

tail of the fuel strand and then with the rest of the fuel strand, allowing the DNA duplex to revert to its original hairpin structure and the tetrahedron to contract. The whole process can be repeated over and over, as long as the fuel strand and the antifuel strand are added in alternating steps into the system. Accompanying the expansion or contraction of the tetrahedron, each cycle produces a duplex from the fuel and antifuel strands.

Although the process of expansion and contraction is well understood, it is not entirely clear how the tetrahedral shape changes. The responsive element functions as a sort of spring, providing the flexibility for the contraction and expansion along the DNA duplex. However, one open question is whether the flexibility is limited to the direction along the length of the DNA duplex, as it is possible that the spring-like hairpin structure might also offer some flexibility in the perpendicular direction. The

hairpin-containing edge is a three-arm branched structure. This structure is known to be flexible, particularly because there is a 'nick' at the branching point. If these arguments hold true in the context of the DNA tetrahedron, which is likely, the reconfigurable edge will be quite flexible and can bend and distort the tetrahedral faces and volume.

Interestingly, another independent research group led by Hanadi Sleiman at McGill in Canada has also reported similar work⁹, a fact that highlights the importance of this research activity. It is likely that both of these studies will lead to responsive molecular cages that can encapsulate guests and release them on demand. For example, it is now possible to enclose proteins in a DNA tetrahedron¹⁰. DNA cages can also serve as structural scaffolds to display or organize other materials, with one recent work demonstrating that a finite number of protein molecules can be displayed on the outside of a DNA

tetrahedron at well-defined positions in three dimensions¹¹. Furthermore, it is conceivable to integrate such responsive structures as structural modules into large sophisticated devices to perform complex physical, chemical or biological functions¹².

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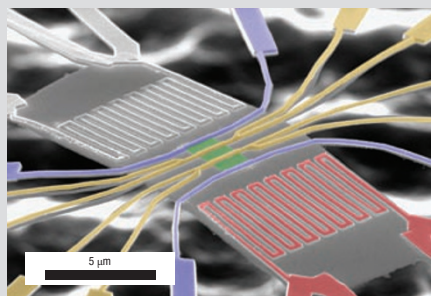
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NANOMATERIALS

Silicon goes thermoelectric

The ability of thermoelectric materials to convert heat into electricity could have many applications, including power generation and solid-state refrigeration. In particular, the fact that the majority of the world's power is generated by systems that typically operate at efficiencies of about 40% or less means there is enormous scope for thermoelectric systems that can 'salvage' the energy currently lost as heat to the environment. Although commercial thermoelectric systems based on metals such as bismuth, tellurium and lead are available for niche applications, it has proved difficult to scale-up production to the levels needed for more demanding tasks. However, two groups in the US have now shown that silicon nanowires demonstrate useful thermoelectric properties. Moreover, silicon-based thermoelectric systems should be able to take advantage of infrastructure that already exists in the semiconductor industry.

Improving the performance of a thermoelectric material involves controlling the motion of phonons, which carry most of the heat, and electrons, which carry the electric current and some of the heat.



Thermoelectric performance is usually quoted in terms of a figure of merit, ZT , which is proportional to the operating temperature, the electrical conductivity and the square of the Seebeck coefficient, and inversely proportional to the thermal conductivity. However, it can be difficult to increase the electrical conductivity or Seebeck coefficient without also increasing the thermal conductivity. Commercial thermoelectric materials have ZT values of about one.

Nanostructured materials offer a solution to this problem because phonons have mean free paths of hundreds of nanometres, compared with about 10 nm or less for electrons. This means that it is possible to restrict the movement of phonons without

hindering the electron motion. Bulk silicon has a ZT value of about 0.01, but Arun Majumdar, Peidong Yang and co-workers at Berkeley have shown that it is possible to reach a value of 0.6 at room temperature by using silicon nanowires with diameters of about 50 nm (*Nature* **451**, 163–167; 2008). And working with nanowires that are 20 nm thick and either 10 or 20 nm wide, Jim Heath and co-workers at Caltech have demonstrated that it is possible to increase the ZT value to about 1.0 at 200 K (*Nature* **451**, 168–171; 2008). Moreover, both groups predict that it should be possible to reach even higher values of ZT by optimizing the diameter, doping and other properties of the nanowires.

This false-colour scanning electron micrograph, which measures 20 μm across, shows the nanowire array (green region) between two joule heaters (one of which is shown in red) on a suspended SiO_2 platform (grey) in the Caltech experiment. The yellow and blue electrodes are used for thermometry and measurements of electrical conductivity.

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