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Generation and detection of gigahertz acoustic oscillations in thin membranes

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ABSTRACT

Single crystalline membranes are a perfect model system for the study of coherent acoustic phonon generation and decay in the time domain. Coherent acoustical modes are excited and detected in thin single-crystalline silicon and gallium arsenide membranes with femtosecond pulses in the ultraviolet and infrared wavelength region using the asynchronous optical sampling technique. The measured acoustic spectra are compared with each other and are discussed in terms of different generation and detection mechanisms. A clear dependence of the generated spectra on the absorption length of the pump and probe pulses is observed. It is shown that a short absorption length for the pump pulse leads to the generation of coherent high frequency phonons up to several 100 GHz frequencies. Membranes are demonstrated to be useful as broadband acoustic cavities and can help to disentangle details of high frequency phonon dynamics. Two-layer membrane systems offer additional insight into energy transfer in the GHz frequency range and adhesion properties.

1. Introduction

High-frequency acoustic phonons in semiconductors in the GHz to THz range are of great importance to both fundamental and applied science. The generation and detection of high frequency phonons has been of interest ever since it was discovered that high frequency phonons could be conveniently generated and detected using ultrashort light pulses [1]. In the last 30 years researchers have been using a variety of different systems to generate high frequency phonons from thin metal layers to specially designed multilayer systems, e.g. superlattices, to study phonon properties [1–5] and to generate new coherent sources [6–9]. In recent years also membranes have proven to be an excellent model system to investigate high frequency phonon in the GHz to THz frequency range [10–12]. The main focus of this article is to summarize our recent results and elucidate acoustic phonon dynamics in single-crystalline membranes generated by ultrashort light pulses.

One of the fundamental questions are the properties of GHz to THz acoustic phonons like intrinsic scattering mechanisms, extrinsic scattering, decay and electron–phonon interaction in semiconductors. Despite intense research these properties are still incompletely understood in this frequency range even for technologically important materials like silicon (Si). These properties are important though for heat propagation which is closely related to acoustic phonon propagation. As semiconductor devices have become smaller and have reached the nanoscale, question regarding the importance of phonons in the heat transfer at the nanoscale have become increasingly important [13,14].

Membranes have also played an important role in other fields such as nanomechanics and cavity optomechanics. One of the long standing goals of these fields has been to cool down a nanomechanical oscillator to its ground state, where the mean phonon number approaches the quantum limit. Such a system would make it possible to test quantum mechanical phenomena in an actual mechanical systems. Membranes have been recently used in the realization of ground state cooling [15–17] and are a very important tool in nanoscience in general. Membranes or layer systems are relatively easy to fabricate and are thereby the method of choice to construct nanosystems with reduced dimensionality.

Our membranes are quantized in one direction because usually only the thickness of the membrane is on the nanoscale while the surface can be in size on the order of square millimeters. Further quantization can then easily be achieved by lateral structuring of the membrane. The acoustic modes discussed in this article are vertically confined to the membrane and do not propagate along

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the membrane surface. These modes are confined between the two free surfaces of the membrane much like photons in an optical resonator. There are a number of other interesting modes in membranes which will not be included in this article but should be mentioned like surface acoustic waves [18] and Lamb waves [19,20].

The reader should be aware though that often in the literature membrane modes refer to so called drum head modes which are modes of the membrane involving displacement of the entire membrane. These modes are strongly dependent on the size as well as shape of the membrane. The modes that are discussed in this article are typically denoted as localized thickness oscillations [21] or also called dilatational modes [22]. The lateral extent of the membrane is not important for these modes, their frequencies are only determined by the thickness of the membrane and they are similar to the modes in thin film bulk acoustic wave resonators (FBAR) [23].

The fact that the frequency is only dependent on the thickness has recently been exploited by Cuffe et al. to investigate Si membranes, that are able to support acoustic modes with very high frequencies [22]. A fundamental dilatational mode at 500 GHz in a 8 nm thin membrane was measured in these experiments. Very high frequencies are desirable to achieve ground state cooling as has been shown in combination with a superconducting circuit [17]. The structure used in this case was not a Si membrane but a FBAR. Transduction in FBARs is achieved by using piezoelectric elements while in the measurements shown here transduction is realized through the absorption of an optical pump pulse. However, the modes as mentioned earlier are similar. Dilatational modes have also been used in “membrane in the middle” approaches for ground state cooling and quantum experiments in optomechanical systems [24,25].

In this article we want to disentangle the mechanisms for acoustic mode generation and detection by optical pump–probe experiments in membranes. We will mainly explore bare membranes made of single-crystalline Si and gallium arsenide (GaAs). Additionally we will present a two-layer membrane consisting of a thin aluminum (Al) layer on top of a Si membrane. In order to gain insight into the details of photoacoustic processes, the membranes are pumped and probed with red light at around 800 nm as well as with frequency doubled light at around 400 nm.

2. Longitudinal acoustic mode spectrum of a membrane

Fig. 1 shows the displacement and the associated strain for odd and even dilatational membrane modes. An even displacement of the left and right surface of the membrane in respect to the center plane of the membrane results in an odd strain distribution while an odd displacement will result in an even strain profile.

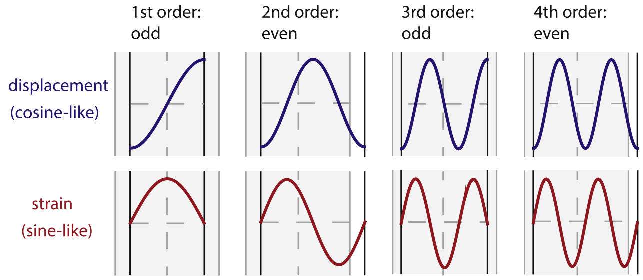

Fig. 1. The strain and displacement profile of the first four dilatational modes in a membrane are shown. The shaded area indicates the non-displaced shape of the membrane. Of special interest is the symmetry of these modes with respect to the center plane of the membrane that is parallel to the left and right surface. An even strain mode results in an odd displacement and vice versa.

The membranes discussed in this article are excited using laser light. Depending on the membrane material different processes will lead to the generation of photo-induced stress in the membrane. To excite a particular mode the generated stress needs to have a non-zero spatial overlap integral with the strain distribution of that mode.

In order to excite odd and even modes it is therefore necessary to have a non-uniform excitation in order to set up an asymmetric stress in the membrane. The frequencies of the dilatational modes in the membrane follow the simple relationship $n\frac{v_{\mathrm{Si}}}{2d}$ with $n = 1, 2, 3, \ldots, v_{Si}$ being the longitudinal speed of the phonon, and d being the thickness of the membrane [21].

The excited modes are strongly dependent on the absorption length of the light used for excitation and detection. We will demonstrate that by changing the absorption profile it is possible to go from a regime where the mode spectrum consists of only odd modes (e.g. by using 800 nm wavelength for excitation of a Si membrane) to the generation of mode spectra that resemble frequency combs analog to optical frequency combs with the membrane serving as an acoustic cavity (e.g. 800 nm wavelength for exciting an Al transducer deposited on a Si membrane).

In order to illustrate this, examples for the cases of a uniform and non-uniform excitation are shown in Fig. 2. In both cases we assume that the membrane is photo-excited from *one* side only. In the first case we assume that the pump and the probe both penetrate the membrane and have a long absorption length. A spatially homogenous photo-excitation of the membrane will then lead to a rectangular stress distribution that will produce a sawtooth like pattern when looking at the reflected signal from the membrane.

A short absorption length of the pump on the other hand will generate an acoustic pulse. That pulse can be measured using a probe beam with an equally short absorption length which will then result in a frequency comb in the Fourier domain. Details regarding the simulation of the stress distribution and associated transient reflectivity changes in the membranes are described elsewhere [12].

This rather generic example should show that the modes being excited in both cases are the same basic membrane modes which are determined by the thickness of the membrane and that the drastic changes in the time domain can be a result of the different amplitude distributions in the frequency domain as can be seen in Fig. 2.

In a real system there are effects that will cause not only the amplitudes to vary but also the phases. For example in the case of thermoelastic generated stresses, thermal conduction will change the phases or in the case of deformation-potential-related-stress, diffusion of the electron–hole plasma will play a

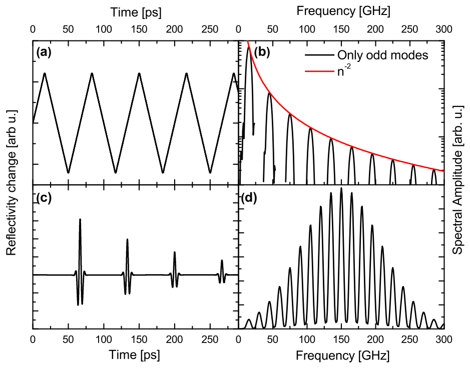

Fig. 2. Time transient reflectivity changes and their Fourier transforms. (a and b) A saw tooth like pattern in the time domain results in a comb of odd modes in the frequency domain with a n^{-2} reduction in amplitude (n: mode number). (c and d) Pulses in the time domain result in a frequency comb in the spectral domain with odd and even modes. The center frequency and the width of the comb are determined by the pulse shape.