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EUV Detection of High-Frequency Surface Acoustic Waves

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Abstract: We use coherent extreme ultraviolet radiation to probe surface acoustic wave propagation in nickel-on-sapphire nanostructures. We observe no acoustic dispersion over SAW wavelengths down to 200nm, meaning the SAW propagation is unaffected by the nanostructure.
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OCIS codes: (240.6690) Surface waves, (320.5390) Picosecond phenomena

Surface acoustic waves (SAW) are a powerful tool for studying thin film, surface, and interface properties because these modes have shallow surface penetration and thus are sensitive to surface structure and properties. In order to study the interfaces underlying a very thin film, SAWs with comparably short wavelengths are required because their penetration depth "η" is proportional to the acoustic wavelength "Λ": $\eta=\Lambda/2\pi$. This presents a challenge to conventional optical methods of creating and detecting SAWs: it is easy to coat a film of sub-micron thickness, but Λ=750nm is the shortest acoustic wavelength generated using the conventional transient grating method [1, 2]. An alternative technique that is limited only by the resolution of lithography is to optically heat a lithographically patterned nanostructure that locally stresses a surface [3]. The concern with this excitation technique is that the SAW propagation is affected by the nanostructure, complicating analysis of the underlying sample characteristics. Preliminary measurements employing thin Al patterned absorbers have suggested that the effect of the nanostructure can be neglected [3-5]; however, these measurements were taken at isolated SAW wavelengths, and did not sample a full dispersion curve to come to a definitive conclusion on this issue.

To enable high-sensitivity probing of SAWs with sub-optical wavelength, we upconvert intense, ultrafast optical laser pulses into the Extreme Ultraviolet (EUV) region of the spectrum through the high harmonic generation (HHG) process. Because HHG is coherent, the generated harmonics retain the coherence of the driving laser, with a low-divergence beam useful for sensitive interferometric studies of surface displacement. Also, the very short ~29nm wavelength used for this experiment, and their short <10 fs time duration provide simultaneous ultrahigh spatial and temporal resolution.

We use a Ti:Sapphire laser-amplifier system to generate 2mJ, 25fs pulses at 800nm and 2kHz repetition rate. The beam is split into pump and probe beams: the probe beam is focused into a gas filled hollow waveguide for HHG while the pump is sent to a computer-controlled time-delay stage before being loosely focused onto the sample with a fluence of $2mJ/cm^2$. A relatively large pump spot (~700μm) is used so that the area probed will see uniform heating. The sample is a sapphire substrate with nanostructured nickel strips 20nm thick, 130μm long, and ranging in width from 50nm-2μm at a fixed 25% duty cycle, i.e. the center-to-center spacing varies from 200nm-8μm

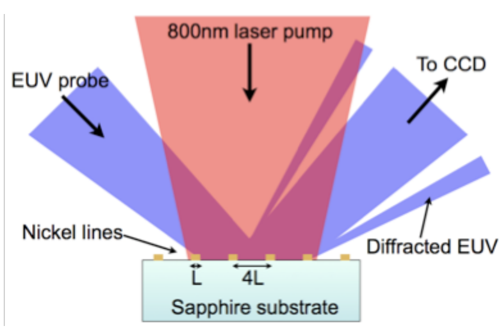

Figure 1: We observe diffraction of EUV light from nickel lines of width "L" and spacing 4L on sapphire. Samples are studied with L from 50nm to 2μm.

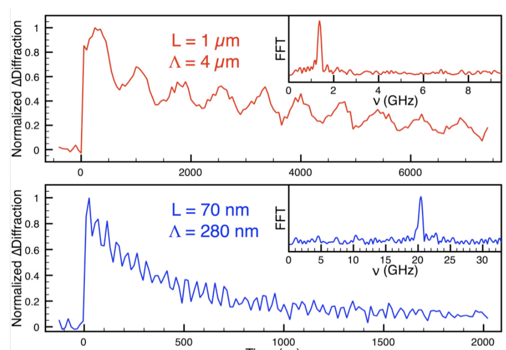

Figure 2: Dynamic changes in diffraction for L=1μm (top, red) and L=70nm (bottom, blue) nickel lines. The signal is composed of a thermal decay and an oscillation due to SAW propagation.

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(Fig. 1). Because the sapphire substrate is transparent to the 800nm pump light, absorption only takes place in the nickel lines. The absorption of these ultrafast pulses rapidly heats the patterned nanostructure, stressing the surface of the substrate in a spatially periodic way, which in turn launches SAWs that travel along the surface of the substrate. These SAWs couple into the nanostructured nickel strips as they travel, slowing them down (since the SAW velocity in nickel is slower than in sapphire) and moving the nanostructure surface. The EUV light diffracting from the nanostructure detects these small displacements as a change in the diffraction efficiency of the structure. By measuring the change in diffraction as a function of pump-probe delay time, we see the dynamic propagation of the SAW in the nanostructure. Two such pump-probe delay scans for 1μm and 70nm-wide nickel lines, along with the Fourier transforms of the narrow-band oscillations from SAW propagation, are shown in Figure 2. The decay in the signal is due to heat dissipation from the nanostructure into the substrate.

We repeated this measurement on similar structures with intermediate linewidths to determine the dispersion of the SAW in the Ni/sapphire nanostructure, shown in Figure 3. At long acoustic wavelengths, the nanostructure can be ignored and the SAW velocity is the Rayleigh velocity in the sapphire substrate. We anticipated a drop in acoustic velocity at the shorter SAW wavelengths since the shorter acoustic penetration depth means that more of the wave is travelling in the nickel. However, the acoustic measurements we made were dispersion-free within experimental error throughout the range of SAW wavelengths studied. This effect has been suggested in previous measurements of Al/quartz [4] and Al/Si [5] structures, and similar measurements showed no SAW generation at all in Au/quartz structures [6]. However, this is the first comprehensive dispersion measurement.

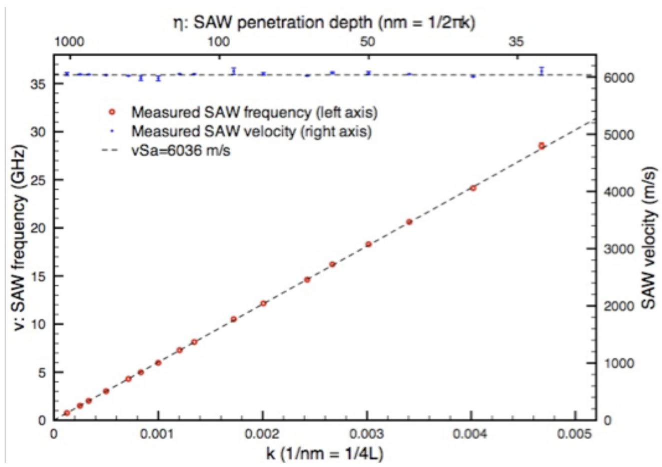

Figure 3: Measured SAW frequency (red hollow circles, left axis) and velocity (blue dots, right axis) for propagation in sapphire overlayed with nanopatterned nickel strips. Dispersionless propagation is observed at all acoustic wavelengths.

These measurements of dispersion-free SAW propagation for acoustic wavelengths as short as 200nm demonstrate the generation and detection of very high-frequency SAWs without signal contamination from the nanostructure. This technique of optical/nanostructure excitation and EUV probing can easily be extended to even shorter wavelengths limited only by lithographic capabilities, and holds potential for studying the materials and interface properties of thinner films than have previously been studied using SAW techniques.

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