Experimental Measurement of Individual Phonon Mean Free Path Contributions to Total Thermal Conductivity

Key Words: Phonon, Mean Free Path, Spectroscopy, Thermal Conductivity

Background: From a young age, we are taught that heat is actually the random jiggling of atoms, but this is only a first approximation intended to provide a broader intuitive picture of what is really going on. A more complete description quantifies this jiggling as an ordered superposition of linearly independent vibrational modes of the solid, each capable of storing and transmitting thermal energy. Much like an impulse propagating down the length of a stretched out spring, quantized bundles of vibrational energy called phonons zip back and forth through a solid material's atomic lattice. The thermal conductivity of a solid largely depends on the physical properties of these phonons, including their mean free paths (MFP), which is the distance that a phonon travels before colliding with an impurity in the solid or another phonon, exchanging energy, and scattering off in a new direction. I propose a research plan that will both increase our fundamental understanding of heat conduction and will enable us to make more accurate models and predictions of heat conduction, while also promoting education and enhancing an outreach program. I intend to experimentally measure how much each phonon mean free path contributes to the total thermal conductivity of crystalline solids.

Motivation: In the current state of the art, engineers and scientists alike typically account for the large distribution of different MFPs and how much each MFP contributes to the total thermal conductivity by using approximate models with empirically fitted constants. While this works for general applications to bulk materials, it blurs the picture of what the phonons are really doing, and it results in *multiple different phonon distribution models* [1]. This leads to very different predictions when examining micro-scale systems where the physical dimensions can interact with MFPs, greatly altering thermal properties. There is a clear need to probe deeper.

Research Plan: In order to fill this awkward gap in our knowledge, I will directly measure how much each MFP actually contributes to the thermal conductivity in SiO_2, Si, and SiGe, representing three important classes of materials. Si is a well-understood and important semiconductor, SiO_2 is a phonon-dominated amorphous dielectric and insulates MOS chip gates, and SiGe is an alloy often used in high speed electronics. SiGe will also be used to *build on previous work* recently published [2] indicating a strong and surprising frequency-dependence on the thermal conductivity of SiGe. This proposal could help explain the nature of this frequency dependence by demonstrating that many different MFPs spanning a large range contribute to the total thermal conductivity. Therefore, this publication is an example of a current question that could be immediately answered by the results of my proposed experiment.

The basic experimental setup will consist of a thin metal strip deposited on a semi-infinite substrate material of interest (the sample). Because the duration of heat pulses used will be on the order of nanoseconds to microseconds, the substrate can be chip-sized and easy to handle while still acting as semi-infinite for the purposes of the experiment. The thin metal strip can be deposited onto the sample using electron-beam evaporation and patterned with photolithography. This can be done at the Marvell Nanofabrication Laboratory, located on UC Berkeley's campus. Therefore, I will be able to prepare samples on campus, saving time and money. This metal strip, on the order of tens of microns wide by a few hundred microns long by a hundred nanometers thick, will function both as the heater (joule heating) and as the thermometer (resistance thermometry). With the heater/thermometer affixed to the sample, a fast heating pulse with a rise time of several nanoseconds will be sent into the sample. Such brief pulses can be accomplished by any of a variety of available fast pulse generators.

As a result of the heater's minimal thickness, the heat from this pulse will rapidly dissipate into the substrate and be transferred away at a rate depending, among other factors, upon the MFPs of the phonons. This time-dependent temperature signal will contain information about the sample's thermal properties. The signal can be extracted cleanly using a fast oscilloscope or a gated integrator with variable offset from the trigger time, and then averaged over many rapid successive trials to significantly increase the signal to noise ratio. For this procedure, sufficient off-the-shelf equipment is available with gate widths down to 0.1 nanoseconds. This setup will allow us to probe the vast majority of potentially important MFPs, corresponding to heat pulse time intervals of 0.1 nanoseconds up to 10 microseconds. However, initial trials will be done at low temperatures corresponding to substantially slower and easier to measure relaxation times.

After the temperature signal is isolated and extracted, the thermal conductivity will be calculated from the Boltzmann transport equation. Examining the transition region of ballistic to diffusive phonon behavior and comparing it to known analytical models will allow us to correlate the thermal conductivity to specific MFPs. Therefore, we can systematically measure the independent contribution of each MFP to the total thermal conductivity. Recent publications [2][3] successfully employed similar (though much less precise) experimental techniques to the one described here, *demonstrating its feasibility*. This experiment utilizes all of the skills learned in my previous research, and combines my love of theory and of experiment.

Outreach: I also intend to continue my lab's tradition of *recruiting undergraduate students* to assist me with my project. This broader impact will promote education and offer real research exposure to undergraduates, encouraging them to consider further education and research as a career path. I will also spend time working as a graduate student instructor, continuing my extensive history of teaching. The results of this research project will later be incorporated into an already existing outreach program set up by my research advisor as part of his existing NSF grant. This program creates hands-on high school workshops, using peltier modules to intuitively teach students about the First Law of Thermodynamics, and enabling them to visualize the nano/micro world on a macroscopic level. After graduating and securing a faculty position at a research university, I will carry on this mantra of education enrichment both through the classes I teach, and through the outreach programs to which I contribute.

Anticipated Results: This research will provide new fundamental knowledge on how heat conduction works, especially at the nanoscale, with direct application to nanotechnology. It will also result in the development of a new high-precision experimental technique that could be used by future researchers. If awarded, I will receive an NSF Fellowship with great humility and gratitude, and ensure that I use it to promote education, enhance the predictive power of our current heat conduction theories, and uncover a little more about how nature works.

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