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Nanomaterials draw electricity from heat

Power generation from low-energy thermal sources might become economical with more efficient thermoelectric materials. Nanostructures offer a new way to improve their performance.

PHILIP BALL

Heat from geothermal systems like hot springs could be converted to electricity using thermoelectric materials.

Nanostructured materials could acquire better thermoelectric properties than their bulk counterparts, two researchers claim, and could attain the kind of performance needed for widespread application of thermoelectric technology in power generation and refrigeration.

Tammy Humphrey of the University of Wollongong in Australia and Heiner Linke of the University of Oregon calculate that thermoelectric nanomaterials could have values of the standard thermoelectric 'figure of merit' ZT – the materials-dependent measure of their performance at interconverting electrical power and temperature gradients – of around 10 (ref. 1), which is twice the value often cited for economical uptake of the technology. Bulk materials currently being explored for thermoelectric applications typically have ZT values of less than 2.

Nanostructured materials have been explored previously as potentially efficient thermoelectrics[2–4]. For example, Yu-Min Ling and Mildred Dresselhaus estimated in 2003 that an ordered array (superlattice) of semiconducting nanowires could have ZT values of around 4–6 (ref. 3). But the structures considered by Humphrey and Linke do even better than that because they have a further crucial property: reversibility.

That's to say, despite the existence of a thermal gradient and the presence of particle (electron or hole) motion in these devices, they operate essentially at thermodynamic equilibrium. This enables the devices to achieve an efficiency more or less equal to the so-called Carnot limit: the maximum efficiency possible for a 'heat engine', which does work by moving heat.

In thermoelectric materials, a temperature gradient creates motion of charged particles – typically electrons and holes in semiconductors – that produces a voltage, leading to the flow of current when the material is connected in a circuit. This effect could be used to extract power from small temperature gradients, such as those produced by some geothermal processes, which are currently too 'dim' to allow for economical energy generation.

The effect also happens in reverse: a current passing through a thermoelectric material can enable it to 'pump' heat against a thermal gradient. This is potentially useful for refrigeration, both at the macroscopic scale and for applications such as cooling of microelectronic circuitry on chips. Some thermoelectric refrigeration devices are

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already available commercially, but only for niche applications. The challenge is to find materials that work efficiently enough to broaden this range of viable applications.

In previous manifestations of thermoelectric nanomaterials, the improved performance has resulted from a number of physical effects, some of them poorly understood. For example, Rama Venkatasubramanian and co-workers in North Carolina showed that control of losses owing to phonon heat conduction in layered superlattices of semiconducting alloys could generate ZT values of around 2.5 (ref. 1).

But Humphrey and Linke obtain their dramatic improvements in ZT by exploiting another characteristic of nanostructures. In principle, confining the charge carriers of semiconducting materials to the nanoscale in one, two or three dimensions (thin films, nanowires and nanocrystal quantum dots) can result in an electronic density of states that is very sharply peaked at a particular energy: all the mobile electrons have essentially the same energy.

The researchers show that, in this situation, there may be a particular temperature gradient for which the population of electron states is identical throughout the nanostructured system: in other words, it is in equilibrium, even though it is not isothermal. In this situation, movement of electrons from place to place is reversible, because it does not disturb the equilibrium – it is rather like moving a frictionless ball from place to place on a flat tabletop.

Under these conditions, the thermoelectric device can operate reversibly, which means that it attains the maximum possible efficiency – the Carnot limit (provided that heat leaks due to phonons can be suppressed). Humphrey and Linke calculate that this energy-specific equilibrium could produce a ZT of around 10 at room temperature: a phenomenal enhancement relative to current bulk thermoelectrics. Given that it should not be difficult to make nanostructured materials of this sort – for example, from arrays of quantum dots – we might hope to see the proposal put to the test in the near future.

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