Phonon engineering by phononic crystal nanostructures

Masahiro Nomura[1,2], Jeremie Maire[1], Anufriev Roman[1], Aymeric Ramiere[1], and Ryoto Yanagisawa[1]
[1]Institute of Industrial Science, the University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo, 153-8505, Japan
[2]PRESTO, Japan Science and Technology Agency, 4-1-8, Honcho, Kawaguchi-shi, Saitama 332-0012 Japan
E-mail: nomura@iis.u-tokyo.ac.jp

ABSTRACT

“Can we tune thermal flow like light waves by using wave nature of phonons?” has been a fundamental question in science since the introduction of the concept of phonon in 1932. We demonstrate thermal conductivity tuning based on wave nature of thermal phonons using silicon phononic crystal (PnC) nanostructures at cryogenic temperatures. We also demonstrate thermal conduction engineering using Si nanostructures based on the understanding of nanoscale thermal phonon transport.

We investigate thermal phonon transport in Si thin membrane PnC nanostructures. The physics of the thermal phonon transport can be classified into the wave and particle regimes. When the phonon transport can be described as a wave, the band engineering is applicable like light wave propagation in a photonic crystal. We demonstrated thermal conductance tuning by controlling the short-range order in PnCs. The disorder is given as a displacement of holes from the original position of the PnC, but the radius is the same. The difference in thermal diffusive time is purely due to the group velocity change caused by thermal phonon interference by the periodicity of the PnC nanostructures. At 3.7 K, thermal decay time shows clear dependence on the short-range order, while no dependence is observed at room temperature. The phonon coherence appears at low temperatures, where the phonon mean free paths (MFPs) are sufficiently longer than the period.

We also investigate efficient thermal conductivity control using multiscale phonon scattering structures. Thermal conductivity for poly-Si PnCs show larger reduction compared to that for single crystalline Si PnC. In poly-Si, transport of phonons with long MFPs is impeded by PnC with a period of 300 nm and that of phonons with short MPFs is impeded by scattering at crystal grain (~ 25 nm) boundaries. This result indicates that thermal phonon MPF spectrum provides important information for efficient thermal conduction engineering and this concept is useful for the development of thermoelectric materials.

Key words: phonon engineering, phononics, phonic crystal, phonon, heat transport