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Article

A new structure of thin-film thermoelectric generators

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ABSTRACT

The development of thin-film thermoelectric generators (TEG) is hampered by the lack of a new approach to their design. A new structure of thin-film TEGs has been proposed. The new structure is made by inverting flat thermocouples of the same name each other, generating electricity from adjacent rows of electrical circuits with the formation of narrow zones between the junctions on the substrate of each layer of a plurality of layers. Formed uniform alternation alternately areas of hot and cold junctions of thermocouples, which are connected in series in electrical circuits located on the substrate of each layer in uniform and parallel rows. The heat flow is brought to the areas of hot junctions, and heat is removed from the areas of cold junctions, respectively, by elements of the heat supply and heat removal circuits. The average temperature difference between hot and cold junctions is more than 100 ℃, which increases the thermo electromotive force. TEG ensures the achievement of several tens of kW of power. The new TEG structure makes it possible to fabricate thermocouples and substrates on the nanoscale.

1. Introduction

One of the alternative energy sources is thermoelectric generators (TEG), which convert heat flow into electrical energy. Thermoelectric conversion of heat flow based on the Seebeck effect has been known for 200 years. The Seebeck effect is that in a closed circuit consisting of dissimilar conductors, a thermo electromotive force arises if the contact points (junctions) are maintained at different temperatures. For two hundred years, a large number of technical solutions have been proposed to improve individual elements of the TEG. These solutions are mainly associated with the implementation of thermocouples in bulk or planar (flat), cascading, supplying heat flow to the junctions of the thermocouples in vertical, horizontal (lateral), and mixed ways, and choosing more efficient thermoelectric materials. Bulk TEGs are characterized by the fact that there is a common surface for supplying heat flow to the hot junctions of the thermocouples and the same surface for removing it from the cold junctions, which are in close contact with the hot and cold junctions, respectively. The heat flow from the common surface, which is in close contact with the heat source, passes to the hot junctions and through the legs to the cold junctions and is removed from the common surface to the environment. Cascading is used to improve the efficiency of bulk TEGs. The heat flow removed from the previous cascade is transferred to the next one, and these cascades have different temperature zones. Thermoelectric elements are selected accordingly for each cascade with its operating temperature. For bulk TEGs, the heat flow is applied vertically. The planar arrangement of thin-film TEGs became possible with the development of technology for their implementation by deposition, sputtering, photolithography, etching, etc. on substrate surfaces. For thin-film TEGs, the heat flux is supplied to the surface of hot junctions and removed from the surface of cold junctions by all the above methods. Thermocouples are connected in series with each other, and hot and cold junctions alternate. It is possible to regulate the length and thickness of the legs of thermoelectric elements, which can improve the supply and removal of heat from the junctions. Thin-film TEGs use several superimposed layers, each of which is thermocouples substrate. Thermocouples are connected in series in continuous electrical circuits. Cascading volumetric and increasing the number of thin-film layers increases the efficiency of the TEG. Comparison of the generated thermo electromotive force with respect to the heat flux shows that the efficiency of bulk

TEGs is noticeably higher than thin-film ones both in terms of generated power and in terms of conversion efficiency. The advantage of bulk TEGs in terms of conversion efficiency is especially noticeable. The problems of thin-film TEGs are the search for new, more efficient thermoelectric materials and the use of special structures [1]. Despite the excess of some indicators of bulk TEGs with comparable indicators of thin-film TEGs, bulk TEGs have practically exhausted the possibilities for further development. For consumers of high power from several tens to several hundreds of kW, in the future, there will be no question of choosing bulk or thin-film TEGs. The application and development of thin-film TEGs have greater opportunities for improving work efficiency. In this regard, let us consider known technical solutions aimed at improving thin-film TEGs.

2. Background

The works [1, 2] show the design of a thin-film TEG, which consists of two shaped halves, each of which is made of p- and n-type thermoelectric material, respectively. A layer of thermoelectric material is deposited on the substrate surface by sputtering (photolithography, etching). The layer with p- and n-type thermoelectric elements are superimposed on each other and connected by soldering. The vertical supply and removal of heat from the surface of the substrates with fuel cells is carried out. The temperature difference between the hot and cold junctions of TEG thermocouples is insignificant due to the close location of these junctions, and the generated thermo electromotive force is low. The TEG design [2] presents a planar arrangement of thin-film thermoelectric elements on substrates, which makes it possible to change the thickness and length of thermoelectric elements legs on substrates. In this case, the heat flow is supplied in a lateral way, which does not provide a sufficient temperature gradient between the junctions. Patent [3] proposes a thin-film TEG containing substrates, on which, for example, by film casting, parallel strips of p- and n-type are deposited, separated by a strip of insulating material. Substrate with parallel stripes p - and n-type are made in the form of a roll. Such a TEG solution contributes to an increase in the fuel cell placement density. For a roll-type TEG, only the lateral supply and removal of the heat flux is possible, which limits the temperature difference between the hot and cold junctions of thermocouples. A multilayer thin-film TEG was proposed [4], in which the surfaces of the mating substrates are alternately covered with Z-shaped strips of p- and n-type thermoelectric elements foil and superimposed on each other, forming one thermocouples layer. Next, another layer is superimposed on this layer, and the successive superimposition of layers makes it possible to obtain a multilayer thin-film TEG. The lateral supply and removal of the heat flow for this multilayer TEG is carried out, resulting in a low-temperature gradient between the junctions. A TEG with thin-film p- and n-elements located between warm and cold temperature sources was proposed [5]. The execution of the thermocouples layer is possible as a single layer due to heat transfer in the direction perpendicular to the layer plane. The temperature difference is insignificant, which means that the generated thermo electromotive force is small and the efficiency of the TEG is low. The thermoelectric converter [6] contains thermoelectric cells with thermoelectric film legs connected in series, which are made of semiconductor materials and are located between the heat exchange layers. The space between the heat exchange layers and thermoelectric legs is filled with an insulator. It is difficult to make a transducer based on this technical solution as a multilayer one because heat exchange takes place between thermocouple junctions, which are separated by an insulator. Heat transfer in a multilayer arrangement does not allow a high temperature gradient to be obtained. Therefore, the efficiency of the thermoelectric module is low. The thermoelectric module [7] consists of semiconductor elements of p- and n-type conductivity, which are connected in an electric circuit in series in alternating order. In this case, the p-type and n-type thermoelectric elements are made on different sides of the dielectric substrate, and the legs of the thermocouples are applied to the substrate by the screen-printing method. With such an arrangement of thermocouple junctions, it is difficult to make and superimpose other layers of thermocouples and the possibility of heat transfer between the layers. The efficiency of the module is low due to the insignificant generation of thermo electromotive force. In the technical solution [8], the thermoelectric battery consists of alternating legs connected in series into an electrical circuit made of semiconductor p- and n-type materials. The electrical connection of the junctions of the legs is carried out using connecting plates. The placement of battery thermocouples is carried out in one layer. The thermoelectric battery can operate in the mode of generating thermal energy or in the mode of generating electricity. Heat transfer is carried out efficiently through a single layer of thermocouples. With multilayer execution, the temperature difference between the junctions is insignificant, and the efficiency of the batteries is low. The thermoelectric converter [9] contains a battery formed by series-connected thermocouples. Each thermocouple is made in the form of a three-layer panel with superimposed layers, a hot junction, legs, and a cold junction. The junctions are located over the entire surface of a pair of legs and are separated from each other by a dielectric insert. The cold junction of each thermocouple is divided into two parts by a dielectric insert. Thermocouples are formed in the form of a multilayer structure containing three-layer panels of series-connected thermocouples superimposed on each other with an offset. The three-layer panel is formed by successive sputtering or electrolysis of layers. When the panels are stacked on top of each other, the heat flow passes through three layers, which leads to heat loss. The temperature difference in the junctions of thermocouples is within fractions of degrees, which reduces the thermo electromotive force. A review of thin-film TEGs shows that attempts have been made to increase the density of thermocouple elements within a known structure. The well-known structure of thin-film TEGs is based on the planar arrangement of the thermocouples on the substrate and the connection in series in an electrical circuit. To increase the density of the thermocouples arrangement, one thermocouples layer on the substrate is superimposed on another similar layer. Thermoelectric materials have been proposed [1, 2] with the best values of thermoelectric figure of merit, such as tin selenide (SnSe), bismuth telluride (Bi_2Te_3), antimony telluride (Sb_2Te_3), etc.

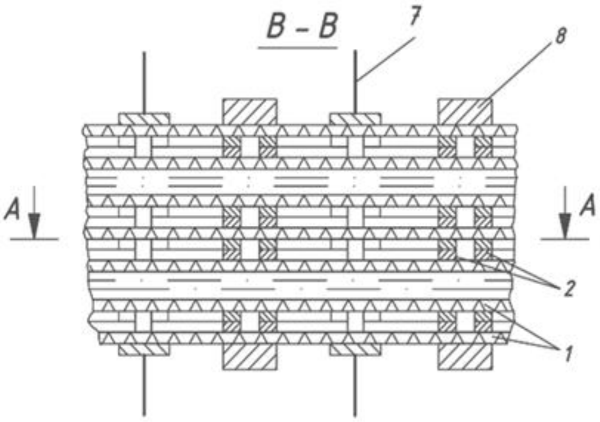
However, the traditional arrangement of thermocouples on substrates and methods of heat flux supply, regardless of the number of superimposed thermocouples layers, did not increase the efficiency of heat transfer to hot junctions. As a result, the temperature difference between the junctions is negligible. Improvement affecting individual elements, rather than the structure as a whole, did not lead to a cardinal improvement in the efficiency of thin-film TEGs. The calculation of the parameters of thin-film TEGs with elements in nano sizes has its own peculiarities. Thus, the known structure of thin films hampers the development of TEG potential for more powerful applications. In this regard, the solution to the problem of a significant increase in the efficiency of thin-film TEGs is very important.

3. Discussion

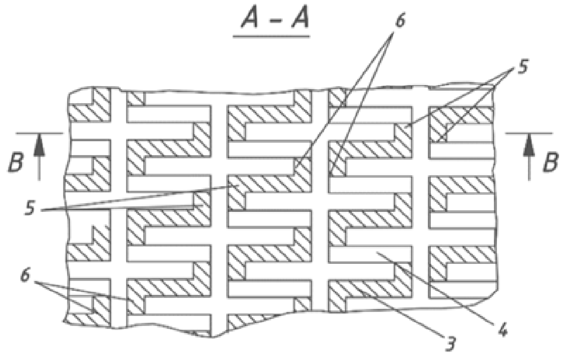
A new structure of thin-film TEGs was proposed [10, 11]. The new structure is made by inverting flat electricity-generating thermocouples of the same name to each other from adjacent rows of electrical circuits with the formation of narrow zones between the junctions on the substrate of each layer of a plurality of layers. Formed uniform alternation alternately areas of hot and cold junctions of thermocouples, which are connected in series in electrical circuits located on the substrate of each layer in uniform and parallel rows. The heat flow is brought to the areas of hot junctions, and heat is removed from the areas of cold junctions, respectively, by parallel metal strips of the external heat-supplying and parallel metal thin ribs of the heat-removing circuits.

All layers with thermocouples are superimposed on each other by tight contact, which ensures the coincidence of the areas of hot junctions and areas of cold junctions in all layers, respectively. In this case, the parallel strips are in contact with the outer substrate, which protects the upper layer of thermocouples along the entire length of a number of electrical circuits in the areas of thermocouple hot junctions. Parallel ribs contact the lower substrate of the lower layer of thermocouples along the entire length of the row of electric circuits in the areas of cold junctions of thermocouples. Heat is supplied from a solar collector in the form of a parabolic mirror tray to concentrate sunlight on its focal line, along which a rod-shaped metal receiver is installed rigidly connected to the strips, or from an external heat source by contacting the strips with their outer sides with elements of this source. The transfer of heat from the strips to the areas of hot junctions occurs by thermal conductivity, the removal of heat from the regions of cold junctions - by thermal conductivity and convection. Forced cooling of thin ribs is provided. The location of electricity-generating thermocouples on the substrate of each layer in a package of thin-film TEG is shown in Figure 1.

Thermocouples are made of inexpensive dissimilar metals (for example, copper-constantan), which is justified for a TEG consisting of many layers with thermocouples. Also, the most common semiconductor materials (for example, chromel - alumel) can be used as materials for TEG thermocouples. Elements of p-type 3 and n-type 4 electricity-generating thermocouples are overlapped 2 on the substrate 1 of each layer, which significantly increases the surface contact area of the p-n junction and reduces the thermal resistance of the junction.



(a)



(b)

Figure1. The layout of electricity-generating thermocouples on the substrate of each layer in a thin-film TEG package: a) a section along the plane B - B; c) section along the plane A-A; 1 - substrates; 2- overlapping p- and n-type thermocouple elements in the junction; 3-p-type thermocouple element; 4-n-type thermocouple element; 5-hot junctions of thermocouples facing each other with the same name; 6 - cold junctions of thermocouples facing each other with the same name; 7- heat-removing ribs; 8 - heat-carrying strips

The substrates 1 of electricity generating thermocouples layers and the outer substrate of the upper electricity-generating thermocouples layer are thin films providing dielectric and thermal conductivity over a wide temperature range, which are made of a material such as aluminum nitride (AlN) by pyrolysis. A rod-shaped metal receiver located along the focal line of the collector is heated under the influence of focused sunlight. The receiver heating temperature can reach more than 300 °C, respectively, parallel metal strips 8 are heated (Figure 1). The heated strips 8, which are in contact with the protective outer substrate, transfer heat to the hot junctions 5 of adjacent rows of circuits by thermal conductivity due to the tight contact of the substrate 1 of the junctions 5 of all layers with each other. The heat from cold junctions 6 of thermocouples of adjacent rows of electrical circuits of all layers that are in close contact with each other is removed by thin ribs 7 that are in close contact with the substrate of the lower layer to the environment. Heat transfer from the areas of cold junctions of all layers to the environment is carried out due to thin metal ribs 7 by thermal conductivity and convection. Strips 8 and ribs 7 are provided on both sides of the package at the same time, or strips 8 are installed on the outer upper surface of the package and ribs 7 on its outer lower surface. Junctions 5 and opposite junctions 6 of thermocouples of adjacent rows of circuits face each other on each layer. Junctions 5 are in the heating area, and junctions 6 are in the cooling area.

During heat transfer from the strips to 8 areas of hot junctions 5 thermocouples and heat removal from areas of cold junctions 6 thermocouples by ribs 7, the average temperature difference between hot 5 and cold 6 junctions is sufficiently high: more than a hundred degrees Celsius. Due to the temperature difference between junctions 5 and 6, located respectively in opposite areas of heating and cooling, in thermocouples, according to the Seebeck effect, a thermo electromotive force is generated. The thermo electromotive force generated by thermocouples is directly proportional to the temperature difference between the junctions, so the efficiency of TEG conversion of thermal energy into electrical energy is significant. Thin-film TEG in its structure also contains at least one layer of thermal energy thermocouples, including a substrate and flat thermal energy thermocouples located on it, which are connected in series in electric circuits forming uniform and parallel rows. The layer is placed between the layers of electricity-generating thermocouples. The supply of thin-film TEG with a layer of thermal energy thermocouples and their location between the layers of electricity-generating thermocouples contributes to the additional generation of thermal energy. The need for additional thermal energy of TEG arises in case of insufficient sunlight or changes in the operating mode of thermal external sources. The generation of additional thermal energy ensures the stability of the TEG operation. The location of electricity-generating thermocouples and thermal energy thermocouples on the substrate of each layer in the package of thin-film TEG is shown in Figure 2.

When all layers are superimposed on each other by close contact, the areas of hot junctions 5 and the areas of cold junctions 6 of electricity-generating thermocouples of adjacent rows of electrical circuits coincide respectively with hot junctions 11 and cold junctions 12 of thermal energy thermocouples of rows of electrical circuits, which ensures internal heat exchange between them. The thermal energy thermocouples elements 9 and 10 are overlapped on the layer substrate. The electrical circuits of the layer are connected to an external current source. The mode of transition to the production of thermal energy is carried out according to the indication of the temperature sensor, if it is below a certain value. The temperature sensor is placed on one of the parallel strips 8. The control and distribution unit (not shown) issues a command to connect the electrical circuits of thermal energy thermocouples to the battery. According to the Peltier effect, when an electric current passes, depending on its direction, some junctions of thermocouples heat up, while other junctions cool down. The control and distribution unit is configured so that the hot junctions of thermal energy thermocouples generate heat and their cold junctions cool. The rechargeable batteries are periodically charged with a part of the generated electrical energy of the TEG in the mode of operation using solar energy or an external heat source.

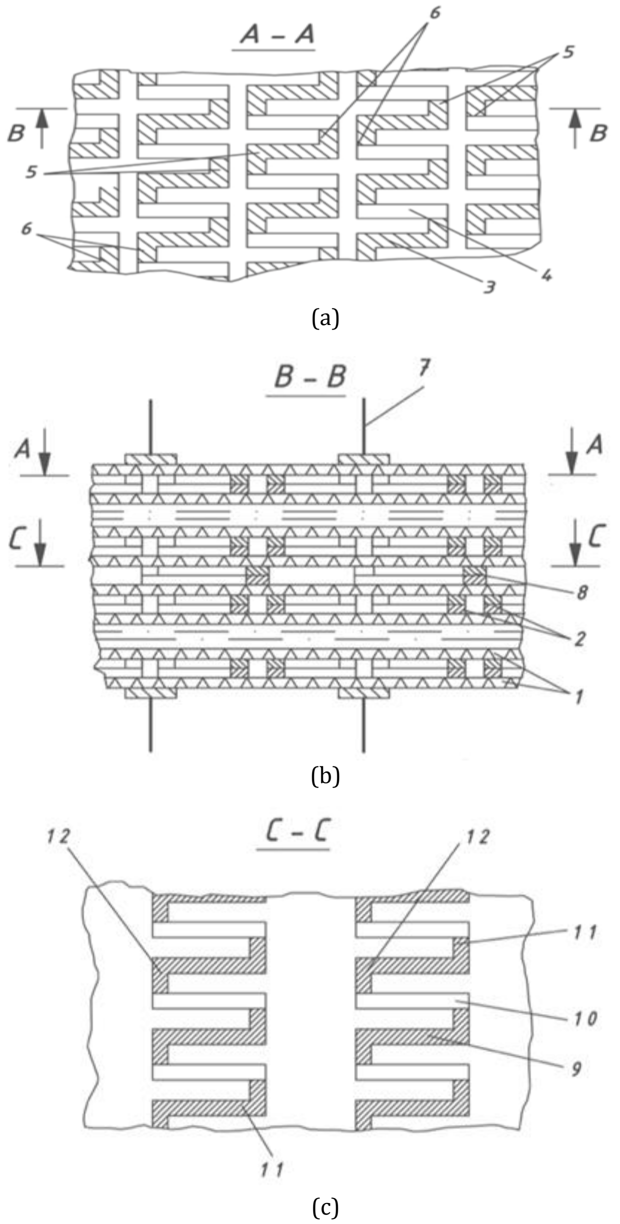


Figure 2. The layout of electricity generating thermocouples and thermal energy thermocouples on the substrate of each layer in a package of thin-film TEG: a) a section along the plane B - B; c) section along the plane A-A; c) section along the C-C plane; 1- substrates; 2- overlapping p- and n-type elements of electricity generating thermocouples in the junction; 3-p-type thermocouple element generating electricity; 4- n-type thermocouple element generating electricity; 5- same-named hot junctions of thermocouples that generate electricity facing each other; 6- same-named cold junctions of thermocouples that generate electricity facing each other; 7- heat-removing ribs; 8- heat supply strips; 9- p-type element of thermal energy thermocouples; 10- n-type element of thermal energy thermocouples; 11- hot junctions of thermal energy thermocouples; 12- cold junctions of thermal energy thermocouples.

When connecting the electrical circuits of thermal energy thermocouples to an external constant current source, hot junctions 11 heat the areas of hot junctions 5 of electricity-generating thermocouples, and cold junctions 12 cool the areas of cold junctions 6 (Figure 2).

Heat is removed from the junctions 12 of the layer of thermal energy thermocouples, which are in close contact with the layers of electricity generating thermocouples, and hence from the areas of cold junctions 6, is carried out by means of thin metal ribs 7 of the heat-removing circuit. When all layers are superimposed by close contact with each other, internal heat transfer occurs. The heat from hot junction 11 of thermal energy thermocouples is transferred to all areas of hot junction 5 by thermal conduction, and heat from cold junctions 12, which are in close contact with areas of cold junctions 6, is removed by ribs 7 to the environment by thermal conductivity and convection. The number of layers of thermal energy thermocouples placed between the layers of electricity-generating thermocouples is provided for more than one layer. Due to the temperature difference in junctions 5 and 6 of each thermocouple, thermo electromotive force is generated, and when the series-connected electrical circuits of thermocouples are closed, an electric current arises. As materials for thermal energy thermocouples of TEG, the same materials are used for electricity-generating thermocouples and are made in the form of thin films.

4. Conclusion

The proposed new TEG structure ensures the mutual arrangement of flat thermocouples on a thin-film substrate of each layer with the formation of areas of hot and cold junctions, to which heat is efficiently supplied and removed, respectively. This facilitates the stacking of a plurality of such layers into a package. The TEG efficiency increases significantly, and several tens of kW of power can be achieved. The electricity generated is sufficient to power powerful applications. Obtaining an output power of up to several tens of kW allows the use of a new generation TEG as the main source of electrical energy when the use of standard sources is difficult or impossible, especially for consumers remote from the power grid. In this case, the output power can be selected depending on the required power of applications. It can be used as an energy source in various fields: automotive industry (the main source of electricity is an electric car), energy (power supply for small industries, agricultural farms, households), electronics (an energy source for electronic devices and gadgets), oil and gas (electrochemical protection stations for main pipelines), space (source of energy for flying orbital artificial objects), marine (an additional source of energy for submarines), etc. Due to compactness, small overall dimensions, flexibility, TEGs can be placed in any spatial niche. TEG adapts to any shape of the surface of the heat source: flat, cylindrical, elliptical, parabolic, etc. The proposed TEG pushes the boundaries of the use of an autonomous source of electricity as the main source in the above areas. Especially promising is the use of TEG in electric cars, power supply, and various electronic devices. Electric current is carried in a nano-sized conductor by electrons, which form an "electron gas" inside the conductor, and electrical conductivity exhibits wave properties. During the passage of current in the conductor, "Joule heat" is not released, and heat conduction is carried out due to "ballistic conduction" and does not depend on the length and thickness of the thermocouple elements; the known formulas of electrical engineering are not applicable to calculate the electrical resistance. Determining the parameters of thin-film TEGs is a task for a separate study.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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