NEW METHODOLOGY OF THERMOELECTRIC MODULES DESIGN TO AN INCREASE OF PERFORMANCES

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Abstract: This paper presents a new methodology of thermoelectric modules design, by defining a new geometric parameter extracted from an analytical model, allowing an optimization of electrical performances.

With the need to increase continuously the electrical performances of thermoelectric modules and the necessity to decrease the modules' size (especially in thin films technology) to facilitate their integration, the design of module (junctions number, legs area…) has to be finely defined.

Thus, to evaluate design impact, we define here a new geometric parameter, called thermoelectric materials ratio (TMR). The choice of TMR appears to be dependent of numerous system parameters, such as TE materials properties, module parameter and environment properties. Thus, we develop in this paper a modeling which introduces TMR and taking into account all system parameters. This model has been applied to classical materials (Bi_2Te_3 and polycrystalline SiGe) and to nanostructured materials, such as silicides QDSL (quantum dots superlattices). The influence of each parameter is studied and we show then that a specific value of TMR optimizes module's performances for each material.

Keywords: thermoelectrics, modules design, modeling, performances optimization

INTRODUCTION

The manufacturing of thermoelectric (TE) modules, especially in thin films technology, consists in a complex study where the goal is to assembly materials by minimizing electrical and thermal resistances, and by optimizing the good geometry. Thermoelectric modules can be realized for cooling or power generation applications [1]. Literature proposes some micro TE modules manufacturing [2-7] and few TE modules design [8-10], but in any case, the choice of the junctions' number or legs surface, for example, is justified. Nevertheless the choice of these parameters is fundamental to maximize performances.

Thus the goal of this paper is to define a new methodology of modules design based on classical thermoelectric models and leading to an optimization of performances.

SYSTEM DEFINITION

The study of a TE system can be summarized by a three-level approach: materials, modules and environment. These three parts are linked: environment conditions are given by the applications for which the module is intended, TE materials are particularly chosen as a function of environment temperatures, and modules are designed as a function of both materials and environment properties. Only the right and single combination of these three parts leads to an optimization of module performances.

The system studied in this paper can be represented as shown in figure 1. The thin film thermoelectric module is based on n and p legs, deposited on an oxidized silicon substrate because of its high thermal conductivity and compatibility with integrated circuits. The SiO_2 layer is used as prevention of electrical shorting. The use of a heat sink is justified by the importance to obtain a significant temperature difference when thin film technology (where thicknesses are very small) is used. The integration of such heat sink has been already used in literature [2]. The parameters related to the environment are T_h, T_f, h and A_{hs}. Those related to the TE materials are λ, σ, S and A_{np}. Finally those related to the module are N, L and A_{te}.

The first step of our methodology consists in defining the power density Q_{gen} and output voltage U as a function of system's parameters. The expressions of output voltage and maximum of power density are given respectively by:

$$U = N \times S \times (T_h - T_c) \qquad (1)$$

$$Q_{gen} = \frac{N^2 \times S^2 \times (T_h - T_c)^2 \times R_L}{R_{tot}^2 \times A_{hs}} \qquad (2)$$

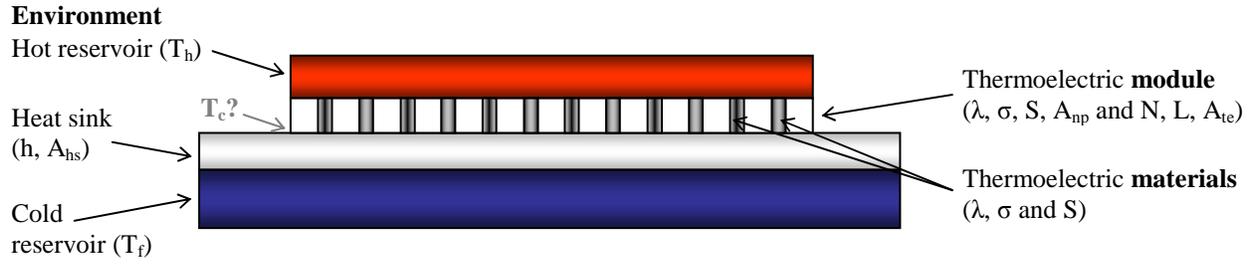where R_L and R_{tot} represent respectively the load resistance and the module internal resistance, i.e.:

Fig. 1: Schematic drawing of the studied system and definition of all parameters.

$$R_{tot} = R_{int} + R_L = 2N \times \left(\frac{L}{\sigma \times A_{np}} + \frac{2R_c}{A_{np}} \right) + R_L \quad (3)$$

The expression of variable parameter T_c ($T_c < T_f$) can be obtained by equating total power entering the heat sink with heat leaving the cold side:

$$P_{Seeb} + P_{cond} + P_{rad} + P_J = P_{hs} \quad (4)$$

where P_{Seeb} represents the Seebeck effect:

$$P_{Seeb} = N \times (S_p - S_n) \times T_c \times I = N \times S \times T_c \times I \quad (5)$$

P_{cond} the heat transfer sent out by conduction:

$$P_{cond} = \frac{2N \times \lambda \times \Delta T \times A_{np}}{L} + \frac{\lambda_{air} \times \Delta T \times A_{air}}{L} \quad (6)$$

P_{rad} the radiative flow:

$$P_{rad} = \sigma_{SB} \left(T_h^4 - T_c^4 \right) \left(\frac{1}{A_{te} \times f} + \frac{2}{A_{te}} \left(\frac{1}{\varepsilon} - 1 \right) \right)^{-1} \quad (7)$$

P_J the Joules effect:

$$P_{Joul} = \frac{1}{2} R_{int} \times I^2 \quad (8)$$

and P_{hs} the power entering the heat sink:

$$P_{hs} = (T_c - T_f) \times h \times A_{hs} \quad (9)$$

The expression of intensity I expressed in equations 5 and 8 is given by:

$$I = \frac{S \times (T_h - T_c)}{2 R_{tot}} \quad (10)$$

By using standard values, as defined in table 1, it is easily to show that, in the studied temperature range, the radiative heat flow can be neglected compared with the conduction heat flow ($P_{rad} \ll P_{cond}$). Thus, by inserting equations 5, 6, 8 and 9 in equation 4, cold side temperature T_c can be obtained, and so, voltage U and power density Q_{gen} too.

To study the influence of system parameters, we attribute them default values as described in table 1. Cold and hot sides of system are fixed at 300K and 400K respectively. Moreover, the TE properties of three different thin films TE materials (Bi_2Te_3 [12], polycrystalline SiGe [13] and quantum dots superlattices QDSL [14]) will be studied to evaluate their influences on performances and design of the optimized module geometry. Seebeck coefficient S, thermal conductivity λ and electrical resistivity ρ of these three materials are given in table 1. We suppose that $\lambda = \lambda_p = \lambda_n$, $\rho = \rho_p = \rho_n$ and S is defined as the sum of n and p legs contributions ($S = S_p - S_n$). In the suggested technology, TE legs are spaced by air with a thermal conductivity λ_{air} [15]. A first and non optimized module's geometry (reference) is given with a module surface of 1 cm²; legs dimensions are 100 x 100 µm² and a thickness of 5 µm. On the whole, 200 junctions (400 legs) are connected, with a thickness of 10 µm and a surface of 100x100 µm². Furthermore, for technological considerations, 100 µm are let free (i.e. no legs) at the outskirt of module. The electrical contact resistance value R_c corresponds to a nickel germanosilicide [16]. The heat sink surface is chosen at 2 cm², i.e. the double of the module surface, to homogenize thermal conduction. The heat transfer coefficient h, used as default value, corresponds here to water in forced convection [17]. In thin films technologies, where active materials thicknesses are very low, one the most important parameter is the heat transfer coefficient h of heat sink. Indeed, the heat draining is very problematic and is necessary to keep a significant temperature difference ΔT. Figure 1 shows the evolution of Q_{gen}, for the three materials, as a function of heat transfer coefficient h. It is shown that power densities are very low for a large range of h (0 to some hundreds of $W.m^{-2}.K^{-1}$), and that high Q_{gen} values can be only obtained for high values of h (with µchannels for ex.).

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		Symbols	Default values	Units	Ref.
materials	*thermoelectric materials parameters (Bi$_2$Te$_3$ / poly-SiGe / QDSL)*	$S = S_p - S_n$	402 / 151 / 400	µV.K^{-1}	[12]
		$\lambda = \lambda_p = \lambda_n$	1.87 / 4.78 / 1.5	W.m^{-1}.K^{-1}	[13]
		$\rho = \rho_p = \rho_n$	1,5.10^{-5} / 2,3.10^{-5} / 1,6.10^{-5}	Ω.m	[14]
		λ_{air}	0,026	W.m^{-1}.K^{-1}	
module	*module electrical parameters*	R_c	1.10^{-11}	Ω.m²	[15]
		R_{int}	-	Ω	(Eq.3)
	module geometric parameters	N	200	-	
		L	1.10^{-5}	m	
		A_{np}	1.10^{-8}	m²	
		A_{te}	1.10^{-4}	m²	
environ^t	*system thermal parameters*	T_h	400	K	
		T_f	300	K	
	heat sink parameters	A_{hs}	2.10^{-4}	m²	
		h	1000	W.m^{-2}.K^{-1}	[16]

Tab.1: Default values of parameters defined in this study.

This figure 2 shows the importance to use an adapted heat sink to obtain a usable TE module and that the more TE materials are efficient, the more quality of heat sink allows increasing modules performances.

Moreover, we define a new parameter τ, called thermoelectric materials ratio (TMR). TMR, expressed in percentage, corresponds to the quantity of integrated thermoelectric materials compared with the total materials quantity in module. It can be written:

$$\tau = \frac{2N \times A_{np}}{A_{te}} \times 100 \qquad (11)$$

By integrating this new parameter in equation 4 and then equations 1 and 2, the evolutions of U and Q$_{gen}$ can be obtained respectively as a function of TMR. Figure 3 presents these evolutions.
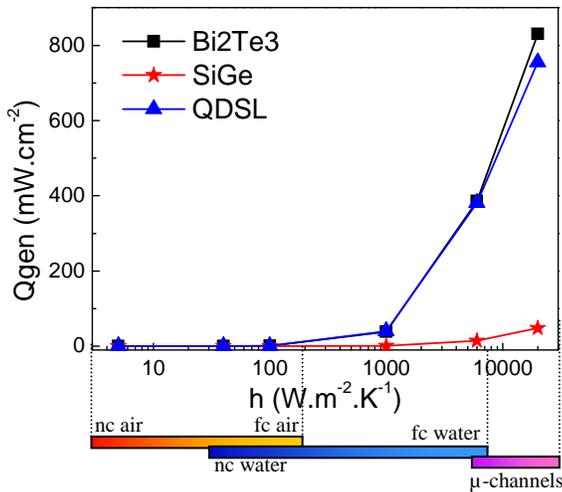
Figure 3a shows that a saturated value of U is obtained from a specific value τ$_{sat}$. As shown, this value τ$_{sat}$ is function of TE materials properties: the more TE materials are efficient, the more τ$_{sat}$ increases, and output voltage U too. Figure 3b presents the evolution of Q$_{gen}$ as a function of TMR for the three materials defined in table 1. Firstly, the evolution of Q$_{gen}$ is clearly dependent of TMR: as it is shown, this evolution can vary significantly with τ and that is why a good choice of TMR is crucial to maximize modules performances.
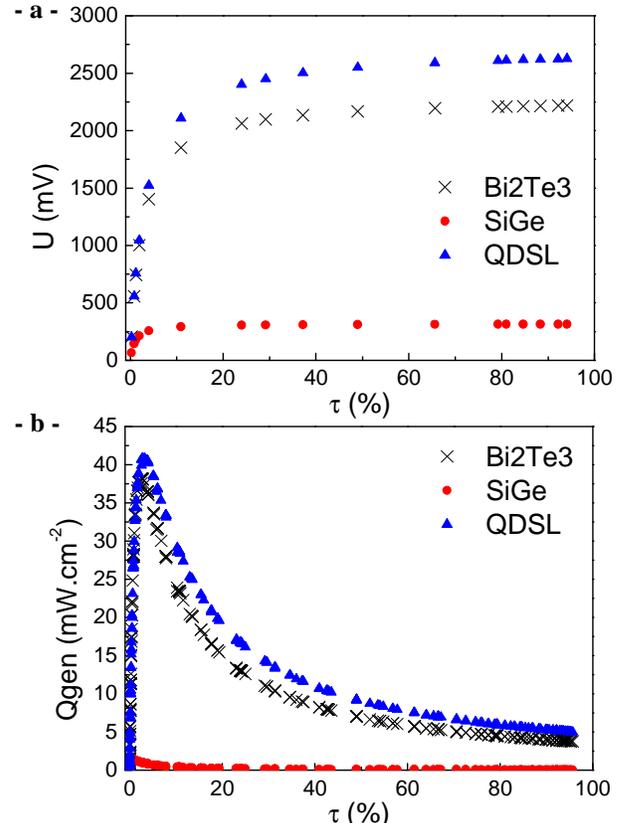

Fig. 2: Evolution of Q$_{gen}$ as a function of heat transfer coefficient h and materials properties.

Fig. 3: Evolution of U (a) and Q$_{gen}$ (b) as a function of TMR τ and materials properties.

Moreover, as it can be expected, Q_{gen} is dependant of the nature of TE materials. But the most important point is the presence of a specific optimized value τ_{opt} maximizing Q_{gen}, and which is particularly dependent of the materials properties. A first note is that τ_{opt} values are rather low (only few percents). It can be explained by the fact that thin films technology is used and so, in this case, thicknesses are low (L_{max} = few µm) and the distance between cold and hot sides too. As thermal conductivity of TE materials is higher than thermal conductivity of air ($\lambda < \lambda_{air}$), it is easily to understand that just few TMR maximizes Q_{gen}; on the contrary, for high values of TMR, the temperature difference ΔT is negligible and so Q_{gen} values are low. A second note is that τ_{opt} increases with an increase of TE materials performances and that the more τ_{opt} is high, the more Q_{gen} is high too.

CONCLUSION

We have defined a new methodology of modules design based on classical thermoelectric models and leading to an optimization of modules performances. The rule of heat sink has been underlined. Moreover, the definition of a new geometric parameter TMR has been introduced. This parameter appears to influence considerably the output voltage U and the power density Q_{gen}. Moreover, a specific value of TMR optimizes Q_{gen} and is function of materials' and environment's properties.

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