Optimization of Microscale Thermoelectric Cooling (TEC) Element Dimensions for Hotspot Cooling Applications

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Microscale thermoelectric cooling elements (TECs) are being proposed to cool down an integrated circuit to maintain its performance. The maximum cooling power of microscale TECs is significantly reduced by the interfacial resistance. For our particular application, we calculate the optimal dimension of the TECs, made of Bi_2Te_3, that reduce the temperature at a hotspot on an IC chip by 10°C. By the one-dimensional analytical model that we developed and numerical solutions of TEC equations using MATLAB$^©$, we obtain performance characteristics that relate the cooling power density to other control variables and material constants. The optimal dimension of microscale TECs is calculated for cooling at a hotspot region by a range of temperature differences, for example from 10°C to 50°C. Further, the percentage change in the optimal thickness for various thermal resistances and electrical contact resistances can be predicted. These results act as a good guideline for two-dimensional analysis and assembly of TECs.

Key words: Thermoelectric cooling elements (TECs), thermocouple, hotspot, thermal and electrical contact resistances, TEC dimensions, packaging density

INTRODUCTION

With ever-increasing transistor density and decreasing transistor size according to Moore's law, the performance of integrated circuits is significantly degraded by the thermal power at the hotspot regions. Microscale thermoelectric cooling elements (TECs) or thermoelectric coolers (TEC) are being proposed as a solution to this problem.[1,2] The interfacial resistance is also proved to influence the cooling power of a microscale TEC significantly.[3]

Our goal is to design a microscale TEC that reduces the temperature at a 3-W hotspot region by 10°C. Following the treatment of previous researchers,[4] a one-dimensional analytical model is developed to describe the TEC performance. By the numerical solution of principal TEC equations using MATLAB$^©$, we obtain performance characteristics that relate the cooling power density to other control variables and material constants. The approach of the design is to calculate the optimal TEC lengths with a range of temperature differences (ΔT) across the TEC, for example from 10°C to 50°C. Then we can study how maximum cooling power densities and optimal TEC lengths are shifted by varying heat-sink materials and electrical contact resistances. These results act as a useful guideline for two-dimensional analysis and assembly of TECs.[5] Finally, the performance of the designed TEC model with a ΔT of 10°C is estimated using a high packaging density, the percentage of area covered with thermocouples with respect to the TEC area, of 80%.

ANALYTICAL MODEL

Although heat transfer in a TEC is two dimensional, a one-dimensional model can greatly simplify the analysis and calculations and still provide adequate accuracy. Figure 1 shows the one-dimensional TEC model used for our analysis, which has
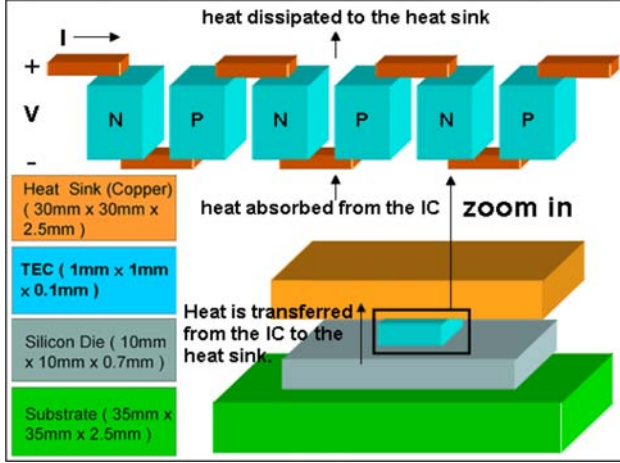
Fig. 1. Relative sizes of the TEC, substrate, and heat sink. The zoomed-in view shows the one-dimensional microscale TEC model. Ceramic plates, highly thermally conductive insulators, are used to isolate the TEC circuit, which is not shown in the figure.
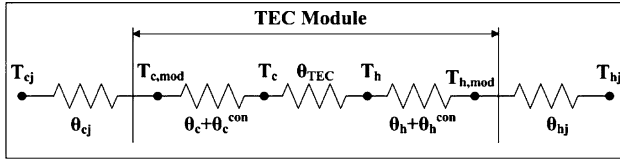

Fig. 2. Thermal resistance network for a TEC module. θ_{TEC} is the thermal resistance of the TEC elements. θ_c/θ_h and $\theta_c^{con}/\theta_h^{con}$ are, respectively, the total thermal resistance and thermal contact resistance from the edge of the TEC element to and including the ceramic plates. θ_{cj} and θ_{hj} are the total thermal resistance to the left of the cold plate and to the right of the hot plate, respectively.

all the thermocouples electrically in series and thermally in parallel. This figure also shows the sizes of the different components in a test chip for our particular application. For this particular application, an air-cooled heat sink is attached to the TEC. Therefore, the upper side of the heat sink is assumed to be cooled by a fan or other air-circulation means to room temperature (T_e) of 27°C. This generic TEC module has a thermal resistance network as shown in Fig. 2.

In our analysis, the TEC model is assumed to have a very thin metal film, a highly thermally conductive ceramic plate, and a direct contact to the hotspots with good thermal grease at the interface to reduce the interfacial thermal resistance; therefore θ_h, θ_c, and θ_{cj} in Fig. 2 can be ignored. To simplify the analysis, θ_h^{con} and θ_c^{con} are also assumed to be negligible. Therefore, the thermal resistance network for our model is simplified to that shown in Fig. 3. However, to further refine the proposed model, a more rigorous modeling of θ_h^{con} and θ_c^{con} should be included. The behavior of this developed TEC model is described by Eqs. 1–3.[4]
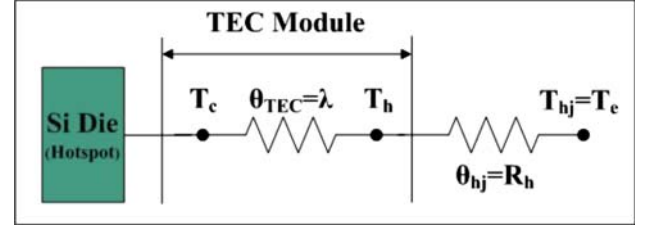

Fig. 3. Thermal resistance network for the proposed TEC model.

Table I. Specifications for Our Particular Application

Thermoelectric material	Bi_2Te_3
Hotspot power	3 W
Uniform background power	100 W
Temperature difference	10°C
$T_h//T_c$	105°C//95°C
Heat sink	Copper

$$q_c = \alpha T_c i - \frac{1}{2} i^2 (\rho L + 2r_c) - \frac{\lambda}{L}(T_h - T_c), \quad (1)$$

$$q_h = \alpha T_h i + \frac{1}{2} i^2 (\rho L + 2r_c) - \frac{\lambda}{L}(T_h - T_c), \quad (2)$$

$$T_h = T_e + r_h q_h, \quad (3)$$

where q (W/cm^2) is power density, I is the current per unit area, r_c ($\Omega \cdot cm^2$) is the electric contact resistance, and r_h (K $\cdot$ cm^2/W) is the thermal resistance at the hot side of a TEC. The first two equations represent heat transferring out of the cold side and to the hot side, respectively. The third equation describes the thermal resistance boundary condition. From these three equations, a main equation is derived to describe cooling power density in relation to other control variables and material constants. The TEC model will be optimized based on the specifications in Table I.

OPTIMIZATION METHOD

The optimization of a microscale TEC includes many variables such as current density, TEC length, packaging density, and material constants such as electrical and thermal resistance and contact resistance. Theoretically, a thermoelectric material with a higher figure of merit (Z) is more desirable, since it can achieve a higher cooling power or temperature difference. However, in most cases, the TEC material is specified. For our particular application, bismuth telluride is used as the thermoelectric material, which has $Z = 2.85 \times 10^{-3}$. Besides Eqs. 1–3, two more constraints are imposed by the specifications in Table I.

$$T_{\mathrm{h}} - T_{\mathrm{c}} = 10°\mathrm{C}, \qquad (4)$$

$$T_{\mathrm{e}} - T_{\mathrm{h}} = -78°\mathrm{C} \quad \text{given} \quad T_{\mathrm{e}} = 27°\mathrm{C}. \qquad (5)$$

The current density is solved providing Eqs. 2–5. By the numerical solution in MATLAB$^{©}$, the cooling power density is calculated for different TEC length, ΔT, r_{c}, and r_{h}. However, the optimization of the packing density is not discussed in this paper, since a two-dimensional analysis is required.

TEC LENGTH OPTIMIZATION

For ideal TEC models, the cooling power increases as the TEC length decreases. Therefore, as the TEC length approaches zero, the cooling power goes to infinity. However, two factors, thermal and electrical contact resistance, limit this ideal behavior. With the presence of contact resistances there is a particular TEC length that will maximize the cooling power. From the method described in the section "Optimization Method," we obtain performance curves that relate the cooling power density to TEC length for different temperature differences (Fig. 4).

This result shows that, for our particular application, which uses a heat sink made of copper, optimal thicknesses of the TEC elements are in the range of 5 μm to 16 μm, and the maximum cooling power density is in the range of 1300 W/cm^2 to 1900 W/cm^2 under temperature differences from 10°C to 50°C.

MATERIAL CONSTANTS

This section explores how the electrical contact resistance and thermal resistance affect the cooling power density and optimal TEC length. Ideally, we want both r_{h} and r_{c} to be zero to produce the largest cooling power. However, from the previous section, we know that the optimal TEC length is on the microscale, which means that electrical contact resistance can significantly affect the cooling power. Using the same method as described in the section "Optimization Method," we can investigate how changing r_{h} or r_{c} shifts the maximum cooling power density and optimal TEC length under different temperature differences, as shown in Figs. 5 and 6.

The results show that the maximum cooling power density increases, and the optimal TEC length decreases significantly as the thermal resistance or the electric contact resistance decreases. Figure 5 points out that, as r_{h} decreases from 0.04 K·cm^2/W (Si) to 0.03 K·cm^2/W (Cu), the optimal TEC length decreases by 18% and the maximum cooling power density increases by around 22%. As shown in Fig. 6, when r_{c} doubles from 10^{-6} Ω·cm^2, the optimal TEC length increases by 36%, and the maximum cooling power density decreases by 18%.
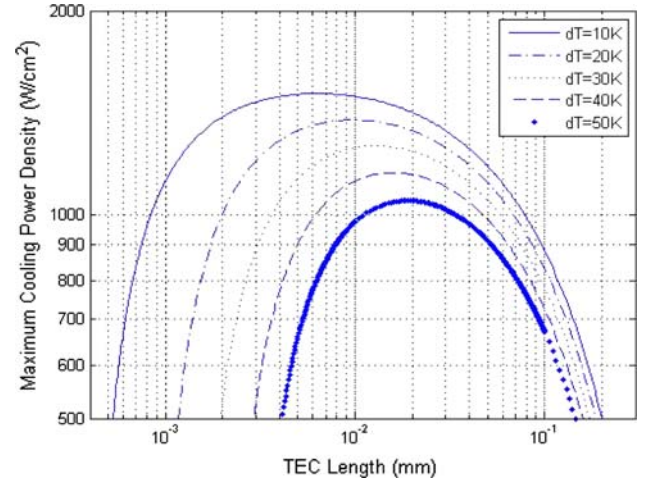

Fig. 4. Maximum cooling power density versus TEC length for ΔT across the TEC from 10 K to 50 K with a copper heat sink.
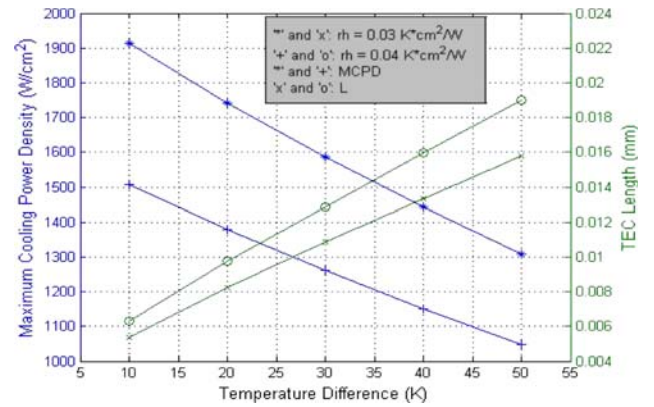

Fig. 5. Maximum cooling power and optimal TEC length versus ΔT for different thermal resistances (r_{h}).
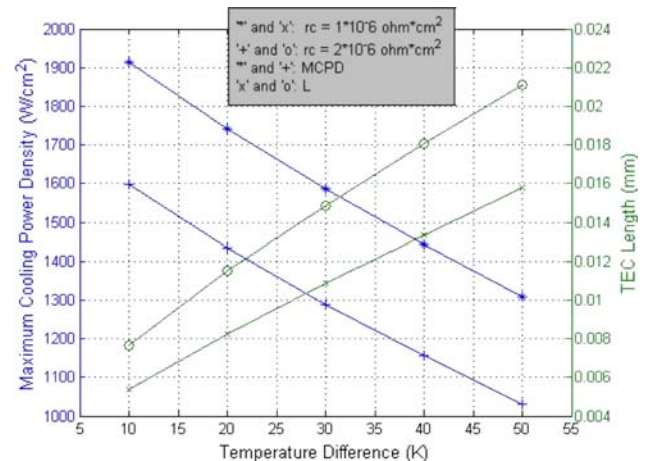

Fig. 6. Maximum cooling power and optimal TEC length versus ΔT for different electrical contact resistances (r_{c}).
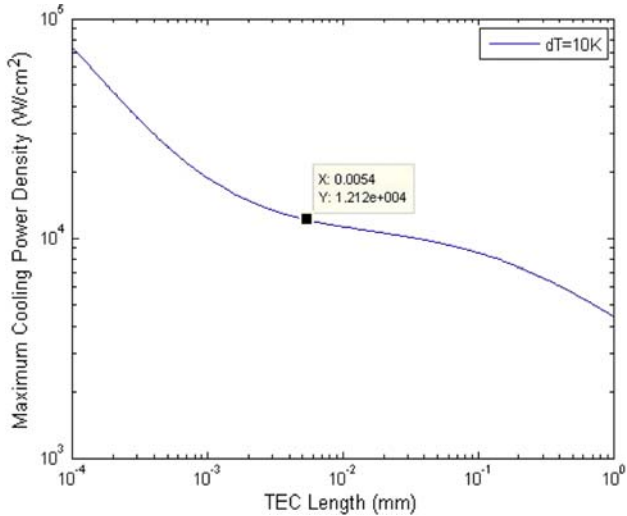
Fig. 7. Current density versus TEC length for ΔT = 10°C.

Table II. Operation Condition and Performance of the Designed TEC

Voltage supply	0.5 V
Current supply	0.865 A
Cooling power	15.2 W
Temperature difference	10°C
Number of couples	112
TEC element length	5 μm
Area of elements	7140 μm^2
Packaging density	80%

developed module is further refined, e.g., by accounting for the thermal contact resistance in the TEC, thermal resistance at the cold side, and even for some two-dimensional effects such as heat spreading, the maximum cooling power will be reduced and the optimal thickness will also shift.

PERFORMANCE OPTIMIZATION

From the results in the previous sections, the operation condition and the performance of the TEC can be determined for our particular application. From the section "TEC Length Optimization," we know that, for ΔT = 10°C, the maximum cooling power density is 1900 W/cm^2 with an optimal TEC length of 5 μm. The actual cooling power can be determined by the packaging density of the TEC, which, according to the experimental work in our laboratory,[5] can be changed from 25% to 90%. A packing density of 80% is used to calculate the cooling power, which turns out to be 15.2 W. From Eq. 6, the number of thermal couples in the TEC can be found.

$$V = N\alpha(T_\mathrm{h} - T_\mathrm{c}). \qquad (6)$$

If the voltage supply is assumed to be 0.5 V, the number of couples is calculated to be 112 with $\alpha = 448 \times 10^{-6}$ V/K (Bi$_2$Te$_3$). Then the cross-sectional area of the TEC element is 0.8 mm^2/112 = 7.14×10^{-3} mm^2. By multiplying the cross-sectional area with the current density, the supplying current can be obtained. Figure 7 shows that the current density at a TEC length of 5 μm is 1.212×10^4 A/cm^2. Therefore, the total current is 7.14×10^{-5} cm^2 $\times$ 1.212×10^4 A/cm^2 = 0.865 A. Summarizing all the results from previous sections, the estimation of the operation conditions and the performance of the TEC are presented in Table II.

The estimated cooling power is much greater than the required cooling at the hotspots. However, if the

CONCLUSION

For the developed TEC model, using Bi$_2$Te$_3$ as the thermoelectric material, the optimal thicknesses of the TEC elements are in the range of 5 μm to 16 μm and, the maximum cooling power density is in the range of 1300 W/cm^2 to 1900 W/cm^2 under temperature differences from 10°C to 50°C. Furthermore, the percentage change in optimal thickness for various thermal resistances and electrical contact resistances can be predicted. Using a packaging density of 80%, the maximum cooling power is estimated to be 15.2 W. This cooling power will be reduced if a more rigorous procedure is used to model the thermal resistance and the two-dimensional effects in the TEC model. This one-dimensional analysis acts as a good guideline for the experimental work in progress in our laboratory and further two-dimensional analysis of TEC, which is required to find the optimal packaging density.

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