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A planar micro thermoelectric generator with high thermal resistance

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ABSTRACT

This paper presents the modelling, design, fabrication and characterization of a planar micro thermoelectric generator (μTEG) which is able to convert waste heat into a few microwatts of electrical power. In order to get a better performance under a large variety of heat sources even if their thermal resistance is high, a planar μTEG with a large thermal resistance was designed and fabricated. It is built of two periodically etched silicon substrates that are respectively used as heat concentrator and heat evacuator, the whole embedding a multilayer membrane which includes a polysilicon-based thermopile with large thermoelement leg length. The thick air cavities etched in the substrates are effective in preventing the direct heat loss from concentrator to evacuator. 3D thermal simulations are carried out to improve the performance of the μTEG. A new definition of the "efficiency-factor" which involves the thermal input power instead of the temperature difference across the chip is suggested to evaluate the efficiency of this kind of μTEGs. The advantage of this new efficiency factor is that it takes the thermal resistance of the μTEG into consideration. With a thermal resistance of 78 K/W, the experimental results show that the μTEG can work under high temperature difference (up to 267 K). With an optimized structure, i.e. 5 membranes and annealed polySi as TE main material, the maximum output power of our μTEG is 138 $\mu W/cm^2$ when the input power is 4 W/cm^2 and its corresponding new efficiency factor is 865 $\mu m^2/W$.

1. Introduction

With the need of decreasing the power consumption of more and more microelectronic systems, the power supply by energy harvesting in the proximate working environment is becoming more and more feasible. The micro thermoelectric generator (μTEG) which converts waste heat into electrical power is one of the many energy harvesting solutions [1]. Though the energy conversion efficiency of μTEGs is generally low [2], it is playing an important role in the field of energy harvesting mainly because of the abundance of sources of waste heat. Indeed, for instance natural ambient temperature cycle [3] or solar energy [4] can be used for thermoelectric power generation. Gathering heat dissipating from the human body through the skin surface by thermoelectric generators [5,6] is an interesting way to develop wearable medical sensors.

There are two main categories of μTEGs related to the arrangement of the thermopile in a vertical or a planar architecture. Currently, most of the commercialized μTEGs are vertical structures (MPG-D751 by Micropelt [7], G2 modules by Tellurex [8], TGM by Kryotherm [9]), since they can usually deliver more output power than the planar μTEGs. This better performance of vertical μTEGs is often due to more powerful thermoelectric (TE) materials such as Bi_2Te_3 resulting in costly and non-environment friendly μTEGs, which limits their applications.

In this work, polysilicon layers are used as the thermoelectric material in the aim to develop a low-cost environment-friendly μTEG. Furthermore, the proposed topology permits the μTEG thermal resistance to reach quite high values: this is related to the planar structure that integrates polysilicon-based legs which have a low thickness and a great length. With such a high thermal resistance, the performance of the μTEG can be less weakened by the external thermal resistances which exist in real working conditions.

In the first part of this paper, will be given basic external-internal temperature analysis which permit to identify a new "efficiency-parameter" for qualifying better the impact of the external resistance. The design, modelling and fabrication of μTEGs will be presented in a second section. Their characterization once submitted to a calibrated heat flux will then be shown in a third section. Finally a comparison between our μTEG and a reference μTEG reported in the literature will close this paper.

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2. Basic considerations

In a vertical µTEG, the thermoelements X/Y of the thermopile are disposed normal to the flat surfaces of concentrator and evacuator, and most often X and Y are based on the same TE material in its two doped forms (n-type and p-type). In a planar µTEG, the thermopile is a flat line and concentrator and evacuator are geometrically structured in order to insure contacts alternatively with one junction over two. A simplified scheme of vertical and planar µTEGs is shown in Fig. 1.

When the concentrator is on contact with a heat source and the evacuator with a heat sink, respectively at temperatures T_{source} and T_{sink}, an effective temperature difference ΔT_e is created between two successive junctions of the thermopile.

As the thermopile is made of thermocouples connected in series, the open-circuit voltage generated at the two extremities of the thermopile is given by:

$$V_0 = n\alpha_{XY}\Delta T_e \quad (\mathrm{V}) \tag{1}$$

Where n is the number of thermocouples, α_{XY} (V/K) is the relative Seebeck coefficient of the two thermoelectric materials X and Y. ΔT_e (K) is the effective temperature difference between each couple of junctions (Fig. 1).

To evaluate the ability of a thermocouple to efficiently produce thermoelectric power, a figure of merit Z [10,11] is defined by way of thermodynamic considerations [12] taking into account all the thermal and electrical parameters of the two materials as:

$$Z_{XY} = \frac{\alpha_{XY}^2}{((\rho_X/S_X)+(\rho_Y/S_Y))(\lambda_X S_X + \lambda_Y S_Y)} \quad (\mathrm{K}^{-1}) \tag{2}$$

Where λ_X, λ_Y (W/(m K)) are the thermal conductivities and ρ_X, ρ_Y (Ω m) electrical resistivities of the thermoelectric materials. S_X and S_Y are the sections of the corresponding thermoelements.

For a µTEG constituted of n thermocouples, Z can be written as:

$$Z_{XY} = \frac{n^2\alpha_{XY}^2}{R_i K_e} \quad (\mathrm{K}^{-1}) \tag{3}$$

Where R_i is the internal electrical resistance and K_e is the internal thermal conductance of the thermopile.

An apt optimization of the architecture design of the µTEG is mandatory so as to enhance the µTEG ability to exploit most of the temperature difference between heat source and heat sink by adjusting thermoelements cross sections S_X and S_Y as:

$$\frac{S_X}{S_Y} = \sqrt{\frac{\lambda_Y\rho_X}{\lambda_X\rho_Y}} \tag{4}$$

And the optimal Z is:

$$(Z_{XY})_{opt} = \frac{\alpha_{XY}^2}{\left(\sqrt{\lambda_X\rho_X} + \sqrt{\lambda_Y\rho_Y}\right)^2} \quad (\mathrm{K}^{-1}) \tag{5}$$

Many applications for energy harvesting [13–15] require µTEGs with low internal thermal conductance. In the next section it is shown that the output power delivered by the µTEG is maximum when the internal thermal conductance is equal to the environment-related conductance.

An easy way to achieve this criterion is to develop µTEGs with horizontal planar thermopile whose the thermal conductance K_e can be adjusted regardless of the electrical resistance R_i.

2.1. Simplified model

For both vertical and planar µTEGs, the thermal equivalent circuit diagram of a µTEG in working condition may be simplified as shown in Fig. 2, where r_{source}, $r_{\mu TEG}$, r_{sink} are the thermal resistances (K/W) of the heat source, of the µTEG and of the heat sink. The thermal contact resistance located between the heat source and the µTEG is noted r_c (K/W) and this one located between the heat sink and the µTEG is noted r_c'.

The thermal resistance of the whole µTEG ($r_{\mu TEG}$) can be divided into two parts: the effective thermal resistance of the thermopile $r_e = 1/K_e$ which leads to an effective temperature difference ΔT_e producing energy through Seebeck mechanism and a "parasitic" thermal resistance r_p which has no contribution on TE generation:

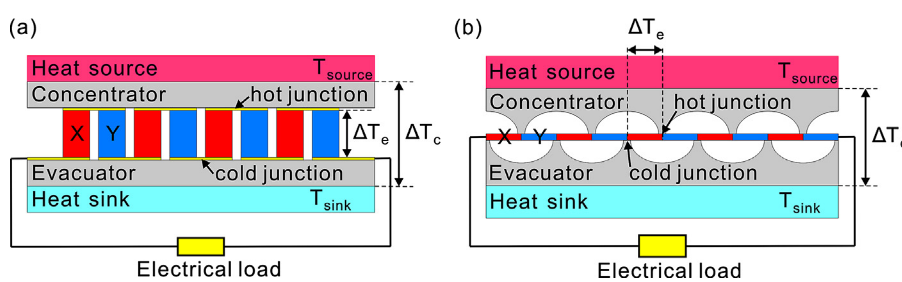

Fig. 1. Schematic of cross-sectional views of a vertical µTEG (a) and a planar µTEG (b) connected to a load resistance.

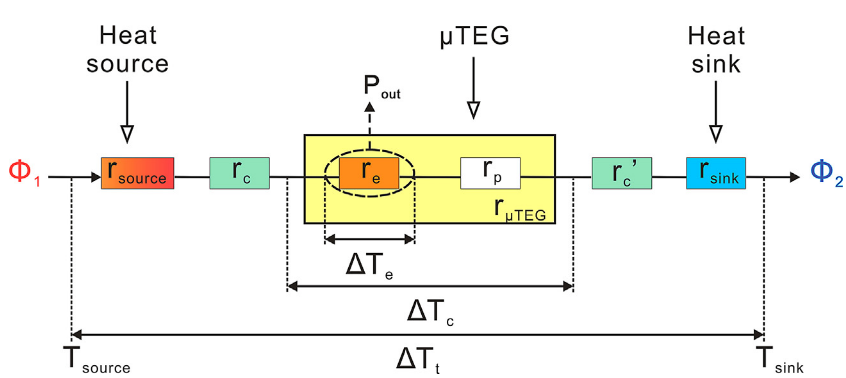

Fig. 2. Simplified thermal equivalent circuit diagram of a vertical or planar µTEG in working condition.