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Enhancing the Power Output of a Thermoelectric Generator through Flexible Composite Substrates and by Improving the Structural Design of a Heteromorphic Electrode#

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ABSTRACT

An advanced composite substrate for the thermoelectric generator is prepared to enhance optical-thermal performance. The process includes precise blending of polydimethylsiloxane, graphene, curing agent, and ethyl acetate. Experimental validation and simulation-based studies through COMSOL Multiphysics software version 5.6 are conducted to ensure precise designs, yielding top-notch substrates for efficient thermoelectric generator applications. The numerical simulations highlight the significance of heteromorphic electrode configurations, with the triangular structure exhibiting a higher power density of 195.168μW/cm^2.

This research scrutinizes the scientific basis for adopting this composite substrate through experimental tests. The surface morphology is thoroughly analyzed using scanning electron microscopy, while Fourier Transform Infrared Spectroscopy is utilized to evaluate the composite substrate's sunlight absorbance for energy harvesting purposes. Additionally, hot wire techniques are employed to precisely quantify thermal conductivity, thus confirming the substrate's effectiveness in enhancing thermoelectric efficiency.

Keywords: composite substrate, energy harvesting, optimization, thermoelectric generator, performance evaluation

NONMENCLATURE

Abbreviations	
f-TEG	Flexible Thermoelectric Generator
TEG	Thermoelectric Generator
Symbols	
A	Absorbance
L	Path length
R_L	Load resistance (Ω)
r	Internal resistance (Ω)
ε	Molar absorption coefficient

1. INTRODUCTION

The ongoing research primarily targets optimizing thermoelectric generator geometric parameters [1][2][3], which are crucial for enhancing the figure of merit and selecting materials to boost output performance [3][4]. Experimental investigations of the proposed composite substrate and a comprehensive analysis of numerical simulations are undertaken to evaluate a three-dimensional TEG device tailored for energy harvesting from human body temperature, emphasizing a structurally efficient thermal design.

The proposed enhancements aim to maximize the utilization of temperature differentials between the human body and its surroundings. Strategies include reinforcing the thermal conductivity of flexible substrates, integrating different-shaped fins for optimized heat dissipation, and refining the structure of heteromorphic electrodes.

Although flexible thermoelectric generators(f-TEGs) hold promise for renewable energy solutions [5], they encounter challenges such as low utilization rates [6], low conversion efficiencies [7], and stability issues in temperature differentials [8]. These stem from factors like parasitic thermal resistance [9] and the limited figure of merit [10] of existing thermoelectric materials. These obstacles contribute to suboptimal power outputs and substantial material costs, exacerbated by inherent stretchability and thermal resistance limitations [11].

The current study aims to enhance the power output of TEG by filling the gap observed so far by considering factors such as thermoelectric materials, heat sink structure, TEG mounting position, and ambient thermal conditions. Precise design decisions directly impact TEG output power, highlighting the importance of careful planning in their development.

This research provides the optimum performance of thermoelectric generator with optimum material

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properties, geometric parameters, and a detailed structural design. It combines numerical simulation and experimental activities to develop an efficient thermoelectric generator for harvesting energy from human body temperature to power small-scale wearable electronics. The generator can harvest energy by introducing heteromorphic electrodes with different structures and a novel composite substrate capable of harvesting energy from human body temperature.

2. MATERIAL AND METHODS

The proposed model incorporates p-type and n-type thermoelectric legs constructed from bismuth antimony telluride ($Bi_{0.4}Sb_{1.6}Te_3$) and bismuth selenium telluride ($Bi_{1.7}Te_{3.7}Se_{0.3}$), respectively. The approach utilizes a flexible composite substrate made of polydimethylsiloxane (PDMS) and graphene.

3. RESULTS AND DISCUSSION

3.1 Fabrication process of a flexible stretchable composite substrate for energy harvesting from human body temperature and sunlight

The initial step in constructing the thermoelectric generator with a flexible and stretchable substrate involved the preparation of a composite substrate. This process, aimed at enhancing the substrate's optical-thermal performance, comprised a series of sequential actions. Firstly, a meticulous blend was formulated by thoroughly combining 10 grams of polydimethylsiloxane (PDMS), 0.5 grams of graphene, 1 gram of base curing agent, and 1.15 grams of ethyl acetate. Emphasis was placed on achieving an even distribution of the graphene within the PDMS matrix to optimize the substrate's optical and thermal characteristics. Once the mixture reached homogeneity, it was carefully poured into an appropriate mold or container, with particular attention paid to achieving uniform spreading for consistent substrate thickness. A flat tool or planar surface was utilized to level the mixture to eliminate any potential air bubbles formed during pouring.

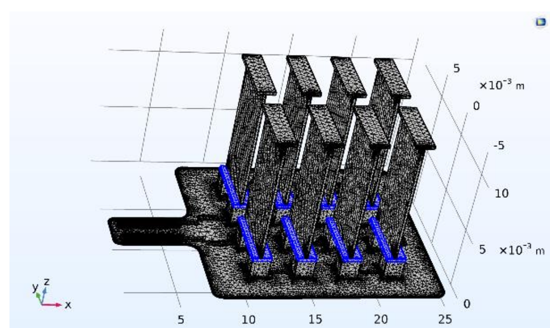
Following the substrate preparation, a vacuum de-gassing procedure was performed to eliminate any residual air bubbles trapped within the mixture. The substrate, housed within a mold, was positioned in a vacuum chamber where vacuum pressure was applied for a designated period. This method facilitated the expulsion of air bubbles, thereby augmenting the mechanical and optical attributes of the composite substrate.

Subsequently, the substrate underwent a curing phase involving exposure to an elevated temperature of 70°C for four hours. The specific temperature and duration varied depending on the mixture composition, desired mechanical properties, and substrate thickness.

An ethyl acetate solution was employed to eradicate any remaining impurities or contaminants. Ethyl acetate, renowned for its ability to dissolve a wide array of organic compounds without causing harm to the substrate, was utilized for this purpose. After vacuum drying, the substrate underwent vacuum plasma cleaning to achieve surface purification and activation.

Fig. 1 (a) showcases the 3D model generated via COMSOL Multiphysics software version 5.6. The model comprises a substrate measuring 42mmX38 mmX240µm, while the thermoelectric legs are sized at 1.4 mm X 1.4 mm X 1.6 mm. Within this investigation, the fin height is established at 10.75mm. Utilizing the stationary solver with pseudo-time-stepping and residual termination criteria facilitated the simulation. The discretized model maintained an average element quality of 0.671, ensuring precise simulation outcomes.

To assess grid independence, a constant load resistance of 0.51Ω was applied. Among the models tested, the one with 545,418 grids exhibited the closest match to experimental results used for validation, boasting a relative voltage error of merely 0.996%. Consequently, the model featuring 545,418 grids was chosen for further simulation iterations.



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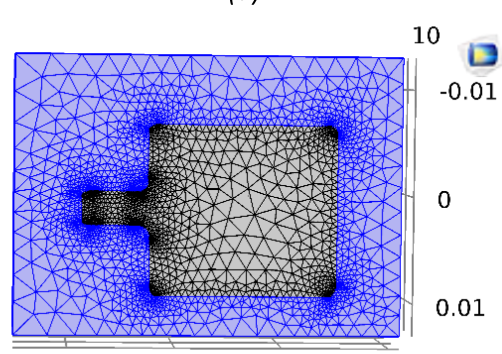

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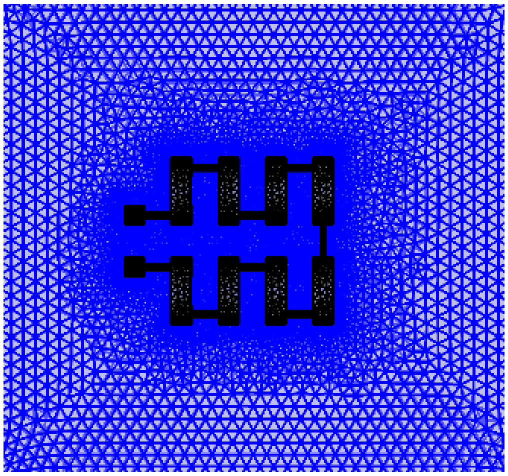

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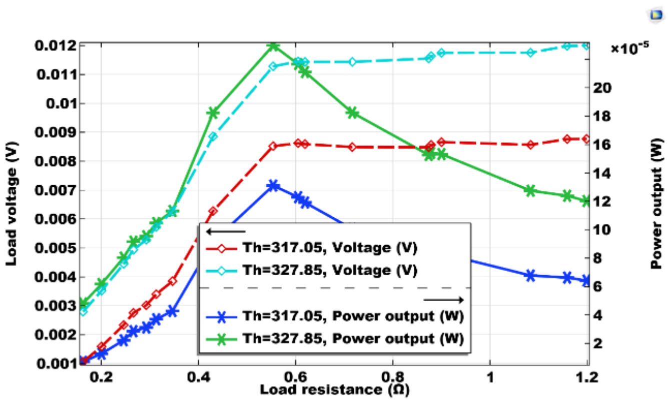

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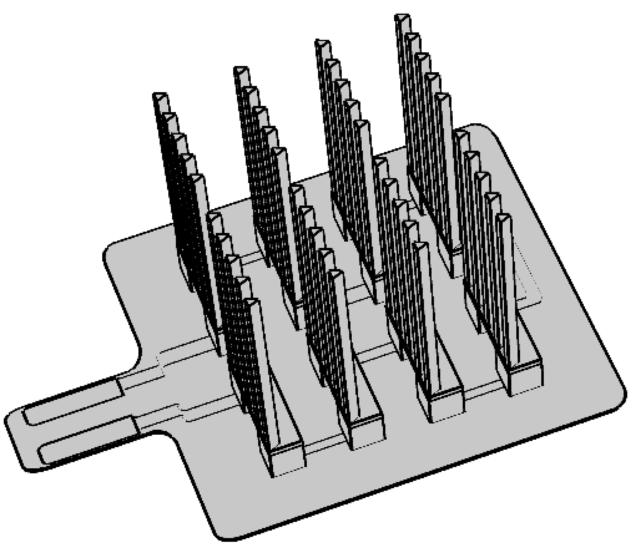

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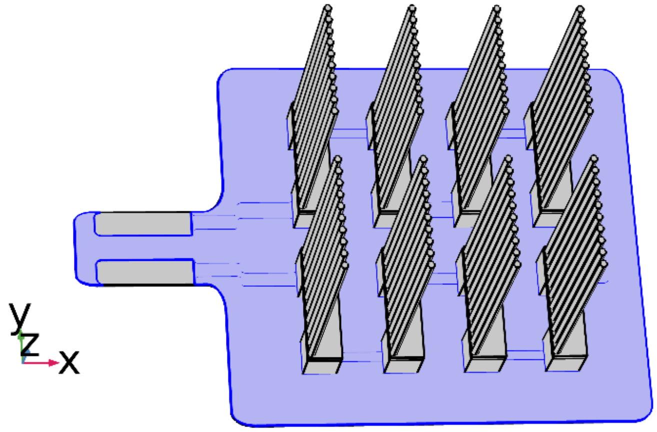

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Fig. 1 3D COMSOL Multiphysics model: a) Flexible thermoelectric generator (f-TEG) with rectangular T-shaped fins; b) Meshing of f-TEG along the side of the substrate; c) Meshing of f-TEG along the side of the heat sink; d) Power output (W), load voltage (V) vs. load resistance (Ω); e) f-TEG featured with triangular shaped heteromorphic electrode fins; f) f-TEG featured with circular shaped heteromorphic electrode fins

Load resistance (Ω)	Upstream temperature [K]	Power output (µW)
0.24	301.8780	242.2211
0.32	301.4140	255.6908
0.42	300.9200	261.7171
0.51	**300.5270**	**262.6183**
0.62	300.2085	254.1127
0.71	299.8936	251.3184
0.81	299.6440	243.6777
0.91	299.4400	235.1154

Table 1. Power output for all specified combinations of load resistance (Ω) and upstream temperature [K] of f-TEG integrated with triangular shaped fins

Analysis derived from this numerical simulation result indicates a notable influence of heteromorphic electrode structural alterations on the power output of thermoelectric generators. Three distinct structural variations were evaluated for analysis: rectangular, triangular, and cylindrical heteromorphic electrodes, each subjected to simulation modeling. Results revealed that the model featuring cylindrical structured heteromorphic electrodes exhibited lower power output than the other two configurations.

Conversely, the model incorporating rectangular structured heteromorphic electrodes demonstrated moderate performance, yielding a maximum power output of 232.064μW.

To analyze the triangular structural changes in heteromorphic electrodes, we employed eight distinct load resistances: 0.24Ω, 0.32Ω, 0.42Ω, 0.51Ω, 0.62Ω, 0.71Ω, 0.81Ω, and 0.91Ω, paired with corresponding upstream temperatures of 301.8780[K], 301.4140[K], 300.9200[K], 300.5270[K], 300.2085[K], 299.8936[K], 299.6440[K], and 299.4400[K]. Concurrently, we recorded power outputs of 242.2211μW, 255.6908μW, 261.7171μW, 262.6183μW, 254.1127μW, 251.3184μW, 243.6777μW, and 235.1154μW, respectively. These results illustrate an increment of 13.61%, 12.87%, 12.298%, 11.63%, 11.20%, 12.32%, 10.81%, and 11.78% across various load resistances as compared to rectangular heteromorphic electrode, attributable solely to the structural modifications in the heteromorphic electrode, with a peak power output of 262.6183μW.

Notably, this design alteration yielded an 11.63% enhancement in power output beyond the maximum of 232.064μW achieved with a rectangular electrode configuration. Optimizing both the substrates and the structural design of heteromorphic electrodes is essential for enhancing the performance of thermoelectric generators.

3.2 Temperature distribution analysis along the composite substrate used in energy harvesting in a thermoelectric generator

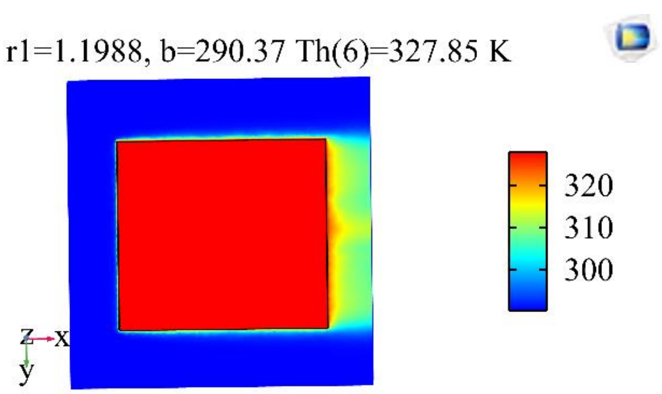

Fig. 2 Temperature distribution across the surface of the proposed thermoelectric generator with a flexible, stretchable substrate at a load resistance of 0.51Ω, an internal resistance of 1.1988 Ω, and an ambient temperature of 290.37 K

As shown in Fig. 2, measurements at a wind speed of 3.18 m/s reveal a load voltage of 8 mV and a hot side temperature of 327.85 K, attributed to the photothermal effect.

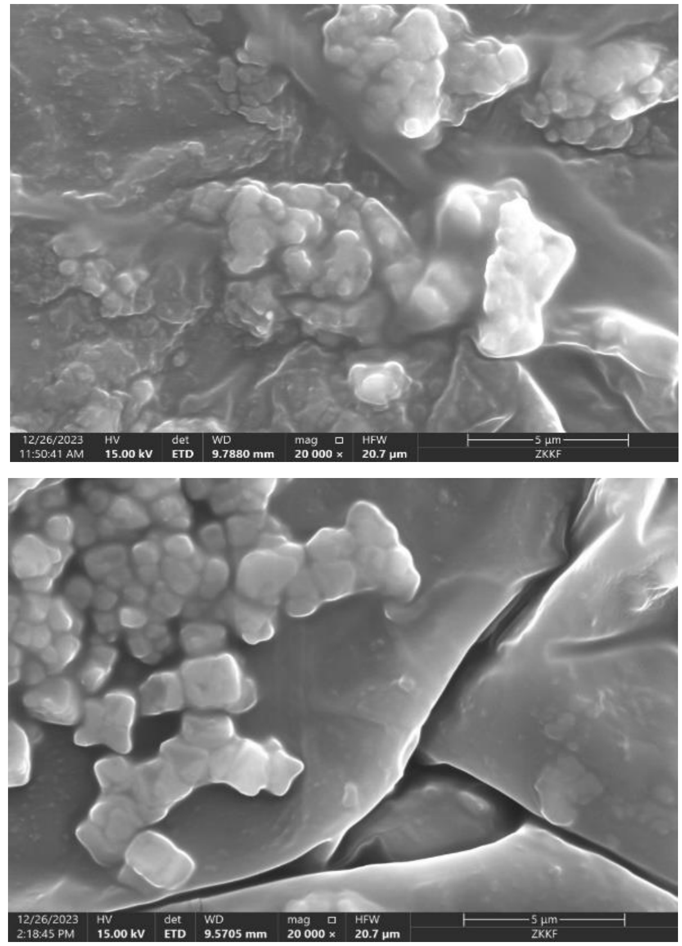

Fig. 3 The scanning electron microscopy image of a composite substrate for enhanced thermoelectric generator energy harvesting capabilities

The composite substrate, derived from a meticulously formulated mixture, presents a compelling amalgamation of materials tailored for optimal thermoelectric performance. The mixture comprises 10 grams of polydimethylsiloxane (PDMS), 0.5 grams of graphene, 1 gram of base curing agent, and 1.15 grams of ethyl acetate. This composition embodies a strategic balance between flexibility, conductivity, and stability, which is crucial for effective energy conversion in TEG applications.

The scanning electron microscopy (SEM) image, at a magnification range of 2500 to 20,000, delineates the composite substrate's microstructural features with remarkable clarity. The surface morphology reveals a homogeneous dispersion of carbon powder within the PDMS matrix, forming a network of interconnected pathways conducive to efficient heat transfer and electrical conductivity. The presence of the base curing agent ensures structural integrity and adhesion, further enhancing the substrate's durability and reliability under varying operating conditions.

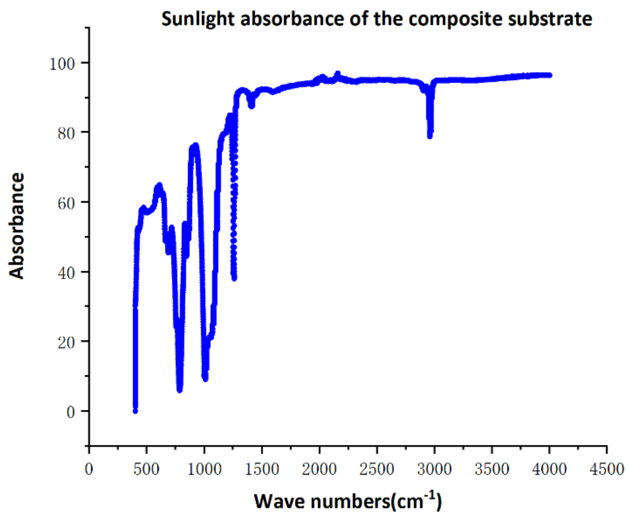

Fig. 4 Sunlight absorbance of the proposed composite substrate to harvest energy

Within the Fourier Transform Infrared Spectroscopy (FTIR), grasping absorption rates are pivotal and are often examined through the Beer-Lambert Law. This foundational concept, encapsulated in A=εlc [12], elucidates the complex relationship between absorbance (A), molar absorption coefficient (ε), path length (l), and concentration (c).

Shifting from absorbance to transmittance (%T) further clarifies this connection, expressed as %T=10^(-A)·100. Specifically, the absorption percentage requires meticulous examination at a specified wavenumber of 1000cm^-1, with an absorbance of 1.225. Utilizing the Beer-Lambert Law with incident light intensity (Io) set as a reference value of 1, the transmitted light intensity (I) is determined to be 0.05956. Consequently, the percent transmittance at 1000cm^-1 wavelength is calculated as 5.9566%, while absorbance constitutes 94.04%. These crucial metrics encapsulate the essence of molecular interactions at this wavelength, unveiling the intricate interplay between light and matter.

No	Experimental Temperature/K using 1V.	Thermal Conductivity (W/(m·K))
1	301.20	0.1828
2	301.21	0.1827
3	301.15	0.1832
4	301.16	0.1829
Average	**301.21**	**0.1829**

Table 2. Experimental temperature and the thermal conductivity value of the proposed composite substrate

The thermal conductivity of a composite substrate, a combination of Polydimethylsiloxane and graphene, was assessed through hot wire techniques, yielding a precise value of 0.1829 W/(m · K). This crucial measurement indicates the material's efficient heat conduction, vital for thermoelectric generators.

4. CONCLUSION

Improving the power output of thermoelectric generators entails developing a flexible, stretchable composite substrate to optimize optical-thermal performance and structural design enhancements for heteromorphic electrodes.

Validation through COMSOL Multiphysics simulations ensures the design's accuracy, with selected models exhibiting minimal relative voltage errors. Moreover, numerical simulations highlight the critical role of heteromorphic electrode configurations in shaping the performance of thermoelectric generators with flexible, stretchable substrates. Evaluation of three structural variations – rectangular, triangular, and cylindrical reveals varied performance outcomes. Notably, thermoelectric generator with a triangular structure heteromorphic electrode achieves a peak power output of 262.6183μW at a load resistance of 0.51Ω. The effective area of the thermoelectric generator with a flexible and stretchable substrate, being 1.3456cm^2, produces a power density of 195.168μW/cm^2.

With a thermal conductivity of 0.1829W/(m·K) and outstanding sunlight absorption performance of 94.04%, the composite substrate shows promising potential for localized heat generation and improved temperature gradients across thermoelectric legs.

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