Thermoelectric Coolers for High-power-density 3D Electronics Heat Management

Amin Nozariasbmarz,[1,*] Ravi Anant Kishore,[2] Wenjie Li,[1] Yu Zhang,[1] Luyao Zheng,[1] Mohan Sanghadasa,[3] Bed Poudel,[1,*] and Shashank Priya[1,*]

[1] Department of Materials Science and Engineering, Pennsylvania State University, University Park, Pennsylvania 16802, United States

[2] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, United States

[3] U.S. Army Combat Capabilities Development Command Aviation & Missile Center, Redstone Arsenal, Alabama 35898, USA

* Corresponding authors: Amin Nozariasbmarz (aln192@psu.edu), Bed Poudel (bup346@psu.edu) and Shashank Priya (sup103@psu.edu)

Abstract

Future advancements in 3D electronics requires robust thermal management methodology. Thermoelectric coolers (TECs) are reliable and solid-state heat pumping devices with high cooling capacity that can meet the requirements of emerging 3D microelectronic devices. Here, we first provide design of TECs for electronics cooling using computational model and then experimentally validate the main predictions. Key device parameters such as device thickness, leg density and contact resistance were studied to understand their influence on the performance of TECs. Our results show that it is possible to achieve high cooling power density through optimization of TE leg height and packing density. Scaling of TECs is shown to provide ultra-high cooling power density.

Thermoelectric (TE) devices can operate as electrical generators or thermal coolers. In power generation mode (known as thermoelectric generator – TEG), a temperature gradient across TEG generates an electric potential via Seebeck effect. In cooling mode (known as thermoelectric cooler – TEC), applied electric current pumps the heat from one side of the TEC to other [1]. TECs are promising solution for high power density thermal management as required for emerging 3D microelectronics. TECs are solid-state devices, compact, noiseless, exhibit fast response time, and generate no vibration [2,3,4].

TEC performance is dependent on device design and the dimensionless figure-of-merit (zT) of TE materials: $zT=(S^2\sigma/\kappa)T$, where S, σ, κ and T are Seebeck coefficient, electrical conductivity, thermal conductivity, and absolute temperature, respectively [5]. TEC performance is evaluated in terms of maximum temperature difference between the hot and cold side temperature (ΔT_{max}), cooling power (Q_C) and coefficient of performance (COP) which is the amount of cooling divided by input electrical energy [6,7]. COP_{max} and ΔT_{max} require a high zT and a low contact resistance, while maximum cooling capacity ($Q_{C_{max}}$) of a TE module depends on TEC module design, TE leg geometry and material zT. Thus, zT is the most important parameter for optimum module design and optimum performance of TECs [8].

Despite recent advances in high zT materials, there have been limited studies on thin profile TE device fabrication for electronic cooling applications. High performance cooling devices require that the contact resistance must be much smaller than TE leg resistance [9]. As electrical current (I) passes through a TEC with an internal resistance (R), it produces Joule heating equal to RI^2 that counteracts the cooling provided by TEC. A highly doped TE material with an electrical resistivity of 10^{-3} Ω·cm and an electrical contact resistance of 10^{-6} Ω·cm^2, requires at least a few tens micrometers of TE leg thickness to minimize the Joule heating at the junction of TE/metal interconnect [10].

Recently, microelectronics have benefited from the increase in switching speed and device packing density due to the reduction in dimensions, but it has resulted in increased need for better thermal management [6,11]. This problem is further exacerbated in 3D electronics where hotspots can emerge in different layers and there could be enhanced heat accumulation if not removed continuously. 3D electronic cooling requires fast response and a high-density heat rejection. Commercial TEC modules are typically fabricated in standard sizes to enable high COP but are not suitable for high cooling power applications, mostly due to high electrical contact resistance and larger dimensions. Here, we analyze the device parameters that drive the high Q_C and COP in TECs as they are scaled to lower dimensions. A three-dimensional (3-D) computational model is utilized to predict the performance of TECs with scaled dimensions. We demonstrate that improved cooling performance in bulk TECs can be obtained by scaling them to dimensions of hundreds of micrometers. The effect of TEC leg height (H), fill fraction (FF) and operating current (I) on the cooling performance are studied both analytically and experimentally, and the pathway to achieve high cooling performance for 3D electronics cooling is discussed.

Metalized p- and n-type TE legs with dimensions of $1\times1\times0.5$ mm^3 were purchased from Align Sourcing LLC [12]. Two modules were assembled with 14% and 56% FF with 18 and 72 pairs of legs. As a comparison, commercial module (Custom Thermoelectric Inc.) with 2 mm height and 34% FF was also tested to gain insight into the role of contact resistance. The device assembly process was performed through the pick and place method using Pb-Sn solder paste and subsequent heating in a conventional oven at 220 °C. The headers (substrates) are made of AlN patterned with gold-coated copper interconnects. TEC modules with a different H and FF were explored and coded as Module I (H=2mm, FF=34%), Module II (H=0.5mm, FF=14%), and Module III (H=0.5mm, FF=56%). The ohmic contact resistance at the interface of TE legs and substrate is measured using a custom-built 4-probe resistance scanning measurement setup where a probe with a few micrometers tip size scans the resistance across the polished surface along the leg length [13].

Analytical modeling. The coupled thermal–electrical governing equations describing the thermoelectric effect in thermoelectric coolers are expressed as: $\nabla(\kappa\nabla T)+\frac{J^2}{\sigma}-T\boldsymbol{J}.\left[\left(\frac{\partial S}{\partial T}\right)\nabla T+(\nabla S)_T\right]=0$, and $\nabla.\boldsymbol{J}=0$, where **J** denotes current density vector, which is expressed as $\boldsymbol{J}=-\sigma(\nabla V+S\nabla T)$ and V is the electrostatic potential [14,15]. We used commercial finite element code COMSOL Multiphysics (version 5.6) to numerically solve these equations. The thermoelectric model was first validated using the experimental results and then parametric analysis was performed to optimize the geometric dimensions of the thermoelectric coolers. For all the simulations, the two sides of TEC were fixed at 20 °C, providing a temperature difference of 0 °C across the module. The FF of TECs was varied between 20% and 80%, whereas H was varied between 0.1 mm and 2.0 mm. The temperature dependent material properties were taken from the published literature [16].

The analytical model reveals that scaling TEC legs size from a few millimeters to several hundred micrometers can dramatically improve both COP and Q_C (Figure 1-a). For example, at 2 A, COPs of TECs with 2mm-leg and 0.5mm-leg are found to be 1.4 to 2.8 respectively, indicating a 100% improvement. Also, the peak of Q_C shifts to higher currents. For a 2 mm-leg device the peak of Q_C appears at ~4 A and for a 0.5 mm-leg the peak is found at ~7 A. More interestingly, further reduction of H to 0.1 mm has a negligible effect on cooling power density (Q_C/Area), but

COP is found to continue to increase. Since thinner legs shift Q_C peak to higher currents, and Joule heating is enhanced by the square of current and electrical contact resistance, there is an optimized current that maximizes Q_C/Area. The Joule heating counteracts the Peltier cooling effect and prevents further cooling. Therefore, scaling TECs is primarily limited to the ohmic contact resistance at the junction of TE leg and metal interconnects. In this model, the specific ohmic contact resistance was assumed as 1 $\mu\Omega\cdot cm^2$ that is close to the measured values of bulk materials used in this study.

Another factor for improving the cooling performance of TECs is FF. Figure 1-b shows that COP remains the same for TECs with different FF, but Q_C increases by 4X as FF is increased from 20% to 80%. According to the numerical model, for a high-performance TEC, modules with very thin profile legs and high FF are needed.

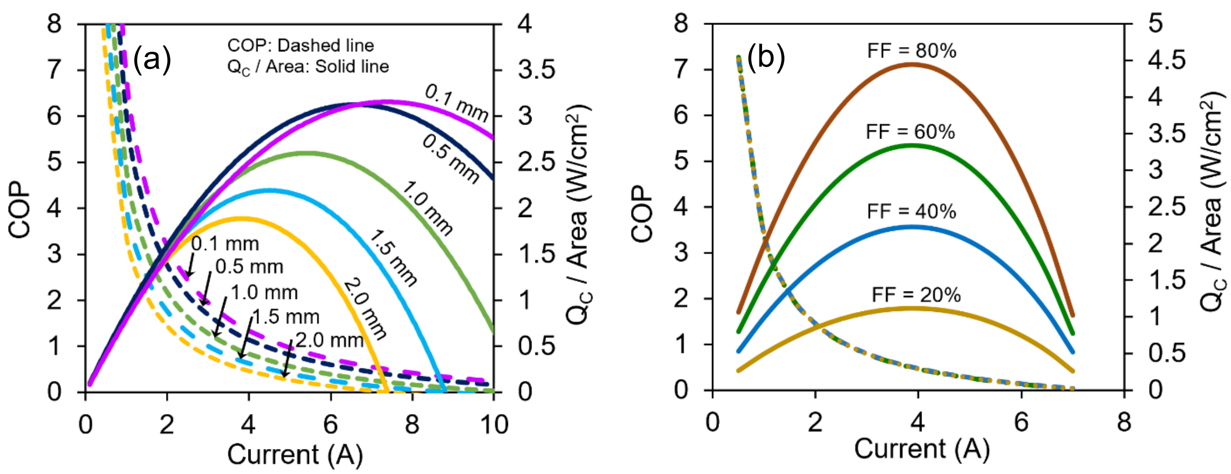

Figure 1. Analytical modeling: COP and Q_C versus current (a) for different H with constant FF=34%, and (b) for different TE leg FF with constant H of 1.5 mm.

COP and Q_C Measurement. COP and Q_C are two major cooling factors that define the performance of TECs. Cooling characterizations are done using a customized test setup (Figure 2-a). It includes a hot and cold copper block as a heatsink, a Q-meter with known dimensions and thermal conductivity, a TE device sandwiched between the cold heatsink and Q-meter which controls ΔT between the hot and cold side of TEC. The ΔT across the Q-meter is accurately measured through four K-type thermocouples with an accurately determined distance. An Aim TTi instrument model CPX200D power supply was used to supply electric current to the TECs during cooling measurements. TE modules are placed between the hot side heatsink and the Q-meter. The copper block maintains the temperature of the hot side and the Q-meter is connected to another TE device to maintain the ΔT across TEC. The hot side temperature (T_H) is kept at 22 °C, 35 °C and 50 °C. The cold side temperature (T_C) is adjusted accordingly to maintain ΔT across TEC. All experiments are performed in a vacuum chamber. TECs require electrical power (W) to drive heat flow from cold side (Q_C) to hot side (Q_H), where $Q_H = Q_C + W$. COP is defined as $COP = \frac{Q_H}{W} = \frac{Q_C+W}{W}$; $W = P_{in} = VI$ and $Q_C = \kappa A \left(\frac{dT}{dx}\right)$, where P_{in}, V, I, κ_Q, A_Q, and $\left(\frac{dT}{dx}\right)$ are input power, applied voltage, current, thermal conductivity of Q-meter, cross-section of Q-meter, and the slope of temperature gradient versus distance on the Q-meter, respectively. According to Figure 2-a, dx = Δx = l, where l is the distance between two thermocouples, and dT = ΔT = T_3-T_2.

Figure 2-b shows three TEC devices used in this study with different H and FFs. The resistance versus length of TE legs linearly increases across the leg and shows ohmic contact behavior without a notable jump at the contacts (Figure 2-c). The specific contact resistance of TE legs is ~1 μΩ·cm^2. Higher contact resistance deteriorates TE device figure-of-merit and increases Joule heating at the interface worsening TEC performance.

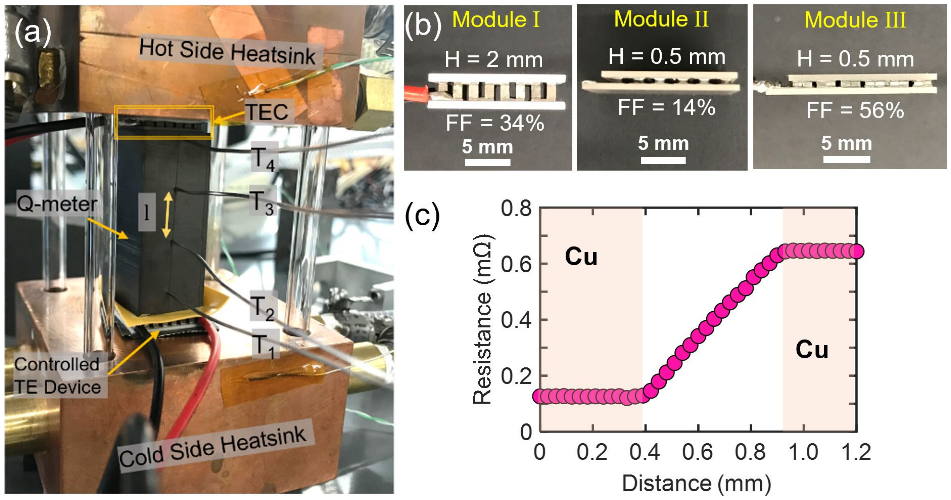

Figure 2. (a) The customized Q-meter setup for COP and Q_C measurement of TEC devices. (b) Three TEC modules with different H and FF described as Module I (H=2mm, FF=34%), Module II (H=0.5mm, FF=14%), and Module III (H=0.5mm, FF=56%). (c) TE resistance versus distance from junction showing ohmic contact resistance behavior.

Figure 3 shows experimental results for COP and Q_C for three modules with various H and FFs. Experimental results follow the computational prediction and indicate that TECs with a thin leg profile show higher COP and Q_C (Figure 3-a). Also, higher FF can dramatically increase the Q_C. COP of Module III (H=0.5mm, FF=56%) improves up to 3 times more than Module I (H=2mm, FF=34%). At a constant current of 1.25 A, Module III achieves a COP of 5.2 and Q_C of 1.9 W while Module I shows COP of 2.3 and Q_C of 2.1 W. At lower currents, taller legs show higher Q_C. The peak in Q_C is shifted to higher current values where Q_C of Module III reaches 11 W at 10 A which is ~3X more than the peak Q_C for Module I.

Figure 3-b demonstrates that at a similar COP, Q_C/Area improves with thin leg and high FF. Taller legs show a peak Q_C at COP=0.45 while this peak can be shifted to lower COP values by scaling down TECs and increasing FF. In addition to Q_C, the total mass of the device is relevant for microelectronics cooling. Figure 3-c shows that the Q_C per TE mass density of Module II

(H=0.5mm, FF=14%) increases by 1200% compared to Module I (H=2mm, FF=34%) due to the low profile of legs and much lower FF.

In cooling performance measurement, COP and Q_C also vary by ΔT across TEC and T_H (Figure 3-d). COP is a temperature-dependent phenomenon and at a fixed T_H of 22 °C, higher ΔT drops both COP and Q_C. For example, Q_C drops by 50% when ΔT increases from 0 °C to 15 °C. Figure 3-e indicates that the Q_C of TECs improves at higher T_H. Higher ΔT shifts Q_C curves to larger currents and at a specific current, higher T_H enhances Q_C.

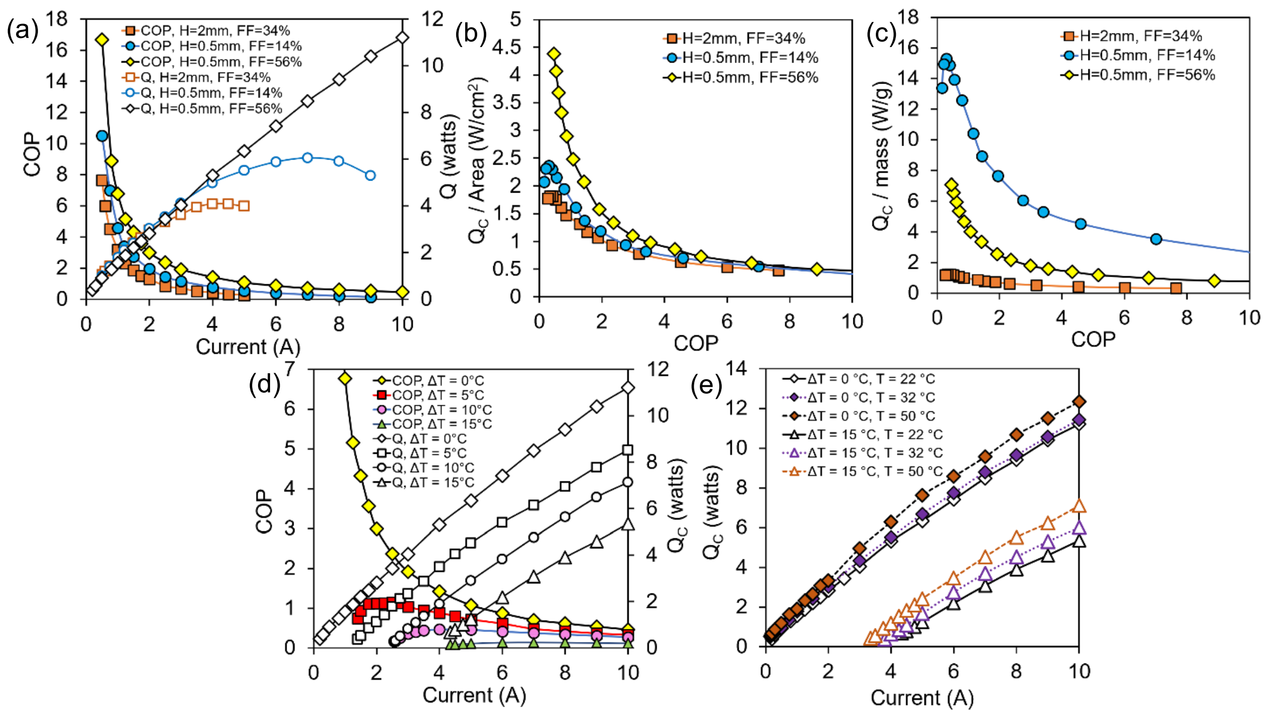

Figure 3. (a) COP and Q_C versus I for three different TEC modules with H of 2 mm, 0.5 mm, and 0.5 mm, and with FFs of 34%, 14% and 56%, respectively. (b) Q_C/Area versus COP, and (c) Q_C per TE leg mass versus COP. (d) Variation of COP and Q_C versus current for ΔT = 0, 5, 10, and 15 °C across TEC at T_H of 22 °C. (e) Q_C versus current for ΔTs of 0 and 15 °C at various T_H of 22, 32, and 50 °C.

As shown in Figure 4, Q_C/Area is considerably affected by the contact resistance. There is a tiny change in Q_C/Area by reducing the TE leg length from 500 µm to 100 µm at a contact resistance of 1 µΩ·cm^2. Although TECs have a high potential for 3D microelectronics cooling, further improvement in hot spot cooling requires extensive research to reduce the electrical contact resistance several orders of magnitude below the state-of-the-art (1 µΩ·cm^2). In an ideal case with zero contact resistance, scaling TE legs to nanometer dimensions can increase Q_C by several orders of magnitude. Thus, further reduction in contact resistance is the most the critical aspect in scaling of high-performance TECs. The design of TEC thin-film based modules will have to account for the manufacturing processes and module architecture to realize least contact resistances. In the thin film form, there is also potential for combining two different solid-state cooling methodologies to achieve further improvements in COP. Feng et al. [17] have modeled a hybrid structure comprising of laminated TECs and electrocaloric devices that was shown to improve the Q_C/Area. Future development of 3D microelectronic thermal management methods will have to leverage such hybrid methods to achieve maximum Q_C/Area within limited form factor and weight criterion.

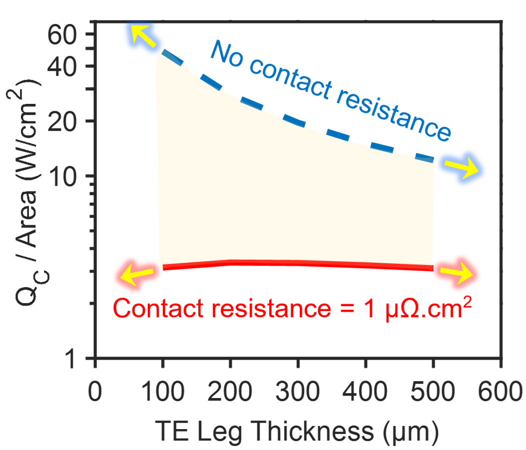

Figure 4. Comparison of Q_C/Area versus TE leg thickness for devices with the state-of-the-art contact resistance (1 µΩ·cm^2) and an ideal contact with no resistance.

A systematic study was conducted to understand the effect of scaling thermoelectric leg dimensions to improve the TEC performance with focus on 3D microelectronics cooling. Our computational model and experimental results show that thinner H enables higher Q_C and shifts COP curves to higher currents. Also, a higher TE leg FF enables improved Q_C up to 400%. A thin profile low FF TEC (Module II, H=0.5mm, FF=14%) provides light-weight module with 1200% enhancement in Q_C per TE leg mass. The scaling of TE legs allows higher Q_C/Area, but challenges in reducing the contact resistance below 1 $\mu\Omega\cdot cm^2$, prevents the realization of full cooling capability. Accordingly, there is not considerable difference between cooling power of 500 μm- and 100 μm-thick devices. Further improvement in cooling power density of TECs should focus on minimizing the contact resistance using thin film architectures.

This work is based upon work supported by the center for 3D Ferroelectric Microelectronics (3DFeM), an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences Energy Frontier Research Centers program under Award Number DE-SC0021118. B.P. acknowledges the financial support from Center for Energy Harvesting Materials and Systems. A.N. acknowledges the financial support through the Office of Naval Research through award number N00014-20-1-2602.

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