New Technology for Thermoelectric Cooling

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Abstract

Thermoelectric coolers in use today have a coefficient of performance (COP) of only about 0.5. This compares to COPs of larger scale machines, such as air conditioners and refrigerators at levels of 3.0 to 5.0. For electronic component cooling there is a new thermoelectric technology emerging for improved efficiency. This paper discusses this new technology which is multi-layer quantum well (MLQW) thermoelectrics, that should increase by four or five times the COP of present thermoelectric coolers used in electronic cooling applications. It also details and updates the experimental work in MLQW thermoelectric materials and will detail the supporting analysis of the predicted higher performance cooling. A specific example of an electronic cooling module configuration is presented

Keywords

Cooling, thermoelectric, quantum well, power

1. Background

Thermoelectric (Peltier effect) cooling is a popular but inefficient way to remove heat from high-power-dissipating electrical components. The requirements for heat removal from critical electronic components are increasing rapidly as electronics become more capable and at the same time more compact. For an example of the rate of increased capability and complexity one can cite Moore's Law that the number of transistors per computer CPU chip doubles every 18 months. As a specific example of cooling requirements, the present and projected cooling load for Intel Pentium® chips is shown in Figure 1 (data from Intel's 2001 International Technology Roadmap [1]). Thermo-electric cooling in this and other electronics cooling applications is often favored over other means because thermoelectrics are silent, compact, reliable and durable. In addition, the cooling power can be modulated to maintain a fixed temperature.

A new class of thermoelectric materials and device has resulted from recent research and development in the field. These are categorized as "low-dimensional" thermoelectrics and they have the potential to greatly increase power generating efficiency and cooler COP. These are superlattice thin-films, also called "quantum wells". These are structures built up by depositing multiple layers of alternating semiconductor materials with differing electronic band gaps to a thickness in the range of 10 to 100Å, on a substrate material. This type of structure provides decoupling of the thermal and electrical conductivities of the material, and further tailoring of the layer materials can yield a higher value of the overall material non-dimensional

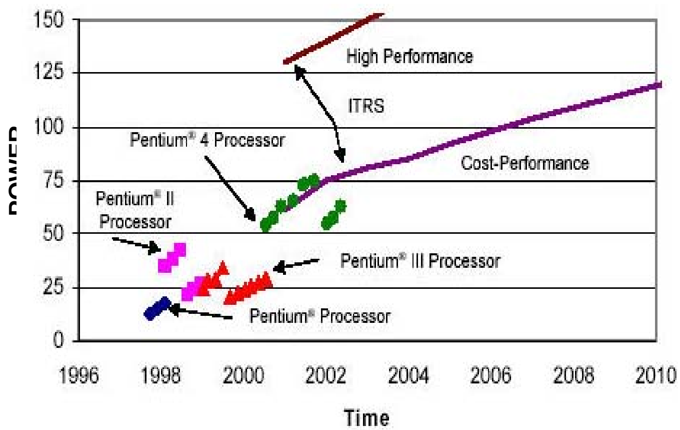

Figure 1 - Intel CPU heat loads increasing every year.

thermoelectric figure of merit, ZT, where Z is the square of the Seebeck coefficient divided by the electrical resistivity and thermal conductivity and T is the average absolute temperature. Figure 2 shows the progress of the increases in ZT since the beginning of the use of semiconductors in thermoelectrics around 1950. It also includes the results of recent DARPA/ONR and DOE programs on quantum well thermoelectric materials [2]. Values of ZT between 3 and 4 are being demonstrated Now and even higher values of ZT are now considered possible in the future.

We have recently measured power and efficiency on a MLQW generating device, demonstrating a couple gross

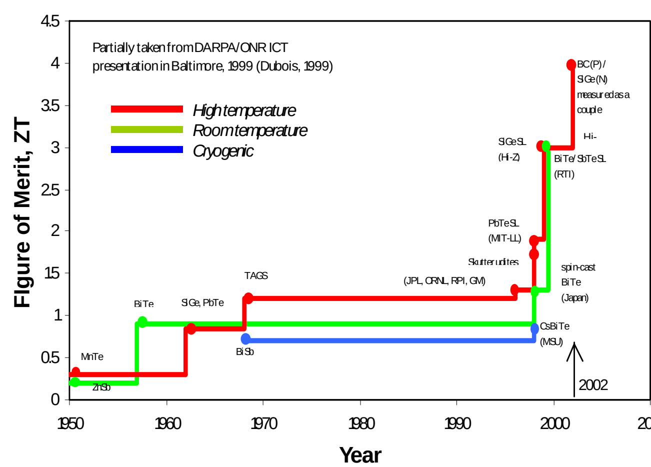

Figure 2. History of the Thermoelectric Figure of Merit, ZT [2]*.

conversion efficiency of 14% [3]. These measurements were made on a small couple shown in Figure 3 that combined a multilayer quantum well films of P-type B_4C/B_9C with a MLQW of N-type Si/SiGe. This couple operated between 70°C and 250°C. The test films were fabricated on 5μm thick Si substrates with ~11μm total MLQW film thickness. The 14% efficiency was calculated by dividing the power out of the couple by the power in. Therefore, the 14% efficiency was obtained with no correction for any extraneous heat losses, such as through the Si substrate and the heater wires or by radiation. The 14% without correction corresponds to $Z^* \overline{T} = 4$.

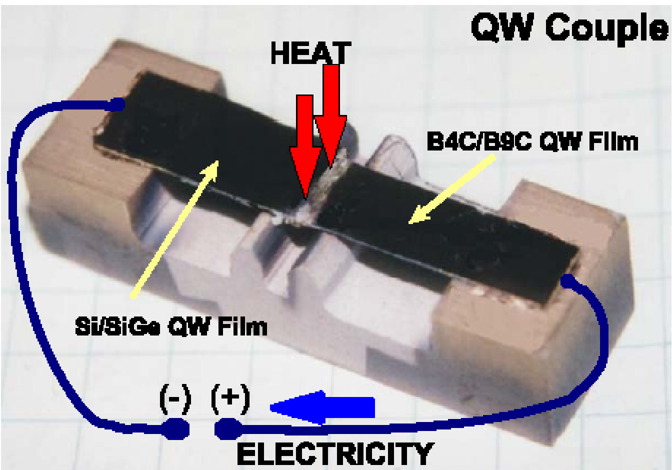

Figure 3. Quantum Well Thermoelectric Couple on 5µm Si

The substrate material used to fabricate the MLQW film is both a thermal and electric short in parallel with the quantum well material. It is therefore important that the total thickness of the quantum well layers be large in comparison with the substrate. Figure 4 presents a curve of the calculated couple efficiency, using measured MLQW film physical properties, as a function of the total film thickness when it is deposited on a 5 µm thick Si substrate. Also shown in the same figure is the data point obtained from the above- mentioned demonstration couple. One can see that a total film thickness of about 30 µm should lead to a conversion efficiency of about 20%

2. Cooling

An additional experiment was conducted to confirm the value of the figure of merit obtained form the demonstration couple test. This experimental consisted of connecting the P-type B_4C/B_9C leg and a copper wire as a cooler to determine the maximum temperature difference that could be obtained. This experiment yielded a maximum temperature difference of about 45ºC. This corresponds to a ZT of about 3 at a temperature of 25ºC. Extrapolation of this data to match the temperature of the power generation couple leads to a ZT value of about 4, supporting the value of ZT obtained in that test.

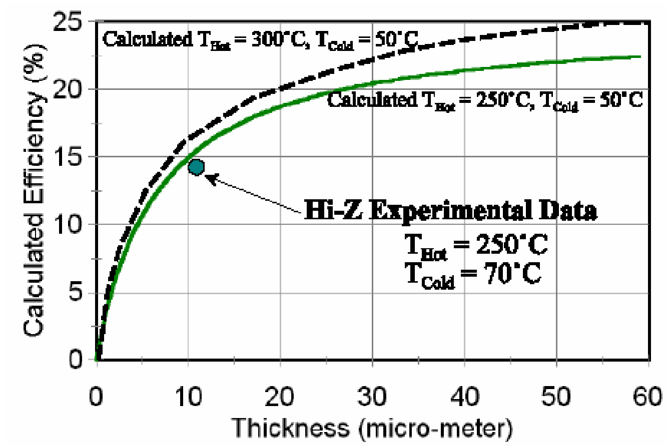

Figure 4. Efficiency of QW Couple Versus Film Thickness on a 5µm Si Substrate. Hi-Z experimental and predicted values are shown for comparison for N type Si/SiGe and P type B_4C/B_9C.

3. Theoretical Performance

The theoretical performance of Si/SiGe MLQW cooling is plotted in Figure 5 for a hot side temperature of 300°K, which of course are temperatures below or near standard ambient conditions. This chart was prepared to show how MLQW compares to Bi_2Te_3-based alloy material for cryogenic cooling, and it can also be seen how in theory a multi-staged MLQW thermoelectric cooler might reach 70°K. A single stage cooler should be capable of reaching 130°K.

As previously mentioned, the MLQW films are usually deposited on a Si substrate. However, we have also sputter deposited the films on Kapton which is an ideal substrate material for a cooler because it is an insulator; has a very low thermal conductivity; has good physical properties in the temperature range of interest and is bondable to other materials.

The approach to fabricating a cooler module would be to sputter deposit both P and N types of Si/SiGe MLQW films

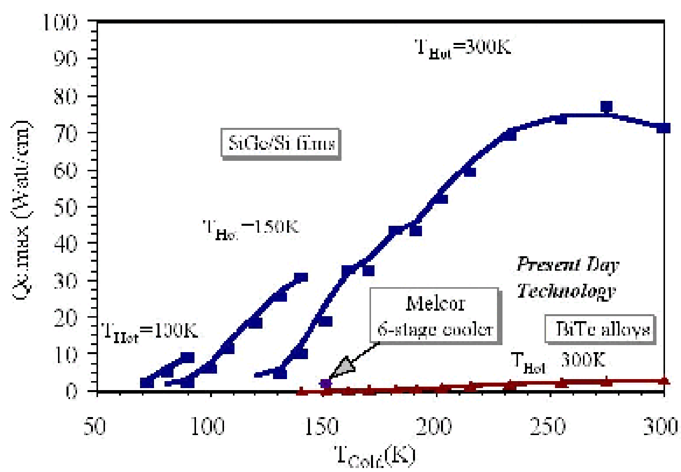

Figure 5 - Theoretical maximum heat pumping rate from the cold side, $Q_{c\,max}$, of Si/SiGe film *vs.* bulk Bi_2Te_3-based

on Kapton to a desirable thickness, such as 11 µm. A number of the MLQW layers of the same type (P or N) material would be stacked together until the thickness of the deposited film is equal to one dimension of the element desired. The stack would then be bonded to form a single piece of N or P material. The bonded stacks would then be cut using a slicing and dicing saw to the two remaining desired element dimensions. The cut elements could then be assembled into a cooler module using standard assembly procedures.

Calculations for a point design of a MLQW thermo-electric cooler were made with a proprietary in-house program using the measured physical properties of the Si/SiGe MLQW films. The film thickness was assumed to be 11 µm, the Kapton substrate 0.0254 mm, and the hot junction was 30°C. Figures 6, 7 and 8 present the results for a range of differential temperatures of 10°C to 40°C and currents up to 5 amperes. Each element consisted of 78 stacks of MLQW films on a Kapton substrrate cut to a cross section of 0.287 cm square by 0.2 cm long. The module consisted of 128 series connected couples in a 16 x 16 element array. The resulting module would be about 4.68 cm square and 0.3 cm thick.

The nominal design point for this module is a terminal voltage of 13.3V, a current of 2.5 amps and produces a temperature difference of 30°C.

Figure 6 present the terminal voltage as a function of current for various differential temperatures. One will note that the terminal voltage is much higher than a typical bismuth telluride based cooler. This is due to the high Seebeck coefficient obtained from MLQW materials.

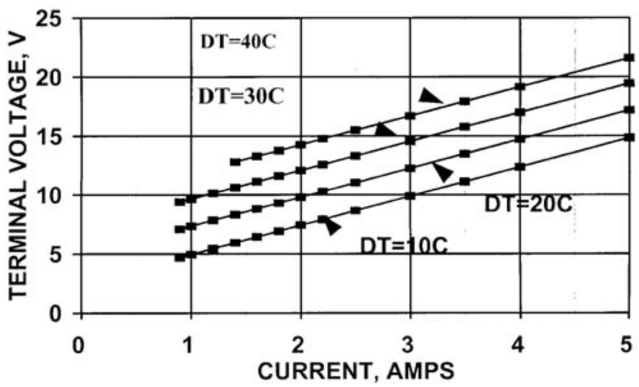

Figure 6. Terminal Voltage *vs* Current QW Cooler Design PT 2.5A, 30C, 13.33V

Figure 7 presents the amount of heat pumped as a function of current for various differential temperatures. The heat pumped at the nominal design point is 102 Watts, which would be very useful for cooling advanced microprocessors.

Figure 8 presents the COP of the module as a function of current for various temperature differences. It will be noted that the COPs are much larger than the 0.5 that would be expected from conventional thermoelectric coolers. The COP is calculated to be 3.05 at the minimal design point, which is more in line with current mechanical refrigeration systems.

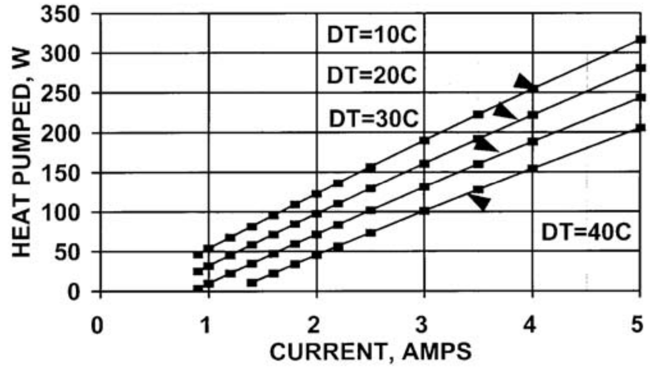

Figure 7. Heat Pumped *vs* Current QW Cooler Design PT 2.5A, 30C, 13.33V

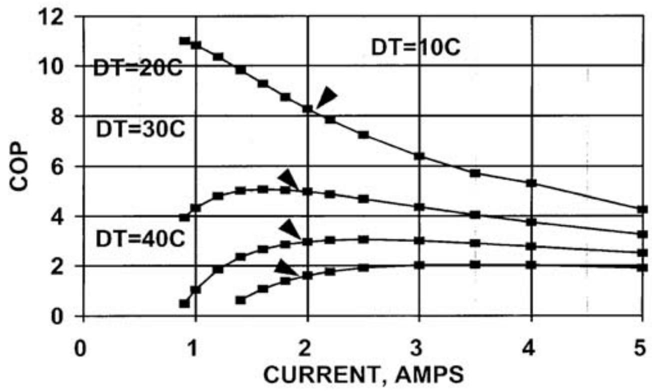

Figure 8. COP *vs* Current QW Cooler Design PT 2.5A, 30C, 13.33V

4. Conclusions

For electronics cooling, which is the subject of this paper, the application is usually more of heat pumping duty, rather than cooling below ambient. The objective is to keep the electronic component at or below a limiting temperature, which is usually above standard ambient, and which can be as high as 100°C for some components. The heat is then "pumped' to a higher temperature and rejected. MLQW coolers, which are currently in the development stage, present the possibility of actually cooling the electronic component to a temperature below ambient that can result in increased CPU speed

References

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