FUNDAMENTALS OF NANOELECTRONICS

A. Basic Concepts
1. The new perspective
2. Energy band model
3. What and where is the voltage?
4. Heat & electricity: Second law & information

B. Quantum Transport
1. Schrodinger Equation
2. Contact-ing Schrodinger
3. More Examples
4. Spin Transport

Supriyo Datta
http://nanohub.org/groups/lnebook
The New Perspective

Source \(-V\) + Drain

Channel

\[ \mu_1 \rightarrow qV \rightarrow \mu_2 \]

NEW

\[ G = \frac{q^2 D}{2t} \rightarrow G_B = \frac{q^2 D \bar{u}}{2L} \rightarrow G = \frac{G_B}{1 + \frac{L}{\lambda}} \]

M: Number of “modes”

Drude Formula

\[ \sigma = \frac{q^2 n \tau}{m} \]

\[ \sigma = \frac{G_B \lambda}{A} \]

\[ G_B = \frac{q^2}{h} M \]

http://nanohub.org/groups/Lnebook
Where is the Resistance?

1. The new perspective
2. Energy band model
3. What and where is the voltage?
4. Heat & electricity:
   - Second law & information

Resistance is associated with:
- **Joule Heating**: $I^2R$
- **Voltage drop**: $IR$

\[
R = R_B \left( 1 + \frac{L}{\lambda} \right) \\
G = \frac{G_B}{1 + \frac{L}{\lambda}}
\]

Supriyo Datta

http://nanohub.org/groups/lnebook
Supriyo Datta

What & where is the voltage?

1. The new perspective
2. Energy band model
3. What and where is the voltage?
4. Heat & electricity:
   Second law & information

➢ Voltage drop: IR

➢ Quasi-Fermi Levels (QFL)

I - V +
Source
Channel
Drain

\[ qV \]

\[ \mu_1 \quad \mu^+ \quad \mu^- \quad \mu_2 \]

\[ \frac{R_B}{2} \quad R_B \frac{1-T}{T} \quad \frac{R_B}{2} \]
Supriyo Datta

I

Source

- V

Channel

Drain

$\frac{R_B}{2}$

$\frac{R_B}{2}$

Mechanics:
Force driven

Thermodynamics:
Entropy driven

$I \sim G(E) \times$

$(f_1(E) - f_2(E))$

$S = k \ell \ln W$

“Elastic Resistor”

1. The new perspective
2. Energy band model
3. What and where is the voltage?
4. Heat & electricity:
   Second law & information

Usually all mixed up !!

http://nanohub.org/groups/Lnebook
Rigorous theory

Part A: Semiclassical Transport

Newton + Schrodinger = NEGF

Part B: Quantum Transport

- Provides approximate physical picture in general
- Agrees with rigorous theory for low bias

Long Resistors

http://nanohub.org/groups/Lnebook
$[G] = \left[ EI - H - \Sigma \right]^{-1}$

$G^n = G \Sigma^{in} G^+$

$\Sigma = \Sigma_0 + \Sigma_1 + \Sigma_2$

$\Sigma^{in} = \Sigma_0^{in} + \Gamma_1 f_1 + \Gamma_2 f_2$

\(\Gamma = i [\Sigma - \Sigma^+]\)

\(\sum_{0,1,2}^{diss}\)

Before 1990

Essential physics

Additional

Unimportant detail

New Perspective

Additional detail

Essential Physics

Supriyo Datta

http://nanohub.org/groups/LNEbook
A Note for Advanced Students

\[
[G] = \left[ EI - H - \Sigma \right]^{-1}
\]

\[
G^n = G \Sigma^{in} G^+
\]

NEG Fowler as esoteric tool accessible to those well-versed in many-body perturbation theory

\[
\Sigma = \Sigma_0 + \Sigma_1 + \Sigma_2 + \left( \Sigma_0 \right)_{diss}
\]

\[
\Sigma^{in} = \Sigma_0^{in} + \Gamma_1 f_1 + \Gamma_2 f_2 + \left( \Sigma_0^{in} \right)_{diss}
\]

Compare Boltzmann Eq

\[\vec{v} \cdot \nabla f + \vec{F} \cdot \nabla_p f = S_{op} f\]

Techniques have evolved

Widely used in nanoelectronics

Should be part of grad / undergrad curriculum

May need non-perturbative techniques

Supriyo Datta

http://nanohub.org/groups/Lnebook
Prerequisite: Calculus, Elementary Differential Equations

Part B requires Matrix Algebra

Text:
Lessons From Nanoelectronics: A New Perspective on Transport
World Scientific (2012)

II Edition 2015:
Manuscript will be available to registered students

First offered on nanoHUB-U, Spring 2012

A. Basic Concepts
1. The new perspective
2. Energy band model
3. What and where is the voltage?
4. Heat & electricity:
   Second law & information

B. Quantum Transport
1. Schrodinger equation
2. Contact-ing schrodinger
3. More examples
4. Spin transport

Supriyo Datta
http://nanohub.org/groups/Lnebook