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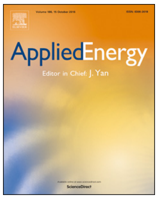

An effective method of evaluating the device-level thermophysical properties and performance of micro-thermoelectric coolers

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HIGHLIGHTS

- A three-dimensional numerical model of micro thermoelectric cooler is developed.
- The joint impact of boundary and size effects on TE properties is discussed.
- A comparison between the numerical and reported experimental results is conducted.
- The impact of interfacial resistances on cooling performance of TEC is discussed.
- The cooling capacity and optimal working condition of the micro TEC is analyzed.

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ABSTRACT

Despite the success of achieving thermoelectric materials with high figure of merit, precisely evaluating the performance of micro-thermoelectric coolers remains challenging at the microdevice level because of various interfacial effects and device construction. This study develops a method for the effective evaluation of the device-level thermophysical properties capturing various interfacial and size effects, and establishes a three-dimensional numerical model to evaluate the cooling performance of micro-thermoelectric coolers. The model is validated by the reported experimental data. The impact of interaction between boundary and size effects is captured in the investigation of Seebeck coefficient, thermal conductivity and electricity resistivity of the thermoelectric materials at the device-level. Contact resistances are also considered in analyzing the cooling performance. Results indicate that the device-level figure of merit decreases by 5–18.1% with decreased thermoelectric element thickness from 20 µm to 5 µm. The boundary effects considerably weaken the cooling performance of the microdevice, and a higher heat flux corresponds to a greater impact of boundary effects. Cooling temperature increases by 6.1 K due to the boundary effects when heat flux is 300 W/cm^2, while the temperature difference decreases by 17.1%. Finally, the three-dimensional numerical model is performed to evaluate the cooling performance and optimal working condition of the micro-thermoelectric cooler. At heat flux of 300 W/cm^2 and 200 W/cm^2, the minimum cold side temperatures of 310.7 K and 287.3 K are predicted to be achieved at 11 µm/20 mA (H_{te}/I), 15 µm/16 mA, respectively.

1. Introduction

Thermoelectric cooler (TEC) is widely used in electronic devices, refrigerators, air conditioning systems, photovoltaic equipment, medical instruments and industrial fields due to its numerous advantages, such as compact size, no moving part, environmentally friendly and temperature control capability [1–3]. Recent advance in fabrication techniques have enabled the fabrication of microdevices [4]. Thin-film micro-TEC has got more attention for its potential application in the on-demand localized cooling of microelectronic and optoelectronic devices [5]. Recognizing the importance of the thermophysical properties of materials evaluated by the figure of merit (ZT) to TECs, many researchers have been devoting themselves to developing new thermoelectric (TE) materials to improve ZT [6]. However, when TE materials with high ZT are fabricated into thin-film microdevices, the effective thermophysical properties at the device level are diminished, and the practical cooling performance is severely limited by interfacial effects [7]. For practical applications, the practical cooling performance of micro-TECs has also been investigated [8].

The low efficiency of common bulk TE materials has limited the

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Nomenclature

ZT	figure of merit
k	thermal conductivity [W/(m·K)]
T	room temperature [K]
T_{h0}	temperature of hot surface of thermoelectric element [K]
T_{c0}	temperature of cold surface of thermoelectric element [K]
T_e	temperature of electron [K]
T_p	temperature of phonon [K]
H_{te}	thickness of thermoelectric element [m]
I	electrical current [A]
$Q_{k,h0-c0}$	heat flow across thermoelectric element [W]
k_D	device-level thermal conductivity of thermoelectric material [W/(m·K)]
A_{te}	cross area of thermoelectric element [m^2]
k_e	thermal conductivity of electron [W/(m·K)]
k_p	thermal conductivity of phonon [W/(m·K)]
j_e	electrical current density [A/m^2]
P	strength of hole/electron–phonon interaction [W/(m^3·K)]
$R_{k,b,p}$	thermal boundary resistance of phonon [K·m^2/W]
$R_{k,b,e}$	thermal boundary resistance of electron [K·m^2/W]
$R_{e,b}$	electrical boundary resistance [Ω·m^2]
$R_{k,b}$	total thermal boundary resistance [K·m^2/W]
R_e^*	dimensionless thermal boundary resistance of electron
R_p^*	dimensionless thermal boundary resistance of phonon
R_k^*	dimensionless thermal boundary resistance
H_{te}^*	dimensionless thickness of thermoelectric element
$R_{e,D}$	electrical resistance [Ω]
$R_{e,p}$	peltier resistance [Ω·m^2]
$Z_D T$	device-level figure of merit of thermoelectric material
Q_{c0}	cooling capacity at the cold junction of thermoelectric elements [W]
Q_{h0}	heating rejection at the hot junction of thermoelectric elements [W]
$K_{D,p-n}$	total thermal conductance of p-type and n-type elements [W/K)]
$R_{e,D,p-n}$	total electric resistance of p-type and n-type elements [Ω]
Q_c	net cooling capacity of micro-thermoelectric cooler [W]
Q_h	net heat rejection of micro-thermoelectric cooler [W]
T_c	temperature of cold surface of micro-thermoelectric cooler [K]
T_h	temperature of hot surface of micro-thermoelectric cooler [K]
$R_{k,s}$	thermal resistance per unit area of substrate [K/W]
$R_{k,cu}$	thermal resistance per unit area of copper connector/lead [K/W]
$R_{k,c1}$	thermal contact resistance between Cu and thermoelectric element [K·m^2/W]
$R_{k,c2}$	thermal contact resistance between Cu and substrate [K·m^2/W]
A_{cu}	cross area of copper connector/lead [m^2]
$R_{e,co}$	electrical resistance of copper connector/lead [Ω]
$R_{e,c1}$	electrical contact resistance between Cu and thermoelectric element [Ω·m^2]
L	Lorenz number [V^2/K^2]
$R_{k,c}$	thermal contact resistance [K·m^2/W]
$R_{e,c}$	electrical contact resistance [Ω·m^2]
T_l	temperature of the lower Cu leads [K]
ΔT_{ext}	external temperature difference, $T_l - T_{c0}$ [K]
ΔT	temperature difference, $T_h - T_c$ [K]
$I_{optimal}$	optimal current achieving the minimum cold side temperature [A]
T_{cmin}	minimum cold side temperature of micro-thermoelectric cooler [K]
ΔT_{max}	maximum temperature difference of micro-thermoelectric cooler [K]

Greek letters

α_s	seebeck coefficient [V/K]
ρ_e	electrical resistivity [Ω·m]
$\alpha_{s,D}$	device-level Seebeck coefficient of thermoelectric material [V/K]
$\Delta\varphi_{h0-c0}$	electromotive force between cold and hot interfaces of thermoelectric element [V]
$\alpha_{s,b}$	boundary seebeck effect [V/K]
γ	ratio of k_e and k_p
δ	cooling length [m]
$\rho_{e,D}$	device-level electrical resistivity of thermoelectric material [Ω·m]
$\alpha_{s,D,p-n}$	total device-level Seebeck coefficient of p-type and n-type elements [V/K]
$\alpha_{s,D,p}$	device-level Seebeck coefficient of p-type elements [V/K]
$\alpha_{s,D,n}$	device-level Seebeck coefficient of n-type elements [V/K]
ψ	change percentage
β_D	device-level properties of thermoelectric material (e.g., $\alpha_{s,D}$, k_D, $\rho_{e,D}$, $Z_D T$)
β_m	intrinsic properties of thermoelectric material (e.g., α_s, k, ρ_e, ZT)

Subscripts

h_0	hot surface of thermoelectric element
c_0	cold surface of thermoelectric element
D	device-level properties of thermoelectric material
te	thermoelectric element
k	thermal properties
b	boundary resistance
co	copper connector
l	copper lead
m	base properties

applications of TECs [9]. Recent developments in nanotechnologies have led to significant ZT enhancement [10–12], and considerable efforts have been made to explore low-dimensional TE materials with high efficiency. Low-dimensional materials and nanostructures, such as quantum wells, super lattices (SLs), quantum wires, and quantum dots, offer new ways to improve ZT by manipulating the electron and phonon properties of materials [13,14]. Venkatasubramanian et al. [15] reported that Bi_2Te_3/Sb_2Te_3 SLs with a period of 6 nm fabricated by MOCVD technique had a maximum ZT of 2.4 at 300 K. Harman et al. [16] presented PbTe/PbSeTe based quantum dots SLs with an intrinsic ZT value of 2.0 at 300 K. However, the measured operating device thermoelectric ZT declined to 1.6 at the system level because of extraneous or parasitic factors. Despite the success of achieving TE materials with high ZT, the ZT of micro- TECs made of high ZT materials is typically lower than expected, presumably because of the fabrication of TE couple, various interfacial effects, and device construction [7,8,16,17].

For practical applications, thin-film microdevices fabricated with high ZT TE materials have also been investigated. Goncalves et al. [18] presented flexible micro-TECs made of ultrathin (10 μm) Bi_2Te_3/Sb_2Te_3 TE elements. However, the tested maximum temperature difference of 5 K between the cold and hot sides of the device was much lower than the simulated value (18 K). Bulman et al. [19] reported the experimental results of thin-film SL thermoelectric modules, demonstrating an