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Lifetime of high-order thickness resonances of thin silicon membranes

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ABSTRACT

Femtosecond laser pulses are used to excite and probe high-order longitudinal thickness resonances at a frequency of ~270 GHz in suspended Si membranes with thickness ranging from 0.4 to 15 μm. The measured acoustic lifetime scales linearly with the membrane thickness and is shown to be controlled by the surface specularity which correlates with roughness characterized by atomic force microscopy. Observed *Q*-factor values up to 2400 at room temperature result from the existence of a local maximum of the material *Q* in the sub-THz range. However, surface specularity would need to be improved over measured values of ~0.5 in order to achieve high *Q* values in nanoscale devices. The results support the validity of the diffuse boundary scattering model in analyzing thermal transport in thin Si membranes.

1. Introduction

A thickness resonance of a suspended plate is perhaps the simplest kind of solid state acoustic oscillator. Thickness resonances have long been used in quartz oscillators, and state-of-the art thin film resonators using thickness resonances of suspended thin films and operating at frequencies up to a few GHz are widely used in telecommunications electronics [1]. In recent years, ultra-short laser pulses have been used to excite thickness resonances of ultra-thin membranes in the sub-THz frequency range [2–5]. These studies are interesting in two respects. In one aspect, it would be interesting to explore the limits for extending the frequency range of acoustic oscillators. At ultrasonic frequencies, acoustic attenuation increases as frequency squared [6], hence the material *Q*-factor, i.e., the *Q*-factor due to material losses only, is inversely proportional to frequency. Considering that typical *Q*-factors at ~1 GHz at room temperature (RT) are on the order of 1000 [7], extrapolating this trend would mean bleak prospects for sub-THz acoustic oscillators at RT. Fortunately, the trend does not continue into sub-THz frequencies due to the transition from the Akhiezer relaxation regime of phonon dissipation at ultrasonic frequencies to three-phonon scattering regime at THz frequencies [6,8]. This transition is expected to yield a local maximum of material *Q* in the sub-THz range [8]. Another interesting aspect is the connection to thermal transport studies. In Si at RT, most heat (~75%) is carried by phonons above 1 THz in frequency [9]. However, sub-THz phonons are not entirely negligible: for example, the onset of the size effect in thermal conductivity of thin membranes is controlled by sub-THz phonon lifetime [10]. Also, we can use acoustic measurements in the sub-THz range to test models used to analyze thermal transport in nanostructures, for example, models describing specular vs. diffuse scattering at the boundaries [11].

Two most important characteristics of an acoustic oscillator are its frequency and damping time. The frequency of membrane thickness resonances in the sub-THz range is still well described by the elastic continuum model and given by $nc/(2h)$, where c is the speed of sound (longitudinal or transverse), h is the membrane thickness and n is a positive integer. In this study, our attention is focused on the damping time, or phonon lifetime, defined as a time in which the acoustic energy decays to the $1/e$ level. In a recent study [4], the lifetime of the fundamental (i.e., lowest frequency) longitudinal thickness resonance was measured in single crystal Si membranes in the thickness range 8–200 nm at RT. Scattering by surface roughness was identified as the main contributor to the observed decay rate of the acoustic oscillations, although this conclusion was made based on a comparison with model calculations of bulk phonon lifetimes rather than directly from the data. One complication in the analysis of the results of Ref. [4] arises from the fact that the frequency of the fundamental resonance depends on the membrane thickness, with the lifetime being affected by both thickness and frequency. It would be interesting to conduct a study including higher-order thickness resonances to look at the frequency dependence of the lifetime for a given membrane thickness, or, alternatively, at the thickness dependence of the lifetime at a given frequency. The former approach was pursued

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Table 1
List of samples and a summary of the measurements. A_2/A_1 is the amplitude ratio of the 2nd and 1st acoustic transients; Q is the quality factor of the observed thickness resonances.

#	Thickness (μm)	Fabrication	Source	RMS roughness (nm)	A_2/A_1	Q
1	0.37	SOI	In-house		0.55	120
2	0.69	SOI	In-house		0.40	150
3	1.16	SOI	Commercial	0.3	0.41	270
4	1.49	SOI	Commercial	0.2	0.43	350
5	1.53	SOI	In-house	2	0.2	190
6	1.69	Polished	Commercial	0.6	0.46	440
7	15.3	Polished	Commercial	0.4	0.27	2400

in Ref. [5] where the lifetime of thickness resonances of Al/Si membranes in the frequency range 30–300 GHz was measured. The observed lifetimes were found to be strongly affected by the presence of the Al film.

In this work, we investigate the lifetime of high-order thickness resonances in a narrow frequency range around ~270 GHz on suspended single-crystal silicon membranes without a metal coating. The dominant role of scattering by surface roughness is established directly from the dependence of the measured lifetime on the membrane thickness. We quantify roughness using atomic force microscopy (AFM) and discuss the dependence of the lifetime on roughness for membranes of similar thickness. We also provide a lower bound for the intrinsic longitudinal phonon lifetime at 270 GHz in silicon at RT.

2. Samples

Samples used in this study are listed in Table 1. All samples were single-crystal suspended Si membranes with the (100) surface orientation. The majority of the membranes were fabricated by etching silicon-on-insulator (SOI) wafers [12], while the two thicker samples were produced by polishing. The size of the free-standing area ranged from 0.5 to 5 mm. Representative photographs of a few samples are shown in Fig. 1. The membrane thickness was measured from the acoustic round-trip time as described in Section 3 below.

Surface roughness of all samples, with the exception of the two thinnest membranes, was measured by AFM, with the measurement results presented in Table 1. Fig. 1 shows representative AFM images. With the exception of sample #5, the root-mean-square (RMS) roughness was well under 1 nm and the lateral scale of topography features was under ~50 nm. Sample #5, in contrast, had a large roughness with large lateral size features. Unfortunately, only one side of membranes was accessible to AFM measurements, as the supporting structure made the back side inaccessible to AFM due to geometric constraints. For polished samples, the same polishing procedure was applied to both sides, therefore the measurement are likely (albeit not guaranteed) to represent roughness on both sides of the sample. For membranes fabricated from SOI wafers, the etching process used on the front and back sides is not the same [12], therefore the back side roughness could be different.

3. Experiment

The measurement configuration is shown schematically in Fig. 2(a). The frequency-doubled output of an amplified Ti:Sapphire system (wavelength $\lambda = 387$ nm, pulse duration 300 fs, repetition rate 250 kHz) was split into excitation and variably delayed probe pulses. The excitation beam (pulse energy 30–80 nJ) was modulated by an acousto-optic modulator at 93 kHz frequency to facilitate lock-in detection and focused to a spot of 50 μm diameter (at $1/e$ intensity level) on one side of the sample, whereas the probe beam (pulse energy ~2 nJ) was focused to a 25 μm diameter spot on the opposite side of the membrane.

The excitation pulse generates a bi-polar strain pulse [13] with the pulse width corresponding to the penetration depth of excitation light $L = 50$ nm [14]. The strain pulse propagates towards the opposite surface of the sample, where it is reflected. When the strain pulse travels within the penetration depth of the probe light, the refractive index variation caused by the transient strain can be

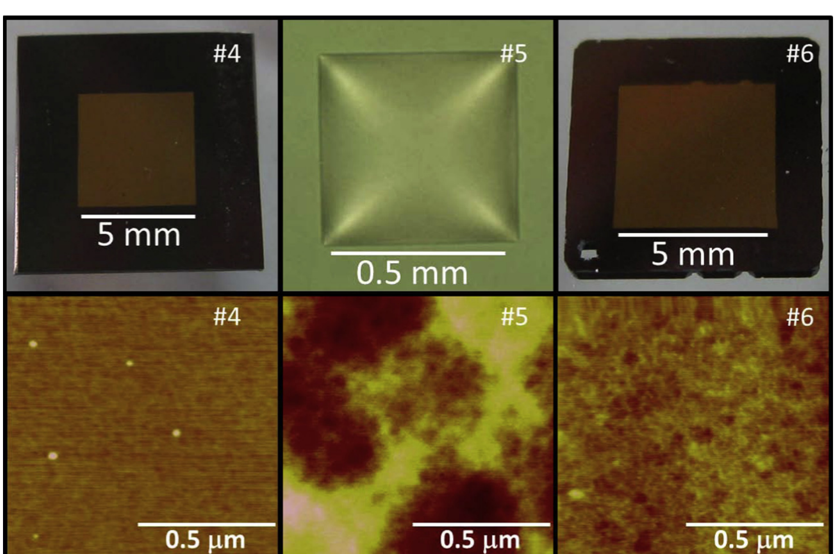

Fig. 1. Photographs and AFM images of samples #4, #5, and #6. The RMS roughness is 0.2 nm for sample #4, 2 nm for sample #5, and 0.6 nm for sample #6.

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