Probing Zone Boundary Phonons at the Nanoscale

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The emerging ability to engineer thermal properties using nanostructures arises in large part from confinement effects on the phonon dispersion. While a number of theoretical predictions have been made for the modification of the phonon band structure due to size confinement, so far, only the high energy regime of optical phonons near the Brillouin Zone center have been accurately measured in nanoscale samples. While techniques such as inelastic x-ray or neutron scattering have been successfully used to study large wave vector phonons in macroscopic samples, their signals become impractically weak in small ensembles of nanoscale objects. Advances in high brilliance x-ray sources at synchrotron facilities have revived interest in the technique of Thermal Diffuse Scattering (TDS), which collects information from elastic scattering of x-rays by phonons. TDS is well suited to probing phonons in nanoscale systems since the scattered intensity diminishes more slowly with the sample size.

Here we describe results of x-ray TDS measurements performed on suspended silicon nanomembranes, probing large wave vector phonon modes residing at zone boundaries. Unsupported membranes with thicknesses down to a few tens of nanometers were fabricated by selective etching of silicon-on-insulator, releasing suspended windows which were further thinned by reactive ion etching. A focused microbeam of 10 keV x-rays was directed at membranes in a geometry designed to sample a slice of reciprocal space from near the zone center out to the zone edges. Deviations from bulk-like behavior are observed in membranes of thicknesses up to several tens of nanometers, beyond the typical regime where confinement has been predicted to play a significant role in the dispersion of phonons.