

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

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Abstract

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 we developed and numerical solutions 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 heat 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.

I. INTRODUCTION

With the ever increasing transistor density and the 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 Cooler (TEC) is 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 3W hotspot region by 10°C . Following the treatment of previous researchers⁴, 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 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%.

II. ANALYTICAL MODEL

Although the heat transfer in a TEC is two-dimensional, a one-dimensional model can greatly simplify the analysis and calculation and still provide adequate accuracy. Figure 1 shows the one-dimensional TEC model for our analysis, which has 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.

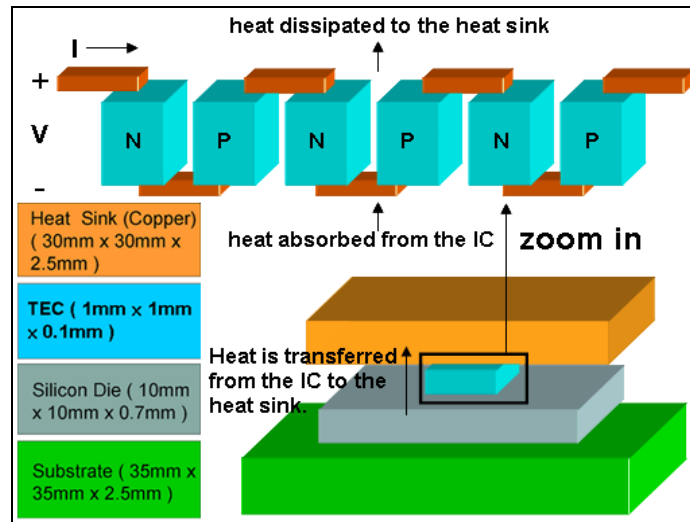


Figure 1: Relative sizes of the TEC, substrate and heat sink. The zoomed-in view of the one-dimensional microscale TEC model.

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 the room temperature (T_c) of 27°C . This generic TEC module has a thermal resistance network as shown in Figure 2.

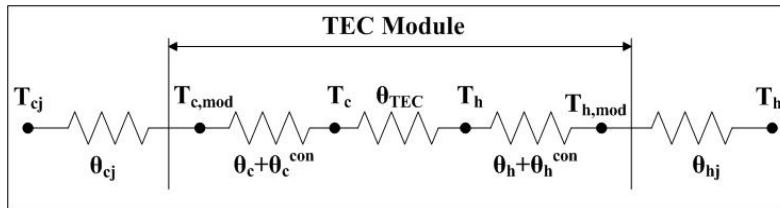


Figure 2: Thermal resistance network for a TEC module.

θ_{TEC} is the thermal resistance of the TEC elements. θ_c/θ_h and $\theta_c^{\text{con}}/\theta_h^{\text{con}}$ are, respectively, the total thermal resistance and thermal contact resistance from the edge of the TEC element to and including the ceramic plate, a highly thermal conductive insulator used to isolate the TEC circuit. 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. In our analysis, the TEC model is assumed to have a very thin metal film, a highly thermally conductive ceramic plate and direct contact to the hotspots with good thermal grease to reduce the interfacial thermal resistance; therefore θ_h , θ_c and θ_{cj} can be ignored. To simplifying 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 Figure 3.

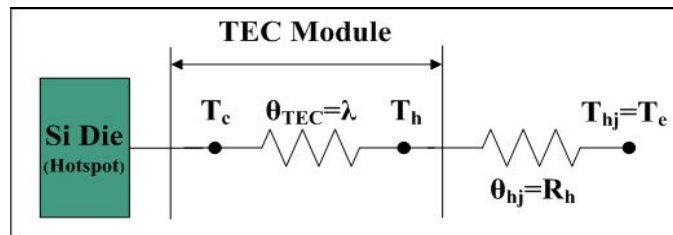


Figure 3: Thermal resistance network for the proposed TEC model.

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 the following equations.³

$$q_c = \alpha T_e i - \frac{1}{2} i^2 (\rho L + 2r_c) - \frac{\lambda}{L} (T_h - T_e) \quad \text{Equation [1]}$$

$$q_h = \alpha T_h i + \frac{1}{2} i^2 (\rho L + 2r_c) - \frac{\lambda}{L} (T_h - T_e) \quad \text{Equation [2]}$$

$$T_h = T_e + r_h q_h \quad \text{Equation [3]}$$

q (W/cm^2) is power density; I is current per unit area; r_c ($\Omega\text{-cm}^2$) is the electric contact resistance; r_h ($\text{K}\cdot\text{cm}^2/\text{W}$) 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 heat 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 below.

Table 1: Specifications for our particular application.

Thermoelectric Material	Bi_2Te_3
Hotspot power	3W
Uniform Background Power	100W
Temperature Difference	10°C
$T_h // T_c$	$105^\circ\text{C} // 95^\circ\text{C}$
Heat Sink	Copper

III. OPTIMIZATION METHOD

The optimization of microscale TEC includes many variables such as current density, TEC length, packaging density, and material constants like electrical and thermal resistance and contact resistance. Theoretically, the thermoelectric material with 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 $Z=2.85 \times 10^{-3}$. Beside the equation [1], [2] and [3], two more constraints are imposed by the specifications in Table 1.

$$T_h - T_c = 10^\circ\text{C} \quad \text{Equation [4]}$$

$$T_e - T_h = -78^\circ\text{C} \text{ given } T_e = 27^\circ\text{C} \quad \text{Equation [5]}$$

The current density is solved providing equation [2], [3], [4] and [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.

IV. 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, which will maximize the cooling power. From the method described in Section III, we obtain performance curves that relate the cooling power density to TEC length for different temperature differences, shown in Figure 2.

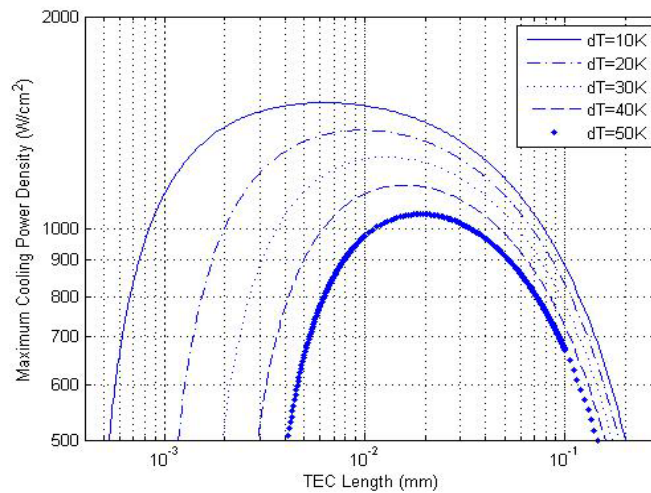


Figure 4: Maximum cooling power density versus TEC length for ΔT from 10K to 50K with heat sink made of copper.

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

V. 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 in microscale, which means that electrical contact resistance can significantly affect the cooling power. Using the same method as described in Section III, 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 Figure 5 and 6.

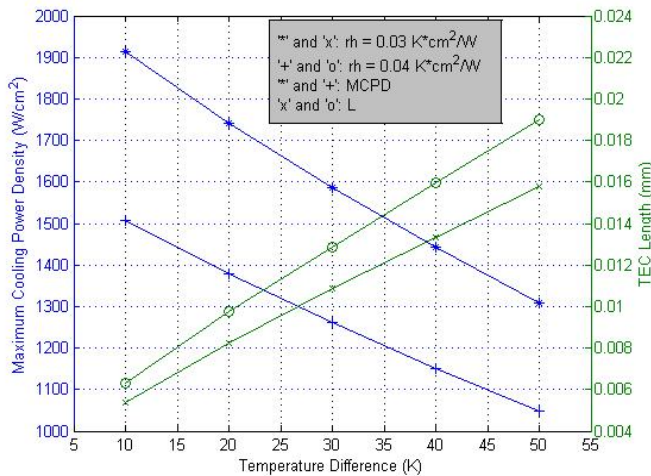


Figure 5: Maximum cooling power and optimal TEC length versus temperature difference for different r_h values.

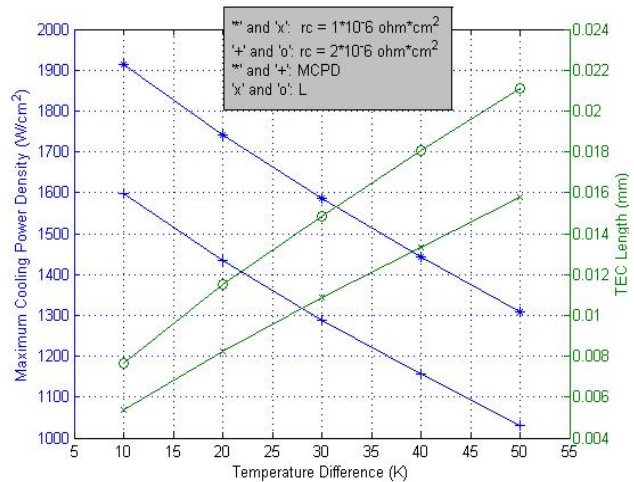


Figure 6: Maximum cooling power and optimal TEC length versus temperature difference for different r_c values.

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 shows that as r_h decreases from $0.04 \text{ K}\cdot\text{cm}^2/\text{W}$ (Si) to 0.03

$\text{K}\cdot\text{cm}^2/\text{W}$ (Cu), the optimal TEC length decreases by 18% and the maximum cooling power density increases by around 22%. As shown in Figure 6, when r_c doubles from 10^{-6} ($\Omega\cdot\text{cm}^2$), the optimal TEC length increases by 36%, and the maximum cooling power density decreases by 18%.

VI. PERFORMANCE OPTIMIZATION

From the results in previous sections, the operation condition and the performance of the TEC can be determined for our particular application. From Section IV, we know for $\Delta T = 10^\circ\text{C}$, the maximum cooling power density is $1900 \text{ W}/\text{cm}^2$ with an optimal TEC length of $5\mu\text{m}$. The actual cooling power can be determined by the packaging density of the TEC, which, according to the experimental work in our lab⁵, can be changed from 25% to 90%. A packing density of 80% is used to calculate the cooling power, which turns out to be 15.2W . From equation [6], the number of thermal couples in the TEC can be found.

$$V = N\alpha(T_h - T_c) \quad \text{Equation [6]}$$

If the voltage supply is assumed to be 0.5V , the number of couples is calculated to be 112 with $\alpha=448\cdot 10^{-6} \text{ V}/\text{K}$ (Bi_2Te_3). Then the cross section area of the TEC element is $0.8 \text{ mm}^2/112 = 7.14\cdot 10^{-3} \text{ mm}^2$. By multiplying the cross sectional area with the current density, the supplying current can be obtained. Figure 7 shows the current density at a TEC length of $5\mu\text{m}$ is $1.212\cdot 10^4 \text{ A}/\text{cm}^2$.

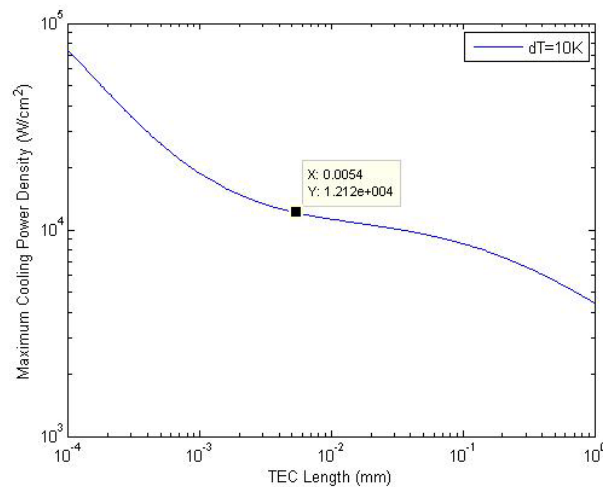


Figure 7: The current density versus TEC length for $\Delta T = 10^\circ\text{C}$.

Therefore, the total current is $7.14\cdot 10^{-5} \text{ cm}^2 \times 1.212\cdot 10^4 \text{ A}/\text{cm}^2 = 0.865\text{A}$. Summarizing all the results from previous sections, the estimation of the operation conditions and the performance of the TEC are presented in Table 2.

Table 2: Operation condition and the performance of the designed TEC.

Voltage Supply	0.5V
Current Supply	0.865A
Cooling Power	15.2W
Temperature Difference	10°C
Number of Couples	112
TEC element Length	$5\mu\text{m}$
Area of Elements	$7140\mu\text{m}^2$
Packaging Density	80%

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

VII. CONCLUSION

For the developed TEC model, using Bi_2Te_3 as the thermal electric material, the optimal thicknesses of TEC elements are in the range of $5\mu\text{m}$ to $16\mu\text{m}$ and, the maximum cooling power density is in the range of 1300 to 1900 (W/cm^2) under temperature differences from 10°C to 50°C . Further, the percentage change in the optimal thickness for various heat resistances and electrical contact resistances can be predicted. Using a packaging density of 80%, the maximum cooling power is estimated to be 15.2W. 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 lab and further two-dimensional analysis of TEC, which is required to find the optimal packaging density.

References

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