Using a Refrigeration System

for Electronic Cooling

The advance in semiconductor technology and leap in transistor density has coerced engineers into looking for more innovative and effective methods to cool semiconductor devices loaded with increasing power density. Traditionally, the air- cooled heat sinks dominate the electronic cooling market, due to their simple design, low cost, high reliability and versatility. But the continuing effort of shrinking MOSFET gate size has made it impossible for pure air-cooled technology to handle the heat load dissipated by some high-power devices such as high end CPUs, power transistors, DSP chips, etc. To keep the junction temperature below the maximum operating temperature and to handle high heat dissipation, engineers are looking for innovative ways to cool the electronic devices. One of the promising cooling techniques is refrigeration.

Refrigeration is a process in which work is done to move heat from one location to another. The work of heat transport is traditionally driven by mechanical work, but can also be driven by magnetism, electricity, laser or other means. By using refrigeration, the junction temperature of electronics can be maintained and reduced to sub-ambient temperature, if required. The lower operating temperature enables the electronics to operate at higher frequency and also increases the device reliability and life.

The common methods of refrigeration can be classified as non-cyclic, cyclic, thermoelectric and magnetic. In non-cyclic refrigeration, cooling is accomplished by melting ice or by subliming dry ice (frozen carbon dioxide). These methods are used for small-scale refrigeration, such as in laboratories and workshops, or in portable coolers.

Cyclic refrigeration cooling consists of a refrigeration cycle, where heat is removed from a low-temperature space or source and rejected to a high-temperature sink with the help of external work. The most commonly used refrigeration cycle for electronic cooling is the vapor-compression cycle.

Thermoelectric cooling (solid state cooling) uses the Peltier effect to create a heat flux between the junctions of two different types of materials. This effect is usually employed in portable coolers and for cooling electronic components that use electro- optic devices and small instruments.

Magnetic refrigeration, or adiabatic demagnetization, is a cooling technology based on the Magneto Caloric Effect, an intrinsic property of magnetic solids. A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and placing the refrigerant into a state of lowered entropy. A heat sink then absorbs the heat released by the refrigerant, due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated, and the magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of the heat sink. Because few materials exhibit the needed properties at room temperature, applications have so far been limited to cryogenics and research [1].

A vapor-compression cycle is the most commonly used refrigeration method. Figure 1 shows a personal computer equipped with a refrigeration system to cool its CPU; the refrigeration system is manufactured by Thermaltake [2] and uses a vapor- compression cycle. Figure 2 illustrates the system's components and refrigeration cycle.

Figure 1. Thermaltake Xpressar Refrigeration System for PC [2]

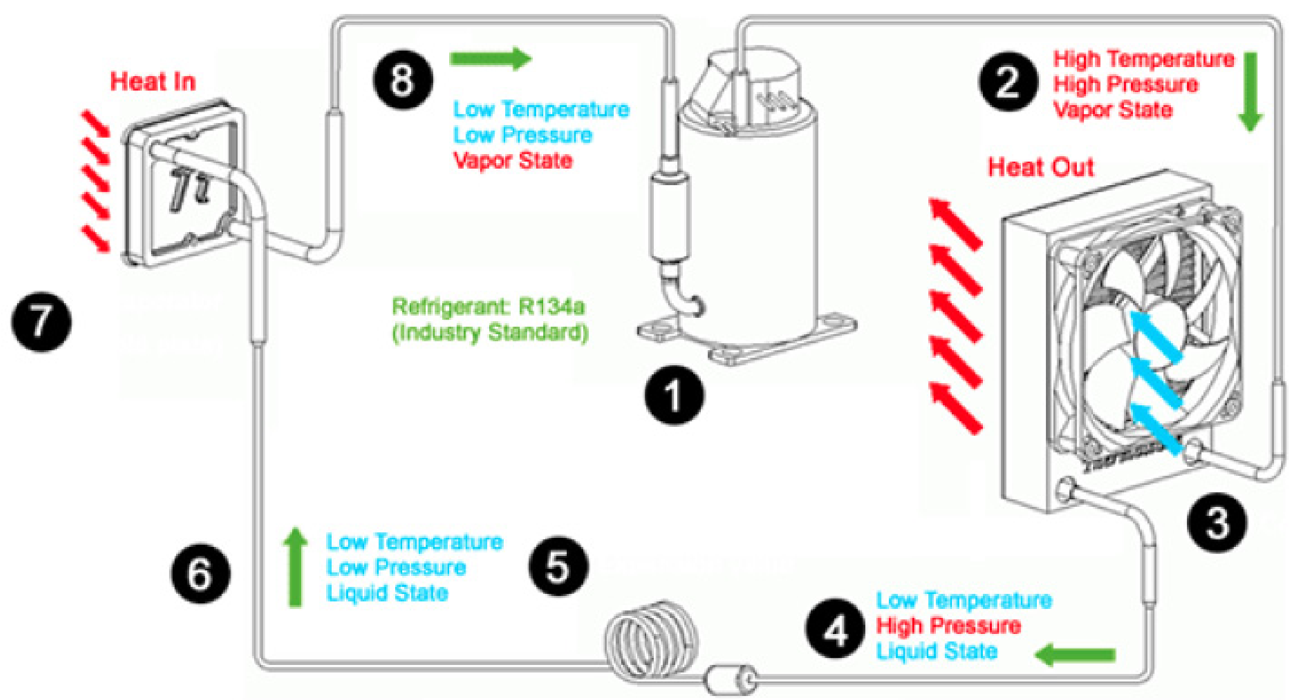

Figure 2. Thermaltake Xpressar Refrigeration System Schematic [2]

Component 1 is a compressor, which compresses the vapor and increases its pressure and temperature simultaneously. The compressor also serves as a pump to move the refrigerant around the loop. Component 3 is a condenser with a fan. When high pressure/high temperature vapor moves through the condenser, it condenses to a high pressure/low temperature liquid. The condenser also works as a heat exchanger and removes the heat from the system to the ambient. Component 5 is the expansion valve/coils, which reduces liquid pressure. Component 7 is a cold plate, which absorbs heat from the CPU and transfers the refrigerant from liquid to vapor. The vapor is then delivered to a compressor and the cycle is repeated again.

To get even better cooling performance, the component can be a micro-evaporator heat sink directly integrated to the back of the electronic chip; this method is generally called “two-phase on-chip cooling”. Figure 3 shows the magnified photo of the deep reactive ion etching (DRIE) microchannel heat sink made by Wei [3]. The DRIE method directly etches the high aspect ratio microchannel on silicon die. This kind of microchannel heat sink can be bonded to a chip die or even integrated in the chip. By doing so, the interfacial resistance between the chip and the heat sink can be minimized.

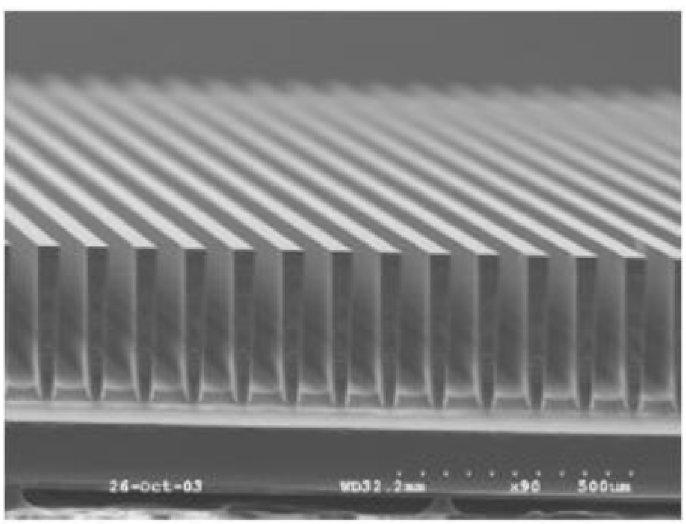

Figure 3. Photo of Magnified Microchannel Heat Sink [3]

In 2010, IBM, École Polytechnique Fédérale de Lausanne (EPFL) and the Swiss Federal Institute of Technology Zurich (ETH) signed a four-year collaborative project called CMOSAIC to understand how the latest chip cooling techniques can support 3D chip architecture. Unlike current processors, the CMOSAIC project considers a 3D stack-architecture of multiple cores with a interconnect density from 100 to 10,000 connections per millimeter square. Researchers believe that these tiny connections, and the use of hair-thin, liquid cooling microchannels measuring only 50 microns in diameter between the active chips, are the missing links to achieving high- performance computing with future 3D chip stacks. The integrated three dimension, two-phase cooling is ideal for this kind of applications.

The next most commonly used refrigeration process is thermoelectric Peltier cooling. Thermoelectric cooling transfers heat from one location to another location without moving parts; hence, the name of solid state refrigeration and heat pump. 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 4.

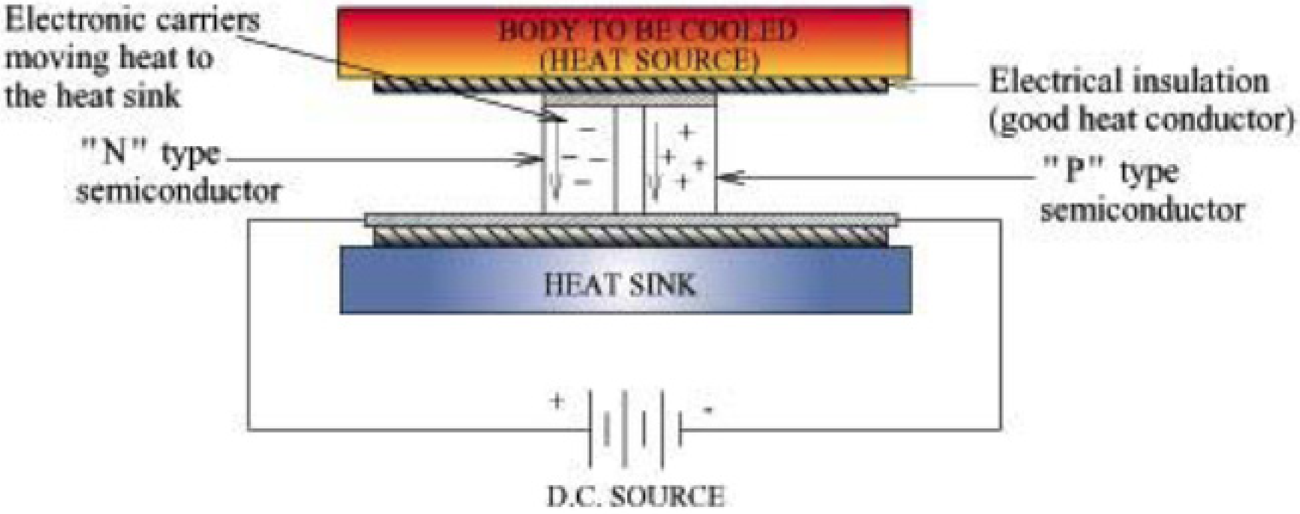

Figure 4. Illustration of Thermoelectric Module [4]

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. They are also used in thermal management of electronic devices, such as microprocessors, memory modules, etc. Figure 5 shows the Cooler Master V10 TEC CPU heat sink.

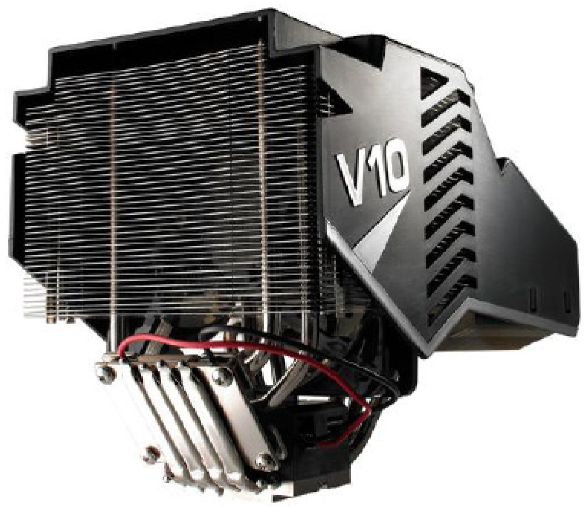

Figure 5. Cooler Master V10 TEC CPU Heat Sink [5]

utilizing TECs keeps hot spots below a critical temperature, thus avoiding unnecessarily overcooling of the rest of the CPU and adding to heat-sink load. Figure 6 shows such a concept of integrating a TEC in a heat spreader proposed by Snyder et al [6]. Figure 7 shows the eTEC they made, which is an embedded thermoelectric cooler with a total height of 100 microns and with a 2.5 mm x 2.5 mm footprint.

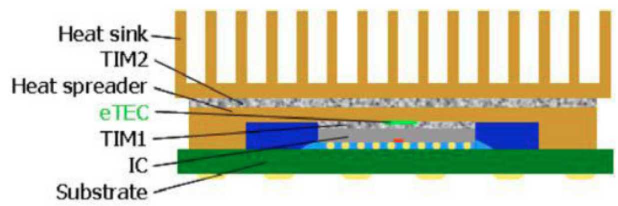

Figure 6. Flip-chip Package with A TEC Mounted on Heat Spreader [6]

Figure 7. Photo of eTEC [6]

Although the TEC provides a very simple and reliable solution for cooling electronic devices, its poor thermal performance prevents it from gaining broader acceptance. Compared with traditional refrigeration systems, the coefficient of performance (COP) of the TEC is only around 1/5 of that of a refrigeration system using a vapor compression cycle. Currently, the use of the TEC in electronics cooling is limited to certain applications, such as systems that require temperature stability, sub-ambient operating conditions, or devices with special design to accommodate TECs. At the chip level, there is active research focusing on using the TEC to cool the hot-spot on microprocessors. Localized areas of high heat flux on microprocessors produce hot spots that limit their reliability and performance. Chip scale thermal solutions

Many researchers have demonstrated that the use of the vapor-compression cycle and two-phase cooling is a very effective way to remove high heat flux from electronics and lower their junction temperature. However, using the vapor-compression refrigeration system still faces many obstacles for commercial applications. The main technical issues that need to be addressed are:

1. The miniaturization of the vapor-compression refrigeration package, especially the compressor.
2. For "two-phase on-chip cooling", the refrigerant should be compatible with electronics.
3. Refrigerants need to be more environmentally friendly and have good thermal properties.
4. The system needs to be field deployable and very reliable.
5. The cost of the refrigeration cooling system needs to be low enough to justify its applications.

For the thermoelectric cooler (TEC), there is continuing research on searching out and identifying better material and manufacturing technology to boost its efficiency. Unless there is a breakthrough in material used in the TEC, its application in electronics cooling is restricted to limited areas.

References:

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