Thermal properties of silicon ultra-thin membranes: A theoretical and experimental approach

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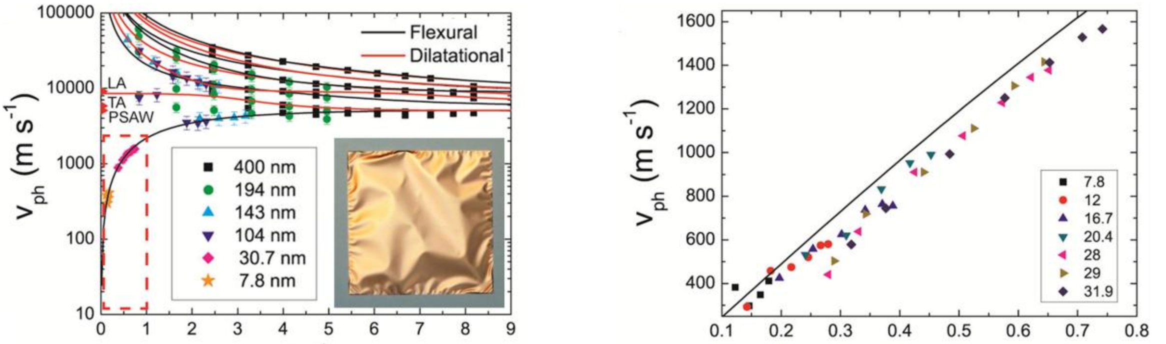
A deep understanding of heat transport in low-dimensional semiconductor structures is a topic of increasing research activities driven by the need for a more energy conscious society. This is motivated in part from the increasing importance of thermal management as a consequence of the large power densities resulting from the continuous miniaturization of electronics components. Moreover, the quest for enhanced thermoelectric properties generally requires large values of the figure of merit ZT [1]. Recent experimental and theoretical reports point to an enhancement of the figure of merit in thin films [2], nanowires [3] and superlattices [4] [5], primarily as a result of the decrease of the thermal conductivity compared to the bulk counterpart, without a corresponding decrease in electrical conductivity. The reduced dimensions lead to the confinement of acoustics modes and the discretization of their spectrum, resulting in the modification of phonon density of states and dramatic decrease of group/phase velocity [6] and phonon lifetime [7].

In the present work we study theoretically and experimentally the thickness-dependence of the thermal properties of Silicon membranes with thicknesses ranging from 9 to 1500 nm. We investigate the dispersion relations and the corresponding modification of the phase velocities of the acoustic modes, which are mostly responsible for the heat transport, using inelastic Brillouin light scattering spectroscopy. A reduction of the phase/group velocities of the fundamental flexural mode by more than one order of magnitude compared to bulk values was been observed and is theoretically explained [6]. In addition, the lifetime of the coherent acoustic phonon modes with frequencies up to 500 GHz was also studied using state-of-the-art ultrafast pump-probe, i.e. asynchronous optical sampling (ASOPS). We have observed that the lifetime of the first-order dilatational mode decreases significantly from ~ 4.7 ns to 5 ps with decreasing membrane thickness from ~ 194 to 8 nm [7]. Finally, the thermal conductivity of the membranes was investigated using a novel contactless technique known as Raman thermometry. We have found that the thermal conductivity of the membranes gradually reduces with their thickness, reaching values as low as 9 W/mK for the thinnest membrane.



(a) (b)

Fig. 1 (a) Dispersion curves plotted in terms of the phase velocity as a function of dimensionless wavevector (q//·d) for membranes with thickness values ranging from 400 to 7.8 nm. Inset: Optical microscope image of the 30 nm Si membrane. **(b)** Magnified image of the highlighted region in showing data for membranes of thickness from 7.8 to 31.9 nm. The linear relationship observed is a direct result of the quadratic dispersion relation. A phase velocity down to approximately 300 ± 40 m/s is recorded for the 7.8 nm membrane [6].

In order to account for the observed thermal behaviour of the ultra-thin membranes we have developed different theoretical approaches to explain the size dependence of the dispersion relations based on an elastic continuum approach, Debye model and fitting models. The size dependence of the lifetimes was modelled considering intrinsic phonon-phonon processes and extrinsic phonon scatterings. The thermal conductivity was modelled using a modified 2D Debye approach and Srivastava-Callaway-Debye model.

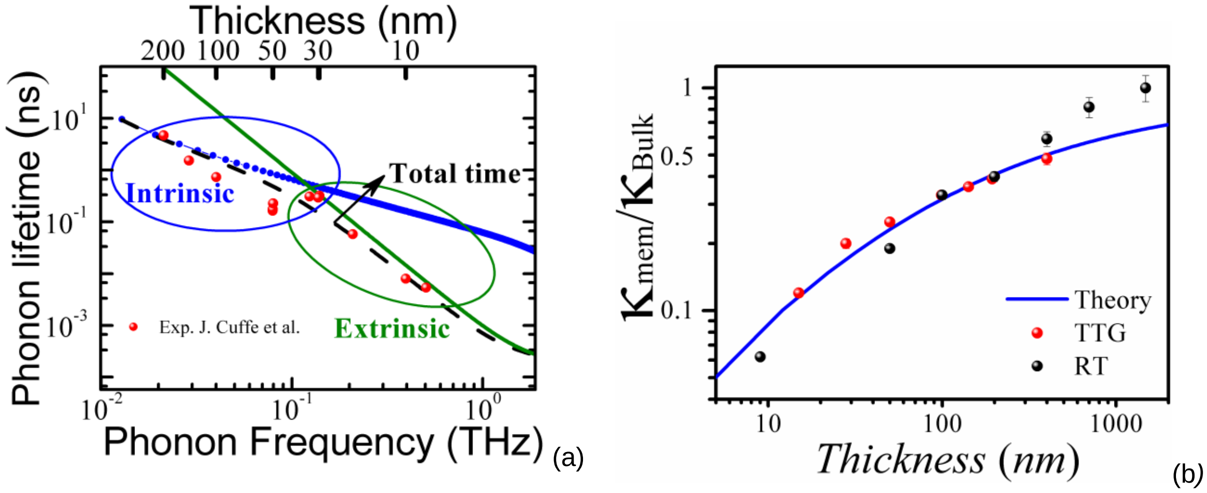


Fig. 2 **(a)** Experimental and theoretical phonon lifetime in free-standing silicon membrane. Red dots: experimental data [7]. Green line: extrinsic boundary scattering processes. Blue-dotted line intrinsic three-phonon normal scattering processes. Black-dashed line: total contribution, calculated through Matthiessen's rule. **(b)** Experimental and theoretical thermal conductivity. Red dots: Experimental thermal conductivity measured by transient thermal gradient technique [8]. Black dots: Experimental thermal conductivity measured by Raman thermometry. Blue line Theoretical prediction.

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