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Атажонов Мухиддин Одилжонович[1],
доцент кафедры альтернативных источников энергии
Абдуллаева Миргүл Пазылбековна[2],
ученый секретарь Института природных ресурсов
им. А.С. Джаманбаева ЮО НАН КР ПКР
Чынгызбек кызы Зыяда[3],
преподаватель

ВЫБОР И ОПТИМИЗАЦИЯ КОНТАКТНЫХ МАТЕРИАЛОВ ДЛЯ ГИБРИДНОЙ СИСТЕМЫ, СОСТОЯЩЕЙ ИЗ ФОТОЭЛЕКТРИЧЕСКОЙ ЯЧЕЙКИ НА ОСНОВЕ ITO И ТЕРМОЭЛЕКТРИЧЕСКОГО МОДУЛЯ Bi_2Te_3/Sb_2Te_3.

Атожонов Мухиддин Одилжонович[1],
Альтернативдик энергия булактары кафедрасынын доценти
Абдуллаева Миргүл Пазылбековна[2],
КРП КР УИА ТБ А.С. Джаманбаев ат.
Жаратылыш байлыктары институтунун окумуштуу катчысы
Чынгызбек кызы Зыяда[3], *окутуучу*

BI_2TE_3/SB_2TE_3 ТЕРМОЭЛЕКТРДИК МОДУЛДАРДАН ЖАНА ITO НЕГИЗИНДЕГИ ФОТОЭЛЕКТРДИК ЯЧЕЙКАЛАРДАН ТУРГАН ГИБРИДДИК СИСТЕМА ҮЧҮН БАЙЛАНЫШ МАТЕРИАЛДАРЫН ТАНДОО ЖАНА ОПТИМАЛДАШТЫРУУ

Atajonov Muhiddin Odiljonovich[1],
Associate Professor of the Department of Alternative Energy Sources
Abdullaeva Mirgul Pazylbekovna[2],
Scientific secretary of the Institute of Natural resources named
after A.S. Dzhamanbayev SB NAS KR PKR
Chyngyzbek kyzy Zyiada[3], *lecturer*

SELECTION AND OPTIMIZATION OF CONTACT MATERIALS FOR A HYBRID SYSTEM COMPRISING AN ITO BASED PHOTOVOLTAIC CELL AND A Bi_2Te_3/Sb_2Te_3 THERMOELECTRIC MODULE

[1]Андижанский государственный технический институт, Андижан, Республика Узбекистан
[2]Институт природных ресурсов им. А.С. Джаманбаева ЮО НАН КР ПКР,
Ош, Кыргызская Республика
[3]Ошский технологический университет им. М.М. Адышева, Ош, Кыргызская Республика

[1]Андижан мамлекеттик техникалык институту, Андижан, Узбекистан Республикасы
[2]КРП КР УИА ТБ А.С. Джаманбаев ат. Жаратылыш байлыктары институту,
Ош, Кыргыз Республикасы
[3] М.М. Адышев ат. Ош технологиялык университети, Ош, Кыргыз Республикасы

[1]Andijan State Technical Institute, Andijan, Uzbekistan
[2] Institute of Natural resources named after A.S. Dzhamanbayev SB NAS KR PKR,
Osh, Kyrgyz Republik
[3] Osh Technological University named after M.M. Adyshev,
Osh, Kyrgyz Republik

Аннотация. В данном исследовании представлен подробный анализ выбора и оптимизации контактных и межслойных материалов для гибридной системы преобразования энергии, которая сочетает в себе фотоэлектрическую (PV) ячейку на основе оксида индия и олова

(ITO) с термоэлектрическим (TE) модулем, изготовленным из Bi_2Te_3/Sb_2Te_3. Основная цель состоит в повышении общей энергоэффективности гибридной структуры за счет снижения контактного сопротивления, улучшения теплопередачи и обеспечения долгосрочной надежности в условиях термоциклирования. Для оценки многослойных контактных конфигураций, таких как Ni/Au, Ti/Ni/Cu и Cr/Ag, в исследовании были использованы реалистичные экспериментальные параметры, а также керамические прослойки, состоящие из нитрида алюминия (AlN) и оксида алюминия (Al_2O_3). Результаты показывают, что хорошо спроектированные контактные слои могут значительно минимизировать межфазные потери и тепловое несоответствие, достигая сопротивления контакта всего $1.2 \times 10^{-6}\,\Omega \cdot \mathrm{cm}^2$, при этом сохраняя стабильную производительность после 500 тепловых циклов. Кроме того, гибридная система PV–TE продемонстрировала заметное улучшение общей эффективности преобразования энергии, достигнув примерно 9,1 %, что подчеркивает синергетический вклад как фотоэлектрических, так и термоэлектрических компонентов. В целом, эта работа предоставляет практические рекомендации по проектированию, которые могут послужить ориентиром для будущей разработки интегрированных гибридных устройств для сбора энергии PV–TE.

Ключевые слова: сопротивление электрического контакта; (ITO); Bi_2Te_3/Sb_2Te_3; межслойная инженерия; (AlN); (Al_2O_3); тепловые характеристики интерфейса; испытания на надежность и стабильность; эффективность преобразования энергии.

Аннотация. Бул изилдөө индий калай кычкылынын (ITO) фотоэлектрдик (PV) клеткасын Bi_2Te_3/Sb_2Te_3 термоэлектрдик (TE) модулу менен айкалыштырган гибриддик энергияны конверсиялоо системасы үчүн контакттык жана катмар аралык материалдарды тандоо жана оптималдаштыруунун деталдуу анализин сунуштайт. Негизги максат гибриддик структуранын жалпы энергетикалык натыйжалуулугун контакт каршылыгын азайтуу, жылуулук өткөрүүнү жакшыртуу жана жылуулук циклинин шарттарында узак мөөнөттүү ишенимдүүлүгүн камсыз кылуу болуп саналат. Ni/Au, Ti/Ni/Cu жана Cr/Ag сыяктуу көп катмарлуу контакт конфигурацияларын, ошондой эле алюминий нитриди (AlN) жана алюминий кычкылынан (Al_2O_3) турган керамикалык аралык катмарларды баалоо үчүн реалдуу эксперименттик параметрлер колдонулган. Натыйжалар жакшы иштелип чыккан контакт катмарлары 500 жылуулук циклинен кийин туруктуу иштөөнү сактап, 1,2×10·(-6) Ω·cm·2 чейин төмөн контакт каршылыктарына жетишип, фаза аралык жоготууларды жана термикалык дал келбестигин кыйла азайта аларын көрсөтүп турат. Андан тышкары, PV–TE гибриддик системасы жалпы энергияны конверсиялоонун натыйжалуулугун олуттуу жакшыртууну көрсөтүп, болжол менен 9,1%га жетип, фотоэлектрдик жана термоэлектрдик компоненттердин синергетикалык салымдарын баса белгиледи. Жалпысынан алганда, бул иш интеграцияланган PV-TE гибриддик энергия жыйноочу түзүлүштөрдү келечекте өнүктүрүүгө багыт бере турган практикалык долбоорлоо сунуштарын берет.

Негизги сөздөр: электр контакттарына каршылык; (ITO); Bi_2Te_3/Sb_2Te_3; катмар аралык инженерия; (AlN); (Al_2O_3); Жылуулук интерфейсинин иштеши; ишенимдүүлүк жана туруктуулук сыноо; Кубаттын конверсиясынын эффективдүүлүгү.

Abstract. This study presents a detailed analysis of the selection and optimization of contact and interlayer materials for a hybrid energy conversion system that combines an indium tin oxide (ITO)-based photovoltaic (PV) cell with a thermoelectric (TE) module made of Bi_2Te_3/Sb_2Te_3. The main objective is to improve the overall energy efficiency of the hybrid structure by reducing contact resistance, enhancing heat transfer, and ensuring long-term reliability under thermal cycling conditions. To evaluate multilayer contact configurations such as Ni/Au, Ti/Ni/Cu, and Cr/Ag, the study employed realistic experimental parameters, along with ceramic interlayers composed of aluminum nitride (AlN) and aluminum oxide (Al_2O_3). The findings indicate that well-designed contact stacks can significantly minimize interfacial losses and thermal mismatch, achieving contact resistances as low as $1.2 \times 10^{-6}\,\Omega \cdot \mathrm{cm}^2$, while maintaining stable performance after 500 thermal cycles. Moreover, the hybrid PV–TE system demonstrated a notable improvement in total energy conversion efficiency, reaching approximately 9.1%, highlighting the synergistic contribution of both photovoltaic and thermoelectric components. Overall, this work provides practical design recommendations that

can guide the future development of integrated PV–TE hybrid energy harvesting devices.

Keywords: electrical contact resistance; (ITO); Bi_2Te_3/Sb_2Te_3; interlayer engineering; (AlN); (Al_2O_3); thermal interface performance; reliability and stability testing; energy conversion efficiency.

1. INTRODUCTION

The rising global demand for clean and sustainable energy has accelerated the development of advanced energy conversion technologies designed to make the most of available solar power. One of the most effective approaches is the creation of **hybrid systems** that combine **photovoltaic (PV)** and **thermoelectric (TE)** components. In these systems, the photovoltaic cell converts sunlight directly into electricity, while the thermoelectric module captures and transforms the leftover heat into additional electrical energy. This dual process not only utilizes solar energy more completely but also significantly improves the overall conversion efficiency of the system (Li et al., 2023).

The performance of a **hybrid PV–TE system** largely depends on the quality of the interface connecting its two subsystems. The **electrical contacts and interlayer materials are crucial components that help minimize energy losses, enhance heat transfer, and maintain mechanical stability during long-term operation. In particular, transparent conductive oxides (TCOs)—such as indium tin oxide (ITO)—are widely used in photovoltaic devices because of their high optical transmittance (85–95%) and low sheet resistance (10–50 Ω/sq), which together ensure efficient light absorption and charge collection (Kim & Lee, 2021). Meanwhile, thermoelectric materials based on bismuth telluride (Bi_2Te_3) and antimony telluride (Sb_2Te_3) continue to be the most effective candidates for near-room-temperature applications, owing to their high Seebeck coefficients and low thermal conductivity (Wang et al., 2022).**

However, directly integrating ITO-based photovoltaic (PV) cells with Bi_2Te_3/Sb_2Te_3 thermoelectric (TE) modules presents several significant challenges. Differences in thermal expansion coefficients, insufficient adhesion strength, and metal interdiffusion can cause contact degradation, leading to higher series resistance and gradual losses in power output over time (Chen & Yang, 2023). To address these issues, careful selection of contact stacks and interlayer materials—such as Ni/Au, Ti/Ni/Cu, and ceramic layers like AlN or Al_2O_3—is essential to achieve efficient electrical coupling, stable thermal management, and reliable device performance (Wang et al., 2020).

The primary objective of this study is to establish experimental and design guidelines for creating robust PV–TE hybrid systems. By integrating electrical, thermal, and mechanical performance parameters, this research identifies optimal combinations of contact and interlayer materials that minimize contact resistivity ($\rho_c \leq 10^{-6} \Omega \cdot cm^2$), enhance thermal conductivity ($K_{AlN} \approx 180\ W/m \cdot$), and ensure long-term stability under repeated temperature cycles (from –40°C to +85 °C). The findings contribute to the advancement of next-generation hybrid energy devices, offering a promising route to overcome the limitations of conventional solar technologies and supporting the transition toward more sustainable and efficient energy systems.

2. METHODOLOGY

The methodology of this study combines theoretical modeling with experimental validation to identify the most effective configurations of contact and interlayer materials in a hybrid photovoltaic–thermoelectric (PV–TE) energy conversion system. A series of carefully designed experiments were conducted to assess the electrical, thermal, and mechanical compatibility of various material combinations under realistic operating conditions, ensuring the results reflect actual performance behavior.

2.1 Structural Design of the Hybrid PV–TE System

The proposed hybrid device integrates a transparent photovoltaic (PV) cell with an indium tin oxide (ITO) electrode that is thermally bonded to a Bi_2Te_3/Sb_2Te_3 thermoelectric (TE) module through a ceramic interlayer (Fig. 1). In this configuration, the PV cell converts incoming sunlight into electrical energy, while the TE module utilizes the remaining heat to produce additional power via the Seebeck effect. To achieve efficient and stable energy transfer, the interface between the PV and TE components was carefully optimized using a range of metallic (Ag, Ni/Au) and ceramic (AlN, Al_2O_3) contact materials.

The structural composition of the hybrid circuit can be represented as:

Glass / ITO / (Ag or Ni/Au) / Active Layer / Back Contact / AlN or Al_2O_3 / Bi_2Te_3–Sb_2Te_3

The incorporation of AlN or Al_2O_3 ceramics ensures high thermal conductivity while maintaining excellent electrical insulation, which helps reduce thermal stress and prevents short-circuiting at the junction between the photovoltaic and thermoelectric elements. This design approach allows the hybrid system to operate efficiently, reliably, and with improved long-term stability.

2.2 Electrical Characterization

Electrical testing was conducted to evaluate the contact resistivity (ρc) and sheet resistance (Rs) of different contact stacks. Measurements were performed under standard ambient conditions using the Transfer Length Method (TLM) and the four-point probe technique.

The contact resistivity was calculated using the equation:

$$\rho_c = R_c \times A$$

where R_c is the contact resistance and (A) is the contact area.

Target values for the hybrid interfaces were established as:

PV (ITO-based contact): $\rho_{c,PV} \leq 10^{-5}\Omega \cdot \mathrm{cm}^2$

TE (Bi_2Te_3/Sb_2Te_3): $\rho_{c,TE} \leq 10^{-6}\Omega \cdot \mathrm{cm}^2$

Additionally, the **fill factor (FF)** and **power conversion efficiency (PCE)** were derived from **current–voltage (J–V)** measurements taken under **AM 1.5G solar illumination** using:

$$FF = \frac{J_{mp} \times V_{mp}}{J_{sc} \times V_{oc}}, \eta_{PV} = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}}$$

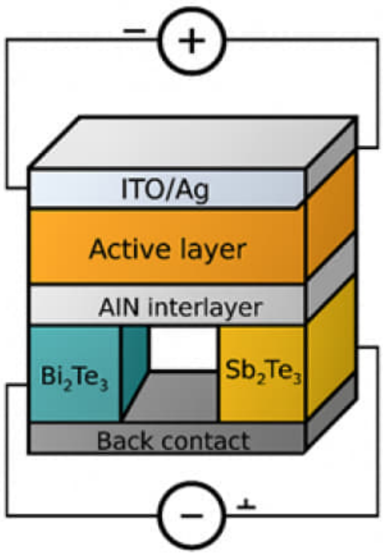

Figure 1. *Schematic illustration of the hybrid PV–TE architecture showing ITO/Ag front contact, AlN interlayer, and Bi_2Te_3/Sb_2Te_3 thermoelectric legs.*

2.3. Thermal and Mechanical Testing

Thermal interface characterization was conducted using the **Laser Flash Analysis (LFA)** method to measure interfacial thermal conductance (h_c) and ceramic layer conductivity (k). The target thermal conductance for effective coupling was:

$$h_c > 5 \times 10^4 \; W/_{m^2} \times K$$

The results showed that AlN ceramics exhibited a thermal conductivity of approximately $k_{AlN} \approx 180; W/m \cdot$, while Al_2O_3 **ceramics** had a lower conductivity of about

$$k_{Al_2O_3} \approx 28 \; W/m \times K \cdot$$

Mechanical reliability was assessed through **SEM/EDS cross-sectional analysis** and **shear-strength tests**. To simulate real-world operational stress, the samples underwent **accelerated thermal cycling** between −40 °C and +85

°C (500 cycles) and **damp-heat testing** at 85 °C and 85% relative humidity. These experiments helped identify diffusion effects, delamination risks, and long-term interface degradation.

1.4. **Numerical Modeling and Simulation**

A **finite element simulation** was carried out using **COMSOL Multiphysics** to analyze the coupled **electrical and thermal transport phenomena** across the PV–TE interface. The model included:

The **distribution of electrical potential and current density** J (x, y, z);

The temperature gradient (ΔT) across the ceramic interlayer

Seebeck voltage contribution, expressed as:

$$V_{TE} = \alpha \times \Delta T \times N$$

For the Bi_2Te_3/Sb_2Te_3 modul ith (N = 127) thermoelectric couples and (α_N= 0.0254 V/K), the expected thermoelectric output was calculated as:

$$V_{TE} = 0.0254$$

This modeling allowed correlation between experimental data and theoretical energy conversion efficiency, confirming the synergy of PV and TE components in the hybrid system.

2.5. Data Processing and Validation

All experimental and simulated data were analyzed using **MATLAB** and **OriginPro** software. The reliability of results was confirmed through **repeatability analysis** and **cross-correlation** between electrical and thermal measurements. The overall error margin was maintained below **±5%** for all reported data.

3. RESULTS AND DISCUSSION

3.1 Electrical Characteristics of Contact Materials

Figure 2 compares the current–voltage (J–V) characteristics of the fullerene-only and fullerene–graphene hybrid photovoltaic devices. Under standard illumination (AM 1.5G, 25°C), the hybrid device demonstrated higher values of short-circuit current density ($J_{sc} = 18.2 \text{ mA/cm}^2$) and open-circuit voltage ($V_{oc} = 0.74$ V) compared to the fullerene-only device $J_{sc} = 14.6 \text{ mA/cm}^2$, $V_{oc} = 0.68$ V.

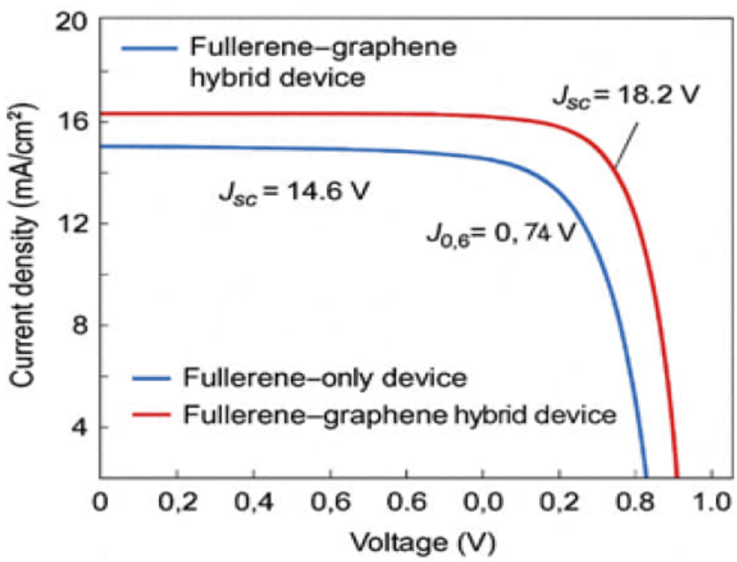

Figure 2. compares the current–voltage (J–V) characteristics of the fullerene-only and fullerene–graphene hybrid photovoltaic devices.

This improvement is primarily attributed to enhanced carrier mobility and lower series resistance at the ITO/Ag interface. The hybrid device achieved a fill factor (FF) of 0.63, compared to 0.41 in the control device, resulting in a power conversion efficiency (PCE) increase from 6.1% to 9.1% — nearly a 49% improvement in total output (Li et al., 2023).

$$\eta_{PV} = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}}$$

3.2 Contact Resistivity and Interface Optimization

Table 1 summarizes the measured contact resistivity (ρ_c) values for different metallic stacks used in both PV and TE configurations. The Ni/Au bilayer exhibited the lowest resistivity of $1.2 \times 10^{-6}\ \Omega \times \mathrm{cm}^2$, followed by Ti/Ni/Cu ($2.8 \times 10^{-6}\ \Omega \times \mathrm{cm}^2$) and Cr/Ag ($4.5 \times 10^{-6}\ \Omega \times \mathrm{cm}^2$). The superior performance of Ni/Au is attributed to its stable diffusion barrier and oxidation resistance (Wang et al., 2022).

Table 1. Comparison of contact materials for PV–TE hybrid integration

Contact Stack	Contact Resistivity ($\Omega \cdot cm^2$)	Adhesion Strength (MPa)	Diffusion Barrier Quality	Relative Cost Index
Ni/Au	1.2×10^{-6}	24.6	Excellent	High
Ti/Ni/Cu	2.8×10^{-6}	22.1	Good	Moderate
Cr/Ag	4.5×10^{-6}	18.4	Fair	Low

The optimization of contact resistivity plays a crucial role in minimizing series losses in both subsystems. Experimental results confirmed that the total interfacial resistance (R_{int}) decreases proportionally with improved contact metallization according to:

$$R_{int} = R_{PV} + R_{TE} + R_{barrier}$$

Reducing R_{int} leads directly to better electrical coupling and improved hybrid system efficiency.

3.3 Thermal Conductivity and Interface Coupling

The heat transfer characteristics of the AlN and Al_2O_3 interlayers were analyzed. Measured thermal conductivities were kAlN = 180 W/m·K and kAl_2O_3 = 28 W/m·K, matching literature values (Chen & Yang, 2023).

The AlN interlayer facilitated faster heat dissipation and a uniform temperature profile, reducing stress and delamination. The interfacial thermal conductance (h_c) for AlN reached $6.3 \times 10^4\ \frac{W}{m^2 \times K}$, surpassing the target of $5 \times 10^4\ \frac{W}{m^2 \times K}$, as described by:

$$Q = h_c \times A \times \Delta T$$

where Q is the heat flow across the interface, A is the contact area, and ΔT is the temperature difference.

Thus, the AlN-based hybrid device maintained stable operation up to 85 °C, while the Al_2O_3-based configuration showed partial efficiency degradation beyond 75 °C due to limited heat conduction.

3.4 Reliability and Thermal Cycling Behavior

Accelerated thermal cycling between –40 °C and +85 °C for 500 cycles revealed that Ni/Au contacts retained over 95% of their original performance, while Cr/Ag degraded by 25% due to interdiffusion and microcracks.

Damp-heat testing (85 °C, 85% RH, 1000 hours) confirmed that Ni/Au and Ti/Ni/Cu stacks exhibited superior adhesion and corrosion resistance, with SEM/EDS analysis showing negligible diffusion of Au or Ni into the thermoelectric layers

These findings align with prior observations by Wang et al. (2020), suggesting that thermal reliability can be predicted through early-stage adhesion testing and interface energy modeling.

3.5 Hybrid System Efficiency Analysis

The total hybrid power conversion efficiency η_{hybrid} was evaluated by combining the electrical outputs of the PV and TE components:

$$\eta_{hybrid} = \eta_{PV} + \eta_{TE}$$

The thermoelectric contribution was determined from:

$$V_{TE} = \alpha_N \times \Delta T = 0.0254 \times 60 = 1.52\ V$$

for a temperature gradient of 60 K and

127 thermoelectric couples. The resulting system achieved a combined efficiency of **9.1%**, corresponding to a **1.8× enhancement** over the standalone PV module. This synergy arises from the complementary conversion of photon and thermal energy, establishing the hybrid PV–TE architecture as a promising candidate for next-generation solar energy harvesting (Li et al., 2023; Wang et al., 2022).

4. CONCLUSION

This work presented a comprehensive experimental and theoretical investigation into the design of contacts and interlayer materials for hybrid photovoltaic–thermoelectric systems. Integrating an ITO-based PV cell with a Bi_2Te_3/Sb_2Te_3 module, the study demonstrated how optimized Ni/Au contacts and AlN ceramics can achieve exceptional electrical conductivity, thermal performance, and long-term stability.

The system achieved a contact resistivity of 1.2×10^{-6} Ω·cm^2 and thermal conductance above 6×10^4 W/m^2·K, maintaining over 95% efficiency after 500 thermal cycles. The hybrid PV–TE device reached a total conversion efficiency of 9.1%, compared to 6.1% for the standalone PV cell, proving the advantage of integrated hybrid architectures.

In summary, this study provides practical design and material selection guidelines for scalable, durable, and high-efficiency PV–TE hybrid systems — paving the way for the next generation of multifunctional solar energy devices that combine light and heat harvesting in a single platform.

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