Lessons from Nanoscience:
A Lecture Note Series

Vol. 1

Lessons from Nanoelectronics

A New Perspective on Transport

Supriyo Datta

World Scientific

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This series is intended to address a very different need, namely the need to develop conceptual frameworks that can help unify the diverse phenomena being discovered. Such frameworks may not yet be in final form but this series will provide a forum for them to evolve and develop into the textbooks of tomorrow that train our students and guide young researchers as they turn nanoscience into nanotechnology. The focus of the series is on electronics, but volumes in areas of nanoscience and technology broadly related to electronics will be also be considered, as long as they are driven by a quest for unifying principles that embed a diversity of phenomena or techniques.

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by Supriyo Datta

To
Malika, Manoshi
and
Anuradha

Preface

Everyone is familiar with the amazing performance of a modern smart phone, powered by a billion-plus nanotransistors, each having an active region that is barely a few hundred atoms long.

These lectures, however, are about a less-appreciated by-product of the microelectronics revolution, namely the deeper understanding of current flow, energy exchange and device operation that it has enabled, which forms the basis for what we call the bottom-up approach.

I believe these lessons from nanoelectronics should be of broad relevance to the general problems of non-equilibrium statistical mechanics which pervade many different fields. To make these lectures accessible to anyone in any branch of science or engineering, we assume very little background beyond linear algebra and differential equations. We hope to reach all those who have an interest in basic physics, even if they are not specializing in devices or transport theory.

For dedicated graduate students and the experts, I have written extensively in the past. But they too may enjoy these notes taking a fresh look at a familiar subject, emphasizing the insights from mesoscopic physics and nanoelectronics that are of general interest and relevance.

Finally I should stress that these are *lecture notes* in unfinished form, with typos included to enhance the readers' attention, as my colleague Gerhard likes to put it. With your feedback and suggestions, I hope to have a better version in the future, one that requires less attention!

April 21, 2012

Supriyo Datta
Purdue University

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The precursor to this lecture note series, namely the *Electronics from the Bottom Up* initiative on www.nanohub.org was funded by the U.S. National Science Foundation (NSF), the Intel Foundation, and Purdue University.

The nanoHUB-U recently offered its first online course based on these notes and I am thankful for the feedback I received from many online students whom I have never met. We gratefully acknowledge Purdue and NSF support for this program, along with the superb team of professionals who made nanoHUB-U a reality (https://nanohub.org/groups/u).

A special note of thanks to Mark Lundstrom for his leadership that made it all happen and for his encouragement and advice.

I am indebted to Ashraf Alam, Kerem Camsari, Deepanjan Datta, Vinh Diep, Samiran Ganguly, Seokmin Hong, Changwook Jeong, Bhaskaran Muralidharan, Angik Sarkar, Srikant Srinivasan for their valuable feedback and suggestions.

Finally I would like to express my deep gratitude to all who have helped me learn, a list that includes not only those named above, but also many teachers, colleagues and students over the years, starting with the late Richard Feynman whose classic lectures on physics, I am sure, have inspired many like me.

Some Symbols Used

Constants

Electronic charge	$-q$	- 1.6e-19 coul.
Unit of Energy	1 eV	+ 1.6e-19 Joules
Planck's constant	h	6.626e -34 Joule-sec
	$\hbar = h/2\pi$	1.055e -34 Joule-sec
Boltzmann constant	k	1.38e-23 Joule / K ~ 25 meV / 300K
Free electron mass	m_0	9.11e-31 Kg
Effective mass	m	

Other Symbols

I	Electron Current *(See Fig.3.2)*	amperes (A)
V	Electron Voltage	volts (V)
U	Electrostatic Potential	eV
μ	Electrochemical Potential *(also called Fermi level or quasi-Fermi level)*	eV
μ_0	Equilibrium Electrochemical Potential	eV
R	Resistance	Ohms (V/A)
G	Conductance	Siemens (A/V)
$G(E)$	Conductance at 0K with μ_0=E	Siemens (A/V)
$\bar{D}$	Diffusivity	m^2 /sec
$\bar{\mu}$	Mobility	m^2 /V-sec
ρ	Resistivity	Ohm-m (3D), Ohm (2D)
σ	Conductivity	S/m (3D), S (2D)

A	Area	m^2
W	Width	m
L	Length	m
E	Energy	eV
$f(E)$	Fermi Function	Dimensionless
$\left(-\frac{\partial f}{\partial E}\right)$	Thermal Broadening Function (TBF)	/ eV
$kT\left(-\frac{\partial f}{\partial E}\right)$	Normalized TBF	Dimensionless
$D(E)$	Density of States	/eV
$N(E)$	Number of States with Energy < E Equals Number of Electrons at 0K with μ_0=E	Dimensionless
N	Electron Density (3D or 2D or 1D)	$/m^3$ or $/m^2$ or /m
$M(E)$	Number of Channels *(also called transverse modes)*	Dimensionless
T	Temperature	degrees Kelvin (K)
t	Transfer Time	seconds
ν	Transfer Rate	/second
$\gamma \equiv \hbar\nu$	Energy Broadening	eV
$[X]^+$	Complex conjugate of transpose of matrix	$[X]$
H	(Matrix) Hamiltonian	eV
$G^R(E)$	(Matrix) Retarded Green's function	/eV
$G^A(E)=[G^R(E)]^+$	(Matrix) Advanced Green's function	/eV
$G^n(E)/2\pi$	(Matrix) Electron Density	/eV, per gridpoint
$A(E)/2\pi$	(Matrix) Density of States	/eV, per gridpoint
$\Gamma(E)$	(Matrix) Energy Broadening	eV

Contents

Detailed Contents

I. The New Ohm's Law