

*Проведено дослідження, спрямовані на оптимізацію конструкції мікромодулів на основі фотоелектричних перетворювачів ITO/CdS/CdTe/Si/Au, використовуваних в автономних установках електропостачання польових таборів. Встановлено, що послідовне з'єднання одиничних сонячних ITO/CdS/CdTe/Si/Au в мікробірці забезпечує стабільність роботи фотоелектричного перетворювача навіть за умови виходу з ладу одного або декількох одиничних сонячних елементів. Отримано експериментальні зразки мікромодулів з ККД 5,3 %*

*Ключові слова: плівковий фотоелемент, мікромодуль, електрична комутація, сонячний елемент, телурид кадмію, вольт-амперна характеристика*

*Проведены исследования, направленные на оптимизацию конструкции микромодулей на основе фотоэлектрических преобразователей ITO/CdS/CdTe/Si/Au, используемых в автономных установках электроснабжения полевых лагерей. Установлено, что последовательное соединение единичных солнечных ITO/CdS/CdTe/Si/Au в микросборке обеспечивает стабильность работы фотоэлектрического преобразователя даже при условии выхода из строя одного или нескольких единичных солнечных элементов. Получены экспериментальные образцы микромодулей с КПД 5,3 %*

*Ключевые слова: пленочный фотоэлемент, микромодуль, электрическая коммутация, солнечный элемент, теллурид кадмия, вольт-амперная характеристика*

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# INVESTIGATION OF THE COMBINATION OF ITO /CdS /CdTe /Cu / Au SOLAR CELLS IN MICROASSEMBLY FOR ELECTRICAL SUPPLY OF FIELD CABLES

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## 1. Introduction

The fulfillment of tasks in a state of emergency, in zones of armed conflicts, in the elimination of catastrophes and natural disasters, usually takes place outside the points of permanent deployment. Solving such problems requires the deployment of mobile field camps, with a developed infrastructure and autonomous power supply.

At the moment, diesel generators and diesel power plants based on them are used as autonomous power plants. However, they have significant drawbacks, among which can be identified: a large consumption of organic fuel, low resource, high operating costs and non-environmental, but at the moment there is no full replacement. Among the most promising alternatives to existing autonomous power supply systems are autonomous power plants equipped with renewable energy sources. As shown in [1], as renewable energy sources, it is advisable to use both photoelectric converters (PEC) and wind turbines, as well as their combinations.

Therefore, it is relevant to study PEC, intended for use in autonomous power plants for field camps.

## 2. Literature review and problem statement

As a renewable source of energy for use in self-contained power plants, film photoelectric converters based on CdS/CdTe are considered. PECs based on CdS/CdTe represent an alternative to conventional silicon photoelectric converters [2]. Modern high-performance CdS/CdTe film-based PECs are fabricated in a rear configuration on a glass substrate. Solar radiation enters the base layer through a transparent glass substrate [3, 4].

The width of the forbidden zone of cadmium telluride, which is 1.46 eV [5], is best adapted to the transformation of solar energy in terrestrial conditions [6]. The light absorption coefficient of cadmium telluride for the visible range exceeds  $10^5 \text{ cm}^{-1}$  [7]. Thus, a layer of CdTe only a few micrometers thick provides almost complete absorption of the incident light flux [8]. This allows the creation of instrument structures based on CdTe, which are characterized by low material capacity [9]. The technology of producing CdS/CdTe films is rapidly reproducible and allows the formation of uniform thin films with an area of more than  $1 \text{ m}^2$ . In ad-

dition, CdS/CdTe-based PECs have the highest efficiency among unconverted PECs – 29 % [10].

To use PECs as power sources, they are combined into micromodules and modules. PECs in a micromodule is connected both in series and in parallel. The efficiency of the whole micromodule depends on the PEC efficiency, which is part of its composition. With a series connection of a photocell, the current flowing through the micromodule can't accustom the current from the "bad" element. The resulting voltage of the micromodule can be found by adding up the voltages on each element that is included in its composition. With a PECs parallel connection, the resulting current of the micromodule is equal to the sum of the currents from each element, and the voltage is reduced by the "bad" element. Therefore, it is necessary to determine the optimal method for connecting the CdS/CdTe-based PECs in the micromodule composition, as well as the contribution of the output parameters of the "bad" element to a decrease in the efficiency of the instrumental structure as a whole.

### 3. The aim and objectives of research

The aim of research is investigation of the optimal scheme for connecting ITO/CdS/CdTe/Cu/Au photovoltaic converters in a microassembly for use in stand-alone power plants for field camps.

To achieve this aim, it is necessary to solve the following tasks:

- to determine the scheme of electrical commutation of photoelectric converters ITO/CdS/CdTe/Cu/Au;
- to test instrument structures based on CdS/CdTe in the composition of micromodules.

### 4. Materials and methods for studying the output parameters of photoelectric converters ITO/CdS/CdTe/Cu/Au

#### 4. 1. Materials and equipment used to produce micromodules made from photoelectric converters ITO/CdS/CdTe/Cu/Au

Micromodules with parallel and series connection of solar cells based on CdS/CdTe are investigated. For their manufacture, a system of masks is developed and manufactured (Fig. 1). The production of solar cells based on CdS/CdTe is carried out by the method of thermal vacuum evaporation in a single technological cycle according to the procedure described in [11].

The application of ITO films (indium and tin oxides) is carried out by the method of non-reactive magnetron sputtering using direct current using a mask without separation into individual electrodes. The preparation of isolated frontal contact pads is carried out by scrubbing. This approach is due to the magnetron layer formation technology, in which it is impossible to form sharp layer boundaries. For the deposition of a layer of sulphide and cadmium telluride, the same mask is used, since the deposition of these layers was carried out in a single technological cycle without disturbing the vacuum.

The formation of a layer of cadmium chloride is carried out using smaller masks. This is due to the fact that layers of cadmium telluride are used as the dielectric layers, to which the layer of cadmium chloride is not applied. Consequently,

they are not subjected to a "chloride" treatment, in which the series resistance decreases. At the final stage, the rear Cu/Au contacts are formed.

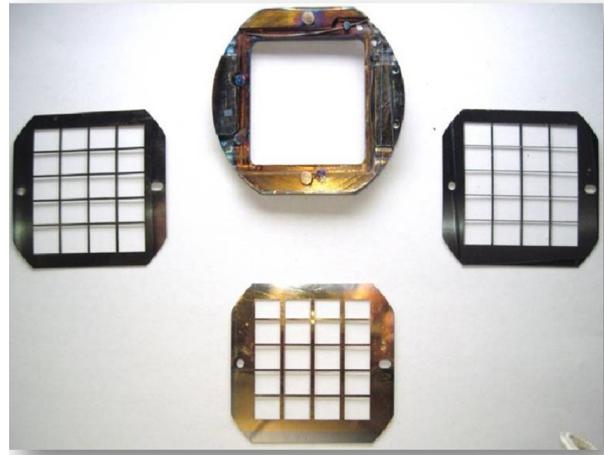


Fig. 1. Photographs of the mask system for manufacturing a micromodule

Each micromodule consists of five solar cells, which are connected in parallel or in series. The size of the micromodule, as well as the number of solar cells in it, is determined solely by the design of the working volume of the apparatus for obtaining laboratory samples. There are 4 described micromodules on the glass substrate (Fig. 2).



Fig. 2. Appearance of the module

Instrument structures with parallel (M2, M4) and sequential (M3, M5) solar cell connections in a micromodule are fabricated.

#### 4. 2. Method of measurement and analytical processing of light current-voltage characteristics

The output parameters of the solar cells (SC) are the short-circuit current density ( $J_{sc}$ ), the open circuit voltage

( $V_{oc}$ ), the filling factor (FF) of the light current-voltage characteristic (CVC) and, ultimately, the efficiency. According to the equivalent SC scheme (Fig. 3), the quantitative characteristics of photoelectric processes are the light diode characteristics: the photocurrent density ( $J_p$ ), the density of the diode saturation current ( $J_0$ ), the diode ideality coefficient ( $A$ ), the series resistivity ( $R_s$ ) and the shunt resistor ( $R_{sh}$ ), which are calculated per unit area of the solar cell. The relationship between the efficiency of solar cells with light diode characteristics in an implicit form is described by the theoretical light SC CVC [12]:

$$J_l = -J_p + J_0 \{ \exp[e(V_l - J_l R_s) / (A k T)] - 1 \} + (V_l - J_l R_s) / R_{sh}, \quad (1)$$

where  $J_l$  – the current density flowing through the load,  $e$  – the electron charge;  $k$  – the Boltzmann constant,  $T$  – the temperature of the solar cell;  $V_l$  – voltage drop on the load.

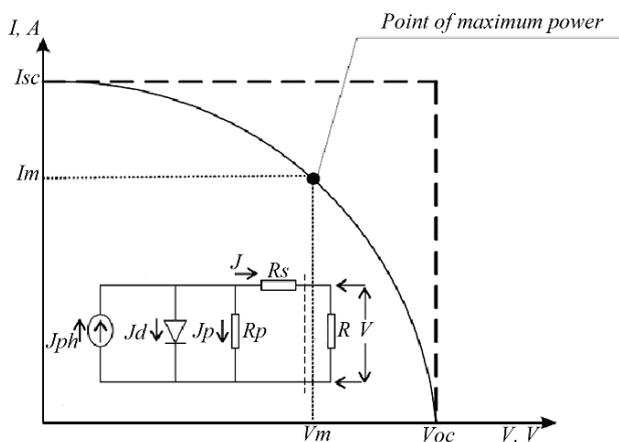


Fig. 3. The current-voltage characteristic and the equivalent circuit of a solar cell with a measuring circuit connected to it [12]

CVC is the most important characteristic of the solar cell, since it determines the efficiency of conversion of the energy of solar radiation into electric power - the efficiency of the solar cell ( $\eta$ ) [13, 14]:

$$\eta = \frac{P_m}{P} = \frac{FF J_{sc} U_{oc}}{P}, \quad (2)$$

where  $P$  – the power of the radiation incident on the SC,  $P_m$  – the maximum output power of the SC, FF – CVC filling factor,  $I_{sc}$  – the short-circuit current, and  $I_{oc}$  – the idling voltage,

$$FF = \frac{I_m U_m}{I_{sc} U_{oc}}, \quad (3)$$

where  $I_m$  and  $U_m$  – the current value and the voltage corresponding to the point of maximum power  $P_m$ .

Measurements of the light CVCs are carried out by the compensation method in a steady-state irradiation mode close to the standard AM1.5 using a universal LED illuminator USO-2 [15], which is installed in a laboratory installation. A general view of this device is shown in Fig. 4.

Along with the USO-2, this installation includes: a stable constant current source TEC 88, a stabilized direct current source HUAYI Electronics HY3020MR, two mul-

timeters MASTECH MS8040. The installation scheme is complemented by a resistive voltage divider to provide a step change in voltage (in the measuring circuit – 0.01 V, at the input of the divider – 0.1 V), as well as the store of reference resistances P-33. The use of this laboratory facility makes it possible to investigate solar cells with a large degree of approximation to terrestrial solar spectra and standard conditions for attestation of laboratory PEC samples. Analytical processing of light CVCs of investigated PECs is carried out with the help of a computer using the method described in [16].

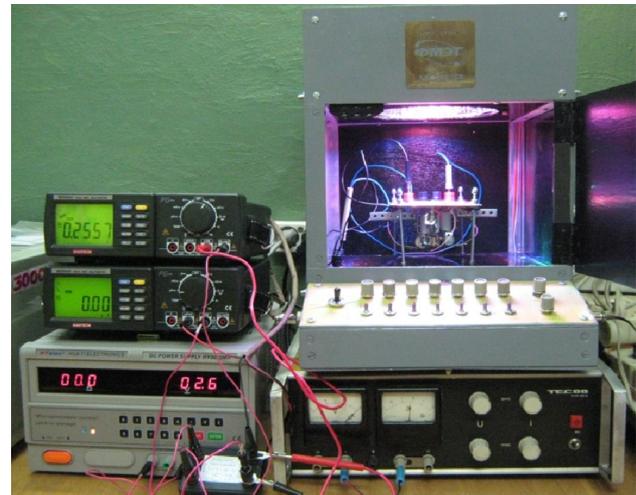


Fig. 4. General view of the mounted installation for measuring the compensating method in a steady-state mode of irradiating the light CVC of test PECs samples [15]

### 5. Results of the investigation of light CVCs of micromodules

The analysis of the output parameters of the ITM/CdS/CdTe/Cu/Au micromodules measured for each module with parallel and series connection of the elements shows the following results. When the elements are connected in series, the efficiency of the micromodules is higher and reaches a maximum efficiency of 5.3 % for the micromodule M5\_3. As can be seen from Tables 1, 2, this value is due to higher open circuit ( $V_{oc}$ =3572 mV) compared to the micromodule M5\_1 ( $V_{oc}$ =2449 mV). With the parallel connection of solar cells, the maximum value of the efficiency of the micromodule is 2.4 %, which is almost 2 times lower than when the same solar cells are connected in series.

Table 1

The output parameters of the ITO/CdS/CdTe/Cu/Au micromodules with the parallel connection of solar cells

Micromodule	$V_{oc}$ , mV	$J_{sc}$ , mA/cm <sup>2</sup>	FF	Efficiency, %
M4_1	740	9,6	0,25	1,8
M4_2	595	10,2	0,26	1,6
M4_3	530	8,1	0,27	1,2
M4_4	660	7,2	0,30	1,4
M2_1	660	13,5	0,27	2,4
M2_2	612	12,1	0,26	1,9
M2_3	613	11,5	0,27	1,9
M2_4	608	12,3	0,30	2,2

Table 2

The output parameters of the ITO/CdS/CdTe/Cu/Au micromodules with the series connection of solar cells

Micromodule	$V_{oc}$ , mV	$J_{sc}$ , mA/cm <sup>2</sup>	FF	Efficiency, %
M3_1	3172	2,3	0,45	3,3
M3_2	3184	2,2	0,45	3,2
M3_3	3077	2,3	0,43	3,1
M3_4	2265	2,7	0,33	2,0
M5_1	2449	2,8	0,59	4,0
M5_2	3489	2,7	0,39	3,7
M5_3	3572	2,8	0,54	5,3
M5_4	3052	2,1	0,56	3,5

It is assumed that the low value of  $V_{oc}$  for the micromodule M5\_1 is due to shunting the solar cells in the micromodule. According to [3], the value of  $V_{oc}$  is limited by the value of the potential barrier and decreases with increasing recombination rate. To confirm the assumption, let's analyze the output parameters and the light diode characteristics of the individual solar elements of the modules M5\_1 and M5\_3. The design of the micromodule, in which the solar cells are connected in series, makes it possible to measure their output parameters.

In the first micromodule (M5\_1) there are two practically shunted solar cells. The second micro-module (M5\_3) had one PEC with a significantly lower efficiency.

The light CVCs of micromodules, measured at a luminous flux of 100 mW/cm<sup>2</sup> and with a series connection of solar cells, are shown in Fig. 5, 6.

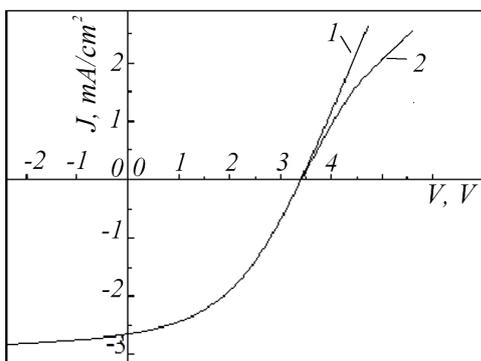


Fig. 5. Light CVC of the micromodule M5\_1 in the series connection of four (1) and five (2) PECs

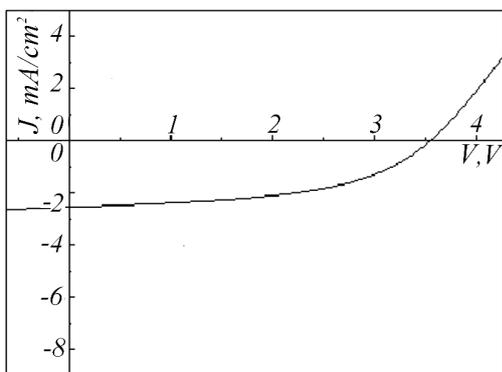


Fig. 6. Light CVC of the micromodule M5\_3 in the series connection of five PECs

The output parameters and the light diode characteristics of investigated PECs separately and when they are connected in series are shown in Tables 3, 4, where C – a single PEC, C2-C5 – micromodule M5\_1 with a series connection of four PECs, and C1-C5 – micromodule with a series connection of five PECs. The relationship between the output parameters and the light diode characteristics is described by the expression (1).

Table 3

Output parameters and light diode characteristics of the PEC micromodule M5\_1

Sample	C1	C2	C3	C4	C5	C2-C5	C1-C5
$V_{oc}$ , mV	97	748	755.5	133	752	2389	2486
$J_{sc}$ , mA/cm <sup>2</sup>	10.6	16.6	18.2	12.6	16.2	3,4	2.7
FF, r.u.	0.27	0.61	0.61	0.26	0.59	0,59	0.58
Efficiency, %	0.3	7.5	8.4	0.4	7.1	4,9	3.9
$R_s$ , Ohm×cm <sup>2</sup>	4.1	8.77	8.47	3.03	8.77	186	239
$R_{sh}$ , Ohm×cm <sup>2</sup>	9.4	498	673	808	623	7×10 <sup>3</sup>	1×10 <sup>5</sup>
$J_0$ , A/cm <sup>2</sup>	9×10 <sup>-4</sup>	5×10 <sup>-11</sup>	4×10 <sup>-11</sup>	9×10 <sup>-6</sup>	6×10 <sup>-9</sup>	2×10 <sup>-14</sup>	2×10 <sup>-14</sup>
A, r.u.	1.8	1.5	1.5	1.1	2.0	3,7	3.8
$J_p$ , mA/cm <sup>2</sup>	18.4	16.7	18.4	17.3	16.5	3,5	2.8

Table 4

Output parameters and light diode characteristics of the PEC micromodule M5\_3

Sample	C1	C2	C3	C4	C5	C1-C5
$V_{oc}$ , mV	752	762	552	758	741	3582
$J_{sc}$ , mA/cm <sup>2</sup>	15.2	16.7	16.9	17.8	16.9	2.7
FF, r.u.	0.54	0.601	0.28	0.60	0.55	0.55
Efficiency, %	6.2	7.7	2.6	8.1	6.8	5.3
$R_s$ , Ohm×cm <sup>2</sup>	5.6	5.7	12.8	6.3	10.1	243
$R_{sh}$ , Ohm×cm <sup>2</sup>	238	476	24	520	400	15630
$J_0$ , A/cm <sup>2</sup>	3×10 <sup>-7</sup>	5×10 <sup>-8</sup>	6×10 <sup>-8</sup>	2×10 <sup>-8</sup>	7×10 <sup>-9</sup>	5×10 <sup>-8</sup>
A, r.u.	2.8	2.3	2.0	2.2	2.0	2.8
$J_p$ , mA/cm <sup>2</sup>	15.6	16.9	25.9	18.0	17.3	2.8

Analysis of Table 4 shows that the solar elements of the first micromodule have light diode characteristics and output parameters in the following intervals:  $R_s=(3-9)$  Ohm cm<sup>2</sup>,  $R_{sh}=(9-620)$  Ohm cm<sup>2</sup>,  $J_0=((4.10^{-11}-9\times 10^{-4})$  A/cm<sup>2</sup>,  $V_{oc}=(97-755)$  mV,  $J_{sc}=(10.6-18.2)$  mA/cm<sup>2</sup>, FF=(0.26-0.61), efficiency=(0.3-8.4) %, the second micromodule –  $R_s=(5.5-10)$  Ohm cm<sup>2</sup>,  $R_m=(24-520)$  Ohm cm<sup>2</sup>,  $J_0=(7\times 10^{-9}-3,0\times 10^{-7})$  A/cm<sup>2</sup>,  $V_{oc}=(550-760)$  mV,  $J_{sc}=(15-17.8)$  mA/cm<sup>2</sup>, FF=(0.28-0.6), efficiency=(2.6-8.1) %.

For the micromodule M5\_1, despite the shunting of the two elements, a successive connection yielded an efficiency of 3.9%. For the micromodule M5\_3, with a successive combination of elements, the efficiency reached 5.3%. The shunting of two solar cells led to a significant decrease in  $J_p$

and an increase in  $R_s$ , compared with the diode characteristics of the micromodule M5\_1, with the series connection of four PECs. Comparison of the output parameters of micromodules M5\_1 and M5\_3 has shown that a significant difference in the efficiency of micromodules is ensured, first of all, by a lower value of  $V_{oc}$  for the same value of  $J_{sc}$  and a larger value of FF.

To assess the quality of commutation, the experimental values of the output characteristics of micromodules are compared with the output parameters in the theoretical sequential addition of experimental light-emitting characteristics of solar cells. In addition, the theoretical output parameters are compared for a series and parallel connection of experimental PECs (Table 5).

**Table 5**  
Theoretical parameters of micromodules for series and parallel PEC connections

Type of micromodule	Type of connection	$V_{oc}$ , mV	$J_{sc}$ , mA/cm <sup>2</sup>	FF	Efficiency, %
M5_1 (2–5)	series	2390	4.2	0.56	5.6
	parallel	388	15.9	0.35	2.1
M5_1 (1–5)	series	2491	3.3	0.53	4.4
	parallel	277	14.8	0.30	1.2
M5_3 (1–5)	series	3568	3.4	0.49	5.9
	parallel	716	16.7	0.49	5.9

As can be seen from Table 5, in the case of PEC series connection, shunting of one instrumental structure does not exert a decisive influence on the magnitude of the efficiency. If there are two shunted samples in the micromodule, their series connection leads to the fact that the efficiency drops by 26 %, but in the case of a parallel connection, the efficiency is reduced by 80 %. This circumstance is essential for determining the PEC connection type during their industrial production.

## 6. Discussion of the research results of photoelectric converters ITO/CdS/CdTe/Cu/Au in microassembly

Investigations of the ITO/CdS/CdTe/Cu/Au photoelectric converter compound in the microassembly show the following results. PECs series connection in the micromodule M5\_1, which contains two practically shunted solar cells, makes it possible to obtain an efficiency of 3.9 %. The efficiency of the micromodule M5\_3 with a PECs series connection reaches 5.3 %.

The experimental and theoretical values of  $V_{oc}$  of micromodules practically coincide. The experimental efficiency

of the second micromodule is less than the theoretical value by 10–12 relative percent. The connection of two PECs with a low efficiency value reduces the efficiency of the first micromodule by 21 relative percent. The lower value of the experimental efficiency of micromodules is due to the significantly lower values of  $J_{sc}$ .  $J_{sc}$  value for M5\_1 is between the maximum and minimum values for the individual PECs.  $J_{sc}$  value for M5\_3 turns out to be less than the value of the short-circuit current density for all individual PECs.

If for M5\_1 it could be considered that the current is limited to the current of the worst elements, then for M5\_3 such explanation does not fit. It can be assumed that the current limitation is due to the presence of a barrier on the rear contact. Simulation of the parallel connection of solar cells shows that for M5\_3 the efficiency of the module corresponds to the efficiency with the series connection of individual elements.

At the same time, for M5\_1, which includes several PEC with significantly worse output characteristics, the efficiency at parallel connection is 2.5–3.5 times worse than with the series connection of these PECs. This is due to the fact that the PEC with low output parameters limit the  $V_{oc}$  of micromodule, which becomes significantly smaller than the average value  $V_{oc}$  of individual PECs. In this case, there is a significant decrease in FF.

Thus, the results of the study indicate the need for a series connection of the PECs in the composition of micromodules for the stable operation of instrument structures based on them.

This research is a continuation of research aimed at developing effective thin-film solar cells based on CdS/CdTe.

As part of the research, the adequacy of applying the expression for the CVC for the analysis of PEC assemblies is not confirmed. Further research may be aimed at eliminating this shortcoming, as well as developing methods for restoring the PEC efficiency that enter the module after deteriorating their output parameters.

## 7. Conclusions

1. It is found that the photoelectric converters ITO/CdS/CdTe/Cu/Au in the composition of micromodules must be connected in series. This type of connection will contribute to the stable operation of the instrument structure when shunting individual PECs.

2. With the series connection of the ITO/CdS/CdTe/Cu/Au PEC in the micromodule composition, experimental samples of micromodules with an efficiency of 5.3 % are obtained, which is almost 2 times higher than in parallel connection of the same solar cells.

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*Розглянуто особливості розробки економічно-легованого титаном алюмінієвого сплаву, володіючого високою міцністю і термостійкістю, для виготовлення виробів електротехнічного призначення. Представлені методи і засоби, а також прибори та обладнання, які використані при експериментальних дослідженнях. Вивчено вплив кількості титану та температури заливки на структуру і властивості економічно легованого сплаву*

*Ключові слова: алюмінієві сплави, легування, титан, міцність, термостійкість, електротехнічні вироби*

*Рассмотрены особенности разработки экономно легированного титаном алюминиевого сплава, обладающего высокой прочностью и термо-стойкостью, для изготовления изделий электротехнического назначения. Представлены методы и средства, а также приборы и оборудования, которые использованы при экспериментальных исследованиях. Изучены влияния количества титана и температуры заливки на структуру и свойства экономно легированного сплава*

*Ключевые слова: алюминиевые сплавы, легирование, титан, прочность, термостойкость, электротехнические изделия*

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## DEVELOPMENT OF LEAN TITANIUM- ALLOYED ALUMINIUM ALLOY FOR ELECTRO- TECHNICAL PURPOSES

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### 1. Introduction

Power engineering has intensively developed in today's world, due to which leading countries export electricity to neighboring developing countries. In this case, power engineers face the task on electricity generation and transmission over long distances. This, in turn, necessitates design of new materials for electro-technical purposes, as well as

priority development of metallurgical technologies and materials science [1, 2].

At present, given their high mechanical, physical-chemical and corrosive properties, as well as high manufacturability, aluminum alloys are widely used in engineering. Another reason, contributing to a wide application of aluminum alloys, is the availability of large amounts of reserves of aluminum ores in the world.