The effective thermal conductivity of ballistic-diffusive heat conduction in nanostructures with internal heat source

Heat transport and Optimization of Micro-nano chip

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Introduction: Heat conduction in silicon

As the typical length of electronic chip arrives at micro even nano scale, the typical heat flux density can reach $10^5\,W/cm^2$, causing the rising of temperature in chips. Because the reliability of chips is greatly influenced by temperature, the study on nanoscale heat conduction in silicon nano-films is especially important.

MFP phonon mean free path

ballistic transport phonons flying directly from one boundary to another

diffusive transport phonons transport dominated by Flourer's law

Introduction:size-dependent thermal conductivity

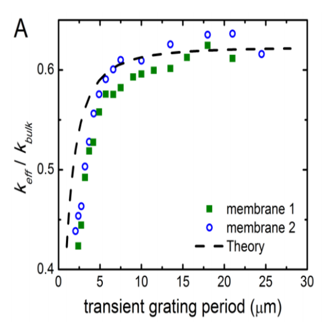

图 1: Thermal conductivity decreases dramatically as the size becomes small (Johnson, Jeremy A ,2013)

As shown in the picture, when the length of the film becomes small and gets close to the MFP of phonon in silicon, Flourer's law won't work. In this region, the transport is both influenced by ballistic and diffusive transport, which is called ballistic-diffusive conduction.

BTE and Monte Carlo simulation

定理 (BTE with the relaxation time approximation)

$$\frac{\partial f}{\partial t} + v_g \nabla f = \frac{f_0 - f}{\tau} + \dot{S_\Omega}$$

There are mainly several ways to solve or study on this equation.

- Experiments
- Mathematical way
- Similation
    - MD
    - Lattice Boltzmann
    - MC

MC Method

Some key points

- Gray body Approximation
- Debyu Approximation(Assume the lattice elastic)
- local thermal equilibrium assumption

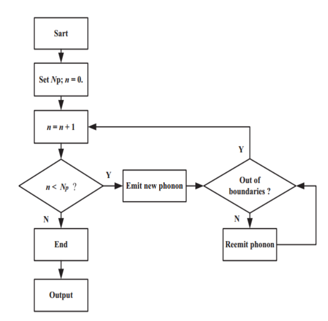

图 2: MC Tracing Method (Yu-Chao Hua, Bing-Yang Cao ,2014)

Cross-plane

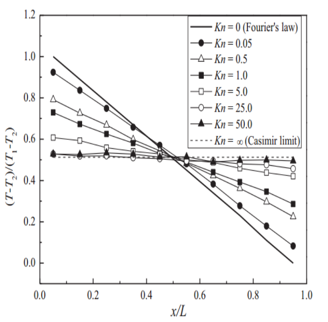

图 3: Dimensionless temperature profiles of Si nanofilms (Yu-Chao Hua, Bing-Yang Cao ,2014)

The temperature profiles within the nanofilms are *linear*. As kn=0, the phonon transport is purely diffusive and that's just the Flourier's law;as Kn $\rightarrow \infty$, since the phonon ballistic transport is dominant, the temperature gradient vanishes and the temperature jump reaches maximum.

Cross-plane

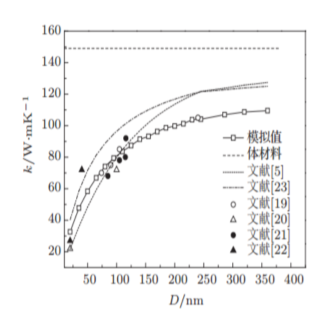

图 4: The thermal condictivity in different depth (Yu-Chao Hua, Dong Yuan ,2013)

As shown in the picture, the size effect is fully displayed as the size of nanofilm is near the MFP. And the Conductivity increases as the depth increases, while the slope decreases.

In-plane and with internal heating

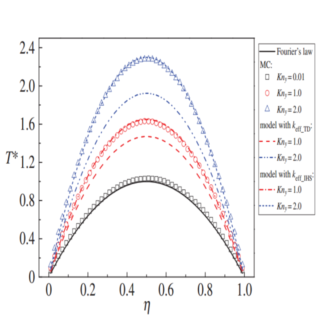

图 5: Transient in-plane thermal transport in nanofilms with internal heating (Yu-Chao Hua, Dong Yuan ,2013)

In the MC simulations, phonons emit within the nanofilms uniformly and can scatter with the lateral boundaries fromthe beginning. Therefore, th e temperature rise can be significantly larger when compared with the heat diffusion equation based on Fourier’ s law even at the initial heating stage.

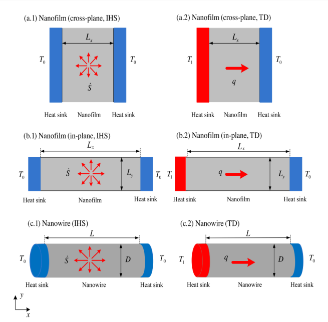

图 6: The effective thermal conductivity of ballistic–diffusive heat conduction in nanostructures with internal heat source (Yu-Chao Hua, Dong Yuan ,2013)

It is found that the effective thermal conductivity in the IHS scheme is significantly lower than that in the TD scheme. **The diffusive heat conduction equation with the effective thermal conductivity is applied to characterize the temperature distributions in the nanostructures with internal heat source.**

Analysis and Next step work

Next steps

1. From One-dimensional to two-dimensinal and three-dimensional
2. Transient transport
3. Complex boundary conditions and different geometry structures
4. Improve thealgorithm and lower the expense

Main nodi

- Interface
- Complexity in actual device
- How to conduct optimization(Without no mathematical method and quite different from Macro problems)

Johnson, Jeremy A (2013)
Direct measurement of room-temperature nondiffusive thermal transport over micron distances in a silicon membrane
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