Acoustic phonon dynamics in free standing group IV semiconductor membranes studied by ultra-fast pump & probe spectroscopy

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Abstract

The ability to control heat and phonon propagation at the nanoscale constitutes a key element for the realization of successful phonon engineering. The mean free path of thermal phonons Λ, which is the physical quantity determining the relaxation time τ of the thermal field, is still not accurately known for a wide range of technologically relevant materials such as e.g. silicon and germanium. Although some experimental and theoretical works suggest values for Λ in Si between 43 nm and 1 µm at 300 K, there is no conclusive evidence of its actual magnitude and temperature dependence. Furthermore, the life-time of the thermal field τ has been only poorly determined and even in the the technologically most relevant case of Si, measurements of phonon lifetimes are scarce [1-3].

In this work, we address these issues by the investigation of the dynamics of low and high energy acoustic phonons using a two femtosecond laser pump and probe technique. The experiment is based on the asynchronous optical sampling method (ASOPS) [4] which compared to standard pump and probe techniques provides a superior signal to noise ratio with a time resolution of about 50 fs (Figure 1). The pump beam locally creates a distribution of non-equilibrium phonons, whereas the probe beam is used to monitor the local temperature through the intensity of the transmitted light. This approach uses the large temperature dependence of the absorption coefficient exhibited by most semiconductors to investigate the decay dynamics of the thermal field.

In addition, we report on the lifetime of acoustic phonon modes in Si and Ge free standing membranes as function of heating power and thickness in reflection and transmission geometry (Figure 2). In particular, free standing silicon membranes are model systems for these studies, as they can be fabricated with precisely controlled dimensions and physical parameters, facilitating the comparison with theoretical models. The analysis is free from any effects of a substrate. A reduction of the lifetime of the first order dilation mode in silicon and germanium membranes of up to one order of magnitude is observed with increasing the pump power due to local increase of the phonon population and increased phonon-phonon scattering (Figure 3).

References

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Figures

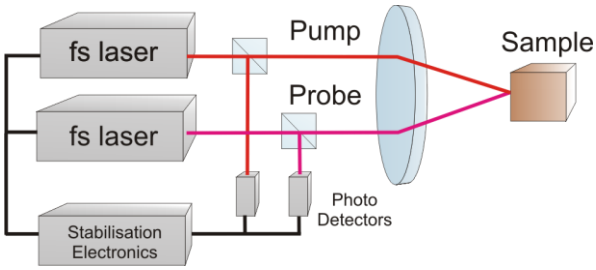

Figure 1: Schematic illustration of an ASOPS experimental setup which employs two actively frequency coupled Ti-Sa lasers with a repetition rate of 1 GHz and a tunable frequency offset of 2-10 kHz to vary the temporal offset between the pump and the probe pulses [5].

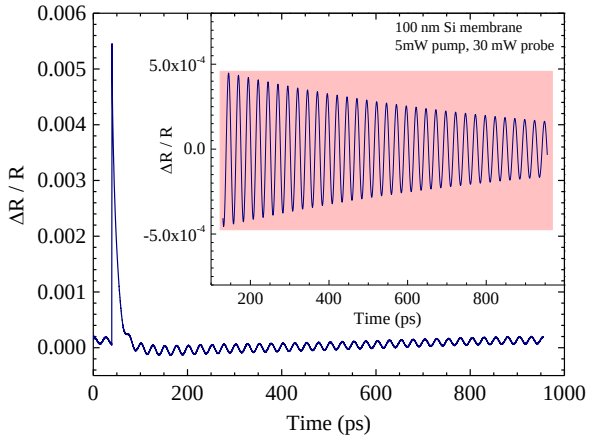

Figure 2: Typical time trace of the change in reflectivity in a 100 nm thick Si membrane within the first nanosecond after excitation with a 50 fs pump pulse. The initial peak is caused by the electronic response of the semiconductor; the damped oscillations shown in the inset after background correction represent the phonon frequency and decay time of the first order dilatational mode of the Si membrane.

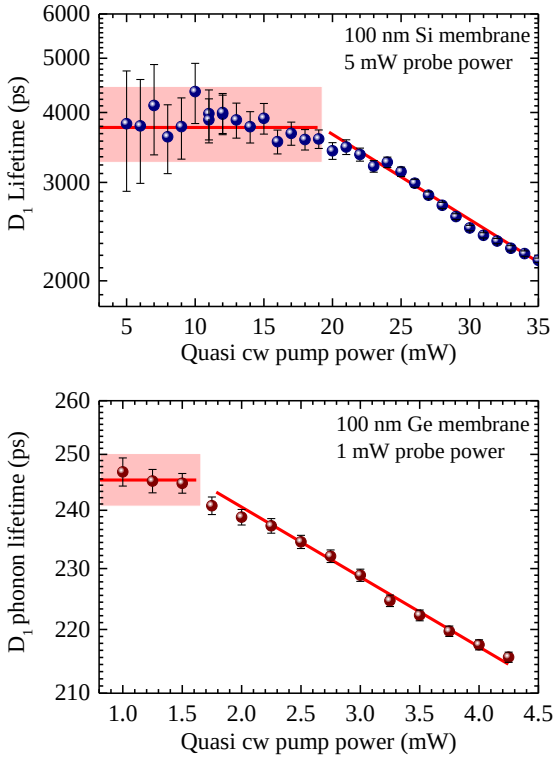

Figure 3: Reduction of the acoustic phonon lifetime (D_1 mode) as function of pump power (local heating). The excitation power dependent decrease of the acoustic phonon lifetimes are shown for a 100 nm thick Si membrane (upper graph) and a 100 nm thick Ge membrane (lower graph). For low pump powers a constant plateau of the lifetime values is observed in which the effects of local heating are negligible.