



Experimental assessment of thermoelectric generator package properties: Simulated results validation and real gradient capabilities



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ABSTRACT

The optimized design of a flexible micro thermoelectric generator (TEG) suitable for self-powered wearable devices and its real temperature gradient performance is proposed and discussed in this paper. Finite element analysis was performed on a three-dimensional p-n thermocouple on wavy-shaped poly-dimethylsiloxane (PDMS)/Kapton assembly using COMSOL Multiphysics software. Electrical and thermal simulations were carried out to determine the geometric effects of the single thermocouple (length and width of the thermoelements, deposition procedure of junction between p- and n-type legs) on output power and efficiency performance of the TEG. The experimental results confirmed that the experimentally measured thermal gradient ranges between 0.20 and 0.64 K higher than the simulated value and such a result has great importance for correct generator design and determination of effective thermal gradient which can be recovered using the proposed package solution. Heat transfer analysis was performed to optimize the proposed package solution and maximize the thermal gradient that can be recovered between the thermocouples junctions. Experimental results confirmed that the thicker package ensures better insulation, with a real gradient about 0.11 K lower than the simulated one. The warm-up time for 4 mm package to completely thermalize the Kapton upper surface is about 500 s; good matching on thermal response times has been found between the experimental and simulated results for all investigated package thicknesses.

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1. Introduction

The Energy Harvesting technology enables to recover the waste energy dispersed into the environment and convert it into electrical energy useful to supply ultra-low power devices. Vibrations, heat and light are some of the most frequently exploited energy sources, and a comparison of their typical power densities is reported in Table 1 [1]. The thermoelectric generation is a particularly interesting technology for the direct conversion of heat into electrical power by using solid state devices characterized by extended maintenance-free durability and noiseless operation without moving parts. A thermoelectric generator consists of an array of pairs of semiconductor materials connected electrically in series and thermally in parallel. Each pair forms a junction in contact with the heat source, while the other ends of the thermoelements are in thermal contact with the substrate, air or a medium which is at a lower temperature than the heat source (Fig. 1). The performance of

a TEG is strongly influenced by temperature distribution inside the materials and thermal gradient which can be recovered between the hot and cold junctions of the thermocouples. The heat transfer from a medium to another one represents an important issue which allows to understand how a physical system containing a heat source and a dissipative medium evolves. The heat can be transferred by three different mechanisms: conduction, convection and radiation. In some cases, depending on the working conditions only one mechanism turns out to be dominating, whereas the others can be neglected.

Recently, the numerical simulation based on Finite Element Method (FEM) has become a very powerful tool to analyze and optimize the performance of thermoelectric devices. In Ref. [2] numerical technique was used to study the effect of geometric design on the performance of a thermoelectric generator (TEG) with constant cross section area, but variable height of the thermoelectric legs. The authors found that the output voltage linearly increases with the legs height until a specific height, after which the output voltage saturates. In Ref. [3] finite element analysis was performed on a 3D model of micro-TEG to investigate the role of the

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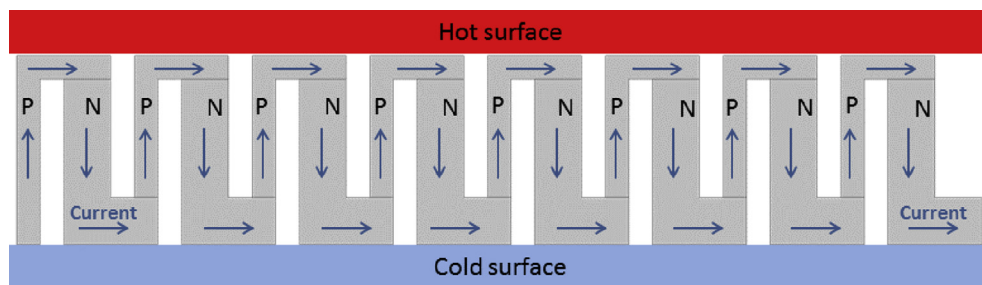
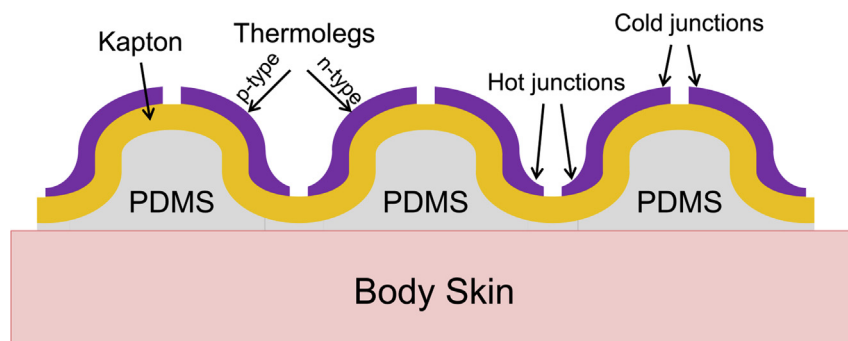
Table 1

Comparison of typical power density of energy harvesting methods.

Energy source	Available power density
Vibration	1–100 $\mu\text{W}/\text{cm}^3$
Thermal	1–10 mW/cm^3
Light	100 mW/cm^3 (outdoor) 100 $\mu\text{W}/\text{cm}^3$ (indoor)

dimensions of the device on the power generation efficiency. To improve the computation efficiency significantly, Chen et al. [4] proposed a 3D compact model of a thermoelectric cooler represented as single “black box” in a computational fluid dynamics simulation environment. In Ref. [5] a 3D TEG model was proposed and implemented to simplify the co-design and co-optimization of the fluid and the thermoelectric device, which are crucial for maximizing the system performance. In Ref. [6] the application of a TEG to harvest energy from the waste heat of a commercial table lamp was investigated experimentally and numerically. Both open-circuit and closed-circuit lamp-TEG system were simulated. A 1D TEG model taking the Peltier and Joule heats into consideration was proposed to predict the power generation rate based on the simulated hot and cold sides thermal conductances of the open-circuit system. In Ref. [7] the optimum efficiency and geometrical dimensions of a segmented TEG module were derived by mathematical methodology and numerical simulations based on FEM calculations were carried out to verify the validity of the optimum segmented TEG model operating in design boundary condition. Wang et al. [8] investigated the performance of a TEG combined with an air-cooling system designed using two-stage optimization: an analytical model was used to model the air-cooling system, a numerical method with a finite element scheme was employed to predict the performance of the TEG. Jang et al. [9] investigated the optimal structure of high-performance micro-TEG using the FEM analysis with 3D models.

In Ref. [10] the authors reported some details about the design and fabrication of a wearable and flexible thermoelectric generator. The proposed TEG was designed to be used as “electronic garment”, in order to recover the heat useful to the thermoelectric generation from the temperature difference existing between the body skin and the environment. Standard UV (Ultraviolet) photolithography and lift-off process were used to deposit 1 μm -thick thermoelectric thin films on Kapton substrate. P-type Sb_2Te_3 and n-type Bi_2Te_3 have been chosen as thermoelectric materials, because of their high thermoelectric efficiency at room temperature. The figure-of-merit of Bi/Sb/Te thin films depends on composition and crystalline structure of materials and it also varies with the deposition technique, as exhaustively reported by Goncalves [11]. Kapton is a flexible and low cost polyimide film extensively used in wearable/bending electronics applications, because of its good physical, chemical, and electrical properties over a wide temperature range. The fabrication process required only two photolithographic steps to complete the thermopile, as the single thermocouple consists of a direct p–n junction. Embedded thermometers and metal pads were deposited by e-beam evaporation, in order to monitor the thermocouples junctions temperature and electrically test single partitions of the array. The proposed device integrates 2778 thermocouples of $\text{Sb}_2\text{Te}_3/\text{Bi}_2\text{Te}_3$ thin films into an area of 25 cm^2 of Kapton substrate. Each thermocouple is 3 mm long, with a width of 50 μm and 145 μm for the p-type and n-type leg, respectively. By a proper package solution (Fig. 2) the device is able to autonomously recover the thermal gradient useful to the thermoelectric energy harvesting, using the temperature difference existing between the body skin and the environment (about 17 K). The realized TEG generates an open-circuit voltage of about 2 V with a thermal gradient of about 5 K between the hot/cold thermocouples junctions, but it exhibits a high internal resistance of about 2.3 $\text{M}\Omega$ which strongly limits the output current. However, such a drawback can be successfully solved by increasing the thin films thickness and extracting the TEG output voltage from a set of different

**Fig. 1.** Schematic of a thermoelectric generator.**Fig. 2.** Cross section of the proposed package, with a typical application on the body skin.

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