Characterizing Highly-confined Heat Flow, Elastic Properties, and Porosity in a Semiconductor Metalattice

Emma Nelson[1, S, C], Brendan McBennett[1], Albert Beardo[1], Theodore Culman[1], Joshua Knobloch[1], Henry Kapteyn[1] and Margaret Murnane[1]

[1]*Department of Physics, JILA, and STROBE NSF Science and Technology Center, University of Colorado, Boulder, CO, U.S.A.*
emne4121@colorado.edu

Nanostructured semiconductors can exhibit thermal properties unachievable in bulk systems due to the increased influence of surfaces and interfaces. The ability to understand and fully characterize the thermal, elastic, and structural properties of these nanostructured semiconductor materials is important for developing new materials with tunable properties for applications in next-generation nanoelectronics and energy efficient devices. Managing thermal transport in nanoscale materials is critical for optimizing the performance of computer chips—however, when the critical dimensions have similar length scales as the phonon mean free paths, traditional theories of heat flow break down. Moreover, first principles models of nanoscale thermal transport are too computationally challenging for 3D nanostructured geometries, while mechanistic approaches make overly simplistic assumptions about the nature of phonon-boundary interactions.

Here, we probe the elastic and thermal properties of a 3D nanostructured silicon metalattice, which consists of an interconnected network of nanoscale pores that dramatically alter the material properties compared to bulk crystalline silicon. We impulsively heat nickel grating transducers that are fabricated on the 3D silicon metalattice sample, using an infrared pump laser pulse. This launches acoustic waves and heat into the metalattice, which we probe using diffraction from an extreme ultraviolet (EUV) probe pulse. The 10s of nanometer wavelengths of the EUV probe provide exquisite sensitivity to dynamics below the visible diffraction limit, along with 10s of femtosecond pulse durations giving ultrafast temporal resolution. The nickel grating periodicity sets the wavelength of the surface acoustic waves launched by the infrared pump pulse, and so by measuring various grating geometries, we can reconstruct the acoustic dispersion inside the metalattice film. We compare the experimental dispersion to finite element models of the 3D silicon metalattice to nondestructively extract porosity, Young's modulus, metalattice film thickness, and substrate elastic properties [1].

Using the experimentally determined porosity and elastic properties, we model heat flow in the metalattice using finite element methods and fit an apparent thermal conductivity two orders of magnitude below bulk silicon. We model the heat flow dynamics using a Fourier-like relation with an apparent conductivity and arrive at two key conclusions: the size of the heat source does not significantly affect the heat flow as the metalattice geometry dominates, and the transport can be described using hydrodynamic-like heat transport equations in highly confined situations where ballistic transport is traditionally expected. We compare our results to other highly-confined nanostructured systems by separating the thermal conduction into a permeability component, which captures the geometry of the system, and a viscosity component related to the intrinsic phonon properties. This treatment reveals a universal trend in the permeability which can be used to predict the thermal conductivity in general nanostructured silicon systems—from nanomeshes, to metalattices, to porous nanowires and nanowire networks.

References

1. *ACS AMI* **14**, 41316 (2022).
2. *Nano Lett.* **23** (6), 2129 (2023)