions of X-ray detectors and have advantageous technical characteristics as compared with counterparts [10].

Thus, the computer design of the thermoelectric cooler for X-ray detectors has made it possible to calculate the configuration and characteristics of the thermoelectric cooler as part of X-ray detector. The designed element contains 5 cascades of thermoelectric material based on Bi_2Te_3, has dimensions 21 × 21 × 9 mm, and provides a cooled area of 10 × 10 mm. Its wattage is $W = 2.85$ W; it ensures a temperature of the detector frame $T_c^{(1)} = -70$ °C and $\Delta T = 90$ K, at a cooling efficiency ratio $\varepsilon = 0.02$.

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Received 04.12.18
Revised 28.02.19
Accepted 01.03.19

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ТЕРМОЕЛЕКТРИЧНІ ОХОЛОДЖУВАЧІ ДЛЯ РЕНТГЕНІВСЬКИХ ДЕТЕКТОРІВ

Вступ. Рентгенівські методи широко використовують для неруйнівних мікроаналітичних досліджень структури та складу матеріалів з високою просторовою роздільною здатністю. Подальше збільшення цього показника суттєво залежить від покращення аналітичних характеристик напівпровідникових детекторів, а також від застосування широкоапертурних позиційно чутливих детекторів випромінювання нових типів.

Проблематика. Роздільна здатність рентгенівських детекторів суттєво залежить від температурного режиму їхньої роботи, що забезпечується використанням термоелектричних охолоджувачів. Однокаскадні термоелектричні охолоджувачі (ТЕО) застосовують для неглибокого охолодження (до 250 К), тоді як для охолодження сенсорів до робочої температури 230 К використовують двокаскадні ТЕО, до 210 К — трикаскадні, а для охолодження нижче 190 К — чотири- та п'ятикаскадні ТЕО.

Мета. Проєктування та оптимізація конструкції термоелектричного багатокаскадного охолоджувача детектора рентгенівського випромінювання.

Матеріали й методи. Методи комп'ютерного об'єктно-орієнтованого проєктування та методи теорії оптимального керування, адаптовані до використання для термоелектричного перетворення енергії. Для створення термоелектричних модулів охолодження використано матеріали на основі телуриду вісмуту (Bi_2Te_3) n- та p- типів провідності.

Результати. Розрахунки конструкції термоелектричного охолоджувача у складі детектора рентгенівського випромінювання показали оптимальну електричну потужність термоелектричного перетворювача W = 2,85 Вт, що при холодильному коефіцієнті $\varepsilon = 0{,}02$ забезпечує температуру основи детектора $T_c = -70$ ° C та $\Delta T = 90$ K, що є оптимальними умовами для роботи детекторів рентгенівського випромінювання та дозволяють значно підвищити їхню роздільну здатність при мінімальних затратах електричної енергії.

Висновки. Наведено розрахунки забезпечують оптимальні режими роботи детектора рентгенівського випромінювання, а комплексне дослідження та оптимізація зазначеного пристрою підтвердили результат. Отримані дані можна застосовувати для створення приладів з підвищеною роздільною здатністю.

Ключові слова: комп'ютерне проєктування, термоелектричне охолодження, рентгенівський детектор.