PDMS Template Generator for Wearable Thermoelectric Energy Harvesting Applications

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Abstract. Thermoelectric pastes based on Sb, Bi, Te powders were prepared, characterized and used to fabricate a flexible thermoelectric generator (TEG) for wearable harvesting applications. By Finite Element Method (FEM) simulations, the TEG design was finalized to optimize electrical model and match typical thermal resistances of human body skin, in order to maximize its thermoelectric performance. The thermopile is composed by 450 couples of p-Sb_2Te_3 and n-Bi_2Te_3 deposited by blade coating into vertical parallel cavities of a patterned polydimethylsiloxane (PDMS) through-holes layer. Each leg has diameter of 1.5 mm and height of 2.5 mm. The p-n couples were electrically connected by printed silver contact. By preliminary functional tests, a Seebeck coefficient of about 75 μV/K for p-n couple on best conditions was measured.

Keywords: Thermoelectric generator · Energy harvesting · Screen printing

1 Introduction

Energy harvesting represents a new promising technology, by means of which fully exploitation of self-powered wearable devices in practical implementations can be achieved. The human body heat can be directly converted into electricity by Seebeck effect to partially or totally supply ultra-low power wearable health monitoring sensors. TEGs are particularly attractive devices, because compact, robust, lightweight, silent, maintenance-free and devoid of moving parts. The flexible technology represents a key for their unobtrusive application in wearable systems, which integrate different materials and functionalities on the same flexible support. A flexible TEG adapts better to the natural curvature of the human body, with the advantage of enhancing the heat transferred from the human body to the device.

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Depending on how the thermocouples and substrate are oriented respect to the direction of the heat flow, transversal (cross-plane) or lateral (in-plane) configuration can be used to build a thermopile. Several works on flexible TEGs were reported in literature [1–5]. To maximize the thermal gradient between junctions, an optimized package is often required to be designed for planar TEGs [6–11].

In this paper, screen printable p-Sb_2Te_3 and n-Bi_2Te_3 thermoelectric pastes were developed and morphologically and electrically characterized. The filling with silver particles was also considered, with the aim to increase the figure of merit of the materials. The inclusion of metallic nanoparticles into the material matrix introduces scattering points for phonons, with the result to reduce the thermal conductivity of the material. The metallic particles can also create favourite pathways for the electron transport, giving rise to a reduction of the electrical resistivity of the material. The thermoelectric pastes were used to fabricate a heat sink-free flexible thermoelectric generator, designed for wearable harvesting applications. Preliminary results of functional characterization of the developed device were presented.

2 Preparation and Characterization of Thermoelectric Pastes

High-purity Bi, Sb and Te powders from Sigma Aldrich were ball-milled for 24 h under purified argon atmosphere, in order to minimize oxygen contamination, for obtaining stoichiometric Sb_2Te_3 and Bi_2Te_3 powders. The alloy powders were incorporated into a solution constituted of 2 wt% polystyrene polymer and alpha-Terpineol for a reliable printable pastes production. The solid load of p- and n-type pastes was 56 and 60%. The viscosity of the prepared pastes was adjusted by using the solvent, in order to facilitate the following printing of the slurries. Ag-filled p- and n-type pastes were also prepared by adding silver particles (5–6 μm, from Sigma Aldrich) to the thermoelectric powder with a 2 vol.% load. Figure 1 shows SEM images of as-prepared pastes, after the milling and mixing of components.

The electrical conductivity of the materials was determined by four-point probe measurements, performed on 150–200 μm thick screen-printed films after hot-pressing and firing under nitrogen gas flow at 250 °C for 1 h (heating rate of 5 °C min^{-1}), in order to compact the materials and to remove the solvent in excess. The mean bulk resistivity of the investigated films is reported in Fig. 2. Poor effect of the metal filling on the film resistivity was noted, with a small decrease of resistivity for Ag filled n-alloy and a small increase for the other one. The latter result is explained by the Ag particles behaviour as metal micro-inclusions embedded between the grain boundaries, forming new interfaces and defects which give rise to a decrease in the material electrical conductivity. Nevertheless, the expected Ag inclusion effect is related to thermal phonon modulation and specific measurements are ongoing for experimental confirmation [12].

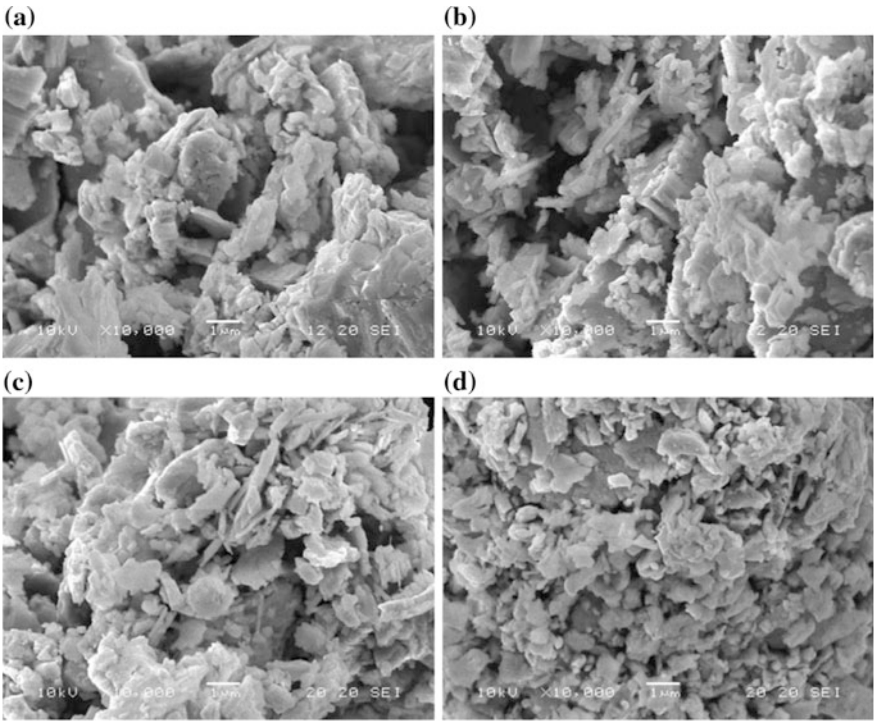

Fig. 1. SEM images of **a** Sb_2Te_3, **b** Bi_2Te_3, **c** Ag-Sb_2Te_3, **d** Ag-Bi_2Te_3, after the milling and mixing of components and before the firing

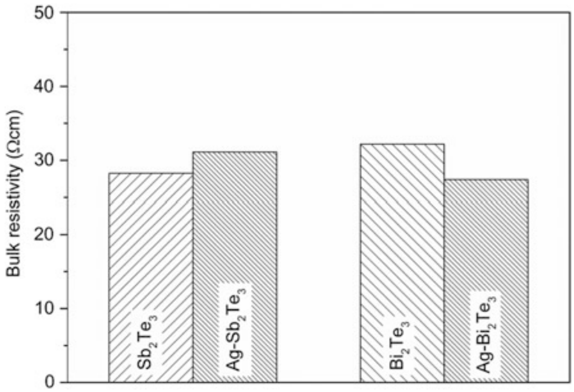

Fig. 2. Bulk resistivity of pristine and Ag-filled p- and n-alloys

3 Design, Fabrication and Electrical Characterization of TEG

Human body produces heat in response to metabolic and muscular activities. The thermoregulatory system keeps the body core temperature within a narrow range around to 37 °C, whereas the heat loss occurs primarily through the skin. Although depending on the body location and environment conditions, the average heat flow observed on human open skin under typical indoor conditions is in the range 1–10 mW cm^{-2}, but it decreases to 4–5 mW cm^{-2} on areas covered by clothes [13].

In this work, an optimal design of the TEG was obtained by matching the thermal and electrical properties of the device at contact with the human body. Heat transfer FEM simulations were performed by using Comsol Multiphysics software, with the aim to optimize the TEG dimensioning for maximizing the output electrical power. A heat flow of 10 mW cm^{-2} was imposed at the hot side of the TEG (supposing thermal contact with human body wrist) [13] and natural convection heat transfer with the environment. The designed TEG is composed by an array of 450 couples of p-n thermoelectric materials, each leg has diameter of 1.5 mm and height of 2.5 mm and the thermopile occupies an area of 74 × 74 mm^2. The thermoelectric alloys were deposited by blade coating into vertical parallel cavities of a patterned PDMS through-holes layer. After printing, hot-pressed annealing in a conventional tubular oven under nitrogen gas flow at 250 °C for 1 h (heating rate of 5 °C min^{-1}) was performed to dry and to compact the materials and to remove the solvent in excess. Silver printed contacts between the p-n legs were optimized to obtain low contact electrical resistance and good adhesion to the PDMS. The electrical functional characterization of the device was performed on a prototype of 45 thermocouples of p-Sb_2Te_3 and n-Bi_2Te_3. The thermal gradient between the hot/cold thermocouples junctions was imposed by two aluminium plates, whose temperature was set by two commercial MCU Peltier controllers, with a temperature set point control of 0.01 °C. Table 1 shows preliminary experimental data obtained for different temperature difference between junctions and increasing load connected at the TEG output ends. Figure 3 shows the fabricated device tested with a custom bench for controlled temperature gradients.

Table 1. Preliminary results obtained by a 45 thermocouples-based TEG, for different temperature difference between junctions and increasing load connected at the output

Thermal gradient (K)	1	2	3	4	5	6
Open circuit						
Output voltage (mV)	2.69	5.43	8.13	10.82	14.55	17.25
Seebeck coefficient per thermocouple (μV/K)	59.11	60.35	60.20	60.11	64.67	63.89
Output power (nW)	7.17E−3	2.91E−8	6.51E−7	1.15E−7	2.08E−7	2.93E−7
Load resistance: 1.0 kΩ						
Output voltage (mV)	3.24	6.45	10.27	13.80	17.32	20.47
Seebeck coefficient per thermocouple (μV/K)	71.97	71.65	76.05	76.68	76.99	75.81
Output power (nW)	0.17	0.68	1.73	3.13	4.93	6.88
Load resistance: 6.8 kΩ						
Output voltage (mV)	2.39	5.29	7.04	9.10	11.77	13.38
Seebeck coefficient per thermocouple (μV/K)	53.02	58.68	52.16	50.56	52.30	53.07
Output power (nW)	0.20	0.99	1.77	2.95	4.94	6.38

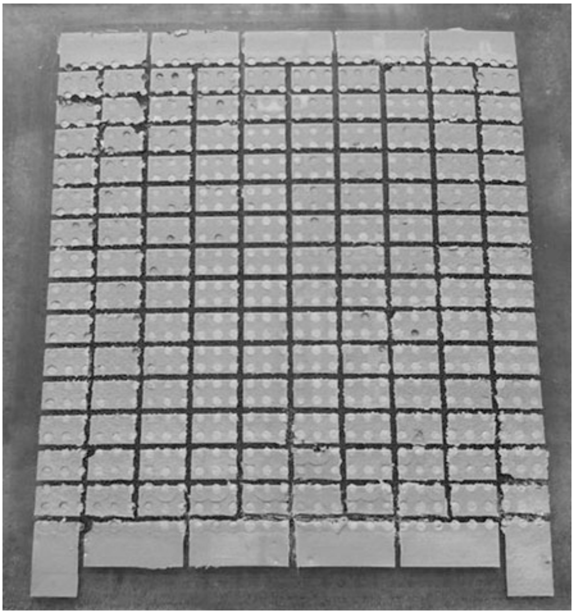

Fig. 3. Fabricated thermoelectric generator with silver metal connections

A Seebeck coefficient of about 75 μV/K for the p-n couple was experimentally measured as a function of the thermal gradient, while silver metal contact resistivity effects are included into average Seebeck coefficient and will be investigated vs different metal films.

Further measurements are in progress in order to evaluate the thermoelectric properties of the materials, in particular the effect of the silver filling on the thermal conductivity of the alloys. Further functional characterization is in progress in order to test a complete system composed by TEG and an ASIC DC-DC converter, the latter designed and realized for the power management of the harvested power on 65 nm technology node. Experimental measurements on pristine and Ag filled alloys are still in progress.

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