Improved maximum cooling by optimizing the geometry of thermoelectric leg elements

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Abstract

In this paper, we investigate the effect of the thermoelectric leg geometry and boundary conditions on the overall device cooling performance. We present a detailed 3D electrothermal analysis of heat and current distribution in a Bi_2Te_3 single-leg element with 50x50μm^2 cold side contact area, which is smaller than the element cross section (410x410μm^2). We compared the cases when a uniform voltage is applied at the contact and when a uniform current density is applied. The finite element calculation results demonstrate that in the latter case the 3D single-leg element has a very non-uniform temperature distribution at the contact area. Maximum cooling in the center region is 92^{0}C, which is 20% higher than the 1D limit (76^{0}C) for a typical Bi_2Te_3 material with ZT~1. Calculations show that it is possible to take away 600W/cm^2 at the center 20x20μm^2 region, which is 6 times better than the 1D device with the same thickness. In contrast, with a boundary condition of uniform voltage at the cold side contact area, the temperature distribution is as uniform as 1D device and reaches the same maximum cooling temperature as 1D. We also propose the possibility of using array contact structures to achieve the uniform current boundary condition that can improve the maximum device cooling performance. These findings add contact geometry as another degree of freedom to engineer the performance of single and multi stage TE devices.

Nomenclature

α	Seebeck coefficient
σ	electrical conductivity
κ	thermal conductivity
Q	heat flux
ZT	Figure of merit, $\alpha^2\sigma T/\kappa$
ΔT	temperature difference
1D limit	$\Delta T=\frac{1}{2}ZT_c^2=76^0C$ for the Bi_2Te_3 (ZT~1)
R_e	electrical resistance of the element
R_{th}	thermal resistance of the element

Introduction

Thermoelectric coolers/power generators attract lots of attention because they are quiet, environmentally-green, and light weight. However, the low efficiency still limits their applications. The traditional approach in improving the thermoelectric efficiency and maximum cooling mainly focuses on improving materials' figure-of-merit, ZT, which could be described by: $ZT = \alpha^2\sigma/k$, α, Seebeck coefficient; σ, electrical conductivity; $\alpha^2\sigma$, power factor; κ, thermal conductivity. Bi_2Te_3 has been the most popular thermoelectric material at room temperature because it has a very low thermal conductivity, on the order of 1.5 W/mK, and at the same time a high power factor. Most of the recent research on thermoelectrics focuses on improving the material properties to get higher ZT values. For example, Harman et. al. [1] have produced an n-type quantum dot structure based on PbSe-PbTe and demonstrated a room temperature ZT of 1.6; Venkatasubramanian et. al. [2] fabricated Bi_2Te_3/Sb_2Te_3 superlattices and got ZT of 2.4. Some other research has concentrated on integrated cooling of electronic devices with monolithic structures. Fan et. al. [3] demonstrated that Si/SiGe superlattice microcoolers can achieve cooling power density exceeding 600W/cm^2.

Figure-of-merit is a dimensionless parameter and it has been shown that maximum cooling and energy conversion efficiency is not affected by the thermoelectric element leg geometry (at least in the conventional 1D cases). Most of the optimization work has been mainly limited to reducing the TEC thickness since it is well know that in an idealized TEC model, the cooling power density is inversely proportional to the TE leg length. [4,5,6] We presented a paper "Three-dimensional high cooling power density thermoelectric coolers" at the International Conference on Thermoelectric in Adelaide in 2004. [7] Electrothermal finite element analysis showed that a single BiTe element with 3D contact geometry, as illustrated in Fig. 1, can reach a maximum cooling that is 20-30% higher than the 1D element and its cooling power density can go up to 700 W/cm^2. Originally, we thought that this improvement in cooling is achieved due to the fact that less Joule-heating flows back to the cold surface compared to the conventional 1D element (1/3 instead of 1/2). However, earlier investigation by Semenyuk [8] already demonstrated that the thermoelectric device efficiency is independent of the leg geometry. More specifically, Semenyuk's analytical model demonstrated that always 1/2 of the Joule-heating flows back to the cold surface independent of the shape of the contacts and maximum cooling is the same as a 1D device. In this paper we have done additional electrothermal modeling and we confirm that Semenyuk's conclusion is valid "on the average" at the cold contact. However, higher maximum cooling could be achieved in the 3D geometry at specific locations.

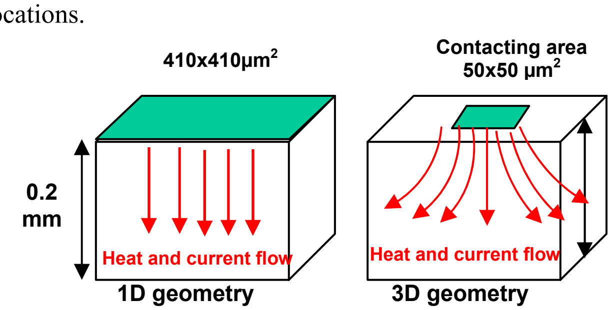

Figure 1: Schematic of the 1D and 3D device geometry

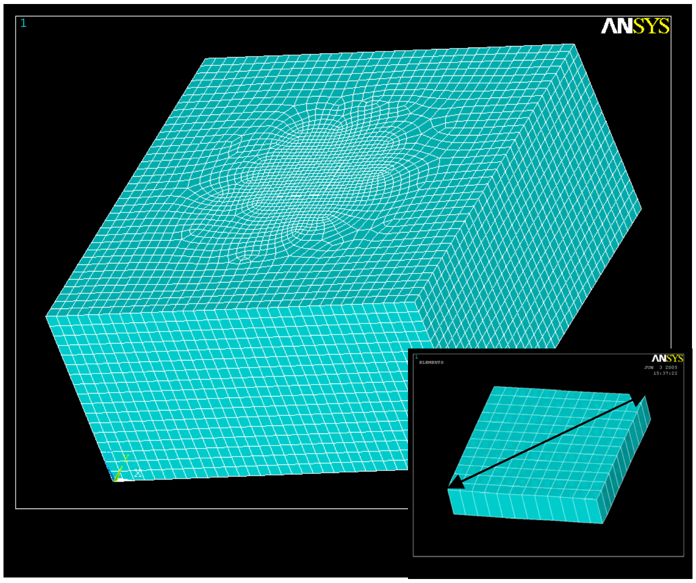

Figure 2: Demonstration of solid brick meshed device structure. The inset in bottom right corner shows the enlarged contact region for 3D device (50x50μm^2) and the diagonal temperature path shown in Fig. 3 and Fig. 4.

Device Modeling

The device geometry used in our model is based on commercially available short-leg, 200μm, TEC from Thermion Corp. [5] We take one element with the surface area of 410x410 μm^2 and leg length of 200μm as the base model. As a comparison to 1D model, the contact area at the cold side of the 3D device was reduced to 50x50 μm^2 (see Fig. 1). The thermoelectric properties used in the model were measured by the Thermion Corp. and reported as follows: Seebeck coefficient, α=205μV/K; electrical conductivity, σ = 1010 (Ωcm)$^{-1}$; thermal conductivity; κ=1.405 K/W; figure of merit, Z=3.02x10^{-3} K^{-1}. To study the inherent effects of current and heat spreading, only the bulk BiTe element is considered and no packaging and metallization contact effects are included. We assume that the bottom surface is attached to an ideal heat sink with a fixed temperature of 300K. At the same time, we also set the bottom surface as the ground contact. All calculations are based on the adiabatic temperature boundary condition at all other surfaces. The 3D electrothermal model is built with the ANSYS™ finite element software and the device with fine meshing is illustrated in Fig. 2. The Peltier effect is applied as an interface cooling source at the top contact area with the cooling power, $\alpha T_c I$ (α, Seebeck coefficient, T_c, cold side temperature, I, supplied current). In our previous model [7], we applied a uniform cooling power at the interface, where we used the total applied current and the maximum cooling temperature at the center. This is valid for 1D model, where the temperature, current and heatflux are all uniformly distributed. However, for the 3D device, the temperature at the contact area is non-uniform. Simply applying a uniform cooling flux at the interface overlooks the effect of non-uniform current and temperature distribution. In this paper, we retrieve the current density and temperature at each calculation node, and apply the exact cooling power as a boundary condition at that node. Since temperature of each node is not known a priori, multiple iterations are needed. Joule heating and heat conduction are automatically calculated by solving the current continuity and heat equations. As we stated above, the cooling power ($\alpha T_c I$) applied at the contact area is directly related to the local temperature. We start our calculation by assuming a temperature T_0 first, and then iterate the program until it converges on a final cold side temperature at each node. We are thus able to predict more accurately the temperature profile of the device under test.

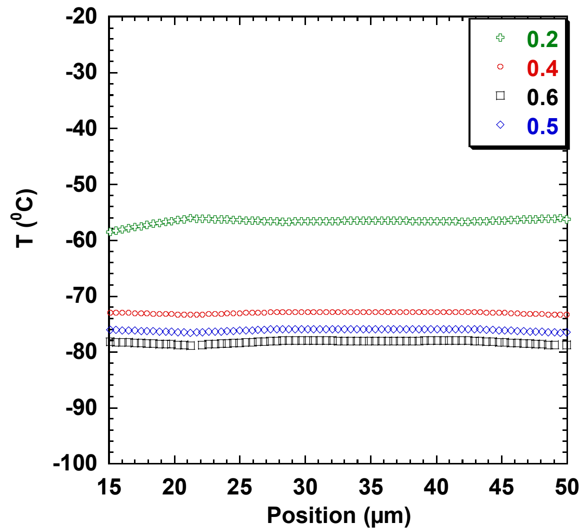

Figure 3: Temperature distribution along the diagonal path of the contact area illustrated in Fig. 2, with the uniform *potential* applied at the cold junction.

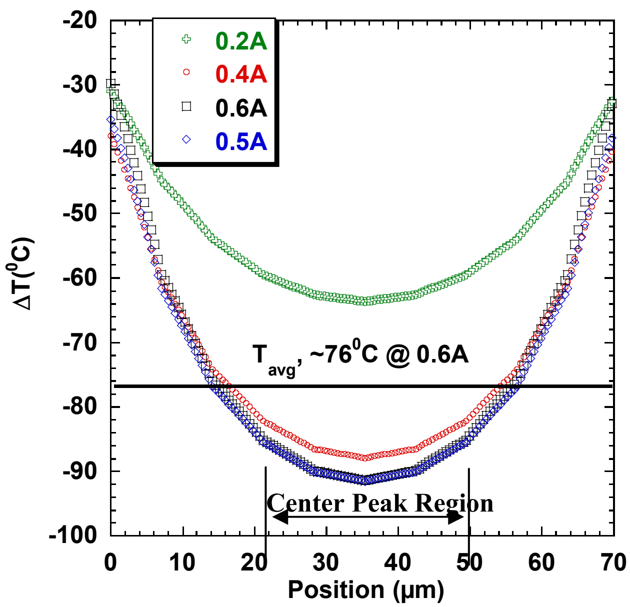

Figure 4: Temperature distribution along the diagonal path of the contact area, illustrated in Fig. 2, with the uniform *current* applied at the cold junction.

Results and Discussions

We find that the maximum cooling performance of the element with 3D geometry depends on the uniform voltage or current boundary conditions. Under the condition of uniform potential applied at the cold contact area, the resulting temperature distribution is uniform and the maximum cooling exactly matches the 1D limit, $\frac{1}{2}ZT_c^2$ ~76^0C. Fig. 3 illustrates the temperature distribution along the diagonal path of the contact area in Fig. 2 at different total currents. The potential value was converted to current value here for better comparison with the uniform current situation. It is clearly see that the temperature is uniformly distributed similar to the 1D device. When we apply the uniform current condition at the contact area, we get a very non-uniform temperature distribution on the cold side, as demonstrated in Fig. 4. The non-uniform temperature distribution gives us a peak cooling temperature of 92^0C, which is 21% higher than the 1D limit, though the average temperature of the contact area is still the same as the 1D maximum cooling. Under the uniform current condition, we could still benefit from higher cooling at the center region: the average cooling temperature in the 20x20μm^2 center region (demonstrated as "center peak region" in Fig. 4) is higher than 85^0C. Besides the higher cooling temperature, the cooling power density at this center peak region is also much higher than the 1D element. Fig. 5 plots the average cooling temperature versus applied heat flux for both the 1D element and the center peak region of the 3D device. We define the maximum cooling power density of the devices to be equivalent to the amount of the heat flux where the cooling temperature equals to zero. The cooling power density for 1D device is ~90 W/cm^2 while it is ~680 W/cm^2 for the 3D device center peak region. The 3D device can thus provide higher maximum cooling for a localized heat source. One should note that by adding a heat spreader on the cold side of a 1D thermoelectric element, one can increase the maximum cooling power for a small hot spot, but one can never reach cooling temperatures beyond 76^oC, if the electrical contact to the cold junction does not have heat and current spreading.

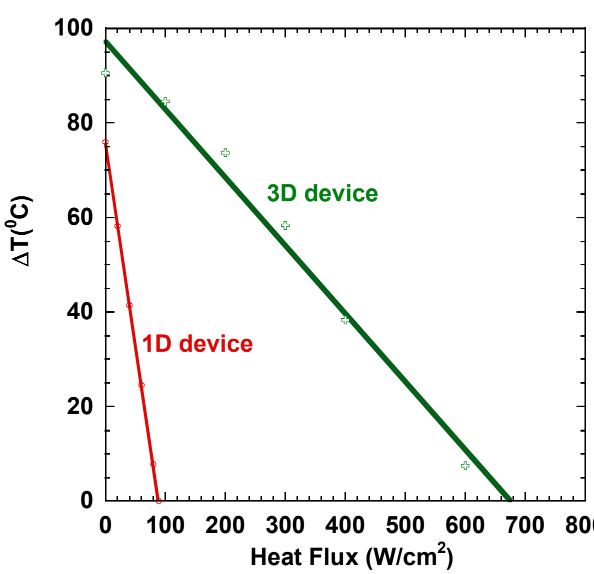

Figure 5: Comparison of the cooling power density of the 1D device (4A current applied) versus the center peak region of 3D device (0.6A current uniformly applied to the contact region).

Fig. 6 summaries the maximum cooling versus supplied current for the 1D device (labeled 1D), 3D device with uniform potential (labeled 3D-50-UniformV) and 3D device with uniform current density (labeled 3D-50-UniformI). In all scenarios, the cooling curves could be fitted well with the conventional heat conduction equation, $Q = \alpha I T_c - \frac{1}{2} I^2 R_e - \frac{\Delta T}{R_{th}}$, Q is the applied external heat. It is equal to zero at the maximum cooling. $\alpha T_c I$ is the Peltier cooling power, $\frac{1}{2}I^2R_e$ is the Joule heating power flowing back to the cooling surface and $\Delta T/R_{th}$ is the contribution from heat conduction. This indicates that in all cases, only half of the Joule-heating flows back to the cold surface. This corresponds to Semenyuk's earlier conclusions. [11] We can see in Fig. 6 that only the 3D element with the boundary condition of uniform applied current density could achieve a maximum cooling temperature better than the 1D limit.

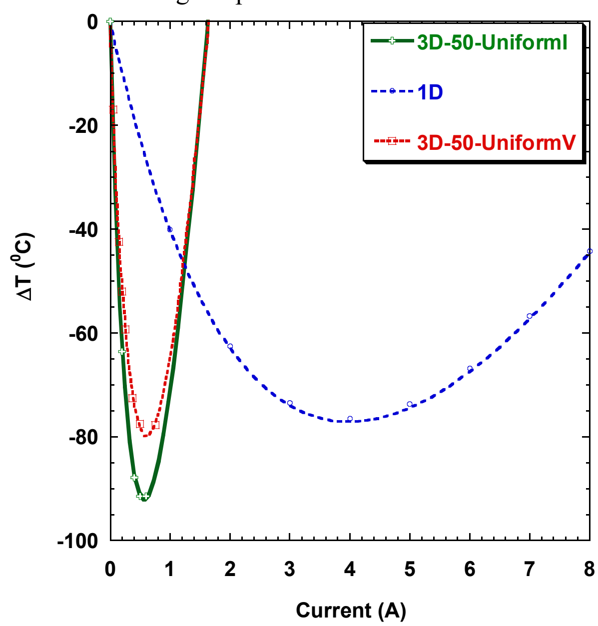

Figure 6: Maximum cooling temperature versus supplied current for 1D element, 3D element under uniform potential and 3D element under uniform current density conditions.

From the previous discussion, we see that in order to achieve a better cooling performance, we have to design a TE element with 3D contact geometry and apply a uniform current density at the cold surface. However, how we could achieve this boundary condition since thick metallic contacts provide a uniform potential at the cold junction? To solve this dilemma, we have to engineer the contact area using an array structure. Thus we could control the potential of each small contact region according to the potential profile from finite element model to achieve the uniform current condition. It is interesting that using contact array structure, one can apply arbitrary potential values at neighboring areas and thus it may be possible to increase the maximum cooling in some regions beyond what was achieved in this paper.

Conclusion

We analyzed the performance of a single-leg 3D Bi_2Te_3 element with a contact area of 50x50 μm^2 using 3D finite element electrothermal model. The simulation results showed that the maximum cooling of the 3D element, 92^0C is 21% higher than 1D device, 76^0C, when we apply the uniform current at the contact area. Under this condition, the temperature at the cold junction is very non-uniform. The cooling temperature at the center 20x20 μm^2 region is over 85^0C, though the cold contact average temperature is still equal to the 1D limit. We could also benefit from the high cooling power density of 650 W/cm^2 at the center region, which has the potential application in cooling localized hot spots in ICs. To achieve the uniform current, we have to engineer the contact area using an array structure. It is interesting to note that if we apply a uniform potential at the contact region as the conventional experimental set-up, even with the 3D geometry, we will not see any benefit as compared to the 1D device.

Acknowledgement

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