ed according to both spatial and temporal scales (see the table). There will be some transmission of signal from one scale to the next, but different variables should emerge at different scales. Thus, variables that best account for species richness on a local spatial scale or recent time scale may not be the same as those accounting for richness at regional spatial scales or longer time scales. We should take this into account during future attempts to model and assess species diversity for conservation purposes.

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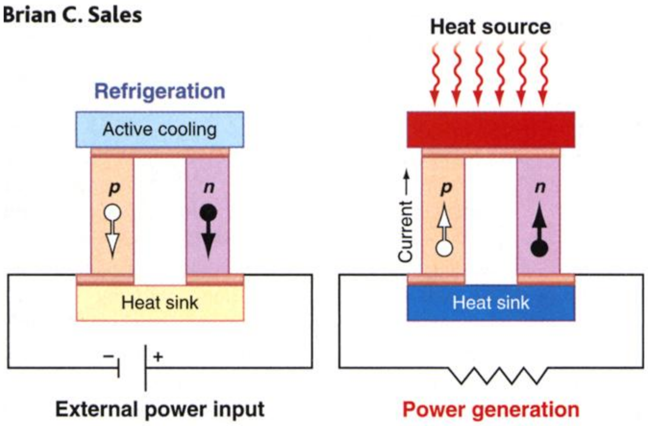
PERSPECTIVES: THERMOELECTRIC MATERIALS

Smaller Is Cooler

Brian C. Sales

To most people, the word "semiconductor" is associated with modern electronics such as the personal computer. In the early 1950s, however, most semiconductor research focused on using semiconductors not in integrated circuits but in thermoelectric modules for home refrigeration. The latter never became practical because of poor cooling efficiency. New materials and synthesis techniques have reawakened interest in the use of semiconductors in refrigeration and power generation. Some of the most promising new thermoelectric structures contain carefully arranged films or clusters on nanometer length scales.



Thermoelectric refrigeration and power generation. A single thermoelectric couple is shown, configured for refrigeration **(left)** or power generation **(right)**. The labels *p* (positive) and *n* (negative) refer to the sign of the charge carriers in each leg; open circles correspond to holes and filled circles to electrons. The copper-colored regions depict electrical connections.

Thermoelectric devices are extremely simple, have no moving parts, and use no greenhouse gases (see the first figure). The devices use two types of semiconductor "legs" that are connected in series. Negatively charged electrons carry electrical current in the *n*-type leg, whereas positively charged holes carry the current in the *p*-type leg.

Refrigeration is possible because electrons and holes carry heat as well as electrical charge. An external battery forces the hot electrons and holes away from the cold side of the device (left panel in the first figure), resulting in cooling. In some multistage thermoelectric modules, temperatures as low as 160 K can be achieved. Today, spot cooling of electronics is the primary application for thermoelectric refrigerators.

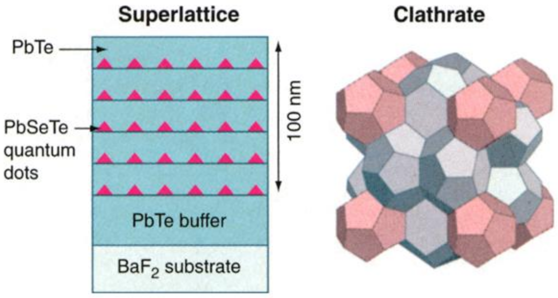
If heat is applied to only one side of the device, a voltage develops across the *n* and *p* legs that can be used to convert part of the heat into electrical power (right panel in the first figure). NASA has used this principle to provide hundreds of watts of electrical power for deep space probes such as Voyager I and II and the Cassini mission to Saturn.

The major problem with thermoelectric devices is poor efficiency. The efficiency of a thermoelectric module is fundamentally limited by the material properties of the *n*- and *p*-type semiconductors—regardless of how cleverly the module is engineered. The inherent efficiency of any thermoelectric material is determined by a dimensionless parameter ZT, where T is the temperature and Z characterizes the material's electrical and thermal transport properties. Effective thermoelectric materials have a low thermal conductivity but a high electrical conductivity (*1*, *2*).

The best thermoelectric materials commercially available today have $ZT \approx 0.9$. This is acceptable for certain specialized applications, but to be economically competitive with the refrigerators in our kitchens, a thermoelectric refrigerator would require $ZT \approx 3$ at room temperature.

At the recent Materials Research Society meeting in Boston (*3*), several materials with $ZT > 1$ for both refrigeration and power generation applications were reported. Particularly exciting were results obtained by Venkatasubramian (Research Triangle Institute), who showed $ZT = 2.4$ for *p*-type superlattices of Bi_2Te_3/Sb_2Te_3 at room temperature and $ZT = 1.2$ for *n*-type superlattices (*4*). The superlattice is produced by alternately depositing thin (1 to 4 nm) films of Bi_2Te_3 and Sb_2Te_3. Harmon (Lincoln Labs, MIT) reported $ZT \geq 2$ just above room temperature for quantum dot superlattices (see the left panel in the second figure) (*5*).

The studies of Venkatasubramian and Harmon imply an increase in ZT when either the layer thickness or the size of the quantum dot is near 1 nm. The results confirm some of the earlier ideas of Dresselhaus and collaborators (*6*), who suggested that nanoengineering of thermoelectric materials could result in higher values of ZT.



Promising new materials. (Left) Nanoengineered thermoelectric materials of this kind are prepared with molecular beam epitaxy. **(Right)** In this model clathrate crystal structure, the cubic crystal structure is composed of two types of polyhedra that consist of clusters of 20 or 24 atoms. In self-assembled structures of this type, nature does the nanoengineering.

CREDIT: LEFT PANEL IN THE SECOND FIGURE ADAPTED FROM (5)

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The films could be used in the spot cooling of electronics if they can be produced quickly and cheaply. More importantly, the studies prove that thermoelectric materials with $ZT >> 0.9$ are possible at room temperature.

An all-solid thermoelectric refrigerator that could cool below the transition temperature of a cuprate superconductor would be extremely attractive for a variety of proposed electronic applications. Kanatzidis (Michigan State University) reported the only new bulk material, $CsBi_4Te_6$, with a high value for ZT below room temperature (0.8 at 225 K) (*7*). A prototype thermoelectric refrigerator with $CsBi_4Te_6$ is being evaluated for possible use near liquid nitrogen temperatures (≈100 K). Singh (Naval Research Lab) predicted that some fully filled skutterudites (complex materials whose chemical formula is $ReTm_4Pn_{12}$, where Re is a rare earth material, Tm is a transition metal, and Pn is P, As, or Sb) should have excellent thermoelectric properties around 100 K. This prediction needs to be tested experimentally.

The most promising new materials for power generation applications are filled skutterudites such as $CeFe_4Sb_{12}$ and $Yb_{0.2}Co_4Sb_{12}$ (*8, 9*), Zn_4Sb_3 (*10*), Tl_2SnTe_5 (*11*), Tl_9BiTe_6 (*12*), and clathrates (see the right panel in the second figure) such as $Sr_8Ga_{16}Ge_{30}$ (*13*). Caillat (Jet Propulsion Laboratory) is evaluating advanced multistage power generation modules that incorporate both filled skutterudites and Zn_4Sb_3. The thallium compounds have good ZT values, but the toxicity of thallium may be a barrier for many applications.

Most terrestrial power generation applications are focused on the conversion of waste heat into useful electricity. Automobiles, steel, and chemical industries could in theory benefit from thermoelectric generators. Peter Hagelstein (MIT) and Yan Kucherov (Eneco) presented the development of an improved device for waste heat power generation (*14*). This device could be important if other scientists can verify the results.

Today you can go to your local supermarket and purchase a thermoelectric picnic cooler powered by the cigarette lighter in your car. Will thermoelectric devices ever extend beyond such niche markets? Maybe. The hard work by many researchers over the past 5 to 10 years suggests nanostructures as a possible path to materials with higher values of ZT. If we can self-assemble in large quantities the types of structures that are now produced with molecular beam epitaxy (a very slow and expensive method), thermoelectrics may become a multibillion dollar industry.

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PERSPECTIVES: SIGNAL TRANSDUCTION

Scaffolding Proteins—More Than Meets the Eye

Gary Johnson

Enzymes called mitogen-activated protein kinases (MAPKs) are crucial components of many signaling pathways that regulate cellular activities as diverse as motility, gene expression, cell division, and programmed cell death (*1*). MAPKs are activated by addition of a phosphate group (phosphorylation) to a tyrosine/threonine (TXY) motif in the activation loop of their catalytic domain (*2*). The MAPK activation pathway consists of a three-kinase "phosphorelay" arrangement. Upstream signals, such as cytokine receptor activation, the inflammatory response to infection, or cell-shape changes, activate a MAPK kinase kinase (MKKK), which in turn phosphorylates and activates a MAPK kinase (MKK). MKKs are selective in recognizing specific MAPKs and phosphorylate both the tyrosine and threonine residues in the TXY motif of the MAPK activation loop (*3*). At last, as reported by Ge *et al.* (*4*) on page 1291 of this issue, a different pathway for MAPK activation has been discovered. The authors show that the TAB1 scaffolding protein binds to a MAPK called p38α, inducing this MAPK to phosphorylate itself (autophosphorylation) and become activated. TAB1, a scaffolding protein that organizes other proteins into complexes, is not a kinase and apparently has no catalytic activity (*5*). The Ge *et al.* discovery of TAB1-mediated autophosphorylation and activation of p38α dispels the notion that MAPKs are regulated only by a three-kinase phosphorelay module. Furthermore, their work implies that MAPKs can be activated by protein interactions that are independent of phosphorylation mediated by MKKs.

Using recombinant purified TAB1 and p38α, the authors show that TAB1 binds to p38α and stimulates autophosphorylation of its TGY motif, resulting in the initiation of kinase activity. Wild-type p38α is unable to phosphorylate a second kinase-inactive p38α in the presence of TAB1, indicating that autophosphorylation is likely to be an intramolecular and not an intermolecular (transphosphorylation) event. TAB1 does not appear to bind to other isoforms of p38 or to the related c-Jun NH_2-terminal kinases (JNKs).

What do we know about TAB1? Human TAB1 is 504 amino acids in length and has an evolutionarily conserved motif in its carboxyl terminus, which binds and activates TGF-β–activated protein kinase 1 (TAK1). Indeed, the TAB1 carboxyl terminus induces autophosphorylation and activation of both TAK1 and p38α (*5, 6*). TAB1 has been characterized as an adaptor protein that forms complexes with other components of the interleukin-1 (IL-1) receptor signaling pathway (*6*). More recently, TAK1-TAB1 complexes have been found to include a second scaffolding protein, TAB2 (*7*). TAK1-TAB1-TAB2 complexes are involved in regulation of the transcription factor NF-κB by TRAF6, and in MAPK signaling. When cells are treated with IL-1β, a chain of ubiquitin molecules is added to TRAF6 (polyubiquitination), altering its interactions with other proteins and resulting in TAK1 acti-

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