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Finite element analysis of miniature thermoelectric coolers with high cooling performance and short response time

Wei Zhu [a], Yuan Deng [a,*], Yao Wang [a], Anliang Wang [b,*]

[a] Beijing Key Laboratory for Advanced Functional Materials and Thin Film Technology, School of Material Science and Engineering, Beihang University, Beijing 100191, China

[b] School of Astronautics, Beihang University, Beijing 100191, China

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ABSTRACT

The miniature thermoelectric cooler (TEC) is a promising device for microelectronics applications with high cooling performance and short response time. In this paper, a comprehensive numerical analysis focusing on the cooling performance and response time of the TEC is performed by finite element methods (FEMs). The effects of load current, geometric size, ratio of length to cross-sectional area and substrate's thermal resistance on the performance of the TEC are studied. The results show that the performance of TECs has been improved by reducing the TEC's size and ratio of length to cross-sectional area, resulting in a maximum cooling temperature difference of 88 °C, a cooling power density of 1000 W cm^{-2} and a short response time on the order of milliseconds. Furthermore, the substrate, which hinders the circulation of heat between the TEC and the atmosphere, also has a significant influence on the performance of the TEC.

1. Introduction

As the feature size of microelectronic devices decreases, very large amounts of heat are generated in very small areas (also called hot spots). Meanwhile, the higher degree of integration of electronics leads to extreme heat flux densities, which prevents the improvement in electronic performance. Therefore, thermal management to ensure that the integrated chips are kept within their operating temperature limits has become crucial [1–4]. Many cooling techniques for microprocessors, such as air cooling and refrigeration, have been proposed in recent years. Among these, the thermoelectric cooler (TEC) is considered to be a potential candidate with high dissipating abilities and a small size. Furthermore, miniaturized thin-film TECs deliver higher cooling power densities than conventional bulk coolers do, and they can serve as excellent coolers for addressing hot spots [5–11].

The performance of TECs is primarily characterized by the following three parameters: the maximum cooling temperature difference, the maximum cooling power or cooling power density and the response time. On the one hand, the performance of the TEC is related to the thermoelectric performance of the materials evaluated by the dimensionless figure of merit (ZT). The value of ZT is a dimensional parameter, which is defined as

$$ZT = \frac{\alpha^2 \sigma}{\kappa} T \tag{1}$$

where α, σ, κ, and T are the Seebeck coefficient, the electrical conductivity, the thermal conductivity and the absolute temperature, respectively. Although there is no theoretical limitation for ZT, thermoelectric bulk materials have not significantly exceeded ZT~1 for nearly 50 years. The research efforts in the field of thermoelectric thin films increased substantially in the last few years to achieve a high ZT value by enlarging the Seebeck coefficient and the electrical conductivity and reducing the thermal conductivity. The increase of ZT leads directly to an improvement in the cooling power density and the cooling temperature difference [12–15], which are two of the three important parameters used to characterize the performance of TECs. The best materials at room temperature for TECs are bismuth telluride-related compounds [13,15]. Bottner [16] has developed a micro-structured thin-film TEC based on bismuth telluride-related compounds that was fabricated on a silicon substrate with micro-electromechanical system (MEMS) technologies, and a maximum cooling power density of 100 mW cm^{-2} was obtained. On the other hand, optimizing the TEC size dimension is an alternative strategy to achieve high cooling performance. Moreover, development of a theoretical model and finite element methods (FEMs) for predictions of the behaviors of the thermoelectric devices is also essential to improve the performance of these devices [17,18]. As for FEM, it is systematic and efficient to handle very complex geometry, restraints and loading, and it can be divided into a set of logical steps

* Corresponding authors. Tel.: +86 10 8231 3482; fax: +86 10 8233 9431.
E-mail addresses: dengyuan@buaa.edu.cn (Y. Deng), wanganliang@buaa.edu.cn (A. Wang).

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Nomenclature

A	area (m^2)
C	specific heat capacity (J kg^{-1} K^{-1})
d	thickness (m)
D	electric flux density (C m^{-2})
E	electric field intensity (V m^{-1})
h	depth (m)
I	current (A)
J	electric current density (A m^{-2})
Q	cooling power (W)
q	cooling power density (heat flux) (W m^{-2})
R	resistance (Ω)
T	temperature (K)
U	electrostatic potential (V)

Greek symbols

ρ	density (kg m^{-3})
α	Seebeck coefficient (V K^{-1})
λ	thermal conductivity (W K^{-1} m^{-1})
κ	thermal conductivity (W K^{-1} m^{-1})
σ	electric conductivity (S m^{-1})
ϕ	electric scalar potential (V)
ε	dielectric permittivity (F m^{-1})
Δ	temperature difference (K)
γ	length to cross-sectional area ratio (cm^{-1})

Subscript

c	cold side
h	hot side
n	n-type
p	p-type

which can be implemented on a digital computer and utilized to solve three dimensional problems with a very good accuracy and a short solution time. Also, after solution, we could extract relative data of temperature, heat flux and so on from any place in the model. Hence, the numerical simulation methods can yield detailed solutions that are not easily obtained through experiments and provide information to guide the design of TEC devices [18]. In the study of Huang et al. [19], micro-thermoelectric coolers suitable for localized hot-spot cooling applications were successfully fabricated using IC-compatible MEMS technology. Goncalves et al. [20] further reported theoretical modeling, FEM simulations, details of the fabrication process and preliminary results for the first on-chip thermoelectric microcooler array, and a temperature difference of 15 K could be achieved in each pixel. Additionally, a numerical analysis of a micro-cooler has been conducted by Lee et al. [21] and Pérez-Aparicio et al. [22] to determine the effect of the thermoelectric and electrical properties of the material on the cooling performance. Kim et al. [7] and Wu et al. [23] then discussed the effect of the thickness and the width-to-depth ratio on the performance of TECs. Chen et al. [24] also performed a numerical study on the performance of thermoelectric coolers affected by the Thomson effect.

The response time, as illustrated above, is another important parameter used to characterize the performance of TECs. It plays a vital role in the fast cooling of quick-response objects, such as IR detectors, various sensors and miniature semiconductor lasers. The response time of common bulk TECs is generally several seconds. The realization of a short response time can accelerate sensors, stabilize emitters and also open up a variety of new opportunities for TEC applications. Commonly, the response time of TECs is evaluated by a Harman-like measurement [25]. However, the testing device is complicated and requires calibration prior to use. By miniaturizing the TECs, the response time is greatly decreased, which introduces additional precision and accuracy challenges in the test. Therefore, there is a substantial need for a simpler method to investigate and predict the response times of TECs.

For TEC devices, the ratio of length to cross-sectional area is an important dimensional parameter because the internal electrical resistance and thermal resistance are constant when the ratio of length to cross-sectional area of the TEC is fixed. Thus, comparisons between different TEC sizes at fixed ratios of length to cross-sectional area become more practical. In the studies introduced above, this parameter has been ignored; only the geometrical properties of thickness and the width-to-depth ratio have been considered. Furthermore, due to the application of TECs in the fields of fast cooling and sensors, the device parameter of response time requires more consideration at present. However, it needs relatively large amount of calculation and solution time to obtain the steady-state behavior of TEC through the theoretical equations, and it is even more difficult to obtain the transient-state behavior of TEC through the theoretical calculation. Therefore, few investigations have been conducted on the response time of TECs and we hope to use this powerful numerical technique to analyze the steady-state and transient-state performance of TEC to obtain the cooling performance and response time of TEC, respectively. Particular emphasis is placed on the effects of the ratio of the length to cross-sectional area, the load current and the geometric size on the cooling performance and response time to obtain an optimal TEC design. Moreover, substrate thermal resistance is taken into account by considering the real working conditions of the TEC, and subsequently, the effect of the specific electrical contact resistance is also discussed.

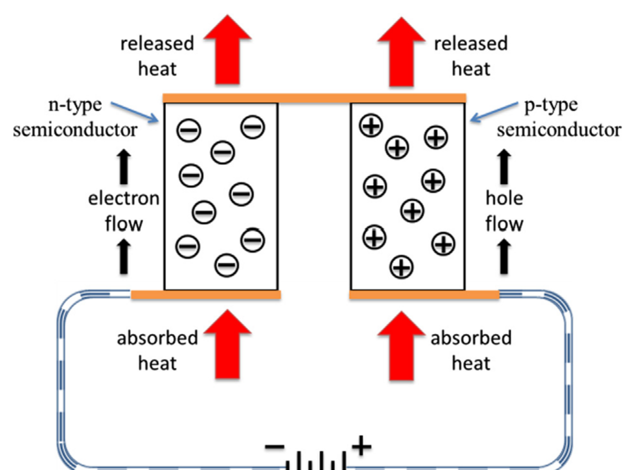

Fig. 1. Working principles of TEC.

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