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Thin-film solar thermoelectric generator with enhanced power output: Integrated optimization design to obtain directional heat flow

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ABSTRACT

Thin-film STEGs (solar thermoelectric generators) show promise in effective use of solar energy as a power supply for wireless sensors and microscale devices. This paper reports a simulation procedure that aims to identify desirable heat flow and temperature distribution to improve the performance of thin-film STEGs. The temperature distribution, heat flux, and voltage of a thin-film STEG are simulated using the finite element method, resulting in an optimal design of the substrate, heat conductive layer, and thermoelectric legs of thin-film STEGs. The effect of air convection on the STEG's performance is also studied. Based on the simulation, a thin-film STEG was designed and fabricated, which exhibits an open-circuit voltage of 22 mV. In addition, the experimental results demonstrate that the measured temperature distribution is in good agreement with the simulated result. To minimize the heat loss from the passive region of the device, an improved design was created in an attempt to confine the heat flow within the thermoelectric legs. This improved design resulted in a 21.4% increase of the output voltage.

1. Introduction

Recent advances in STEGs (solar thermoelectric generators) have demonstrated the potential of using these devices to convert solar energy into electricity [1–9]. In a STEG device, the solar irradiation is initially converted into thermal energy in a solar absorber, and in turn, the thermal energy is converted into electricity using TE (thermoelectric) materials based on the Seebeck effect. To improve the performance of a STEG, a key challenge is to establish a large temperature difference across the TE device with a relatively low irradiation flux. One approach to produce a larger temperature difference is to focus solar irradiation onto a specific area of the STEG using optical or thermal concentration. For example, Baranowski et al. [2] developed a model to predict the efficiency limit of a STEG and provided a set of generalized rules for STEG design. With the use of optical tracking and concentration systems, STEG can typically achieve approximately 13–15% system efficiency. In reports published by Hasan et al. [3], Fresnel lens and TE module were utilized to concentrate solar beam and generate electrical power. The maximum thermal efficiency during the experiments was approximately 52.45%. In addition, Chen et al. [4] investigated a thermal-concentrated STEG using a numerical method based on the three-dimensional finite element scheme. Based on the Seebeck effect and high thermal concentration, a flat-panel solar thermal to electric power conversion technology was demonstrated. The developed STEGs achieved a peak efficiency of 4.6% [5]. A planar thin-film STEG has also been designed and optimized for micro-fabrication processing by Tayebi et al. [6] The performance of a STEG can also be improved by improving the figure-of-merit of the TE materials. The TE figure-of-merit is defined by $ZT = S^2\sigma T/\kappa$, where T, S, σ, and κ are the absolute temperature, Seebeck coefficient, electrical conductivity, and thermal conductivity, respectively. Recently, significant efforts have been made to enhance the ZT value by introducing the nanostructures into TE materials [10–14]. Many high-performance thin-film TE materials have been developed [15–17]. A recent work by Amatya and Ram [18] indicated that a system efficiency of 5.6% can be achieved in a STEG using a novel high-ZT TE material. The emergence of new high-ZT materials provides a good opportunity to develop improved TE devices.

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Nomenclature

A	area (m^{2})
c_p	specific heat capacity (J kg $^{-1}$ K^{-1})
D	electric flux density (C m^{-2})
E	electric field intensity (V m^{-1})
h	air convection coefficient (W K^{-1} m^{-2})
I	current (A)
J	electric current density (A m^{-2})
K	thermal conductance of device (W K^{-1})
L	length (m)
N	number of thermoelectric leg
P	output power (W)
Q	heat flux (W)
q	heat flux density (W m^{-2})
R	resistance (Ω)
$R_{thermal}$	thermal resistance (K W^{-1})
S	Seebeck coefficient of device (V K^{-1})
T	temperature (K)
t	time (s)
Greek symbols	
ρ	density (kg m^{-3})
η	Efficiency
α	Seebeck coefficient (V K^{-1})
λ	thermal conductivity (W K^{-1} m^{-1})
δ	thickness (m)
σ	electric conductivity (S m^{-1})
φ	electric scalar potential (V)
Δ	temperature difference (K)
Subscript	
c	cold side
h	hot side
TE	thermoelectric

The recent demonstrations of STEGs are mostly based on bulk TE materials and devices. However, small-scale energy harvesting devices have received increasing attention as power supply devices for wireless sensors and microscale devices. Hence, more studies need to be conducted on thin-film STEGs. Thus far, the low conversion efficiency and fabrication complexity have been identified as the main obstacles to their development. A TEG (thermoelectric generator) is usually characterized under fixed a temperature difference to evaluate its intrinsic performance determined mainly by the properties of the materials. However, in a thin-film STEG, the thermal flux is normally fixed rather than the temperature difference. In this case, the temperature distribution varies with many factors, including the geometry of the TE device and the external environment. The temperature difference across the device is vital, and hence, the temperature distribution should be considered carefully in STEGs. Many studies on the development of thin-film TE generators and coolers have been reported [19–22]. Mizoshiri et al. [23] fabricated thin-film TE modules for power generation using focused solar light. The development of a theoretical model and simulation procedures for the prediction and optimization of thin-film STEG behavior is essential [5,9,24–26]. In work reported by Chen et al. [9], the theoretical efficiency of a bulk STEG was investigated, and the conditions leading to the maximum efficiency were obtained based on a developed model for STEGs. The results suggested that a system efficiency of larger than 5% could be achieved in a STEG with little or no concentration. In further work reported by Weinstein et al. [1] on the theoretical analysis of thin-film STEGs, the properties and geometries of the devices were lumped into two parameters, which were optimized to guide device design. The predicted efficiency of over 5% for thin-film STEGs is comparable to those of existing bulk STEGs. To date, studies have mainly focused on the theoretical calculation on the efficiency via the optimization of the device geometry. There have been limited reports on the temperature distribution of the devices for integrated design and optimization.

To prepare a high-performance thin-film STEG, the key challenge is to restrict the heat flow within the TE legs. Hence, in this paper, an integrated optimal design of the heat flow and temperature distribution in a device has been conducted using finite element method (ANSYS). ANSYS can solve three-dimensional problems with good accuracy and high speed. This approach can systematically and efficiently address very complex geometry, restraints, and loading, providing detailed solutions that cannot be easily obtained using analytical or experimental approaches. ANSYS has been used to study the performance of TE modules [26–28]. Thus, we employ ANSYS to investigate the heat flow and temperature distribution of the device to achieve integrated optimal design of the substrate, heat conductive layer, and TE legs, and to determine the effect of air convection. The optimized thin-film STEG was fabricated, and an experimental investigation was performed to assess the effectiveness of directional thermal transport on the performance of STEGs.

2. General description of TEG

2.1. Performance of TEG

A TEG consists of n-type and p-type semiconductor elements connected by metal electrodes. As shown in Fig. 1, when a temperature difference is established across the semiconductor elements, the holes in the p-type semiconductor and the electrons in the n-type semiconductor move from the hot side to cold side to produce an electrical current in the circuit. The generation

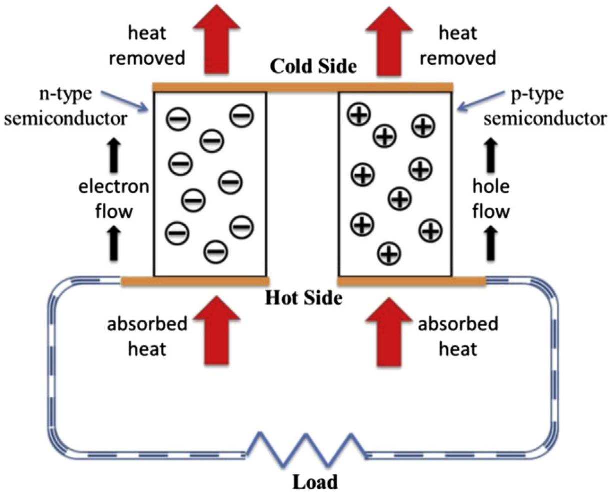

Fig. 1. Working principle of a thermoelectric generator.