Hot Tech

By **Tim Stephens**

Electrical engineering professor Ali Shakouri has brought together a multidisciplinary team of researchers to develop new technology for direct conversion of heat to electricity.

Here's something to ponder the next time you fill up your gas tank: Two-thirds of the energy produced from burning that fuel in your car's engine will be wasted as heat, while only one-third will actually be used to get you where you want to go.

Ali Shakouri wants to change that. An associate professor of electrical engineering at UCSC, Shakouri leads the Thermionic Energy Conversion (TEC) Center, a collaborative project involving researchers at seven major universities working to develop new technology for direct conversion of heat to electricity.

To achieve this, the TEC Center is taking a new approach to an old concept. "Thermoelectric" materials, in which temperature differences can produce an electric voltage, were first described in 1821 by physicist Thomas Johann Seebeck. By the 1830s, physicists knew that the effect also works in reverse: An electric current can be used to pump heat from one side of a thermoelectric material to the other.

In theory, this thermoelectric effect could be used to generate power from all kinds of heat sources, including waste heat from cars and factories, and to build

Graduate student Javad Shabani adjusts a Raman spectroscopy machine in Ali Shakouri's lab.

compact refrigerators with no moving parts. Unfortunately, developing practical thermoelectric devices has proven to be a daunting challenge.

"Until recently, the efficiency was so low it was not economical to build thermoelectric refrigerators or power generators for use on a large scale," Shakouri says.

With advances in nanotechnology, however, engineers may finally be able to develop efficient thermoelectric materials for a variety of practical applications. That's because at "nanoscale" dimensions, where distances are measured in nanometers (billionths of a meter), weird quantum effects begin to govern the properties of materials. As a result, Shakouri says, engineers can use techniques such as molecular beam epitaxy—which deposits layers of material a few atoms thick—to manipulate features such as electron transport and heat transport in ways never before possible.

Shakouri's work in this field began with a project to help solve the problem of overheating in computer chips. He and his collaborators developed tiny thermoelectric refrigerators that can be deposited onto potential hot spots on computer chips. This application did not require high efficiency, but Shakouri thought the approach he used to build a successful chip cooler could also lead to the development of thermoelectric materials efficient enough to be practical for power generation.

When the Office of Naval Research (ONR) issued a call for proposals to develop technology for direct conversion of heat to electricity, Shakouri jumped at the opportunity. He brought together a team of researchers from around the country with expertise in different fields, and their proposal for the TEC Center won a $6 million grant from ONR in 2003. With UCSC as the lead institution, the center also includes researchers from UC Berkeley, UC Santa Barbara, Harvard University, Massachusetts Institute of Technology, Purdue University, and North Carolina State University.

Shakouri and research assistant Rajeev Singh with the molecular beam epitaxy machine used to create nanostructured materials.

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Ali Shakouri and graduate student Xi Wang in one of the TEC Center labs, where researchers use sophisticated equipment to evaluate materials that convert heat to electricity

"It is a very multidisciplinary team, with experts in mechanical engineering, electrical engineering, materials science, and physics," Shakouri says.

The U.S. Navy is interested in using thermoelectric technology to build quiet all-electric ships. But the possibilities for applying this technology are almost endless. Thermoelectric materials could be used to increase the efficiency of everything from cars to power plants by converting waste heat to electricity.

But first, there are some major technical hurdles to overcome, Shakouri says. An efficient thermoelectric material requires three crucial features: high electrical conductivity, low thermal conductivity, and a favorable Seebeck coefficient (the measure of voltage created by temperature difference within the material). The challenge is to control these features independently so that, for example, increasing the electrical conductivity does not also increase thermal conductivity.

Shakouri describes the TEC Center's approach as a method of energy filtering within a semiconductor material. The basic idea is to structure the material so that "hot" electrons that have absorbed energy from a heat source can flow more easily than "cold" electrons, resulting in high electrical conductivity with a high Seebeck coefficient and low thermal conductivity.

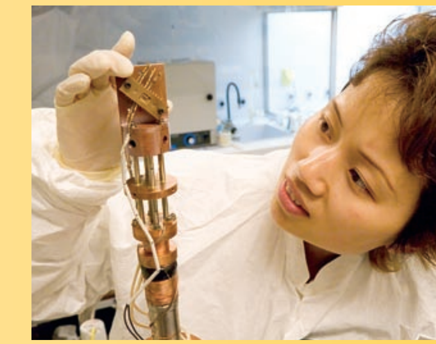
The energy filtering is based on "thermionic emission" (from which the TEC Center gets its name). Thermionic emission also operates in vacuum tubes (such as the cathode ray tubes used in televisions and computer monitors), in which hot electrons are emitted from a heated filament.

"We knew that the same principle could be used for power generation," Shakouri says. "Our idea was to combine this conventional vacuum thermionics with semiconductors and do the energy filtering inside a semiconductor material."

The center also has a team doing complementary research to improve vacuum thermionic emitters for power generation. "It helps to combine various approaches and look at the problem from different perspectives," Shakouri says.

The results from the first two and a half years of this five-year project have been promising, he says. "We now understand the physics much better and are able to engineer the material properties in the way we anticipated, so I think we are going in the right direction."

In addition to Shakouri, the UCSC group includes Holger Schmidt, assistant professor of electrical engineering, and about a half-dozen graduate students, undergraduates, and postdoctoral researchers.



Graduate student Yan Zhang with a cryostat used to test thermoelectric materials over a range of temperatures, from near absolute zero to over 1,000 degrees Fahrenheit

Shakouri is also looking to expand his research into other areas of renewable-energy technology. He and other UCSC faculty in engineering, physics, and chemistry have started a discussion group that meets every other week to discuss how recent advances in nanomaterials might be used to address problems in renewable energy, such as the design of photovoltaic cells for solar energy. Shakouri also plans to offer a new undergraduate course on renewable-energy technologies this year.

"There has been very little fundamental research in this area," he says. "But the ways we generate power now are not very environmentally friendly, so we really need to find better ways to do this."