Unified View of Electron and Phonon Transport

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ABSTRACT

A simple, unified view of electron and phonon transport is presented. Similarities and differences are identified, and new insights that come from addressing phonon transport from an electron transport perspective will be discussed.

INTRODUCTION

Computational electronics has focused on simulating electron transport, and over the years as device dimensions have shrunk, a suite of powerful tools has been developed. Devices dissipate power and generate heat, but the treatment of heat transport has largely been the work of other communities, but the evolution of technology with device structures such as extremely Thin Silicon On Insulator (ETSOI) MOSFETs and FinFETs has increased the importance of self-heating in nanodevices. The average mean-free-path of phonons in bulk silicon is over 100 nm, meaning that ballistic phonon transport may be even more important than ballistic electron transport. Just as we have learned how to think about electrochemical potentials at the nanoscale, we must now learn how to think about temperature at the nanoscale. The problems we face in modern electronic devices require us to treat electrons and phonons on an equal footing.

Those of us who come to this field from electronics naturally ask: "How can we adapt the tools, techniques, and concepts developed for electronics to phonons?" "What is different for phonon transport and what is similar to electron transport." This talk will use two simple approaches to address these questions. Another important question is: "How do we connect rigorous simulations to the phenomenological equations that device designers and experimentalists need?" This talk will also address this important question.

TWO SIMPLE EQUATIONS

Two simple equations will be used. The first is the Landauer approach,

$$I = \frac{2q}{h}\int \mathcal{T}\left(E\right)M\left(E\right)\left(f_1 - f_2\right)dE \qquad (1)$$

and the second is the McKelvey-Shockley version of the Boltzmann equation,

$$\frac{dI^{+}(x)}{dx} = -\frac{I^{+}(x)}{\lambda} + \frac{I^{-}(x)}{\lambda} = \frac{dI^{-}(x)}{dx}. \qquad (2)$$

The talk will discuss how these two approaches can be applied to both electrons and phonons and how they can be connected to rigorous simulations.

RESULTS

Figures 1-6 are some of the results that will be discussed.

CONCLUSION

As discussed in this talk, the approaches that have been developed for electron transport can be readily extended to phonon transport, and they provide useful tools as well as new insights.

ACKNOWLEDGMENT

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REFERENCES

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[2] J. Maassen and M. Lundstrom, "Steady-State Heat Transport: Ballistic-to-Diffusive with Fourier's Law," *J. Applied Phys.*, **117**, 035104, (2015).

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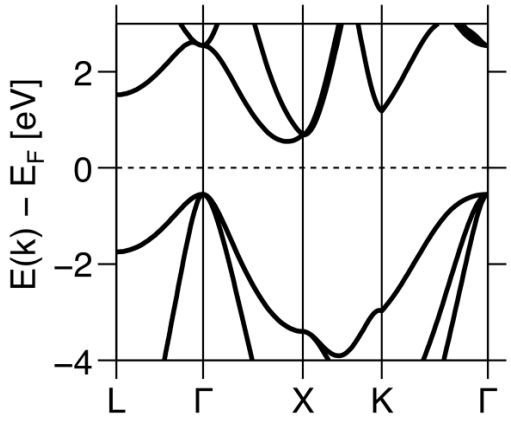

Fig. **1**. The electron dispersion for bulk Si as computed by DFT simulation.

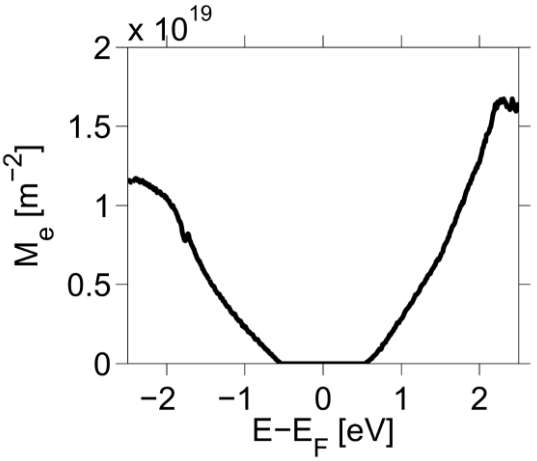

Fig. 2. The number of channels vs. energy for bulk Si. The initial increase from the band edges is linear for parabolic energy bands.

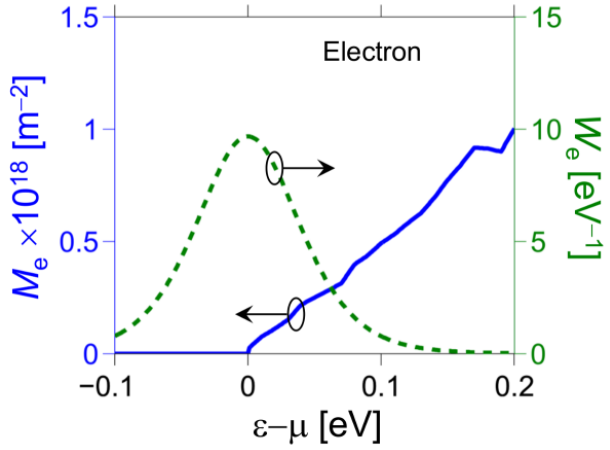

Fig. 3. The electron window function (which indicates which channels are occupied) and $M_{el}(E)$ for Si. Note that only electron channels very near the bottom of the band are occupied.

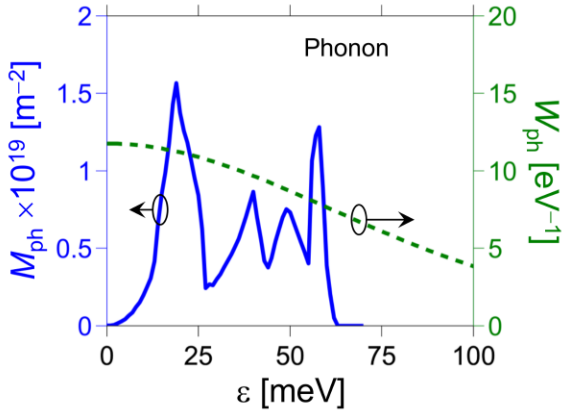

Fig. 4. The phonon window function, which indicates which channels are occupied and $M_{ph}(\hbar\omega)$ for Si. Note that all phonon channels are occupied at 300 K.

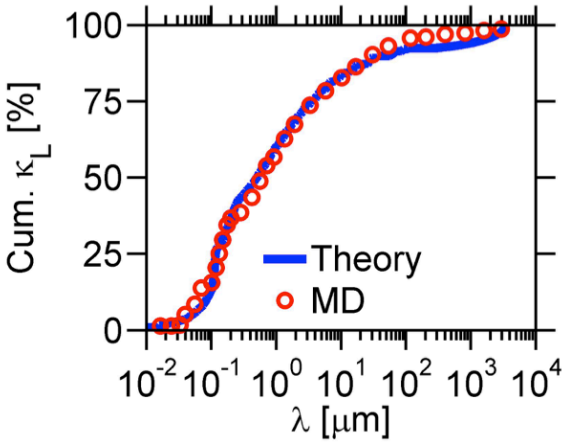

Fig. 5. Illustration showing that in bulk Si, phonons with a MFP greater than one micrometer contribute 50% to the thermal conductivity.

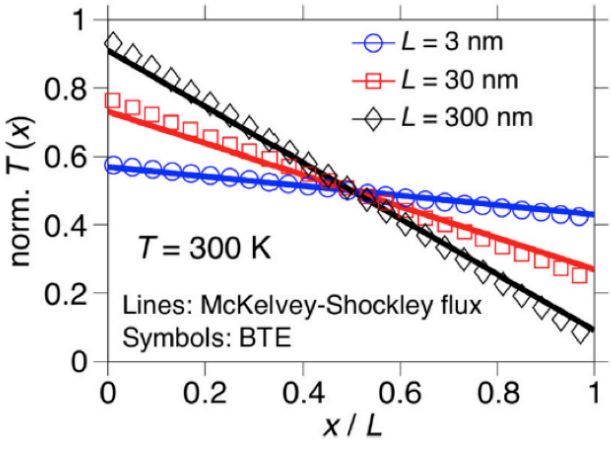

Fig. 6. Temperature vs. position in a Si films showing temperature jumps at the contacts due to ballistic transport. Symbols, BTE solutions, lines: Fourier's Law when properly implemented (from [2]).