ECE-656: Fall 2017

Electronic Transport in Semiconductors:

A Modern Approach

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PURDUE UNIVERSITY

About this course

This course addresses the fundamentals of charge and heat transport by electrons and phonons − fundamentals that every semiconductor materials and device researcher should **understand** and be able to **apply**.

Learning objectives

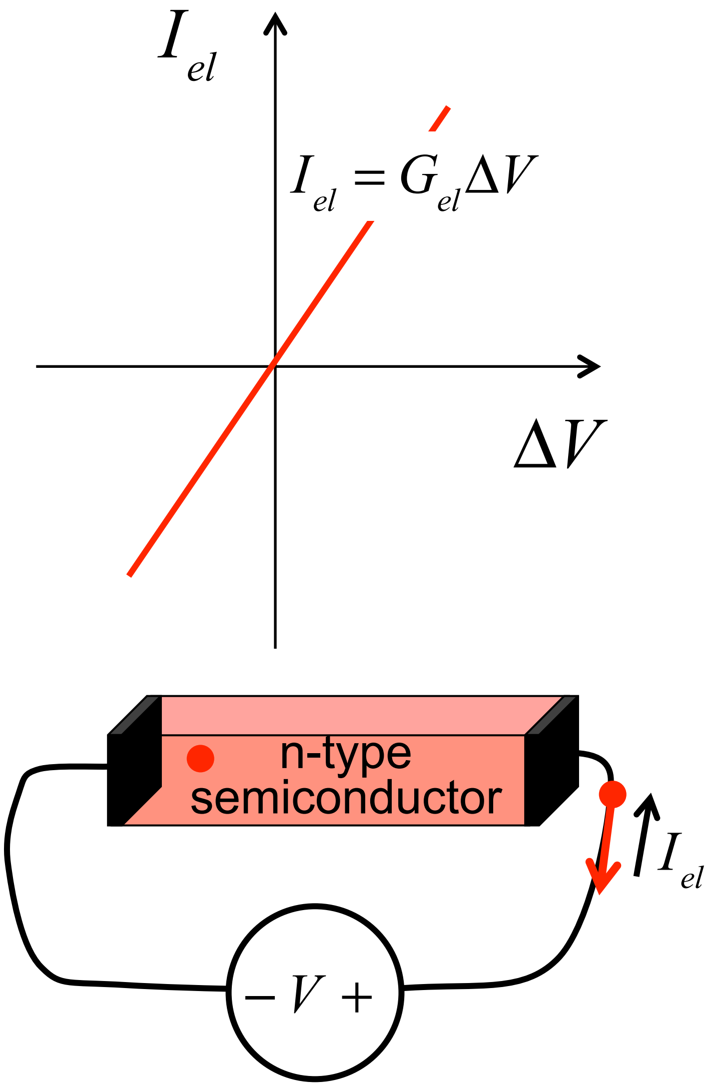
A successful student will have demonstrated:

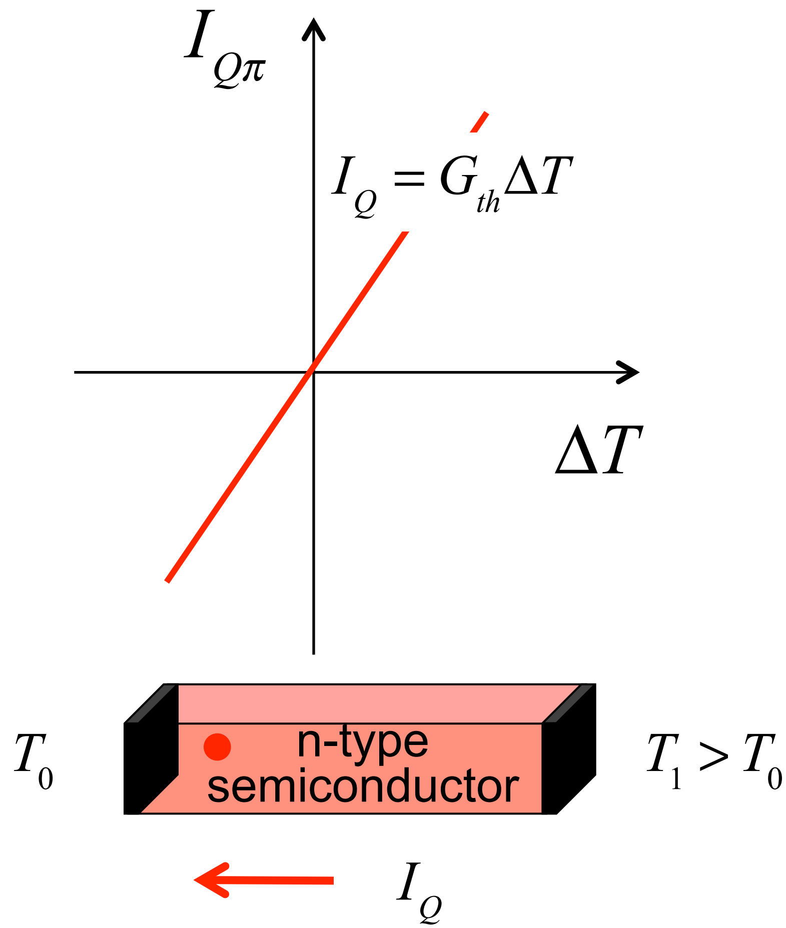
i. An understanding of **electron and phonon scattering** in semiconductors, the Boltzmann Transport Equation (BTE), and how to solve it.

ii. Knowledge of **near-equilibrium semi-classical electron and phonon transport**. An ability to relate transport coefficients to material parameters and to analyze and interpret common measurements.

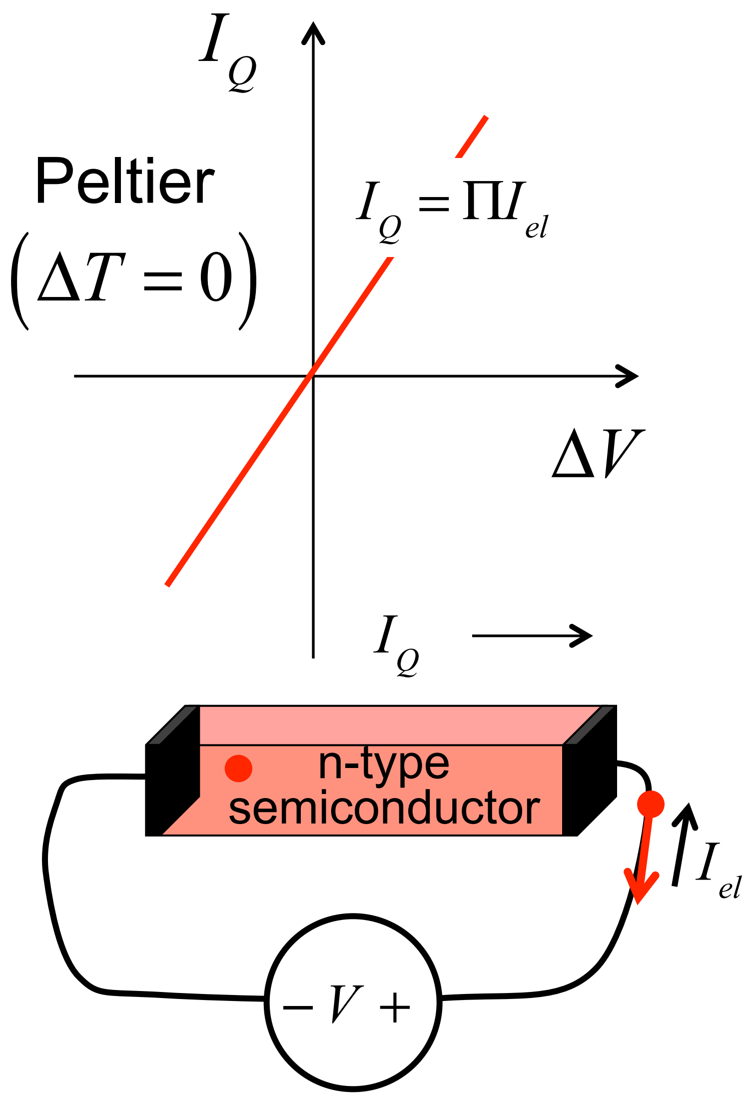
iii. An understanding of **far-from-equilibrium semi-classical transport** in bulk semiconductors and devices and an acquaintance with quantum transport in small devices.

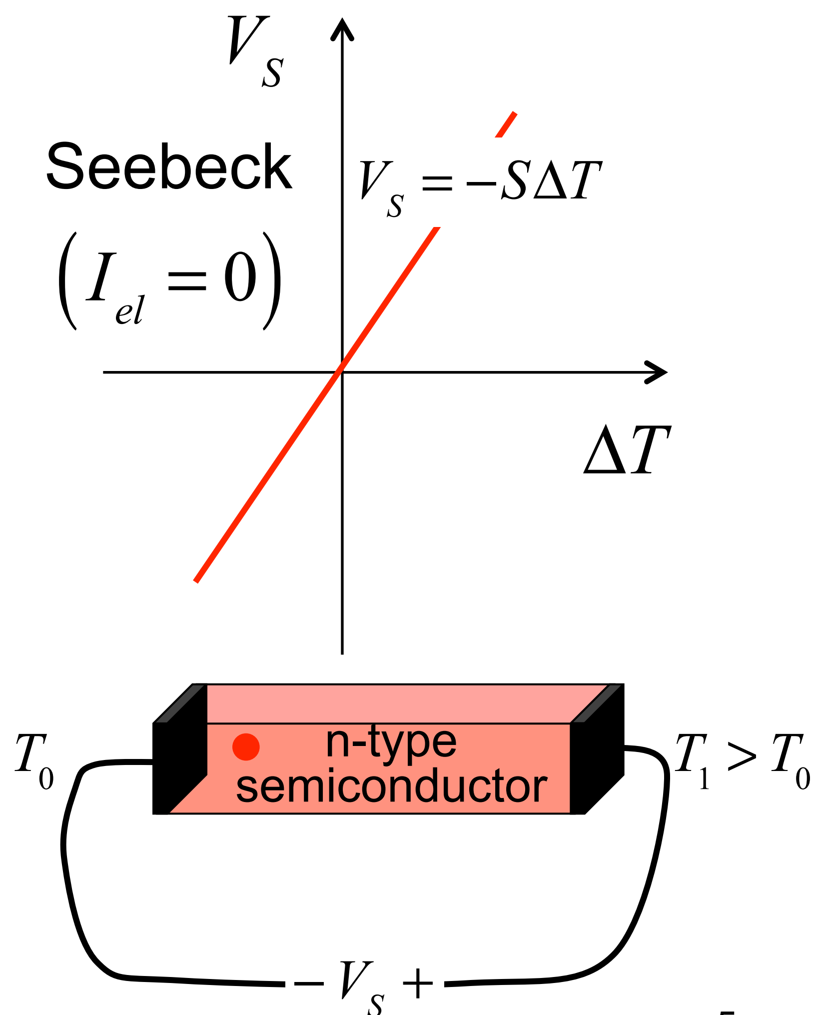
Near-equlibrium (linear) transport



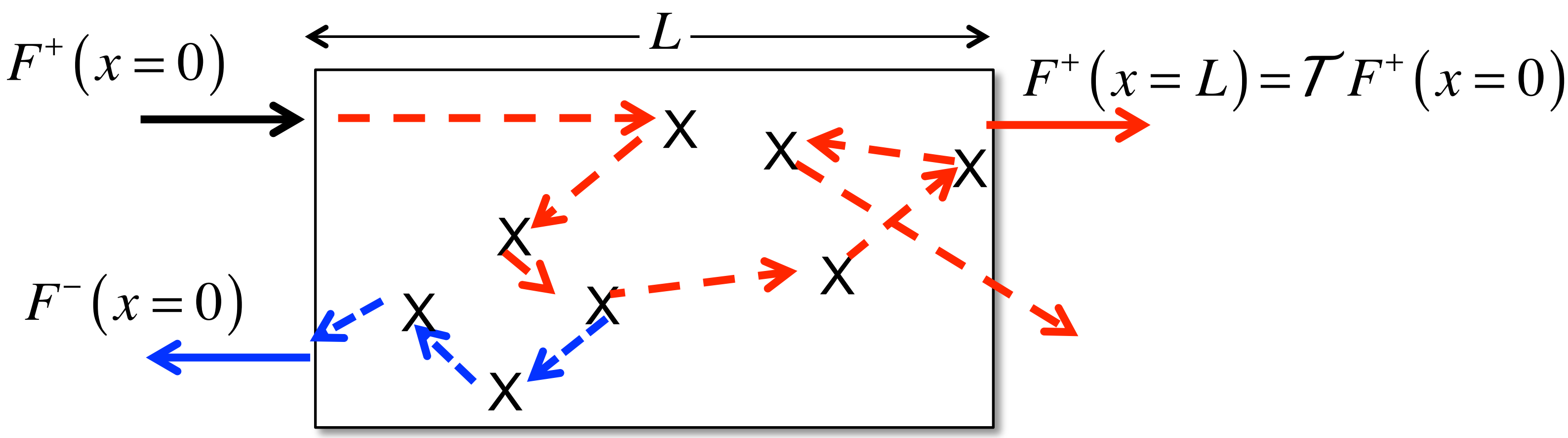


Thermoelectric transport





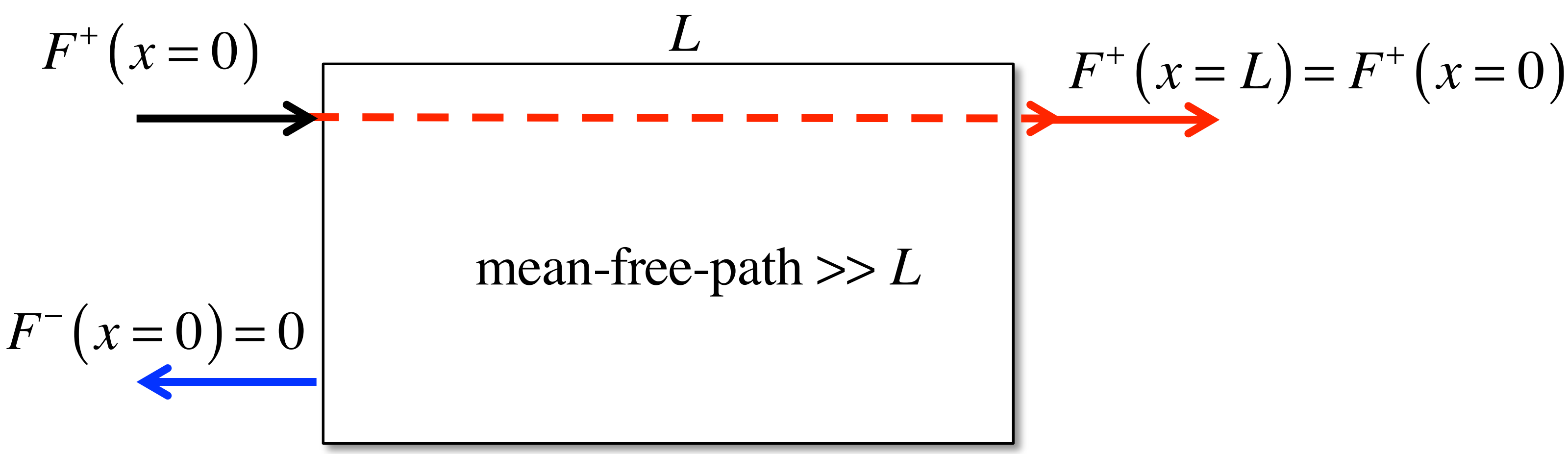
Diffusive vs. ballistic transport



$\mathcal{T} << 1$

"diffusive transport"

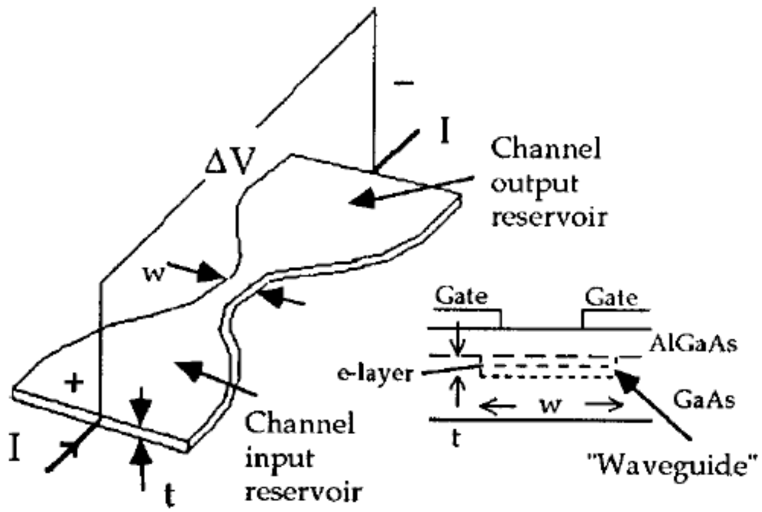
Diffusive vs. **ballistic** transport

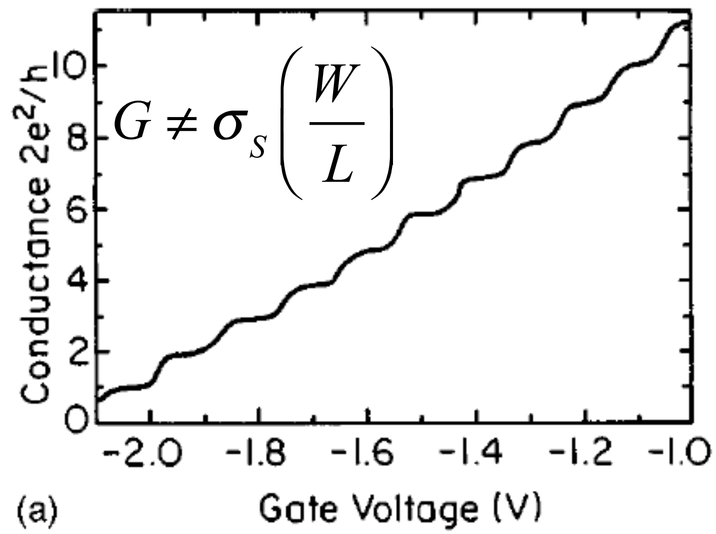


$\mathcal{T}=1$

ballistic transport:

Quantized conduction





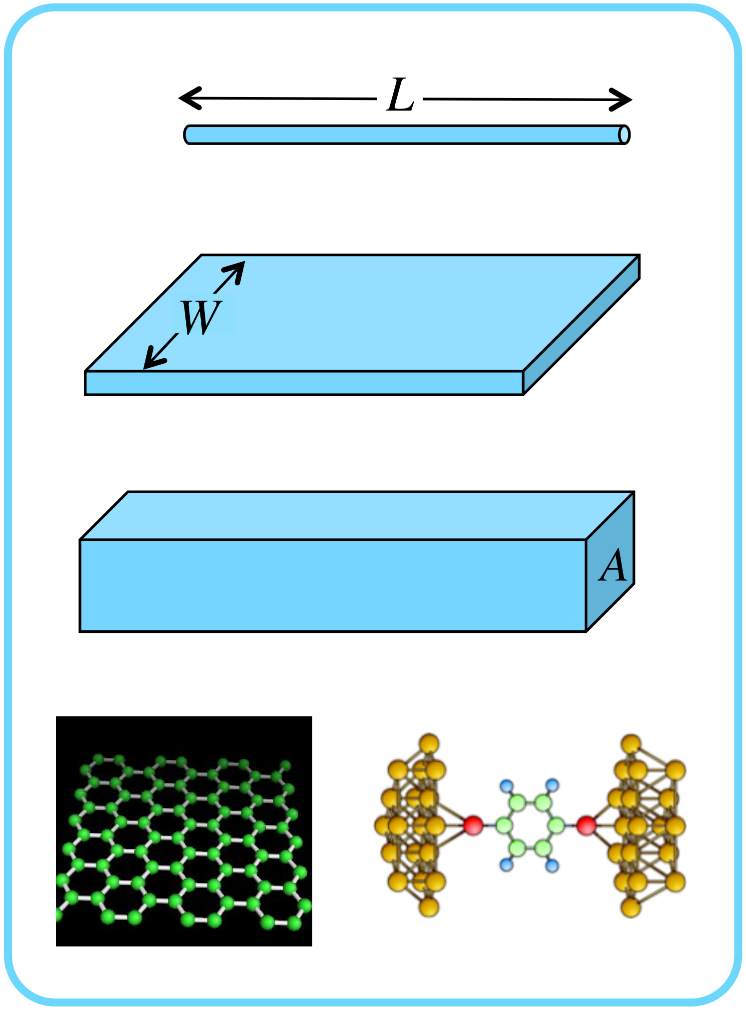
W -->

1) Conductance is quantized in units of $2q^2/h$

2) The conductance is finite $L \rightarrow 0$.

B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, "Quantized conductance of point contacts in a two-dimensional electron gas," *Phys. Rev. Lett.* **60**, 848–851,1988.

Near-equilibrium transport in nanostructures



How do we understand near-equilibrium transport (electrical and heat currents):

- In 1D, 2D, and 3D?
- From the ballistic to diffusive limits?
- In the presence of voltage and temperature differences?
- For any material?

Near-equilibrium transport equations

$$\vec{J}_p = pq\mu_p\vec{\mathcal{E}} - qD_n\nabla p$$

$$\vec{J}_Q = -\kappa\nabla T$$

1) Under what conditions are the drift-diffusion equation and Fourier's Law valid?

2) How are the transport coefficients (mobility, diffusion coefficient, and thermal conductivity) related to material parameters?

The Boltzmann Transport Equation

$$\frac{\partial f}{\partial t} + \vec{\upsilon} \bullet \nabla_r f + \vec{F}_e \bullet \nabla_p f = \hat{C} f$$

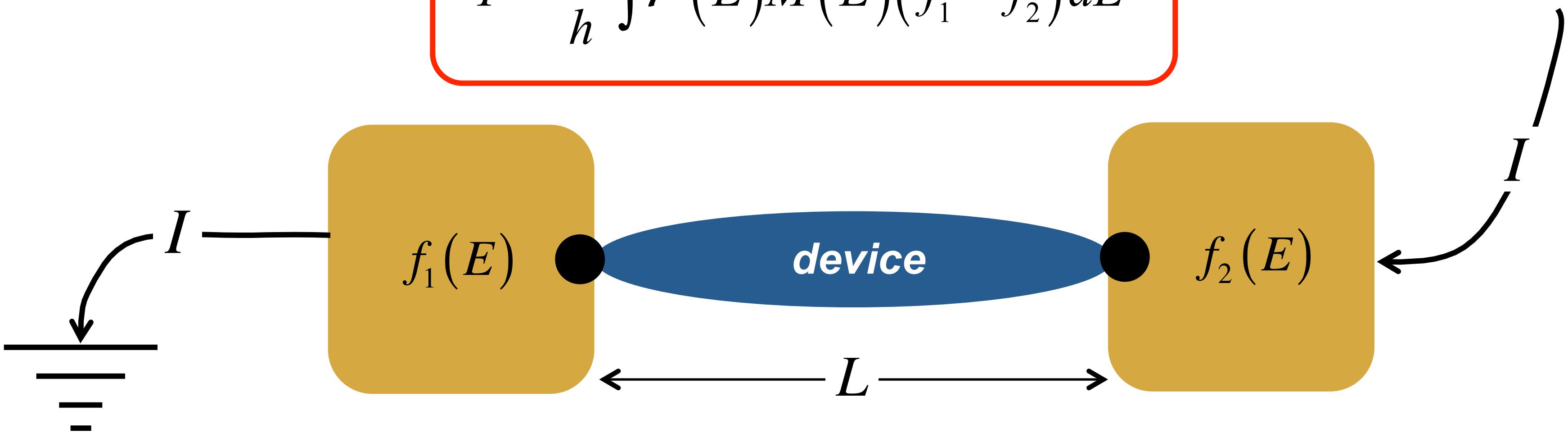
$$f_0 = \frac{1}{1 + e^{(E - E_F)/k_B T}} \qquad f = \frac{1}{1 + e^{(E - F_n)/k_B T}} ?$$

1) The BTE is a highly simplified description of semi-classical transport.

2) The BTE is generally taken as the starting point for semi-classical transport.

The Landauer Approach

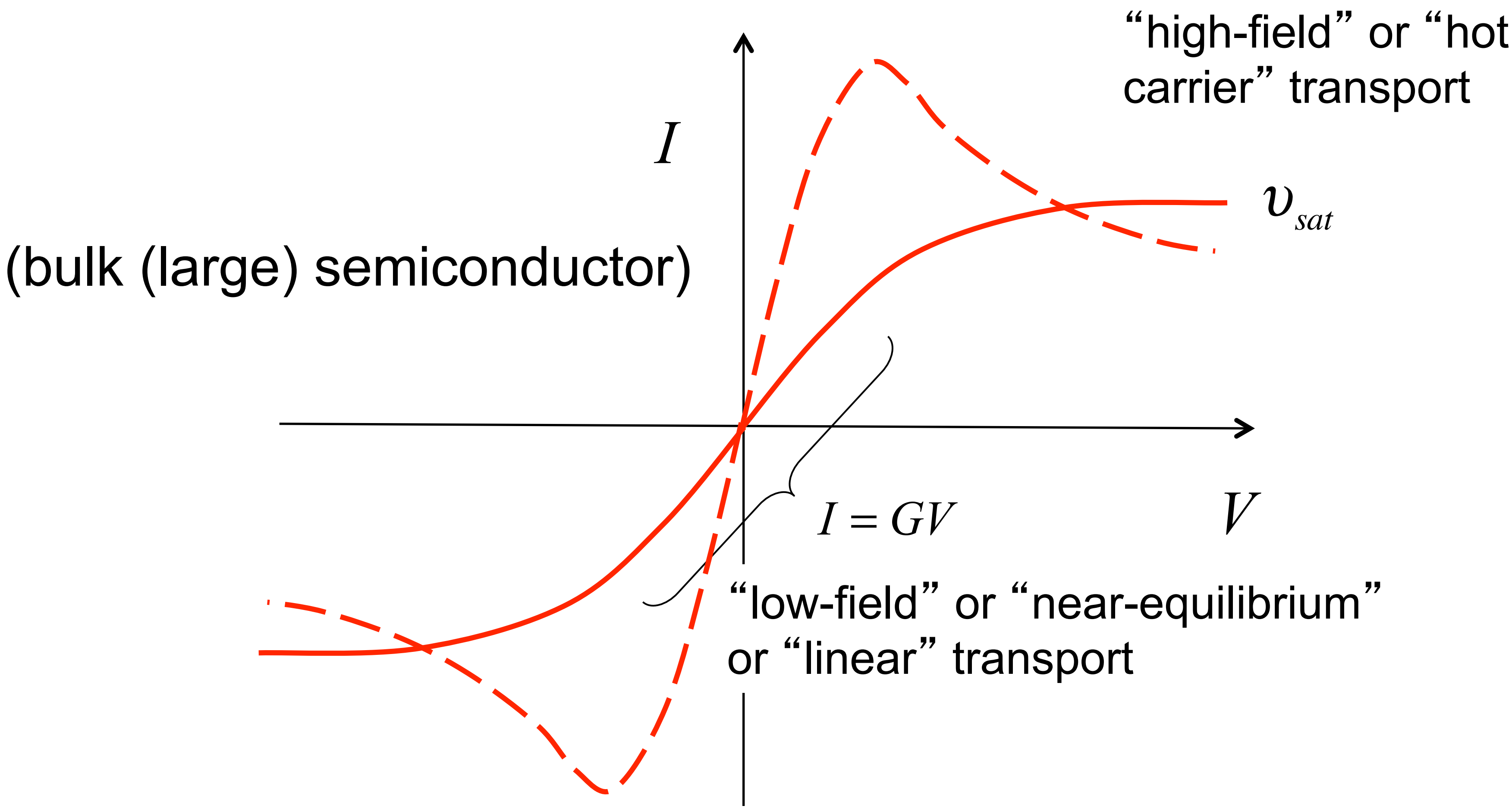
$$I = \frac{2q}{h}\int \mathcal{T}(E)M(E)(f_1 - f_2)\,dE$$



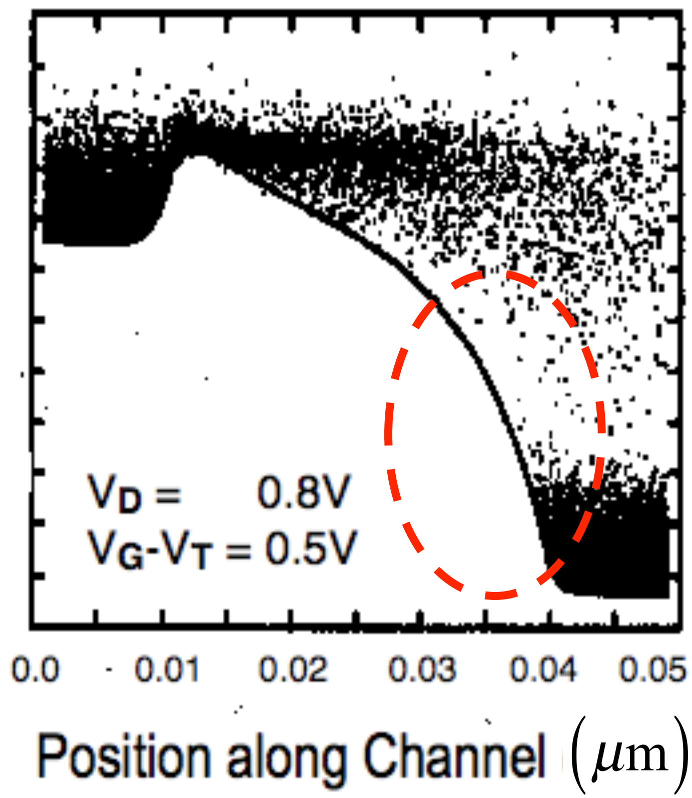
1) Widely-used to describe transport in nanostructures.

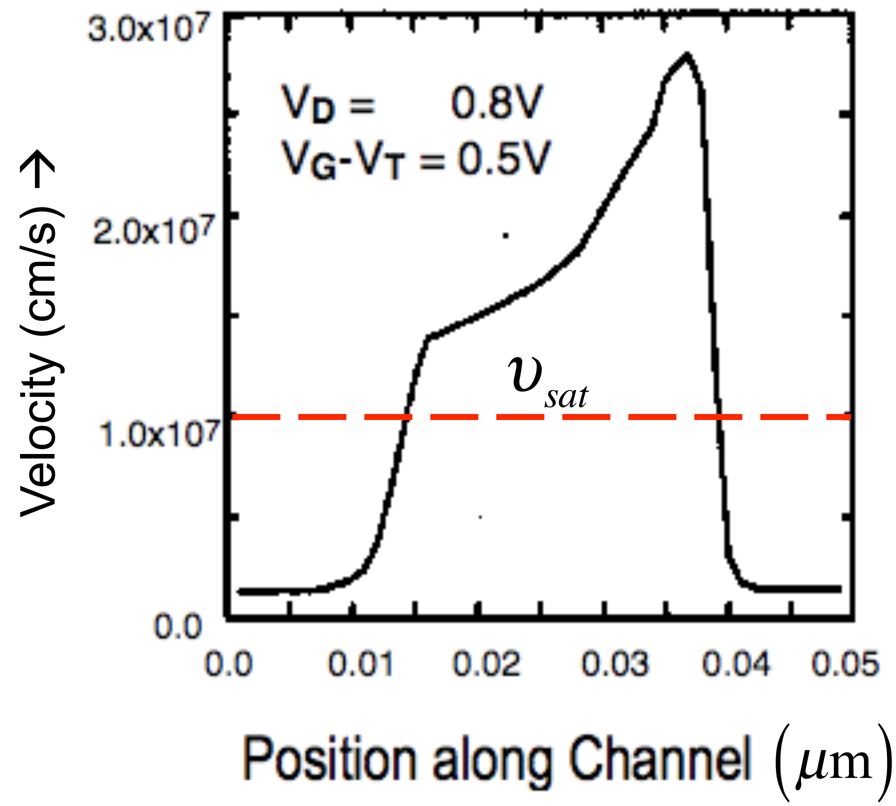
2) We will find that is it useful from the nanoscale to the macroscale, from ballistic to diffusive transport.

Far-from-equilibrium transport (bulk)



Far-from-equilibrium transport (devices)

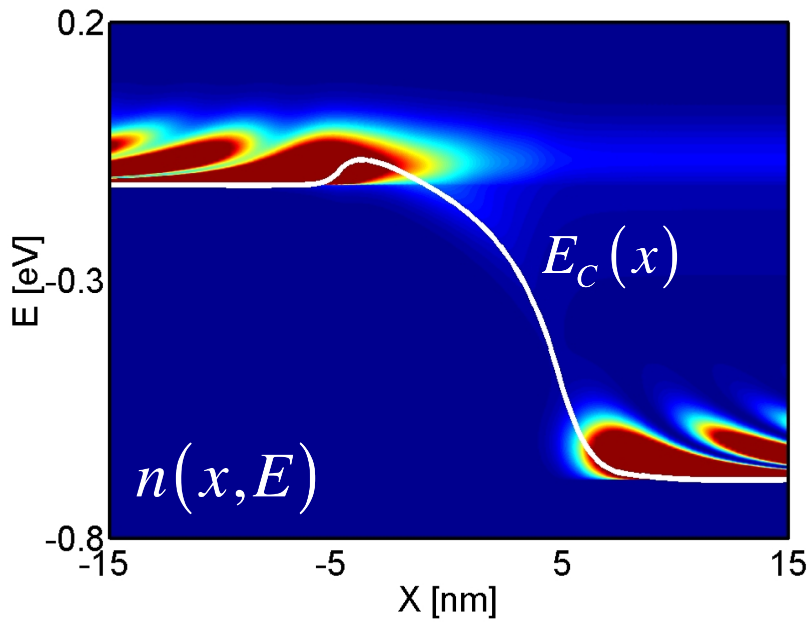




D. Frank, S. Laux, and M. Fischetti, Int. Electron Dev. Mtg., Dec., 1992.

Quantum transport in devices

L = 10 nm, double gate, Si N-MOSFET



nanoMOS (www.nanoHUB.org)

Landauer again

Semi-classical (Boltzmann):

$$\frac{\partial f}{\partial t} + \vec{\upsilon} \bullet \nabla_r f + \vec{F}_e \bullet \nabla_p f = \hat{C} f$$

Quantum (NEGF):

$$\left[G(E,x)\right] = \left[E[I] - [H] - [\Sigma_1] - [\Sigma_2] - [\Sigma_S]\right]^{-1}$$

$$[G^n(x,E)] = [G]\left[\Sigma_1^{in}\right][G]^+ + [G]\left[\Sigma_2^{in}\right][G]^+ + [G]\left[\Sigma_S^{in}\right][G]^+$$

→

Landauer:

$$I = \frac{2q}{h}\int \mathcal{T}(E) M(E)\left(f_1 - f_2\right) dE$$

Course outline

Part 1: Advanced semiconductor fundamentals: 5 weeks

Review of band structure, quantum confinement, DOS,
and treatment of charge carrier and phonon scattering in common semiconductors

Part 2: Near-equilibrium (linear) transport 5 weeks

General model, conductance, thermoelectric effects,
heat transport by phonons, Boltzmann Transport Eq. (BTE),
measurements.

Part 3: Far-from-equilibrium transport 5 weeks

moments of the BTE, Monte Carlo simulation,
hot carrier transport in bulk semiconductors,
ballistic, quasi-ballistic, and non-local transport in devices.
(and quantum transport).

What’s missing from 656?

1) Transport in random media (amorphous and polycrystalline materials).

   “Percolation Theory” by M.A. Alam, 2009.

   http://nanohub.org/resources/7168

2) Electronic noise (shot and thermal noise)

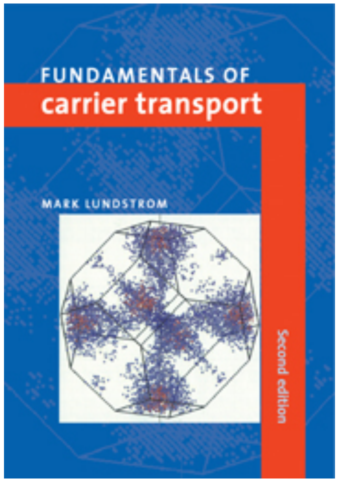
3) ...

About the course

See handout

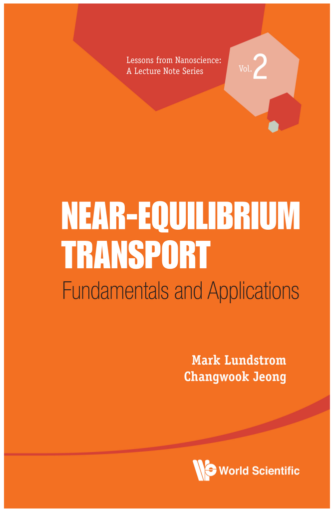
A course in transition...

1) Fundamentals of
Carrier Transport, 2nd Ed.
Mark Lundstrom



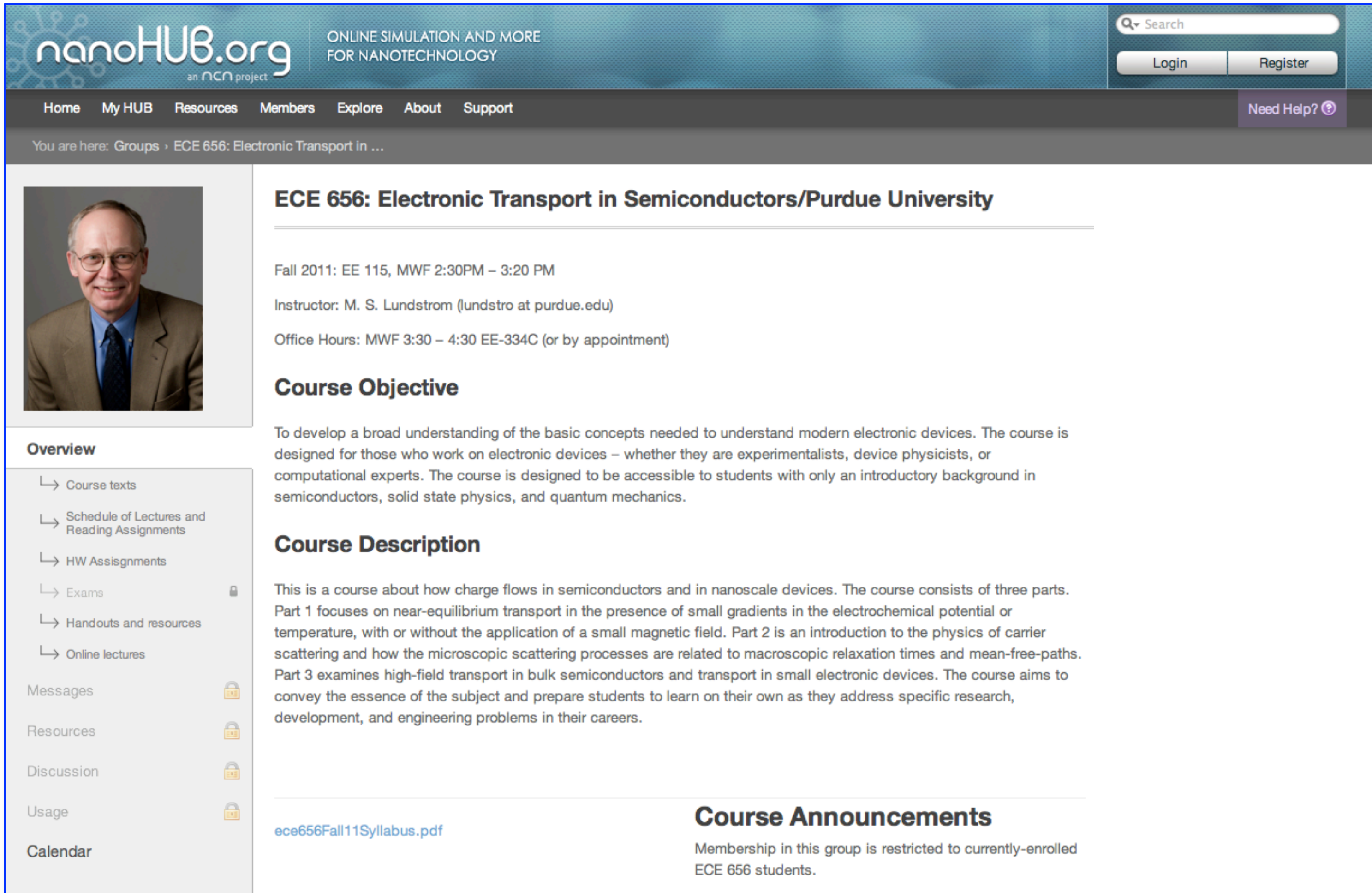
Cambridge Univ. Press, 2000
www.cup.cam.ac.uk/

2) Near-equilibrium Transport:
Fundamentals and Applications
Mark Lundstrom and
Changwook Jeong



World Scientific, 2012
(draft provided to ECE-656 students).

course web page



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Overview
- Course texts
- Schedule of Lectures and Reading Assignments
- HW Assisgnments
- Exams
- Handouts and resources
- Online lectures

Messages
Resources
Discussion
Usage
Calendar

ECE 656: Electronic Transport in Semiconductors/Purdue University

Fall 2011: EE 115, MWF 2:30PM – 3:20 PM

Instructor: M. S. Lundstrom (lundstro at purdue.edu)

Office Hours: MWF 3:30 – 4:30 EE-334C (or by appointment)

Course Objective

To develop a broad understanding of the basic concepts needed to understand modern electronic devices. The course is designed for those who work on electronic devices – whether they are experimentalists, device physicists, or computational experts. The course is designed to be accessible to students with only an introductory background in semiconductors, solid state physics, and quantum mechanics.

Course Description

This is a course about how charge flows in semiconductors and in nanoscale devices. The course consists of three parts. Part 1 focuses on near-equilibrium transport in the presence of small gradients in the electrochemical potential or temperature, with or without the application of a small magnetic field. Part 2 is an introduction to the physics of carrier scattering and how the microscopic scattering processes are related to macroscopic relaxation times and mean-free-paths. Part 3 examines high-field transport in bulk semiconductors and transport in small electronic devices. The course aims to convey the essence of the subject and prepare students to learn on their own as they address specific research, development, and engineering problems in their careers.

ece656Fall11Syllabus.pdf

Course Announcements

Membership in this group is restricted to currently-enrolled ECE 656 students.

https://nanohub.org/groups/ece656_f17