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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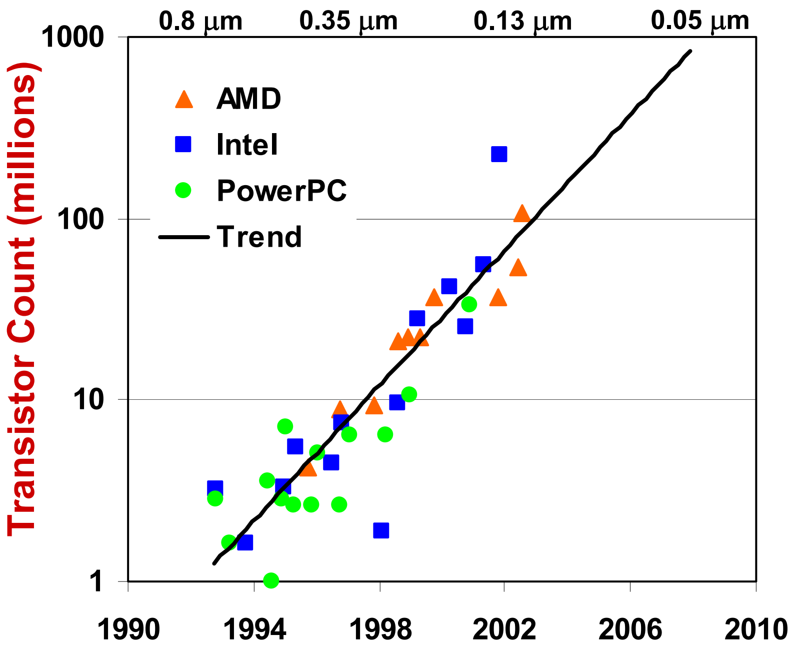
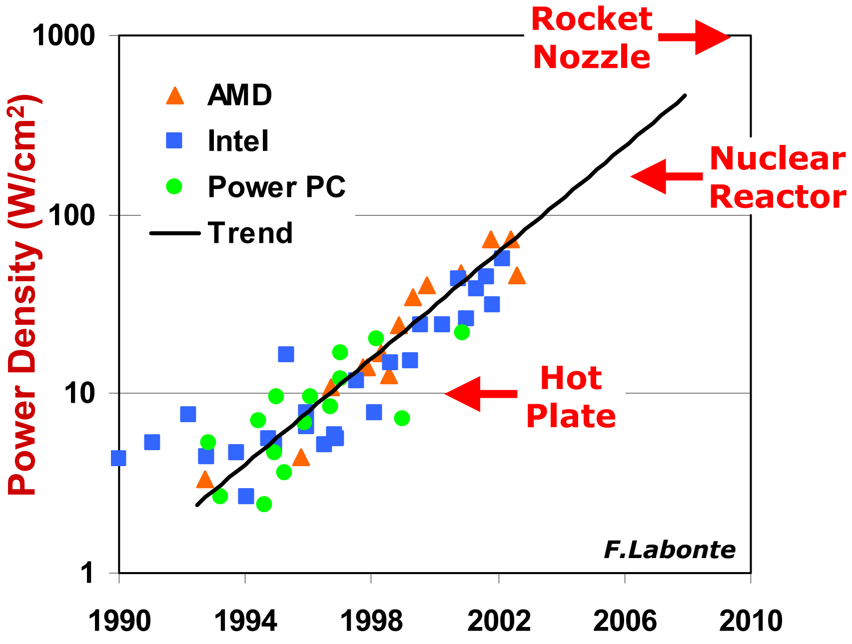
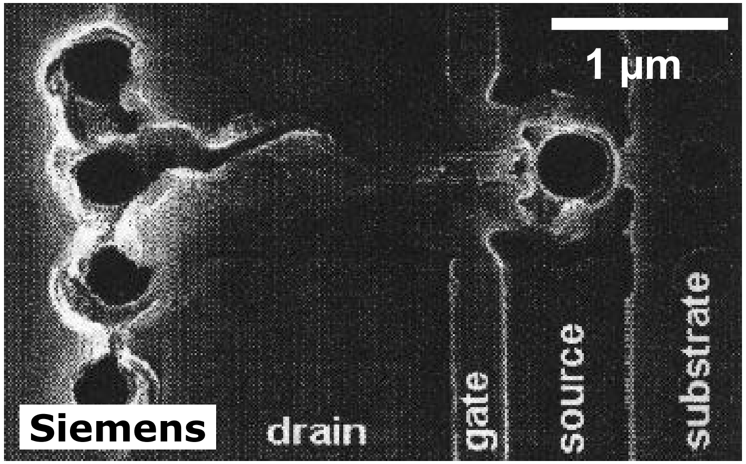
Transistor Thermal Challenges



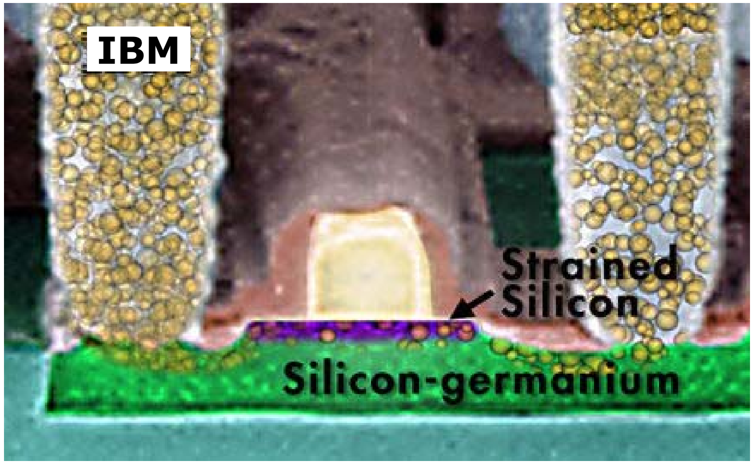


F.Labonte

Electrostatic Discharge (ESD)



Confined Geometries, Novel Materials



Packaging Work and Challenges

Heat sinks are 3000x larger & heavier than the chip

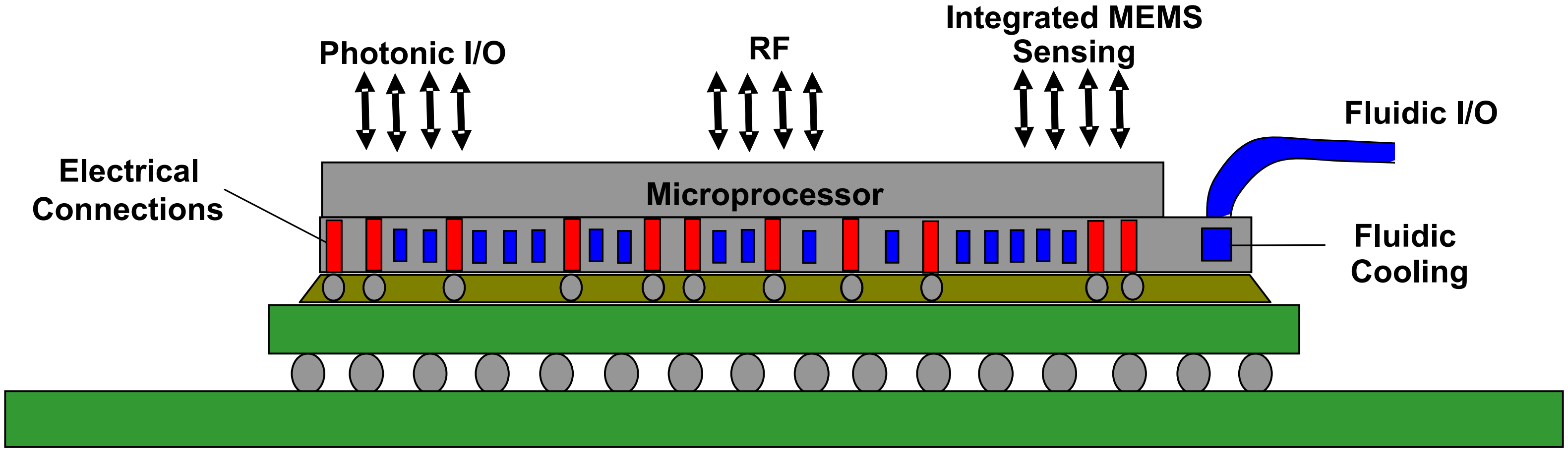
- They crowd away power deliver components
- Unable to address local chip-level hotspots
- Mixed signal integration competes for I/O area

conventional heat sink

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 » Λ)**

$$C_s \frac{\partial T}{\partial t} = \nabla \cdot \left(k_s \nabla T\right) + Q'''$$

- **Nanoscale (D < Λ)**

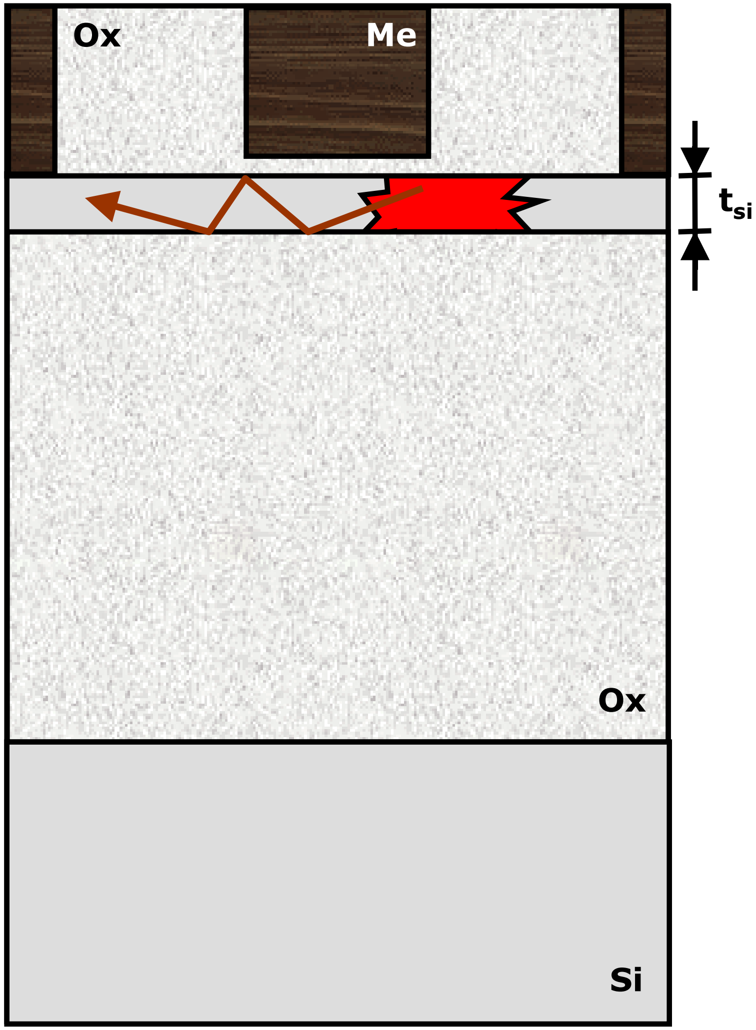
$$\frac{\partial e''}{\partial t} + \vec{v} \cdot \nabla e'' = \frac{e''_{eq} - e''}{\tau_{phon}} + Q'''$$

- **Heat transfer issues**

Bulk Devices

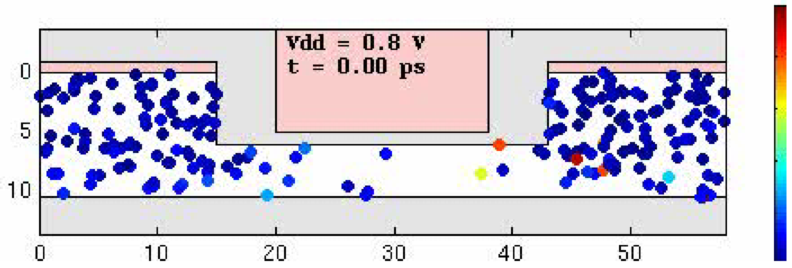
- optical-acoustic
- small heat source
- impurity scattering
- boundary scattering
- boundary thermal res.

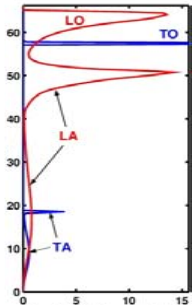
Thin Body Devices



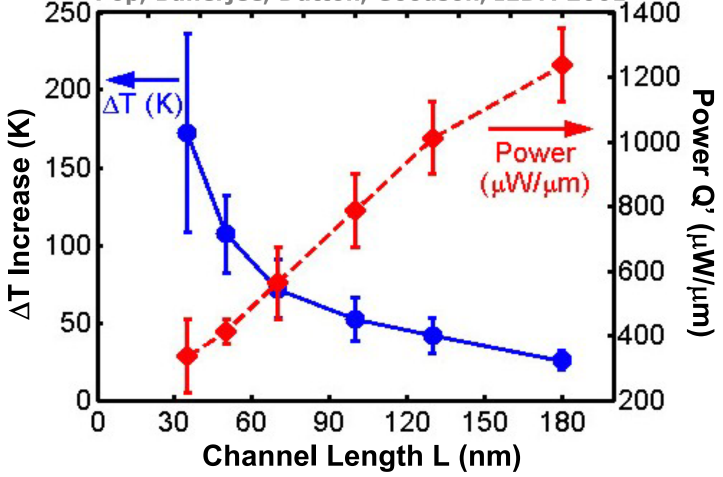
Nanodevice Thermal Projections

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

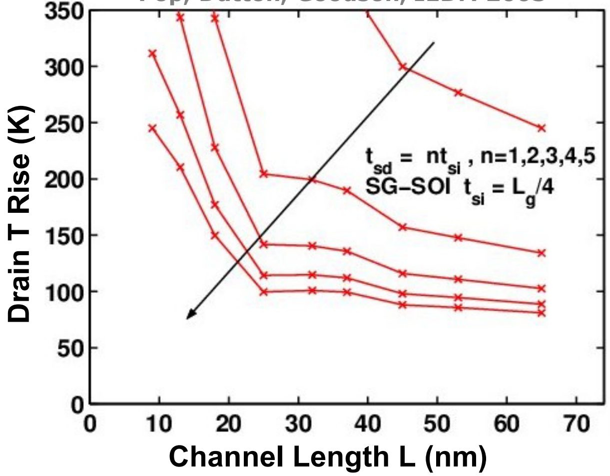




Pop, Banerjee, Dutton, Goodson, *IEDM 2001*



Pop, Dutton, Goodson, *IEDM 2003*



- **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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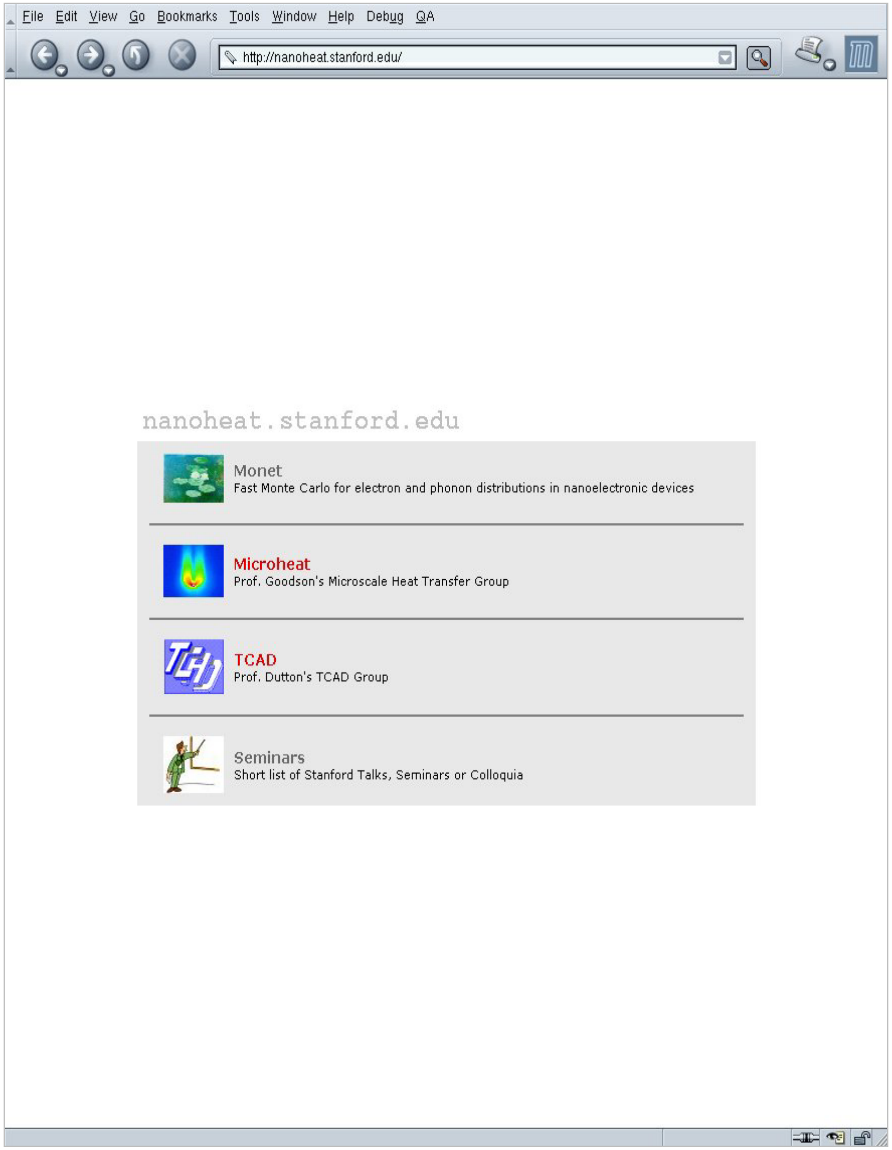

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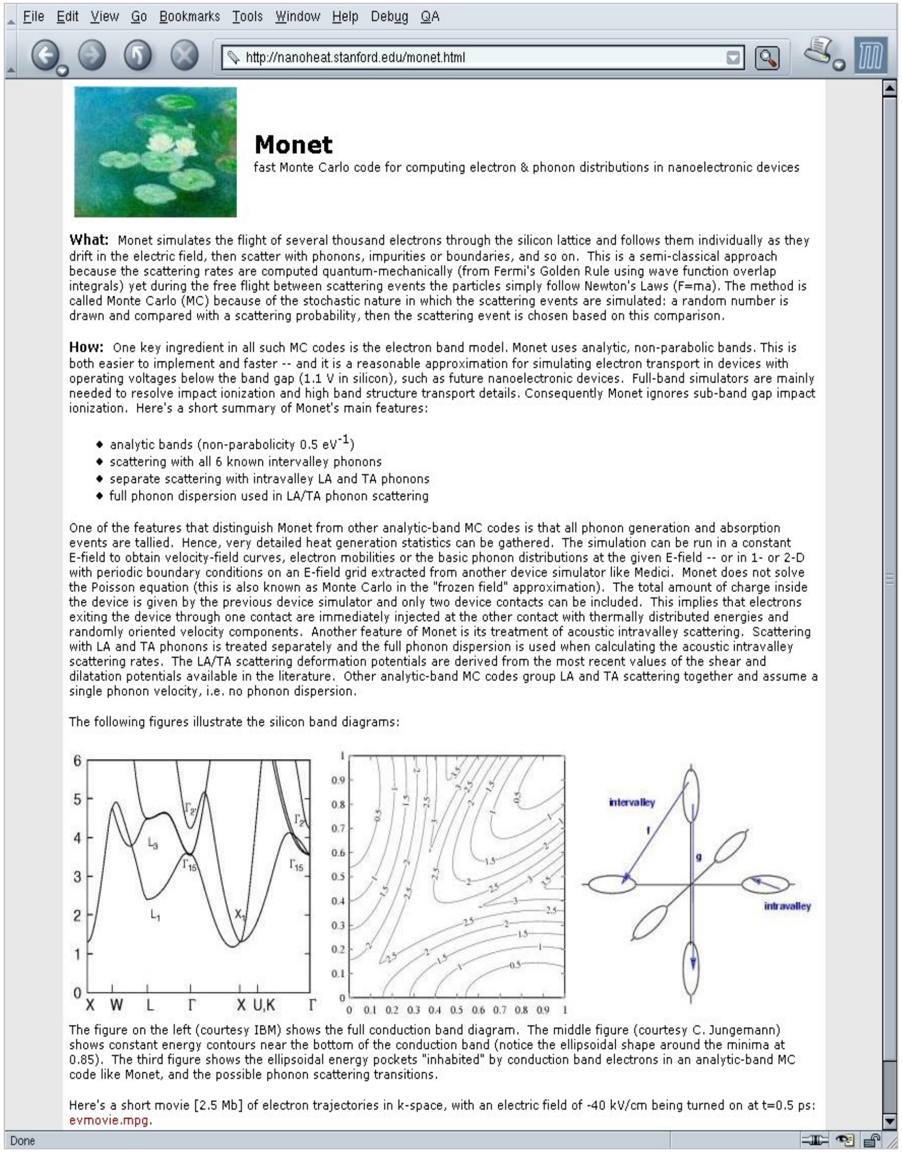
Monet
Fast Monte Carlo for electron and phonon distributions in nanoelectronic devices

Microheat
Prof. Goodson's Microscale Heat Transfer Group

TCAD
Prof. Dutton's TCAD Group

Seminars
Short list of Stanford Talks, Seminars or Colloquia



Monet

fast Monte Carlo code for computing electron & phonon distributions in nanoelectronic 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 Rule using wave function overlap integrals) yet during the free flight between scattering events the particles simply follow Newton's Laws (F=ma). 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, then the scattering event is chosen based on this comparison.

How: One key ingredient in all such MC codes is the electron band 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 nanoelectronic devices. Full-band simulators are mainly 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 0.5 eV^{-1})
- scattering with all 6 known intervalley phonons
- separate scattering with intravalley LA and TA phonons
- full phonon dispersion used in LA/TA phonon scattering

One of the features that distinguish Monet from other analytic-band MC codes is that all phonon generation and absorption events are tallied. 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- 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 "frozen field" approximation). The total amount of charge inside the device is given by the previous device simulator and only two device contacts can be included. This implies that electrons exiting 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 intravalley scattering. Scattering with LA and TA phonons is treated separately and the full phonon dispersion is used when calculating the acoustic intravalley 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.

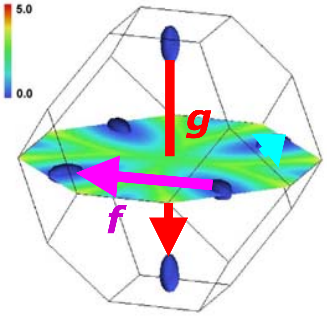
The following figures illustrate the silicon band diagrams:

The figure on the left (courtesy IBM) shows the full conduction band diagram. The middle figure (courtesy C. Jungemann) shows constant energy contours near the bottom of the conduction band (notice the ellipsoidal shape around the minima at 0.85). The third figure shows the ellipsoidal energy pockets "inhabited" by conduction band electrons in an analytic-band MC code like Monet, and the possible phonon scattering transitions.

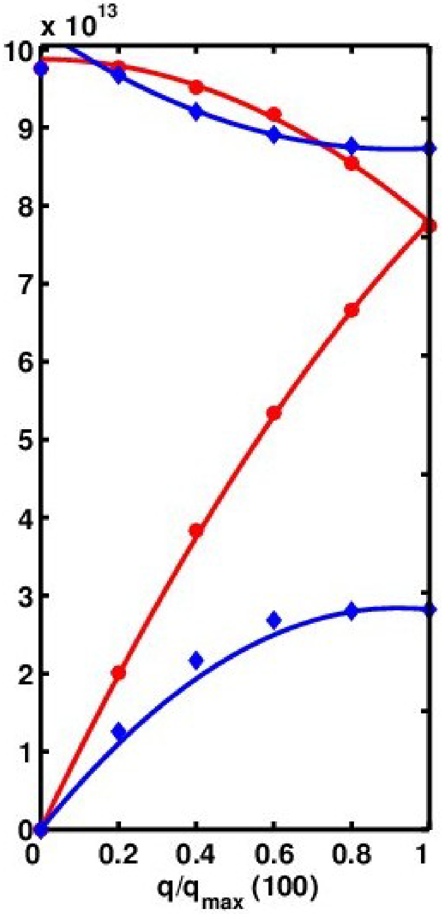
Here's a short movie [2.5 Mb] of electron trajectories in k-space, with an electric field of -40 kV/cm being turned on at t=0.5 ps: evmovie.mpg.

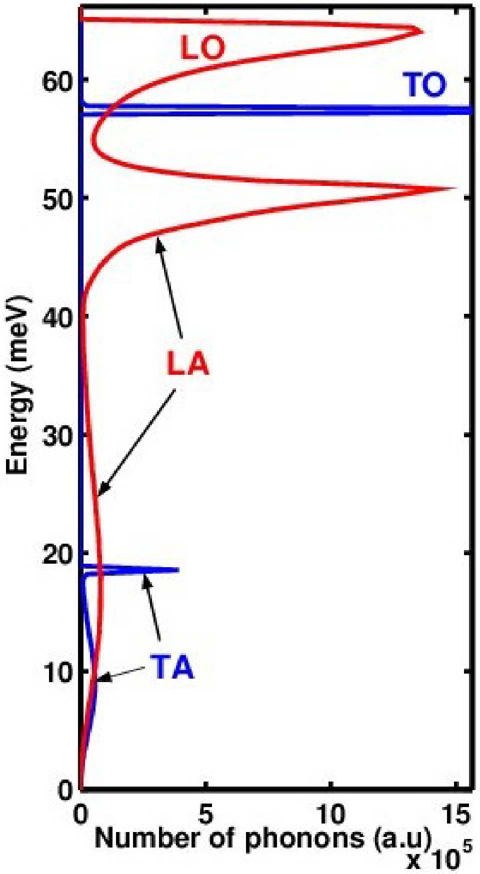
Summary

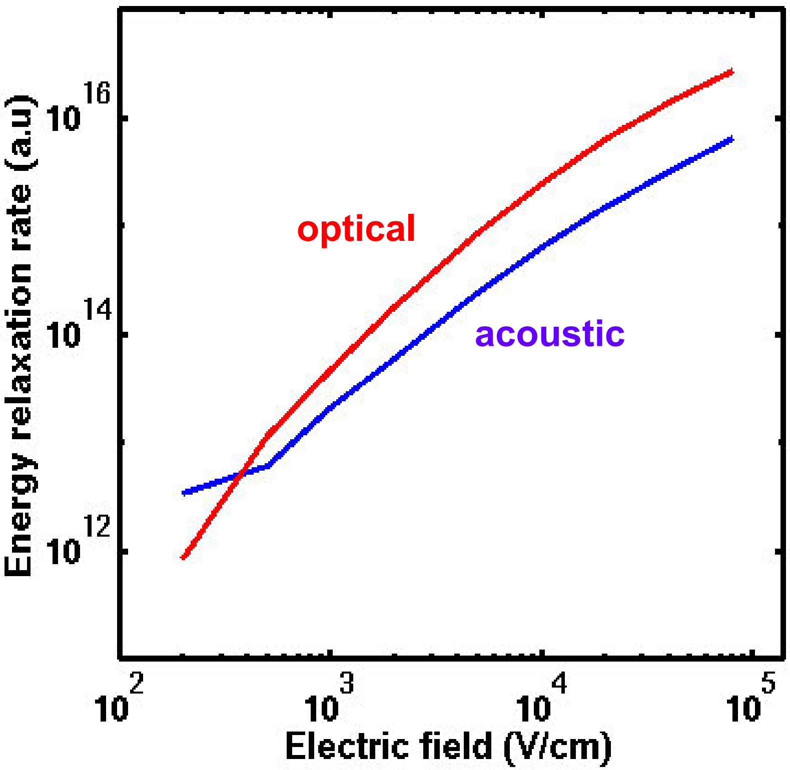
- Device dimensions ↓↓ , k_{th} ↓ , power $(I \cdot V)$ ↓
  - Result → power density and T ↑
- Fundamental aspects of nano-heating
  - Complex codes fast enough for device design
  - Side-effect → compact, physical models
- Nanoscale temperature rise is significant
- Must learn electro-thermal device 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



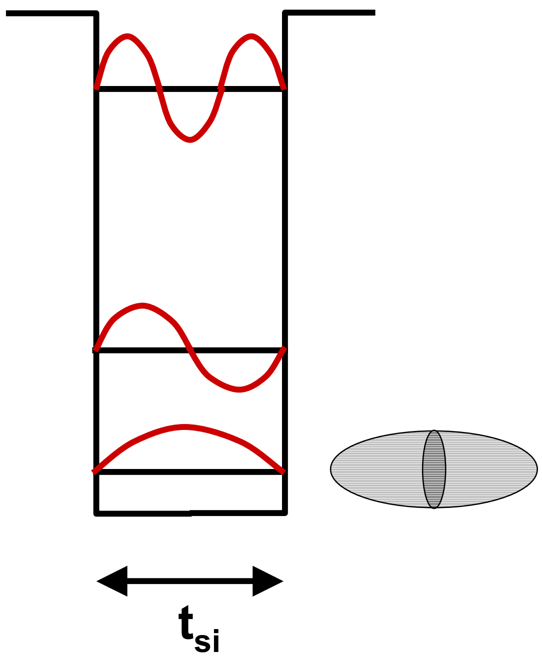




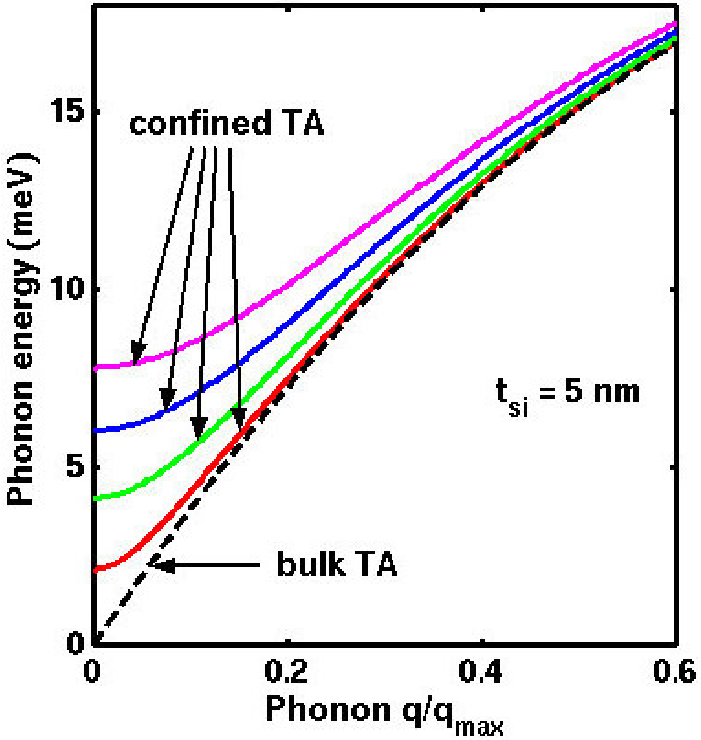
- **Near-full band MC complexity for analytic-band MC speed – towards a device designer's MC?**

Confined Electrons and Phonons

2-D Electrons



2-D Phonons



- **Electro-thermal transport in ultra-thin silicon films (t_{si} ~ 5 nm): role of electron and phonon *confinement***

Overview

- Device dimensions scale quicker than power (I·V)
  - **Result → power density and T ↑**
- Work on fundamental aspects of nano-heating
  - **Electron Monte Carlo → heat generation rates**
  - **Phonon Molecular Dynamics → 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**