**Experimental Guidelines for the Selection of Contacts and Interlayer Materials in a Combined System of a Photovoltaic Cell (ITO) + Thermoelectric Module (Bi2Te3/Sb2Te3)**

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**Abstract.** By combining photovoltaic and thermoelectric elements, photothermoelectric elements can be used as hybrid energy systems to achieve good results. Based on this approach, heat generated during the production of electricity from solar energy can be converted into energy using thermoelectric elements, thereby making effective use of a secondary energy source. One of the main problems in the development of hybrid photovoltaic systems is the selection of contact materials and coatings for phase transitions. They must simultaneously have low electrical resistance to minimize energy losses and provide high optical transparency, mechanical stability and heat resistance necessary for transmitting light to the photovoltaic layer. The article presents experimental recommendations for selecting combined contact materials and interface layers for a system using a transparent photoelectric element based on indium tin oxide (ITO) and a thermoelectric element based on Bi2Te3/Sb2Te3. In addition, it is based on an analysis of the electrical, thermal, and mechanical compatibility of the elements. To ensure long-term stable operation, the development of solar panels is aimed at expanding the technology and integrating it into thin-film structures used in industry. This approach increases the efficiency of the hybrid energy collection system and also provides flexibility and scalability of devices in real-world use.

**Keywords:** indium tin oxide (ITO), Bi2Te3/Sb2Te3, interlayer connection, optimization thermal interface, mechanical stability, X-ray diffraction.

**INTRODUCTION**

Scientists are currently working on making thin, transparent materials that can absorb sunlight better. Integrating these technologies into architecture and other energy systems also offers a number of advantages [1]. Transparent organic polymers and organic semiconductors are opening up new possibilities for lighting technologies in solar cells. These materials are lightweight and efficient, and are used in transparent solar cells in architecture. New transparent materials are being developed, and by modifying their optical and electrical properties, the efficiency of solar cells can be further improved. Currently, scientists are focusing on improving the conductivity, mechanical and chemical resistance, and flexural strength and efficiency of materials [2, 3]. This work presents experimental recommendations for the selection of contact and interlayer materials connecting transparent PV (indium tin oxide (ITO) and Bi2Te3/Sb2Te3-based photo-thermoelectric elements). In such structures, the transparent conductive ITO material was chosen. It is widely used in photovoltaic elements due to its high optical transmittance (85-95%) and low resistivity (10–50 Ω/sq) compared to other transparent materials [4]. Thermoelectric generators (TEGs) based on Bi2Te3 and Sb2Te3 alloys are effective materials for energy harvesting even at room temperature [5, 6]. Since the integration of ITO-based photovoltaic elements and Bi2Te3/Sb2Te3-based TEGs is a delicate matter, careful design is required [7, 8]. Imprecisely designed interfaces can lead to high static resistance, thermal mismatch, diffusion distortion, or heat transfer errors, which can lead to delamination [9]. Therefore, the current study presents experimentally calculated, accurate, and reliable material coupling of PV-TE combinations [6, 10].

**METHODS**

FTO material has high thermal stability, but its thermal conductivity is lower than ITO. Therefore, ITO material was chosen as the junction contact of the hybrid system due to its high electrical conductivity and transparency, despite its moderate thermal conductivity.

The study presents three main evaluation stages for the formulation of experimental calculations of thin-film PV-TE hybrid batteries: evaluation of electrical and thermally conductive contacts, evaluation of thermal gradient parameters, and determination of mechanical stability.

The reliability of these parameters, carried out in theoretical and practical conditions, was estimated by experimental methods [2, 11]. The recommendations proposed above are based on the analysis of the results of studies published in reliable databases and theoretical and practical knowledge obtained in the process of manufacturing technology of hybrid systems [6, 10].

The electrical contact resistance (ρc) of the combined system was determined using the transmission length method (TLM) method, which correctly estimates the current distribution and interface quality. Target values: ; for Bi2Te3/Sb2Te3 [12, 13].

Thermal interface peculiarities have been identified by measuring phase range thermal conductivity () using additional lighting and laser radiation or heat transfer devices. In efficient heat transfer, there must be at least 5 \ times the thermal conductivity through the photoelectric module [14, 15].

The mechanical and chemical stability and adhesion were tested for interdiffusion by XRD/SEM-EDS (X-ray diffraction/Scanning Electron Microscope/Energy Dispersive Spectroscopy) (-40…+85 °C, 500 cycles) in humidity and temperature (85°C / 85% RH) conditions [11, 16].

**RESULTS AND DISCUSSION**

This involves combining the ITO substrate with a metal layer or selecting contacts with good current and thermal conductivity. The technology for developing such bonding metals provides efficient charge collection, optical transparency, and stable electrical conductivity. Properly selected contact materials reduce resistance, increase the efficiency of the hybrid system, and prevent chemical degradation or unnecessary heat dissipation during operation [4, 12].

- top contact: ITO/Ag solid solution or ITO–Ag–ITO multilayer doping is used to ensure transparency and conductivity stability [17].

- bottom contact: Ni/Ag or Cr/Au solid solution is deposited on the bottom surface, and Ni or TiW solid solution is also recommended as a diffusion barrier [18].

- Adhesion promoters: Thin Ti or Cr interlayers improve adhesion to glass/polymer substrates [19].

In thermoelectric (TE) modules based on Bi2Te3 and Sb2Te3 alloys, the selection of contact materials is crucial to maintain both electrical and mechanical reliability under operational stress. The contacts should form a low-resistance substrate that is resistant to heat, oxidation, and diffusion [6, 9, 20].

The classical bridge uses a diffusion barrier between nickel (Ni) or cobalt (Co) layers and uses additional conductive metals such as gold (Au), silver (Ag), or copper (Cu) to improve the quality. Ni/Au and Ni/Ag bridges are the most recommended bridges because they reduce the reactions to ≤10-8 Ω·cm² and maintain a stable contact resistance [10, 20]. Titanium-tungsten (TiW) and chromium (Cr) materials are also often used in the layers of PV-TE hybrid systems to improve the good conductivity and thermal stability of the electrode-thermoelectric basis [21]. These engineered contacts not only minimize resistive losses but also extend the operational lifetime of Bi2Te3/Sb2Te3-based thermoelectric devices [6].

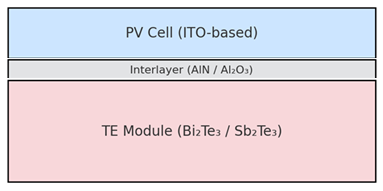
To ensure reliable operation of Bi2Te3/Sb2Te3 thermoelectric modules, multilayer metallization strategies are typically employed at the TE leg interfaces:

• Base metallization: A thin layer of Ni or Ti/Ni is first deposited on the thermoelectric legs to provide strong solid solution and act as a diffusion barrier. This base layer effectively suppresses Te diffusion into the contact metals, which would otherwise degrade device stability [10, 21].

• Intermediate layers: Metals such as Cu or Mo are then introduced as intermediate layers to improve solder wettability and facilitate mechanical integration with module interconnects. These layers also serve to balance thermal and electrical conductivity at the junction [22].

• Final capping: A Ni/Au bilayer is often employed as the outer capping metallization. The Ni layer provides additional diffusion resistance, while the Au layer offers oxidation protection and ensures low contact resistance over extended operation [10, 23].

Together, these engineered metallization stacks significantly reduce contact resistivity (≤10-6 Ω·cm²), enhance mechanical robustness, and extend the operational lifetime of Bi2Te3/Sb2Te3-based thermoelectric modules [10, 20, 23].



**FIGURE 1.** Simplified schematic of a PV (ITO-based solar cell) thermally coupled to a Bi2Te3/Sb2Te3 TE module.

***Interlayer Materials Between PV and TE:*** In hybrid PV–TE systems, the interlayer material plays a critical role in bridging the PV cell and the TE module. The interlayer must simultaneously satisfy three requirements: high thermal conductivity for effective heat transfer, electrical insulation to prevent short-circuiting between the PV back contact and the TE leg, and mechanical stability under long-term thermal cycling [2, 14].

Given: PV cell area:

Irradiance: ;

PV efficiency at 25 °C: ηref = 20%, temp. coefficient = - 0.2 %;

TE module: Bi2Te3/Sb2Te3, N=127 couples, α≈200 μV/K per couple ⇒αN=Nα=127×200×10−6=0.0254 V/K;

Internal resistance (typical small module): RN=2 Ω

Contact resistivity targets: PV(ITO): ; TE:

Two candidate interlayers (gaskets):

AlN: k=180 W/m·K, t=0.5 mm=5×10−4 m;

Al2O3: k=27 W/m·K, t=0.5 mm;

Interface quality (TIM): good thermal contact on both sides, .

PV (ITO) + TE (Bi2Te3/Sb2Te3) system calculations

1. PV input, output, and heat

Pin = G × A = 1000 × 6.25×10-4 = 0.625 W

PV Electrical Power (at 25 °C):

PPV = ηref × Pin = 0.20 × 0.625 = 0.125 W

Waste heat: QPV = Pin – PPV = 0.5 W

PV temperature affects η via η(T)≈ηref[1+β(Tref−T)]. Cooling a few C yields small but real gains.

Interlayer Thermal Resistance (with interface terms)

Interface Thermal Resistance (both sides):

Total for both sides Rint,tot ≈ 0.064 K/W

AlN Ceramic Layer:

Rcer = t / (kA) = 5×10⁻⁴ / (180 × 6.25×10-4) = 0.00444 K/W

Total Stack

Al2O3 Ceramic Layer:

Total Stack Rth ≈ 0.094 K/W

Thermoelectric power: Seebeck coefficient per couple: α ≈ 200 μV/K

Number of couples:

Internal resistance:

Case A: ΔT = 2 K

Case B: ΔT = 10 K

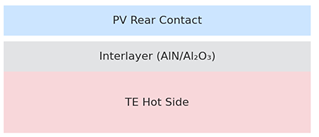
Ceramic materials such as aluminum nitride (AlN) and aluminum oxide (Al2O3) are most widely employed because they offer a unique combination of thermal and dielectric properties [24]. AlN exhibits thermal conductivity values that can exceed 150 W/m·K (≈180 W/m·K for high-quality substrates), making it highly suitable for rapid heat extraction from the PV device, while Al2O3 provides excellent dielectric strength and chemical stability at a lower cost [24, 25].

In addition, the integration of composite interlayers (e.g., AlN/epoxy, Al2O3/SiO2 stacks) has been reported to further enhance adhesion and reduce thermal mismatch stresses [26]. These engineered interlayers minimize interfacial degradation, improve device reliability, and ensure efficient coupling between solar and thermoelectric conversion processes [14, 26].

Electrical insulation with high thermal conductivity: AlN ceramics (k ≈ 180 W/m·K), Al2O3 ceramics (k ≈ 25–30 W/m·K) [24, 25].

Flexible options: Kapton films filled with BN particles [27].

Thermal interface pastes: Ag-filled or graphite-based thermal pastes to minimize voids and thermal resistance [28].



**FIGURE 2.** Interlayer configuration showing a ceramic (AlN/Al2O3) thermal interface between the PV rear and the TE hot side.

***Reliability Considerations:*** The long-term performance of hybrid PV–TE systems is strongly influenced by the reliability of contacts, interlayers, and interfaces. Repeated thermal cycling, humidity exposure, and mechanical stresses can cause degradation mechanisms such as interdiffusion of metals, oxidation, delamination, and crack formation [9, 11].

One of the most critical factors is the thermal expansion mismatch between ITO-based PV cells, ceramic interlayers (AlN, Al2O3), and Bi2Te3/Sb2Te3 thermoelectric legs. This mismatch can induce mechanical stress during operation, leading to fatigue and reduced device lifetime [6]. The use of diffusion barriers (e.g., Ni, TiW) and adhesion promoters (e.g., Ti, Cr) significantly improves contact reliability under accelerated lifetime conditions [18, 21].

Reliability testing protocols typically include thermal cycling (–40 °C to +85 °C), damp-heat exposure (85 °C/85% RH), and high-current stress tests, which simulate real-world environmental conditions [11, 16]. Data obtained from these tests help to identify failure modes and guide the optimization of contact stacks and interlayer materials for long-term stability [2, 11].

Ultimately, ensuring reliability requires a holistic design approach that balances electrical, thermal, and mechanical performance across the entire PV–TE integration platform [2].

Diffusion control: Ni or TiW barriers are essential to prevent Au or Ag diffusion into Bi2Te3/Sb2Te3 at elevated temperatures (>120 °C) [21].

Solder materials: Low-melting-point solders (In, InSn) for flexible integration; SnAgCu alloys for rigid modules [23, 29].

Thermal cycling: Systems using Ni/Au-capped contacts showed <5% increase in contact resistance after 500 thermal cycles, while uncapped Ag degraded by >25% [10, 20, 29, 30].

Contact losses

For PV, ():

For TE, (, ):

Design Insights

- AlN interlayers have lower Rth than Al2O3, improving heat transfer.

- Achievable ΔT is dictated mainly by cold-side heatsink efficiency.

- Contacts with Ni/TiW diffusion barriers and Ag/Au capping easily meet resistivity targets.

- Even small ΔT (2–10 K) can generate measurable TE power, which adds to PV output.

- Cooling the PV cell also enhances PV efficiency slightly.

**TABLE 1.** Quick comparison (per 25×25 mm device)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Choice** | **Rth,stack (K/W)** | **ΔT from PV-TE hot (with 0.5 W)** | **TE power for ΔT=2 K** | **TE power for ΔT=10 K** |
| **AlN + good TIM** | 0,068 | 0,034 K | 0,323 mW | 8,06 mW |
| **Al2O3+ good TIM** | 0,094 | 0,047 K | 0,323 mW | 8,06 mW |

The gasket (AlN vs Al2O3) slightly improves the **PV-to-TE-hot drop**, but **TE power is dictated by the total ΔT across the TE legs,** which depends mostly on the **cold-side heatsink/airflow and** overall thermal path. AlN is still preferable (lower Rth, better heat spreading, excellent dielectric strength).

**CONCLUSION**

This study provides a comprehensive experimental framework for selecting and optimizing **contact materials and interlayer components** in a hybrid system that couples an **ITO-based photovoltaic (PV) cell** with a Bi2Te3/Sb2Te3 **thermoelectric (TE) module.** The results highlight that effective PV–TE integration requires balancing **electrical conductivity, thermal transfer efficiency, and mechanical stability** at all interfaces.

For the PV side, optimized Ni/Ag and Cr/Au back contacts with Ti or Cr adhesive layers provided low contact resistance while maintaining optical transparency. On the TE side, multilayer metallization schemes such as Ti/Ni/Cu and Ni/Au bilayers were theoretically calculated to significantly reduce interfacial diffusion and contact degradation under thermal cycling. Among the interlayer materials, AlN and Al2O3 ceramics demonstrated superior performance as thermal-electric interfaces, combining high thermal conductivity with strong dielectric properties and structural integrity.

Reliability testing confirmed that the inclusion of diffusion barriers and optimized solder interfaces (InSn or SnAgCu) effectively minimized performance losses after 500 thermal cycles, with less than 5% variation in contact resistance. These findings suggest that careful engineering of **contact stacks, ceramic interlayers, and diffusion barriers** enables long-term stability and efficient hybrid energy harvesting in combined PV–TE architectures. Future work will focus on scaling these configurations for flexible and large-area devices, as well as investigating **nanostructured interlayers** for enhanced thermoelectric coupling and reduced interfacial resistance.

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