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In search for the phonon mean free path with optical, EUV and x-ray time-resolved measurements

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In non-metallic solids, heat is carried primarily by acoustic phonons. At cryogenic temperatures, the phonon mean free path (MFP) can be large, and ballistic propagation of heat over macroscopic distances has been well documented in the "phonon imaging"studies. At room temperature, the MFP of thermal phonons is small and heat typically propagates via diffusion: once the thermal conductivity is known one can forget about the phonon MFP and rely on the ubiquitous heat equation. In recent years, the interest to the phonon MFP has greatly intensified in the context of micro/nanoscale thermal transport studies stimulated by practical applications such as thermal management of microelectronic devices and designing low thermal conductivity thermoelectric materials. Size effects and non-Fourier transport in practically important materials such as silicon have been observed at room temperature at surprisingly large (~1 μm) distances, indicating that long-MFP phonons play a much larger role in heat transport than previously thought. On the other hand, coherent acoustic phonons at frequencies above 1 THz, comparable to the frequencies of heat-carrying thermal phonons, can now be generated by ultrashort laser pulses.

Hitherto optical pump-probe experiment has been the workhorse in studying nanoscale thermal transport as well as coherent phonons. However, optical techniques have a number of limitations; in particular, wave vectors of thermal phonons across the Brillouin zone are not directly accessible to optical excitation and probing. The increasing availability of ultrafast EUV and x-ray sources opens many new avenues for studying phonons. In this talk, I will give an overview of some recent research pertaining to the phonon MFP and involving time-resolved measurements with optical, EUV and x-ray pulses. We will discuss studies of non-diffusive heat conduction at small distances using optical and EUV transient grating techniques, including the recent observation of thermal transport near the ballistic limit in diamond. We will also review experiments aimed at measuring the single mode MFP directly: these involved optical pump-probe measurements of sub-THz and THz coherent phonons, as well as diffuse x-ray scattering by "squeezed"thermal phonon populations. While the ultimate goal of getting phonon MFP data across the entire Brillouin zone has not yet been achieved, a number of insights into phonon-phonon, electron-phonon, and phonon-disorder interactions have been obtained. We will conclude by discussing further prospects for studying phonons using short-wavelength radiation.

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