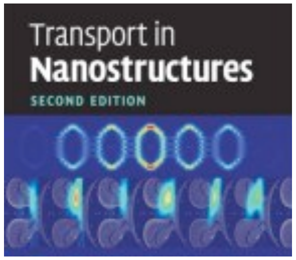
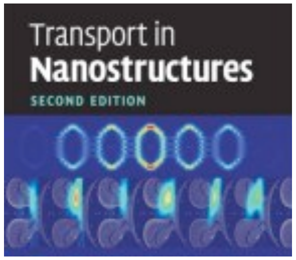


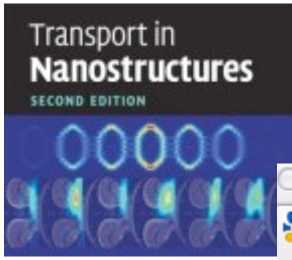
GENERAL ASPECTS OF MESOSCOPIC TRANSPORT: I

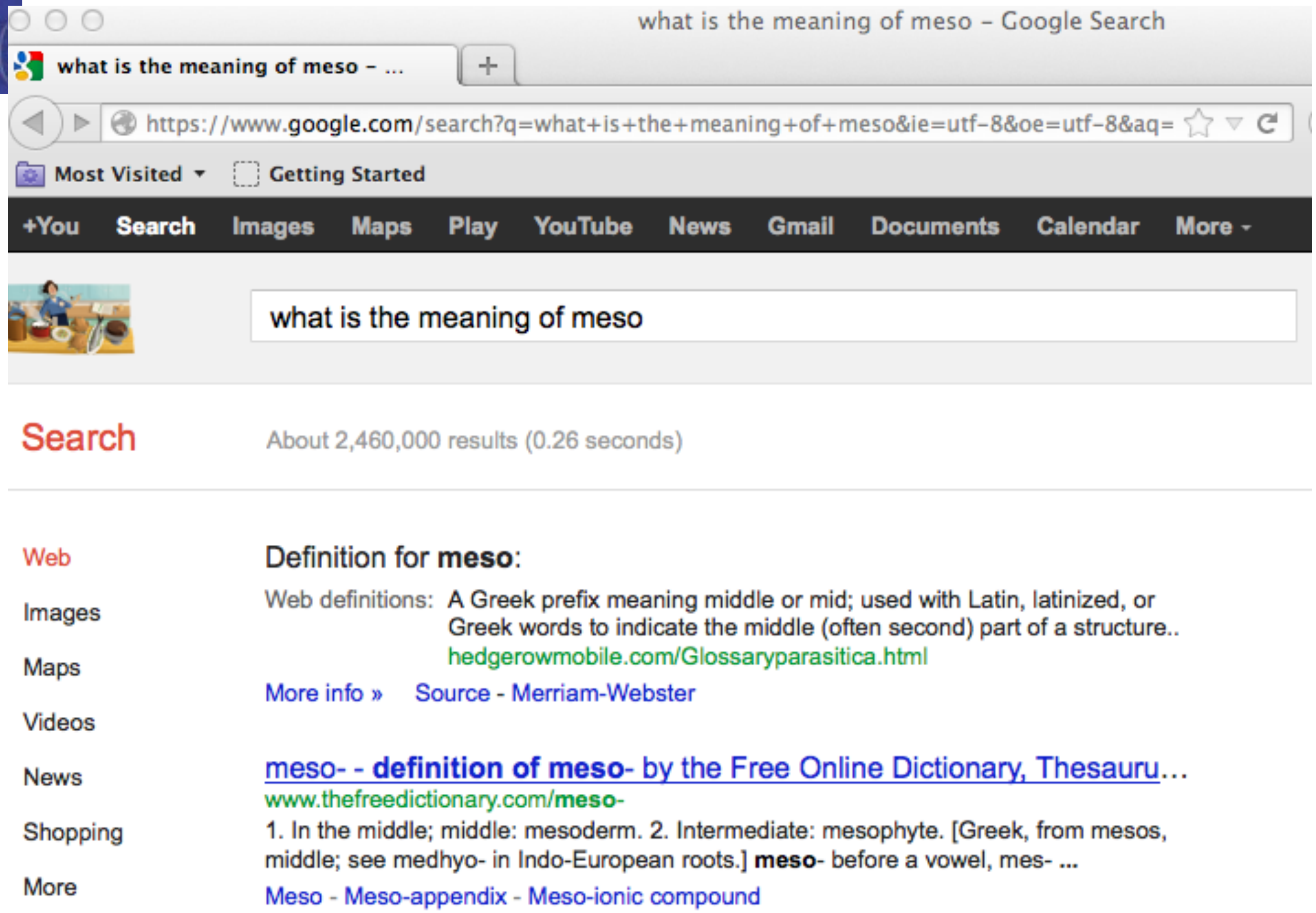
Jonathan Bird
Electrical Engineering,
University at Buffalo,
Buffalo NY, USA



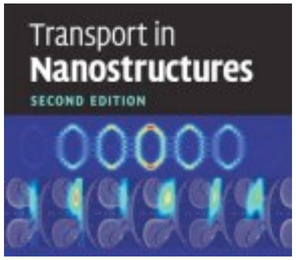
GENERAL ASPECTS OF MESOSCOPIC TRANSPORT I

- An Introduction to Mesoscopics
- Some Features of Mesoscopic Systems
- Some Common Mesoscopic Phenomena
- Realizing Mesoscopic Systems
- 1-D Mesoscopic Systems

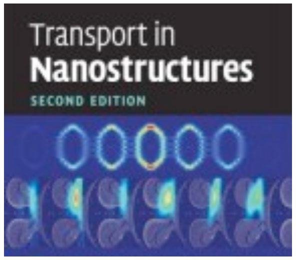




What does “MESOSCOPIC” mean?

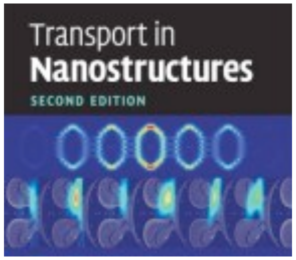


MESOSCOPIC PHYSICS – concerns the physical description of systems that are INTERMEDIATE between the macroscopic and microscopic realms



GENERAL ASPECTS OF MESOSCOPIC TRANSPORT I

- **An Introduction to Mesoscopics**
- **Some Features of Mesoscopic Systems**
- **Some Common Mesoscopic Phenomena**
- **Realizing Mesoscopic Systems**
- **1-D Mesoscopic Systems**

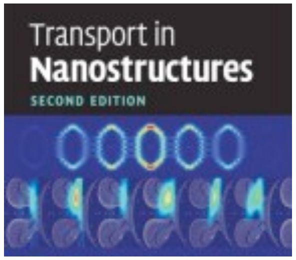


What are the GENERAL FEATURES of Mesoscopic Systems?

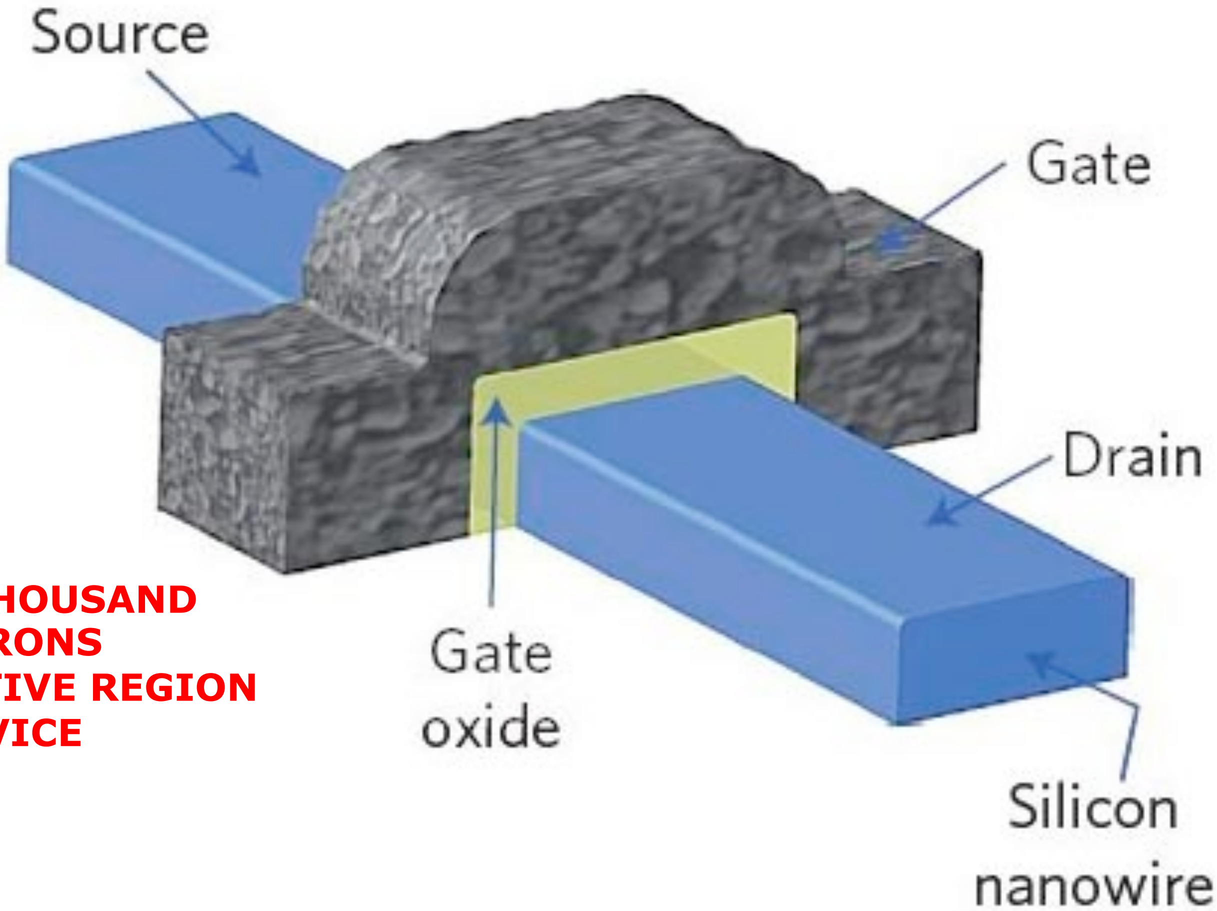
Typically (not always) contain LARGE numbers of particles – reminiscent of classical systems …

… But, the QUANTUM character of these particles is strongly apparent

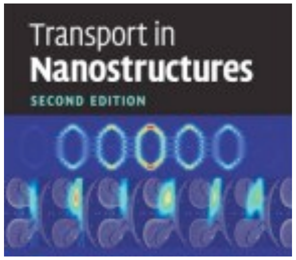
- **➔Exhibit pronounced effects due to QUANTUM INTERFERENCE & ENERGY QUANTIZATION**
- **➔MANY-BODY effects …**



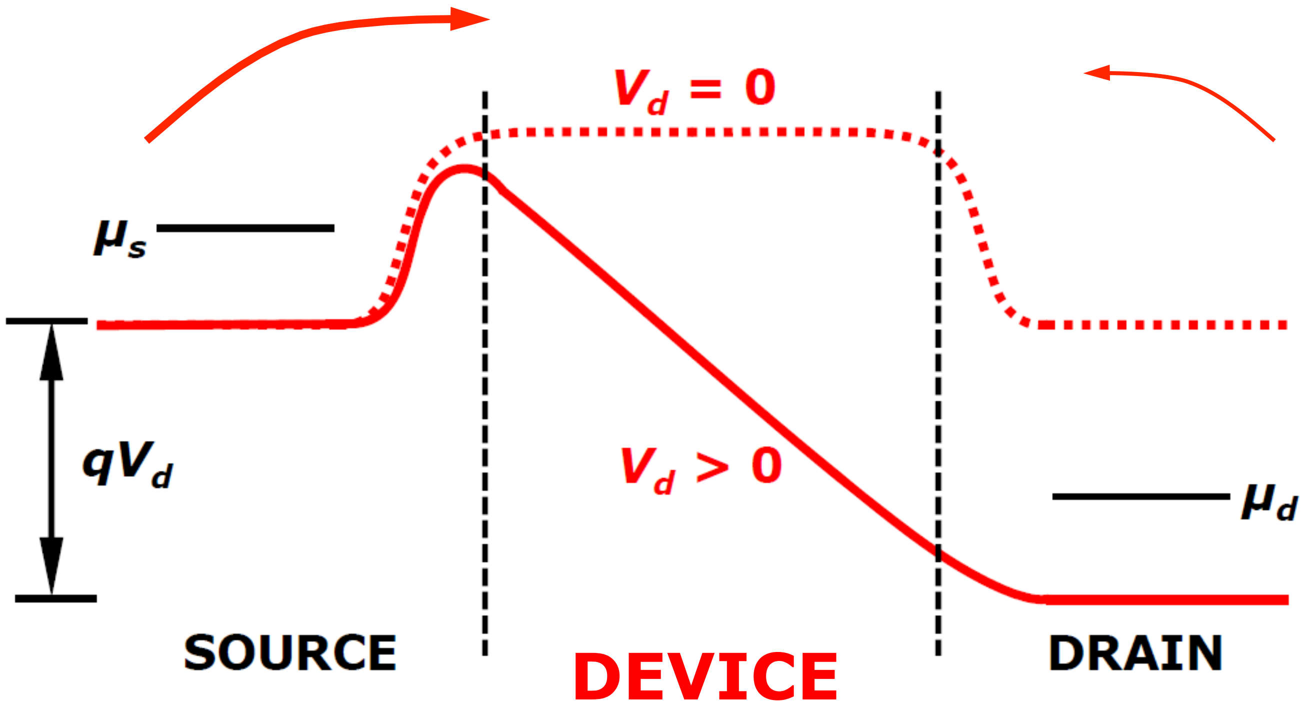
Semiconductor devices: ARCHETYPAL mesoscopic system

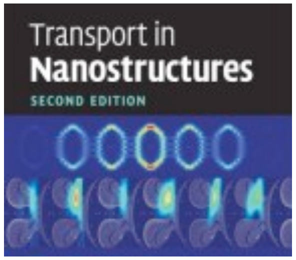


FEW THOUSAND ELECTRONS IN ACTIVE REGION OF DEVICE



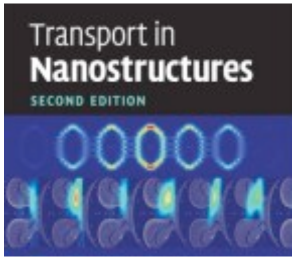
Device current calculated in a TRANSMISSION approach – the LANDAUER formula





GENERAL ASPECTS OF MESOSCOPIC TRANSPORT I

- **An Introduction to Mesoscopics**
- **Some Features of Mesoscopic Systems**
- **Some Common Mesoscopic Phenomena**
- **Realizing Mesoscopic Systems**
- **1-D Mesoscopic Systems**

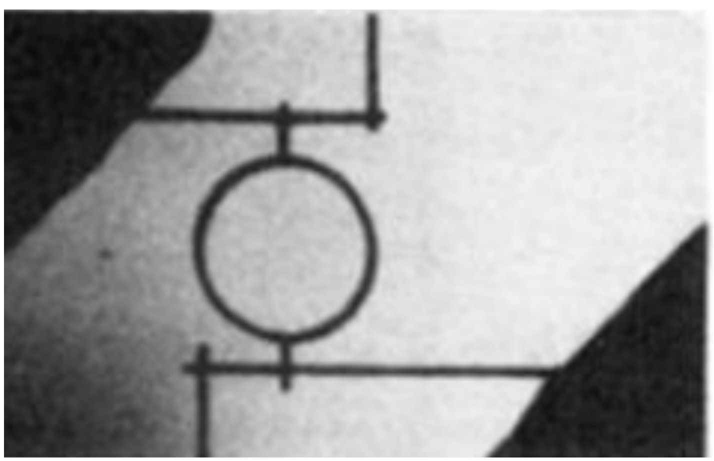


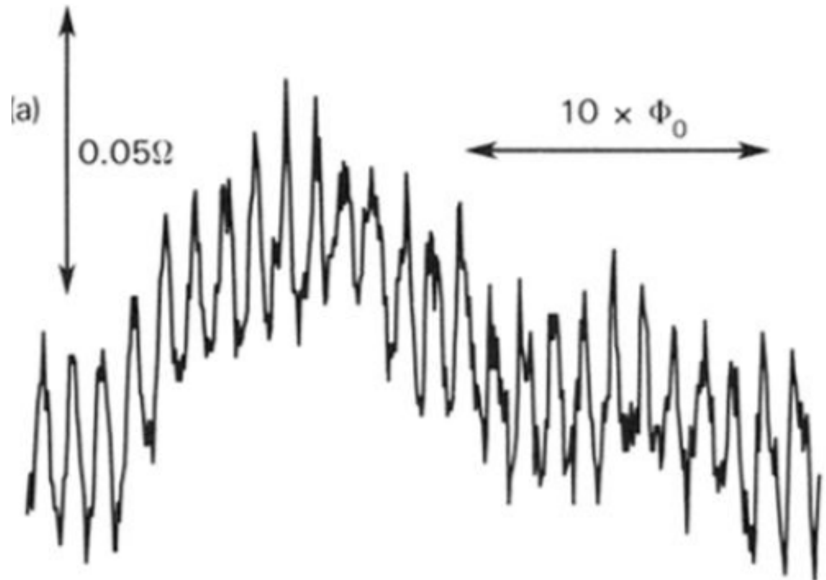
QUANTUM INTERFERENCE
Due to COHERENT wave transport

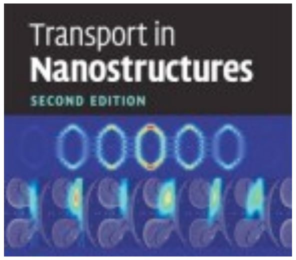
VOLUME 54, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 1985

Observation of h/e Aharonov-Bohm Oscillations in Normal-Metal Rings

R. A. Webb, S. Washburn, C. P. Umbach, and R. B. Laibowitz
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598







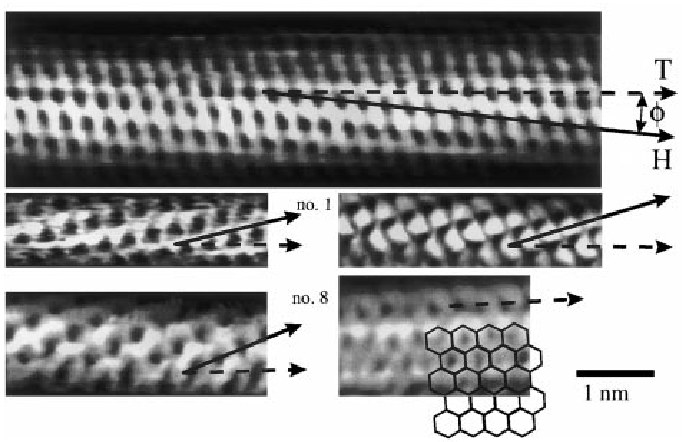
ENERGY QUANTIZATION

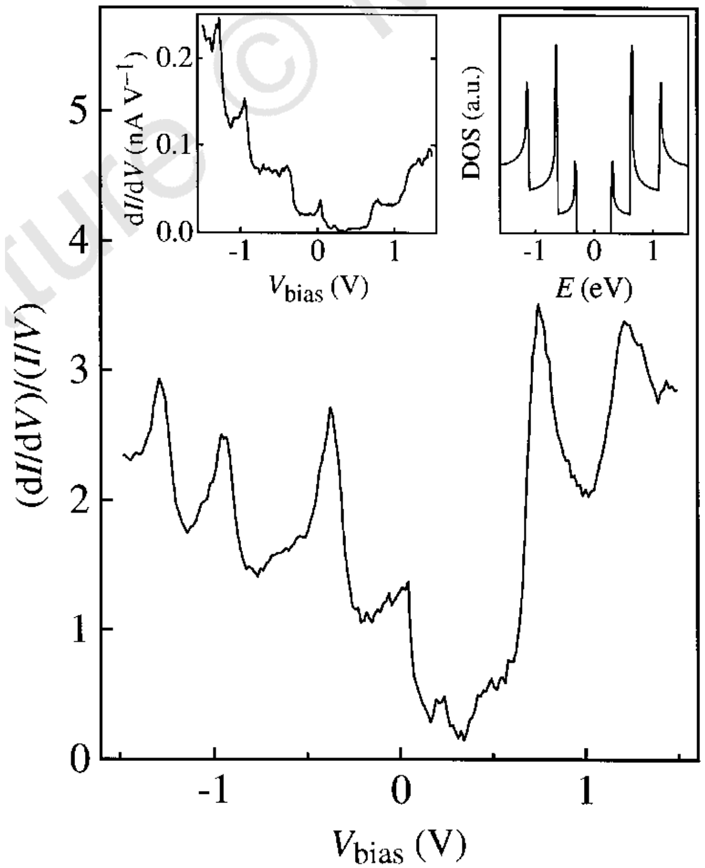
due to spatial confinement of carriers

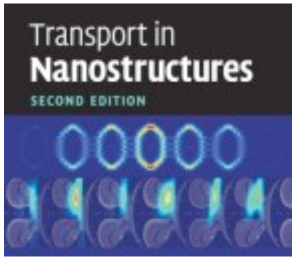
Electronic structure of atomically resolved carbon nanotubes

Jeroen W. G. Wildöer*, Liesbeth C. Venema*, Andrew G. Rinzler†, Richard E. Smalley† & Cees Dekker*

** Department of Applied Physics and DIMES, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
† Center for Nanoscale Science and Technology, Rice Quantum Institute, Departments of Chemistry and Physics, MS-100, Rice University, PO Box 1892, Houston, Texas 77251, USA





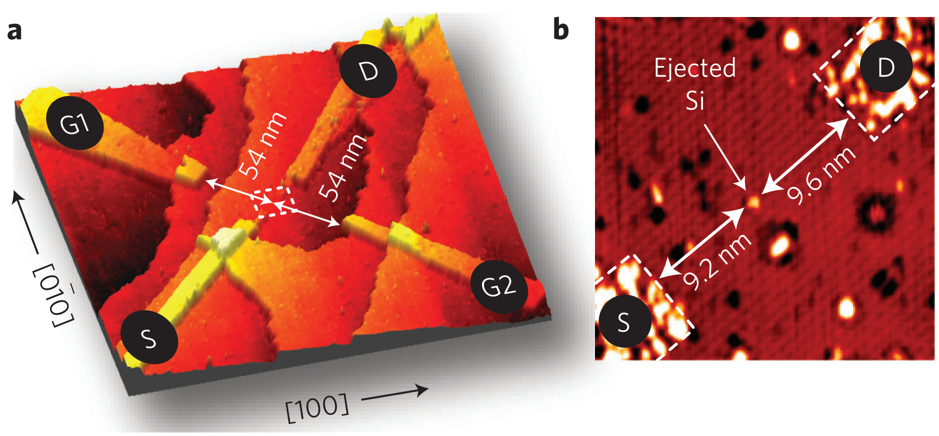


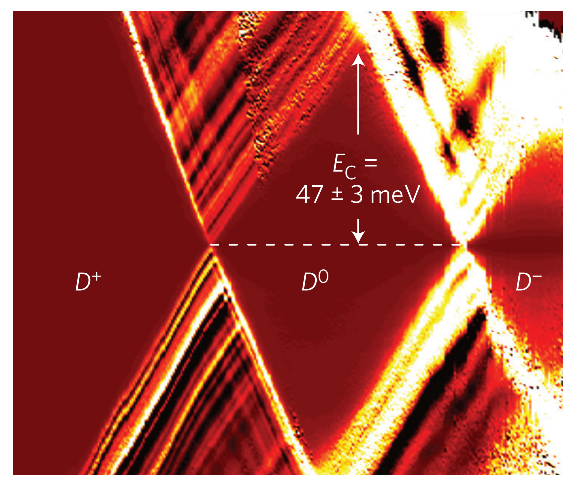
SINGLE-ELECTRON control of currents in nanostructures

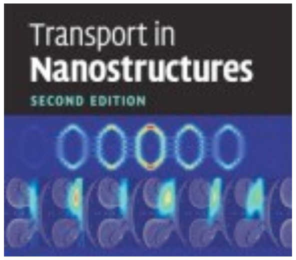
LETTERS
PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21
nature nanotechnology

A single-atom transistor

Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*

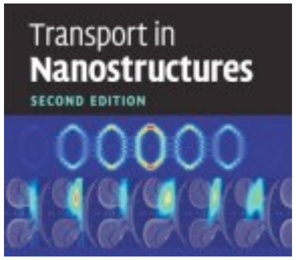






GENERAL ASPECTS OF MESOSCOPIC TRANSPORT I

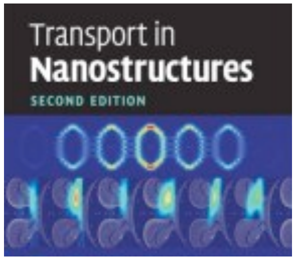
- **An Introduction to Mesoscopics**
- **Some Features of Mesoscopic Systems**
- **Some Common Mesoscopic Phenomena**
- **Realizing Mesoscopic Systems**
- **1-D Mesoscopic Systems**



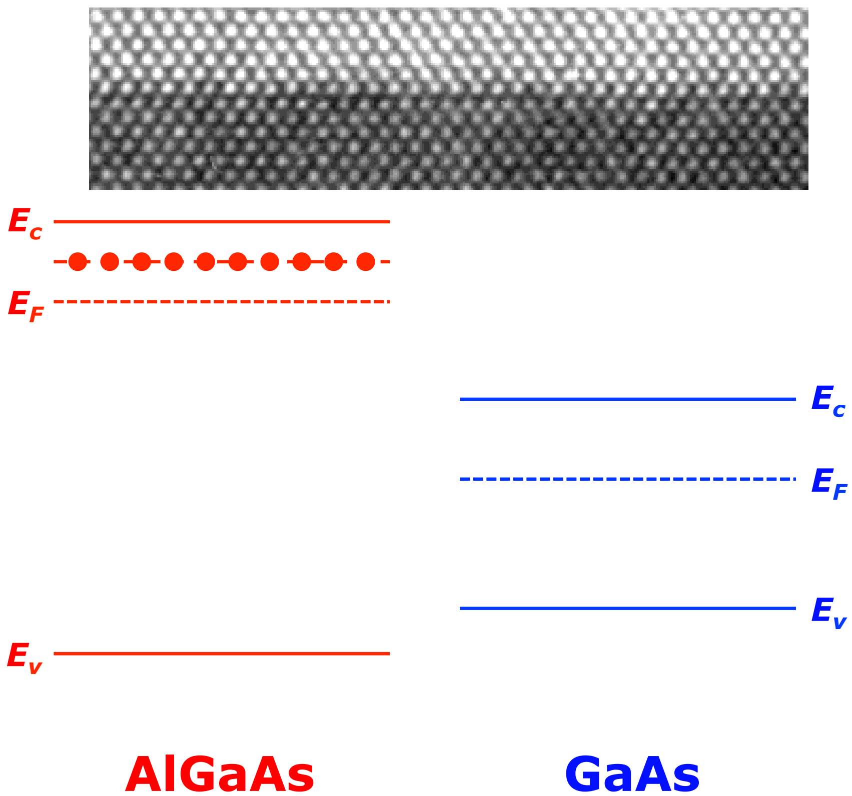
Mesoscopic Devices Can Be Realized via TWO Distinct Approaches

TOP-DOWN methods utilize standard approaches of semiconductor micro-fabrication to perform NANOSCALE patterning of semiconductors or metals

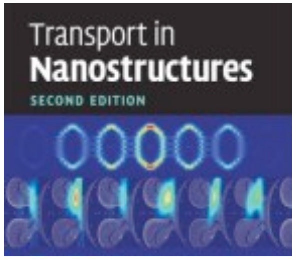
BOTTOM-UP approaches exploit NATURAL nanostructures that form via SELF-ASSEMBLY



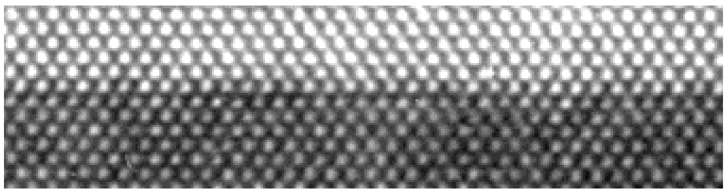
TOP-DOWN Approaches: Two-Dimensional Electron Gas (2DEG)

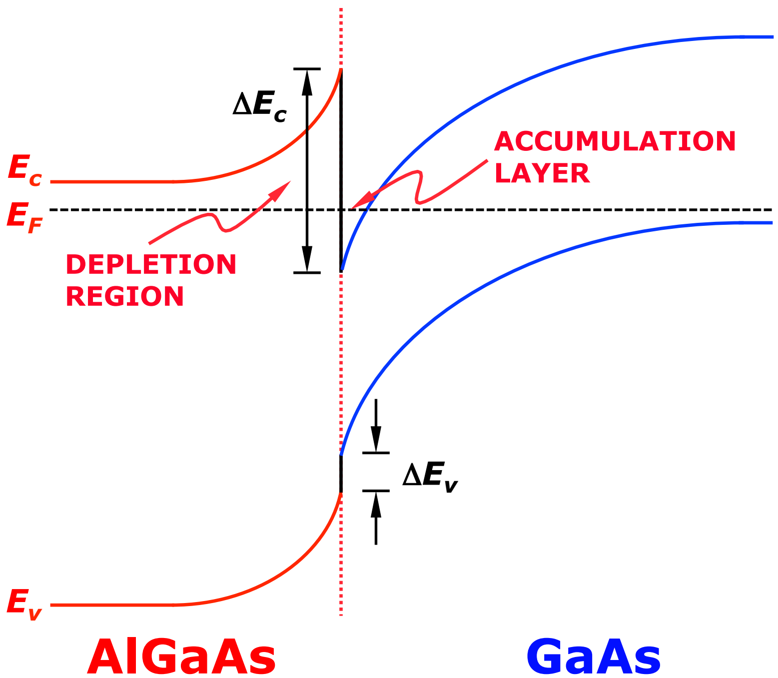


- **MOST COMMONLY BASED ON GaAs/ AlGaAs HETEROJUNCTION**
- **FORMED BY GROWING AlGaAs ON TOP OF GaAs**
- **AlGaAs HAS A LARGER BANDGAP THAN THAT OF GaAs AND IS DOPED *n*-TYPE WITH AN EXCESS OF ELECTRONS**
- **PRIOR TO HETEROJUNTION FORMATION FERMI LEVEL IN THE TWO MATERIALS IS DIFFERENT**

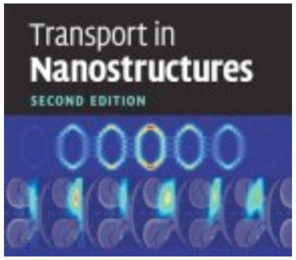


TOP-DOWN Approaches: Two-Dimensional Electron Gas (2DEG)

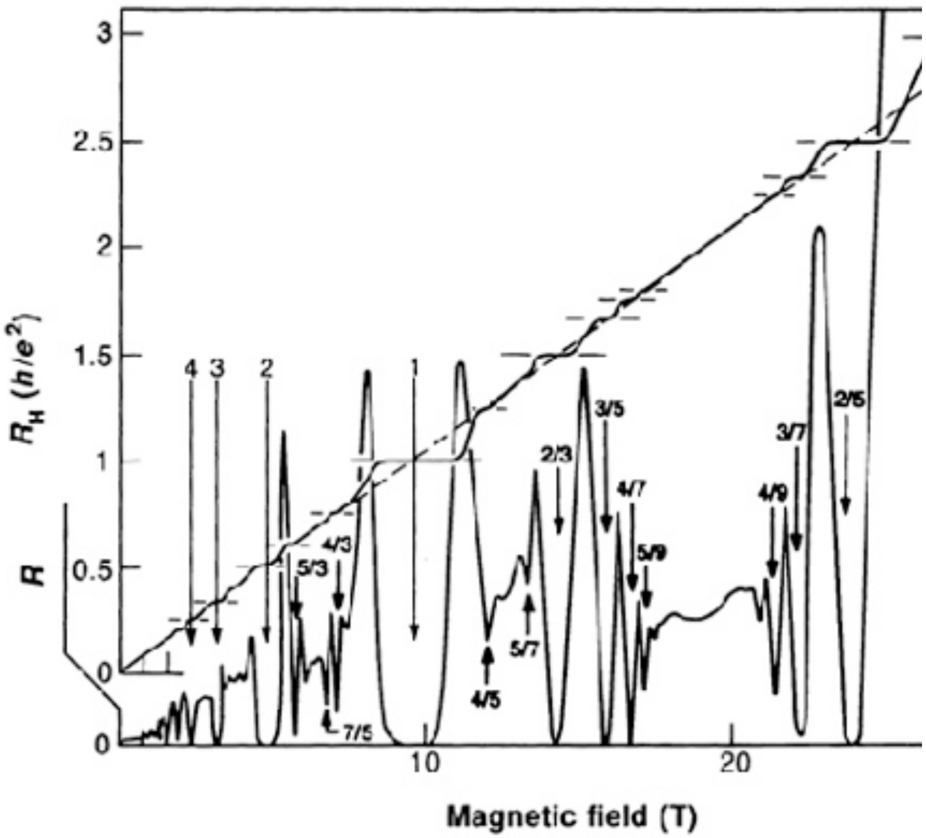




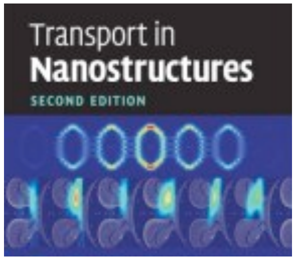
- **AT THERMAL EQUILIBRIUM THE FERMI LEVEL IS ALIGNED AT A CONSTANT POSITION ACROSS THE TWO MATERIALS**
- **THIS IS ACHIEVED BY THE TRANSFER OF ELECTRONS FROM THE AlGaAs TO THE GaAs**
- **THE RESULTING BAND BENDING – IN COMBINATION WITH THE BAND OFFSETS – RESULTS IN THE FORMATION OF A NARROW POTENTIAL WELL**
- **CARRIER MOTION IN THE WELL IS CONFINED NEAR THE INTERFACE FORMING A 2DEG**



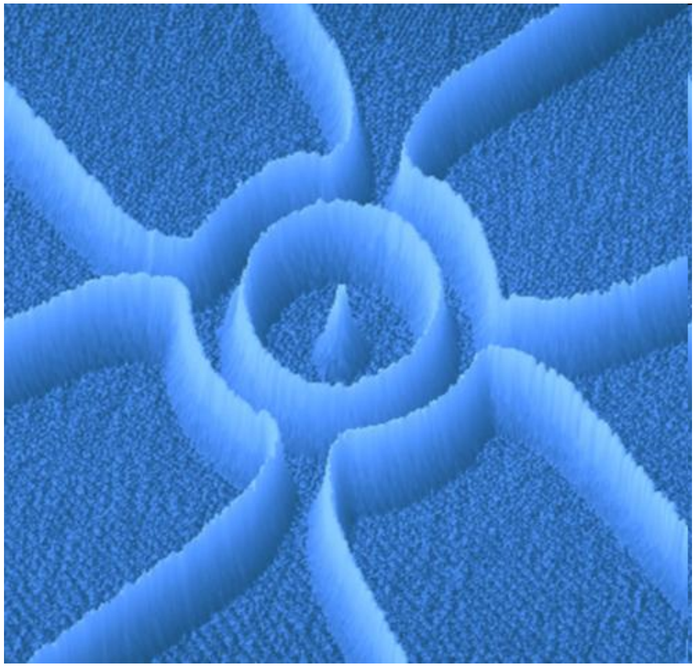
TOP-DOWN Approaches: Two-Dimensional Electron Gas (2DEG)



- THE 2DEG FORMED IN A HETEROJUNCTION CAN EXHIBIT SUPERIOR ELECTRICAL CHARACTERISTICS
- REMOVAL OF DOPANTS FROM CONDUCTING LAYER RESULTS IN EXCELLENT LOW-TEMPERATURE MOBILITY
- MEAN FREE PATH FOR TRANSPORT CAN EXCEED A HUNDRED MICRONS AT LOW TEMPERATURES!
- ALLOWS THE EXPLORATION OF A VARIETY OF NOVEL MESOSCOPIC TRANSPORT PHENOMENA

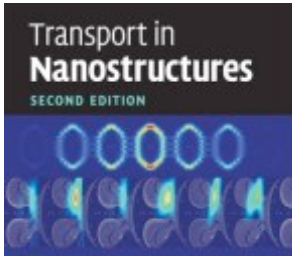


TOP-DOWN Approaches: Two-Dimensional Electron Gas (2DEG)

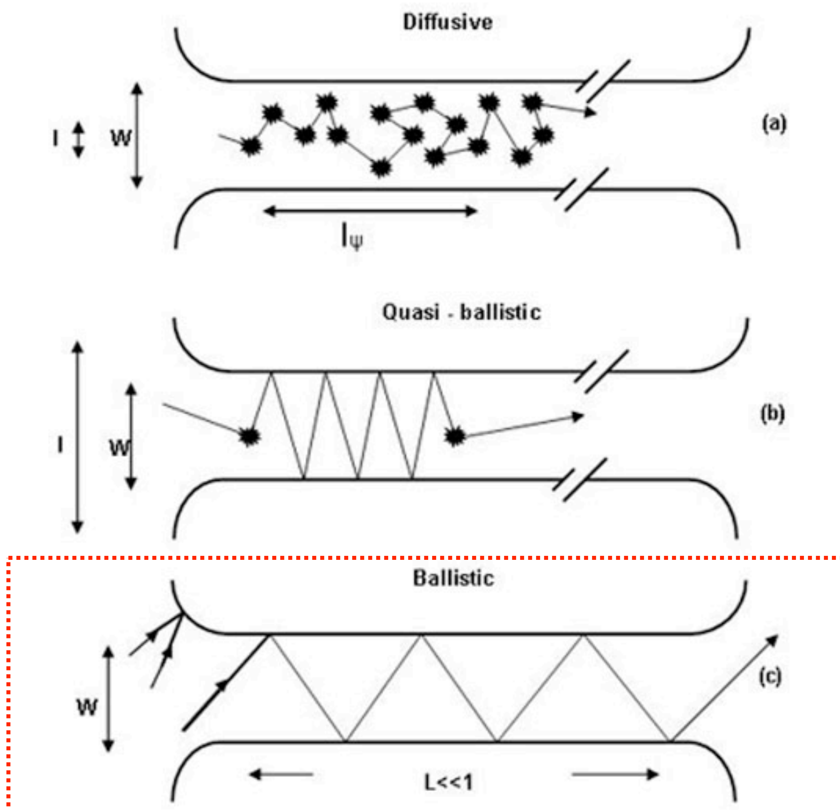


Ensslin Group
ETH Zurich

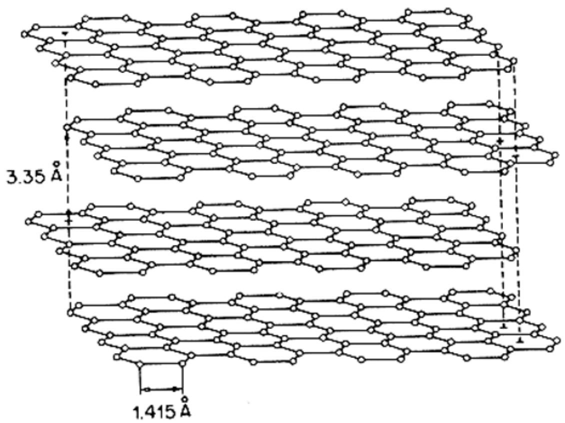
Easily PATTERNED to Form Mesoscopic Devices

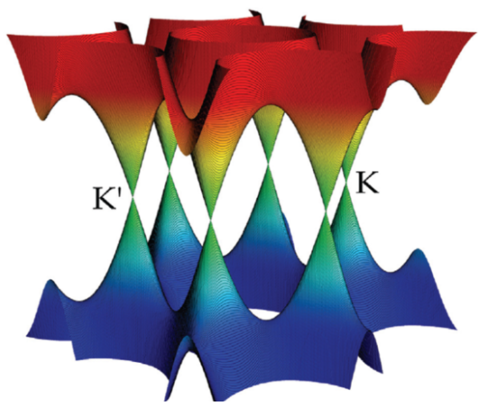


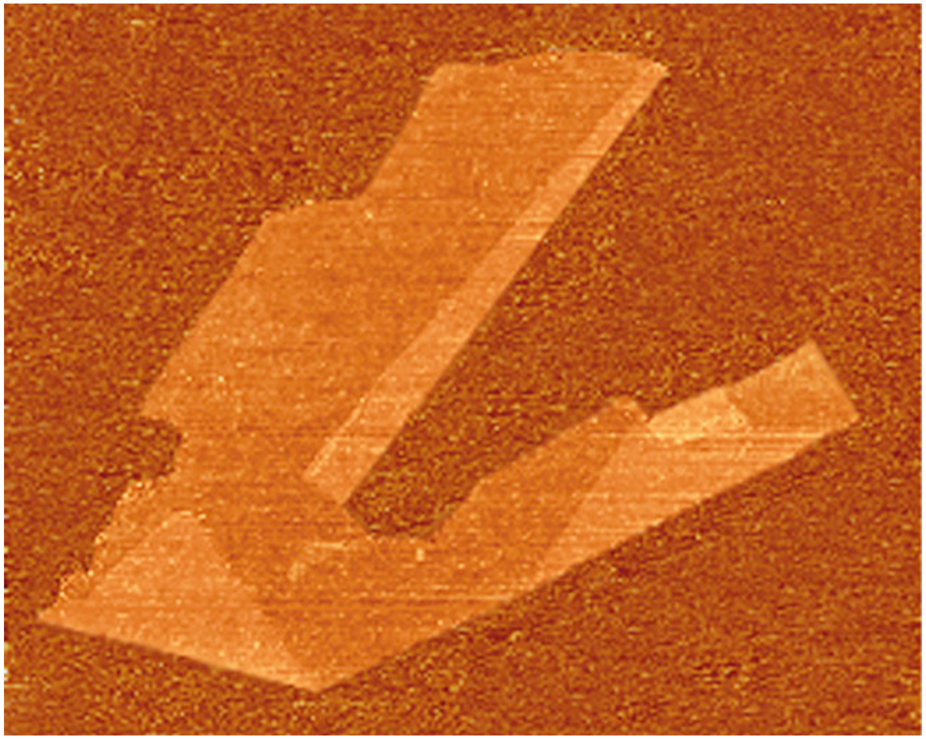
LONG Mean-Free Path Allows BALLISTIC Transport

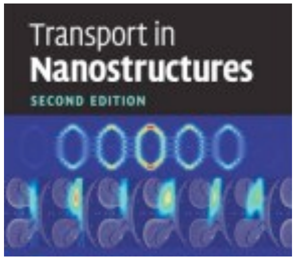


BOTTOM-DOWN 2DEG: GRAPHENE





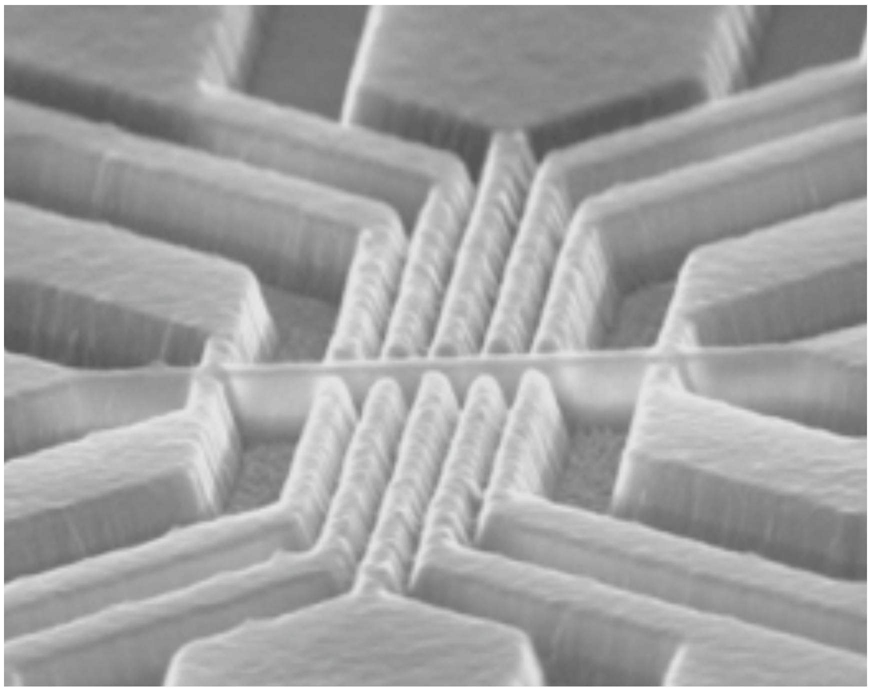




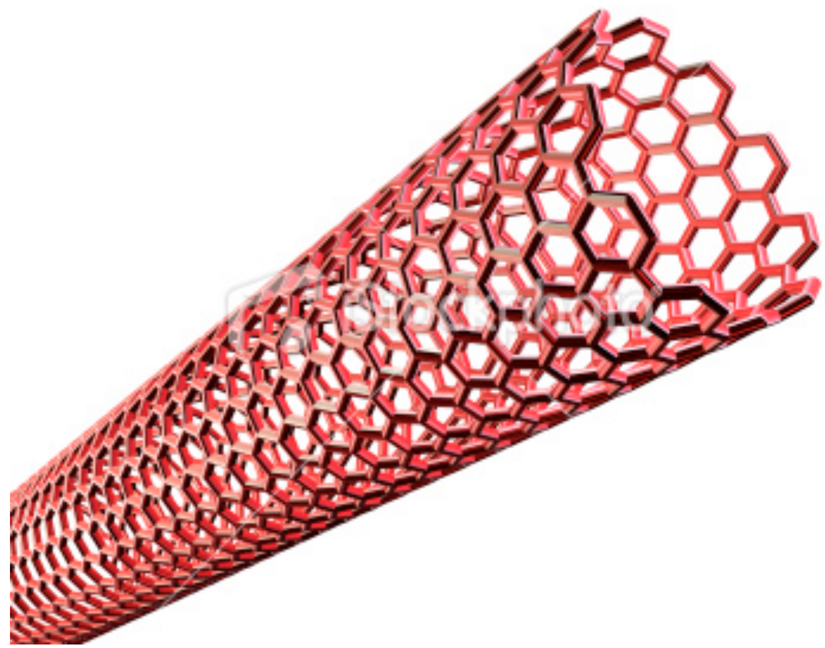
GENERAL ASPECTS OF MESOSCOPIC TRANSPORT I

- **An Introduction to Mesoscopics**
- **Some Features of Mesoscopic Systems**
- **Some Common Mesoscopic Phenomena**
- **Realizing Mesoscopic Systems**
- **1-D Mesoscopic Systems**

1-D Wires Can Be Realized By Top-Down **OR** Bottom-Up Methods



Etched Nanowire



Carbon Nanotube

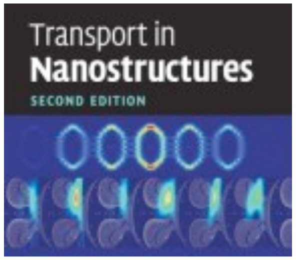
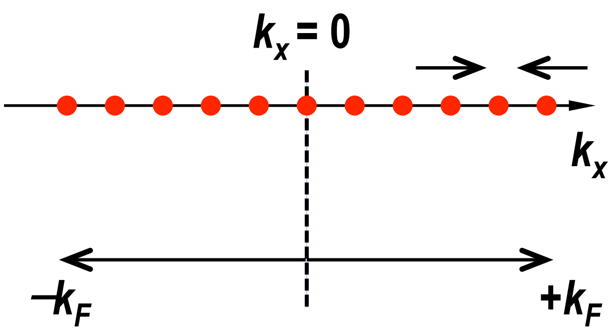


Exhibit UNIQUE Density of States That Governs Electrical & Optical Properties

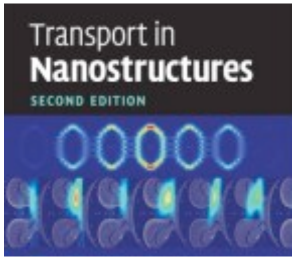


$$dk_x = \frac{2\pi}{L}$$

$$k_x = \frac{2\pi}{L} n_x \,, \quad n_x = 0, \pm 1, \pm 2, \ldots$$

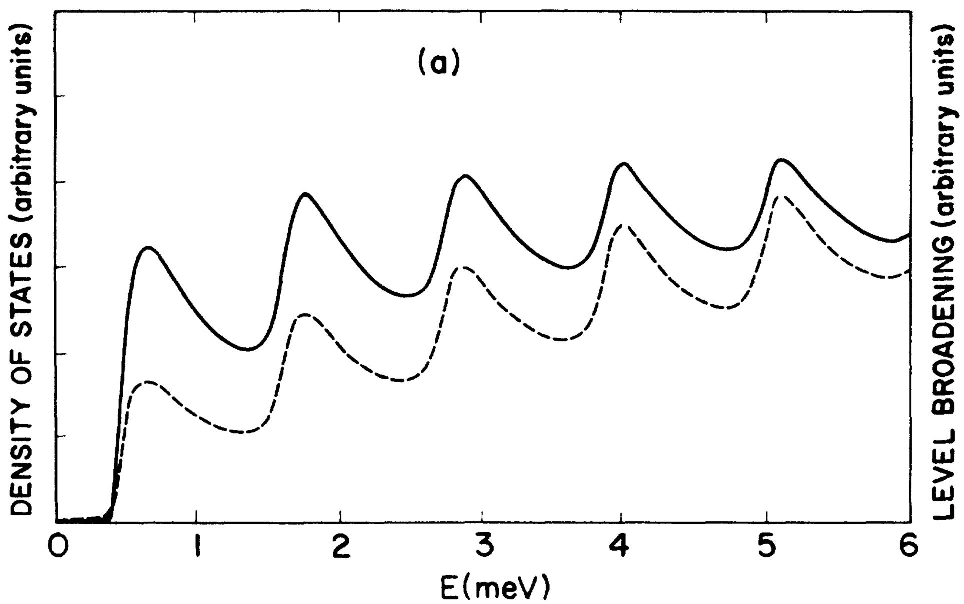
$$g_{1D}(E) = \left[\frac{2m^*}{\pi^2 \hbar^2}\right]^{1/2} \frac{1}{\sqrt{E}}$$

DoS OF PURELY 1-DIMENSIONAL – NON-INTERACTING - ELECTRONS

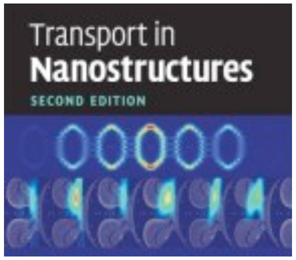


In Real Systems DoS Follows from a SUM Over Multiple 1-D SUBBANDS

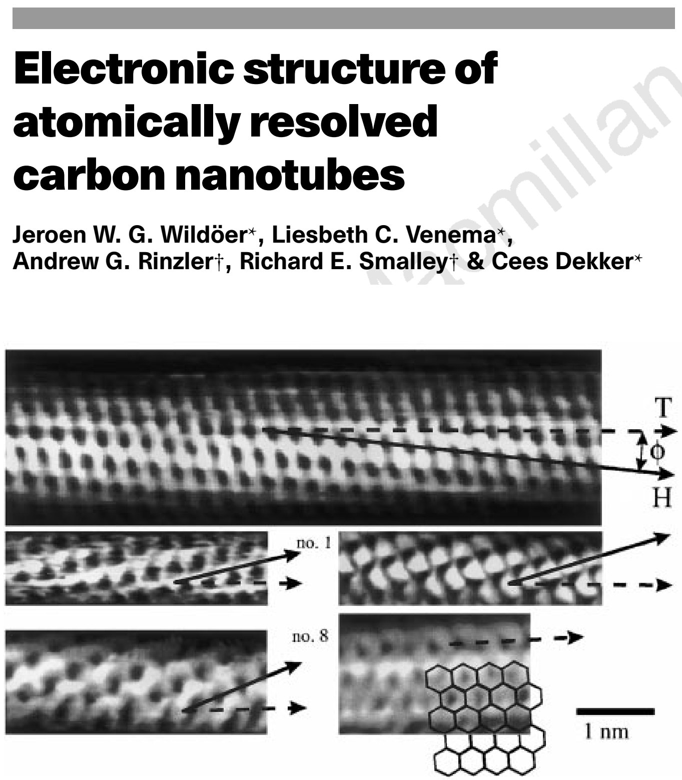
$$g_{1D}(E) = \left[\frac{2m^*}{\pi^2\hbar^2}\right]^{1/2} \sum_{E_n \le E} \frac{1}{\sqrt{E - E_n}} \Theta(E - E_n)$$



K. F. Berggren et al.
PRB 37, 10118 (1988)

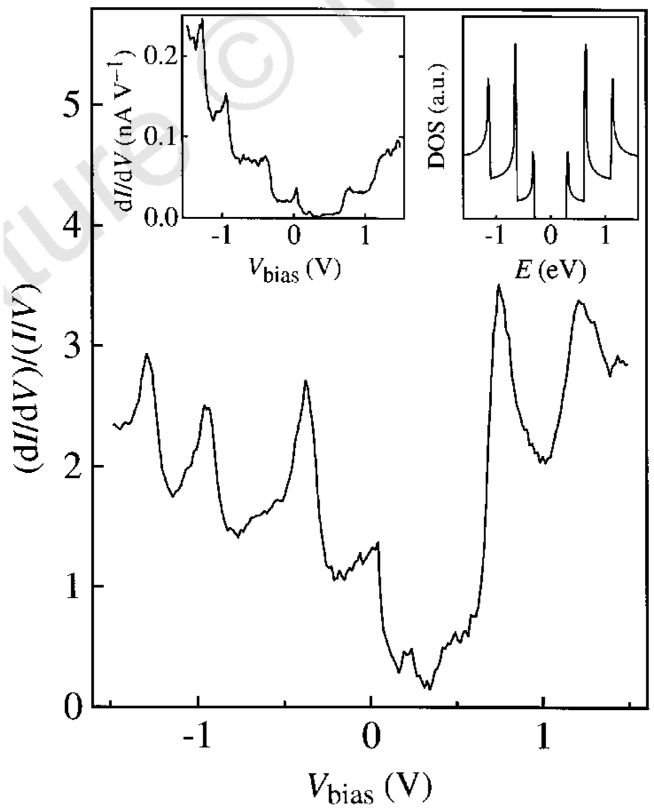


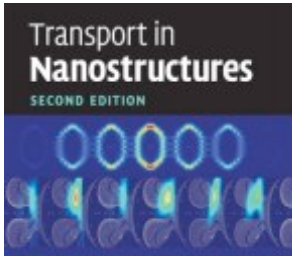
In Real Systems DoS Follows from a SUM Over Multiple 1-D SUBBANDS



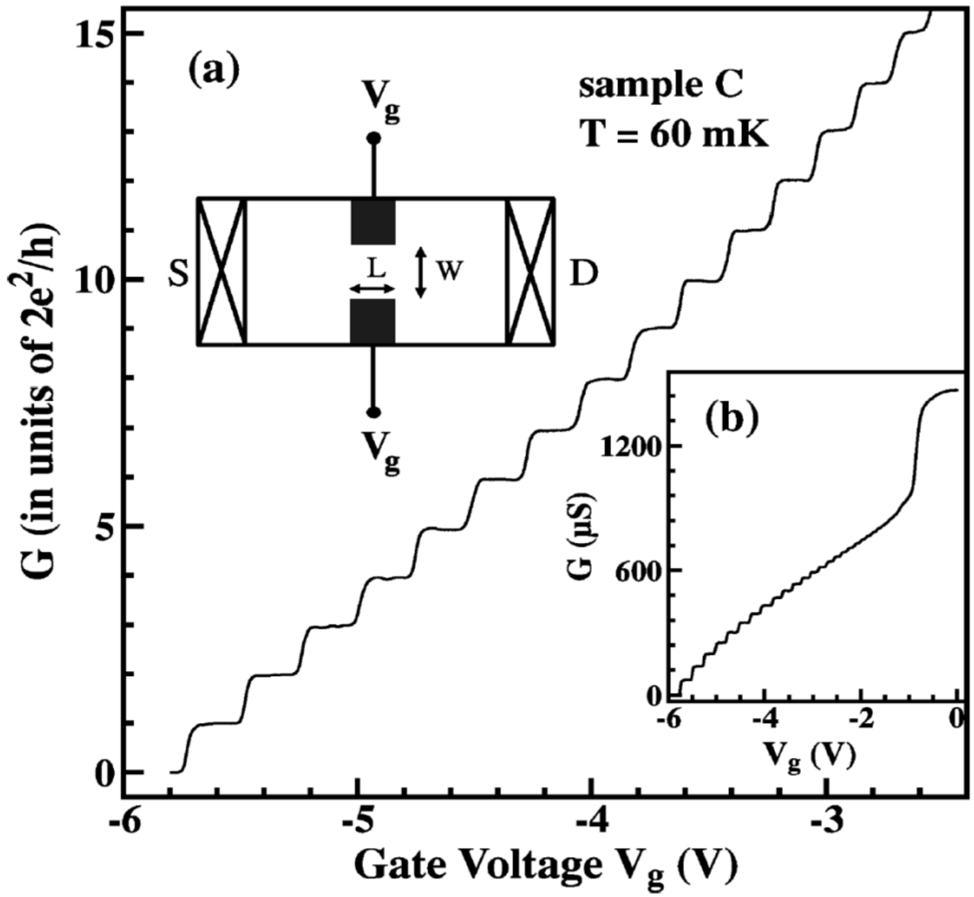
Electronic structure of atomically resolved carbon nanotubes

Jeroen W. G. Wildöer*, Liesbeth C. Venema*, Andrew G. Rinzler†, Richard E. Smalley† & Cees Dekker*





1-D DoS Responsible for a Unique Conductance QUANTIZATION



Pepper Group
Cambridge (U.K.)