Thermal Challenges in Nanoscale Devices and Packaging

http://nanoheat.stanford.edu

Silicon Nanoelectronics and Beyond
SRC/Intel/NNI Workshop, October 29-30, 2003

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Transistor Thermal Challenges

Transistor Count (millions)

- AMD
- Intel
- PowerPC
- Trend

Power Density (W/cm²)

- AMD
- Intel
- PowerPC
- Trend

Electrostatic Discharge (ESD)

Confined Geometries, Novel Materials
Packaging Work and Challenges

Heat sinks are 3000x larger & heavier than the chip
- They crowd away power deliver components
- Unable to address local chip-level hotspots
- Mixed signal integration competes for I/O area

Grand Challenge – power delivery & heat removal
- Microchannel cooling of chip-level hotspots
- Solid-state electroosmotic pumping
- Thermofluidic CAD

Microprocessor with Integrated Power Module:
(Stanford - MARCO)
Sub-Continuum Heat Transport

- **Macroscale** ($D \gg \Lambda$)
  \[ C_s \frac{\partial T}{\partial t} = \nabla \cdot (k_s \nabla T) + Q'' \]

- **Nanoscale** ($D < \Lambda$)
  \[ \frac{\partial e''}{\partial t} + \vec{v} \cdot \nabla e'' = \frac{e''_{eq} - e''}{\tau_{phon}} + Q'' \]

- **Heat transfer issues**
  - optical-acoustic
  - small heat source
  - impurity scattering
  - boundary scattering
  - boundary thermal res.

**Bulk Devices**

**Thin Body Devices**
Nanodevice Thermal Projections

Extract device self-heating from comprehensive electron-phonon Monte Carlo

Bulk Devices
- optical-acoustic bottleneck
- small heat source
- peak drain T estimate

Thin Body (FD-SOI)
- boundary scattering
- thin, doped layers
- boundary thermal resistance
- role of raised source & drain
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Monet
Fast Monte-Carlo code for computing electron & phonon distributions in nano-electronic devices

What: Monet simulates the flight of several thousand electrons through the silicon lattice and follows them individually as they drift in the electric field, then scatter with phonons, impurities or boundaries, and so on. This is a semi-classical approach because the scattering rates are computed quantum-mechanically from Fermi's Golden Rules using wave function overlap integrals, yet during the free flight between scattering events the particles simply follow Newton’s laws (class). The method is called Monte Carlo (MC) because of the stochastic nature in which the scattering events are simulated: a random number is drawn and compared with a scattering probability, thus the scattering event is chosen based on this comparison.

How: One key ingredient in all such MC codes is the electrostatic model. Monet uses analytic, non-parabolic bands. This is both easier to implement and faster — and it is a reasonable approximation for simulating electron transport in devices with operating voltages below the band gap (1.1 V in silicon), such as future nano-electronic devices. Full-band simulations are only needed to resolve impact ionization and high-band structure transport details. Consequently, Monet ignores sub-band-gap impact ionization. Here’s a short summary of Monet’s main features:

- analytic bands (non-parabolicity 3.5 x 10^-3)
- scattering with all 5 known inter-valley phonons
- separate scattering with inter-valley LA and TA phonons
- full phonon dispersion used in LATT phonon scattering

One of the features that distinguish Monet from other analytic-band MC codes is that all phonon generation and absorption events are tracked. Hence, very detailed heat generation statistics can be gathered. The simulation can be run in a constant E-field to obtain velocity-field curves, electron mobilities or the basic phonon distributions at the given E-field — or in 1-D or 2-D with periodic boundary conditions on an E-field grid extracted from another device simulator like Medici. Monet does not solve the Poisson equation (this is also known as Monte Carlo in the “Born approximation”). The total amount of charge inside the device is given in the previous device simulator and only two device contacts can be included. This implies that electrons entering the device through one contact are immediately injected at the other contact with thermally distributed energies and randomly oriented velocity components. Another feature of Monet is its treatment of acoustic inter-valley scattering. Scattering with LA and TA phonons is treated separately and the full phonon dispersion is used when calculating the acoustic inter-valley scattering rates. The LA/TA scattering deformation potentials are derived from the most recent values of the shear and dilatation potentials available in the literature. Other analytic-band MC codes group LA and TA scattering together and assume a single phonon velocity, i.e., no phonon dispersion.

The following figures illustrate the silicon band diagrams:

The figure on the left (courtesy BHP) shows the full conduction band diagram. The middle figure (courtesy C. Jungemann) shows constant energy contours near the bottom of the conduction band (note the ellipsoidal shape around the minima at 0.05). The third figure shows the ellipsoidal energy pockets “inhibited” by conduction band electrons in an analytic-band MC code like Monet, and the possible phonon scattering transitions.

Here’s a short movie [2.5 MB] of electron trajectories in k-space, with an electric field of -0.6V/cm being turned on at t=0.5 ps: electronmovie.mpq
Summary

- Device dimensions ↓↓, $k_{th} \downarrow$, power (I·V) ↓
  - Result $\rightarrow$ power density and $T \uparrow$
- Fundamental aspects of nano-heating
  - Complex codes fast enough for device design
  - Side-effect $\rightarrow$ compact, physical models
- Nanoscale temperature rise is significant
- Must learn electro-thermal device scaling
- We CAN improve thermal device design
- Need research on thin film phonon dispersion
- New materials & boundary thermal properties
- Strong ties with industry, information sharing
Computed Phonon Generation

Near-full band MC complexity for analytic-band MC speed – towards a device designer’s MC?
Electro-thermal transport in ultra-thin silicon films ($t_{si} \sim 5$ nm): role of electron and phonon confinement
Overview

- Device dimensions scale quicker than power (I·V)
  - Result $\rightarrow$ power density and $T \uparrow$
- Work on fundamental aspects of nano-heating
  - Electron Monte Carlo $\rightarrow$ heat generation rates
  - Phonon Molecular Dynamics $\rightarrow$ scat./transport
- Finite volume methods for BTE
  - Goal: electro-thermal simulator
- Compact, physical models for devices
  - Goal: trends, circuit simulation
- Apply to bulk and SOI/FinFETs
  - Goal: improve device design