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Procedia Engineering 47 (2012) 76 – 79

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Design and modelling of SOI-based solar thermoelectric generators

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Abstract

In this work, solar micro-thermoelectric generators are designed with a lens concentrating solar radiation onto the membrane of a thermoelectric generator (TEG). By focusing solar radiation, the input heat flux increases; leading to an increase in the temperature gradient across the device. Consequently, a significant improvement in the device efficiency can be achieved. The TEG design involves the use of the SOI wafer's device layer as the first thermoelement and aluminum as the second thermoelement. Isolation trenches are also added to the design for electrical insulation. Heat transfer simulations in COMSOL are performed to verify the viability of the proposed system and an analytical model based on energy balance and heat transfer equations is developed to investigate the performance of solar TEGs with varying geometries, lens parameters, and external conditions. It is found that efficiency is improved by increasing both the concentration factor and the absorptance of the TEG membrane.

Keywords: thermoelectric generators; solar concentration; heat transfer simulations; thermal equivalent model

1. Introduction

The global energy crisis has motivated researchers to explore alternative means of generating power. One approach to providing electrical energy is by direct conversion of heat to electricity using thermoelectric generators (TEGs). It is attractive to use TEGs because they have no mechanical parts, resulting in a power system that is silent, reliable, environment-friendly, and virtually unlimited lifetime.

A major challenge in the design of TEGs is its limited efficiency. A typical thermoelectric device exhibits only 5-10% conversion efficiency depending on the materials used and the temperature difference involved [1]. Meanwhile, the best solar cell at present is 3-5 times more efficient than thermoelectric devices [2]. One way to increase the conversion efficiency of a TEG is by increasing the

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doi:10.1016/j.proeng.2012.09.088

temperature difference across the thermoelements, which can be realized by using a high input heat flux such as that coming from the sun [3]. In this regard, we propose to improve the efficiency of TEGs by utilizing a solar concentrator to focus solar radiation onto the hot junction of the TEG. By doing so, the temperature gradient across the device can be increased; subsequently improving the TEG's efficiency.

2. Solar TEG Design, Simulation, and Modeling

The proposed system, illustrated in Fig 1a, of using solar concentrators in conjunction with TEGs has already been demonstrated using commercially-available components [4-5]. At the micro scale, 7-8 times efficiency improvement by utilizing both solar and thermal concentration on a pair of vertically-oriented nanostructured bismuth telluride alloys has been established [6]. Although no implementation of solar TEGs employing lateral thermoelectric materials have been found at the micro scale, the concept of using a lens in conjunction with lateral TEGs to serve as on-chip supply to a microactuator have been presented [7]. This motivates further work on the design, simulation, and modelling of lateral solar micro-TEGs.

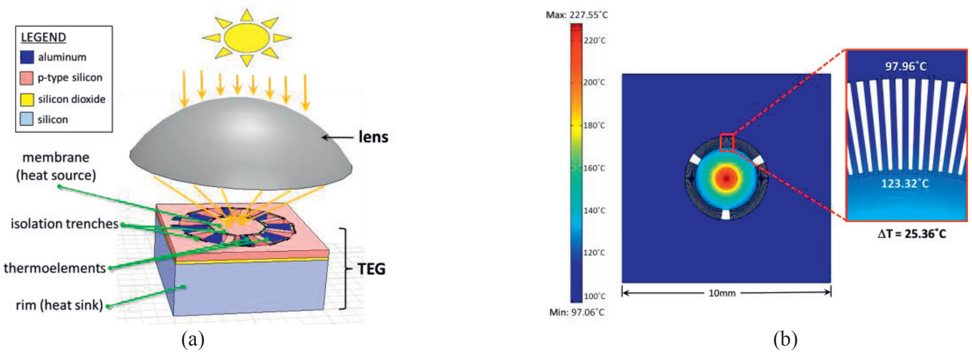

Fig. 1. (a) Solar TEG with a lens concentrating solar radiation onto the device; (b) Heat transfer simulation of a TEG with L=500μm, W= 30μm, D=3mm, and N=81 for a γ= 900, τ_{ens}=90%, and α_{mem}=50%, with a 1mm-diameter solar radiation spot size.

Suppose the sun uniformly irradiates an energy density q_s onto the lens, then the heat power density q_h of the incoming heat flux to the TEG membrane is given by:

$$q_h = \gamma\, \tau_{lens}\, \alpha_{mem}\, q_s \tag{1}$$

where γ is the concentration factor, τ_{lens} is the lens transmittance, and α_{mem} is the membrane absorptance. With this approach, we can generate an input heat flux in the order of hundreds of kW/m^2. Based on the general heat transfer equation, an increase in the input heat flux would translate to a corresponding increase in the temperature difference across the thermoelements; also resulting in an effective increase in its output voltage.

To further verify the functionality of the proposed system, heat transfer simulations of the proposed TEG device are performed using COMSOL. Fig 1b shows a sample finite element heat transfer simulation of the proposed thermoelectric generator design. With the device layer of the SOI wafer set to have a thickness of 5μm, COMSOL's two-dimensional out-of-plane heat transfer module is employed as there is no significant temperature variation across the thickness of the TEG. The amount of input power on the TEG membrane is the product of the input heat flux, q_h, and the heated membrane area, A_h.

To investigate effects of variations in several design parameters, an analytical model of the solar TEG system is developed. The thermal and electrical equivalent circuits are shown in Fig 2.

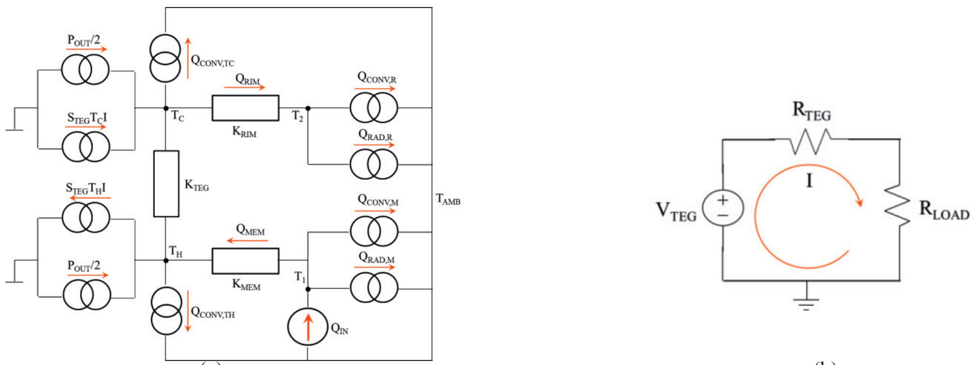

Fig. 2. (a) Thermal equivalent circuit and (b) Thevenin equivalent circuit of solar TEG.

The following equations are then derived from Figs 2a and 2b:

$$Q_{MEM} = Q_{MEM} - Q_{RAD,M} - Q_{CONV,M} = q_h A_h - \varepsilon\sigma A_{MEM}(T_1^4 - T_{AMB}^4) - h_c A_{MEM}(T_1 - T_{AMB}) \quad (2)$$

$$Q_{MEM} = Q_{CONV,TH} + K_{TEG}(T_H - T_C) + S_{TEG}T_H I - {}^1/_2 P_{OUT} = h_c A_{TEG}(T_H - T_{AMB}) + K_{TEG}\,\Delta T + S_{TEG}(T_1 - (Q_{MEM}/K_{MEM})) - {}^1/_2 P_{OUT} \quad (3)$$

$$Q_{RIM} = K_{TEG}(T_H - T_C) + S_{TEG}T_C I - Q_{CONV,TC} + {}^1/_2 P_{OUT} = K_{TEG}\,\Delta T + S_{TEG}(T_2 + (Q_{RIM}/K_{RIM})) - h_c A_{TEG}(T_C - T_{AMB}) + {}^1/_2 P_{OUT} \quad (4)$$

$$Q_{RIM} = Q_{RAD,R} + Q_{CONV,R} = \varepsilon\sigma A_{RIM}(T_2^4 - T_{AMB}^4) + h_c A_{RIM}(T_2 - T_{AMB}) \quad (5)$$

$$T_1 - T_2 = Q_{MEM}/K_{MEM} + \Delta T + Q_{RIM}/K_{RIM} \quad (6)$$

$$P_{OUT} = V_{TEG}^2 / (4 \cdot R_{TEG}) = (S_{TEG} \cdot \Delta T)^2 / (4 \cdot R_{TEG}) \text{ -- under matched load conditions} \quad (7)$$

where K_{MEM}, K_{RIM}, and K_{TEG} are the lumped thermal conductance of the membrane, rim, and thermocouples, respectively; A_{MEM}, A_{RIM}, and A_{TEG} are the surface area of the membrane, rim, and thermocouples, respectively; ε is the surface emissivity; σ is the Stefan-Boltzmann constant; h_c is the convective heat transfer coefficient; and S_{TEG} is the Seebeck coefficient of the TEG. Solving the above equations simultaneously then allows us to calculate ΔT numerically using Matlab.

Fig 3a gives a comparison between COMSOL simulations and the thermal model in deriving the

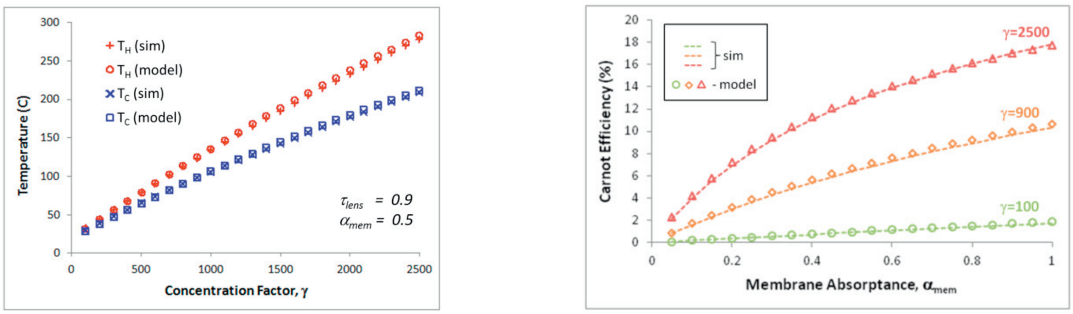

Fig. 3. (a) Hot and cold side thermoelement temperatures derived from simulations and the thermal model; (b) TEG Carnot efficiency increases with increasing α_{mem} and increasing γ. TEG dimensions are the same as in Fig 1b.

Table 1. Performance parameters derived using the thermal model for various geometries. In all cases, γ= 900, τ_{ens}=90%, α_{mem}=50%, and solar radiation is concentrated on the TEG membrane with a spot size diameter of 1mm.

L (μm)	W (μm)	D (mm)	N	ΔT	V_{OUT} (V)	η_c (%)	L (μm)	W (μm)	D (mm)	N	ΔT	V_{OUT} (V)	η_c (%)
200	15	1	31	70.14	0.82	15.4	500	30	3	81	26.61	0.81	6.7
500	15	1	34	156.24	2.00	29.0	1000	15	3	114	68.84	2.96	15.7
200	15	3	108	16.50	0.67	4.2	200	15	5	188	6.49	0.46	1.8
500	15	3	111	38.35	1.60	9.4	500	15	5	188	15.31	1.08	4.1
500	20	3	91	35.22	1.21	8.7	1000	15	5	191	27.18	1.95	7.1

temperatures at the hot and cold sides of the thermoelements. The thermal model agrees well with COMSOL simulations, making it applicable to use the model in characterizing TEG performance. Aside from increasing the concentration ratio, the efficiency of the system can also be improved by improving membrane absorptance as shown in Figure 3b. This can be done by coating the surface with a high absorptance material. Table 1 lists the expected performance of TEGs with geometries that are currently undergoing fabrication at the Southampton Nanofabrication Center.

3. Conclusion

The design and modelling of SOI-based solar TEGs is presented. The model includes conduction, convection, and radiation; as well as Joule heating and Peltier effect. There is good agreement between the model and simulations, making it suitable for characterizing solar TEG performance. By focusing solar radiation onto the membrane of a TEG with a 1mm-diameter spot size, Carnot efficiencies of almost 30% can be achieved with a concentration factor of 900. If materials with better thermoelectric properties, such as nanostructured silicon, are used, we predict that solar TEGs can have conversion efficiencies comparable to that of solar cells.

Acknowledgements

M. T. de Leon is supported by the University of the Philippines and the Department of Science and Technology, Philippines.

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