New Perspective on Transport

Drude formula:

\[
\frac{m}{nq^2\tau} = R = \frac{\rho}{A} L
\]

\[
R = \frac{h}{q^2 M} \left( 1 + \frac{L}{\lambda} \right)
\]

- **Source**
- **Drain**
- **Channel**

1984 - 10 µm
1 µm
0.1 µm
10 nm
0.1 nm

10 µm
1 µm
0.1 mm

**Diffusive**

1984 → Clear

2014 → Ballistic

Atoms → 0.1 nm

0.1 nm

- **q**: Electronic charge (magnitude)
- **h**: Planck’s constant
- **\(\lambda\)**: Mean free path
- **M**: Number of “modes”

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Spring 2015

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

1. The new perspective
2. Energy band model

Resistance is associated with

- **Joule Heating**: $I^2R$
- **Voltage drop**: $IR$

$R = R_B \left(1 + \frac{L}{\lambda}\right)$

$M$: Number of “modes”

$$R_B = \frac{h}{q^2} \frac{1}{M}$$
1. The new perspective
2. Energy band model
3. What and where is the voltage?

\[ \frac{R_B}{2} \quad R_B \frac{L}{\lambda} \quad \frac{R_B}{2} \]

**Mechanics:**
Force driven

**Thermodynamics:**
Entropy driven

Usually all mixed up!!

Landauer’s Principle

\[ S = k \ln W \]
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Longer Resistors

➢ Provides approximate physical picture in general

➢ Agrees with rigorous theory for low bias

Mechanics: Force driven

Thermodynamics: Entropy driven

Usually all mixed up !!
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

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A: Semiclassical

\[ \text{Newton} + \text{Schrodinger} = \text{NEGF} \]

B: Quantum

Why Approximate Pictures

From Feynman Lectures, 2-1

“.. people say there is nothing which is not contained in the equations .. if I understand them mathematically, I will understand the physics ..

Only it doesn’t work that way.

A physical understanding is completely unmathematical, imprecise and inexact .. but absolutely necessary for a physicist.”

A Different Physical Picture

\[ J = \sigma F \rightarrow \sigma = \frac{nq^2\tau}{m} \]
FUNDAMENTALS OF NANOELECTRONICS

Prerequisite: Calculus, Elementary Differential Equations
Part B requires Matrix Algebra

First offered on nanoHUB-U, Spring 2012

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

II Edition 2015:
Manuscript will be available to registered students

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

From Semiclassical To Quantum

B. Quantum Model
1. Schrodinger Equation
2. Contact-ing Schrodinger
3. NEGF Method
4. Spin Transport

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