Physics of Nanoscale Transistors

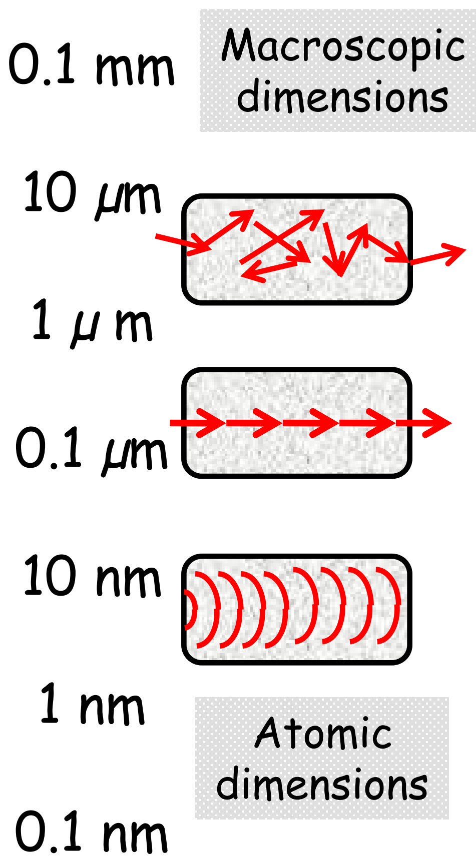
Mark Lundstrom

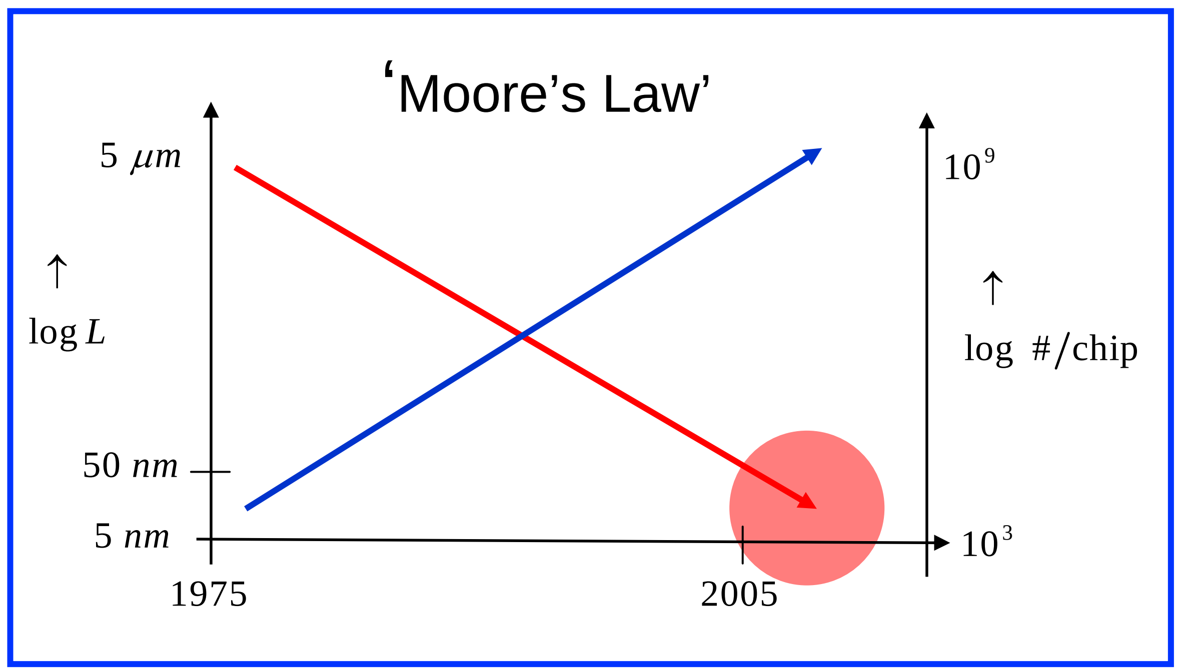
Network for Computational Nanotechnology

Discovery Park, Purdue University

West Lafayette, Indiana USA

Electronics from the Bottom Up





specific objectives

1) To apply the 'electronics from the bottom up' approach to the nanoscale silicon MOSFET.

2) To interpret measured transistor characteristics in terms of this approach.

3) To relate serious simulations to the simple approach presented here.

4) Along the way, to identify research questions that are still open, to discuss the ultimate MOSFET, to indicate how the approach can be applied to other types of transistors (e.g. III-V MOSFETs, nanowire MOSFETs, etc.)

broad objective

To develop a very simple, model that describes the essential physics of a nanoscale MOSFET.

- not a comprehensive course on the Si MOSFET
- not to replace numerical simulation, but to help interpret the results of detailed simulation results.
- to provide a conceptual framework for interpreting experiments, guiding device design, ‘sanity checking’ numerical simulations and compact models.

Physics of Nanoscale MOSFETs

1) Review of MOSFET Fundamentals

2) Elementary Theory of the Nanoscale MOSFET

3A) Theory of the Ballistic MOSFET

3B) Theory of the Ballistic MOSFET

4) Scattering in Nanoscale MOSFETs

5) Application to State-of-the-Art MOSFETs

6) Quantum Transport in Nanoscale MOSFETs

7) Connection to the Bottom Up Approach

lecture 1

1) Review of MOSFET Fundamentals

A quick review of the traditional theory of the MOSFET along with a review of key device performance metrics. A short discussion of the limits of the traditional (drift-diffusion) approach and the meaning of ballistic transport is also included.

lecture 2

2) Elementary Theory of the Nanoscale MOSFET

A very simple (actually overly simple) treatment of the nanoscale MOSFET. This lecture conveys the essence of the approach using only simple mathematics. It sets the stage for the subsequent lectures.

lecture 3A

3A) The Ballistic MOSFET

The *IV* characteristic of the ballistic MOSFET is formally derived. When Boltzmann statistics are assumed, the model developed here reduces to the one presented in lecture 2. There is no new physics in this lesson - just a proper mathematical derivation of the approach that was developed intuitively in lecture 2.

Supplementary material: Notes on Fermi-Dirac Integrals

lecture 3B

3B) The Ballistic MOSFET

This lecture describes how 2D and subthreshold electrostatics are included in the ballistic model.

lecture 4

4) Scattering in Nanoscale MOSFETs

No MOSFET is ever fully ballistic - there is always some carrier scattering. Scattering makes the problem complicated and requires detailed numerical simulations to treat properly. Our objective in this lecture is to present a simple, physical picture that describes the essence of the problem and that allows us to interpret the results of detailed simulations.

lecture 5

5) Application to State-of-the-Art FETs

The previous lessons may seem a bit abstract and mathematical. To see how this all works, we examine measured data and show how the theory presented in the previous lessons help us understand the operation of modern FETs.

lecture 6

6) Quantum Transport in Nanoscale FETs

The previous lessons developed an analytical (or almost analytical) theory of the nanoscale FET, but to properly treat all the details, rigorous computer simulations are necessary. This lecture presents quantum transport simulations that display the internal physics of nanoscale MOSFETs. We use these results to elucidate the physics discussed in previous lessons and to identify issues that still need to be clarified.

lecture 7

7) Connection to the Bottom Up Aproach

While the previous lectures have been in the spirit of the bottom up approach, they did not follow the generic device model of Datta. In this lecture, the ballistic MOSFET theory will be formally derived from the generic model to show the connection.

Physics of Nanoscale Transistors

1) Review of MOSFET Fundamentals

2) Elementary Theory of the Nanoscale MOSFET

3A) Theory of the Ballistic MOSFET

3B) Theory of the Ballistic MOSFET

4) Scattering in Nanoscale MOSFETs

5) Application to State-of-the-Art MOSFETs

6) Quantum Transport in Nanoscale MOSFETs

7) Connection to the Bottom Up Approach

acknowledgement

For help in reviewing my lecture materials, developing the exercises, and running the laboratory sessions, I would like to thank my students:

Yunfei Gao

Changwook Jeong

Yang Liu

Shuaib Salamat