BERKELEY LAB RESEARCH HIGHLIGHT
MATERIALS SCIENCES DIVISION 08-9

Silicon Nanowire Thermoelectrics: Electricity from Waste Heat

As reported in *Nature**, MSD Scientists Arun Majumdar and Peidong Yang have discovered a new silicon-based device that can convert heat to electrical power. By making use of otherwise wasted heat in applications ranging from power plants to cell phones, the new device could have a profound impact on global energy supplies.

The concept of converting heat to electricity is not new Approximately 90 per cent of the world's power is generated by heat engines that use fossil fuel combustion as a heat source and typically operate at only 30–40 per cent efficiency, releasing roughly 15 terawatts of heat to the environment. If this "wasted heat" could be recycled at even the 5% level, the impact globally would be enormous.

Devices based on thermoelectrics would seem to be ideal for this application; in these materials, an electrical current is created in a wire if one end is heated and the other cooled. However, for this process to continue, one end of the wire must remain hot, and the other cold and this presents a materials design challenge because most materials that conduct electricity well also conduct heat. This is true, for example, for bulk silicon, leading most scientists to conclude that this otherwise attractive material (because of the silicon manufacturing infrastructure already in place) is not a very good candidate for thermoelectric conversion devices.

Majumdar and Yang have discovered that nanostructural engineering can change this picture. In the course of developing an inexpensive method to form nanowires, they immersed a silicon wafer in a chemical solution of etchant. They succeeded in growing a microscopic forest of Si nanowires on the wafer's surface but were initially disappointed when the surface of the nanowires appeared very rough. However, thermoelectric testing showed that rough nanowires allowed current to flow from a heat source toward a cold source but, astonishingly, the heat did not flow. By optimizing the roughness of the wires they were able to reduce the room temperature thermal conductivity by a factor of 100. While the physics behind the effect is not completely understood at this time, it may be that thermal transport is impeded as heat waves simply bounce off the rough contours on the surface of the nanowires, but current flow is not impeded, as electrons are not similarly slowed down. A well-accepted "figure of merit" for thermoelectric devices is the so-called ZT ratio(where Z is the square of the thermoelectric power divided by the product of the electrical resistivity and thermal conductivity). The rough Si nanowires have a ZT of 0.6 while the value for bulk Si is only 0.01. Only complex materials made of relatively rare elements such as Bi, Te, Pb, Sb, and Ag have values above 0.6.

Although the results so far are very promising, there are still many potential roadblocks on the road to the marketplace. Nevertheless, the range of applications is very broad. One can imagine recharging a cell phone with electricity produced by the user's body heat or reclaiming the heat that is released through a car's exhaust system to power electronic devices. And, when prototype devices are developed, the $100 billion semiconductor industry will be fully prepared to manufacture them.

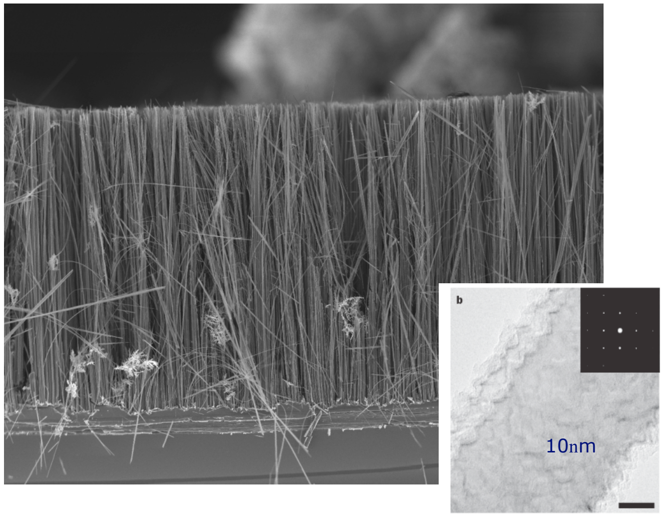
A. Majumdar (510) 643-8199 and P. Yang (510) 643-1545, Materials Sciences Division (510) 486-4755, Berkeley Lab.

---

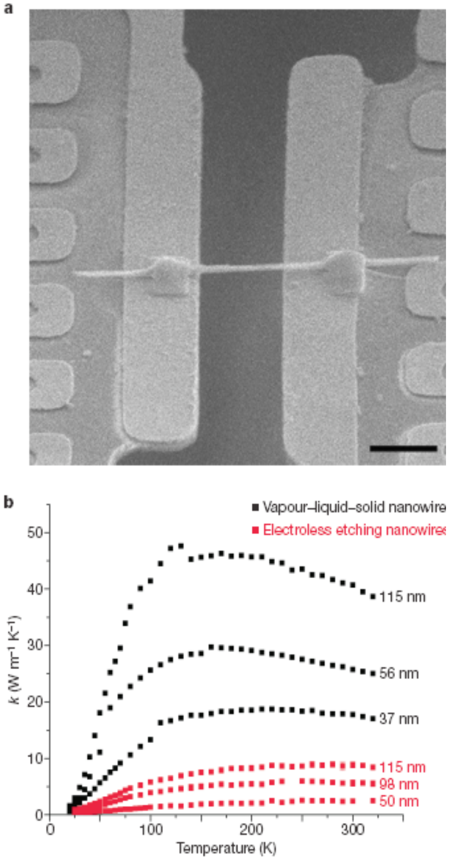
*A. I. Hochbaum, R. Chen, R. D. Delgado, W. Liang, E. C. Garnett, M. Najarian, A. Majumdar, and P. Yang, "Enhanced thermoelectric performance of rough silicon nanowires," Nature **451**, 163 (2008).

The authors thank T.-J. King-Liu and C. Hu for discussions and J. Goldberger for TEM analysis. They acknowledge the support of the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, DOE. Their co-workers thank the NSF-IGERT, ITRI-Taiwan programs, and GenCat/Fulbright programme for fellowship-related support. They also thank the DOE National Center for Electron Microscopy and the UC Berkeley Microlab for the use of their facilities.

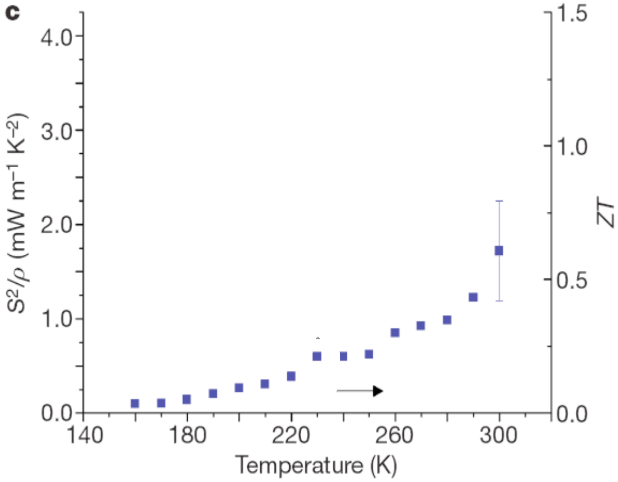
Silicon Nanowire Thermoelectrics: Electricity from Waste Heat



Forest *of Si nanowires produced by electrochemical etching of a Si wafer. The inset shows the rough surface that is produced by the etching process.*



Thermal conductivity of single nanowires (top). Rough wires (red points below) have lower thermal conductivities than smooth wires (black points).The smallest wires appear to have the lowest thermal conductivity.



ZT is a thermoelectric figure of merit which balances heat-driven electrical conductivity and thermal conductivity (larger values are desirable and only a few exotic materials are known to have ZT > 1). 48 nm rough Si nanowires have a room temperature (300 K) ZT of 0.6 compared to ~0.01 for bulk Si.