NANOSCALE HEAT TRANSPORT PROBED WITH ULTRAFAST SOFT X-RAYS

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On length scales that are short compared with the phonon mean free path (Λ~100nm), thermal transport is not expected to follow the diffusive Fourier law of heat conduction. Although various methods for predicting heat flow in this regime have been proposed [1], no experiments have yet validated the predictions for phonon heat transport surrounding a nanoscale heat source. This is technologically relevant because it relates to thermal dissipation in a nanoscale transistor.

High harmonic generation (HHG) is an ideal coherent light source for studying nanoscale thermal transport effects because of the spatial coherence and short wavelength (tunable from 100-1 nm) of the generated light. We previously demonstrated the use of HHG beams in a Gabor holography geometry to observe laser heating-induced surface displacements and acoustics [2].

We diffract 30nm light from HHG off of an array of nanostructured nickel lines on a sapphire substrate to probe thermal and acoustic dynamics. The sample is impulsively heated by an 800 nm pulse from a Ti:Sapphire laser amplifier which heats only the nickel lines. By monitoring the change in the probe diffraction from the grating as a function of pump-probe delay, we obtain both the surface acoustic wave (SAW) propagation in the nanostructure and an exponential decay as the heat in the nickel lines dissipates into the unheated sapphire substrate. This thermal decay is an indicator of phonon transport efficiency between the nanostructure and the substrate.

At room temperature, heat transport in this sample is diffusive since the characteristic length (nickel wire width L=1 μm) is much greater than the phonon mean free path (Λ~150 nm) in sapphire. In order to observe ballistic heat transport in this sample, we cool the substrate to increase the phonon mean free path. To determine the rate of heat transport, we fit thermal response curves (Figure 2) to a decaying exponential. The decay time as a function of temperature is plotted in Figure 3, along with a prediction based on temperature-dependent diffusive heat conduction, where $k = Cv\Lambda/3$. Below 130 K, we observe significant deviation from bulk behavior, consistent with a transition to the quasi-ballistic regime of heat transport.

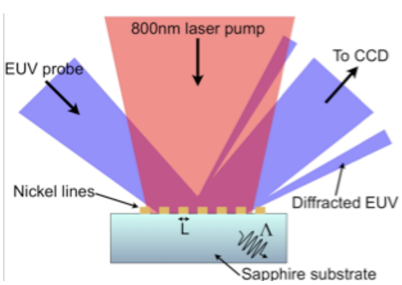

Figure 1: Experimental schematic showing the sample with 1μm wide nickel lines on sapphire.

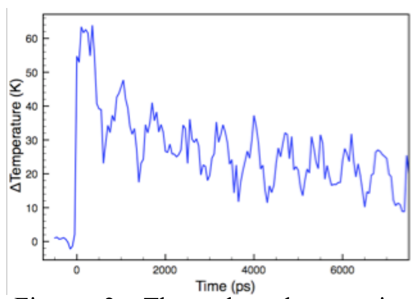

Figure 2: Thermal and acoustic dynamics in the 1μm nickel lines.

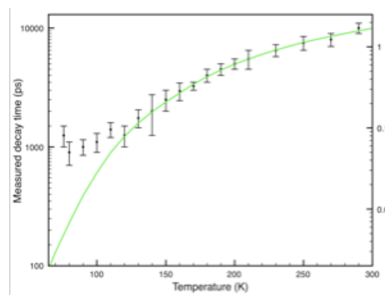

Figure 3: Measured decay time in ps (points- scale on left axis) and diffusive prediction (line- right axis).

1 R. G. Yang, G. Chen, M. Laroche and Y. Taur, “Simulation of nanoscale multidimensional transient heat conduction problems using ballistic-diffusive equations and phonon Boltzmann equation”, Journal of Heat Transfer-Transactions of the ASME 127, 298 (2005)

2 R. Tobey, M. Siemens, O Cohen, M. M. Murnane, H. C. Kapteyn, and K. A. Nelson “Ultrafast Extreme Ultraviolet Holography: Dynamic Monitoring of Surface Deformation“, Optics Letters 32, 286 (2007).