Ultrafast Photoacoustic Characterization Of Buried Nanostructures Using COMSOL Multiphysics

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Abstract

As semiconductor devices continue to shrink and incorporate complex 3D architectures, conventional optical metrology faces limitations in resolving features smaller than the optical wavelength or those hidden beneath opaque layers. Ultrafast photoacoustic spectroscopy provides a powerful, non-invasive method to characterize such buried nanoscale structures with high resolution.

In our approach, femtosecond laser pulses generate high-frequency acoustic wave packets at the sample surface. These acoustic waves, containing wavelength components below 100 nm, propagate through the material and diffract from buried nanoscale features. The resulting strain modulates the local refractive index and alters optical reflectivity, which we detect via time-resolved reflectivity measurements using a delayed probe pulse. This enables the retrieval of subsurface structural details with nanometer-scale resolution. We applied this technique to characterize nanoscale gratings buried beneath opaque films, revealing grating linewidth, pitch, and edge shape with 10-100 nm sensitivity. COMSOL simulations validate our results, highlighting the method's potential for non-invasive, high-resolution metrology.

To model this process, we developed a model in COMSOL Multiphysics The structure includes a Zr membrane with a surface grating fabricated on the back side. A femtosecond pump laser pulse illuminates the front surface. Laser absorption is simulated using the Radiative Beam in Absorbing Media interface. Ultrafast electron-lattice heating is captured via the Two-Temperature Model, implemented using two coupled Heat Transfer interfaces. The resulting thermoelastic expansion launches acoustic strain pulses, modeled using the Solid Mechanics interface coupled with heat transfer in a time-dependent study. For optical detection, we employ the Electromagnetic Waves, Frequency Domain interface to calculate reflectivity changes induced by strain-modulated permittivity. This enables us to link acoustic echoes to specific subsurface features and extract their geometrical parameters.

Our simulations replicate the experimental signals and provide insight into how acoustic wave diffraction by nanoscale gratings encodes fine structural details. We find that this diffraction is sensitive not only to grating pitch but also to edge profiles and linewidth variations on the scale of tens of nanometers. These findings show the ability of photoacoustic methods to resolve buried nanostructures beyond the limits of conventional optical metrology.

This work demonstrates the utility of COMSOL Multiphysics® to simulate complex ultrafast phenomena involving coupled thermal, mechanical, and optical processes. The developed model provides a valuable framework for designing advanced metrology tools capable of imaging deeply buried, subwavelength features critical for next-generation integrated circuit manufacturing.

Reference

M. Illienko et al., Characterization of Sub-Optical-Wavelength Structures through Optically Opaque Films Using Picosecond Ultrasonics, Nano Letters 2025 25 (22), 8909-8914

Figures used in the abstract

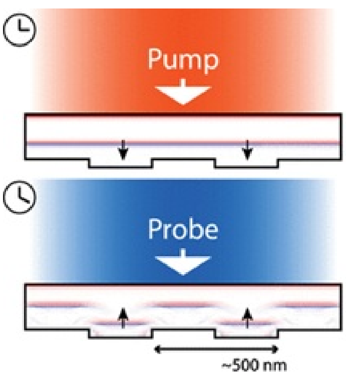

Figure 1 : Fig 1. : Femtosecond laser pulse generates acoustic waves that diffract from buried nanostructures and are probed with a delayed pulse to reveal subsurface details.