Study on the Heat transport and Optimization of Micro/Nano chip

微纳芯片热输运和优化研究

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Introduction and Background

The failure of Moore's Law

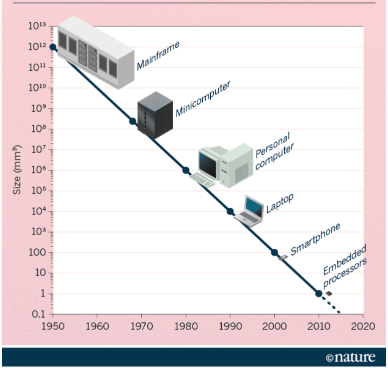


图 1: For the past five decades, the number of transistors per microprocessor chip has doubled about every two years[6].

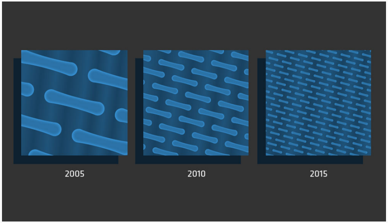


图 2: According to Moore's Law, the number of transistors on a computer chip doubles roughly every couple of years. Each one is also proportionally smaller.

Heat Flux Extrapolation and Size Effect

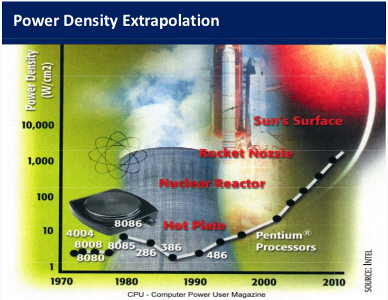


图 3: The heat flux density has reached as high as the sun which causing cooling even harder and harder

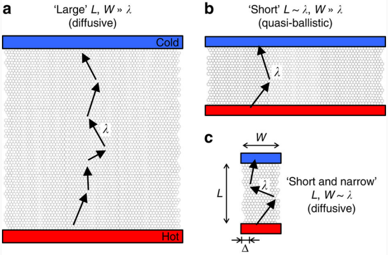


图 4: The size effect when characteristic length is compatible to MFP of phonons[1]

Traditional Chip cooling and heat management

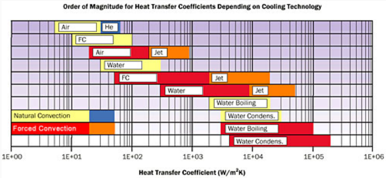
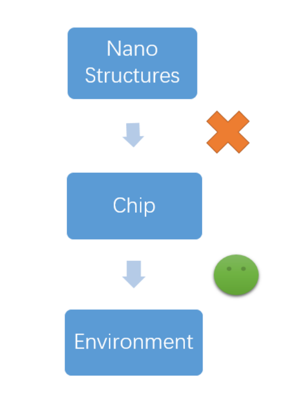


图 5: Heat transfer coefficient attainable with natural convection, single-phase liquid forced convection and boiling for different coolants[4].



Studying aims and steps

- Simulate the actual temperature profile in nano devices, especially in silicon chips and understand the deep mechanism behind it.
- Simulate the multi-structure heat generation(hotspots problems) and heat conduction
- Figure out what matters in the heat conduction and get the new temperature profile by simulation.
- Conclude a new method to conduct optimization in nano devices

Problem and Method

The fundamental model

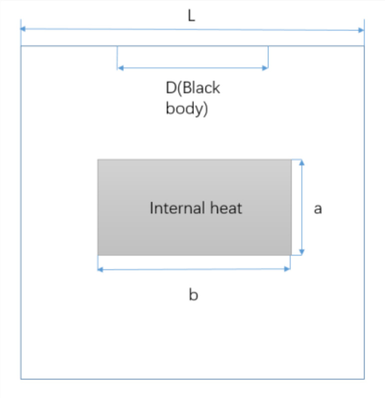


图 6: Two dimensional thermal transport in silicon films with internal heating

- Fourier's Law

$$q = -k\nabla T \tag{1}$$

- Governing Equation

$$\frac{\partial f}{\partial t} + v_g \nabla f = \frac{f_0 - f}{\tau} + \dot{S}_\Omega \tag{2}$$

- The gray approximation
- **The similarity between phonon and photon**
  - $$E = \sigma T^4 \tag{3}$$
  - $$dQ_{em} = 4\epsilon\sigma T^4 dT \tag{4}$$

MC Method

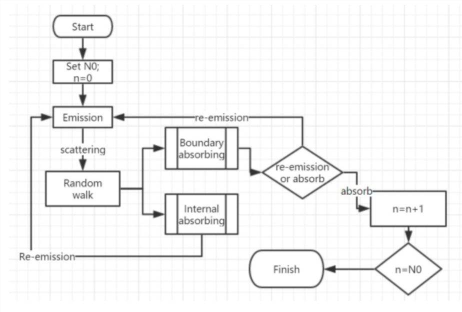


图 7: Block diagram of the tracing algorithm

- Phonon bundle vector $\mathsf{S} = [\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\phi]$
- Emission angle
  - From the boundary, $\sin\theta = (R_{\theta b})^{1/2}$, $\phi = 2\pi(R_{\phi b})^{1/2}$
  - In the media, $\cos\theta = 1 - 2R_{\theta m}$, $\phi = 2\pi(R_{\phi m})^{1/2}$
- The average travel distance $\Delta l = -LKn\ln(1 - R_s)$

Results and Conclusion

Temperature Profile in different Kn number(D=1)

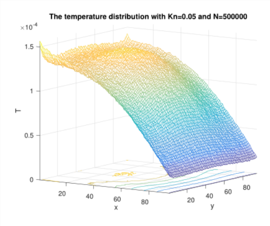


图 8: Kn=0.05

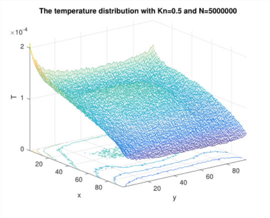


图 9: Kn=0.5

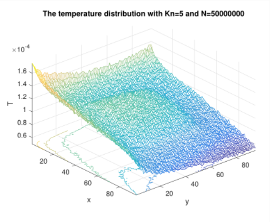


图 10: Kn=5

Temperature Profile in different Kn number(D=0.5)

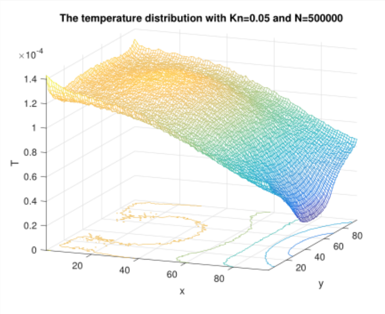


图 11: Kn=0.05

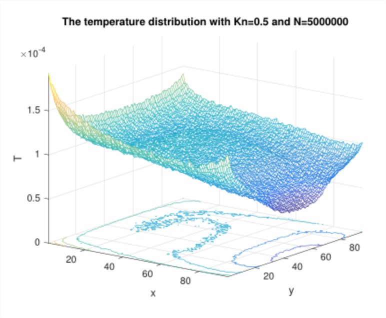


图 12: Kn=0.5

Discussion and Conclusion

Size effect

As Kn number becomes bigger, the ballistic effect begins governing the transport.

Strongly Boundary-influenced

Though boundary conditions here are simple, the great influence compared to in bulk materials was clearly shown.

Summary

1. The phonon-boundary scattering significantly suppresses the in-plane thermal transport, leading to **different temperature distribution** and **lower thermal conductivity** when compared with the heat diffusion equation based on Fourier's law.
2. An efficient MC method based on establishing a model of **phonon scattering processes** is employed to simulate the ballistic-diffusive heat conduction in silicon nanofilms. And it is believed effective to simulate the phonon-phonon interaction and phonon-boundary interaction.
3. This MC method can effectively consider **the effects of different boundary conditions**, which makes it possible to do the optimization in real devices.

Forecast and Prospects

Three main challenges

Interface

We still know little about the mechanisms behind the phenomenons and cannot get a universal theory or model to describe and predict what happens at the boundary.

Multi-structured

When we consider bulk or thin film materials that contain a collection of nanostructured units, we may find the collective behavior of a large number of units can add to more complexity.

Heat hotspots in devices

The region with strong lattice heat generation has dimensions near tens of nanometers and is much smaller than the channel length(50-150nm) and the MFP of phonon.This effect will cause the temperature of phonon ”hotspot” to be larger than that predicted using diffusion theory.

Three main challenges

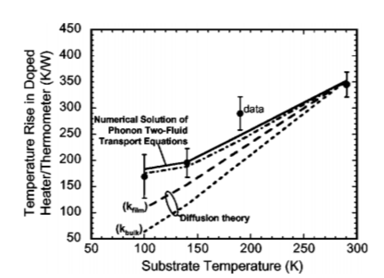


图 13: Data and predictions for the membrane ther- mal resistance as a function of temperature.[2, 5].

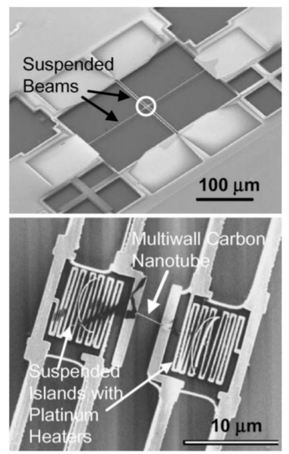


图 14: A multi-structured nano device[3]

What MC method can do?

Three main advantages

- Quantitatively study the phonon scattering effects
- Complicated boundary and transient transport
- Distinguish the different phonon scattering processes

Two main challenges

- Transition between polarizations
- The dispersion relations

Next Work

- Conduct studies on devices and get the temperature profile and focus more on more detailed issues, for example,heat hotspots.
- Consider more complicated and real boundaries conditions and try to improve the MC method(Especially in three-dimensional).
- Based on the above two steps, I will use some Quantum Mechanics Calculation or some experiments to get some essential and better parameters to do the optimization.

My several thoughts.

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