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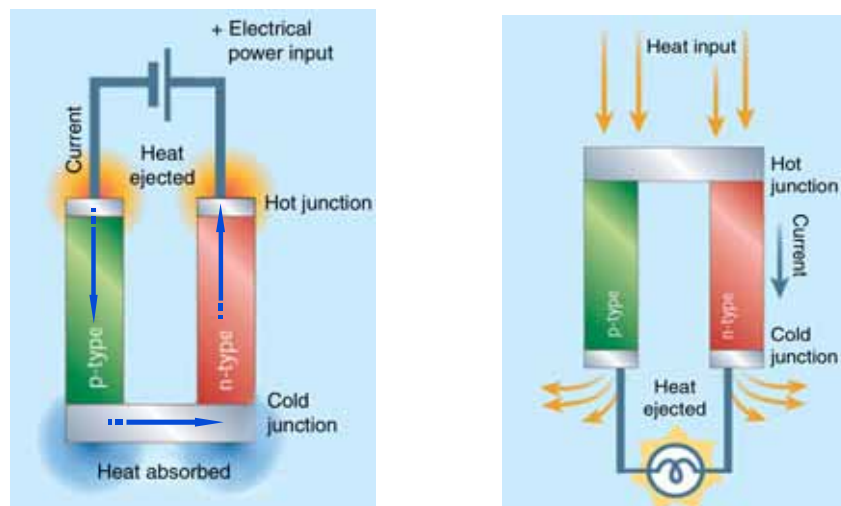
Thermoelectric Cooling and Power Generation

Establishing a New Performance Paradigm with Ultra-Thin Thermoelectric Modules

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A Quick Overview of Thermoelectrics

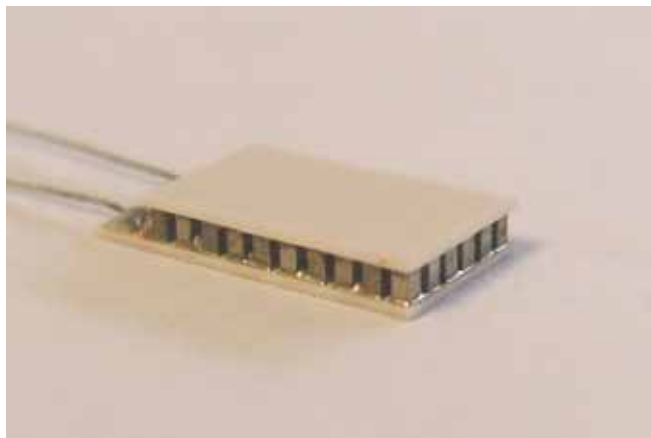
Solid-state cooling and power generation have long been sought after as a solution for challenging thermal management and energy problems and, to address some of these issues, thermoelectric modules have been available for decades. The core component of a thermoelectric module is a *thermocouple*. A thermocouple consists of two dissimilar semiconductors (referred to a p-type and n-type to describe dissimilar electrical conduction mechanisms in the two materials) connected together by a metal plate. Electrical connections at the top complete an electric circuit. Thermoelectric cooling (TEC) occurs when current is supplied, in which case the thermocouple cools on one side and heats on the other by what is known as the Peltier effect. Thermoelectric generation (TEG) occurs when the couple is put in a thermal gradient (i.e., the top is hotter than the bottom), in which case, the device generates current, converting heat energy into electrical power by what is known as the Seebeck effect. Schematic representations of these effects are shown in Figure 1.



• Figure 1: Schematic representations of a PN-couple used as TEC (left) based on the Peltier effect or TEG (right) based on the Seebeck effect.

Conventional Thermoelectric Technology

In practical applications a large number of P- and N-type pellets are cut from boules of thermoelectric material and thermocouples are assembled together (electrically in series, thermally in parallel) to form a TEC or a TEG. Conventional modules are referred to as 'bulk' modules because of their size and fabrication approach. A commercially available thermoelectric module is shown in Figure 2. Such devices found early (and continued) use for power generation in space flight aerospace applications and for cooling and temperature control in instrumentation, telecommunications and a host of other specialty applications.

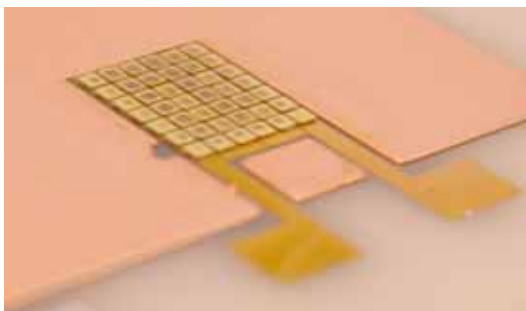


- Figure 2: A standard, commercially available TEC. The size of the device is 6.2 mm x 10.3 mm x 1.8 mm. The large pellets are cut from boules of material – these modules are referred to as 'bulk' thermoelectric modules.

Thin-Film Thermoelectric Technology

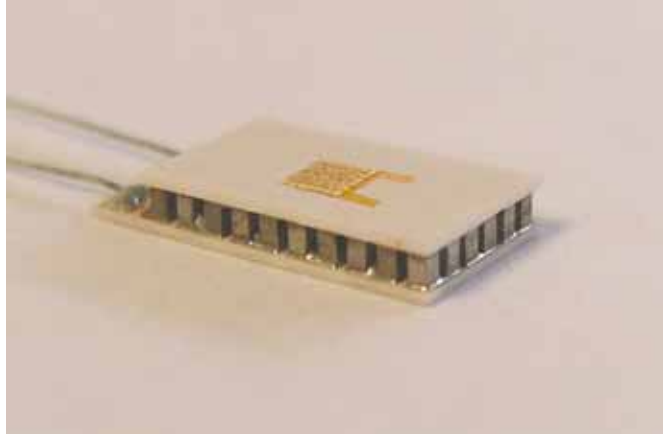
While thermoelectric modules deliver the benefit of solid-state operation, they suffer from numerous shortcomings in that they are generally inefficient, fragile and – big! The very size and discrete nature of conventional thermoelectric modules severely limit their implementation.

More recently a significant amount of development has been focused on thin-film thermoelectric devices. Thin-film thermoelectric materials can be grown by conventional semiconductor deposition methods, and devices can be fabricated using conventional semiconductor micro-fabrication techniques. The resulting devices (see Figure 3) are much smaller than conventional offerings and show promise for direct integration into modern manufacturing methods.



- Figure 3: A thin film thermoelectric module available from Nextreme. This device is 3.5 mm x 3.0 mm x 0.1 mm in size. Devices as small as 0.3 mm x 0.3 mm x 0.1 mm are feasible.

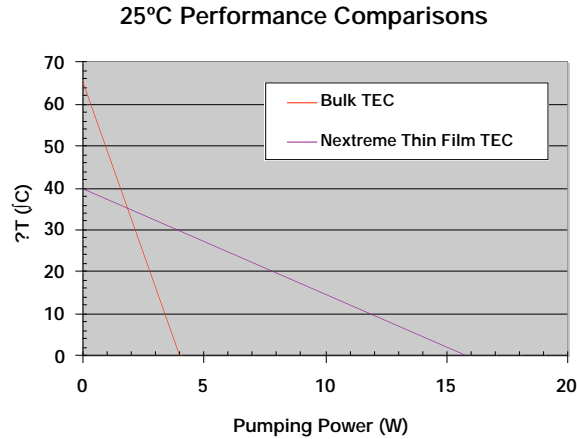
For reference, a thin-film TEC is shown relative to a conventional bulk TEC in Figure 4. The thin-film TEC is ~6x smaller in its x-y dimensions and ~18x smaller in the z dimension. Thus, on a volume bases the thin-film TEC is ~110x smaller in size.



• Figure 4: The Nextreme TEC shown on top of the bulk TEC for comparison.

Thin-Film vs Bulk – A Performance Comparison

While it is interesting to compare thin-film and bulk thermoelectric modules on the basis of size, it is much more useful to compare them on the basis of performance. The most common measure of the performance of a thermoelectric module is its load line. A load line is generated at fixed operating current and specified reference temperature by plotting the temperature difference, ΔT , that the device can achieve between its top and bottom plate as a function of the power, Q , it can pump against the temperature gradient. Figure 5 shows the load lines of the Nextreme and bulk devices, both measured at a reference temperature of 25°C. In this case the characteristic load line for a module is shown at its maximum operating current (I_{max}). Under I_{max} conditions, the ΔT at zero Q is referred to as ΔT_{max} and the power pumped at zero ΔT is referred to as Q_{max} . While neither ΔT_{max} nor Q_{max} are practical operating conditions for the device, they define the performance envelope of a device and are often used as a basis of comparison.

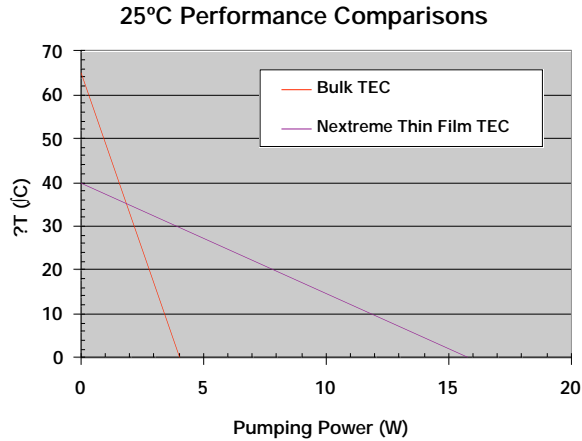


• Figure 5: The respective load lines for the bulk TEC shown in Figure 2 and the Nextreme thin-film TEC shown in Figure 3.

Thin-Film Materials: A New Paradigm in Thermoelectric Performance

At first glance, and without context, the performance comparison shown in Figure 5 is in of itself interesting – the thin-film TEC pumps almost 4x the power of the bulk device, although it holds off only ~60% of the temperature difference. Yet, if we take dimensional differences into account, the intrinsic performance of the thin-film TEC is actually quite amazing. The thin-film TEC holds off a maximum of 40°C (ΔT_{max}) across the thickness of a piece of paper! And it pumps a maximum of almost 16 watts (Q_{max}) through the area of a piece of confetti! Not shown here is the respective response time of the bulk and thin-film devices. Whereas the thermal response time of bulk devices are on the order of seconds (for example, to achieve a cooling target) the response time of thin-film TECs, by means of their small size, are on the order of milliseconds.

Figure 6 shows the measured load lines of the bulk and thin-film TECs, recast to account for dimensional performance differences. In this case, ΔT is divided by the thickness over which it is achieved, and Q is divided by the area over which it is achieved. In other words, the vertical axis represents the temperature gradient the device is capable of holding off across the thickness, and the horizontal axis shows the power density that the device is capable of pumping over its area. The complete bulk-thin film comparison is summarized in Table 1.



• Figure 6: Dimensionless load lines for the bulk TEC and the Nextreme thin-film TEC.

The comparison in Figure 6 illustrates a fundamentally new operating regime offered by thin-film TECs. In the cooling mode, thin-film thermoelectric devices deliver unprecedented power-density pumping capability (Q/area) combined with an extraordinary temperature gradient ($\Delta T/H$). Similarly, in power generating mode these devices achieve unmatched performance characteristics.

• Table 1: Room temperature performance comparison of bulk and thin-film TECs

TEC	L (cm)	W (cm)	H (cm)	ΔT_{max} (°C)	Q_{max} (W)	$\Delta T_{\text{max}}/H$ (°C/cm)	Q_{max}/A (W/cm ²)	Response Time
Bulk	1.03	0.62	0.18	64	4.0	360	6.3	seconds
Nextreme Thin Film	0.35	0.30	0.01	40	16	4000	150	milliseconds

Implications for Applications Development

Nevertheless, in order to take advantage of the characteristics shown in Figure 6, the thin-film devices need to be put into the right thermal and dimensional form-factor environment. Because they are so small the devices can be integrated directly into a semiconductor or optoelectronic package to achieve localized cooling and temperature control that has never been available to product engineers in these industries. At the same time the devices are small enough and pump enough power to enable new applications in power generation, medical devices and instrumentation. Finally, the concept of integrated, localized cooling and power generation is now available to make a temperature control or energy delivery a complementary function in an electric circuit.