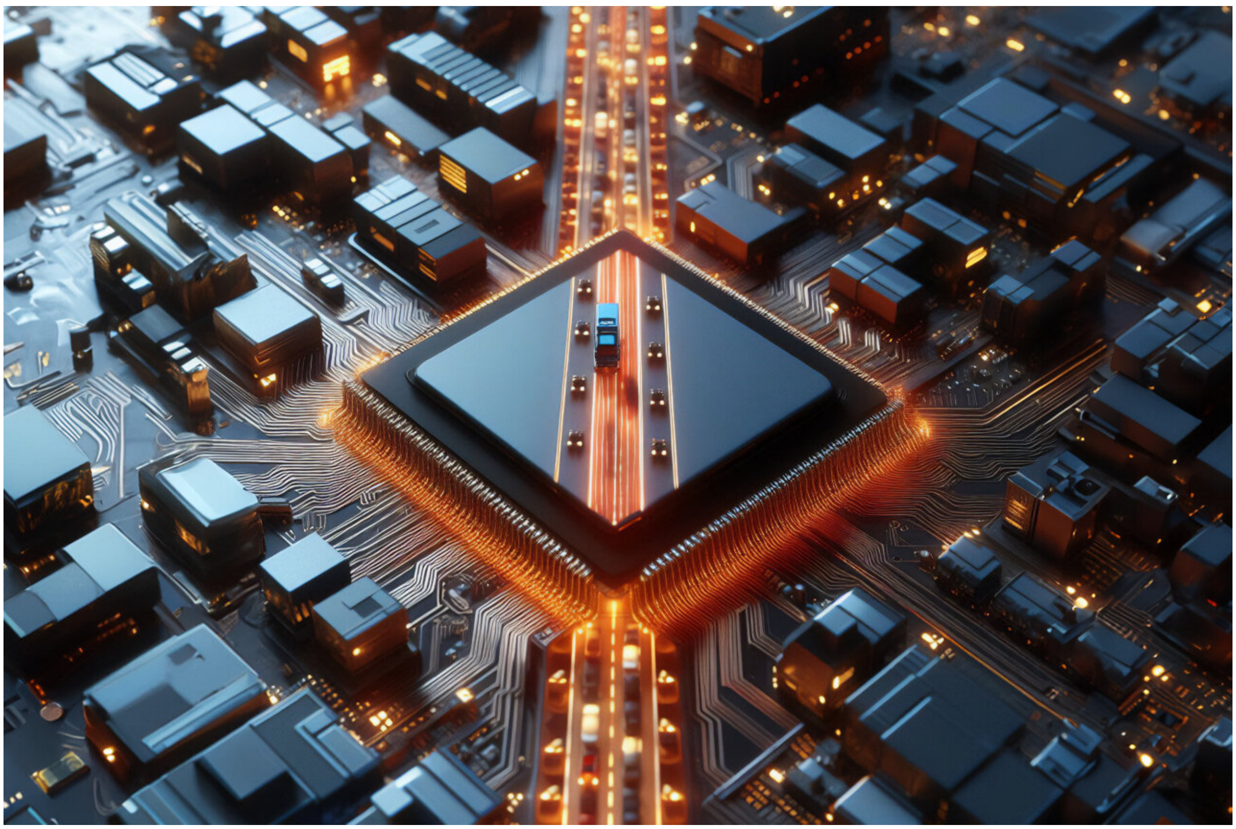
Polaritons open up a new lane on the semiconductor highway

December 7 2023, by Jared Pike



On the highway of heat transfer, thermal energy is moved by way of quantum particles called phonons. But those phonons don't remove enough heat at the nanoscale of today's most cutting-edge semiconductors. That's why Purdue University researchers are focused on opening a new nanoscale lane on the heat transfer highway by using hybrid quasiparticles called "polaritons." Credit: Purdue University/DALL-E

On the highway of heat transfer, thermal energy is moved by way of quantum particles called phonons. But at the nanoscale of today's most cutting-edge semiconductors, those phonons don't remove enough heat. That's why Purdue University researchers are focused on opening a new nanoscale lane on the heat transfer highway by using hybrid quasiparticles called "polaritons."

Thomas Beechem loves heat transfer. He talks about it loud and proud, like a preacher at a big tent revival.

"We have several ways of describing energy," said Beechem, associate professor of mechanical engineering. "When we talk about light, we describe it in terms of particles called 'photons.' Heat also carries energy in predictable ways, and we describe those waves of energy as 'phonons.' But sometimes, depending on the material, photons and phonons will come together and make something new called a 'polariton.' It carries energy in its own way, distinct from both photons or phonons."

Like photons and phonons, polaritons aren't physical particles you can see or capture. They are more like ways of describing energy exchange as if they were particles.

Still fuzzy? How about another analogy. "Phonons are like internal combustion vehicles, and photons are like electric vehicles," Beechem said. "Polaritons are a Toyota Prius. They are a hybrid of light and heat, and retain some of the properties of both. But they are their own special thing."

Polaritons have been used in optical applications—everything from stained glass to home health tests. But their ability to move heat has largely been ignored, because their impact becomes significant only when the size of materials becomes very small. "We know that phonons do a majority of the work of transferring heat," said Jacob Minyard, a

Ph.D. student in Beechem's lab.

"The effect of polaritons is only observable at the nanoscale. But we've never needed to address heat transfer at that level until now, because of semiconductors."

"Semiconductors have become so incredibly small and complex," he continued. "People who design and build these chips are discovering that phonons don't efficiently disperse heat at these very small scales. Our paper demonstrates that at those length scales, polaritons can contribute a larger share of thermal conductivity."

Their research on polaritons has been selected as a Featured Article in the Journal of Applied Physics.

"We in the heat transfer community have been very material-specific in describing the effect of polaritons," said Beechem. "Someone will observe it in this material or at that interface. It's all very disparate. Jacob's paper has established that this isn't some random thing. Polaritons begin to dominate the heat transfer on any surface thinner than 10 nanometers. That's twice as big as the transistors on an iPhone 15."

Now Beechem gets really fired up. "We've basically opened up a whole extra lane on the highway. And the smaller the scales get, the more important this extra lane becomes. As semiconductors continue to shrink, we need to think about designing the traffic flow to take advantage of both lanes: phonons and polaritons."

Minyard's paper just scratches the surface of how this can happen practically. The complexity of semiconductors means that there are many opportunities to capitalize upon polariton-friendly designs. "There are many materials involved in chipmaking, from the silicon itself to the dielectrics and metals," Minyard said. "The way forward for our research is to understand how these materials can be used to conduct heat more efficiently, recognizing that polaritons provide a whole new lane to move energy."

Recognizing this, Beechem and Minyard want to show chip manufacturers how to incorporate these polariton-based nanoscale heat transfer principles right into the physical design of the chip—from the physical materials involved to the shape and thickness of the layers.

While this work is theoretical now, physical experimentation is very much on the horizon—which is why Beechem and Minyard are happy to be at Purdue.

"The heat transfer community here at Purdue is so robust," Beechem said. "We can literally go upstairs and talk to Xianfan Xu, who had one of the first experimental realizations of this effect. Then, we can walk over to Flex Lab and ask Xiulin Ruan about his pioneering work in phonon scattering. And we have the facilities here at Birck Nanotechnology Center to build nanoscale experiments and use one-of-a-kind measurement tools to confirm our findings. It's really a researcher's dream."

More information: Jacob Minyard et al, Material characteristics governing in-plane phonon-polariton thermal conductance, *Journal of Applied Physics* (2023). DOI: 10.1063/5.0173917

Provided by Purdue University

https://phys.org/news/2023-12-polaritons-lane-semiconductor-highway.html