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Power density optimization for micro thermoelectric generators

Marc T. Dunham [a], Michael T. Barako [a], Saniya LeBlanc [b], Mehdi Asheghi [a], Baoxing Chen [c], Kenneth E. Goodson [a, *]

[a] Department of Mechanical Engineering, Stanford University, Stanford, CA, 94305, United States
[b] Department of Mechanical Engineering, The George Washington University, Washington, DC, 20052, United States
[c] Analog Devices, Inc., Norwood, MA, 02062, United States

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ABSTRACT

Microfabricated thermoelectric generators (μTEGs) can harvest modest temperature differences to provide reliable solid-state electricity for low-power electronics, sensors in distributed networks, and biomedical devices. While past work on μTEGs has focused on fabrication and demonstration, here we derive and explore comprehensive design guidelines for optimizing power output. A new closed-form thermoelectric device model agrees well with the traditional iterative approach. When thermoelectric leg length is limited by thin-film fabrication techniques, a very low (<10%) active thermoelectric fill fraction is required to optimize device power output, requiring careful selection of filler material. Parasitic resistance due to electrical interconnects is significant when a small number of thermocouples is used, and this loss can be reduced by increasing the number of thermocouples while decreasing the cross-sectional area of the legs to maintain the same fill fraction. Finally, a discussion of the "incompleteness of *ZT*" shows that different combinations of thermal conductivity, electrical conductivity, and Seebeck coefficient resulting in the same *ZT* will result in different device performance and optimization decisions. For μTEGs, we show it is best to increase Seebeck coefficient, followed by decreasing thermal conductivity for short leg lengths and increasing electrical conductivity for long leg lengths.

1. Introduction

Microfabricated thermoelectric generators (μTEGs) are used to produce electrical power for devices, such as wireless sensors, requiring micro-Watts to milli-Watts of power per device. These generators scavenge thermal energy from waste heat sources that have temperature differences or spatial dimensions that are too small for conventional thermodynamic heat engines to effectively utilize. In this domain, only a small fraction of available thermal energy needs to be extracted from the thermal reservoir to achieve a target power output, often without concern for thermal efficiency. In the limit where the heat capacities of heat source and sink are very large, the temperatures of the source and sink are not appreciably perturbed by the small amount of heat drawn through the μTEG system, which is dependent on device configuration (*i.e.* the geometry, interfaces, boundary conditions, etc.). This fixed temperature assumption is an ideality that benefits from the relatively high thermal resistance of a μTEG, compared to larger devices for which local temperature perturbations may be a more present concern [1]. Under a fixed temperature assumption, optimization for either maximum thermal efficiency or maximum power output will lead to two different devices [2,3]. Since many microfabricated devices, sensors, and actuators have well-defined power and footprint requirements, this work defines and optimizes performance based on electrical power generated by the device rather than thermal efficiency and presents a comprehensive design methodology for microfabricated waste heat scavenging devices.

The field of μTEGs emerged in the early/mid-1990s, reducing feature sizes to mm and μm following decades of successful use of high-temperature, bulk-scale devices for applications such as spacecraft power generation [4]. Microfabricated devices offer an advantage over traditional bulk-processed devices by allowing for streamlined assembly in semiconductor process lines and direct on-chip integration. One of the first discussions of the use of thermoelectric generators for the recovery of "low-grade" waste heat examined mm-scale devices exposed to temperature sources up to 240 °C [5]. In 1997, Fleurial et al. [6] suggested the use of thin-film fabrication methods for "micropower sources" to

* Corresponding author.
E-mail address: goodson@stanford.edu (K.E. Goodson).

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accommodate the advance in miniaturized systems, particularly for space applications. In the same year, Stordeur and Stark [7] reported on the successful fabrication and testing of a μTEG, produced by thin-film sputtering in a planar pattern followed by dicing and vertical assembly. Fleurial et al. [8,9] achieved thicker (~10–50 μm) thermoelectric films deposited by electrodeposition for low-power, high-voltage harvesting of small temperature gradients. In 2004, Böttner et al. [10] discussed a novel sandwich-type wafer assembly with interlocking substrates prepared by co-sputtering. Strasser et al. [11] prepared and analyzed a CMOS-compatible generator design based on Si and SiGe semiconductors in a design where heat flows laterally in the device. Electrodeposition of bismuth-telluride and nickel-copper devices using polymer molds was reported by Glatz et al. [12] to extend the regime of thin film thermoelectric leg lengths, which is a limiting factor in microfabricated devices.

While significant progress has been made in fabrication and preliminary demonstration of μTEGs, there has been little attention on the challenge of optimizing these devices for power output. Optimizing ZT at the materials level has been the focus of much of the thermoelectrics community, though these reports may not be complete as the μTEG community strives to improve power generation per unit footprint area for practical applications, a particularly important metric for small thermoelectric modules converting waste heat to electricity. The use of the metric ZT as an indicator of the quality of thermoelectric generators [4,13–15] may not be appropriate for μTEGs. This quantity encapsulates the operating temperature and three primary material properties contributing to the thermoelectric rate equations into a dimensionless parameter, the so-called thermoelectric figure-of-merit:

$$ZT = \frac{S^2}{\rho k}\left(\frac{T_h + T_c}{2}\right) \tag{1}$$

In Eq. (1), S is the Seebeck coefficient (units of $\mu V\ K^{-1}$), ρ is the electrical resistivity (Ω m), k is the thermal conductivity ($W\ m^{-1}\ K^{-1}$), and T_h and T_c are the hot and cold temperatures across the thermoelectric. In reality, an “incompleteness of ZT” exists where a single value of ZT does not uniquely predict power output or provide an absolute roadmap to device optimization due to the many combinations of S, k, and σ that yield a single ZT value.

The impact of filler material, which surrounds the active thermoelectric material (see Fig. 1) and may exist as a byproduct of manufacturing or intentionally for mechanical stability, is often overlooked despite observed effects on performance [16]. External thermal resistances (*i.e.* the pathways to heat sources/sinks) play a significant role in the performance of μTEGs, and some attention has been given to these effects [17–19]. However, without the inclusion of realistic filler material effects and device design considerations, these analyses are incomplete. Additional factors become important in the realization of a practical generator device, including adjustment of device fill fraction to compensate for fabrication limitations to thermoelectric element length and appropriate selection of number of junctions when accounting for the electrical resistance of interconnects.

The present work develops a comprehensive design methodology for μTEG devices, particularly those harvesting energy from small temperature differences, paying close attention to several parameters that are commonly neglected in the existing literature, such as the effects of fill fraction in combination with different filler materials, limitations and workarounds when restricted to short leg lengths, the impact of the number of thermocouples, and the different contributions of the parameters in the figure of merit ZT to device performance. Further, a robust closed-form model for the power output of a μTEG is derived, which includes the Peltier effect, external thermal resistances, parasitic resistive losses, fill fraction/filler material, and accounts for variable electric loading.

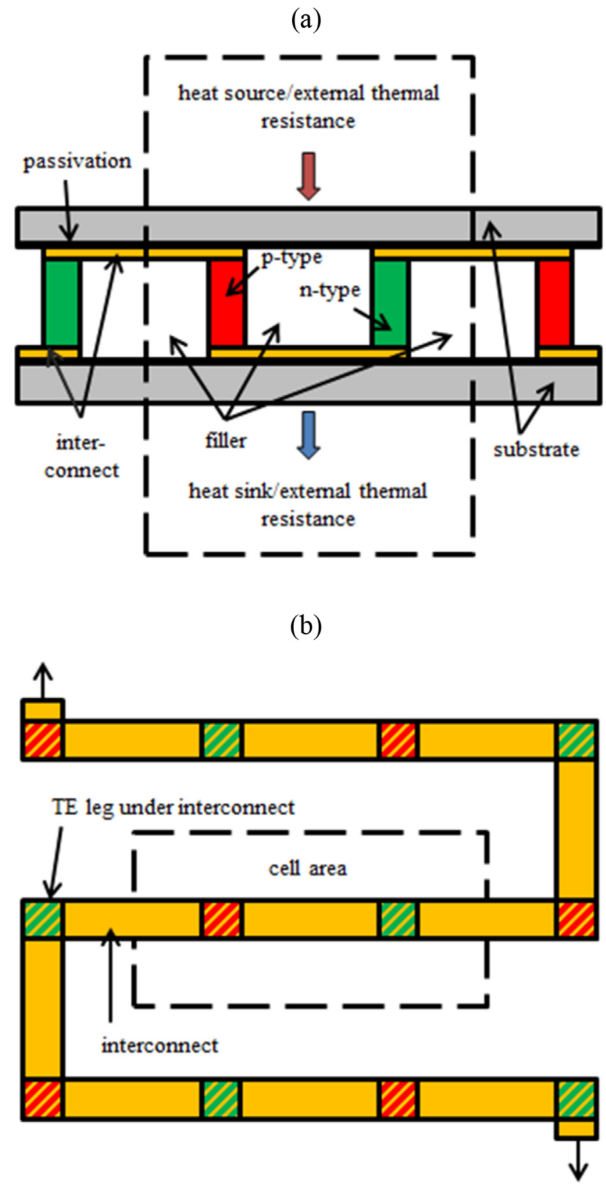

Fig. 1. Diagram of vertically-aligned thermoelectric generator, showing (a) side and (b) top views.

2. Model

The analysis presented in this paper considers a thermoelectric generator with heat flowing through the individual thermoelectric elements in parallel and electric current flowing in a serpentine series pattern. Simulations use a thermocouple unit cell that can be repeated to scale up to a full device. The unit cell area and relevant segments of the generator for simulation are illustrated in Fig. 1.

The illustration in Fig. 1 shows both a side view with heat flowing from one substrate to the other and a top-down view with heat flowing into/out of the page. A one-dimensional heat transfer model with parallel heat flows is assumed for the vertical structure shown in Fig. 1, and the thermal and electrical resistance networks are provided in Fig. 2. For simplicity, we assume that the thin passivation layers and high thermal conductivity metal interconnects in