Semiconductor Physics, Quantum Electronics & Optoelectronics, 2026. V. 29, No 3. P. 374-382.

Optoelectronics and optoelectronic devices

Concentrator solar photoreceivers on thermally conductive aluminum–polyimide lacquer-foil dielectrics

V.M. Borshchov[1], O.M. Listratenko[1], M.A. Protsenko[1], I.T. Tymchuk[1], O.V. Kravchenko[1], I.V. Borshchov[1], M.I. Slipchenko[2], V.P. Kostylyov[3]

[1] *"Research and production enterprise "LTU" LLC, Kharkiv, Ukraine*
[2] *Institute for Scintillation Materials of the National Academy of Sciences of Ukraine, Kharkiv, Ukraine*
[3] *V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine*
[*] *Corresponding author e-mail: vkost@isp.kiev.ua*

Abstract. New approaches to creation of high-efficiency single concentrator photovoltaic (CPV) receivers by reducing their mass and cost by using thermally conductive aluminum boards have been introduced. Optimized combined printed circuit boards on rigid aluminum substrates with flexible multilayered thermally conductive composite polymer thermal interface dielectrics foiled with thin lightweight aluminum coatings have been developed. Dependences of maximal operation temperatures on combined boards on board size have been simulated using COMSOL MULTIPHYSICS software. Thermal properties of test quality structures (TQS) of single CPV receivers with improved thermal characteristics based on thermally conductive composite polyimide (PI) layers with the thermal conductivity of 1.0…3.0 W/(m·K) and novel high-efficiency concentrator triple-junction 3C44-type solar cells (SC) from AZUR SPACE Solar Power GmbH (Germany) with increased efficiency of about 43.6% at solar radiation concentration ratio of $500^{\times}$ have been investigated. The electrical and mechanical properties of the improved combined printed circuit boards on aluminum substrates and more technological lacquer-foil aluminum-PI dielectrics with the average filled volume concentration of heat-conductive particles in thin PI layers of the order of 50 vol.%, which ensure operation temperatures of the single CPV receiver boards in the SC area of no more than 70–90 °C and allow maintaining high operational reliability and increasing operation life of the single CPV receivers under favorable operation conditions, have been investigated.

Keywords: CPV receivers, thermally conductive PI composite materials, thermally conductive aluminum-polyimide lacquer foil dielectrics, CPV receiver quality test structures.

https://doi.org/10.15407/spqeo29.03.374
PACS 44.10.+i, 81.05.Lg, 84.60.Jt

Manuscript received 12.01.26; revised version received 11.08.26; accepted for publication 16.09.26; published online 25.09.26.

1. Introduction

Reducing manufacturing costs and increasing photo-electric conversion efficiency of solar cells (SC) and solar modules [1] have ensured long-term competitiveness of photovoltaics in global energy production. Solar power has become a key and rapidly growing sector of the electric power industry [2], and it is expected to continue expanding in the near future [3]. It is forecasted that the production capacity of solar photo-voltaic systems worldwide will reach approximately 3000 GW by the end of 2025 [2]. Over the next five years, the total capacity of solar panels installed in the European Union may double. European Solar Photovoltaic Industry Alliance, established by the European Commission, favors innovation expansion and accelerates deployment of solar energy harvesters in the EU by increasing annual production capacity of solar photovoltaic systems in Europe to 300 GW by 2025 [2] as well as by stimulating investments, reducing sectoral risks, and supporting Europe's decarbonization. Taking into account all losses associated with converting fossil fuels into useful work, our planet receives approximately 18,000 times more energy from the Sun than all the energy the humanity consumes per year. This is not simply a large amount – it is an excess of such scale that, according to the estimates by Carbon Tracker analytical center, meeting all the current global energy needs would require covering only

0,3% of the Earth's land surface with solar panels. At the same time, solar energy does not produce additional heat or CO_2 as compared to extraction, processing, and transportation of fossil fuels. Solar and wind power are not merely clean alternatives. They are the only known energy sources that enable civilization to grow and develop successfully during long time without disrupting ecological and thermal balance of the Earth [4].

Supporting ongoing transition of the energy sector from traditional fossil fuels to renewable energy sources is a key objective of both existing and newly developed photovoltaic technologies. At present, state-of-the-art flat photovoltaic (PV) modules based on monocrystalline silicon have reached mass-production efficiencies of about 22–24%. In 2025, the highest results were demonstrated by the Chinese company Trina Solar, which achieved nearly 27% efficiency in mass production of commercial tandem modules composed of perovskite and silicon.

On the other hand, high-efficiency concentrator photovoltaic (CPV) modules equipped with dual-axis solar-tracking systems and quadruple-junction (4J) solar cells currently demonstrate efficiencies of the order of 46%, when converting concentrated direct normal solar irradiance. Therefore, more efficient CPV technologies may be considered as true competitors to modern flat solar modules, which were able to compete quite successfully with the offers of coal and gas companies on the market during years of aggressive price dumping. However, this competitive issue is already slowing down. Once a threshold is reached, it may pave a way for a large-scale return of CPV technologies to the renewable energy market. Despite the fact that the efficiency of the best commercial silicon solar cells can reach 24% or even higher, the efficiency of multijunction CPV solar cells has already reached 46% and continues to grow. This positive performance gap can also be observed at a CPV module level, even considering currently significant optical losses in the modules. In turn, the efficiency of silicon solar cells is highly sensitive to the operation temperature. During summer, the cell temperature often reaches 80 °C, which can reduce the efficiency of commercial flat panels down to about 14–15%. In contrast, CPV solar cells are made of materials with very low temperature coefficients – about 0.05%/°C, which is almost an order of magnitude less than that for silicon solar cells. This allows CPV cells to operate reliably at very high temperatures (100 °C and above) [5].

In all modern industrial solar systems, active components most frequently fail or degrade during operation, and flat PV modules are no exception. Price competition also prevents manufacturers from using the highest-quality components in the PV modules that reduces the module operation lifetime especially in extremely hot climates with high solar potential. For example, transparent polymers used for encapsulation and front-glass bonding in modules undergo yellowing due to thermal cycling. The typical degradation rate is about 0.5% per year in moderate climates and up to 3% per year in hot regions. In contrast, CPV solar cells are manufactured using space- and military-grade technologies and are practically insensitive to thermal or radiation damage even after 20 years of operation. Currently, the cost of the multijunction CPV solar cells has begun to decrease much faster than before. Using automated equipment designed for LED manufacturing enables production of small-area cells at high throughput and very low manufacture error rates. Typical dimensions of the SC might be 25 times smaller than a decade ago (4 mm^2 compared to 100 mm^2), which significantly reduces the cost of the CPV modules. Open surfaces of the CPV modules are manufactured using various inorganic materials (glass, aluminum), which do not degrade over time. In the long term, the CPV technology may prove to be less expensive. However, this advantage is not sufficient to compensate the much higher capital costs associated with installation and operation of the CPV modules, which can be 2.5-4 times higher than those of traditional PV technologies. Reducing the mass of the CPV modules is also crucial when it comes to lowering operational expenses. This makes it possible to use supporting concentrator solar trackers of larger dimensions with the same precision and cost and install a greater number of lighter CPV modules. The higher number of modules significantly reduces maintenance costs when using cost-efficient automated equipment, for example, during cleaning or by reducing service personnel requirements. Furthermore, mass optimization of advanced modern CPV modules enables lowering their specific weight to nearly 10 kg/m^2, compared to an average of 40 to 45 kg/m^2 for existing modern CPV modules [5].

A certain drawback of the CPV technology is its ability to effectively convert only the direct component of sunlight, while the diffuse component is lost. The strengths and weaknesses of the photovoltaic technologies (planar photovoltaics – PV and concentrator photovoltaics – CPV) have motivated many researchers to develop advanced more efficient hybrid solar modules that combine both of the aforementioned technologies. The goal of this approach is to maximize the efficiency of solar energy conversion and output electrical energy at an acceptable production cost, particularly in regions with medium levels (from 60% to 80%) of direct normal irradiance (DNI) relative to global normal irradiance (GNI). State-of-the-art innovative hybrid solar modules with integrated solar tracking utilize lenses and multijunction SCs to concentrate and convert direct solar radiation as well as silicon SCs with bifacial sensitivity to convert diffuse sunlight. The efficiency of such hybrid modules is generally lower than that of pure concentrator modules under conditions of domination of direct sunlight. However, the output power per unit area of the hybrid solar modules at medium DNI values of 60–80% reaches the levels significantly higher (by 15–20%) than those of standard CPV modules under similar conditions [5–7].

Therefore, the objective of this work is development and investigation of test quality structures (TQS) of single CPV receivers based on modern industrial concentrator triple-junction SCs with small dimensions of 3×3 mm^2 and an increased efficiency of about 43.6% at concentration levels up to 500, intended for creating high-efficiency hybrid bifacial solar modules mounted on advanced lightweight combined printed circuit boards with polyimide (PI) dielectrics. This solution will enhance competitiveness and ensure maximization of solar radiation conversion efficiency in electrical energy production.

An additional objective is selecting new approaches for creating design and technological schemes for manufacturing optimized combined printed circuit boards for single CPV receivers by reducing their mass through using lightweight aluminum (Al) substrates and more technologically advanced multilayer thin composite thermally conductive polymer dielectrics foiled with Al. These solutions are intended to maintain operation temperatures of the SCs below their permissible limits and to ensure high reliability of the CPV receivers.

2. Subject and methods of research

2.1. Design and technological solutions for combined printed circuit boards on aluminum substrates with aluminum-foiled polymer thermal interface dielectrics for single CPV receivers

Fig. 1 shows structural diagram of a combined board on a rigid thermally conductive Al substrate, which includes a thin adhesiveless thermally conductive lacquer-foil aluminum–polyimide (Al-PI) dielectric with Al or copper (Cu) foil. The single-layer thermally conductive composite lacquer-foil dielectric is bonded to the rigid Al substrate using a single-component thermally conductive poly-dimethylsiloxane moisture-cured adhesive material. The generated heat passes through the thermally conductive polymer dielectrics and is then dissipated through the flat Al heat sink. Thermally conductive boards on the Al substrates are used in electronic devices with a sufficiently small area of up to 20 cm^2 that do not require forced cooling. With identical board parameters such as area, foil thickness for interconnects, thickness of the adhesive or solder layer between the semiconductor chip and the mounting pad on the foil, thickness and thermal conductivity of the dielectrics are determining factors for overall thermal resistance of the combined board.

New approaches to develop the coefficient of thermal expansion (CTE) of combined boards on Al substrates with thin thermally conductive polymer dielectrics are primarily based on using in their structure various types of thin PI layers and thin layers of silicone dielectric materials, which ensure sufficiently low total thermal resistance of the board heat dissipation system (from ~0.23 down to ~0.06 °C/W). Thermally conductive adhesiveless lacquer-foil dielectrics based on Al and Cu foils with the thicknesses from 100 to 150 µm and PI layers were investigated. Although Cu has better thermal conductivity, Al is more commonly used for producing budget printed circuit boards because it is a cheaper lightweight and mechanically durable material. The adhesiveless Al-PI lacquer-foil dielectrics was attached to the Al substrate of the board with the thickness of about 1000 um using single-component moisture-cured thermally conductive polydimethylsiloxane (silicone) adhesive material Kafuter K-5204K manufactured by Guangdong Hengda New Materials Technology Co., Ltd. (China). The thermal conductivity of this material is up to 1.6 W/(m·K) [8].

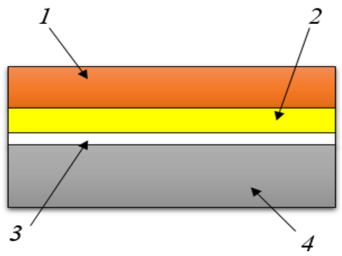


Fig. 1. Structural diagram of the combined board: *1* – Al foil layer, *2* – PI layer, *3* – adhesive material layer, *4* – Al substrate.

The chosen technological scheme for manufacturing optimized combined boards on Al substrates includes the following main stages:

– preparing 100…150 µm thick Al foil of 8011 or A-5T grade and preparing 1000 µm thick Al substrate of 1100 grade having a small area of about 10…20 cm^2;

– manufacturing adhesiveless Al-PI lacquer-foil dielectric on the 100…150 µm thick Al foil based on 25…30 µm thick thermally conductive composite PI layer with the thermal conductivity from 0.7 to 3.0 W/(m·K);

– fabricating experimental samples of combined boards with specified dimensions using silicone adhesive material Kafuter K-5204K with the thermal conductivity of 1.6 W/(m·K). 1000-µm thick Al substrates are placed on thermally conductive Al-PI lacquer-foil dielectrics with an applied adhesive layer, conditioned for about 10 min in air at room temperature and humidity of 55–65%, and then placed into special technological tools under a load of approximately 4-5 kg. The boards are kept under compression until complete curing for 24 hours.

Therefore, this study includes manufacturing and both theoretical and experimental investigation of Al-PI lacquer-foil dielectrics at different configurations on advanced composite PI layers with the thicknesses of 25…30 µm and effective thermal conductivity from 0.7 to 3.0 W/(m·K) at the volume concentration of AlN fillers in the PI matrix from 30 to 70 vol.%. The AlN particle sizes are about 10 µm [9, 10].

2.2. Design and technological solutions of TQS for single CPV receivers

Since the main purpose of using optimized combined printed circuit boards is to improve heat transfer from the concentrator semiconductor solar cell (SC) to the thermal management system, it is reasonable to consider the thermal resistance in the system "semiconductor structure – back side of the Al base of the combined board" of a single CPV receiver as a key criterion in theoretical studies. Figs 2 and 3 show an appearance and a structural diagram of the TQS of single CPV receivers on optimized thermally conductive combined boards intended for modeling and theoretical investigation of their thermal properties.

New technical solutions were used in the structural diagram of the heat dissipation system of a single CPV receiver on an optimized thermally conductive combined board to develop an improved receiver design and their manufacturing technology, including:

1. Combined printed circuit boards with an area of up to 20 cm^2 created on rigid substrates with a thickness of up to 1000 µm made of Al of 1100 grade and multilayer thermally conductive composite polymer thermal interface dielectrics, which are foil-clad with Al coatings, including:

– adhesiveless thermally conductive lacquer-foil Al-PI dielectrics of the LTU-TFPA150-30 type manufactured by the “Research and Production Enterprise “LTU” LLC (RPE LTU) (Ukraine) with a layer of thin (30 µm thick) medium-filled thermally conductive PI composite (55 vol.%) with the thermal conductivity of about 1.2 W/(m·K) and highly filled thermally conductive PI composite (70 vol.%) with the thermal conductivity of about 3.0 W/(m·K). White aluminum nitride (AlN) powders with the particle sizes of about 10 µm were used as filler powders for the PI layers.

– top layers of the combined printed circuit boards are made of 150 µm thick foil of 8011 grade Al for connecting concentrator solar cells by soldering to mounting pads, which are coated by a 2-3 µm thick nickel layer with the thermal conductivity of about 90 W/(m·K) and by an about 30 µm thick SnBi layer with the thermal conductivity up to 45…50 W/(m·K).

– adhesive layers with the thickness of about 40 µm for bonding the adhesiveless Al-PI lacquer-foil dielectrics to the rigid Al board substrates were created using a Kafuter K-5204K type silicone dielectric material with the thermal conductivity of 1.6 W/(m·K).

2. A 3C44 type industrial concentrator triple-junction solar cell with the dimensions of 3.1×3.5 mm^2 from Azur Space Solar Power (Germany). At the concentration level of 500$^\times$ under the AM 1.5 illumination conditions (1000 W/m²), the efficiency amounts to 43.6% and the power to 2.4 W [11].

3. Materials for connecting the 3C44 solar cell to the combined printed circuit boards by soldering. To connect the CPV receiver solar cell to the top layer of the combined Al foil board for ensuring reliable electrical and mechanical connection by soldering, high-quality solder paste NC254 of the $Sn_{62}Pb_{36}Ag_2$ type from AIM Solder (Canada) was selected. The area of the mounting pad for thermal contact with the solar cell is about 16 mm². The maximal melting temperature of the paste is T = 179 °C. The thermal conductivity of approximately 30 µm thick solder paste is about 50 W/(m·K) [12].

4. Adhesiveless thermally conductive lacquer-foil Al-PI dielectrics manufactured by RPE LTU for creating thin flexible interconnection printed circuit boards to obtain reliable electrical connections of ribbon Al leads to the solar cell and to the mounting areas of the top Al layers of the combined printed circuit boards using ultrasonic welding process. To connect the contacts of the 3C44 solar cell with the mounting pads on the conductive pattern of the combined receiver circuit board, the design of a thin interconnection Al-PI board was selected, developed and manufactured by RPE LTU based on flexible lacquer-foil dielectrics (15 µm thick Al foil, 10 µm thick PI layer). The ribbon Al leads of the flexible interconnection board are welded to Ag/Au contacts on the front side of the solar cell using ultrasonic welding with a wedge with the working tip diameter of about 170 µm to ensure maximum weld strength values of at least 15 g. The maximal weld strength values of the ribbon Al leads of the thin interconnection board with the Al mounting pads of the top layer of the combined receiver circuit board reach at least 18 g.

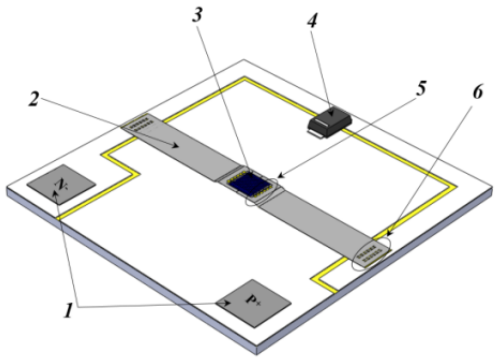


Fig. 2. Appearance of the TQS of a single CPV receiver: *1* – N$^-$ and P$^+$ contact pads of the combined board, *2* – flexible Al-PI interconnection board, *3* – SC, *4* – protection diode, *5* – flexible board lead for welding to the SC, *6* – flexible interconnection board lead for welding to the combined board.

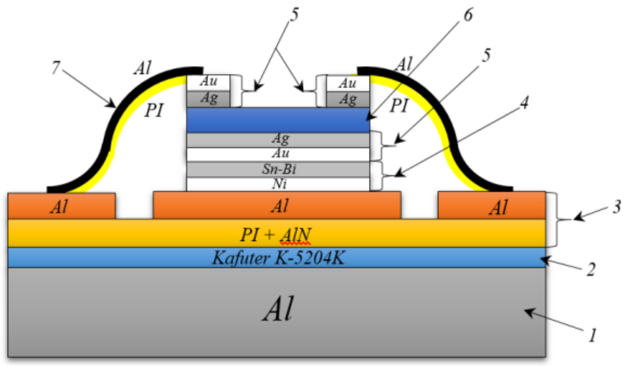


Fig. 3. Structural diagram of the TQS of a CPV receiver: *1* – board base, *2* – adhesive dielectric material, *3* – adhesiveless thermally conductive lacquer-foil Al-PI dielectric material, *4* – mounting pad on the board, *5* – mounting pad on the SC, *6* – SC, *7* – flexible Al-PI interconnection board.

3. Thermal modeling of heat dissipation system of single CPV receivers on optimized combined boards with Al substrates

The dependences of the maximal expected operation temperatures on combined boards on the board dimensions were simulated. The thermal models of the heat dissipation systems of single CPV receivers on optimized boards with adhesiveless lacquer-foil PI dielectrics on Al foil with the thickness up to 150 µm and on 30 µm thick composite PI layers with the thermal conductivity of 1.2 W/(m·K) (Model 1) and 3.0 W/(m·K) (Model 2) were investigated using COMSOL MULTIPHYSICS software. Favorable operation conditions were chosen for the simulations, which were identical to the operation conditions of concentrator receivers in open air under natural convection at an ambient temperature T_a = 25 °C and a convective heat transfer coefficient h = 22 W/(m²·K) [8].

Thermal properties of the TQS of the receiver were investigated on optimized combined boards, on which 3C44 solar cells with an area of about 10.85 mm² and an output power of about 3 W at the concentration ratio of 500 and efficiency of 43.6% were mounted by soldering. Fig. 4 shows the dependence of temperature (T_{hs}) of the optimized boards of the TQSs of the single CPV receivers (Model 1, Model 2) in the solar cell plane on the dimensions of the investigated boards ranging from 30×30 to 45 ×45 mm for relatively favorable receiver operation conditions.

It may be concluded from the results presented in Fig. 4 that during thermal modeling of the TQS of the single CPV receivers on optimized combined printed circuit boards with a rigid Al substrate and adhesiveless thermally conductive lacquer-foil Al-PI dielectrics of the LTU-TFPA150-30 type, which are combined with thermally conductive composite polymer thermal interfaces based on polydimethylsiloxane dielectric adhesive material of the Kafuter K-5204K type, the maximal temperature in the plane of the 3C44 solar cell does not exceed 105 °C.

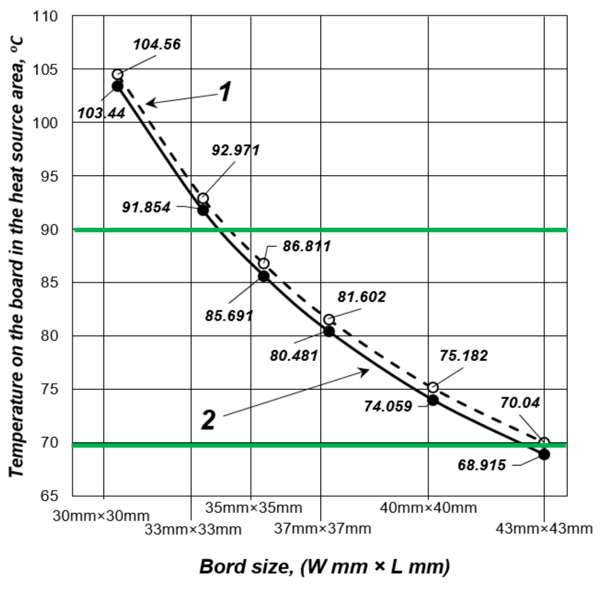


Fig. 4. Estimated dependence of the temperature of the boards of the TQS of CPV receiver in the heat source plane on the selected dimensions of the investigated boards: *1* – Model 1, *2* – Model 2.

Table. Results of calculations of total thermal resistances of combined boards and temperatures on the board in the solder layers at the heat source output power of about 3 W and the heating temperature of the reverse side of the Al substrates under steady state thermal distribution at favorable operation conditions of the TQS of a single CPV receiver.

Thermal model variant	Total thermal resistance of the combined board, R_k, °C/W	Temperature on the board at h = 22 W/(m²·K), T_a = 25 °C	
		T_{hs}, °C	T_{Al}, °C
Model 1	0106	86.8	79.7
Model 2	0.094	85.7	79.9

The table below presents the results of the calculations of total thermal resistances of optimized combined boards with the dimensions of 35×35 mm^2 together with a solder layer for the investigated TQS of the single CPV receiver. Moreover, the results of calculations of temperatures in the solder layers at the temperature of the heat source T_{hs} and the heating temperature of the reverse side of the Al substrates T_{Al} of the boards under steady state thermal distribution at favorable operation conditions are provided.

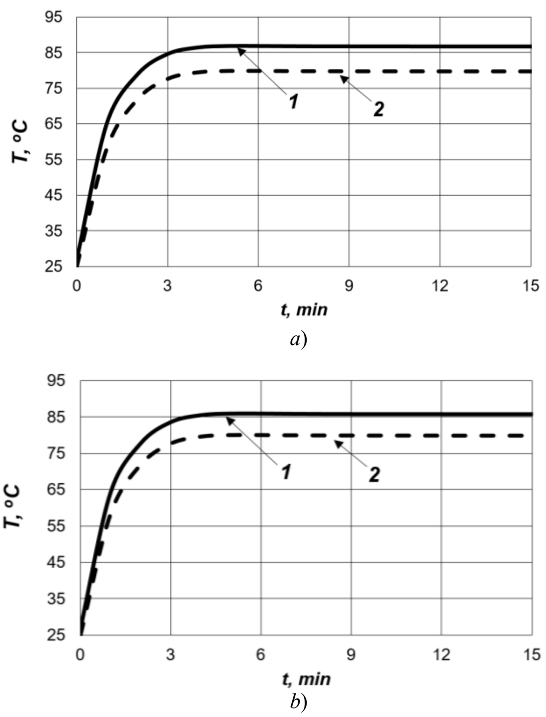


Fig. 5. Time dependence of the heating temperature on the boards in the heat source plane T_{hs} (1) and on the reverse side of the Al substrate T_{Al} (2) during transition to a steady thermal state under favorable operation conditions: a – Model 1, b – Model 2.

Fig. 5 presents the time dependences of the heating temperature on the boards with the dimensions of 35×35 mm^2 in the plane of the heat source and on the reverse side of the Al substrates during transition to a steady thermal state under favorable operation conditions of the TQS of a single CPV receiver.

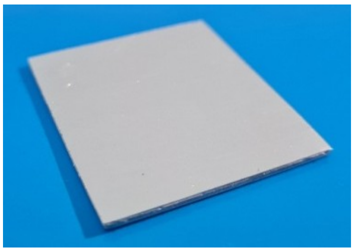
At the optimized combined board dimensions of 35× 35 mm^2 and a solar cell power of about 3 W, the theoretical investigations of the temperature on the boards in the heat source plane (Model 1, Model 2) show that their operation temperatures do not exceed 90 °C that ensures high efficiency and durability of these boards under favorable operation conditions.

4. Experimental investigations of combined printed circuit boards for TQS of single CPV receivers

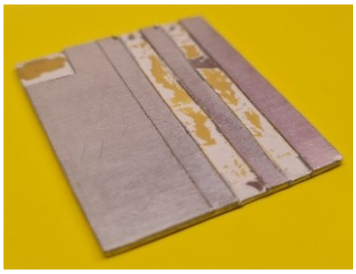
The experimental investigations of samples of combined printed circuit boards on aluminum substrates with multilayer composite polymer thermal interface dielectrics for TQS of a CPV receiver were carried out at air temperatures from +15 to +35 °C, relative humidity from 50 to 80%, and atmospheric pressure of $8.6\cdot10^4…10.6\cdot10^4$ Pa.

The peel strength of the aluminum foil was tested according to the harmonized standard IPC-TM-650, test method 2.4.9. For the tests, TQSs of the single CPV receiver were manufactured with adhesiveless lacquer-foil thermally conductive PI composite dielectrics. These dielectrics were bonded with a thin layer of a Kafuter K-5204K type adhesive material with the thermal conductivity of 1.6 W/(m·K) to a 1 mm thick Al board substrate. Fig. 6 presents the combined printed circuit boards of the TQS of the CPV receiver for verifying their main electrical and mechanical properties.

The average peel strength values of the adhesiveless lacquer-foil thermally conductive Al-PI dielectrics (150 µm thick Al foil from the 30 µm thick PI layer and 30 µm thick composite PI layer from the 40 µm thick Kafuter K-5204K type silicone adhesive material) were not less than 0.5…0.6 kgf/cm (5…6 N/cm). The values of the average breakdown voltage of the about 30 µm thick experimental high thermally conductive composite PI layers with the thermal conductivity of 1.2 W/(m·K) and more were more than 3.0 kV/mil (120 V/µm). The electric strength of the PI dielectrics of combined boards on a thermally conductive Al substrate was tested according to the harmonized standard IPC-TM-650, test method 2.5.6.3 "Dielectric Breakdown Voltage and Dielectric Strength", using an AIM-90 breakdown voltage tester. In combined printed circuit boards with Al substrates and adhesiveless Al-PI lacquer-foil dielectrics, Al is used as a lighter and more economical electric current conductor and effective heat dissipator. In this work, for modern lightweight compact concentrator receivers for hybrid solar modules by RPE, LTU proposed new design and technological approaches for creating combined boards from thermally conductive adhesiveless lacquer-foil Al-PI dielectrics of its own production.



(a)



(b)

Fig. 6. Combined printed circuit boards of the TQS of the CPV receiver for verifying electrical and mechanical properties: *a* – for testing electric strength, *b* – for testing Al foil peel strength.

Therefore, using rigid Al substrates and thin light-weight Al foils allowed one to reduce the costs of main thermally conductive materials used in combined boards as well as lower the manufacturing costs of these boards. This also significantly reduces the manufacturing cost of innovative lacquer-foil PI dielectrics on Al foil with the same thermal efficiency as of those based on Cu, by increasing the thickness of Al compared to the Cu thickness, since the market price of the Cu foil currently remains stably 3-4 times higher than that of the Al foil [8, 13, 14].

5. Results and discussion

Thermal modeling and investigation of the thermal properties of the TQS of single CPV receivers with combined board dimensions of 35×35 mm^2 at the SC power of about 3 W (Table and Figs. 4, 5) showed achieving the lowest total thermal resistance values of the combined boards of about 0.1…0.09 °C/W, when composite PI layers of lacquer-foil Al-PI dielectrics with the thermal conductivities of 1.2 and 3.0 W/(m·K) were used (Model 1 and Model 2). The theoretical studies of the temperature on optimized combined CPV receiver boards demonstrated the possibility of maintaining the maximum temperatures in the heat-source region of about 85.7 °C and 86.8 °C under relatively favorable operation conditions, which fully meets the operation temperature requirements for *p-n* junctions of 3C44 concentrator solar cell not to exceed 110 °C. The obtained technical result, in terms of its thermal characteristics, is not inferior to the boards of the High Power Lighting HPL-03015 (Single side Cu/Al base) type from Bergquist (USA) company manufactured from a Thermal Clad industrial material with the thermal conductivity of ~3 W/m·K and the average total dielectric thermal resistance values of about 0.3 °C/W.

Hence, the investigated thermal properties of the TQS of new single CPV receivers with optimized combined board sizes from 30×30 to 45×45 mm^2 on Al basis with lightweight Al foil instead of Cu foil make possible further reducing the material and manufacturing costs of the improved optimized boards, demonstrating commercial potential of developing new production technologies for single CPV receivers with more affordable cost.

Development of optimized combined boards on Al basis with thermal conductive polymer dielectrics is primarily based on using various types of thin composite PI layers and thin silicone moisture-curing adhesive dielectric layers. Theoretical and experimental research has been carried out on new approaches to lacquer-foil Al-PI dielectrics, manufactured in various versions on improved thin composite PI layers with the thicknesses up to 30 µm, the effective thermal conductivity of about 1.2 W/(m·K) and an average filled volume concentration of AlN particles with the particle sizes of approximately 10 µm, of about 50 vol.%. This approach ensured more cost-effective and technologically effective method of filling composite thin PI matrices. Bonding of adhesiveless Al-PI lacquer-foil dielectrics with Al foil up to 150 µm thick to a rigid Al board base with the thickness of approximately 1000 µm was performed using a high-reliabile silicone adhesive of the Kafuter K-5204K type.

During experimental studies of the manufactured samples of combined printed circuit boards intended to retrieve their electrical and mechanical properties (Fig. 6), the average values of the peel strength of the adhesiveless lacquer-foil thermally conductive Al-PI dielectrics (150 µm thick Al foil) from the 30 µm PI layer, as well as of the 30 µm thick composite PI layer from the 40 µm thick adhesive layer of the Kafuter K-5204K type, were not less than 0.5…0.6 kgf/cm (500…600 g/cm or 5…6 N/cm). The average dielectric breakdown voltage of the experimental high thermally conductive composite PI layers with the thickness of about 30 µm exceeded 3.0 kV/mil (120 V/µm).

In this work, the authors developed new approaches by proposing optimized Al-based boards for single CPV receivers to provide sufficiently low thermal resistance and weight while maintaining such key advantages as manufacturability and reliability. The experimentally confirmed research results may be useful in the development of cheaper concentrator photovoltaic devices for innovative hybrid CPV/PV solar modules. At the moment, hybrid CPV/PV modules are a high-tech niche product that is at the stage of transition from demonstration projects to industrial scaling. The closest to comercialization are the projects Insolight (Switzerland) and Fraunhofer ISE (Germany, EyeCon project [6]).

It can be concluded from the data presented in [6] that the characteristics of the optimized Al-based board for single CPV receivers proposed by us in this work and the module used there are close.

Hence, a new approach to developing more advanced and optimized Al-based composite boards for individual CPV receivers provides a very low overall thermal resistance of the heat transfer system, while maintaining exellent key properties such as hardness, stiffness, and processability, along with a significant reduction in manufacturing and operation costs.

6. Conclusions

In this work, new approaches for developing single high-efficiency CPV receivers with reduced weight by using lightweight thermally conductive Al bases of combined boards and more technologically advanced adhesiveless lacquer-foil Al-PI dielectrics with medium filled volume concentrations of thermally conductive particles in PI matrices have been proposed.

The optimized combined aluminum boards with flexible multilayer thermally conductive composite polymer thermal-interface dielectrics, foil-coated with thin lightweight aluminum layers for electrical interconnection of the receivers, have been developed.

Theoretical models and thermal properties of the test quality structures of the single CPV receivers with improved thermal characteristics based on novel high-efficiency concentrator triple-junction SCs of 3C44 type from AZUR SPACE Solar Power GmbH were investigated. It was shown that for the optimized combined board dimensions of 35×35 mm^2 and the SC power of about 3 W, the theoretical values of the temperature in the heat-source plane do not exceed 90 °C ensuring high efficiency under favorable operation conditions.

Electrical and mechanical properties of the optimized combined boards were experimentally studied. It was found that the average peel strength in the advanced combined printed boards (Fig. 6) between the Al foil and the PI layer as well as between the composite PI layer and silicone adhesive material of the Kafuter K-5204K type was not less than 5…6 N/cm. The average values of the breakdown voltage of the investigated high-thermal conductive composite PI layers exceeded 3.0 kV/mil (120 V/µm).

It has been demonstrated that single CPV receivers can be effectively used in development of innovative hybrid bifacial solar modules for competitive generation of renewable electrical energy due to improved thermal management and high reliability of cost-effective CPV receivers with more affordable manufacturing cost.

References

1. Green M.A., Dunlop E.D., Yoshita M. *et al.* Solar cell efficiency tables (version 66). *Prog. Photovolt.: Res. Appl.* 2025. **33**. P. 795–810. https://doi.org/10.1002/pip.3919.
2. Photovoltaics Report. Fraunhofer Institute for Solar Energy Systems ISE with the support of PSE Projects GmbH Freiburg, 14 July 2026. www.ise.fraunhofer.de (Last accessed: 29.09.2025).
3. Kostylyov V.P., Sachenko A.V. Semiconductor photovoltaics: current state and actual directions of research. *Optoelectron. Semicond. Tech.* 2018. **53**. P. 13–37. https://doi.org/10.15407/jopt.2018.53.013.

4. Developing a resilient European solar PV manufacturing value chain. https://solaralliance.eu (Last accessed: 21.08.2025).
5. Loidi O. The Future of Solar Energy: High Concentrated Photovoltaic (CPV) Cells. https://www.ennomotive.com/future-of-solar-energy (Last accessed: 21.08.2025).
6. Martínez J.F., Steiner M., Wiesenfarth M. *et al.* Development and outdoor characterization of a hybrid bifacial HCPV module. *Prog. Photovolt.: Res. Appl*. 2020. **28**, Issue 5. P. 347–435. https://doi.org/10.1002/pip.3239.
7. Alzahrani M., Baig H., Shanks K. *et al*. Estimation of the performance limits of a concentrator solar cell coupled with a micro heat sink based on a finite element simulation. *Appl. Therm. Eng*. 2020. **176**. P. 115315. https://doi.org/10.1016/j.applthermaleng.2020.115315.
8. Thermal Conductive Silicone Glue Kafuter K-5204. https: www.kafuter.cn/product-item-106.html (Last accessed: 21.08.2025).
9. *Patent for a utility model No 158709*, Ukraine, CI (2006.01): B32B 33/00 B32B 15/08. Method for manufacturing flexible heat-conductive lacquer foil polyimide material. G.I. Nikitsky, I.V. Borshchov, O.V. Kravchenko, O.M. Listratenko. Appl. No u 2024 01467, 19.03.2024. Publ. 12.03.2025. Bul. No 11/2025.
10. Borshchov V., Listratenko O., Slipchenko M. *et al.* Flexible heat-conductive polyimide composite materials *Funct. Mater*. 2024. **31**, No 3. P. 359–370. http://doi.org/10.15407/fm31.03.359.
11. Concentrator Triple Junction Solar Cell 3C44 – 3×3mm^2. https://www. AZUR SPACE Solar Power GmbH (Last accessed: 13.04.2025).
12. Solder paste NC254 of the company AIM Solder. www.aimsolder.com. (Last accessed: 13.04.2025).
13. Standard IPC-TM-650:2002. Test Methods Manual.
14. Borshchov V.M., Listratenko O.M., Slipchenko M.I. *et al*. Study of thermal properties of electronic modules on combined plates with polyimide dielectrics. *Radiotekhnika*. 2024. No 217. P. 139-147 (in Ukrainian) https://doi.org/10.30837/rt.2024.2.217.13.

Authors and CV

Vyacheslav M. Borshchov, Doctor of Technical Sciences, Professor, First Deputy Director – Chief Designer of the "Research and Production Enterprise "LTU" LLC. Expert in microelectronic technologies with more than 40 years' experience in designing microelectronic devices and technologies both for terrestrial and space applications. Author and co-author of more than 300 scientific publications and about 100 patents.
E-mail: viatcheslav.borshchov@cern.ch,
https://orcid.org/0000-0002-5579-8932

Oleksandr M. Listratenko, PhD, Leading Researcher of the "Research and Production Enterprise "LTU" LLC. Expert in development of photovoltaic devices and technologies with more than 30 years' experience. Author and co-author of more than 120 publications and about 30 patents. https://orcid.org/0000-0001-7643-5295, e-mail: sasha.listratenko.12@gmail.com

Maksym A. Protsenko, PhD, Division Head – Deputy Chief Designer of the "Research and Production Enterprise "LTU" LLC. Expert in microelectronic and photovoltaic device development. Author and co-author of about 110 publications and 10 patents. E-mail: max.protsenko.1978@gmail.com,
https://orcid.org/0000-0001-9313-1701

Ihor T. Tymchuk, PhD, Chief Technologist of the "Research and Production Enterprise "LTU" LLC. Expert in developing technologies and designing microelectronic devices. Author and co-author of more than 100 publications and more than 10 patents.
E-mail: ihortymchuk78@gmail.com,
https://orcid.org/0000-0002-6436-7253

Oleksandr V. Kravchenko, PhD, Department Head of the "Research and Production Enterprise "LTU" LLC. Expert in developing technologies and assembling microelectronic devices. Author and co-author of about 20 publications and 2 patents.
E-mail: kravcenkoaleksandr671@gmail.com,
https://orcid.org/0000-0002-7145-4304

Illia V. Borshchov, Researcher of the "Research and Production Enterprise "LTU" LLC, PhD Student. Field of interests: modeling thermal and other operational parameters of microelectronic devices. Co-author of 10 publications and 1 patent. E-mail: illia.borshchov1@nure.ua,
https://orcid.org/0000-0002-6598-6988

Mykola I. Slipchenko, Doctor of Physical and Mathematical Sciences, Professor, Leading Researcher of the Institute for Scintillation Materials, NAS of Ukraine. Author and co-author of more than 200 publications and about 75 patents.
E-mail: naukovets.big@gmail.com,
https://orcid.org/0000-0002-4242-4800

Vitaliy P. Kostylyov, Doctor of Physical and Mathematical Sciences, Professor, Leading Researcher, Head of the Center for Testing Solar Cells and Solar Modules of the V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine. Author and co-author of more than 250 scientific publications. Areas of scientific interests: photovoltaics and betavoltaics, research, analysis and modeling of solar cells, characterization and tests of solar cells, characterization of optical and recombination properties of photovoltaics materials.
E-mail: vkost@isp.kiev.ua,
https://orcid.org/0000-0002-1800-9471

Authors' contributions

Borshchov V.M.: supervision, analysis, data curation (partially), project administration, writing – review & editing.

Listratenko O.M.: conceptualization, methodology, validation, analysis, data curation, writing – original draft, writing – review & editing.

Protsenko M.A.: investigation, resources, analysis, discussing results, writing – review & editing.

Tymchuk I.T.: investigation, resources, analysis, discussing results, writing – review & editing.

Kravchenko O.V.: investigations, software, discussing results, validation, writing – original draft.

Borshchov I.V.: investigations, software, discussing results, validation, writing – original draft.

Slipchenko M.I.: conceptualization, investigation, writing – review & editing, project administration.

Kostylyov V.P.: conceptualization, validation, analysis, data curation, writing – review & editing.

Концентраторні сонячні фотоприймачі на теплопровідних алюміній-поліімідних лакофольгових діелектриках

В.М. Борщов, О.М. Лістратенко, М.А. Проценко, І.Т. Тимчук, О.В. Кравченко, І.В. Борщов, М.І. Сліпченко, В.П. Костильов

Анотація. У роботі запропоновано нові підходи для створення одиничних високоефективних концентраторних фотоелектричних (КФЕ) приймачів за рахунок зменшення їх маси та витрат при використанні теплопровідних алюмінієвих плат. Розроблено оптимізовані комбіновані друковані плати на жорстких алюмінієвих основах з гнучкими багатошаровими теплопровідними композиційними полімерними термоінтерфейсними діелектриками, які фольговані тонкими полегшеними алюмінієвими покриттями. За допомогою програмного комплексу COMSOL MULTIPHYSICS проведено моделювання залежностей максимальних робочих температур на комбінованих платах від розмірів плат. Досліджено теплові властивості тестових структур якості одиничних КФЕ приймачів з покращеними тепловими характеристиками на основі теплопровідних композиційних поліімідних (ПІ) шарів з теплопровідністю 1,0…3,0 Вт/(м·K) та сучасних високоефективних концентраторних триперехідних сонячних елементів (СЕ) марки 3C44 компанії AZUR SPACE Solar Power GmbH (Німеччина) з підвищеною ефективністю порядку 43,6% при концентрації сонячного випромінювання до $500^{\times}$. Проведено експериментальні дослідження електричних та механічних властивостей удосконалених комбінованих друкованих плат на алюмінієвих основах та більш технологічних лакофольгових алюміній-ПІ діелектриках з середньонаповненою об'ємною концентрацією теплопровідних часток в тонких ПІ шарах порядку 50 об.%, що забезпечують робочі температури плат одиничних КФЕ приймачів в області СЕ не більші за 70…90 °C, та дозволяють підтримувати високу надійність роботи і підвищення строків експлуатації одиничних CPV приймачів за сприятливих умов їх експлуатації.

Ключові слова: КФЕ приймачі, теплопровідні ПІ композиційні матеріали, теплопровідні алюміній-поліімідні лакофольгові діелектрики, тестові структури якості КФЕ приймачів.