Application of a Thermoelectric Cooler

in Chip Temperature Reduction

Thermoelectric coolers (TECs) are semiconductor modules which use the Peltier effect to create a heat flux between the junctions of two different types of materials. Named after the French physicist, Athanase Peltier, the Peltier Effect shows that a temperature differential is created when DC current is applied across two dissimilar materials. The Peltier Effect is one of the three thermoelectric effects; the other two are known as the Seebeck Effect and Thomson Effect. The typical thermoelectric module is manufactured using two thin ceramic wafers with a series of P and N doped bismuth-telluride semiconductor material sandwiched between them. The ceramic material on both sides of the module adds rigidity and the necessary electrical insulation. The N type material has an excess of electrons, while the P type material has a deficit of electrons. One P and one N make up a couple, as shown in Figure 1.

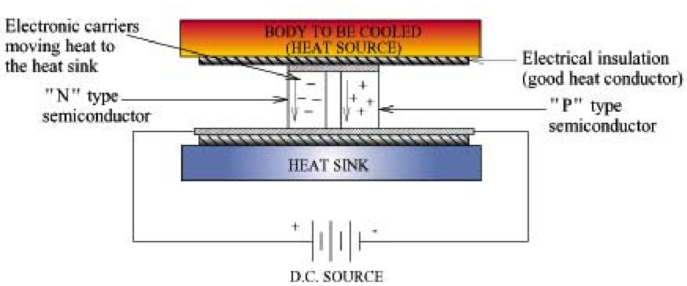


Figure 1. Illustration of Thermoelectric Module [1]

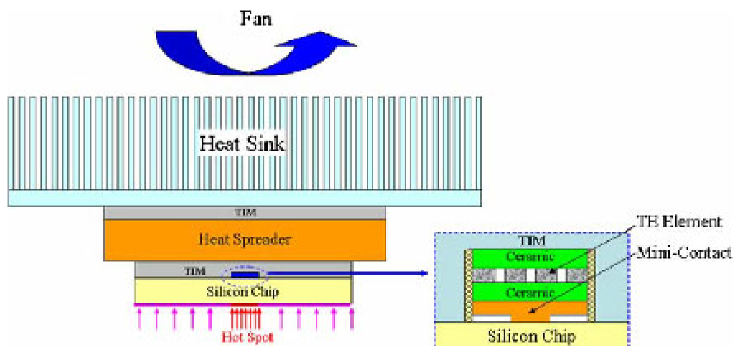


Figure 2. Illustration of Mini-contact Enhanced TEC for Hot Spot Remediation [2]

When a DC current is applied to the circuit, a thermoelectric module can work as a cooler or heater depending on the direction of current. A thermoelectric cooler (TEC), or solid state heat pump, transfers heat from one side of the device to the other side against the temperature gradient. There are many products using thermoelectric coolers, including small refrigeration systems, CCD cameras, laser diodes and portable picnic coolers. In addition to these products, they are also used in thermal management of electronic devices, such as microprocessors, memory modules, etc. Although the TEC provides a very simple and somewhat reliable solution for cooling electronic devices, its poor thermal performance prevents its broader usage. Compared with a traditional refrigeration system, the coefficient of performance (COP) of a TEC is only around 1/5 of that of a refrigeration system using a vapor compression cycle.

However, because of their simplicity, reliability, and miniaturized size, researchers are finding intuitive ways to use TECs to lower the chip temperature. One promising method is using mini-contact enhanced TEC for on-chip hot spot remediation for chips with highly non-uniform heat flux. Conventional thermoelectric coolers can only provide a cooling heat flux about 5 to 10 W/cm^2, which severely limits the application of these devices for hot spot remediation. The mini-contact enhanced TEC is a novel design, which uses a high conductivity material to contact the high heat flux region of the silicon chip with a mini-contact pad and connect the TEC on the top with a much larger area. Figure 2 illustrates the concept of a mini-contact enhanced TEC.

By using the mini-contact enhanced TEC, the local heat flux the TEC can extract is multiplied many times. Wang et al. [2] used the finite element thermal model to demonstrate the effectiveness of the mini-contact enhanced TEC on hot spot temperature reduction. They combined a 20 µm-high Bi2Te3 legs TEC with a mini-contact to cool a 400 µm × 400 µm, 1250 W/cm^2 hot spot, which is on a chip, with an average 70 W/cm^2 heat flux. Their simulation results of the temperature profile

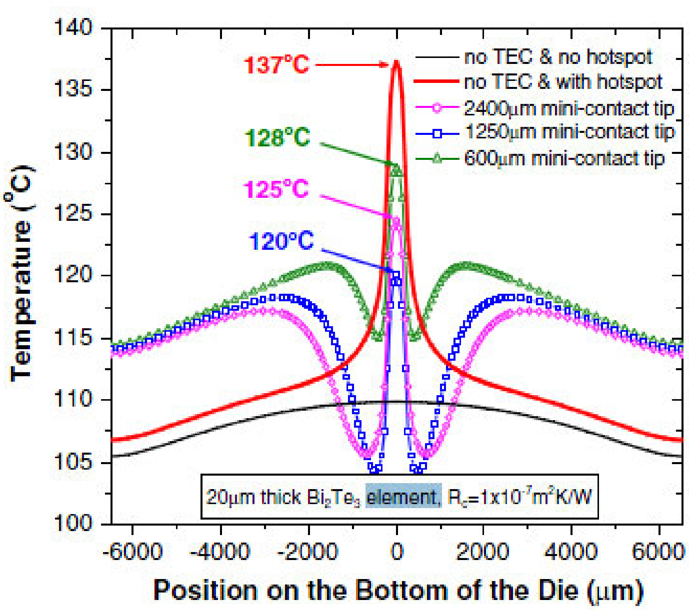


Figure 3. Effect of Mini-contact Enhanced TEC on Hot Spot Temperature [2]

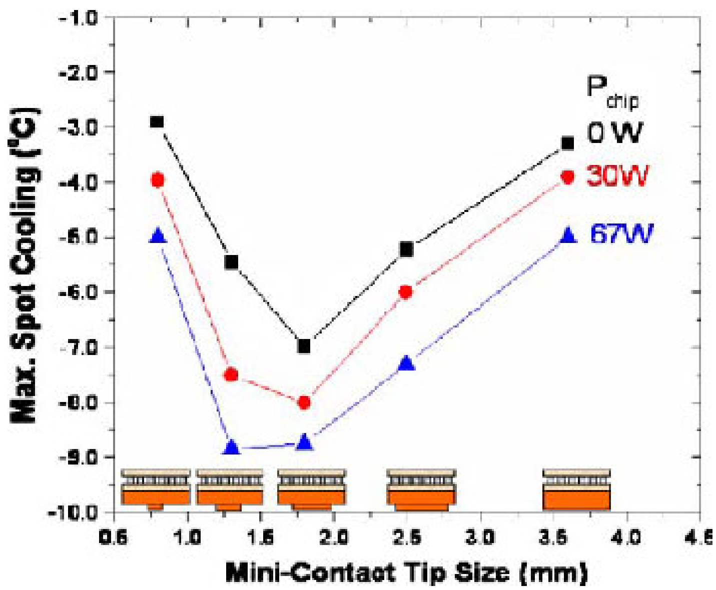


Figure 4. Variation of Measured Spot Cooling with Copper Mini-contact Size [2]

across the hot spots are shown in Figure 3. Wang et al. found that a 17 ºC hot spot temperature reduction can be obtained when the miniaturized TEC is activated with a 10W power input and enhanced with a 1,250 µm × 1,250 µm mini-contact pad. However, due to the effect of the heat concentrating/spreading resistance inside the mini-contact pad and the silicon chip, this is the "optimum" geometry for this application and if the mini-contact size is extended to 2,400 µm × 2,400 µm or reduced to 600 µm × 600 µm, the hot spot cooling is decreased to 12 ºC and 9 ºC, respectively.

To verify the performance of the mini-contact enhanced TEC, Wang et al. tested the concept by using a 200 µm-thick miniaturized TEC from Thermion (model number: 1MC04-018-02-2200D) (www.thermion-company.com). The effect of the mini-contact tip size on the temperature reduction at the targeted spot of a uniformly heated 2 mm × 2 mm × 500 µm chip for three different power dissipations is displayed in Figure 4. They found a 1.8 mm × 1.8 mm mini-contact tip size will lead to the largest temperature reduction. Their test proves

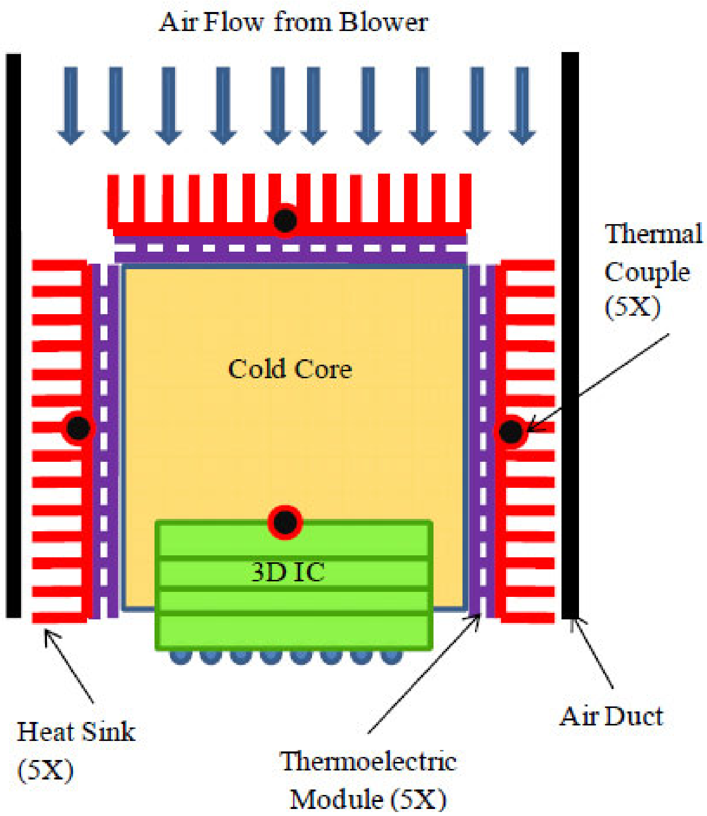


Figure 5. Multidimensional Heat Transfer System (MHTS) [3]

the feasibility and effectiveness of the mini-contact enhanced TEC on temperature reduction, but the implementation of the mini-contact enhanced TEC needs collaboration of both chip designers and thermal engineers.

Phan and Agonafer [3] proposed another method of using TECs, which is named the Multidimensional Heat Transfer System (MHTS) to reduce the chip temperature. The device Phan and Agonafer suggested uses a large, high conductivity material as an interface between the chip and TECs to increase heat the multiple TECs can extract from the chip. The concept of the Multidimensional Heat Transfer System is illustrated in Figure 5. Phan and Agonafer [3] compared the MHTS with a conventional passive heat sink inside a wind tunnel (see Figure 6). In these tests, the air flow rates were varied from 16.4 to 27 CFM. For the comparison, a conventional passive heat sink, directly mounted on top of the chip, was tested first. All experiments were conducted at room temperature of 20°C and 50% humidity, the chip's heat flux is set at 0.4 W/mm^2.

For a conventional passive heat sink, the chip temperature at different air flow rates is shown in Figure 7. For MHTS, the chip temperature at different air flow rates and thermoelectric module (TEM) power is shown in Figure 8. The MHTS enables the chip's temperature to reach sub-ambient temperature at low air flow rate, which is beneficial for some applications requiring sub-ambient cooling.

Researchers of thermal management and thermoelectric coolers are trying innovative ways to take advantage of the benefits of TEC devices and to avoid the shortcomings of these devices. Because TECs have to consume energy to transfer heat from one side to the other side, it is critical for designers to boost the TEC's coefficient of performance (COP) when they put them in cooling system. To achieve better COP, the TEC has to operate at a point where the heat flux is much less than its maximum heat flux and the temperature difference between TEC's hot and cold side should be as small as possible.

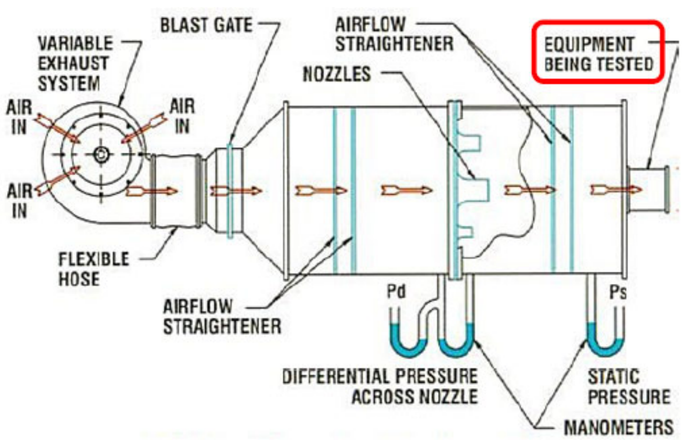


Figure 6. Heat Sink Test Bench [3]

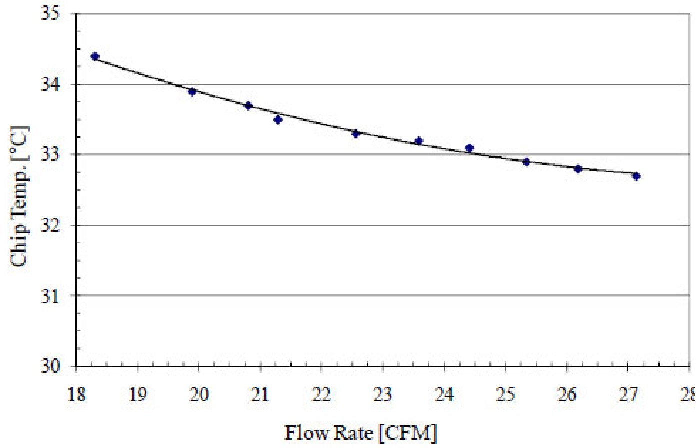


Figure 7. Chip Temperature of the Conventional Heat Sink [3]

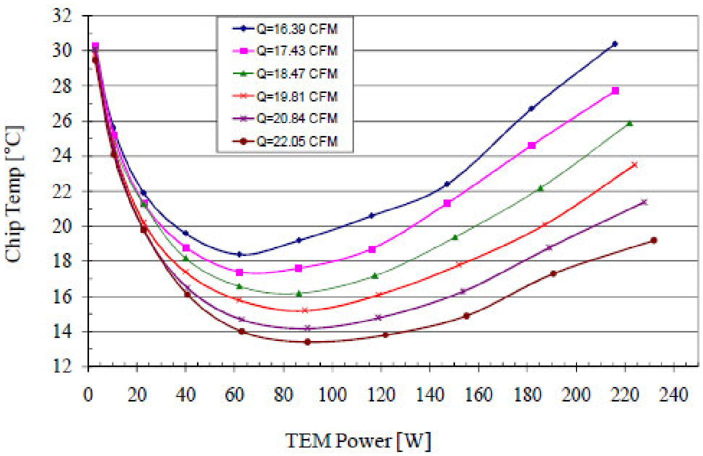
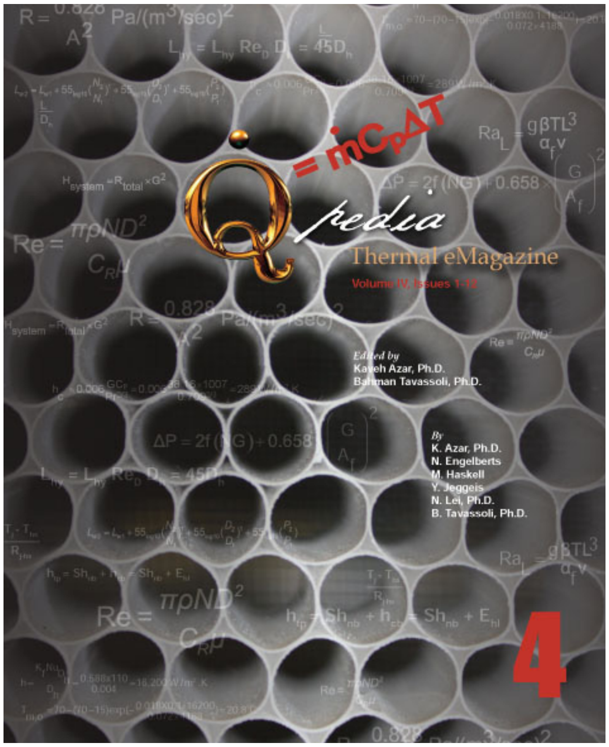


Figure 8. Chip Temperature of the MHTS [3]

The electric and thermal performance of current TECs is still low as compared to other refrigeration methods. Researchers in physics and material science are actively looking for new materials and packaging methods to improve the TEC's efficiency. For example, thin-film thermoelectric coolers (TF-TEC) have been developed with active material as thin as 10-20 µm. These TF-TECs have demonstrated as much as 30× higher power pumping capabilities per unit area as compared to conventional thermoelectric modules. A single TF-TEC element as small as 600 × 600 × 100 µm can pump a maximum power of more than 0.5W. These elements can be placed into arrays with varying densities, or packing fractions, to achieve different levels of performance. Following the advancement of technology, the TEC will likely find more applications in electronic cooling in the future.

References:

1. http://www.melcor.com/tec_intro.html
2. Wang, P., Bar-Cohen, A., Yang, B., "Mini-contact enhanced thermoelectric coolers for on-chip hot spot cooling",. Heat Transf. Eng. 30(9), 736–743 (2009)
3. Phan, H. N., Agonafer, D., "Experimental Analysis Model of an Active Cooling Method for 3D-ICs Utilizing Multidimensional Configured Thermoelectric Coolers", Electron. Packag. 132, 024501 (2010)



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