THE ELECTRONICS SCIENTIST

Thermoelectric Modules
MF-10 Universal Active Filter

By Forrest M. Mims, III

A Solid-State Heat Pump

THE only time I ever bridged a couple of leads from a germanium transistor across the poles of a 6-V battery (mistakenly, of course), the transistor became so hot it glowed bright orange. The incident sticks in my mind because I burned my fingers yanking the transistor away from the battery leads.

Excessive heat has always been the scourge of solid-state devices, but there's another side of the solid-state thermal coil. Certain kinds of semiconductor junctions become icy cold when a current is passed through them. Let's examine some of these devices—beginning with one that can burn your thumb while freezing your finger.

The device is a cream-colored wafer a bit larger than a postage stamp and about 4 mm thick. From it emerges a pair of wires, one red and the other black. When these wires are connected to a 6-V battery, one side of the wafer becomes very warm, even hot. Remarkably, the opposite side becomes very cold. If the air is sufficiently humid, frost will appear within seconds.

This extraordinary wafer is known as a *thermoelectric module.* However, it might more appropriately be termed a *solid-state heat pump.* Its operation is completely reversible, too. When the connections to the battery are switched, the hot side of the wafer becomes cold and the cold side becomes hot. Moreover, the module will generate an electric current when its two opposing surfaces are maintained at different temperatures.

The phenomena I've described are collectively known as the *thermoelectric effect.* While most people knowledgeable about electronics know about the heat and power generation aspects of the effect, surprisingly few are aware of the cooling phenomenon.

The cooling ability of a thermoelectric module can be easily demonstrated with the help of some commonly available hardware. Figure 1 is a photograph of the 801-2003-01 module made by the Cambion Division of the Midland-Ross Corporation (Cambridge Thermionic, 445 Concord Ave., Cambridge, MA 02138). An extruded aluminum heat sink and a small aluminum box attach to opposite sides of the module with a rubber band (Fig.2). Heat-sink compound ensures a good thermal bond between the module and the two attachments.

The heat sink, which should be attached to the hot side of the module, is placed in a shallow pan of water. A teaspoon or so of water is then placed in the aluminum box. Within minutes after the module is connected to a 6-V battery, the water in the aluminum box will freeze solid and the box will be coated with a layer of frost. Add more water and the module will produce a cube of ice. The efficiency of this miniature freezer can be increased by making an insulating chamber for the box from foamed plastic panels held together by tape or a rubber band.

Discovery of the Thermoelectric Effect. The discovery of the thermoelectric effect can be traced to 1821 and the German physicist Thomas J. Seebeck. He took two conductors of different materials, connected them to

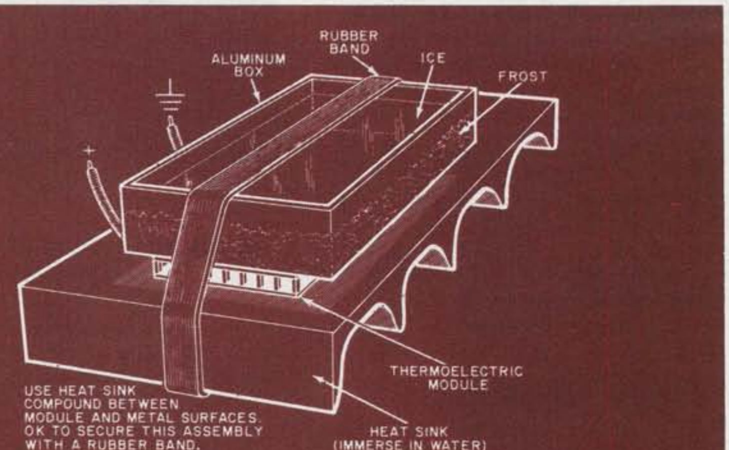

Fig. 2. Simple thermoelectric ice-cube maker.

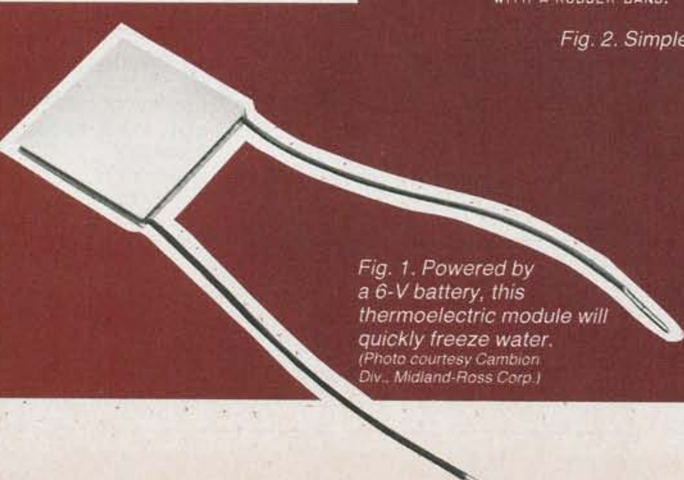

Fig. 1. Powered by a 6-V battery, this thermoelectric module will quickly freeze water. (Photo courtesy Cambion Div., Midland-Ross Corp.)

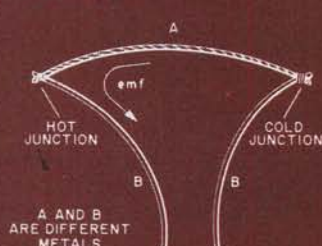

Fig. 3. Construction of a simple Seebeck junction.

form two junctions as shown in Fig. 3, and found that if the junctions are maintained at different temperatures, a voltage will appear across the free ends of the conductors. Seebecks's discovery formed the genesis of temperature-sensing thermocouples.

The Seebeck effect can be easily demonstrated using ordinary hardware or even pocket change to make one-half of a Seebeck junction. For example, a homemade thermocouple made by wrapping a few turns of copper wire around one end of a steel nail will generate 6 or 7 μA at a few millivolts when heated by a match. Even more power can be obtained by overlapping the edges of a penny and a nickel and securing the coins together with an alligator clip. After heating the coins with several matches I produced 60 μA at 6 mV.

In 1834, Jean-Charles-Athanase Peltier, a French watchmaker, passed a current through a junction of two dissimilar metals. He found that, depending upon the current's direction, the junction would become warm or cool.

Metal remained the exclusive thermoelectric material for many years. Some of the better thermoelectric junctions are copper-constantan, iron-constantan, and chromel-alumel. Constantan is an alloy of copper and nickel; chromel is an alloy of nickel and chromium; and alumel is an alloy of nickel and aluminum. These and other junctions are widely used today in the manufacture of temperature-sensing thermocouples.

In the Seebeck mode, metal junction thermocouples generate only a few microvolts per degree Celsius. Semiconductor couples may exhibit Seebeck coefficients of hundreds or even thousands of times greater. In the early 1950's, Abram F. Ioffe in the Soviet Union and H.J. Goldsmid in England independently found that semiconductors such as bismuth telluride make excellent thermoelectric materials. Ioffe's group made demonstration power generators and refrigerators. Goldsmid's group made junctions that exhibited a drop of as much as 65° C below room temperature. Scientists in the United States later discovered that lead telluride is also an excellent thermoelectric material.

Semiconductor Thermoelectric Devices. Today most semiconductor thermoelectric devices are based on lead telluride or bismuth telluride. The selection of the alloy depends largely on the preferred operating temperature of the module. For example, one firm employs a quaternary alloy of bismuth, tellurium, selenium and antimony. The alloy is appropriately doped to provide an n-type or p-type semiconductor.

Figure 4 shows the construction of a simple single-junction semiconductor thermoelectric device. The upper ends of the two semiconductor bars are soldered to a common header, and their opposite ends are soldered to separate copper headers to which electrical connections are made. Since practical thermoelectric modules are usually arrays of many such junctions or couples, thin plates of ceramic are attached to both sides of the module to electrically isolate the individual junctions. The ceramic permits reasonably good heat transfer while preventing electrical shorts between adjacent modules.

Referring back to Fig. 4, when a direct current is passed first through the n-type semiconductor bar and then through the p-type bar, heat is pumped from the upper side of the module to the lower side. Conversely, when the polarity of bias is reversed, heat is pumped from the lower side to the upper side.

In either case, the side from which heat is removed rapidly cools while the opposite side becomes very warm. If the heat isn't removed from the warm side, some of it will be radiated and conducted back to the cold side. Eventually the module will reach a point of equilibrium and little or no cooling will occur.

In a practical system, heat can be extracted from the hot side of the module by a forced air blower or a circulating liquid. In both cases, conventional heat sinks and miniature plumbing components can be used.

Commercial thermoelectric modules have more than the single junction shown in Fig. 4. Figure 5, for example, shows an assortment of miniature FRIGICHIP modules made by Melcor (Materials Electronic Products Corp., 990 Spruce St., Trenton, NJ 08648). These modules may have from four to 66 individual couples. They can produce a hot-side/cold-side temperature difference of 67.5° C.

Figure 5 also shows how two module arrays can be stacked or cascaded to achieve a temperature differential of 85° C or more. Three- and four-stage coolers can achieve temperature differentials of 105°C and 125° C or more, respectively. An eight-stage module designed to cool an infrared detector has achieved a temperature drop of 171° C (308°F) below room temperature!

The thermoelectric module in Fig. 1 is a single-stage device having 71 couples. It provides a temperature drop of 60° C or more and has a maximum current rating of 6 A and a maximum forward voltage of 10 V. The unit sells in single quantities for $31.20, but the price drops to $17.80 in quantities of a thousand.

Figure 6 shows a single-stage Cambion module (#801-1029-01) designed to cool dual-in-line ICs. This module

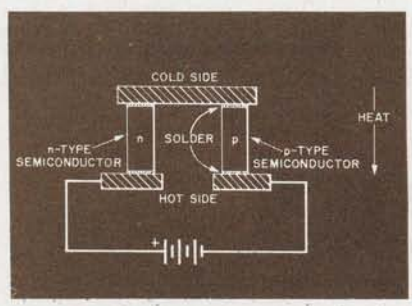

Fig. 4. How a simple single-junction semiconductor thermoelectric device is constructed and energized.

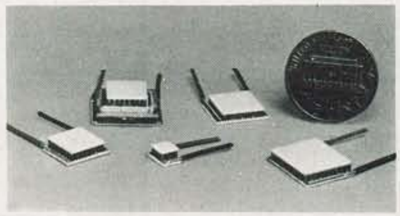

Fig. 5. Miniature single and two-stage Frigichip® thermoelectric modules. *(Photo courtesy Melcor.)*

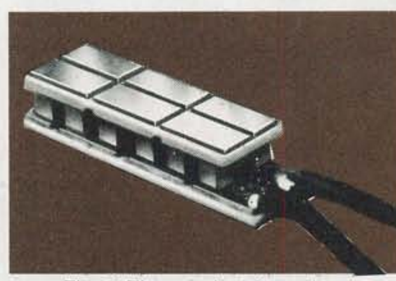

Fig. 6. Thermoelectric cooler to pump heat from dual in-line ICs. *(Photo courtesy Cambion.)*

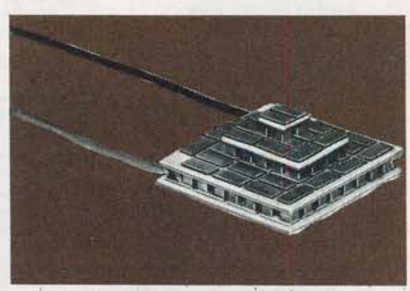

Fig. 7. This 3-stage cooler can give a temperature drop of 115°C or more. *(Cambion photo.)*

achieves a temperature difference of up to 60° C or more. It is specified for a maximum current of 7 A at 0.7 V. Individual units are available for $10.40 each. In 1000 lot orders, the cost falls to $5.95.

Figure 7 shows a 3-stage thermoelectric module also made by Cambion (# 801-1006-01). This unit can achieve a temperature drop of 115° C or more. Its maximum operating current is 6 A at 3.2 V. The dark rectangles atop the various stages are copper pads that permit the attachment by direct soldering of additional stages. The copper pads are *not* in electrical contact with the couples beneath them.

Applications. Thermoelectric modules are used in a surprisingly diverse array of applications. Modules such as those shown in Figs. 1, 6 and 7 are used to make solid-state refrigeration and heating systems. One Cambion thermoelectric cooling/heating assembly comes complete with a blower fan and can be used to make a portable refrigerator that can double as a food warmer when the power connections are reversed. Several such systems designed to be powered by the 12-V supply of trucks and cars have been marketed.

Thermoelectric ice makers, baby bottle cooler/warmer units, and even room air conditioners have also been developed. Westinghouse's Advanced Energy Systems Division developed a noise-free 5-ton cooling capacity air-conditioning system for the Navy's *USS Dolphin* submarine. This system consists of ten modules, each measuring 23" × 21" × 4.25" and incorporating 120 couples.

Thermoelectric modules also have many applications in engineering and research. For example, thermoelectric coolers extract excess heat from computer cabinets and microwave waveguides. They also are used to cool laser diodes, far-infrared detectors, CCD imaging arrays, avalanche photodiodes, and photomultiplier tubes. Medical researchers and chemists use thermoelectric coolers to chill and thus immobilize objects and substances being observed with a microscope.

Though still limited to specialized applications, thermoelectric power generators show considerable promise. Several companies in various countries have developed 10-to-100-W thermoelectric generators fueled by propane, gasoline, or kerosene burners. A system designed to power communications systems in remote regions of the Soviet Union delivers 200 W when fueled with 4 to 5 pounds of firewood per hour. Smaller thermoelectric generators installed in the chimneys of kerosene lamps provide power for radio receivers in remote Russian homes.

Many kinds of compact nuclear power generators use thermoelectric modules to convert the heat produced by radioactive decay to electricity. Such generators power remote lighthouse beacons in England, unmanned weather monitoring systems floating at sea and installed at remote sites near the north and south poles, and the electrical systems of various kinds of satellites and space probes. Thermoelectric modules can also convert sunlight into electricity.

Finally, a thermoelectric module can convert alternating current into direct current. The alternating current is passed through a heating element attached to one side of a module. If the opposite side is kept at a cooler temperature, the module will generate a ripple-free direct current.

For More Information. You can find out much more about thermoelectrics by researching the subject at a good library. Specific articles you may find particularly helpful have appeared in *EDN* ("Thermoelectric Coolers Tackle Jobs Heat Sinks Can't," Jim McDermott, May 20, 1980, pp. 111-117) and *Electronics* ("Thermoelectric Heat Pumps Cool Packages Electronically," Dale Zeskind, July 31, 1980, pp. 109-113). The *Encyclopedia Britannica* has a very thorough article on the subject.

Thermoelectric module manufacturers have published helpful literature about their field. By far the most complete reference quide is Cambion's "Thermoelectric Handbook." Specification sheets from Cambion and other manufacturers include helpful design, installation, and application information. Prices for the Cambion modules given above are contingent upon a minimum order of $100. However, Cambion distributors do not necessarily impose an order minimum.

Melcor is another good source of information about thermoelectric modules. Its applications information is very understandable and well illustrated. Best of all are the performance curves for each of the firm's modules. Melcor's modules range in cost from $8.95 to $48 each in small quantities. The company requires a minimum billing of $25.

Before ordering thermoelectric modules, you should first request specification sheets and pricing information from the various manufacturers. In addition to Cambion and Melcor, thermoelectric module manufacturers include Borg-Warner Thermoelectrics (3570 N. Avondale Ave., Chicago, Il 60018) and Marlow Industries, Inc. (1021 S. Jupiter Rd., Garland, TX 75042).

An Easy-to-Use Universal Active Filter

Imagine a single-chip active filter that can be tuned with a single resistor, uses no external capacitors, and simultaneously functions as a lowpass, bandpass and notch filter. Such a filter could save countless hours of design and breadboard evaluation time.

Happily a new generation of such filters is now available. They are collec-

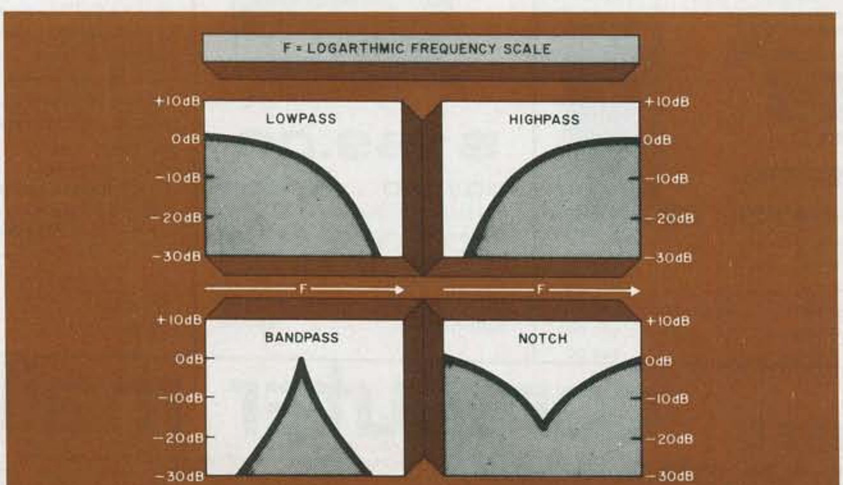

Fig. 8. Frequency responses for the four filter categories.