ECE-656: Fall 2013

Fundamentals of Carrier Transport

Professor Mark Lundstrom
Electrical and Computer Engineering
Purdue University, West Lafayette, IN USA
DLR-103 and EE-334C / 765-494-3515
lundstro at purdue.edu

nanoHUB.org

8/19/13

PURDUE UNIVERSITY

course objectives

» *To **introduce** students to the fundamentals of charge carrier transport in semiconductor materials and devices.*

» To give students a **foundation**, a starting point, so that they can learn what they need to when confronted with new problems.

designed for students interested in building, designing, analyzing, and/or simulating electronic devices.

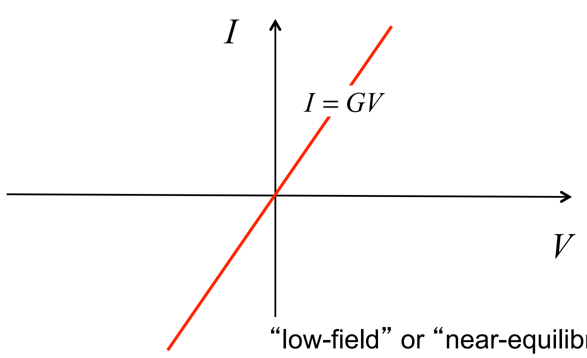
course outline

Part 1: Advanced Semiconductor fundamentals: 5 weeks
Reivew of bandstructure, quantum confinement, DOS, and treatment of carrier scattering in common semiconductors

Part 2: Near-equilibrium transport 5 weeks
general model, conductance, thermoelectric effects Boltzmann Transport Eq. (BTE), measurements

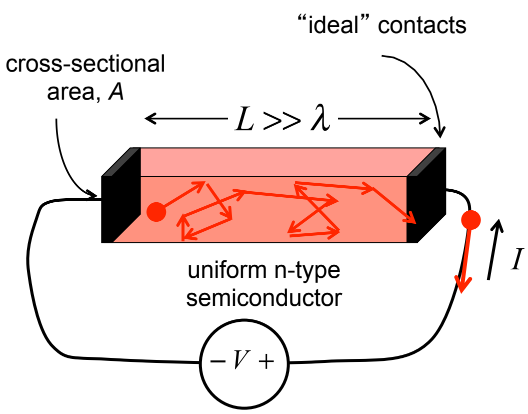
Part 3: Far from equilibrium transport 5 weeks
moments of the BTE, Monte Carlo and quantum transport simulation, hot carrier transport in bulk semiconductors ballistic, quasi-ballistic, and non-local transport in devices

near-equlibrium transport



"low-field" or "near-equilibrium" or "linear" transport

near-equilibrium, diffusive transport



$R = \rho L/A \qquad \rho = 1/nq\mu_n$

1) random walk with a small bias from left to right

2) electric field

$$\mathcal{E}_x = -\frac{dV}{dx} = -\frac{V}{L}$$

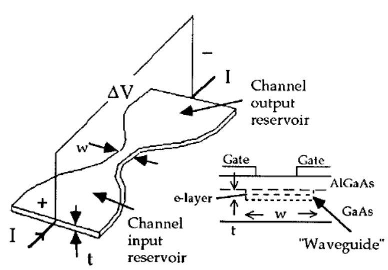
3) force on an electron

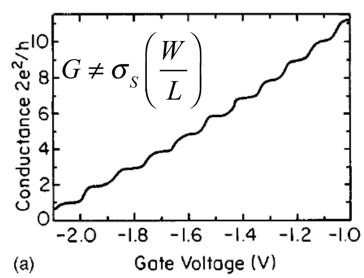
$$F_e = -q\mathcal{E}_x$$

4) average velocity:

$$\upsilon_d = -\mu_n \mathcal{E}_x$$

near-equilibrium, ballistic transport





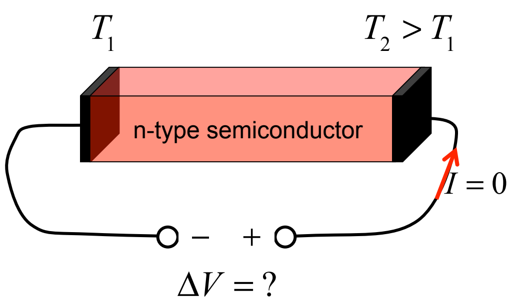
W -->

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.

thermoelectric effects



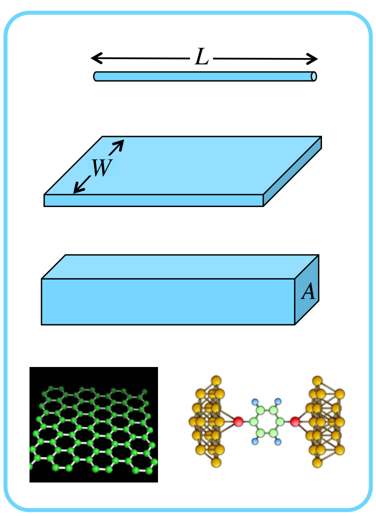
$$\Delta V = -S\Delta T$$

S is the "Seebeck coefficient" in V/K

S < 0 for n-type conduction

S is also called the "thermopower"

more generally



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

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

near-equilibrium transport theories

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

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

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

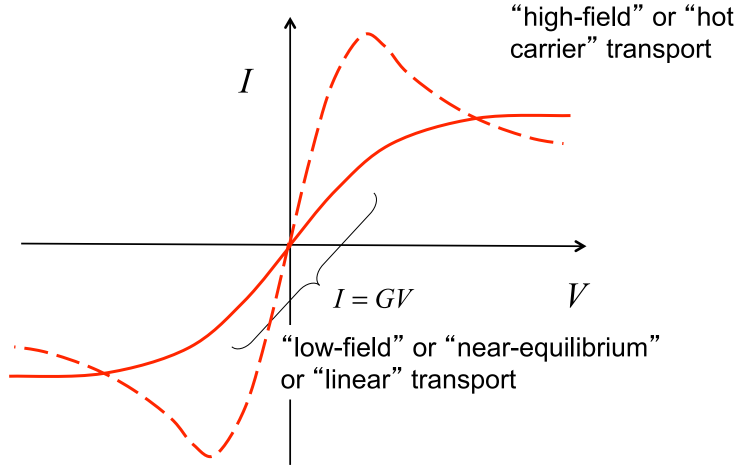
near-equilibrium transport theories

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

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

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

carrier transport in bulk semiconductors



hot carrier transport theories

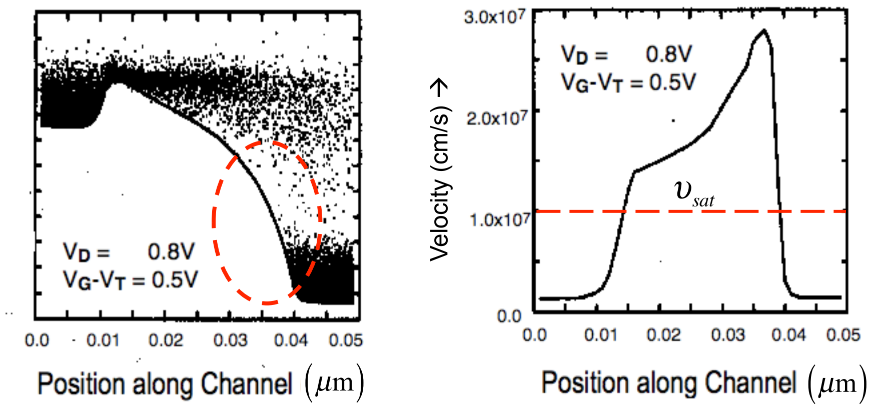
$$\vec{J}_p = pq\mu_p(\mathcal{E})\vec{\mathcal{E}} - qD_n(\mathcal{E})\vec{\nabla}p$$

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

$$\vec{J}_p = pq\mu_p(W)\vec{\mathcal{E}} - \frac{2}{3}\mu_p(W)\vec{\nabla}W$$

Monte Carlo simulation

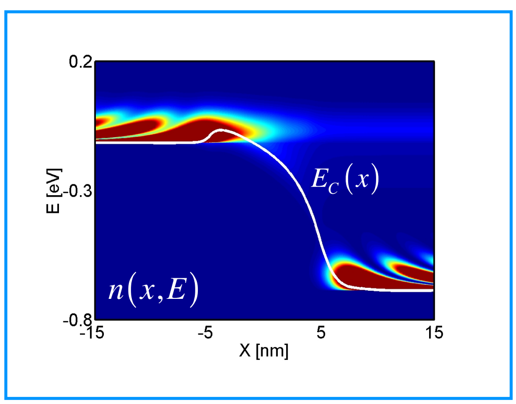
non-local carrier transport in devices



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)

course outline

Part 1: Advanced Semiconductor fundamentals: 5 weeks

Reivew of bandstructure, quantum confinement, DOS, and treatment of carrier scattering in common semiconductors

Part 2: Near-equilibrium transport 5 weeks

general model, conductance, thermoelectric effects Boltzmann Transport Eq. (BTE), measurements

Part 3: Far from equilibrium transport 5 weeks

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

what's missing from 656?

Transport in random media (amorphous and polycrystalline materials).

"Percolation Theory" by M.A. Alam, 2008.

http://nanohub.org/resources/7168

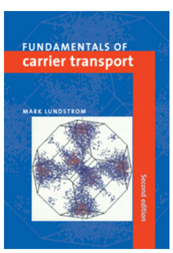
course prerequisites

» Introductory level understanding of semiconductor physics and devices (ECE 606 at Purdue).

» "Fundamentals of Nanoelectronics" (Datta – Purdue) and a course on solid-state physics (e.g. Phys. 545 at Purdue) are helpful, but not essential.

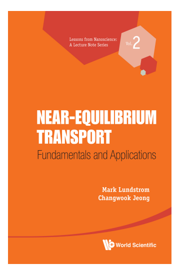
course texts

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



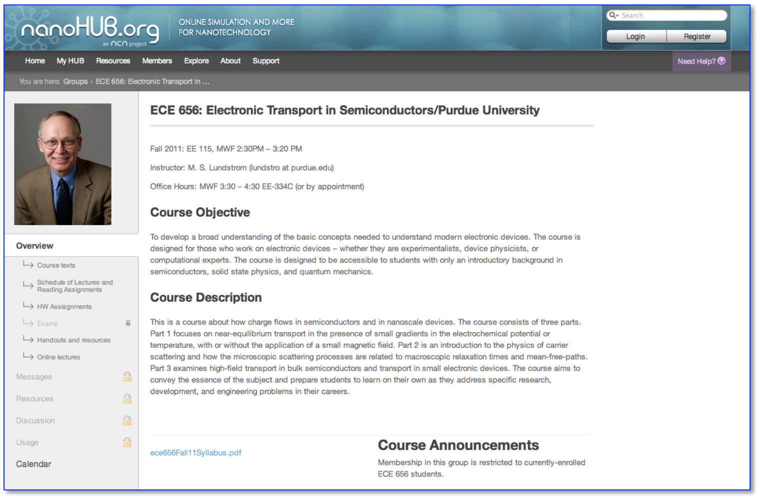
Cambridge Univ. Press, 2000
www.cup.cam.ac.uk/

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



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

course web page



https://nanohub.org/groups/ece656_f13

course format: "flipped"

Week 1: Introduction (Week of 8.19.13)

Reading Assignment: FCT 1.1-1.4.1, 1.5 / NET 1.1-1.7

L1: Course Introduction slides (1.9 Mb)
L2: ECE 656 Lecture 1: Bandstructure Review
L2a: ECE 656 Lecture 33: Heterostructures (Slides 2-11)
Week1 L2 Quiz (370.71 Kb)
L3: ECE 656 Lecture 2: Sums in k-Space/Integrals in Energy Space
Week1 L3 Quiz (279.61 Kb)

Week1 HW Assignment (415.61 Kb)
Week 1 Homework Solutions
Week 1 Quiz Answers

Week 1: References and Supplementary Information
Week 1 References (83.11 Kb)
Notes on FD Integrals (213.96 Kb)
Heterostructure Fundamentals (2.69 Mb)

http://nanohub.org/groups/ece656_f13

grading

Lecture quizzes and questions: **25%**

Exams (best 5 out of 6 at 15% each) **75%**

Quiz score = x/total times 25%, where x is the number of quizzes you turned in and passed and total is the total number of lectures in the course.

Exam score = average of the percentage scores of the 5/6 best exams scores including up to two **retakes**.

Approximate curve:

A:	91 – 100%
B:	81 – 90%
C:	71 – 80%
D:	61 – 70%
F:	60% or less

course outcomes

1) Understand advanced semiconductor fundamentals such as bandstructure, density-of-states, quantum confinement, and **carrier scattering.**

2) Understand the **Landauer Approach** to carrier transport and be able to use it to treat carrier transport in nanoscale structures as well as in bulk semiconductors.

3) Be able to derive, understand, and use the **coupled current equations** that describe near-equilibrium charge and heat transport by electrons and heat transport by phonons and be acquainted with basic, near-equilibrium **semiconductor measurement techniques.**

4) Be familiar with the **Boltzmann Transport Equatio**n (BTE) and how to solve it under near-equilibrium conditions with and without a magnetic field applied.

5) Be acquainted with the treatment of **far from equilibrium transport** with moments of the BTE, by Monte Carlo simulation, and by quantum transport. Understand high-field or “hot carrier” transport in bulk semiconductors.

6) Appreciate **the non-local, ballistic and quasi-ballistic transport** effects that occur in modern semiconductor devices.

Why flipped?

I believe that it is a better way to learn the material.

It will help you become self-learners, which is what you will be doing for the rest of your careers.

Technology is going to re-shape education; we need to figure out how to use new technologies most effectively.

It's going to take some trial and error, and there may be mid-course corrections, but please give it a try and give me your feedback.

Steven Chu:

"Learning science and thinking about science or reading a paper in science is not about learning what a person did. You have to do that, but **to really absorb it, you have to turn it around** and cast it in a form as if you invented it yourself. … you **try to internalize it in such a way that it really becomes intuitive.**"

wrap up

No class Wed, Aug. 21 and no office hours Tuesday, 8.19

See Vicki Johnson in DLR 103 to get your copy of NET

Friday: Hand in the week's quizzes and question
20 minute summary lecture
Questions, answers, discussion

In general (subject to change)

No class on Mondays
Discuss HW and Q&A on Wednesdays
Turn in quizzes and summarize the week on Fridays