mesoscopic and nanoscale physcis

mesoscopic physics deals with the physics of small objects consisting of a collection of atoms

nanometer scale

Length scale →

atoms | **molecules & clusters** | **electron mean free path** | **bulk materials**

micro | meso | macro

Menno Poot
Room: F390
(MED group)
m.poot@tudelft.nl

Herre van der Zant
Room: F286
(MED group)
h.s.j.vanderzant@tudelft.nl

TU Delft
Delft University of Technology
Faculty Of Applied Sciences

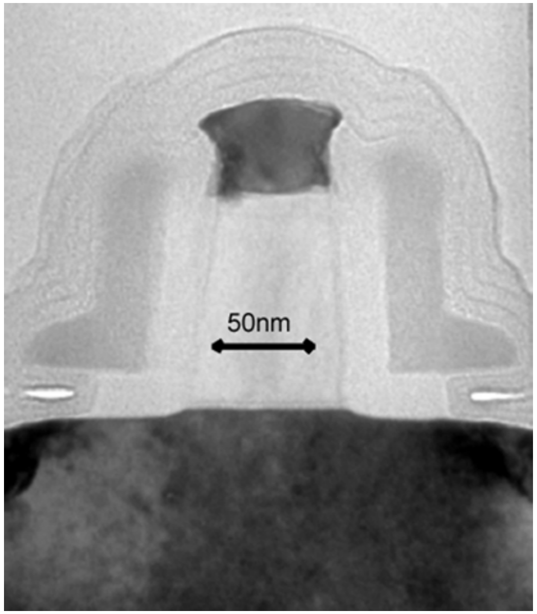
Kavli Institute of Nanoscience

modern electronic devices belong to mesoscopic scale

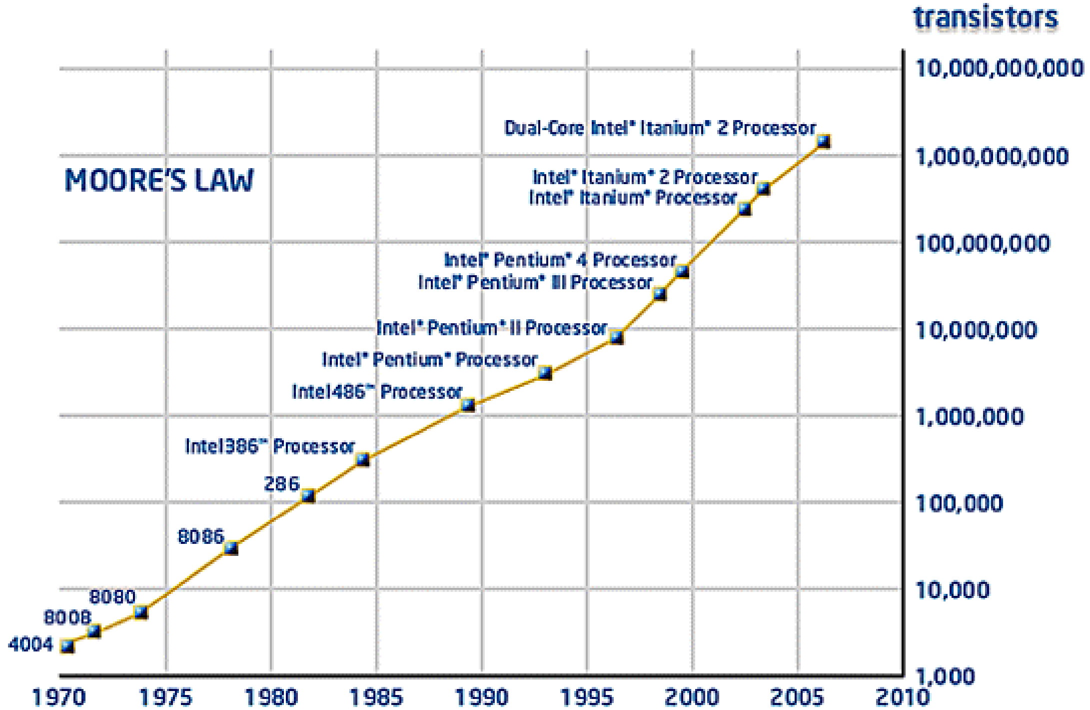
The development of the modern microelectronics industry is made possible by IC technology: the INTEGRATION of large numbers of TRANSISTORS into densely-packed integrated circuits

- **To satisfy the demand for IC with improved MEMORY and SPEED characteristics the size of transistors (nowadays: submicron) continues to SHRINK at a RAPID rate**

- **The SCALING of transistor sizes in integrated circuits is governed by an EMPIRICAL principle known as MOORE'S LAW**

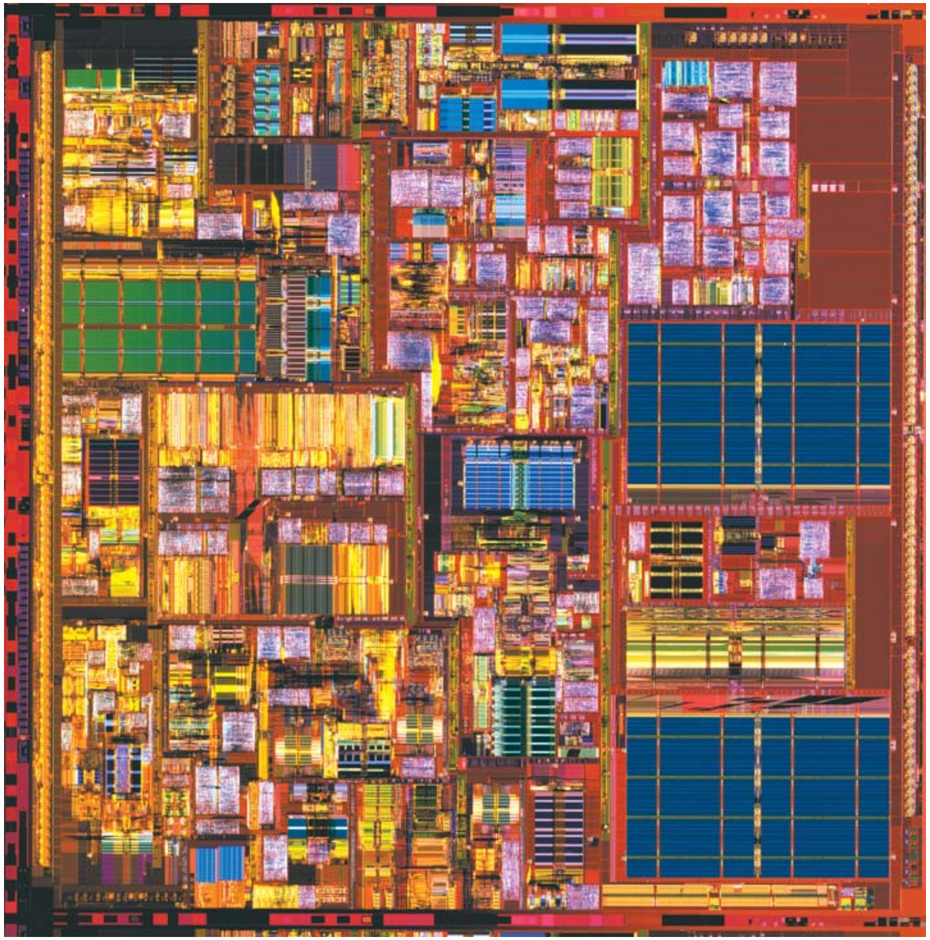


TRANSISTOR WITH 50 nm GATE LENGTH BY INTEL Corp.



MOORE'S LAW … THE TRANSISTOR DENSITY ON A CHIP DOUBLES EVERY EIGHTEEN MONTHS

CMOS TECHNOLOGY



Intel's Norwood (Pentium 4 - 130 nm) processor

Intel's Prescott processor

(released March 2004):

- 150 million transistors
- 90 nm design rules
- 3.4 GHz clock frequency

DRAM chips:

4 Gb chips demonstrated

($\sim 10^9$ transistors/cm^2)

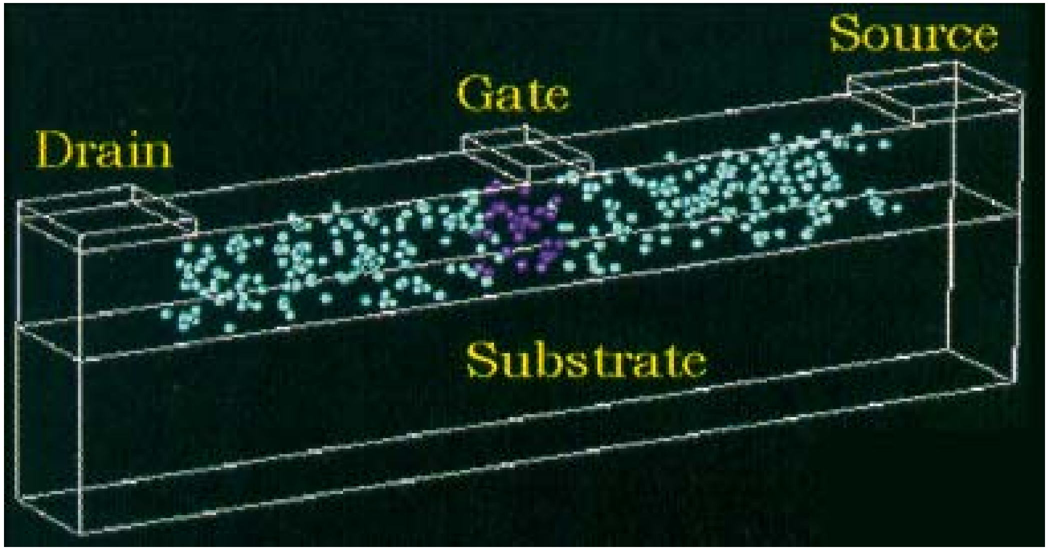
We are already inside nanotechnology!

modern integrated circuits cannot be scaled down to the atomic level

* When the thickness of the GATE OXIDE in MOSFETs is reduced to less than few nm TUNNELING between the gate and channel can become a serious problem

* The definition of WELL-DEFINED doping profiles becomes extremely DIFFICULT

* As the DISCRETE nature of the dopants becomes resolved the electrical behavior of transistors should exhibit large device-to-device FLUCTUATIONS



A TRANSISTOR STRUCTURE WITH A GATE THAT IS 24 nm LONG AND 42 nm WIDE
… THERE ARE ONLY ROUGHLY 36 DOPANTS UNDER THE GATE!

mesoscopic and nanoelectronics

The reduction of device dimensions to the NANOMETER scale offers the possibility of realizing a range of NEW technologies, which are based on the exploitation of QUANTUM-MECHANICAL transport phenomena

DEVICE	RESONANT TUNNELING DIODE	SINGLE ELECTRON TRANSISTOR	RAPID SINGLE QUANTUM FLUX LOGIC	QUANTUM CELLULAR AUTOMATA	NANOTUBE DEVICES	MOLECULAR DEVICES
TYPES	3-Terminal	3-Terminal	Josephson Junction + Inductance	Electronic & Magnetic	3-Terminal	2-Terminal & 3-Terminal
ADVANTAGES	1. Density 2. Performance 3. RF	1. Density 2. Power 3. Function	1. High Speed 2. Robust	1. High Density 2. Speed 3. Low Power	1. Density 2. Power	1. Molecular Functionality 2. Size
CHALLENGES	Matching Device Properties Across Wafer	New Device, Dimensional Control, Noise, Lack Drive Current	Low Temperatures, Complex Circuitry	Limited Fan Out, Dimensional Control, Architecture	New Device & System, Difficult Route for Circuit Fabrication	Stability,
MATURITY	Demonstrated	Demonstrated	Demonstrated	Demonstrated	Demonstrated	Demonstrated

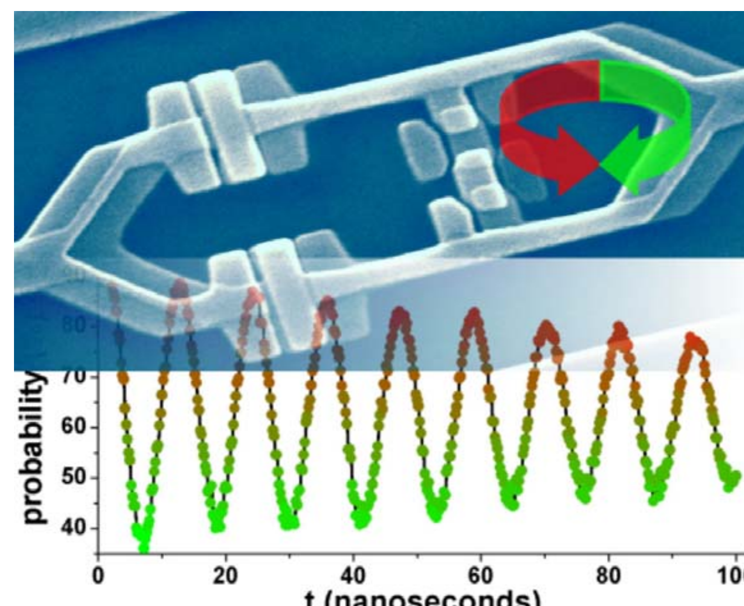
SOURCE: NATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS
2001 Ed., http://public.itrs.net/

a few other examples of new device concepts (not treated in this course)

* QUANTUM COMPUTING in which the SUPERPOSITION states of quantum-mechanical systems are exploited to implement purely QUANTUM-MECHANICAL algorithms for computing with MASSIVE speedup compared to classical calculations (for some types of problems)

* SPINTRONICS: devices in which the intrinsic electron spin states electron are used to realize new logic devices

* OPTOELECTRONIC devices that can be used to generate or detect radiation with SINGLE photon accuracy



this course: mesoscopic and nanoscale physics

The development of new technologies requires a FULL understanding of the basic QUANTUM MECHANICAL, ELECTRONIC-TRANSPORT processes that occur in nanoelectronic devices

The AIM of this course is to develop an understanding of the basic PHYSICS of electron transport in nanostructures involving concepts such as:

$\Rightarrow$ QUANTIZATION of the electronic density of states and its implications for the electrical properties of nanostructures

$\Rightarrow$ CONDUCTANCE QUANTIZATION due to ballistic transport in low-dimensional electron systems

$\Rightarrow$ QUANTUM-INTERFERENCE phenomena arising from the wave-mechanical properties of the electron

$\Rightarrow$ TUNNELING AND COULOMB BLOCKADE phenomena

$\Rightarrow$ MESOSCOPIC PHONONS: interaction between mechanical motion and electric transport

$\Rightarrow$ ELECTRON SPIN: manipulation of a single spin

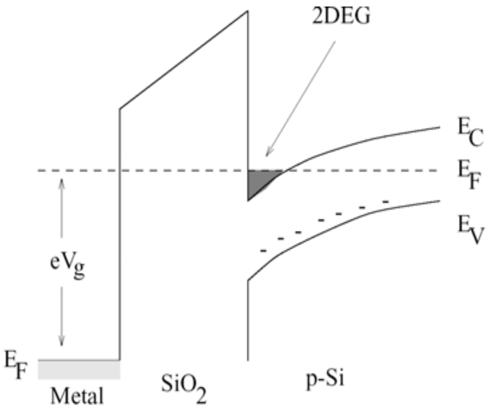
Preliminary program Mesoscopic physics 2007

week 1	introduction, material systems, density of states, energy scales	section 1.1 and 1.2 of the lecture notes of Kees Harmans
week 2	length scales, transport regimes, review conduction in the classical regime	section 1.3, 2.1, 2.2
week 3	phase-coherent transport 1	section 2.3
week 4	phase-coherent transport 2	section 5.1 and 5.2
week 5	ballistic transport; quantum point contact	section 3.1, 3.2, 3.3 (not negative Hall effect), 4.1, 4.2
week 6	Quantum Hall effect	section 4.3, 4.4
week 7	S-N interface: Andreev reflection	section 6.1, 6.2, 6.3
week 8	charging effects, Coulomb blockade, electron box	section 7.1, 7.2,
week 9	SET, quantum dots 1	section 7.2 plus additional notes
week 10	quantum dots 2	section 7.2 plus additional notes
week 11	nanomechanics 1: elastic beams and zero-point motion	additional notes
week 12	nanomechanics 2: thermal conductance quantum, Casimir forces	
week 13	optics with quantum dots	transparencies
week 14	to be decided	

Oral exam: emphasis on the important experiments in the field and their understanding on the conceptual level

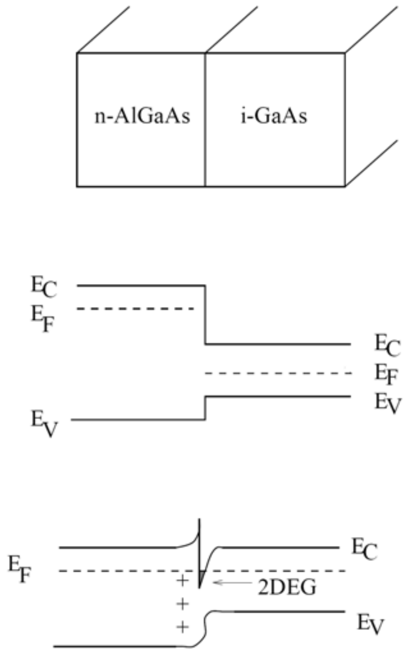
two-dimensional electron gas

band gap engineering



Metal-Oxide-Semiconductor (MOS) structures

2DEG is formed at the semiconductor-insulator interface



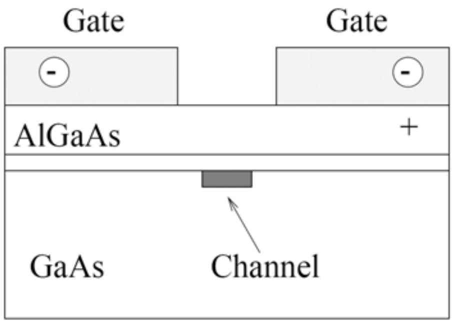
semiconductor heterostructure

2DEG is formed at the interface between two semiconductors

2DEG is a generic object for new physics

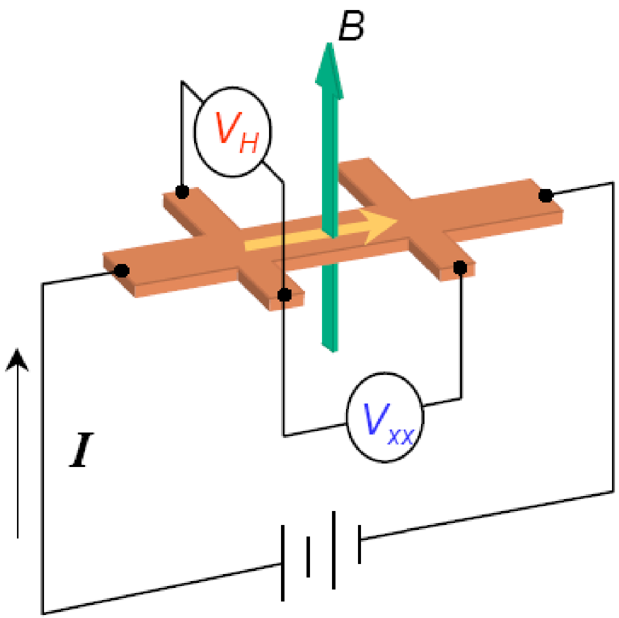
Nobel Prizes 1985, 1998, 2000

It serves as a building block for electronic devices

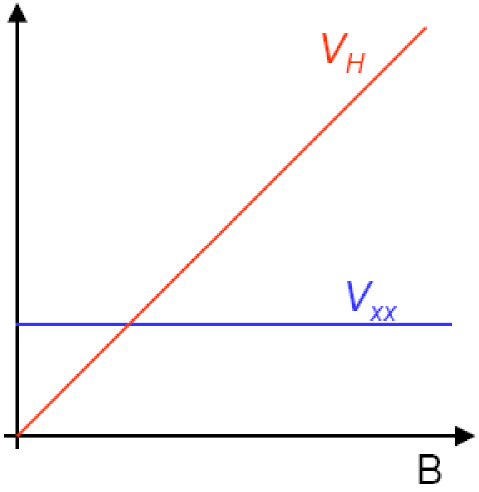


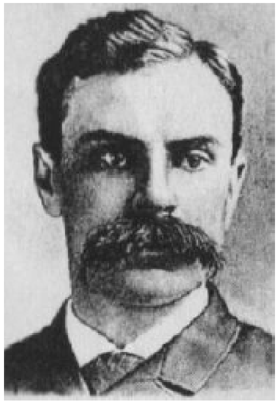
gates define device structures

the quantum Hall effect



Ordinary Hall effect





Ed Hall, 1879

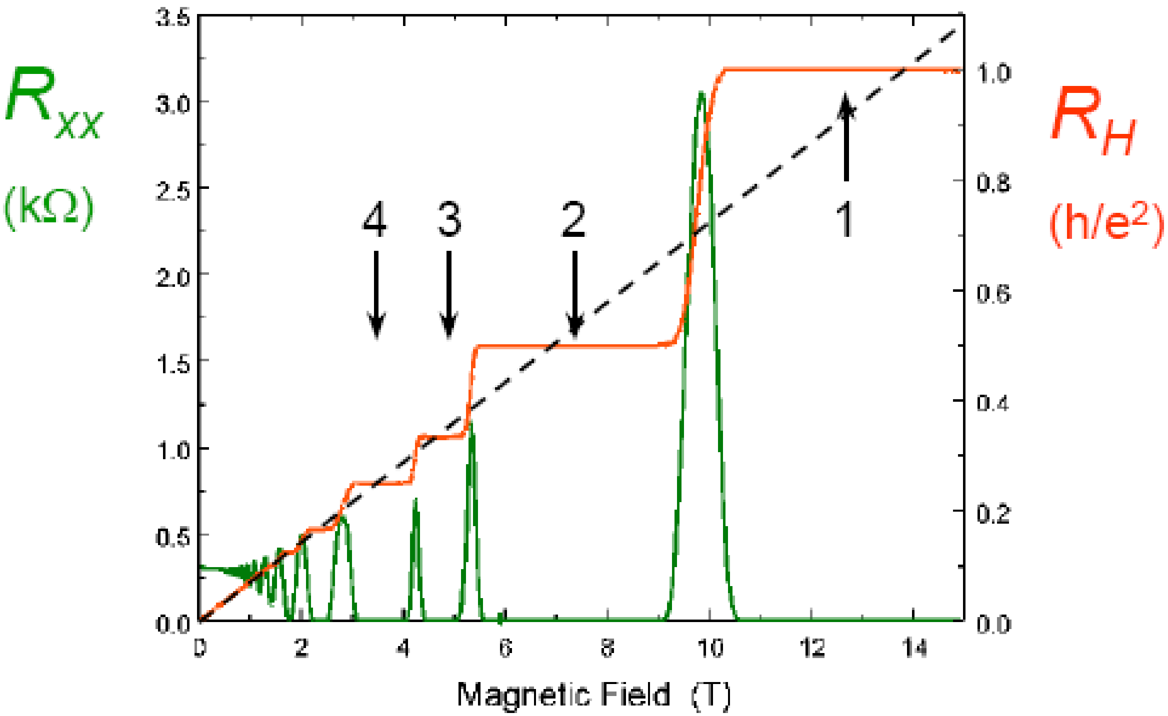
$$R_H = V_H / I = B/ne$$

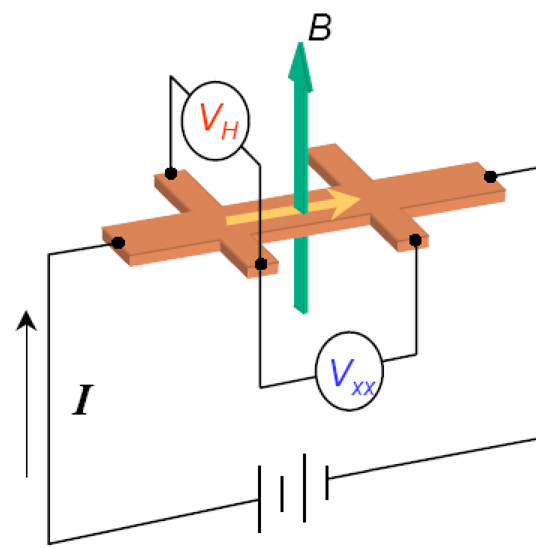
the quantum Hall effect in a 2DEG

1985

Si-MOSFET: two-dimensional device

Klaus von Klitzing

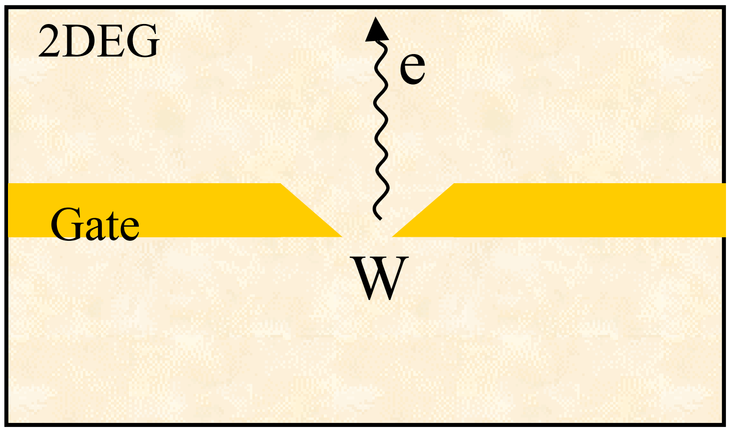




$$R_{Hall} = \frac{h/e^2}{j} = 25812.807 \text{ Ohms} / \textit{integer}$$

Hall resistance (R_{xy}) increases in step-wise way to well defined quantized values).
At these well-defined values: $R_{xx} = 0$!!!

point contacts: one-dimensional devices conductance quantization



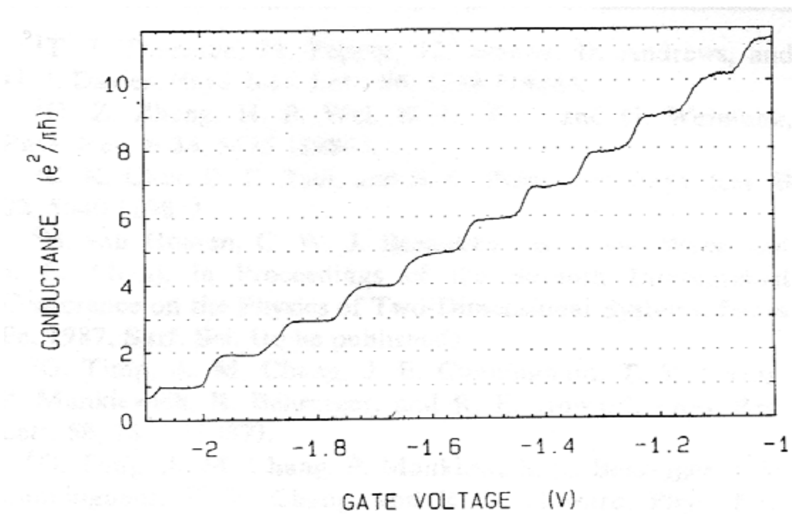
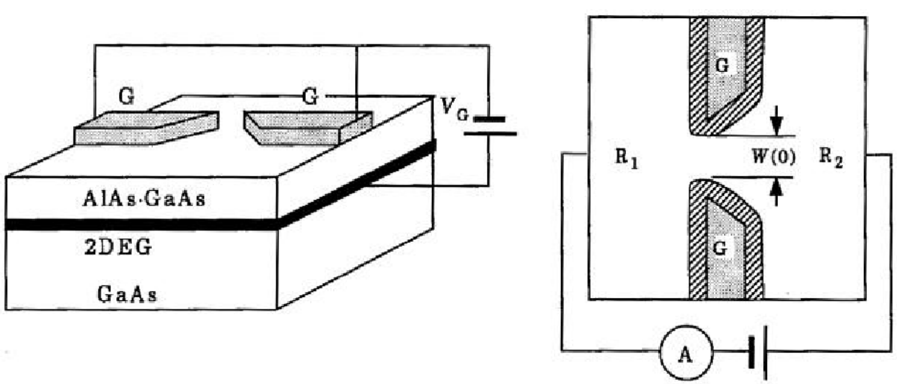


FIG. 2. Point-contact conductance as a function of gate voltage, obtained from the data of Fig. 1 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi\hbar$.



$$G = \sum_{n=1}^{N_c} \frac{2e^2}{h}$$

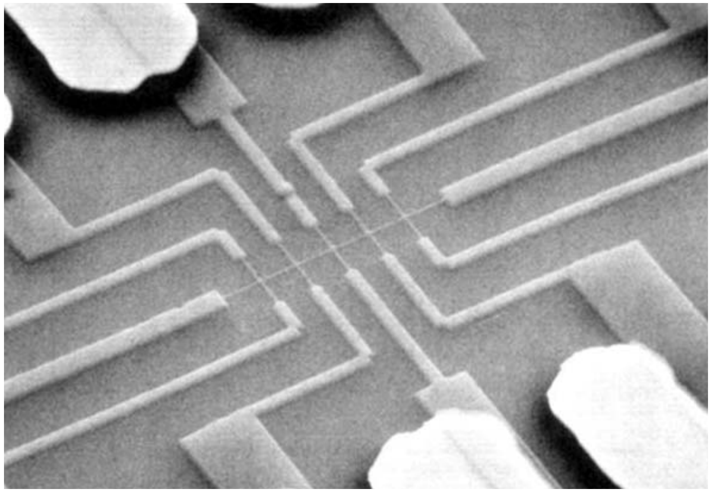
B.J. van Wees, *et al.*, *Phys. Rev. Lett*. **60**, 848 (1988); D.A. Wharam, *et al.*, *J. Phys*. C **21**, L209 (1988).

quantum wires

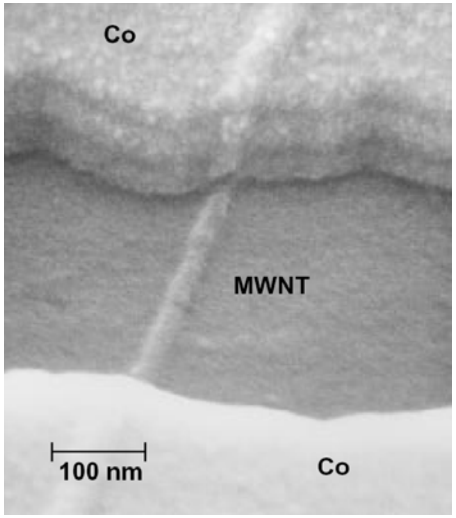
QUANTUM WIRES: free electron motion is restricted to ONE dimension (1D)

⇒ These QUASI-ONE-DIMENSIONAL structures may be realized using a variety of techniques

⇒ They also occur quite NATURALLY and examples of such structures include CARBON NANOTUBES and long MOLECULAR CHAINS



75-nm WIDE ETCHED QUANTUM WIRE



CARBON NANOTUBE BRIDGING TWO COBALT CONTACTS

M. L. Roukes *et al.*
Phys. Rev. Lett. 59, 3011 (1987)

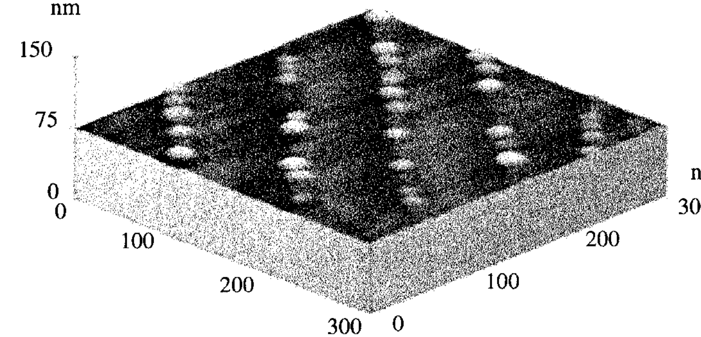
K. Tsukagoshi *et al.*
Nature 401, 572 (1999)

semiconducting quantum dots

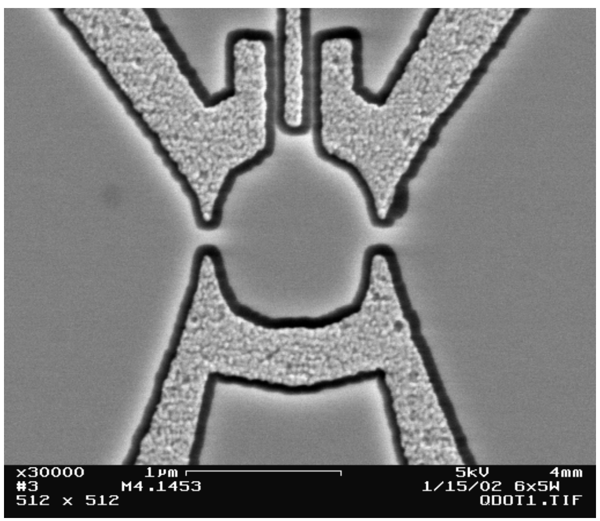
QUANTUM DOTS are structures (called zero-dimensional, 0-D) in which electron motion is strongly confined in ALL THREE dimensions (QUANTIZATION) so that these structures may be viewed as ARTIFICIAL ATOMS

- **These structures may be realized by a variety of different techniques and in a range of different materials**

- **Dominant transport mechanism: SINGLE-ELECTRON TUNNELING**

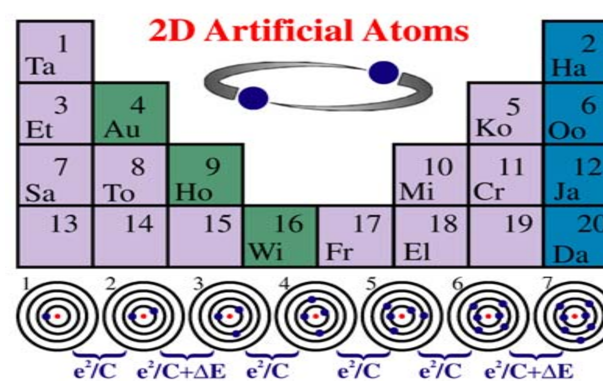


AFM IMAGE OF SELF-ASSEMBLED InGaAs QUANTUM DOTS

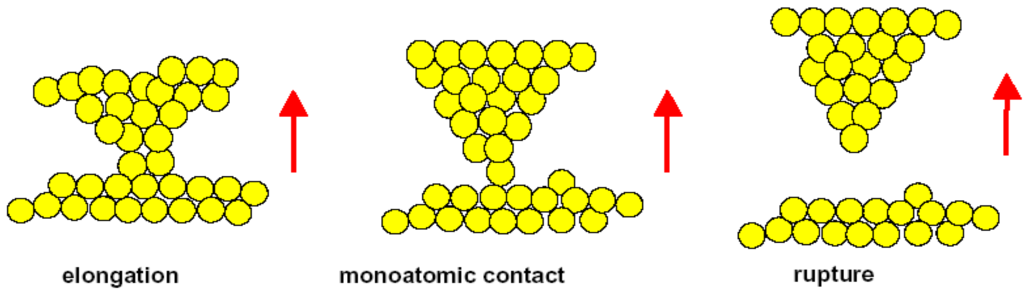


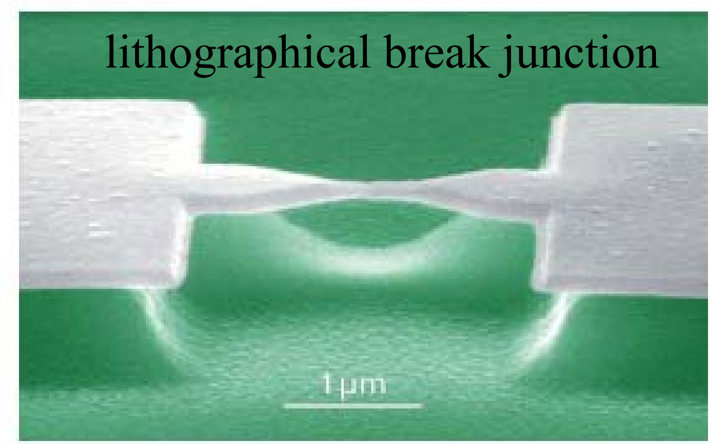
SEM IMAGE OF A GaAs/AlGaAs QUANTUM DOT REALIZED BY THE SPLIT-GATE METHOD

VERTICAL QUANTUM DOTS (DELFT, KOUWENHOVEN)



mechanically controllable break junctions: variable atomic contacts





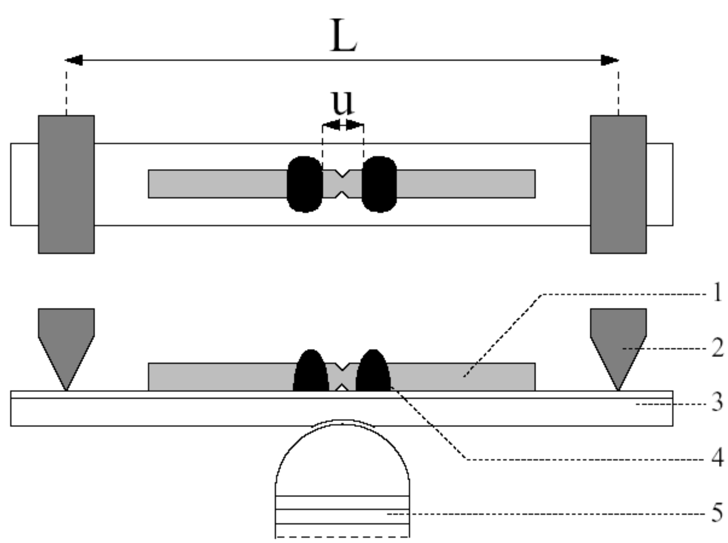
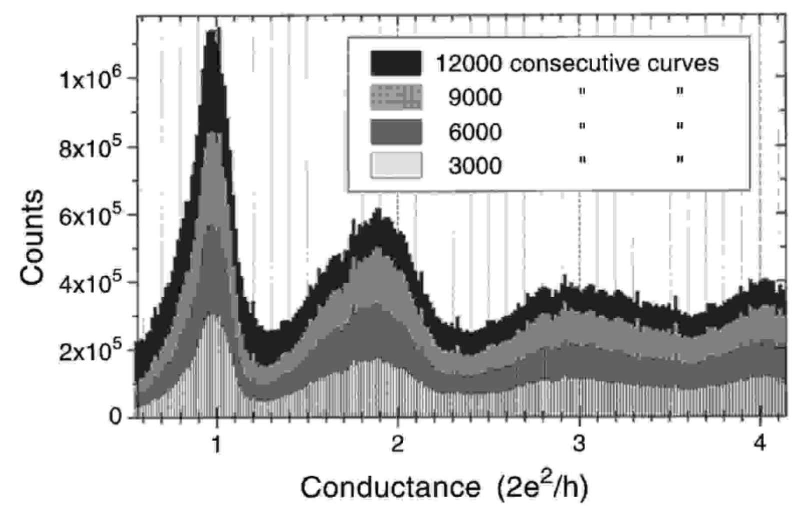


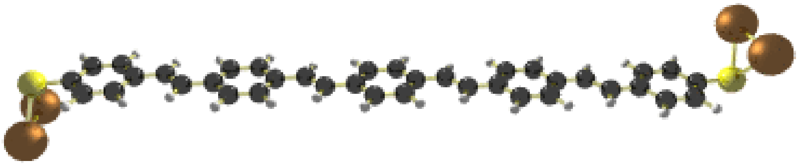
FIG. 6: Schematic top and side view of the mounting of a MCBJ, with the notched wire (1), two fixed counter supports (2), bending beam (3), drops of epoxy adhesive (4) and the stacked piezo element (5).



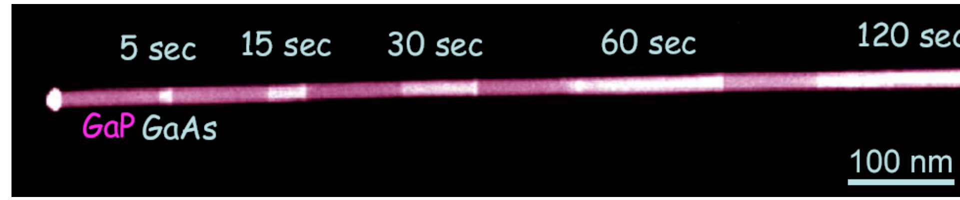
Review: Agrait, Yeyati and Ruitenbeek
*Physics Reports **377** (2003) 81*

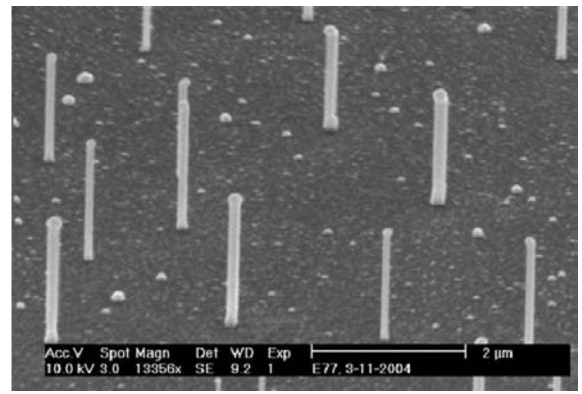
nanoscale building blocks: bottom-up

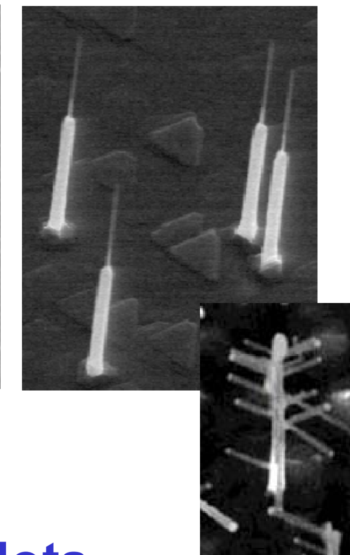
(organic) molecules



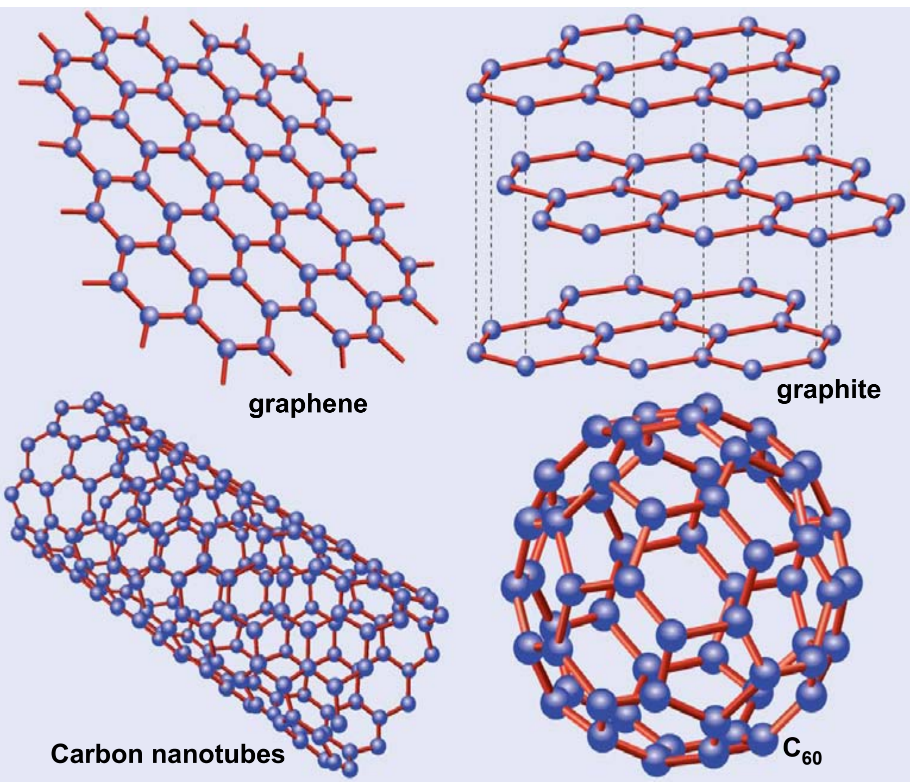
inorganic nanowires



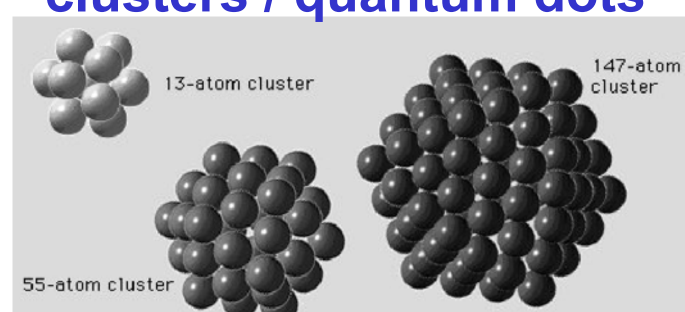




Carbon-based materials



clusters / quantum dots



density of states (DOS)

Solving the free-electron Schrödinger equation subject to periodic boundary conditions yields QUANTIZATION CONDITIONS on the allowed electron wave numbers: the allowed wave numbers may be represented as a series of DISCRETE points in a three-dimensional *k*-SPACE

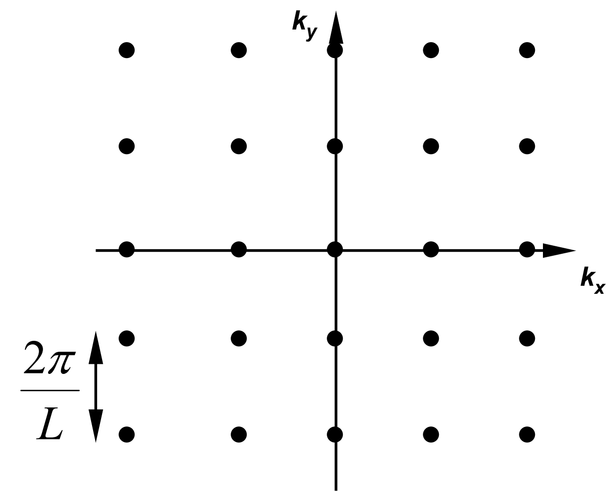
Each point in *k*-space then corresponds to a particular momentum state which may be occupied by TWO electrons because of the PAULI EXCLUSION PRINCIPLE

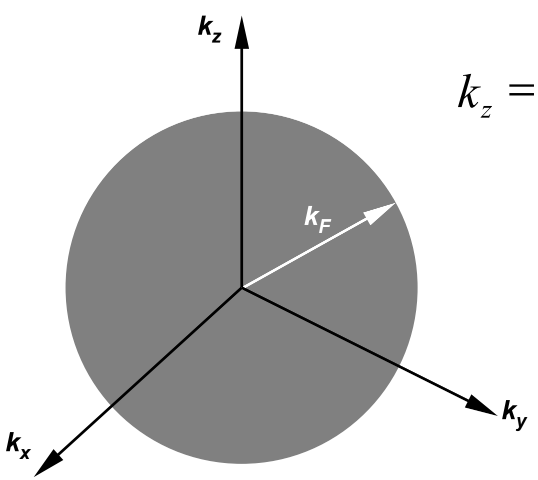
The total VOLUME of the sphere in *k*-space is just $4\pi k_F^3/3$ where k_F is referred to as the FERMI RADIUS while the volume of *k*-space enclosed by EACH wave vector is $8\pi^3/L^3$

$$k_x = \frac{2\pi n_x}{L}, \; n_x = 0, \pm 1, \pm 2, \pm 3$$

$$k_y = \frac{2\pi n_y}{L}, \; n_y = 0, \pm 1, \pm 2, \pm 3$$

$$k_z = \frac{2\pi n_z}{L}, \; n_z = 0, \pm 1, \pm 2, \pm 3$$





$$\frac{N}{2} = \frac{Volume\ of\ Sphere}{Volume\ per\ State} = \frac{4\pi}{3} k_F^3 \frac{L^3}{8\pi^3}$$

see for example Kittel, Introduction to Solid State Physics

density of states (D(E))

- use the results from the previous slide and the free-electron model

$$k_F = \left[\frac{3\pi^2 N}{L^3}\right]^{1/3} = [3\pi^2 n_s]^{1/3} \qquad N = \frac{k_F^3 L^3}{3\pi^2} \qquad E = \frac{\hbar^2 k^2}{2m^*}$$

n_s: electron (charge) density

- to express the number of electrons (N) in terms of the energy (E)

$$\text{number of states with energy} < \text{E}: N(E) = \frac{L^3}{3\pi^2}\left[\frac{2m^* E}{\hbar^2}\right]^{3/2}$$

$$\text{density of states (n = dimension)}: D(E) = \frac{1}{L^{n=3,2,1}} \frac{dN(E)}{dE}$$

- density of states depends on the dimension (calculate yourself D(E) for 1D and 2D))

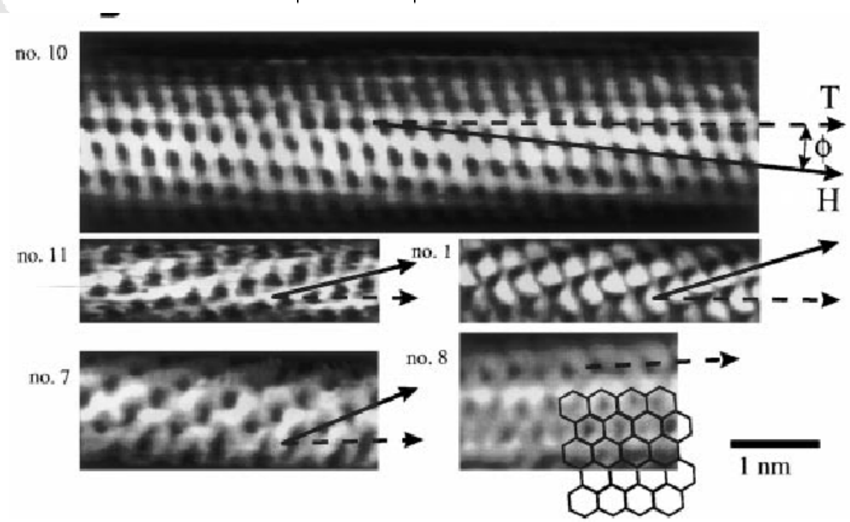
$$D_{3D}(E) = \frac{1}{2\pi^2}\left[\frac{2m^*}{\hbar^2}\right]^{3/2} E^{1/2} \qquad D_{2D}(E) = \frac{m^*}{\pi\hbar^2} \qquad D_{1D}(E) = \left[\frac{2m^*}{\pi^2\hbar^2}\right] E^{-1/2}$$

Important quantity that is used in many calculations and that can be measured

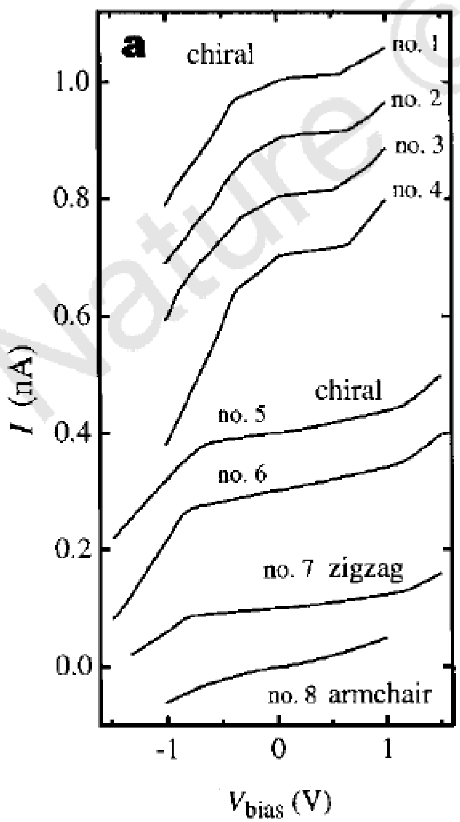
Electronic structure of atomically resolved carbon nanotubes

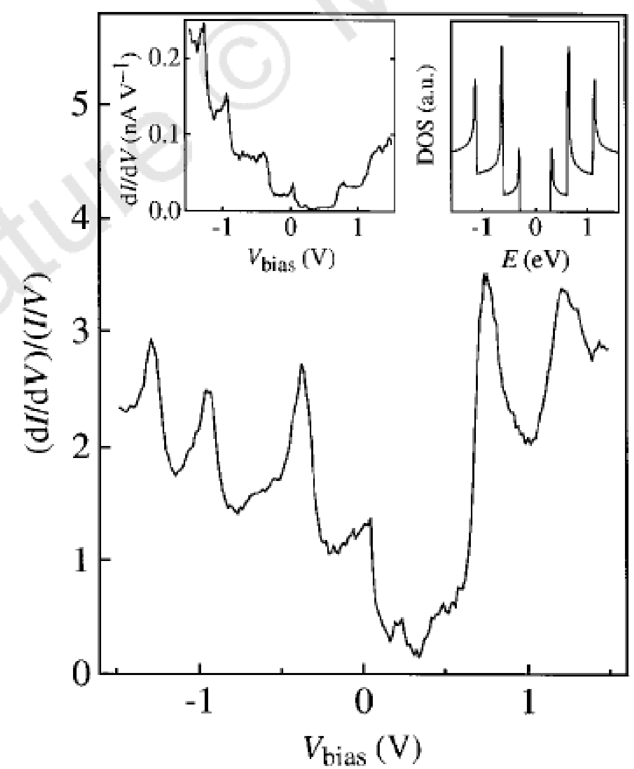
Jeroen W. G. Wildöer*, Liesbeth C. Venema*, Andrew G. Rinzler†, Richard E. Smalley† & Cees Dekker*

NATURE | VOL 391 | 1 JANUARY 1998



With an STM one can image nanoscale objects but one can also perform spectroscopy: the measured dI/dV at a particular location is proportional to the DOS.

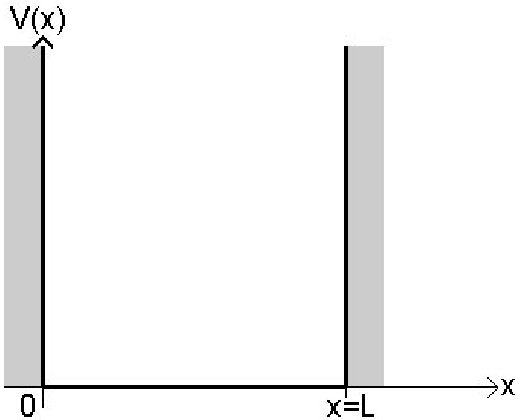




density of states

energy quantization and level spacing

• solve Schrödinger equation for particle in a box (1D)



$$-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2}+V(x)\psi(x)=E\psi(x)$$

$$-\frac{\hbar^2}{2m}\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2}=E\psi(x)$$

$$\psi(0)=\psi(L)=0$$

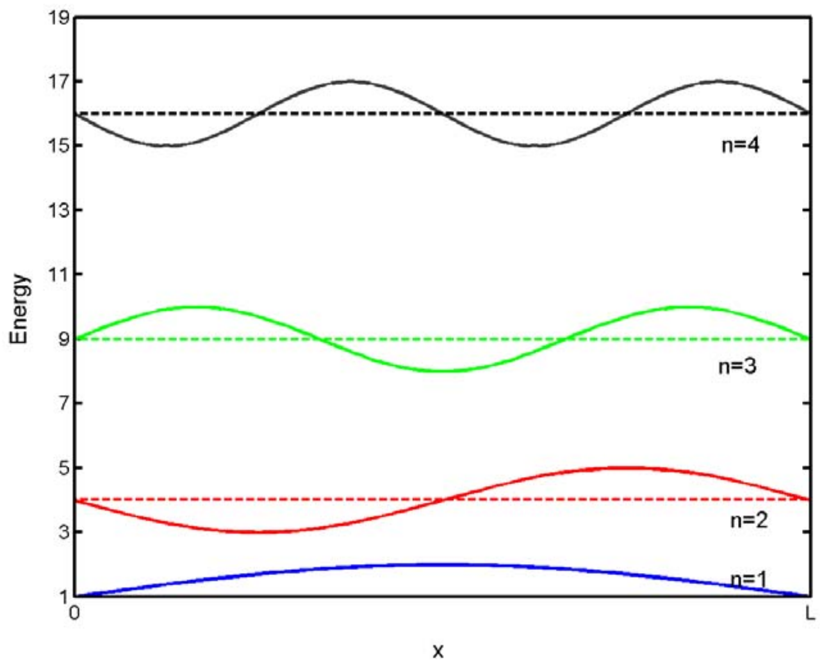
$$k=\frac{n\pi}{L} \quad \text{where} \quad n\in\mathbb{N}^+$$

$$\psi(x)=A\sin(kx)+B\cos(kx)$$

• solutions are sine waves with energy E_n

$$\psi_n(x)=\sqrt{\frac{2}{L}}\sin\left(\frac{n\pi x}{L}\right) \qquad E=\frac{k^2\hbar^2}{2m}$$

$$E_n=\frac{n^2\hbar^2\pi^2}{2mL^2}=\frac{n^2h^2}{8mL^2}$$



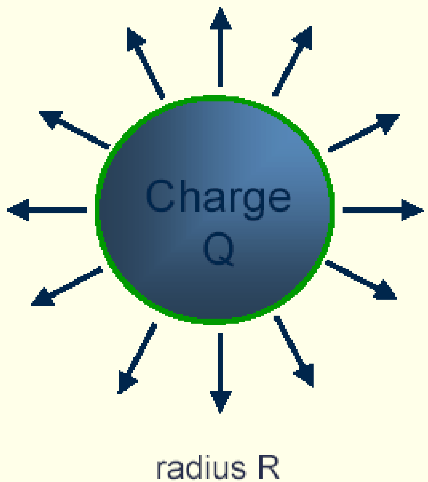
• level spacing ΔE (increases as system size decreases):

$$\Delta E=E_{n+1}-E_n\approx\frac{dE}{dN}=\frac{1}{L^{n=1,2,3}D(E)}$$

source: Wikepedia (also 2D and 3D solutions)

charging energy: $E_C = e^2/2C$

• What is the capacitance of an isolated piece of metal (for example a sphere)?



Electric field:

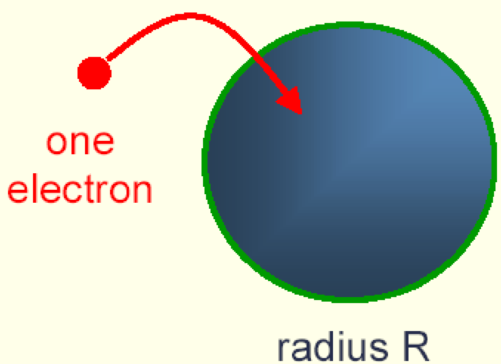
$$\vec{E}(\vec{r}) = \frac{Q}{4\pi\varepsilon_0 r^2}\hat{r} \quad (r > R)$$

Voltage:

$$V(R) = -\int_R^\infty \vec{E}(\vec{r})\cdot d\vec{r} = \frac{Q}{4\pi\varepsilon_0 R}$$

$$C = Q/V = 4\pi\varepsilon_0 R$$

• What is the energy needed to charge the sphere with one electron (1/2QV with Q = e)?



R	C	E/k_B
10 μm	1.1×10^{-15} F	0.84 K (^{3}He)
1 μm	1.1×10^{-16} F	8.4 K (LHe)
0.1 μm	1.1×10^{-17} F	84 K (LN_2)
0.01 μm	1.1×10^{-18} F	840 K (spa)

$C = 4\pi\varepsilon_0 R$