Lecture 0: Introduction

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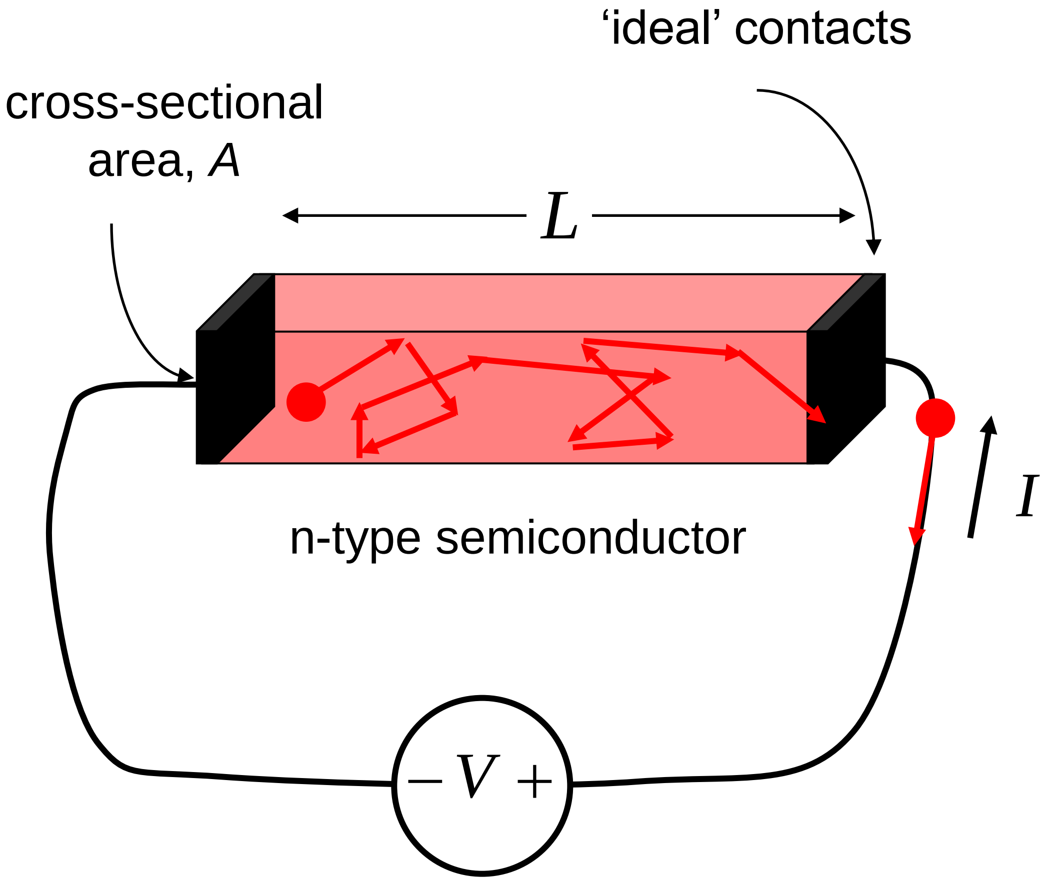
carrier transport in semiconductors



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

2) electric field

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

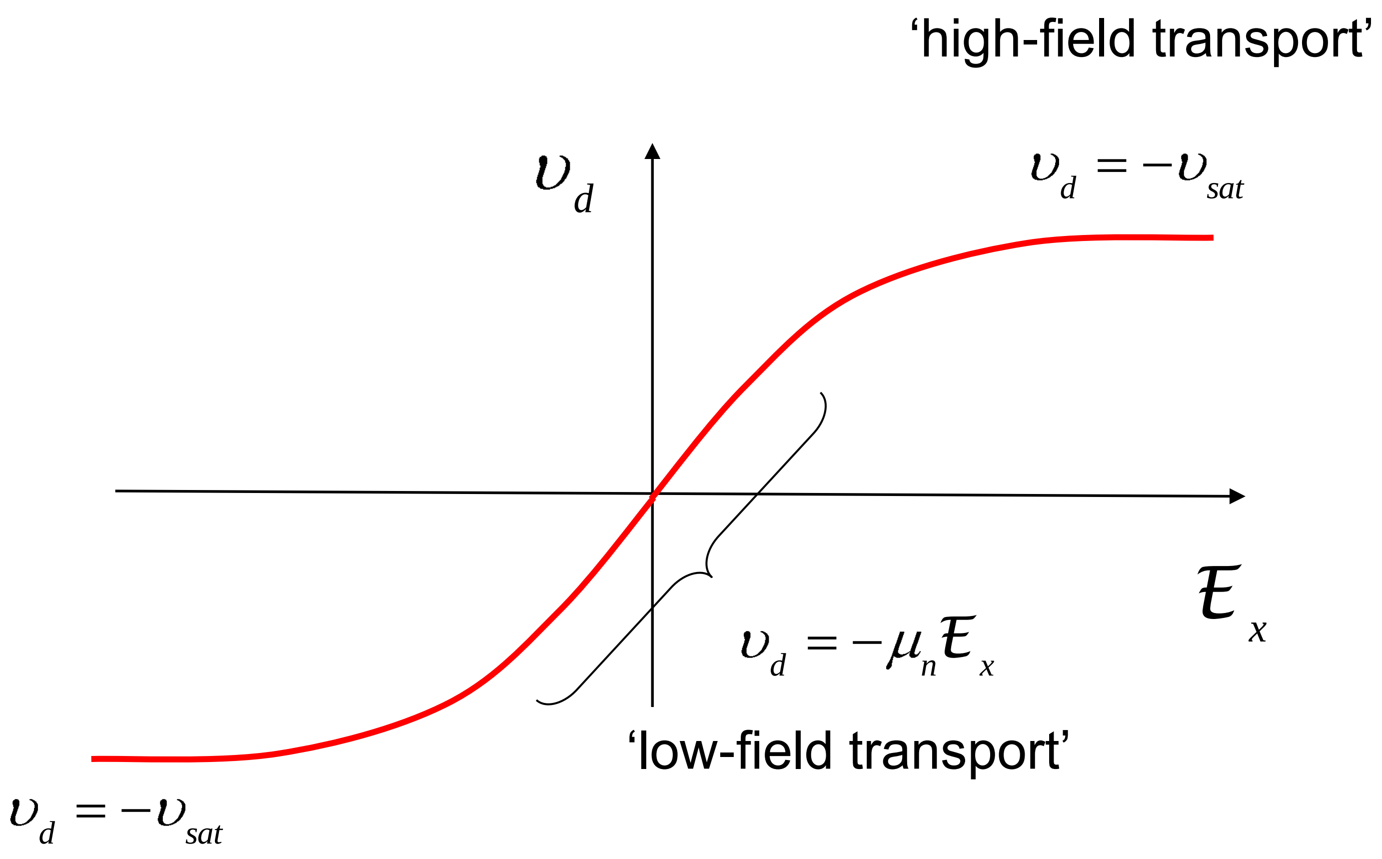
3) force on an electron

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

4) average velocity:

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

carrier transport in semiconductors



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the drift-diffusion equation

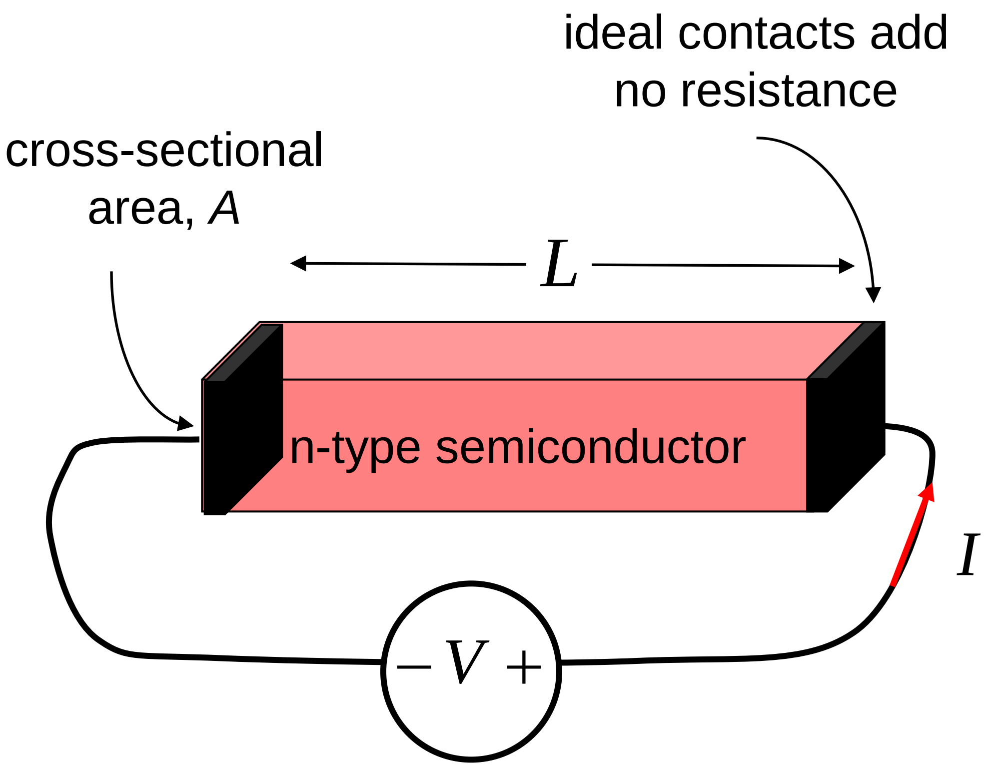
$$J_{px} = pq\mu_p \mathcal{E}_x + qD_p \frac{dp}{dx}$$

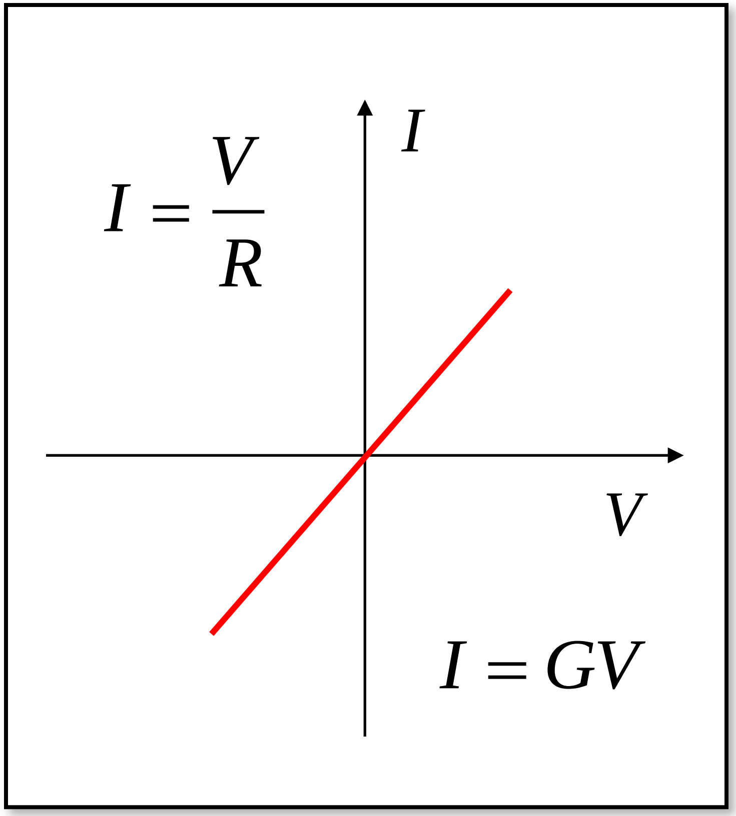
hole current = drift current + diffusion current

$$\frac{D_p}{\mu_p} = \frac{k_B T_L}{q}$$

Einstein relation

low-field transport

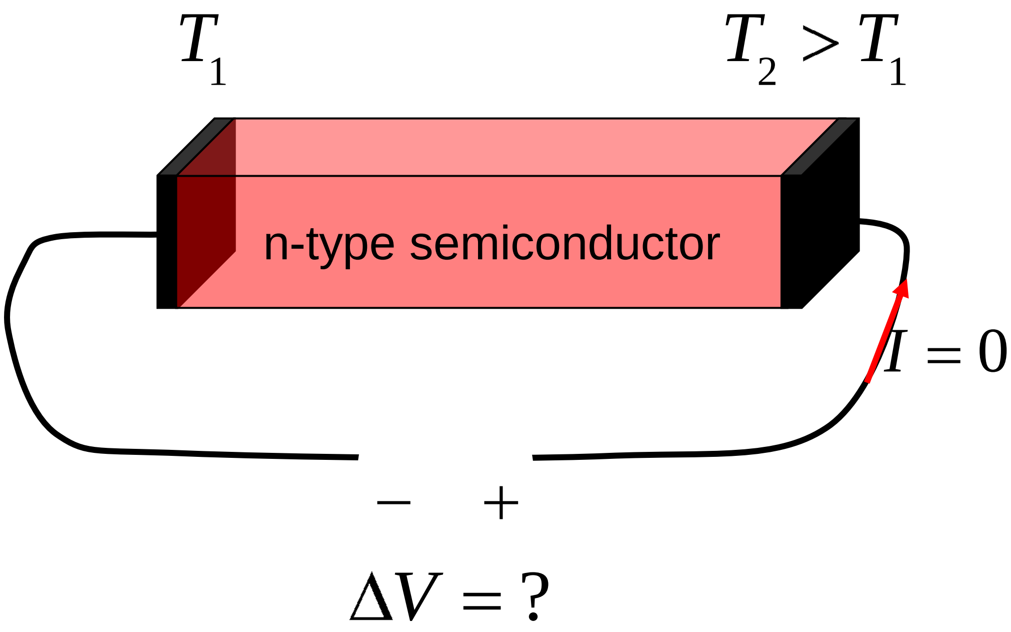




$V > 0$ --> $I > 0$

when V is small, $I \propto V$ (‘near-equilibrium’)

more on low-field transport



$$\Delta V \propto \Delta T$$

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

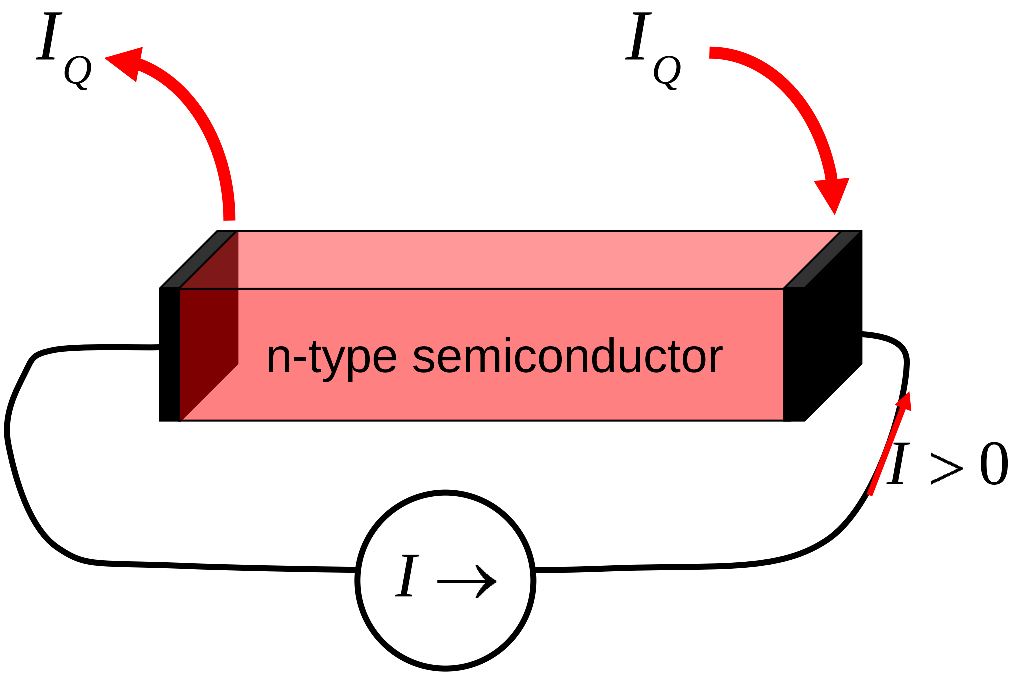
S is the 'Seebeck coefficient' in V/K

S < 0 for n-type conduction

S is also called the 'thermopower'

The Seebeck effect was discovered in 1821 by Thomas Seebeck. It also occurs between the junction of two dissimilar metals at different temperatures. It is the basis for temperature measurement with thermocouples and for thermoelectric power generation.

still more on low-field transport



$$I_Q \propto I$$

$$I_Q = \pi I$$

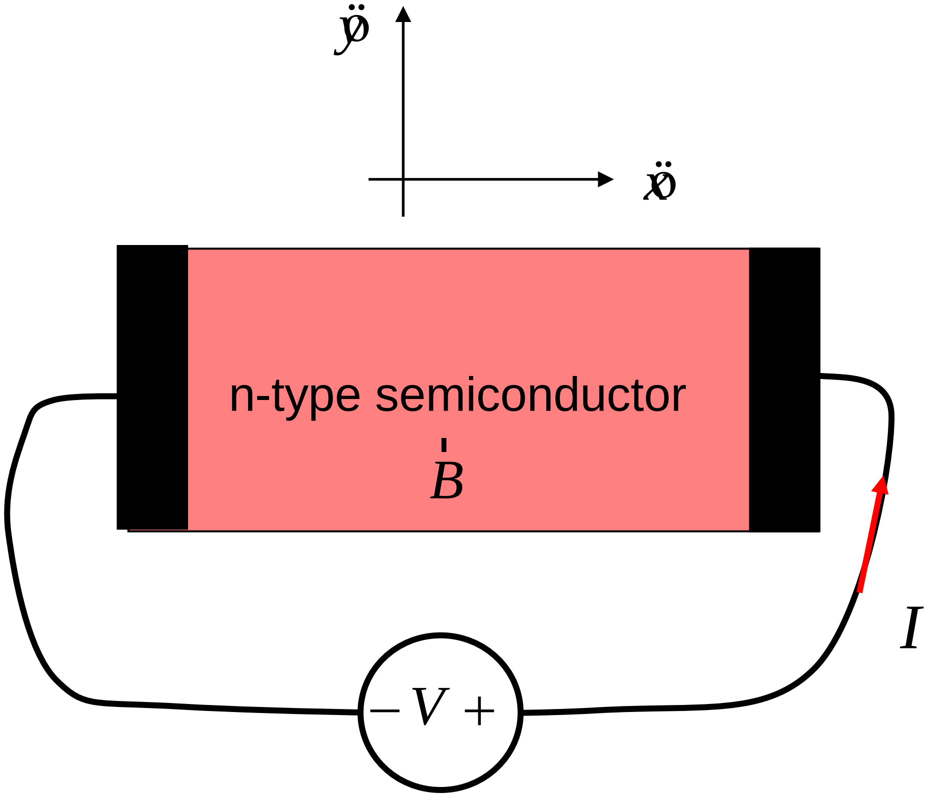
π is the 'Peltier coefficient' in W/A

There is a close connection between the Peltier coefficient and the Seebeck coefficient.

$$\pi = TS$$

The Peltier effect was discovered in 1834 by Jean-Charles Peltier and explained in 1838 by Lenz. It finds use in thermoelectric cooling.

magnetic fields and low-field transport



$$R = R(\vec{B})$$

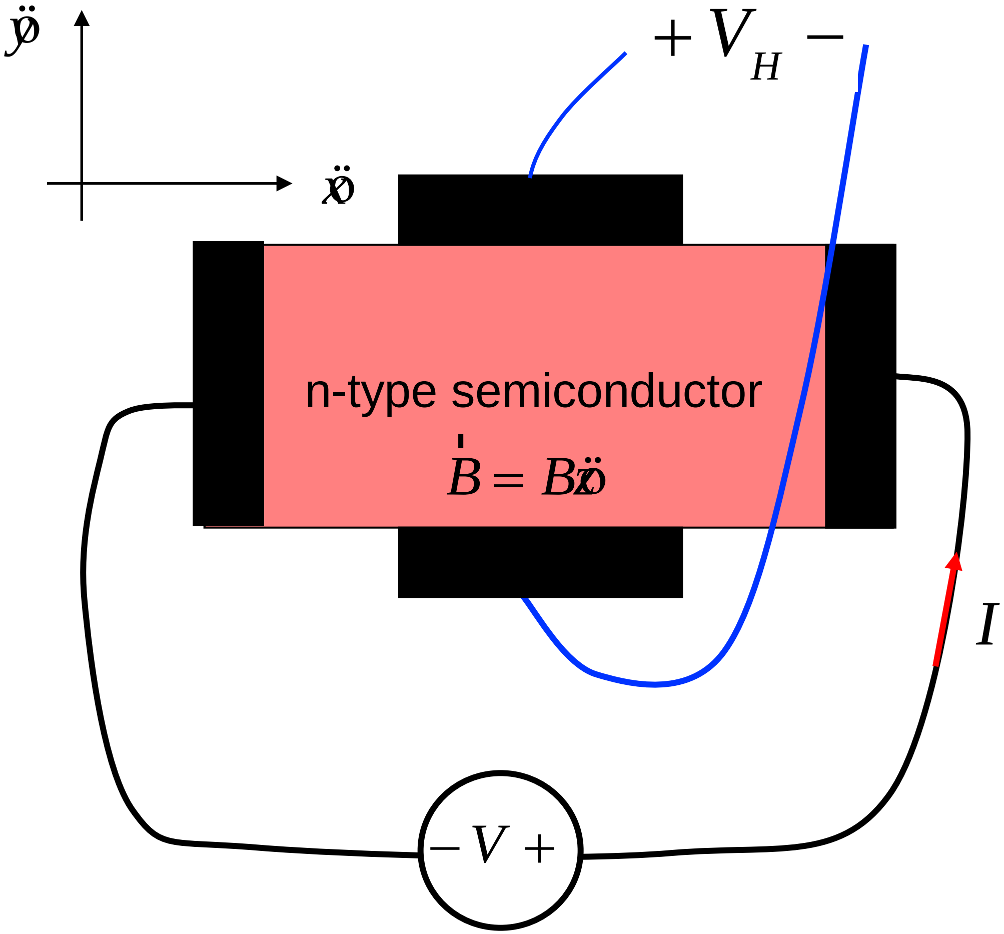
$$\vec{B} = B\hat{x}$$

longitudinal magnetoresistance

$$\vec{B} = B\hat{z}$$

transverse magnetoresistance

“Hall effect”



current in x-direction:

$$I_x$$

B-field in z-direction:

$$\vec{B} = B\hat{z}$$

Hall voltage measured in the y-direction:

$$V_H < 0 \quad (\text{n-type})$$

The Hall effect was discovered by Edwin Hall in 1879 and is widely used to characterize electronic materials. It also finds use magnetic field sensors.

Integer quantum Hall effect

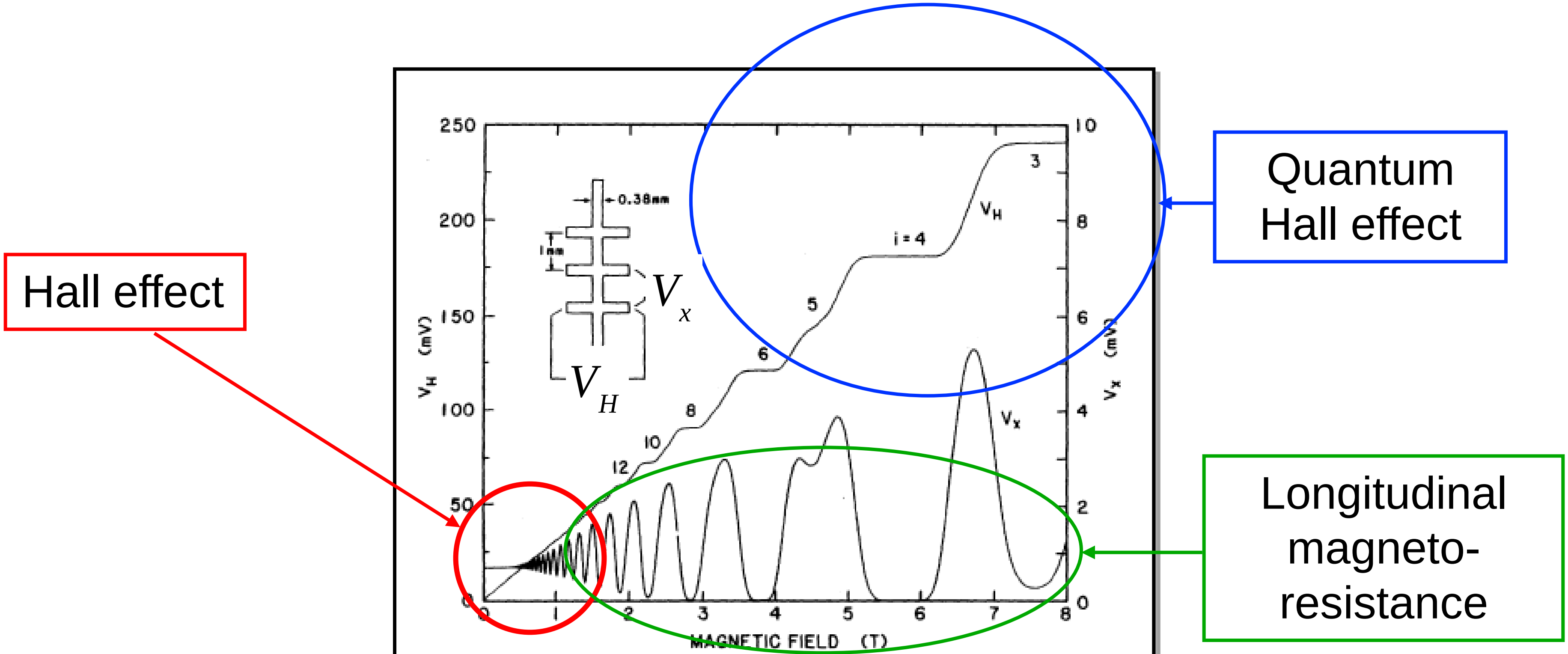
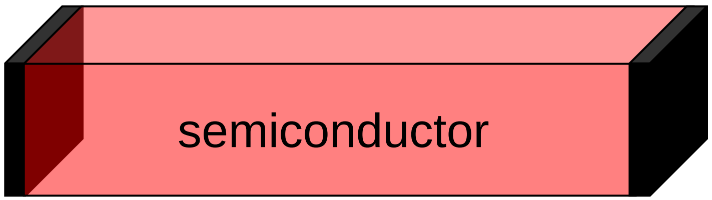


Fig. 1. Recording of V_H and V_x versus magnetic field for a GaAs device cooled to 1.2 K. The current is 25.5 μA.

M.E. Cage, R.F. Dziuba, and B.F. Field, "A Test of the Quantum Hall Effect as a Resistance Standard," *IEEE Trans. Instrumentation and Measurement*," Vol. IM-34, pp. 301-303, 1985

low-field transport summary



1) The ‘driving forces’ for current flow are voltage differences (electric fields) and temperature differences (thermal gradients).

2) In low-field (linear or near-equilibrium) transport, the **response is proportional to the driving force.**

3) In general, voltage and temperature gradients may be present simultaneously, and there may or may not be a magnetic field present too.

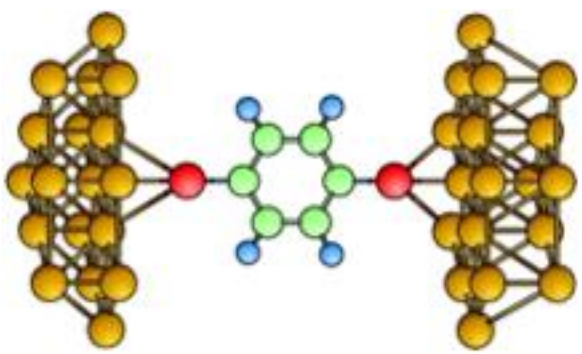
4) Voltage gradients produce temperature gradients, and temperature gradients produce electrical currents; charge and heat flows are **coupled**.

why learn about low-field transport?

1) To design or analyze electronic devices.

2) To characterize the properties and quality of materials used for electronic devices.

why develop a new approach?



$$\vec{J} = nq\mu_n \vec{E} + qD_n \vec{\nabla} n \; ?$$

$$\mu = \frac{q\tau}{m^*} \; ?$$

"Electronics from the Bottom Up"

objectives

1) To introduce students to low-field transport using a ‘bottom up’ approach that works at the nanoscale as well as at the (traditional) macroscale.

2) To acquaint students with some key results (e.g. the quantum of conductance).

3) To give students a basic foundation upon which they can build.

lectures

Lecture 1: Review
A review of some basic, traditional concepts.

Lecture 2: General Model
Datta's model of a nanodevice (his version of the Landauer approach) is introduced as a general way of describing nanodevices – molecular, semiconductor nanowires, carbon nanotubes, graphene, etc

Lecture 3: Resistors in 1, 2, and 3D
The theory presented in Lecture 2 is used to compute the resistance of traditional bulk materials (3D), MOSFET inversion layers and graphene (2D), and nanowires and nanotubes (1D).

Lecture 4: Thermoelectric effects
Electronic and conduction are coupled. The theory of these coupled flows is developed and their practical applications in diagnostic measurements and for applications such as cooling and power generation are mentioned.

questions