Nanoscale Knowledge: Discovering how small is different

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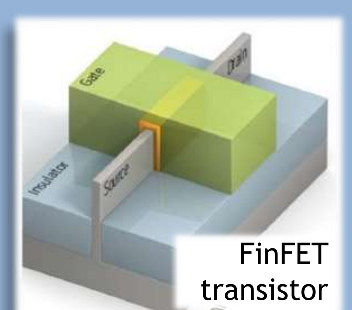
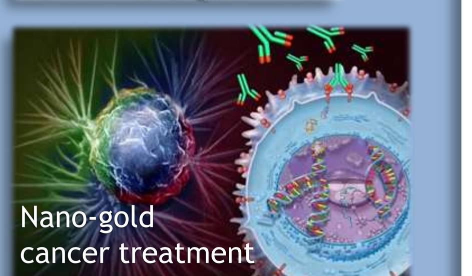
Introduction

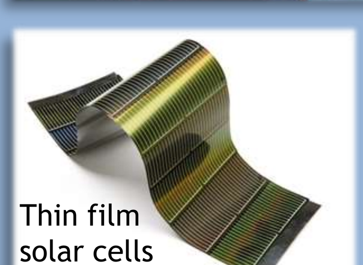
The shrinking size of the building blocks that make up today's ubiquitous electronic devices has given us smartphones at our fingertips that offer much more computing power than supercomputers of past decades. However, to design smaller, faster and more efficient hard drives, transistors, energy harvesting and recovery systems, or materials for nano-medicine, we need a better, more fundamental understanding of how energy flows in nano-systems at unprecedented small dimensions - length scales of only a few nanometers - where bulk models of materials break down and where reliable measurement tools or models do not yet exist. Moreover, heat and sound waves can move through a tiny nano-system on time scales of picoseconds, or about one hundred-billionth of the time it took you to read the word 'picosecond'.



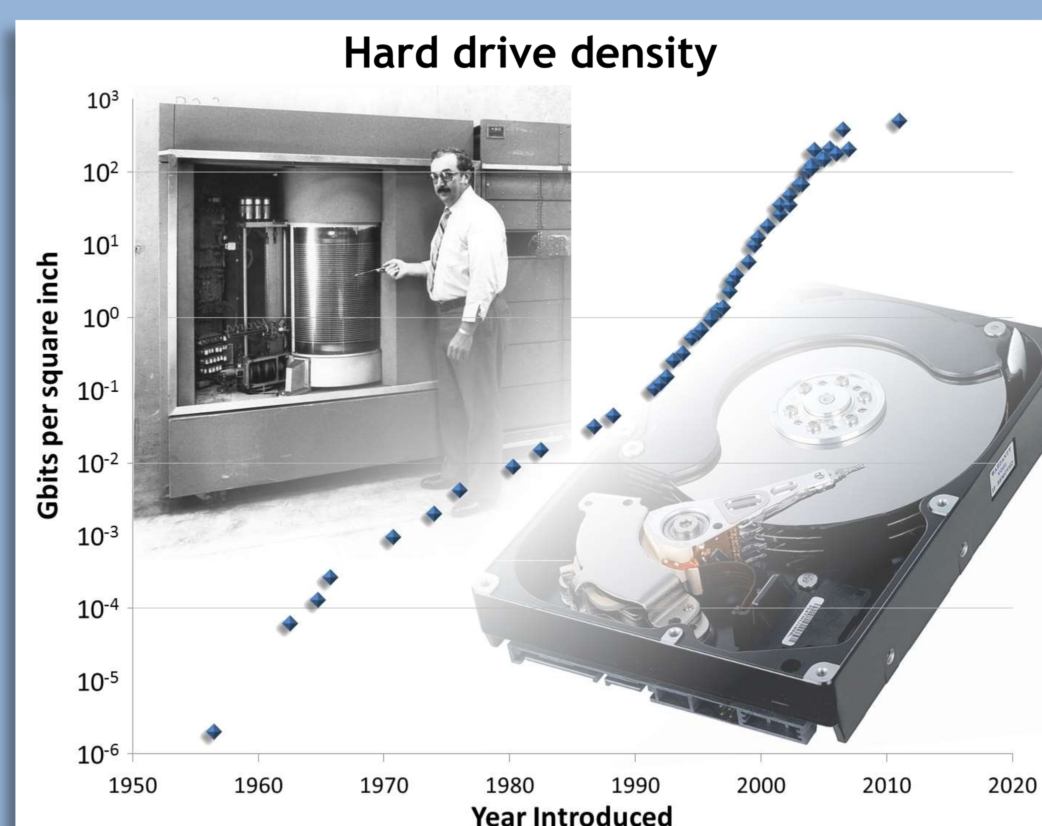
FinFET transistor



Nano-gold cancer treatment



Thin film solar cells



For my Ph.D. research I am inventing new and powerful measurement tools for capturing how heat, strain, sound, charge and spin waves move through nanostructured and composite materials. By using the fastest strobe light in existence, I can peer into the nano-world to watch what is happening in real time. Our combination of advanced laser science and extreme nonlinear optics with optical sensing and computational modeling of the systems we study will help us to understand how the mechanical and thermal transport properties of nanostructured systems change as the size shrinks to only a few atoms.

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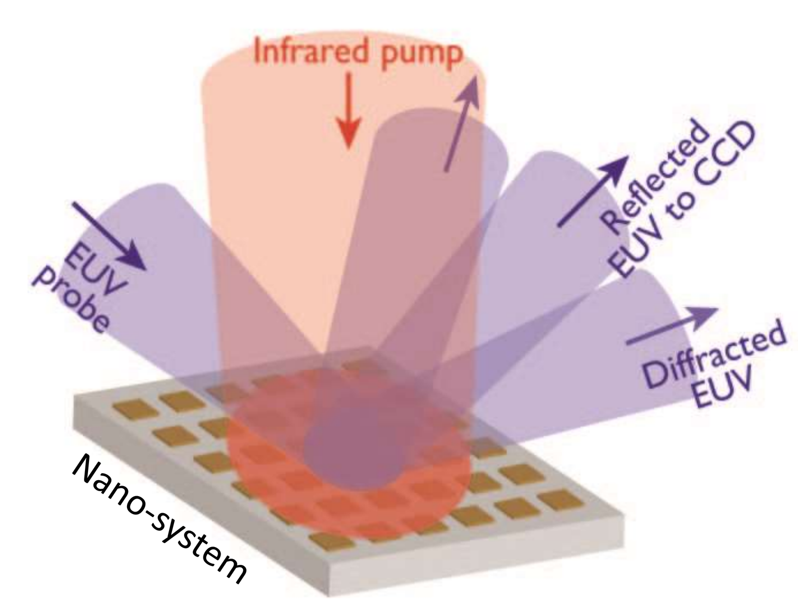
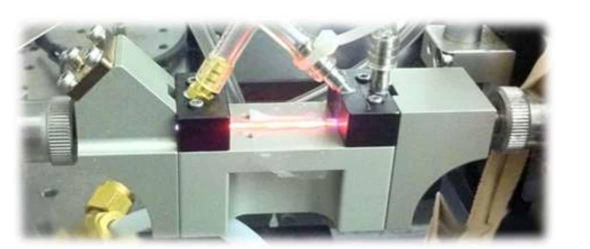
Hoogeboom-Pot et al., *in prep* (2013).

Measurement method

In stroboscopic photography, some motion is initiated (for example, when a bullet shoots into an apple), and then captured by a time-delayed camera flash. However, the flash of a standard camera is a million times too slow to capture nanoscale motions. Instead we use a femtosecond laser pulse as our 'shot' to excite a sample, and a second, shorter-wavelength probe pulse to record what happens in real time.





Extreme ultraviolet laser strobe

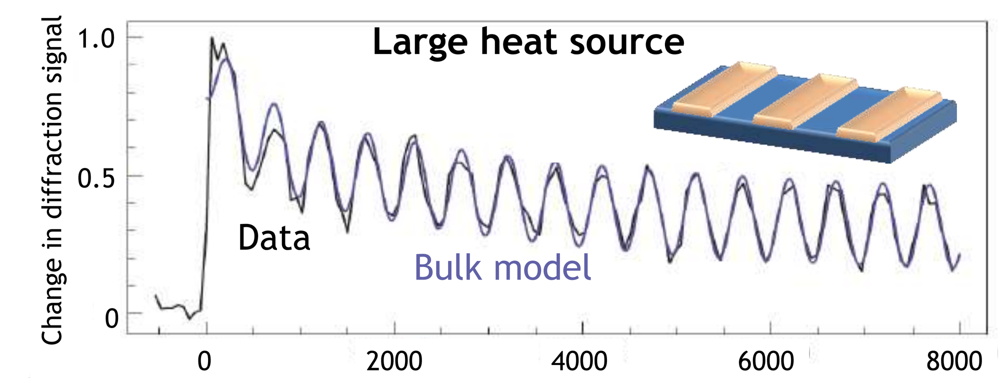
In our experiment, the excitation laser light is absorbed by metallic nanostructures leading to rapid heating, thermal expansion and acoustic wave oscillations. The probe light wavelength is small enough to offer the resolution needed to see tiny features, and it makes this measurement sensitive to shape changes as small as a few picometers - less than the diameter of a single atom!

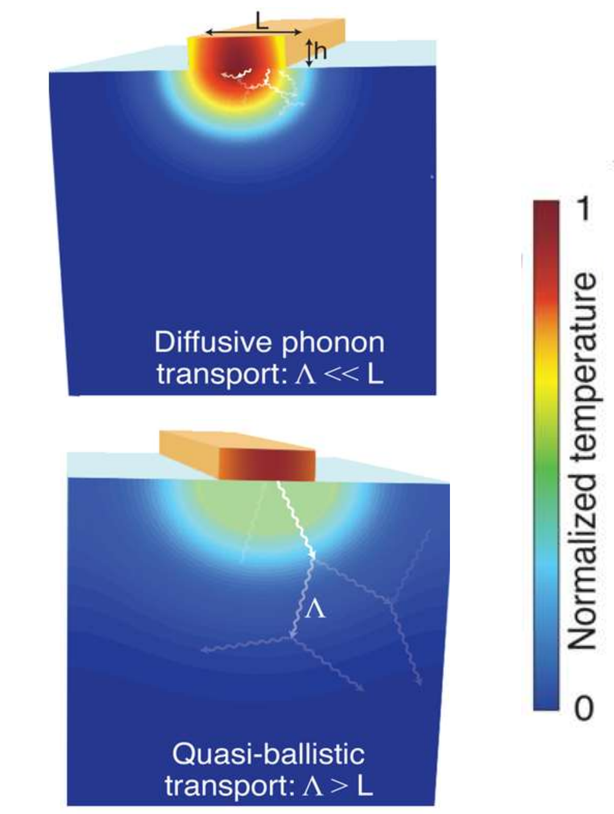
To generate fast bursts of short wavelength probe pulses, we focus an ultrafast laser into a gas, exploiting extreme nonlinear optics to produce laser-like beams in a table-top setup. Choosing the appropriate gas and driving-laser wavelength allows us to make probe beams spanning the ultraviolet to the X-ray region. The heart of this process is a glowing, gas-filled waveguide - which fits in the palm of your hand.

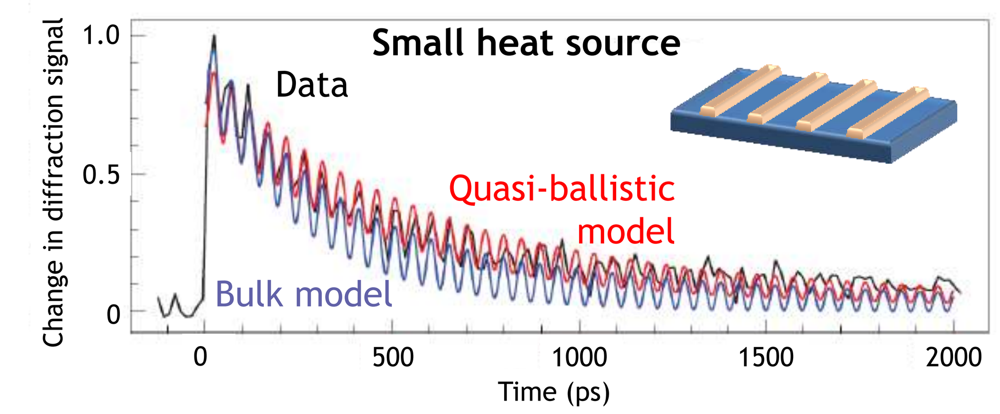
Heat flow

When a material is heated, the extra energy causes vibrations, called phonons, in the crystal lattice. In a bulk system, collisions among such phonons tend to transfer heat from hot regions to colder regions. However, in tiny nano-systems, the phonons can travel through the system without colliding with other phonons - a phenomenon that is called ballistic transport. One can imagine that such a phonon will basically keep its excess energy to itself, leading to less efficient heat dissipation than bulk models would predict.

This effect becomes more important once the size, L, of the heat source (like a nanowire or a transistor) is smaller than the phonon mean free path, Λ (the characteristic length scale for collisions to take place), in the substrate below. When we compare large-L thermal decay of our signal (below, top left, black curve) to a bulk model (blue curve), they are quite consistent. However, for a small-L sample, the bulk model (blue curve, bottom left) decays much more rapidly than the measured data (black curve).

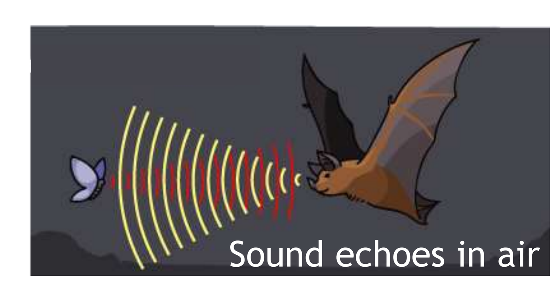




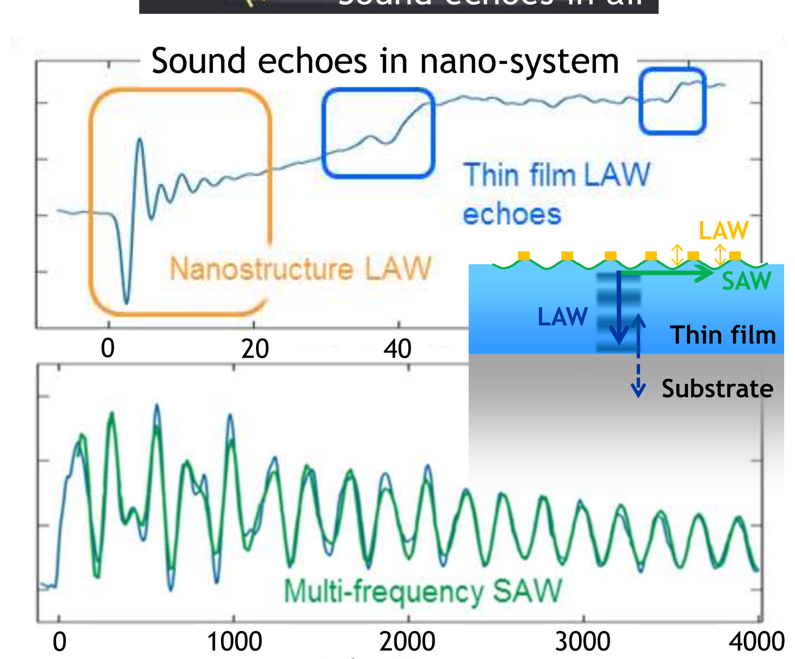


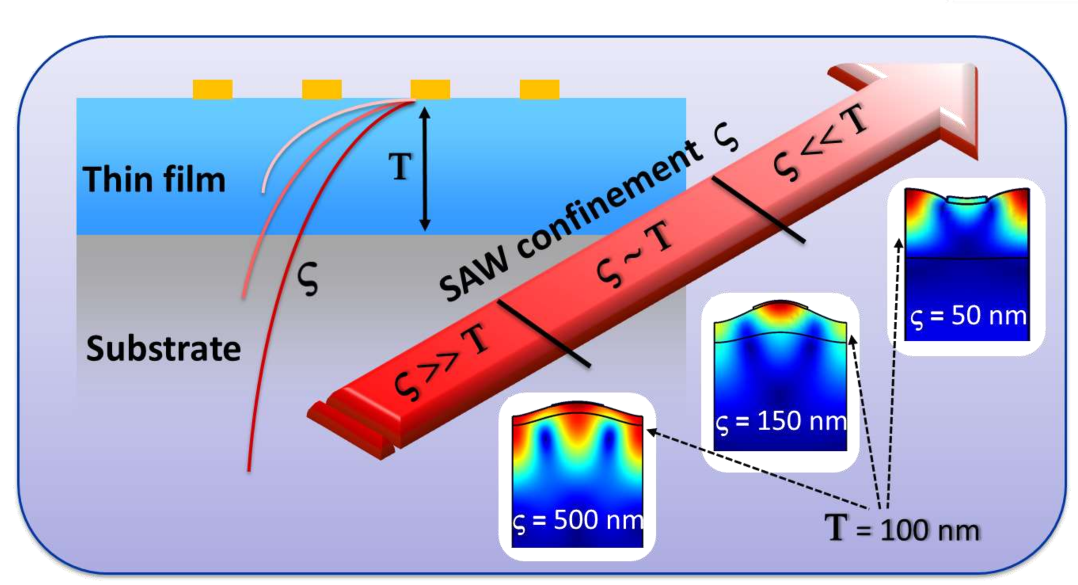
Acoustic waves

Like bats using sound waves traveling through air to learn about their surroundings, we can use acoustic waves traveling through nano-systems to study material properties. And in small systems, like a 10-nm-thin film or nanowire, material properties like density or elasticity may change significantly from bulk values for a given material due to increasing importance of surface and interface effects.



Our sensitivity to small structures allows us to observe longitudinal and transverse surface acoustic waves (LAW and SAW) which are confined within the nanostructures or films of interest. The velocities of these waves are directly related to density and elasticity of the material in which they travel. The change-in-diffraction signal (right) for each component of the dynamics allows us to selectively isolate the material properties of each part of the system.



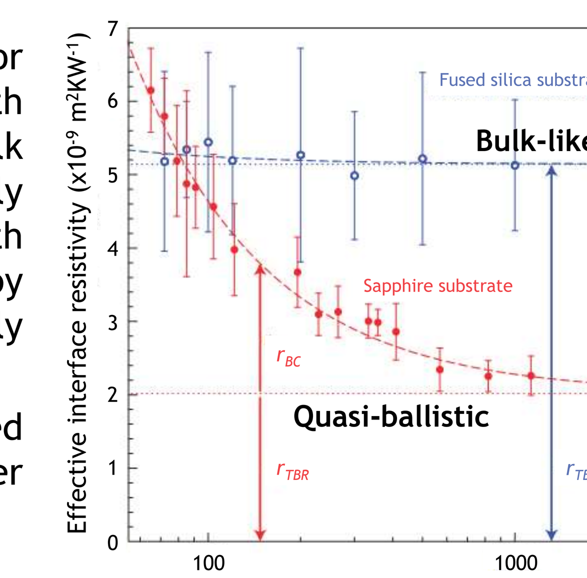


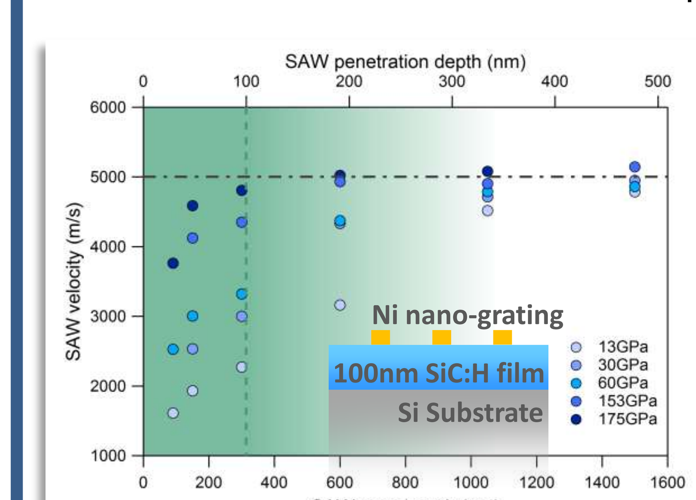
Surface acoustic waves are particularly useful because they penetrate below the surface to a depth which is only a fraction of their wavelength - which is set by the period of the nanostructure on top. This means that a long SAW wavelength from a large period can be used to characterize a substrate layer, while short SAW wavelengths from small periods isolate thin film properties.

Conclusions and Outlook

Nanoscale heat flow: How important is the ballistic effect? For nanowires on fused silica with small phonon mean free path (blue), we do not observe significant deviation from bulk behavior - the effective thermal resistance we measure is nearly constant for all linewidths. However, in the case of sapphire with a phonon mean free path over 100nm, the resistance increases by up to 3x for the smallest linewidths (red), indicating significantly less efficient heat dissipation than bulk theory predicts.

⇨ Current work seeks to extend similar analysis to 2D-confined nano-dots, where preliminary results suggest an even stronger deviation from bulk behavior for comparable size scales.





Thin film metrology: How many atomic layers make a bulk material? We've demonstrated selective measurement of ultrathin film layers with varying Young's moduli (stiffness). Long-wavelength SAW velocities gather near the Si substrate property (grey dash-dot line), but as the SAW penetration depth becomes comparable to the film thickness (green dotted line), the measured velocities isolate the wide range of film characteristics (shades of blue).

⇨ We will apply this new measurement technique to even thinner films to understand when bulk behavior breaks down.

Nano-materials: What are our detection limits? Even adding a sub-nm layer of tantalum to a nanostructure changes its acoustic response (blue). The slope of this line reveals the sound wave velocity in this tiny structure. The additional mass also affects the wave underneath (green), revealing the material densities.

⇨ Ongoing analysis is comparing these density and velocity measurements to bulk values to understand how bulk properties emerge.