Fractals aid efforts to understand heat transport at nanoscale

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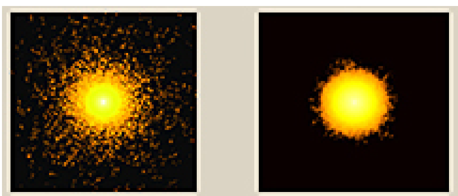

Researchers for the first time have used a modern theory of heat transport in experiments with semiconductors used in computers, lasers and thermoelectrics. The left image shows a rendering of heat spreading in a semiconductor using the modern transport theory. The image on the right shows a rendering using the conventional heat-transport theory. Credit: Purdue University image/ Bjorn Vermeersch and Ali Shakouri

Researchers for the first time have applied a modern theory of heat transport in experiments with semiconductors used in computers and lasers, with implications for the design of devices that convert waste heat into electricity and the control of overheating in miniaturized and high–speed electronic components.

For more than a century heat transport in solids has been described in terms of the random chaotic motion of "energy carriers" similar to a milk drop dispersing in coffee and gradually transferring heat from hotter to colder regions. However, over the tiny distances of a few nanometers the motion of thermal energy behaves differently and resembles the structure of fractals, which are made up of patterns that repeat themselves at smaller scales infinitely.

"When we look at the problem of heat transport what is surprising is that the theory we use dates back to Fourier, which was 200 years ago, and he developed it to explain how the temperature of the Earth changes," said Ali Shakouri, Purdue University's Mary Jo and Robert L. Kirk Director of the Birck Nanotechnology Center and a professor of electrical and computer engineering. "However, we still use the same theory at the smallest size scale, say tens of nanometers, and the fastest time scale of hundreds of picoseconds."

A team from Purdue and the University of California, Santa Barbara, has applied a theory based on the work of mathematician Paul Lévy in the 1930s, in experiments with the semiconductor indium gallium aluminum arsenide, which is used in high-speed transistors and lasers.

"The work we have done is applying Lévy theory for the first time to heat transport in actual materials experimental work," Shakouri said.

Findings will be presented in December during the Materials Research Society fall meeting in Boston. Findings were detailed in a research paper appeared in July in the journal *NanoLetters* and featured as a cover story.

The research has shown that inserting nanoparticles made of the alloy erbium arsenide significantly reduces thermal conductivity and doubles the thermoelectric efficiency of the semiconductor. Potential applications include systems to harvest waste heat in vehicles and power plants.

"For example, two-thirds of the energy generated in a car is wasted as heat," Shakouri said. "Even our best power plants waste half or two-thirds of their energy as heat, and that heat could be converted to electricity with thermoelectrics."

Thermoelectric devices generate electricity from heat, and their performance hinges on having a pronounced temperature difference - or gradient - from one side of the device to the other side. Having lower thermal conductivity preserves a greater temperature gradient, improving performance

The nanoparticles cause the material's thermal conductivity to drop three fold without changing the fractal dimension. The energy carriers - quasiparticles called phonons - are said to undergo "quasiballistic" motion, meaning they are transported without colliding with many other particles, causing the heat to conduct with "superdiffusion." The approach mimics the effect of "Lévy glasses," materials containing spheres of glass that change the diffusion of light passing through. The same principle can be used to design semiconductors that diffuse heat differently than conventional materials. In addition to thermoelectrics, the approach could be used to reduce heating in electronics and improve performance for high-speed devices and high-power lasers.

More information: "Fractal Lévy Heat Transport in Nanoparticle Embedded Semiconductor Alloys." *Nano Lett.*, 2015, 15 (7), pp 4269–4273 DOI: 10.1021/nl5044665

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