Low temperature thermal properties of two-dimensional phononic crystals

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Abstract

Controlling thermal properties in the nanoscale has become more and more relevant in recent years, in light of the strong push to develop novel energy harvesting techniques based on thermoelectricity, the need to improve the heat dissipation out of semiconductor devices, and the push to increase the sensitivity of bolometric radiation detectors [1]. A lot of research has lately focused on lowering phonon thermal conductivity using nanoscale structuring of materials to increase scattering. On the other hand, much less attention has been given to controlling phonon thermal conductance by engineering the phonon dispersion relations, in other words the phonon 'band structure'.

Dispersion relations determine both the group velocity and the density of states, and therefore directly influence thermal conduction. Many of the phonons involved in thermal conduction actually have wavelengths much larger than the atomic lattice constant [1], and thus, by structuring material at some longer length scale, phonons with wavelengths around that length will undergo strong coherent Bragg interference. If this extra structuring is periodic, the devices are called phononic crystals [2], with strongly modified band structure, density of states and group velocity for long wavelength phonons. This modification is expected to be extremely strong in the low-temperature limit, where thermal wavelengths can be of the order of 1 µm and where incoherent phonon-phonon and phonon-impurity scattering is negligible.

Here, we discuss this line of approach for controlling thermal conduction [3] and present our recent experimental and computational studies in two-dimensional phononic crystals (PnCs) at sub-Kelvin temperatures. A typical sample consists of a periodic array of holes etched into a 0.5 µm thick silicon nitride membrane. We compared the results of two PnCs with different periodicities to an uncut membrane sample and observed a strong reduction of thermal conductance up to a factor of 30, with a concurrent change in the temperature dependence, agreeing quantitatively with our numerical computation based on finite element method (FEM) simulations of the modified dispersion relations of the PnC devices. As our calculation of the thermal conduction was performed in the fully ballistic limit, we draw the conclusion that coherent, interference-based phonon band structure modification is behind the observations and thus phonon thermal conduction can be controlled by using the wave-properties of phonons, instead of just the particle (scattering) properties.

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[3] N. Zen, T. A. Puurtinen, T. J. Isotalo, S. Chaudhuri, and I. J. Maasilta, *Nat. Commun.* **5**, 3435 (2014).