

Lessons from Nanoscience:
A Lecture Note Series

Vol. 1

Lessons from **Nanoelectronics**

A New Perspective on Transport

Supriyo Datta

Purdue University, USA



NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Detailed Contents

<i>Preface</i>	vii
<i>Some Symbols used</i>	ix
I. The New Ohm's Law	1
1. The Bottom-Up Approach	3
2. Why Electrons Flow	15
2.1. <i>Two Key Concepts</i>	18
2.2. <i>Fermi Function</i>	18
2.3. <i>Non-equilibrium: Two Fermi Functions</i>	21
2.4. <i>Linear Response</i>	22
2.5. <i>Difference in "Agenda" Drives the Flow</i>	24
3. The Elastic Resistor	27
3.1. <i>How an Elastic Resistor Dissipates Heat</i>	30
3.2. <i>Conductance of an Elastic Resistor</i>	32
3.3. <i>Why an Elastic Resistor is Relevant</i>	35
4. Ballistic and Diffusive Transport	39
4.1. <i>Ballistic and Diffusive Transfer Times</i>	42
4.2. <i>Channels for Conduction</i>	45
5. Conductivity	47
5.1. <i>E(p) or E(k) Relations</i>	52
5.2. <i>Counting States</i>	53
5.3. <i>Drude Formula</i>	55
5.4. <i>Is Conductivity proportional to Electron Density?</i>	59
5.5. <i>Quantized Conductance</i>	61
6. Diffusion Equation for Ballistic Transport	65
6.1. <i>Electrochemical Potentials Out of Equilibrium</i>	72
6.2. <i>Currents in Terms of Non-Equilibrium Potentials</i>	76

7.	What about Drift?	79
7.1.	<i>Boltzmann Transport Equation, BTE</i>	82
7.2.	<i>Diffusion Equation from BTE</i>	85
7.3.	<i>Equilibrium Fields Do Matter</i>	88
7.4.	<i>The Two Potentials</i>	89
8.	Electrostatics is Important	93
8.1.	<i>The Nanotransistor</i>	94
8.2.	<i>Why the Current Saturates</i>	96
8.3.	<i>Role of Charging</i>	98
8.4.	<i>Rectifier Based on Electrostatics</i>	102
8.5.	<i>Extended Channel Model</i>	104
9.	Smart Contacts	111
9.1.	<i>Why p-n Junctions are Different</i>	112
9.2.	<i>Contacts are Fundamental</i>	119
II.	<i>Old Topics in New Light</i>	123
10.	Thermoelectricity	125
10.1.	<i>Seebeck Coefficient</i>	129
10.2.	<i>Thermoelectric Figures of Merit</i>	131
10.3.	<i>Heat Current</i>	133
10.4.	<i>“Delta Function” Thermoelectric</i>	138
11.	Phonon Transport	145
11.1.	<i>Phonon Heat Current</i>	147
11.2.	<i>Thermal Conductivity</i>	151
12.	Measuring Electrochemical Potentials	155
12.1.	<i>The Landauer Formulas</i>	161
12.2.	<i>Büttiker Formula</i>	165
13.	Hall Effect	173
13.1.	<i>Why n- and p- Conductors Are Different</i>	178
13.2.	<i>Spatial Profile of Electrochemical Potential</i>	179
13.3.	<i>Measuring the Potential</i>	184
13.4.	<i>Non -Reciprocal Circuits</i>	188

14.	Spin Valve	191
14.1.	<i>Mode Mismatch and Interface Resistance</i>	194
14.2.	<i>Spin Potentials</i>	201
14.3.	<i>Spin-Torque</i>	209
14.4.	<i>Polarizers and Analyzers</i>	217
15.	Kubo Formula	221
15.1.	<i>Kubo Formula for an Elastic Resistor</i>	224
15.2.	<i>Onsager Relations</i>	227
16.	Second Law	229
16.1.	<i>Asymmetry of Absorption and Emission</i>	233
16.2.	<i>Entropy</i>	235
16.3.	<i>Law of Equilibrium</i>	240
16.4.	<i>Fock Space States</i>	242
16.5.	<i>Alternative Expression for Entropy</i>	246
17.	Fuel Value of Information	251
17.1.	<i>Information-Driven Battery</i>	255
17.2.	<i>Fuel Value Comes From Knowledge</i>	258
17.3.	<i>Landauer's Principle</i>	260
17.4.	<i>Maxwell's Demon</i>	261
III.	Contact-ing Schrödinger	265
18.	The Model	267
18.1.	<i>Schrödinger Equation</i>	270
18.2.	<i>Electron-Electron Interactions</i>	275
18.3.	<i>Differential to Matrix Equation</i>	278
18.4.	<i>Choosing Matrix Parameters</i>	281
19.	Non-Equilibrium Green's Functions (NEGF)	293
19.1.	<i>One-level Resistor</i>	299
19.2.	<i>Multi-level Resistors</i>	308
19.3.	<i>Conductance Functions for Coherent Transport</i>	314
19.4.	<i>Elastic Dephasing</i>	315
20.	Can Two Offer Less Resistance than One?	321
20.1.	<i>Modeling 1D Conductors</i>	322

20.2. <i>Quantum Resistors in Series</i>	326
20.3. <i>Potential Drop Across Scatterer(s)</i>	331
21. Quantum of Conductance	337
21.1. <i>2D Conductor as 1D Conductors in Parallel</i>	337
21.2. <i>Contact self-energy for 2D Conductors</i>	343
21.3. <i>Quantum Hall Effect</i>	349
22. Rotating an Electron	355
22.1. <i>One-level Spin Valve</i>	359
22.2. <i>Rotating Magnetic Contacts</i>	363
22.3. <i>Spin Hamiltonians</i>	366
22.4. <i>Vectors and Spinors</i>	369
22.5. <i>Spin Precession</i>	374
22.6. <i>From NEGF to Diffusion</i>	380
23. Does NEGF Include “Everything”?	389
23.1. <i>Coulomb Blockade</i>	392
23.2. <i>Fock Space Description</i>	397
23.3. <i>Entangled States</i>	402
24. The Quantum and the Classical	409
24.1. <i>Spin coherence</i>	410
24.2. <i>Pseudo-spins</i>	412
24.3. <i>Quantum Entropy</i>	415
24.4. <i>Does Interaction Increase the Entropy?</i>	417
24.5. <i>Spins and magnets</i>	419
References / Further Reading	423
Appendices	433
A. <i>Fermi and Bose Function Derivatives</i>	433
B. <i>Angular Averaging</i>	435
C. <i>Hamiltonian with E- and B-Fields</i>	437
D. <i>Transmission Line Parameters from BTE Equations</i>	439
E. <i>NEGF Equations</i>	443
F. <i>MATLAB Codes for Text Figures</i>	449