Gigahertz Surface Acoustic Waves on Periodically Patterned Layered Nanostructures

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Primary CNF Tools Used: E-beam lithography, CVD, thermal evaporation

Abstract:

We used the ultrafast pump-probe technique known as picosecond ultrasonics to generate and detect surface acoustic waves on nanoscale aluminum (Al) lines on SiO_2 on silicon (Si). In all cases we identified a Rayleigh-like surface acoustic wave with wavelength equal to the pitch of the lines and frequency in the range of 5 GHz - 24 GHz. In some samples, we detected additional, higher frequency surface acoustic waves or independent modes of the Al lines with frequencies close to 50 GHz.

Summary of Research:

In recent work we measured surface acoustic waves (SAWs) in a complicated structure consisting of titanium nitride (TiN) wires of nanometer scale cross-section grown on a multilayered stack of porous and non-porous oxides on an Si wafer [1]. These unique samples yielded pitch-dependent frequencies that in some cases compared favorably with Rayleigh-like or Sezawa-like surface waves [2,3], but in other cases corresponded to modes that radiated significant acoustic energy into the substrate. In this work we studied a simpler set of samples consisting of aluminum (Al) lines on thin silicon dioxide (SiO_2) on Si and we detect multiple SAWs that can be identified by comparison with coarse-grained molecular dynamics simulations. The number of modes detected was found to depend on the pitch of the patterned Al as well as on the wavelength and polarization of the probe light. We detected Rayleigh-like SAWs and Sezawa-like SAWs with wavelength equal to the pitch of the Al lines as well as SAWs with wavelength equal to one-half or one-third of the pitch.

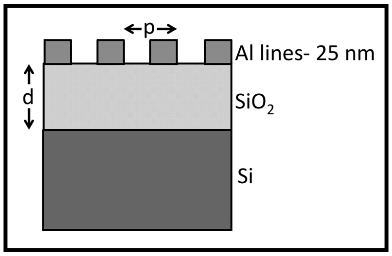

Figure 1: Schematic diagram of the samples. Film thickness d *was either 60 nm or 112 nm as measured by picosecond ultrasonics. Al lines pitch* p *varied from 1000 nm down to 140 nm. The duty cycle was close to 50% (+/- 10%) in all cases as measured by SEM.*

The ultrafast optical pump-probe experiment known as picosecond laser ultrasonics (PLU) has been described extensively in the literature [4]. We performed this experiment with a Ti:Sapphire oscillator operating at a 76 MHz repetition rate with pump wavelength of 800 nm and probe wavelengths of 800 nm or 400 nm. The ten patterned samples that we studied are illustrated schematically in Figure 1.

The samples were fabricated at the Cornell NanoScale Facility by the following process: thermal oxidation to produce the amorphous SiO_2 layer of thickness $d = 60$ or 112 nm, thermal evaporation of 25 nm of Al, and e-beam lithography and dry etching to create the nanometer scale Al pattern. The lines were etched perpendicular to the <110> direction in the Si substrate, they varied in pitch p ranging from 140 nm up to 1000 nm, and they were all etched near 50% (ranging from 40-60%) duty cycle. The patterned samples were placed into the optical setup, where pump and probe beams were both focused onto the same 20 μm diameter spot, so that anywhere from 20 to 140 periods of the pattern were strongly illuminated. The ultrafast pump pulses were absorbed by the Al lines, and the resulting rapid thermal expansion launched ultrasonic waves both downward into the SiO_2 film and Si substrate, and laterally as SAWs in the direction perpendicular to the line pattern. The ultrasonic waves can be detected by the time-delayed probe pulses due to transient changes in the reflectivity ΔR that they cause. The sources of these transient changes include the dependence of the optical constants of the Al on strain as well as the changes in reflectivity of the optical grating produced by the nanostructure as it responds to the acoustic oscillations.

In this work, we focus on the signals caused by laterally propagating ultrasound and not the signals caused by acoustic waves traveling normal to the sample surface.

Figure 2a shows an example of the ΔR signal with 800 nm probe as a function of probe delay time for two of the samples (p/d = 400 nm / 112 nm and 200 nm / 112 nm). The exponentially decaying thermal background and the initial jump at $t = 0$ have been subtracted off so that the dominant oscillations are easier to observe. Figure 2b shows the Fourier transform for these two data sets. For both samples, the data are dominated by oscillations at two frequencies. As is expected, the smaller pitch sample produces higher frequency oscillations. The frequencies of the observed oscillations are strongly dependent on the pitch of the samples, and so it is evident that they must represent SAWs, independent bar modes, or a wave propagating very near to the surface of the sample. Other data sets show as few as one or as many as seven detected surface modes, and in the following sections we identify the nature of many of these modes. After an analysis of the many detected SAW frequencies in this experiment we conclude that we detected Rayleigh-like and Sezawa-like modes with frequencies as high as 50 GHz, as well as a number of independent bar modes.

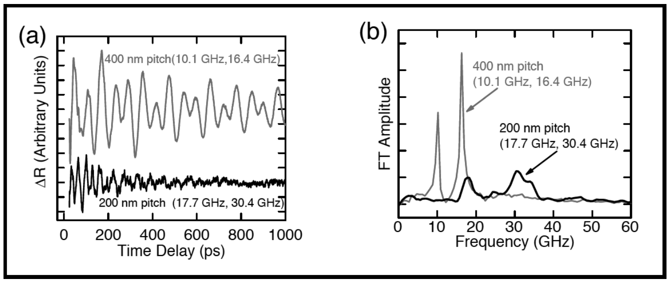

Figure 2: (a) ΔR for two samples with d *=112 nm and* p *= 400 nm and 200 nm. (b) Fourier transform amplitude of the signals in (a).*

We compared our results to analytical calculations of an SiO_2/Si structure and to coarse-grained molecular dynamics simulations of the complete structure in order to accurately label the detected modes.

References:

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