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Dispersion of Confined Acoustic Phonons in Ultra-Thin Si Membranes

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The dispersion curves of confined acoustic phonons in ~10 and ~30 nm Si membranes were measured using Brillouin Light Scattering (BLS) spectroscopy. The dispersion relations of the confined phonons were calculated from a semi-analytical model based on continuum elasticity theory. Green's function simulations were used to simulate the Brillouin spectra.

The acoustic properties of ultra-thin Si layers are important for many areas of nanofabrication, impacting on both structural integrity and thermal transport. The effect of phonon confinement is particularly important, affecting both heat dissipation and charge carrier mobility^{1,2}. The goal of this work is to obtain a deeper understanding of phonon confinement and propagation in materials with dimensions comparable to thermal phonon wavelengths. Previous studies have investigated out-of-plane confined acoustic phonons in 30 nm Si membranes by inelastic light scattering at normal incidence, with use of a triple grating Raman spectrometer^{3,4}. In this work the in-plane propagation of these modes is investigated as a function of the parallel component of the wavevector, using a high-resolution Tandem Fabry-Perot Interferometer. The effect of the ~1 nm native oxide layer in such thin systems was also calculated using a three-layer model.

Methods

Brillouin Light Scattering (BLS) spectroscopy is an inelastic light scattering technique, which can directly measure acoustic phonon dispersion in a non-destructive manner. Using an angle-resolved approach, out-of-plane confined phonons as well as flexural, dilatational, and shear modes propagating in the plane of the membrane were investigated. The dispersion curves were calculated from numerical solutions to the analytic equations for the acoustic modes in a membrane, based on a continuum elasticity model⁵. Green's function simulations were also used to calculate the density of states of the phonon modes and to simulate the Brillouin spectra⁶. The membranes of area 500 x 500 μm^2 were fabricated on nominally undoped 150 nm thin SOI wafers using Si MEMS processing techniques. The thin SOI wafers were produced by bonding the standard SOI wafers from SOITEC company⁷ with a Si oxidized wafers.

Results

The BLS spectra of the membranes corresponded to calculated thicknesses of 12 and 28 nm. Calculations for the 12 nm membrane showed that mode frequencies exhibit a detectable shift of 8% with changes in the thickness of the membrane of 1 nm, which is of the order of the uncertainty in the thickness measurement. The ultra-thin nature of the membranes resulted in a slow phase and group velocity for the first order flexural (A0) modes, with a phase velocity down to 320 m s^{-1} recorded for the 12 nm membrane. This is 15 times smaller than the comparable bulk value (Rayleigh Wave)

$v_{\text{RSAW}} = 4921 \text{ m s}^{-1}$. This resulted in a large phonon density of states, as evidenced by an enhanced acousto-optic interaction and therefore a strong scattered signal. It was observed that the experimental

data agree with the dispersion curves calculated from continuum elasticity theory to within experimental error, apart from the dilatational mode of the 12 nm membrane (Figure 1a), which is under further investigation.

Calculations for a three layer system were also performed to take account of the native oxide layer, which was found to cause a detectable change in the dispersion of the higher order ($n > 0$) acoustic modes. (Figure 1b)

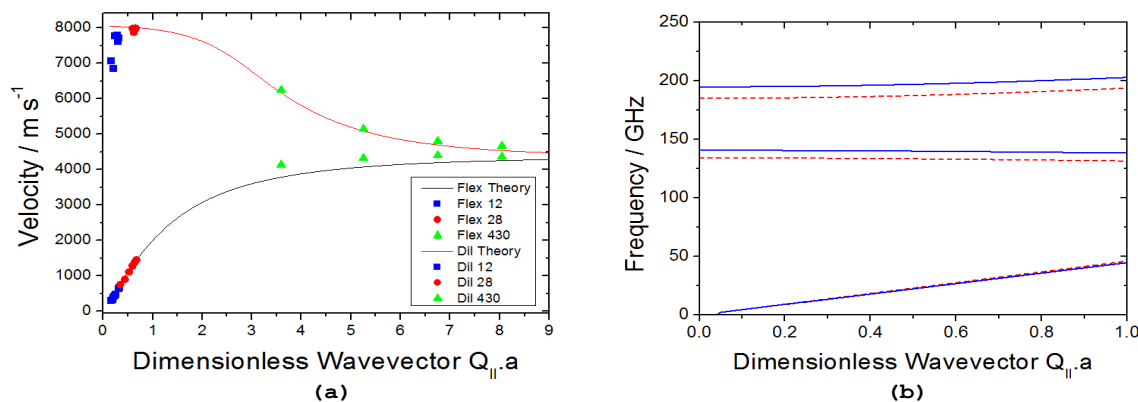


Fig. 1: (a) Phase velocity vs. dimensionless parallel wavevector for 12 nm (blue squares), 28 nm (red circles) and 430 nm (green triangles) membranes, with theoretical calculations for the first order flexural (black line) and dilatational (red line) modes of a Si membrane. (b) : Dispersion curves of the dilatational modes of a 30 nm Si membrane, (blue solid line) and 28.4 nm Si with 1.6 nm SiO₂ on the top and bottom surfaces (red dashed line).

Conclusions

The acoustic dispersion relations of confined phonons in ultra-thin Si membranes, with thicknesses of 12 and 28 nm, were measured. The experimental results were compared with semi-analytic and Green's function calculations with satisfactory agreement, confirming a small phase and group velocity for the first order flexural mode. Calculations show that the spectra are sensitive to changes in thickness of the membrane on the order of 1 nm. The higher order acoustic modes were also shown to be sensitive to the presence of the thin native oxide layer. This work provides a basis to investigate the effect of acoustic phonon confinement on thermal transport in systems with sub- 50 nm dimensions.

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