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Taking the Measure of the Seebeck Effect

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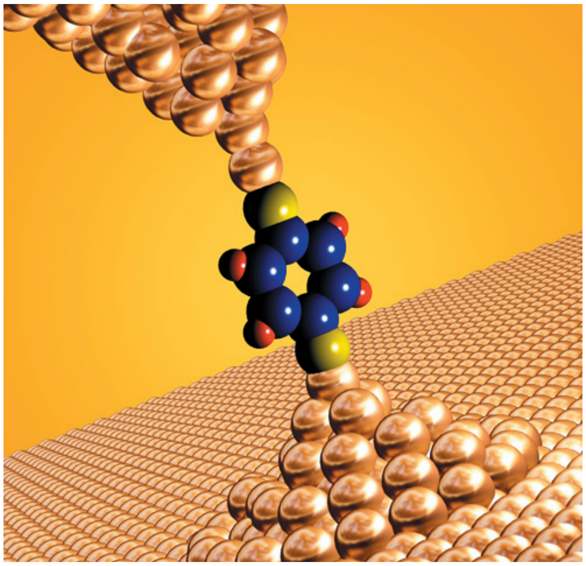
Coming soon, *The Seebeck Effect*: “A physical phenomenon discovered two centuries ago may hold the key to meeting future energy needs, while reducing global warming....”

Although it sounds like the title and plotline of a summer thriller movie, the Seebeck effect is quite real, and its potential for helping to solve the energy crisis is not Hollywood hype. The Seebeck effect involves the direct conversion of temperature differences into electricity. It was first reported in 1821 by the German-Estonian physicist Thomas Johann Seebeck, who observed that a temperature difference between two ends of a metal bar created an electrical current in between, with the voltage being directly proportional to the temperature difference (the Seebeck coefficient).



One side of an organic molecule trapped between two gold surfaces is heated, and the temperature difference induces an electrical current to flow. The phenomenon is an example of the Seebeck effect. (Image after Ben Utley, UC Berkeley).

Scientists have long recognized that the Seebeck effect could be exploited as an environmentally clean way of producing electricity. As yet the process is far too inefficient, however, and involves materials much too expensive for practical commercial applications.

The situation may soon be changing. Mechanical engineer Arun Majumdar and chemical engineer Rachel Segalman, who both hold joint appointments at Lawrence Berkeley National Laboratory and the University of California at Berkeley, have recorded the first measurements of the Seebeck effect in inexpensive organic molecules.

Working with Pramod Reddy, a graduate student, and Sung-Yeon Jang, a postdoctoral fellow, Majumdar and Segalman trapped electron-conducting organic molecules between a pair of gold electrodes, then measured the thermopower (voltage) at room temperature with their own technique of scanning tunneling microscopy (STM). Although this study was done on nanoscale materials, it cracks open the door to an entirely new field of thermoelectrics, which in turn could lead to a new generation of low-temperature solar cells and thin films, and low-cost plastic power generators.

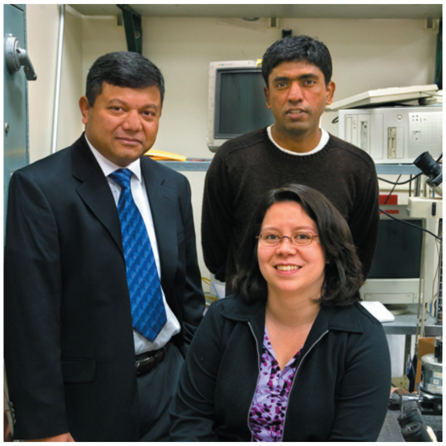
“This is a significant step and major departure from traditional inorganic semiconductor materials,” says Majumdar. “For the past 50 years, researchers have been working to improve the efficiency of thermoelectric materials, but progress has been extremely hard to come by, mainly due to the coupling between various properties of the material like electrical conductivity, thermal conductivity, and the Seebeck coefficient, which determines the efficiency of the device. Recently, through nanotechnology, the efficiency has been increased—but only with expensive semiconductor materials that require high-temperature processing.”

Nearly all the world’s electrical power, approximately 10 trillion watts, is generated by heat engines: giant gas or steam-powered turbines that convert heat to mechanical energy, which in turn is converted to electricity. In accordance with thermodynamics, however, much of the heat isn’t converted but released into the environment instead. To generate 10 trillion watts of electricity means wasting another 15 trillion watts as heat.

If even a small fraction of the lost heat could also be converted to electricity, its impact on the energy situation would be enormous. “We are talking about massive savings on fuel and atmospheric carbon dioxide,” Majumdar says.

In their experimental setup, Majumdar, Segalman, and their students use an STM whose gold stylus tapers off to a single atom at its tip. The STM features a customized control circuit that moves the gold tip at a constant speed toward a substrate, also made of gold. While the STM gold tip is maintained at ambient temperature, an electric heater is used to warm the gold substrate. This creates a temperature difference between the tip and the substrate. Using chemical handles, the experimenters trap a molecule in the gap between tip and substrate and then measure the Seebeck effect.

“As we would expect,” Majumdar says, “we saw a thermoelectric voltage generated across the metal/molecule junctions—which depended on the type of molecule and lasted as long as one or more of those molecules were trapped, but vanished once all of the molecules broke away.”



Arun Majumdar (left), Pramod Reddy, and Rachel Segalman have recorded the first measurements of the Seebeck effect in organic molecules. Their achievement opens the door to an entirely new field of thermoelectrics, with the promise of cleaner, more efficient electrical power. (Photo Roy Kaltschmidt, CSO)

For their organic molecules the Berkeley researchers elected to work with the benzenedithiol family. The electronic properties of these chemicals are well known, and they are easy to use.

Says Segalman, “One of the primary advantages of organics is that molecular structure is directly related to physical properties. And because we can tune the structure through synthetic chemistry, we have a seemingly infinite toolbox to tune and optimize the thermoelectric efficiency. Since organic molecules are abundant, relatively inexpensive, and easily processed, they hold great promise for widespread application.”

Says Majumdar, “I am sure most conducting molecules will display the Seebeck effect when sandwiched in a metal junction. We will be measuring a number of thiol-terminated molecules in metal/molecule/metal junctions, and we will also be looking into ways to tune the thermopower, such as introducing various chemical moieties in the molecule, or controlling the metal/molecule chemical bond.”

The ability to measure the Seebeck effect in metal/molecule junctions offers promise that extends beyond the field of energy, according to Majumdar and his coauthors. For example, in the emerging arena of molecular electronics, a key issue has been the alignment of electronic energy levels when new chemical bonds are formed. This is a critical factor in the operation and performance of a device, but until now it has been difficult to determine such energy alignments at metal/molecule junctions.

“The ability to measure the Seebeck effect resolves this important issue and can be directly used to estimate the energy levels of the junction,” Majumdar says. “This is a fundamental step in the design and understanding of molecular electronic devices for information processing and storage, and of molecular solar cells for converting sunlight to electricity.”

Berkeley Lab has applied for patents on behalf of Majumdar and Segalman for the use of their metal/molecule heterojunction assemblies in thermoelectric energy conversion, batteries, and supercapacitors. The research was funded by the U.S. Department of Energy’s Basic Energy Sciences program (DOEBES), the National Science Foundation, the Berkeley-ITRI Research Center (ITRI is the Industrial Technology Research Institute of Taiwan), and the Thermoelectrics Program and DOEBES Plastic Electronics Program at Berkeley Lab.

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