Thermal Conductance of Hole- and Pillar-Based Phononic Crystals at Low Temperatures

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Phononic crystals (PnC) belong to a class of acoustic metamaterials that can control heat conduction at low temperatures based on the design of the structure. PnCs proposed for most applications are typically two-dimensional and typically consist of periodic arrays of either holes in a silicon membrane (hole-based PnCs) or pillars on top of the membrane (pillar-based PnCs), as shown in Fig. 1. In such periodic structures, phonon interference flattens phonon dispersion, which causes reduction in the phonon group velocity, modifications in the density of states (DOS), and overall change in thermal conductance [1].

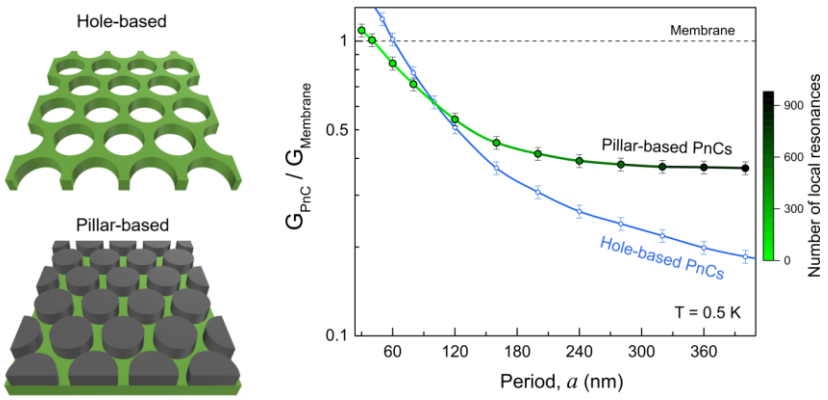

Fig. 1. Schematic of the hole- and pillar-based two-dimensional phononic crystals and relative thermal conductance as function of period.

In this work, we simulate heat conduction in PnCs of both types within the purely coherent regime and systematically investigate how various geometrical parameters, lattices and pillar materials affect the thermal conductance. Figure 1 shows that PnCs of both types can not only suppress heat conduction when the period is sufficiently long, but even on the contrary, enhance thermal conductance when the period is short (< 60 nm). This counterintuitive effect of higher thermal conductance in porous membrane than in unpatterned membrane is known as thermal conductance boost effect [2].

In pillar-based PnCs, where local resonances play an important role, we show that the resonances increase the DOS and thus surprisingly contribute to enhancement rather than suppression of heat conduction [3]. The lowest thermal conduction is achieved when pillars are short and thus the number of local resonances in the pillars is small; as pillar height is increased, the presence of local resonance start increasing the thermal conductance[3]. Thus, we conclude that the overall suppression of thermal conductance in pillar-based PnCs appears despite (not due to) the local resonances and is caused by periodicity of the structure. The strongest suppression of thermal conductance is achieved when both pillar- and hole-based PnCs have the longest period have the highest possible radius-to-period ratio [1,3]. In general, we show that pillar-based PnCs can match the efficiency of the conventional hole-based PnCs and have richer physics, which opens new possibilities for heat conduction engineering.

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References:

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