Contact Resistances for Miniature Thermoelectric Devices

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Abstract

This project presents the consideration of the contact resistance in miniature thermoelectric module farther progress in the development of short-legged thermoelectric (TE) micro modules for the cooling of high power density electronic components. Theoretical analysis study is made to define an available temperature lowering and flux densities of maximum heat for short-legged coolers to get efficient cooling power. When sort-long leg length is used, the materials' properties (Seebeck coefficient, figure of merit, thermal conductivity, and electrical conductivity) are different if the leg length is less than 0.5 mm. All the materials properties are same while the leg length is more than 0.5 mm. The lower temperature deference is at leg length about 0.2 mm. The substrate material which is used in this project is Aluminum Nitride ceramic.
Nomenclature

\( A_c \) Cross-section area of thermoelement (m²)

**COP** The coefficient of performance, dimensionless

I Electric current (A)

\( I_{\text{max}} \) Maximum current (A)

K Thermal conductance (W/K)

\( L_c \) The thickness of the contact layer (m)

\( L_0 \) The leg length of the element

k Thermal conductivity (W/mK)

\( k_c \) Thermal conductivity of ceramic (W/mK)

n Number of thermocouples

\( Q_1 \) Cooling power, heat absorbed at cold junction (W)

\( Q_2 \) Heat liberated at hot junction (W)

\( Q_{\text{cmax}} \) Maximum cooling power (W)

\( T_1 \) Low junction temperature (°C)

\( T_2 \) High junction temperature (°C)

V Voltage of a module (V)

\( V_{\text{max}} \) Maximum voltage (V)

\( \Delta T \) Temperature difference \( T_2 - T_1 \) (°C)

\( \Delta T_{\text{max}} \) Maximum temperature difference (°C)
Ge

Geometry factor (m)

Greek symbols

$\delta$  Seebeck coefficient (V/K)

$\rho$  Electrical resistivity ($\Omega \cdot \text{cm}$)

$\rho_c$  Electrical resistivity of ceramic ($\Omega \cdot \text{cm}^2$)
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1. Introduction

Over the last decade, the research and development of thermoelectric (TE) devices has attracted a great deal of attention because of their potential applications in green energy and energy management. As a whole, TE devices in semiconductor can be classified into two different groups: one is the thermoelectric generator (TEG) and the other the thermoelectric cooler (TEC).

Thermoelectric cooler (TEC) is a cooling device for specific purposes, it has been widely used in military, aerospace, instrument, and industrial or commercial products [3,4]. This technology has existed for about 40 years. Many researchers are concerned about the physical properties of the thermoelectric material and module, the system analysis of a thermoelectric cooler is equally important in designing a high-performance thermoelectric cooler.

In this research, we will focus on the miniature thermoelectric cooler as it is shown in the figure 1-1, the miniature thermoelectric coolers (TECS) is widely used in thermal management of such electronic components as microprocessors, semiconductor-laser, light-emitting diodes, and other small electronics.
The figure 1-2 represents the miniature thermoelectric cooler that consists of three parts, two ceramic plates, the layer conductors (copper) and two elements (P-type element and N-type element). This project will focus on the contact resistance in the miniature thermoelectric module farther progress in the development of short-legged thermoelectric micro modules for cooling high power density electronic components. Theoretical analysis study is made to define an available temperature lowering and maximum heat flux densities for short-legged coolers to get high cooling power. When sort-long leg length is used, the materials properties (Seebeck coefficient, figure of merit, thermal conductivity, and electrical conductivity) are difference if the leg length is less than 0.5 mm.
Figure 1-2. The device of the miniature thermoelectric cooler
2. Mathematical formulation and modeling

2-1 Ideal equations including contact resistance

A simple thermoelectric cooling (TEC) is shown in Figure 1-2. The amount of heat absorbed at the cold junction is associated with the Peltier cooling, the half of Joule heating including contact resistance, and the thermal conduction. The basic equations used in this analytical are:

The cooling power is:

\[ Q_1 = \frac{A_e \cdot k_c}{l_c} \cdot (T_1 - T_{1c}) \]  

(1)

\[ Q_1 = \partial \cdot I \cdot T_{1c} - \frac{1}{2} \cdot I^2 \cdot \left( \frac{\rho \cdot l_o}{A_e} + \frac{\rho_c}{A_e} \right) - \frac{A_e \cdot k}{l_o} (T_1 - T_{1c}) \]  

(2)

The amount of heat rejected from the hot plate is also obtained as shown in Figure (1):

\[ Q_2 = \partial \cdot I \cdot T_{2c} + \frac{1}{2} \cdot I^2 \cdot \left( \frac{\rho \cdot l_o}{A_e} + \frac{\rho_c}{A_e} \right) - \frac{A_e \cdot k}{l_o} (T_{2c} - T_{1c}) \]  

(3)

\[ Q_2 = \frac{A_e \cdot k_c}{l_c} \cdot (T_{2c} - T_2) \]  

(4)
Where \( \partial = \partial_p - \partial_n \) and \( k = k_p + k_n \).\( k \) is the thermal conductivity of the thermoelements, \( k_c \) the thermal conduct conductivity which includes the thermal conductivity of ceramic plates and the thermal conduct, \( l \) the thermoelement length, and \( l_c \) the thickness of the contact layer, \( \rho \) is the electrical resistivity, \( A_c \) is cross-section area for the element, \( T_{2c} \) and \( T_{1c} \) are hot and cold junction temperatures respectively, \( T_1 \) and \( T_2 \) are cold and hot side temperatures, \( L_0 \) is leg length for element, and \( \rho_c \) represents the electrical resistivity.

### 2-2 Maximum Performance Parameters \[^2\]:

The maximum performance parameters below are useful in math analytical. Equation (5) is virtually the maximum current for the given material and geometry.

\[
I_{\text{max}} = \frac{\partial}{R} \left( \sqrt{(T_2 + \frac{1}{Z})^2 - T_2^2} - \frac{1}{Z} \right) \tag{5}
\]

Or

\[
I_{\text{max}} = \frac{\partial^* (T_2 - \Delta T_{\text{max}})}{R} \tag{6}
\]

the maximum possible temperature difference is

\[
\Delta T_{\text{max}} = (T_2 + \frac{1}{Z}) - \sqrt{(T_2 + \frac{1}{Z})^2 - T^2} \tag{7}
\]

Where \( Z \) is figure of merit.
the maximum possible cooling rate for the given material and geometry, we have

\[
Q_{c_{\text{max}}} = \frac{n \cdot \sigma^2 \cdot (T_2^2 - \Delta T_{\text{max}}^2)}{2 \cdot R}
\]

The equations (5-8) are used in this project to create the equation that joins each of maximum current, different temperature, and cooling power as a function of the leg length (l_o).

2-3 Mathcad Analysis

The Mathcad software was used to make analytical way for the miniature thermoelectric cooler. The analysis is made to describe the behavior of the cooling power and different temperature with contact resistance and short leg length elements. The ideal equations including the contact resistance are used in this project.

Figure 2-1. Cold side and cold junction temperature versus current
The figure 2-1 shows the relation between cold junction temperature and cold side temperature with current supply [Appendix 1]. Where it is shown that the cold junction and cold side temperature is the same with different current supply. When the current increased, both the cold side and cold junction temperature were decreased to the current value equal to 3.8A at first and then increased.

In another hand, [Appendix 1] the hot junction temperature is increased when the current supply is increased as that is shown in the figure 2-2.

Figure 2-2. Hot junction versus current supply
3. Effect material properties [2], [Appendix A]

The effective material properties are defined here as the material properties that are extracted from the maximum parameters provided by the manufacturers or from measurements. The effective figure of merit is obtained from Equation (9), which is

\[ Z^* = \frac{2 \cdot \Delta T_{\text{max}}}{(T_2 - \Delta T_{\text{max}})^2} \]  

The effective Seebeck coefficient is obtained from Equation (6) and (8), which is

\[ \xi^* = \frac{2 \cdot Q_{\text{cmax}}}{n \cdot I_{\text{max}} \cdot (T_2 + \Delta T_{\text{max}})} \]  

The effective electrical resistivity can be obtained using Equation (6), which is

\[ \rho^* = \frac{\xi^* \cdot (T_2 - \Delta T_{\text{max}}) \cdot A_c / L}{I_{\text{max}}} \]  

The effective thermal conductivity is now obtained, which is

\[ k^* = \frac{\xi^*}{\rho^* \cdot Z^*} \]  

By using the equation 9-12 as a function of thermoelement length \( l_o \)}, where the figure 3-1
shows the effect leg length of element, it’s noted that the value of the figure of merit and Seebeck coefficient are changed according to thermoelement length’s value in 0 mm to 0.5 mm, in another hand, all the values of figure of merit and Seebeck coefficient have same value when the leg length’s value is bigger than 0.5 mm.

Figure 3-1. Figure of merit and Seebeck coefficient versus leg length

In addition, the electrical resistivity and thermal conductivity take same way as figure of merit and Seebeck coefficient. The figure 3-2 explains that the values of the electrical resistivity and thermal conductivity are decreased because of the increased of the leg length’s value in 0mm to 0.5mm.
Furthermore, the thermoelement is effective on the maximum cooling power and maximum current as it is shown in figure 3-3. Where the decrease of the leg length leads to increasing the maximum cooling power and maximum current. To be attention, When the value of the leg length in 0.5 mm to 0 mm, the slop is prominent increased.
4. Literature validation and results comparing

4-1 Difference temperature

Maximum temperature difference versus leg length as it is shown in the figure 4-1, the solid red line represents calculation by using ideal equation including contact resistance while the dote points refers to experiment values by V. Semenyuk’s paper (2001) [1]. Where there is a good agreement between calculation results and experiments results [Appendix A].

![Figure 4-1. Calculation and experiment values versus leg length](image)

\[
\Delta T_{\text{max}} \left(A_e, l_{oi}, l_c, k_c\right)_{70} \quad \Delta T_{\text{exp}}
\]


\( l_{oi} \quad l_{oexp} \quad \text{Experimental Value} "\]
4-2 Heat load characteristics of TE micro cooler

The figure 4-2 plots the variations of $\Delta T$ as a function of a heat load $Q_c$ at the cold side for the AlN-module when different electrical currents are supplied. When $\Delta T$ is completely suppressed the module demonstrates cooling power near 4.5 W which corresponds to heat flux density of 75.6 W/cm² at the cold junctions. Where the cross-section area of thermoelement is 0.41mm*0.41mm [Appendix B].

![Figure 4-2. Heat load characteristics of TE micro cooler versus difference temperature](image)
5. Cooling power and Geometry Factor

The figure 5-1 shows the cooling power versus the geometry factor with change in the thermoelement length at different current supplied. Where the cooling power increases with increasing the current supplied because of increasing in current leads to increasing in geometry factor as that in the figure [Appendix B].

Figure 5-1. Cooling Power versus Geometry Factor
6. ANSYS Simulation

The thermoelectric cooler (one couple) has been simulated by using ANSYS program include thermal-electric. It helped to make double sure to check fit with values which are obtained analytically by using Mathcad software. The results are shown good agreement with it. The simulation is made on two kinds of the thermoelectric cooler. The figure 6-1-A shows the geometry of the first kind model which it is simulated. It consist of the two elements of the material (ALN) with leg length (0.2mm) and cross-section (0.41mm*0.41mm) [1]. In addition, the model has on two ceramic plates (0.62mm*0.41mm) one of them at top and another at bottom. Furthermore, there is a layer of copper under each ceramic which has thickness (0.03mm) with depth (0.41mm). While in the figure 6-1-B refers to second kind that has on two ceramic plates with thickness (0.15mm) and a layer of copper with thickness (0.5mm).

Figure 6-1-A. Thermoelectric cooler with thickness (0.62 mm ceramic) and (0.03 mm copper)
The main procedures that are applied to complete the simulation of the thermoelectric model are:

**6-1 Mesh**

Mesh generation is one of the most critical aspects of engineering simulation. Too many cells may result in long solver runs, and too few may lead to inaccurate results. ANSYS Meshing technology provides a means to balance these requirements and obtain the right mesh for each simulation in the most automated way possible. The figure 6-2-A explains the mesh for the first kind of the thermoelectric cooler model (one couple) While figure 6-2-B shows the second kind of the model.
Figure 6-2-A. Mesh of the first kind of the model

Figure 6-2-B. Mesh of the second kind of the model
6-2 Temperature Distribution

The first kind if the thermoelectric cooler model is shown in the figure 6-3-A. It shows distribution the temperature from cold side to hot side. The cold side has junction cold temperature about 242.161 K and junction hot has temperature about (304.6 K) with current supply (2 Amber). As it is shown in the figure, the distribution starts of the cold to hot side. While the figure 6-3-B explains second kind, where the junction cold temperature is about (263.4K) and hot junction temperature is about (303.225K).

![Figure 6-3-A. Temperature Distribution](image-url)
6-3 Current Distribution

The final step in this simulation is to distribute the current when it is supplied through the thermoelectric. In the figure 6-4-A, it is shown current distribution of the right side to the left side that has a value (2 Amber) for the first kind and figure 6-4-B shows the second kind.
7. Results and Discussion

The change in value of current supply and thickness of the ceramic and copper effect on the junction temperatures and heat flow. Where the increasing in supplying the current leads to increase in the junction temperatures (cold and hot) and heat flux. In addition, this increasing leads to increasing in error percentage between results that are obtained from Mathcad software and ANSYS program. While the increasing copper thickness also effects on the results, where when the copper has increasing in the thickness, the values of junction cold and hot temperatures becomes close to values that are obtained of Mathcad software with decrees the ceramic thickness. Below the compare between the values obtained of the ANSYS simulation for two kinds and Mathcad calculations.
8. Conclusion

The short thermoelement length less than 0.5 mm for thermoelectric cooler has effect on each of cooling power, and effective materials. Mathematically analysis study are made to define an available temperature lowering and maximum heat flux densities for short-legged coolers by using ideal equations which including contact resistance. The temperature differences is about 71K are obtained with TE leg lengths down to 0.2 mm. In addition, the project has a validation for ‘Thermoelectric Micro Modules for Spot Cooling of High Density Heat Sources’ [1]. Where this validation includes two main important things, difference temperature as a function of the cooling power and the maximum difference temperature with thermoelement length. The prediction which is obtained from equations as a validation has a good agreement with experiment work by V. Semenyuk. Finally, ANSYS simulation has improved great matching with the prediction results.
References


