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 silicon dioxide (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 5-24 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. Our new focus is on the effect of the probe beam polarization on which modes are detected.

Summary of Research:

In two recent papers, we have reported measurements of surface acoustic waves (SAWs) in periodically patterned nanostructures [1,2]. In these experiments we used an ultrafast optical pump-probe technique known as picosecond ultrasonics to generate and detect the SAWs. We then compared the experimental measurements to molecular dynamics simulations of the nanostructures in order to identify which modes we detected. In the second of these two papers, we measured samples that were fabricated at CNF and detected Rayleigh-like SAWs and Sezawa-like SAWs with wavelength equal to the pitch of Al lines that were etched on the sample. In some cases we also measured SAWs with wavelength equal to one-half or one-third of the pitch.

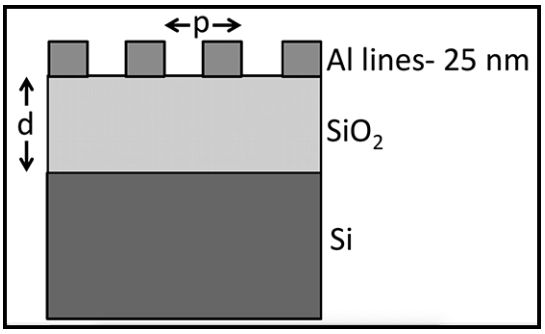

Figure 1: Schematic diagram of the samples. Film thickness d was either 60 nm or 112 nm as measured by picosecond ultrasonics. Al lines with pitch p varied from 1000 nm down to 140 nm. The duty cycle was close to 50% (+/- 10%) in all cases as measured by SEM imaging.

The ultrafast optical pump-probe experiment known as picosecond laser ultrasonics (PLU) has been described extensively in the literature [3]. 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 10 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 μR 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.

The conclusions about the types of surface acoustic waves we detected are described in Ref. 2. The next step in this project is to determine the impact of the polarization of the probe beam on the detection mechanism.

Figure 2 clearly demonstrates that for certain nanostructure periodicities, the polarization can dramatically effect which modes are detected. We are currently exploring this question computationally using a finite difference frequency domain (FDFD) calculation, and experimentally on a new set of samples to be fabricated at CNF this summer. We will pattern the Al lines on a sapphire substrate rather than a silicon substrate. The use of a transparent substrate will simplify the optical interaction of the probe beam with the sample and give us more insight into the mechanism behind the polarization effect.

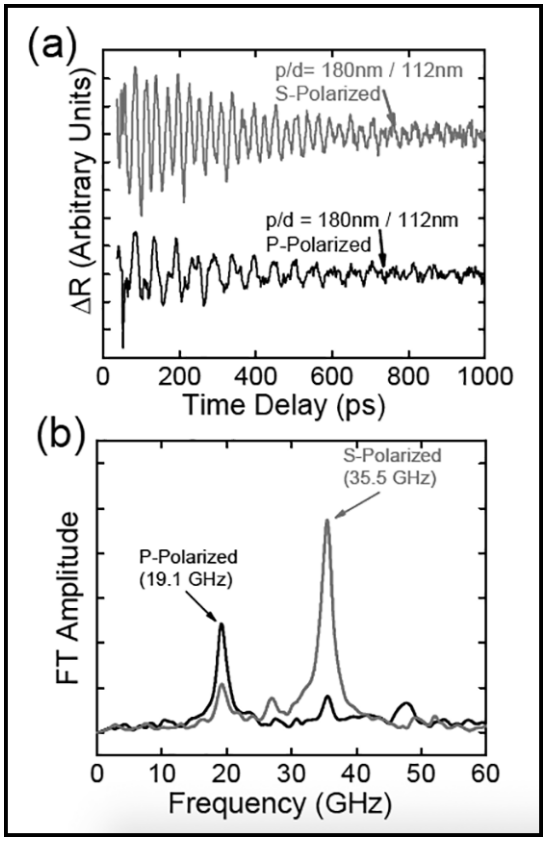

Figure 2: (a) μR for a sample with a pitch of 180 nm using 400 nm probe in the S-Polarized and P-polarized configurations. (b) Fourier transform amplitude of the signals in (a).

References:

[1] M.M. Bjornsson et al., J. Appl. Phys. 117, 095305 (2015).

[2] M. Colletta, et al., Ultrasonics 87, 126 (2018).

[3] C. Thomsen, H. T. Grahn, H. J. Maris, and J. Tauc, Phys. Rev. B 34, 4129 (1986).