NANOSYSTEMS: PHYSICS, APPLICATIONS, PERSPECTIVES

V.O. Nesterenko

BLTP, JINR, Dubna, Russia

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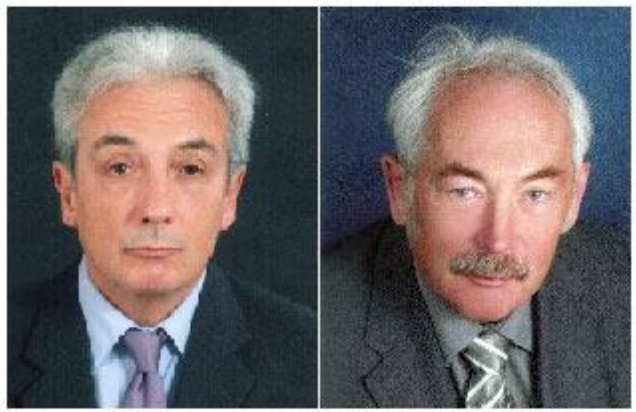
Nanosystems:

- One of the main streams in modern science
  (Nobel prizes in physics: 2000, 2007, 2010, …)

2000

Zhores Alferov:
geterostructures

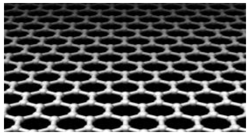
2007



Albert Fert Peter Grunberg
giant magnetoresistance

2010

Andre Geim, Konstantin Novoselov
discovery of graphene

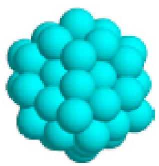


- One of the main sources of new technologies

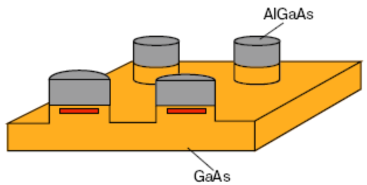
Short review on basic nanosystems

Basic nanosystems

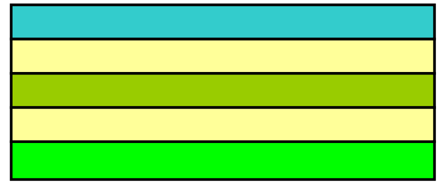
Atomic clusters



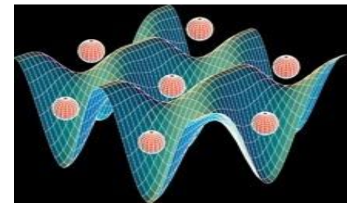
Quantum dots



Geterostructures

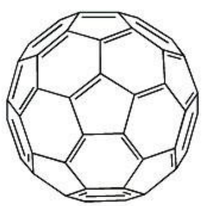


Optical lattice



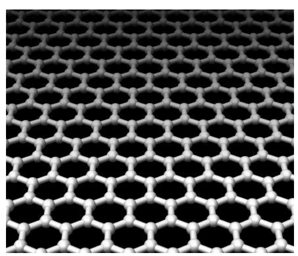
Carbon nanosystems

Fullerenes

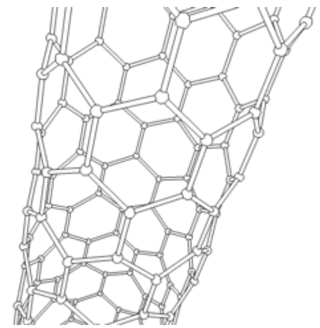


C_{60}
"Buckminster-Fulleren"

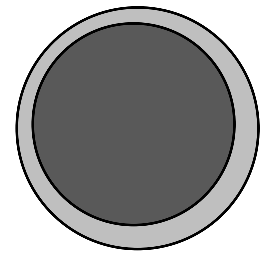
Graphene



Nanotubes

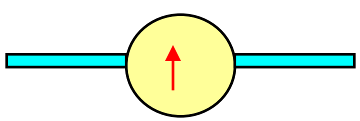


Topological insulators

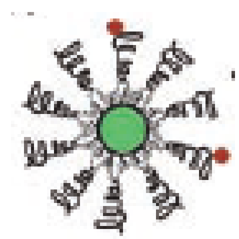


Electron quantum transport

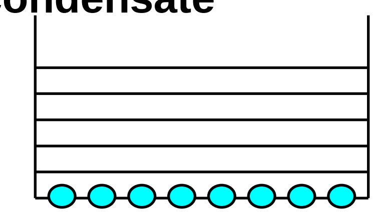
Spintronics



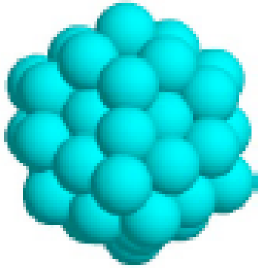
Bio-complexes



Trapped Bose-Einstein condensate



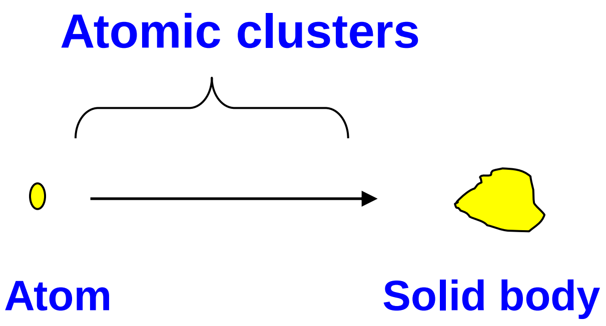
Atomic clusters



Atomic clusters

* Atomic cluster is a **bound** system of **identical** atoms.

* Bridge between one atom and bulk:



* Now it is possible to produce clusters with **any number of atoms** and for **any element** of the periodic table. Fundamental physics + applications!

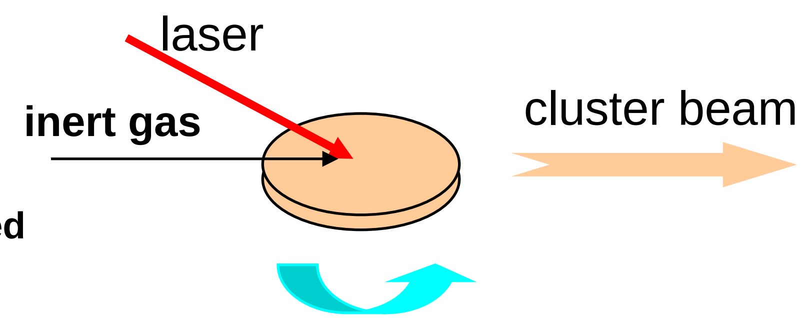
* The most interesting size interval is **1<N<1000.**

Au_{55}

* **Numerous applications**
  -- new materials with cluster admixtures,
  -- catalysis,
  -- clusters to cure cancer,
  -- ….

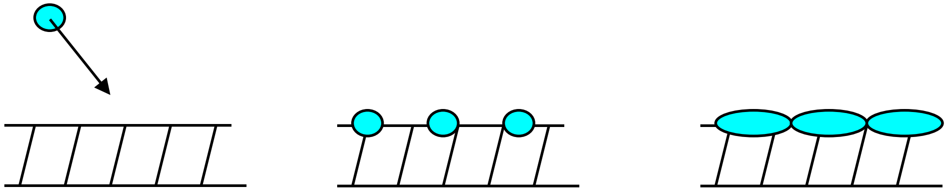
Various methods of cluster production

Laser vaporization cluster source (condensation of supersaturated vapor)

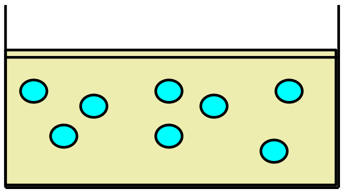


Production of small clusters with well controlled number of atoms.
Relevant for scientific aims.

Epitaxy (growth at the surface)



Colloidal synthesis (growth in solutions)



The cheapest way for commercial production.
Mainly for large clusters with an approximate number of atoms.

Clusters in our life

Colloidal gold: **known in ancient Egypt**

Gold clusters:

- stained-glass windows in cathedrals:

Metallic micro-grains added to the glass result in various colors of the penetrated light. The light wave length depends on the kind of the metal and grain size.

- British museum, Licurgus cup, IV century AD

The green cup becomes red if to light it from inside (the glass with colloidal gold and silver)

Silver clusters: **photography:**

Silver films used in photography consist on silver clusters.

Different kinds of powders.

Clusters as small metal particles are known since ancient times but only ~ 25 years ago we have mastered production of small clusters with given number of atoms .

Metal clusters

1. W.D. Knight, et al, PRL 52, 2141 (1984) -- experiment
2. W. Ekardt, PRB, 1558 (1984) -- theory

* Clusters of some metals (alkali and noble) are very similar to atomic nuclei.

* Two subsystems in metal clusters:

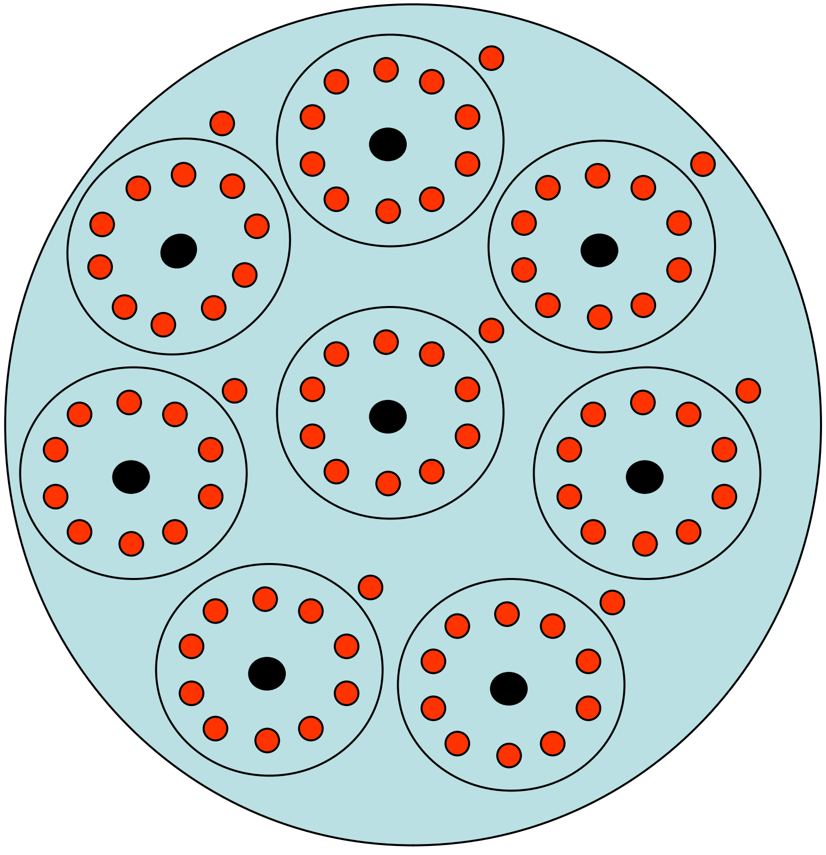
-- valence electrons (quantum properties),

-- ions (classical particles).

* Mean free path of valence electrons is of the same order of magnitude as the cluster size. So their motion can be quantized and they can create the mean field of the same kind as nucleons do in atomic nuclei.

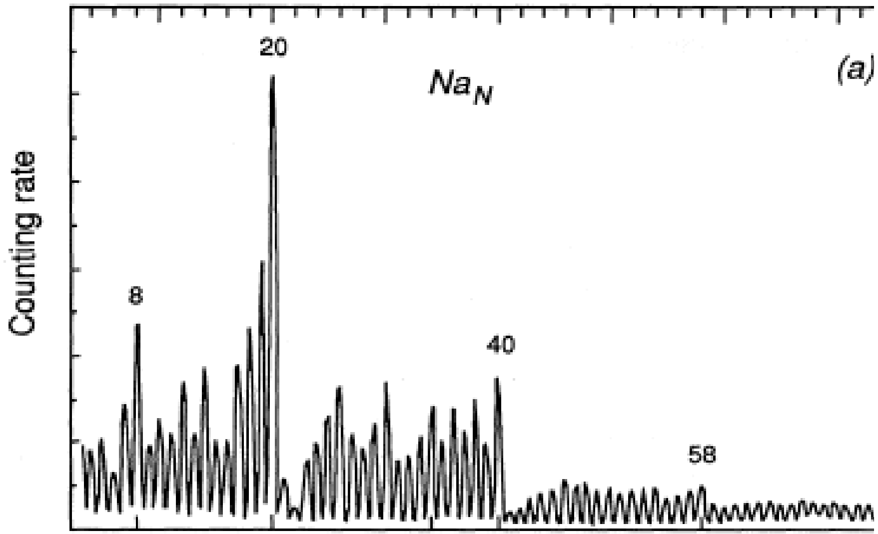
valence electrons in metal clusters	⟷	nucleons in nuclei

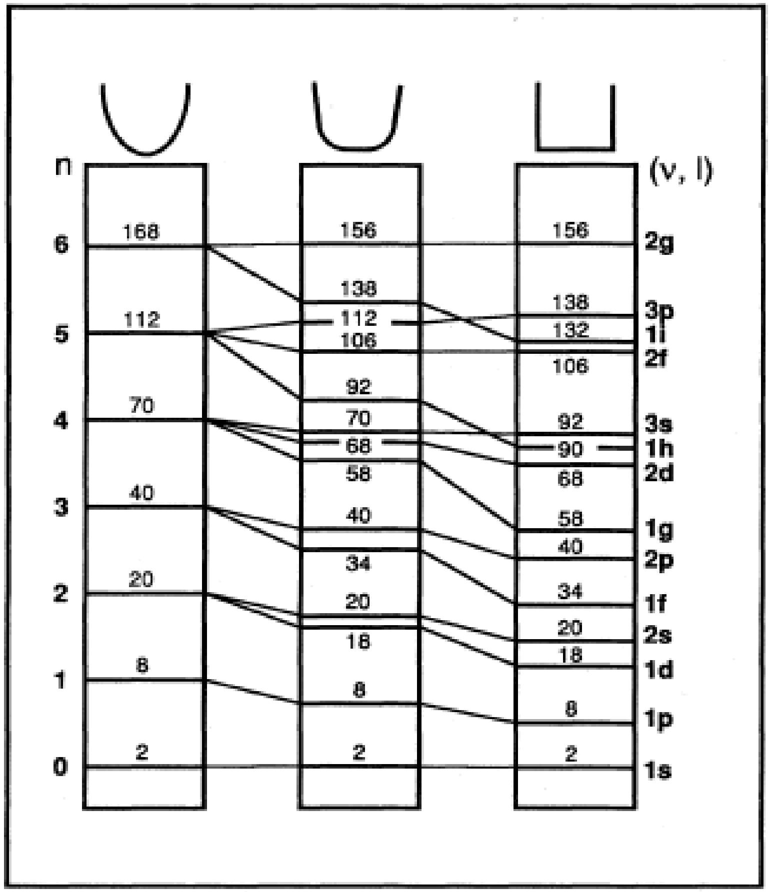
Metal cluster Na_8



Metal clusters: mean field and magic numbers

Experiment of Knight et al, 1984



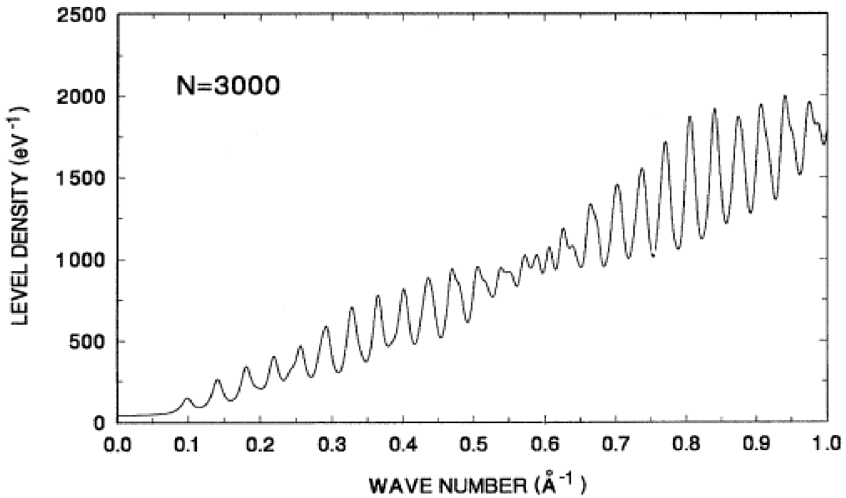


- **Magic numbers 8, 20, 40, 58, … like in typical quantum wells and atomic nuclei (8, 20, 28, 50)!**
- **The remaining difference in magic numbers is caused by a weak spin-orbital splitting in electronic systems.**

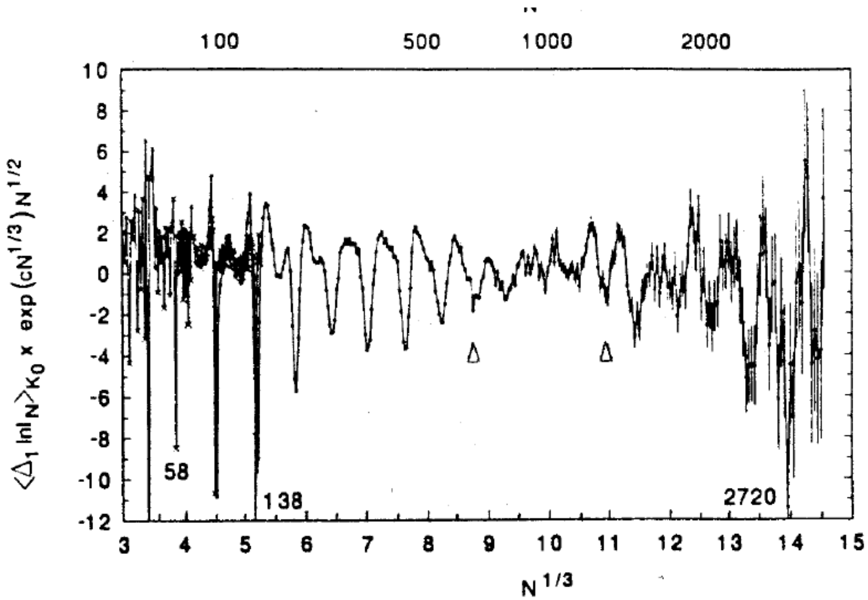
Discovery of supershells

- prediction of the periodic orbit theory

R. Balian and C. Bloch,
Ann. Phys., 69 (1971) 430.



H. Nishioka,
ZPD, 19 (1991) 2331.



Experiment for Na clusters:

J. Pedersen, S. Bjornholm, et al,
Nature, 353 (1991).

A general fundamental effect for a rigid-boundary confinement.

Nanofilms with embedded nanoparticles

Super-hydrophobic (water-repellent) films against icing

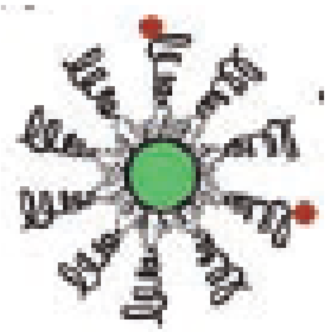
(Pittsburgh Univ., USA)

- **Anti-icing protection of roads, planes, electric lines, … by adhering water-repellent films**

- **Experiments with organic resin with embedded silicon nanoparticles 20 – 50000 nm.**

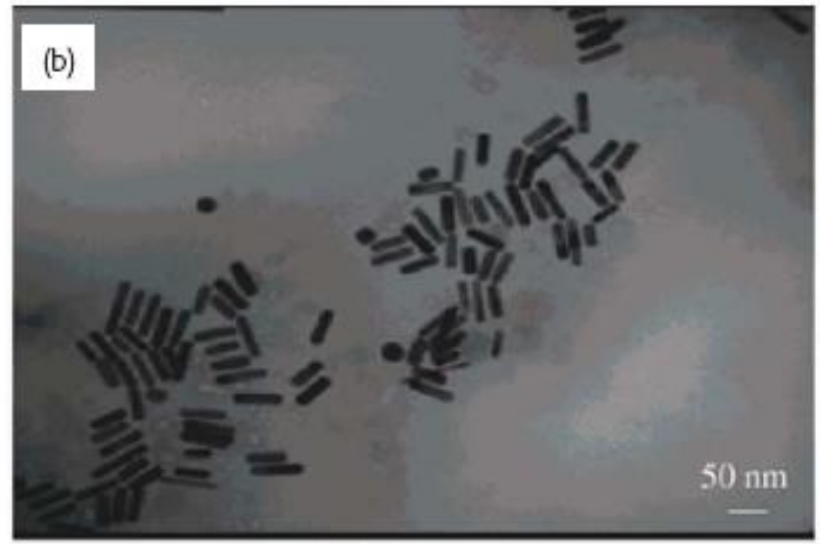
- **Only nanoparticles with D< 50 nm fully prevent icing.**

Photothermolise of cancer tumors

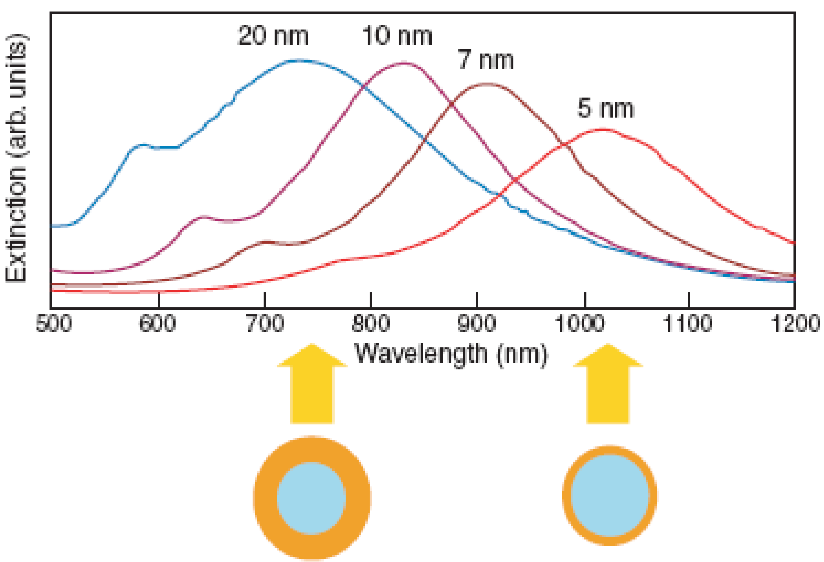


- functionalization
- bioconjugate

Nanorods with different aspect ratio

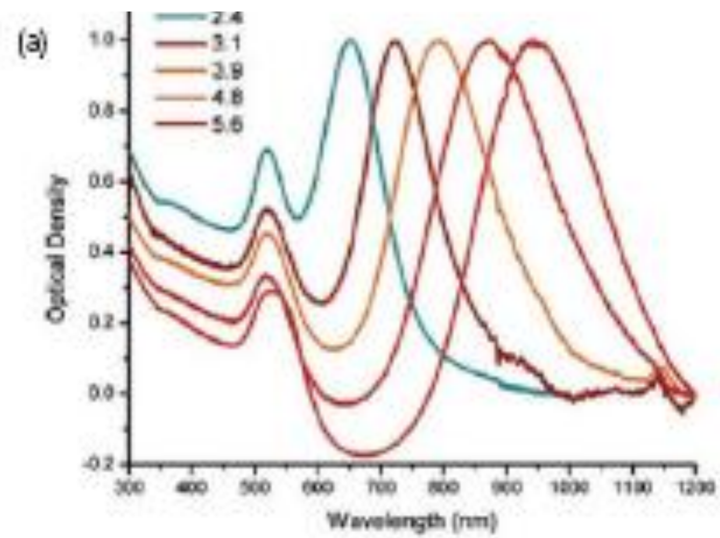


Silica-core Au-shell nanoparticles



60 nm core radius
20 nm shell

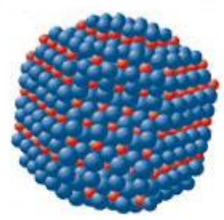
60 nm core radius
5 nm shell



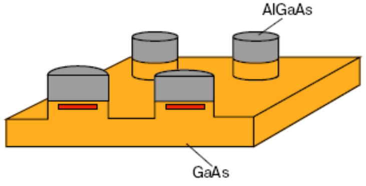
P.K. Jan et al, "Au nanoparticles taget cancer", Nanotoday, v.2, 18 (2007)

Quantum dots:

- 3D



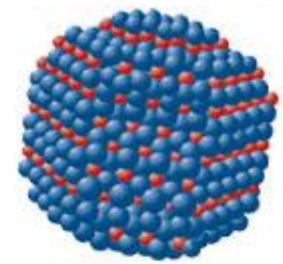
- 2D



3D quantum dots

Fluorescence induced by uv-light in vials containing CdSe QD of different size

3D quantum dot CdSe

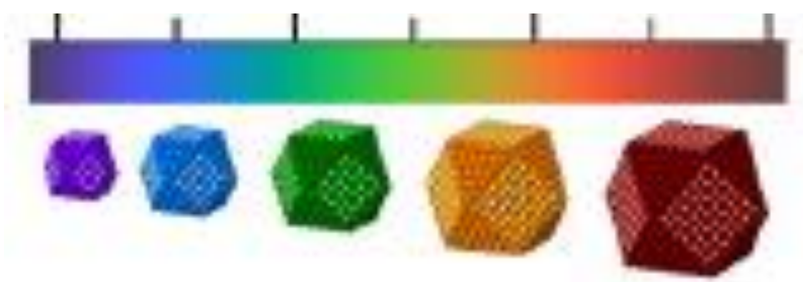


3D quantum dots are similar to atomic clusters

High fluorescence in narrow (~30nm) wave range: depends on QD size and structure:

ZnS, CdS, ZnSe → **UV**
CdSe, CdTe → **VL**
PbS, PbSe, PbTe → **IR**

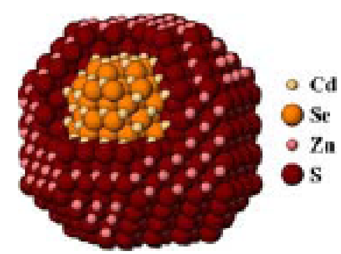
400 nm **500 nm** **600 nm** **700 nm**



UV
< 400 nm

Visible light
400-700 nm

IR
> 700 nm



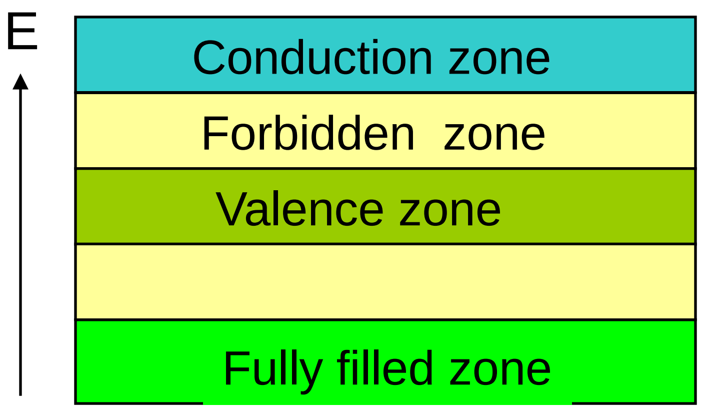
← GeteroQD

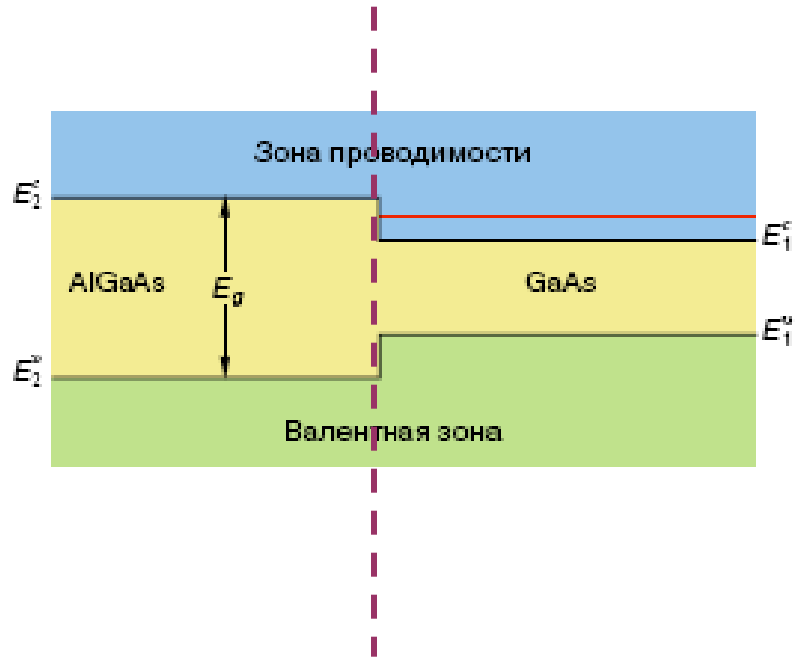
2D quantum dots

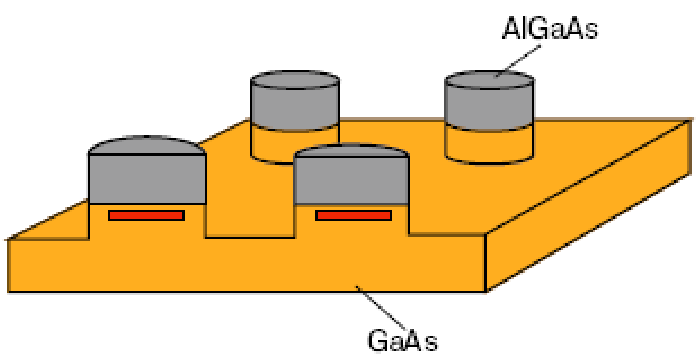
Quantum dot is a semiconductor nanostructure that confines motion of electrons (holes, excitons) in a limited 2D space.

2D electron gas at semiconductor interface

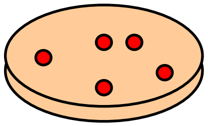
Zone structure in semiconductor







Finally one gets quasi two-dimensional (2D) system confining 2-200 electrons



New kind of a finite 2D Fermi-system !

Harmonic confinement

$$V(\vec{r}) = \frac{m}{2}(\omega_x^2 x^2 + \omega_y^2 y^2)$$

⟵ Electrons move at 2D oscillator mean field

Various applications:

- **Energy spectrum of QD can be engineered by controlling its size and shape as well as the confinement potential:** — **nano-electronics**

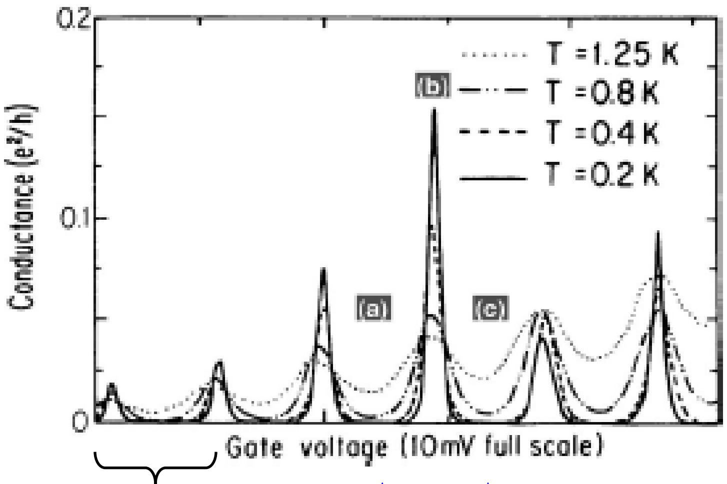
- **It is rather easy to connect QD by tunnel barriers to conductive leads:** — **electronic and spin transport**

[single-electron transistors, amplifiers, blue QD laser, displays and light sources, solar cells…]

QD: Coulomb blockade

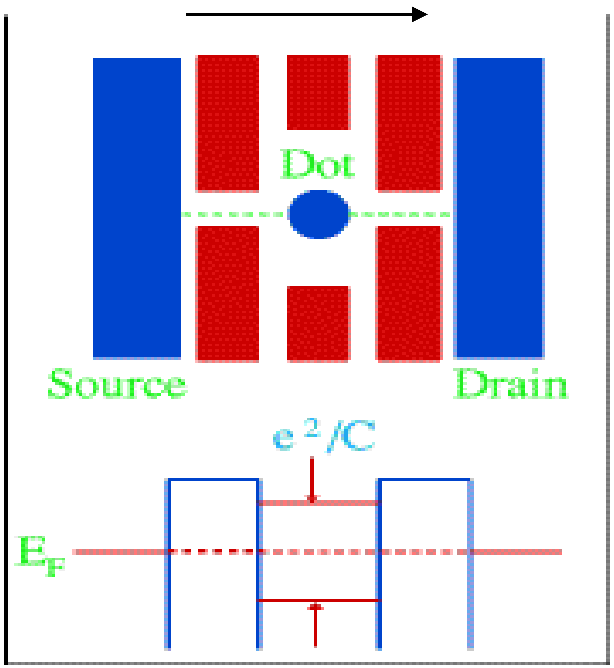
Tunneling transfer of a single electron

conductance



ΔU

Coulomb blockade



- Electrostatic energy of capacitor

$$E_c = Q^2 / 2C$$

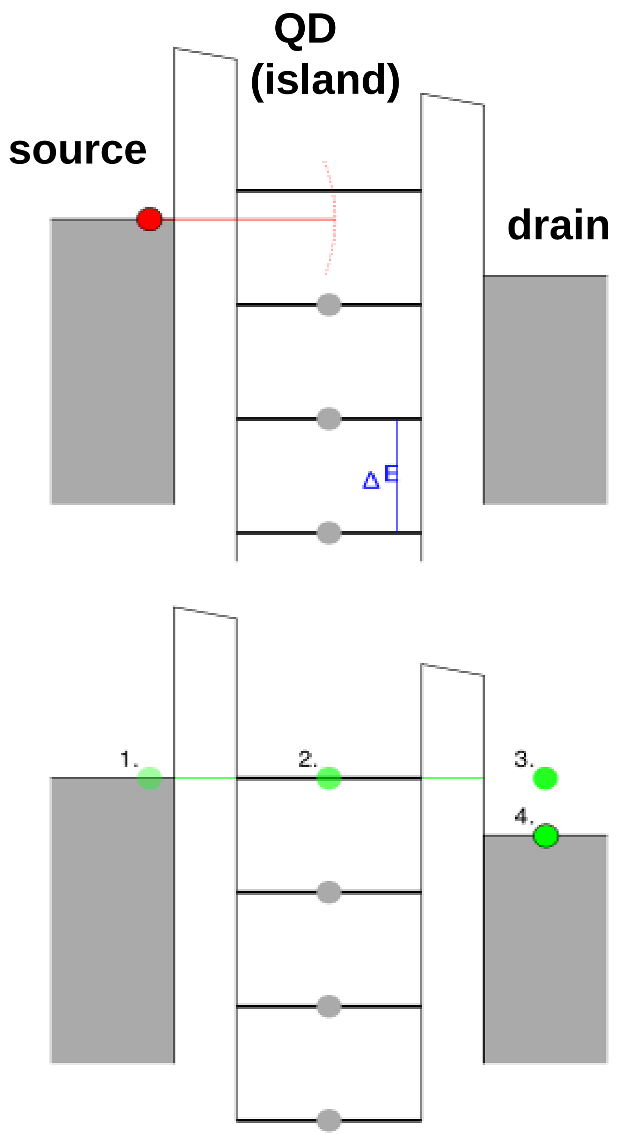
- Charging energy when adding one electron $\Delta E_c^e = e^2 / 2C$

- The applied voltage should be at least $\Delta U = e / C$

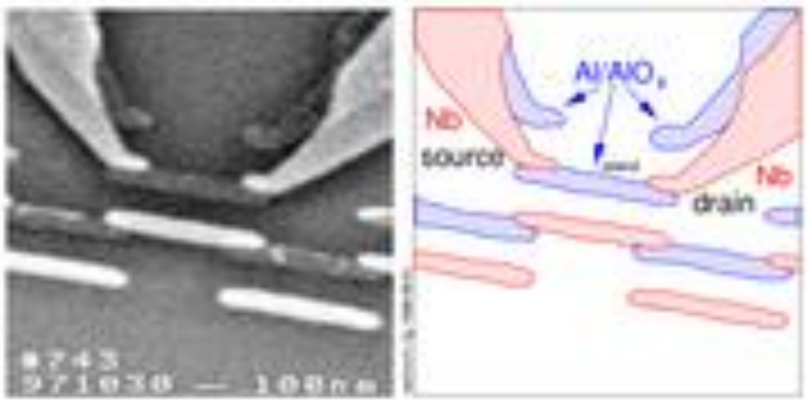
to supply the electron by ΔE_c^e

- CB takes place only at:
  - low temperature $E_t \ll E_c^e$
  - low voltage ΔU

QD: single-electron transistor



- **Exploits Coulomb blockade**
- **Shift of the QD spectrum by applied voltage from 3rd gate lead**

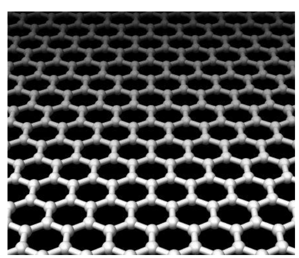


Carbon nanosystems:
- fullerenes,
- nanotubes,
- graphene, ….

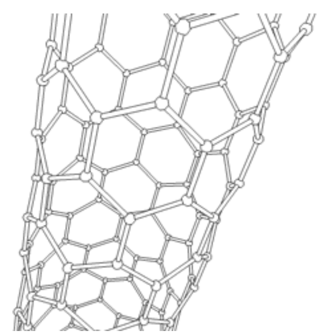
Fullerenes

C_{60}
"Buckminster-Fulleren"

Graphene

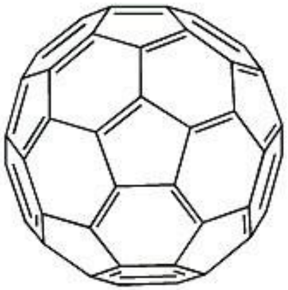


Nanotubes



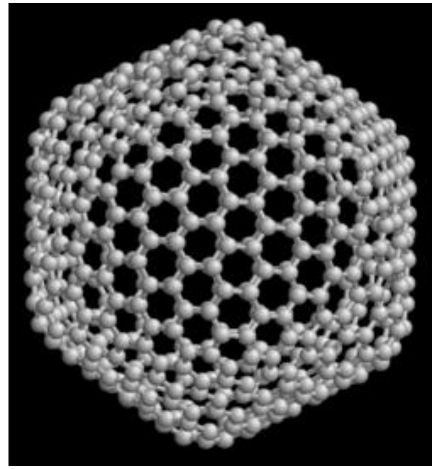
Carbon macrosystems: diamond, graphite, soot

Fullerenes

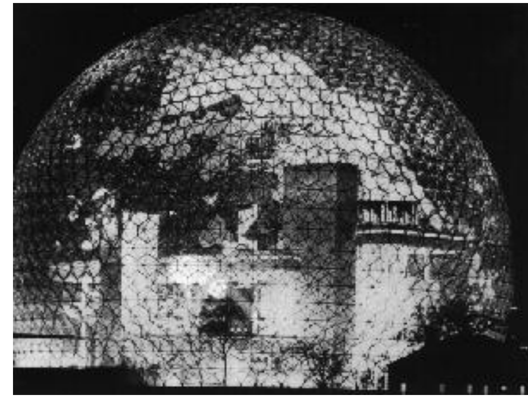


C_{60}

"Buckminster-Fulleren"



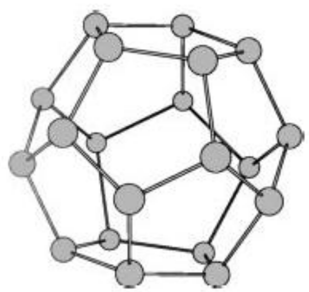
icosahedral fullerene C_{540}



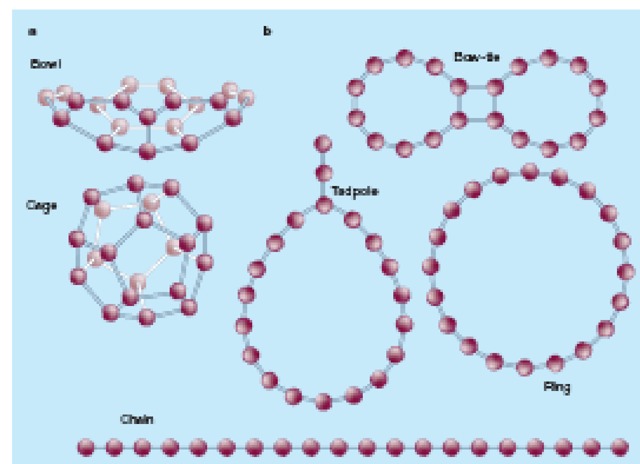
Buckminster Fuller's Dome
Expo' 67, Montreal

Fullerenes were discovered in molecular beam experiments in 1985 (Rice University, US).

Lightest fullerene C_{20}



- **created in 2000,**
- **consists only from pentagones,**
- **few forms,**
- **perspectives for creation of fullerite with high-T superconductivity**



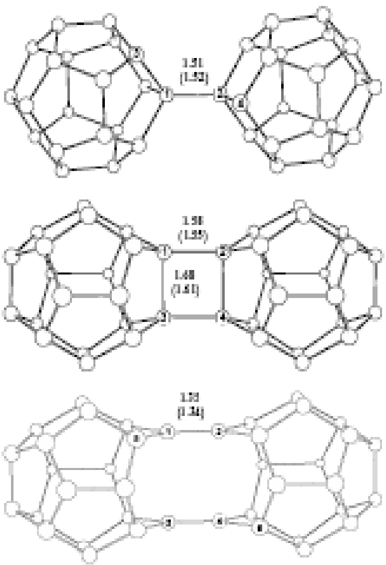
Applications of fullerenes

C_{60}
"Buckminster-Fulleren"

Endohedral fullerenes:

-**unique kind of atomic trap:**
- **good isolation,**
- **room temperature,**
- **arbitrary long trapping**

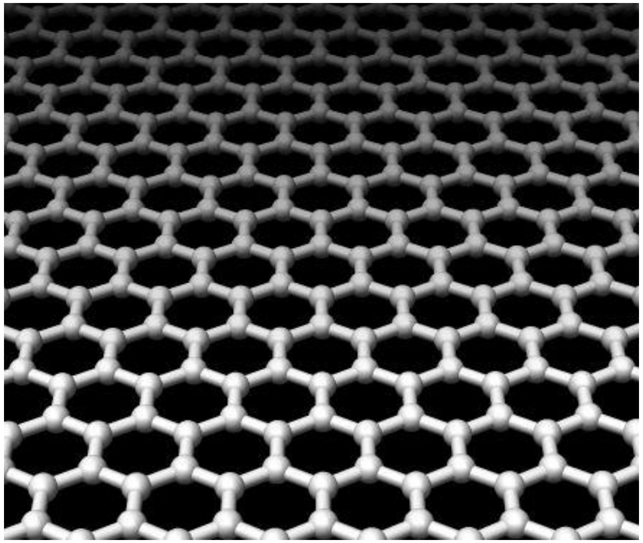
- **first complex La@Ca60 in 1985**
- **may capture atoms and ions of ~ 1/3 elments**
- **can trap radioactive elements for medical aims**



Fullerites: crystals from C_{60}

- **can be high-temperature superconductors**

Graphene



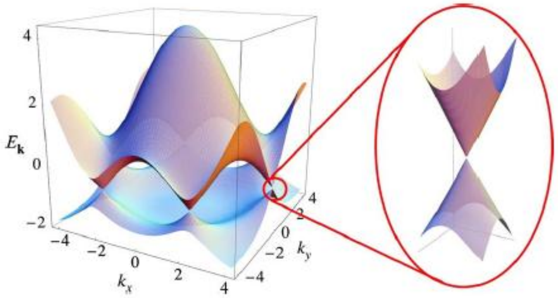
- theoretical studies at least since 1947
- first obtained in 2004 ← **Novoselov K.S. + Manchester Univ.**
-exclusively hexagonal cells
- single planar sheet of carbon atoms
  (one graphite layer with the thickness of one atom)
- semimetal, zero forbidden zone, linear spectrum
- can be used for:
    - planar field-effect transistors,
    - quantum interference devises
    - …
- high mechanical rigidity and heat conductance

- Electrons obey a massless relativistic Dirac equation

$$E=\hbar v_F k$$

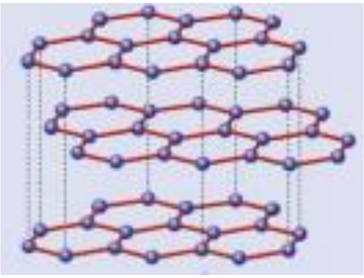
like photons with $v_F \sim 10^6 ms^{-1}$ instead of speed of light.

- Mobility μ up to 104 $cm^2V^{-1}s^{-1}$ is reported:
  - almost independent of temperature,
  - electrons in graphene can move easier
    than in any other known material at room temp.

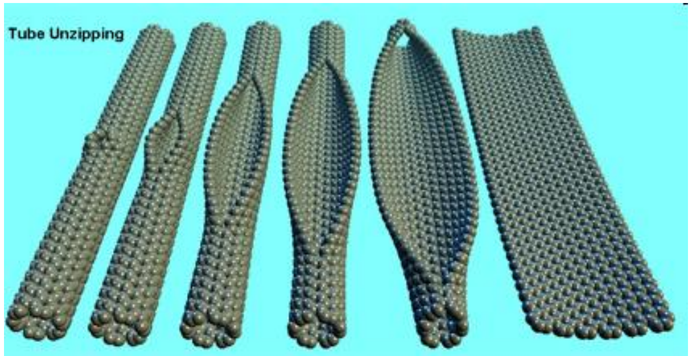


$$v = \mu E$$

For semiconductor-like electronics one needs a **small forbidden zone**.
How to make graphene semiconductor-like?

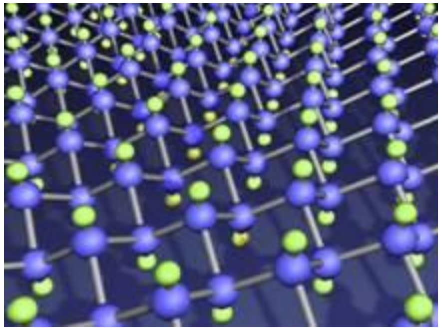


Double- and triple-layer graphene



Nature **458**, 872 (2009): SWCNT Unzipping

Nanoribbons
- produced e.g. by unzipping nanotubes
- applications from computers to solar sells

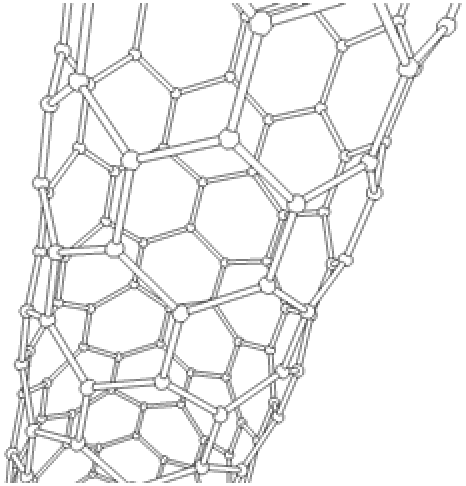


- Novoselov/Geim

Ftorographene (fluorographene)

-C + F atoms
- reminds teflon
- stable until 400 K
- 1.5 times stronger than steel

Carbon nanotubes



- -- observed accidentally in 1991,
- -- cylindrical fullerenes,
- -- few nm wide but μm – mm in length,
- -- can be single- and multi-walled,
- -- quantum physics of one-dimensional systems,

-- unique macroscopic properties:

- high tensile strength
  (63 GPa ⟷ high-carbon steel: 1.2 GPa)
- multi-walled NT: striking telescopic property,
- high plastic deformation,
- high electrical conductivity:
  - can be metallic or semiconductor,
    (in metallic CT electrical current density 1000 times lager than in Cu or Ag!)
- high heat conductance along the tube,
- high lateral heat resistance,
- chemical inactivity,
- can merge at a high pressure thus forming unlimited length wires,
- easily soluble in most solvents.

Applications of nanotubes:

Still high price: 500$/g

Structural:

- **waterproof tear-resistant clothes,**
- **combat jackets,**
- **sports equipment,**
- **ultra-high speed flywheels.**

Chemical:

- **water filter,**
- **air-pollution filter**

Electromagnetic:

- **artificial muscles,**
- **bucky-paper** **(250 times stronger, 100 times lighter),**
- **computer circuits** **(two joined CT of a different diameter act as diode)**
- **brushes for commercial electric motors,**
- **light filaments,**
- **solar cells,**
- **superconductor at low temperature,**
- **ultracapacitors by using NT and their defects** ⟶ **batteries for mobile phones**
- **displays,**
- **transistor from one nanotube** **[applied few volts change current 10^5 times]**

Emission of electrons by CNT heads

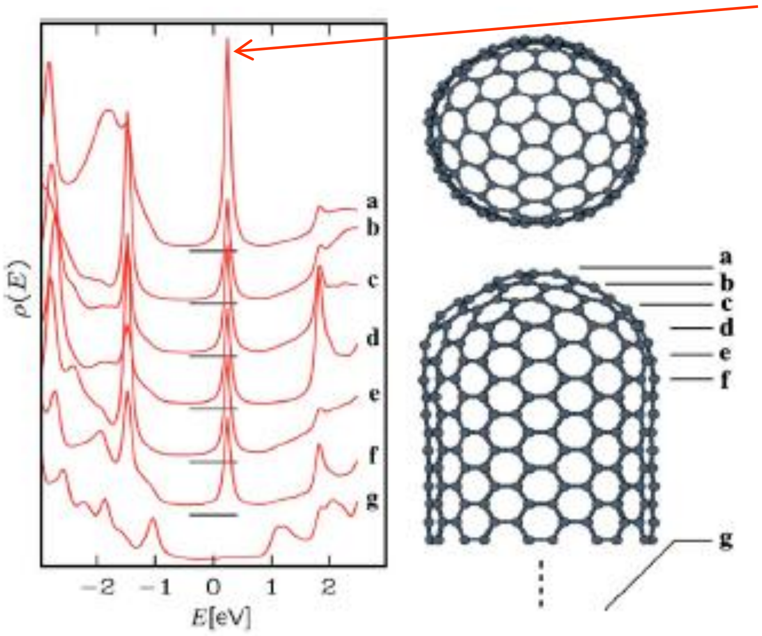


FIG. 25. (Color online) Densities of states along a (10,10) nanotube capped with half a C_{240} molecule. The horizontal bars indicate zero densities. The Fermi level is located at zero energy. The DOS curves are averaged over the atoms composing the sections labeled by a–g on the right-hand side. Adapted from Charlier, 2002.

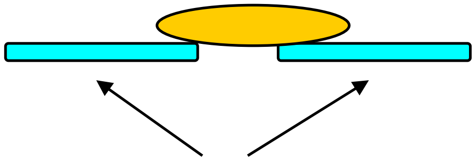
Soft TV displays

Quantum transport

Quantum transport

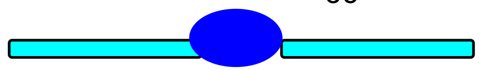
- not ohmic laws,
- fundamental effects (Hall effects),
- wide applications!

Organic molecule



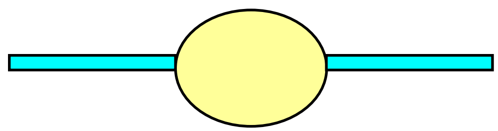
leads

molecule, cluster C_{60}



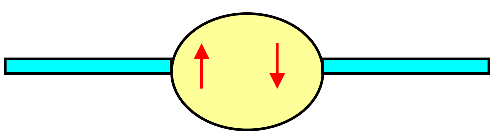
Chain of atoms Au, Ag

Quantum dot



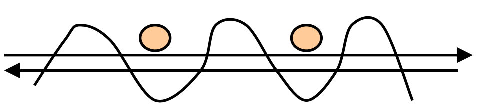
Transport of electrons

Quantum dot



Transport of spin

Atoms or BEC in optical lattice

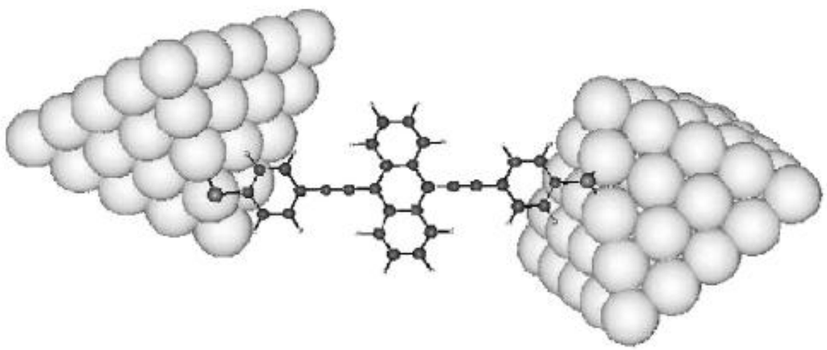


Atoms or BEC in multi-well traps

Transport of atoms

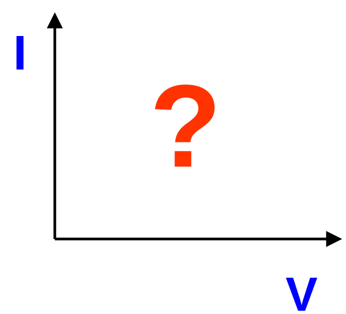
Examples:

Conductance via organic molecule.
The contacts are modeled by Au-clusters with 55 atoms each



F. Evers et al,
Physica E, 18, 255 (2003).

Typical problem is to determine current-voltage characteristics **I (V)**



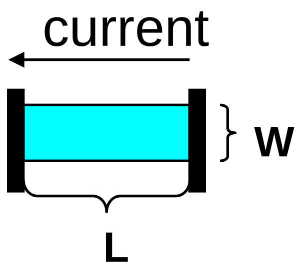
Conventional electricity:

Ohmic law **I=V/R**

Quantum transport:

Complicated no-Ohmic laws
(resonances, influence of contacts, …)

Landauer formalism



Conductance: $G = \dfrac{1}{R}$

Ohmic equation

$$G = \sigma W / L$$

Landauer equation

$$G = \frac{2e^2}{h} MT$$

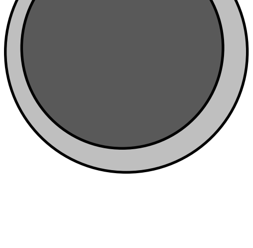
σ -- conductivity (depends on the material propeties, independent on W and L)

T – transmission probability (probability to transmit electron through the sample)
M – number of transversal modes

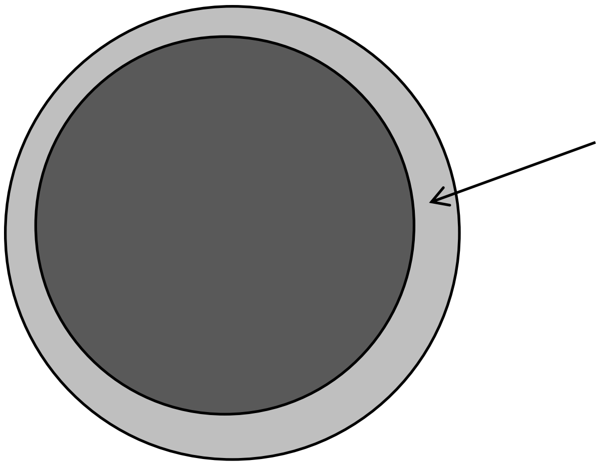
Mesoscopic transport:

- Conductance does not depend on the length L.
  For $L < \overline{r}_D$ ballistic conductor has resistance R_C .
- Conductance depends on W not linearly but in discrete steps (determined by number of transversal modes).

Topological insulators



Topological insulators



$$H_{so} = \frac{\partial V(r)}{\partial r}(\vec{l} \cdot \vec{s})$$

Chern invariant: surface integral of Berry flux in the Brillouin zone:

$$n_m = \frac{1}{2\pi}\int d\vec{k}^2[\vec{\nabla} \times \vec{A}_m]$$

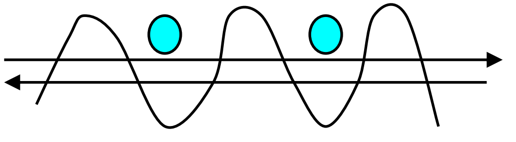
- theoretically predicted in 2005 and then obtained experimentally in 2007-2008,
- can be 2D and 3D,
- consist of heavy elements like mercury or bismuth with a strong spin-orbital inetraction,
- behave like dielectric in the interior and conductor at the surface,
- special surface states which cannot be destroyed by impurities or imperfections:
  - no forbidden zone, Dirac points E ~ k,
  - determined by a topological invariant,
- no resistance, dissipationless surface current,
- analogy to the integer Hall effect and graphene,

- new kind of classification of electronic systems by their topological order,

-Chern topological invariants, theory of fiber bandles (n=0 - dielectrics, n=1 - TI, n=2 - graphene, ….,)

- promising for:
  - spintronics,
  - search of Majorana fermions,
  - topological quantum computing

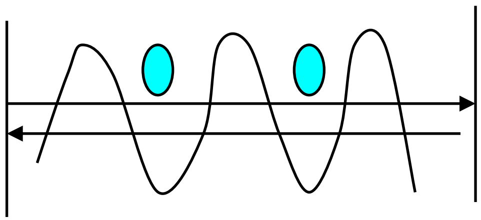
Optical lattices

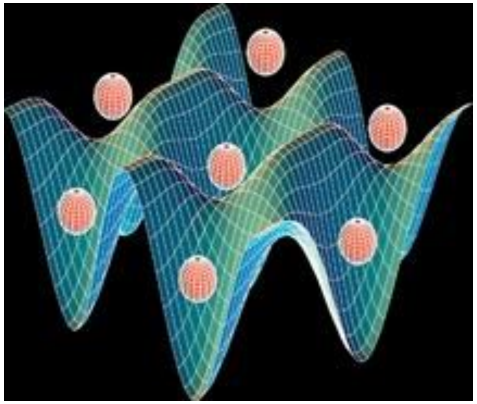


Optical lattice

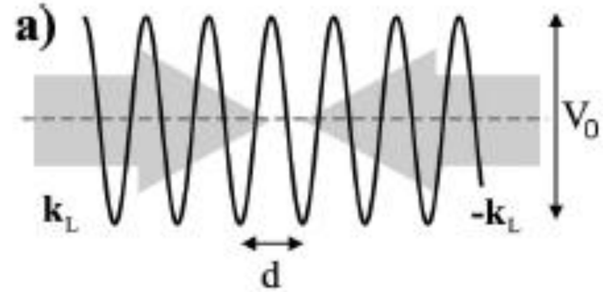
Optical lattice: periodic potential produced by standing waves of opposite laser beams.

- 1D, 2D, 3D
- trapped atoms, BECs, …





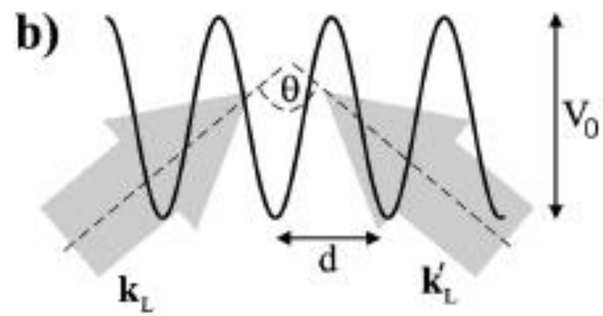
Control of OL characteristics



Potential depth V_0 is controlled by the laser intensity I

$$V(x) = V_0 \cos^2(\pi x / d)$$

$$V_0 \propto I$$



Potential period d is controlled by the angle θ between the laser beams

$$\omega_1 - \omega_2 = 0$$ **static OL**

$$\omega_1 - \omega_2 = \Delta$$ **motion of OL with a constant velocity**

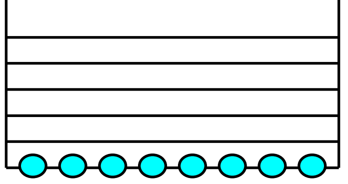
$$\omega_1 - \omega_2 = \Delta(t)$$ **OL acceleration:**

- **generates forces acting on the trapped atoms**
- **creates transitions of atoms to OL excited states**

⇒ **nonlinear physics !**

Fantastic variety of matter-wave and solid-body simulations!

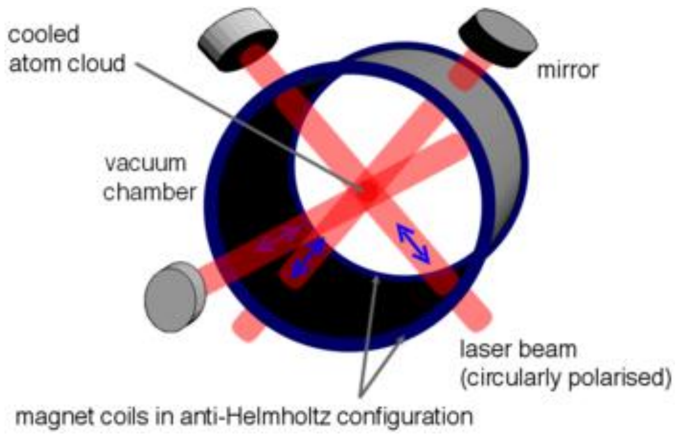
Bose-Einstein condensates



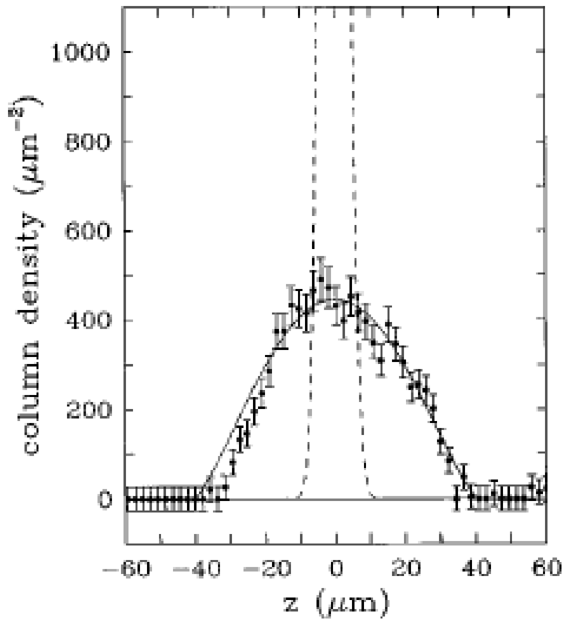
Trapped Bose-Einstein condensate (matter waves)

$$V(\vec{r}) = \frac{m}{2}(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2) = \frac{1}{2} m\omega_\perp^2 \rho^2 + \frac{1}{2} m\omega_z^2 z^2 = \frac{1}{2} m\omega_\perp^2 (\rho^2 + \lambda^2 z^2)$$

- spherical, $\omega_x = \omega_y = \omega_z$
- ellipsoidal, $\omega_x = \omega_y \neq \omega_z$
- disc-shaped, $\omega_\perp < \omega_z, \quad \lambda > 1$
- cigar-shaped, $\omega_\perp > \omega_z, \quad \lambda < 1$



Density distribution of BEC atoms at the trap



$N \approx 10^2$-10^9 atoms

$n \approx 10^{14} - 10^{15}\ cm^{-3}$

$L \approx 10 - 50\ \mu$m

$T_c \approx 500$ nK - 2 μK

$\hbar\omega_0 \approx 5$ nK

Interaction between BEC atoms is reduced to s-scattering and is fully determined by the scattering length a_s

BEC peculiarities:

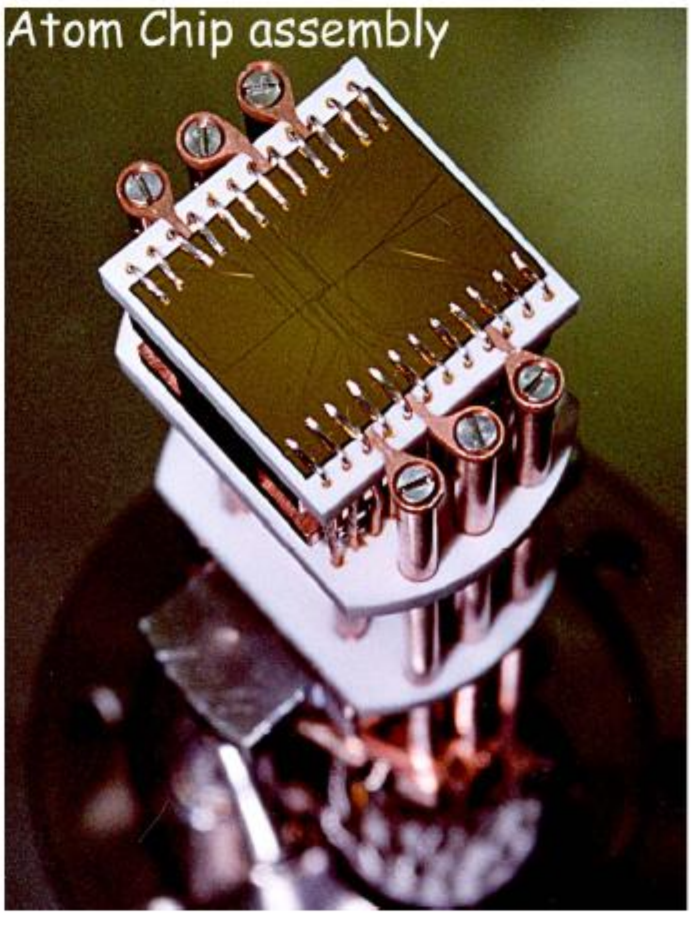
- dilute gas of weakly interacting atoms in trap, 1d, 2d, 3d forms,	⟺	strongly interacting ^4He condensate
- to control magnitude and even sign of the interaction via Feschbach resonance,	⟺	new kinds of BEC
- easy to generate different kinds of dynamics: (rotation, various vibrational modes, …),	⟺	scissors mode, …
- superfluidity,	⟺	vortices, vortex lattice
-multi-component BEC, tunneling, transport	⟺	Josephson effect
- coherence,	⟺	interferometry, geom. (Bery) phases

New quantum system which is unique in the precision and flexibility with which it can be controlled and manipulated.

Atomic chips

J. Schmiedmayer, E. Hinds, EPJD, 32, n.2(2005)
T. Schumm et al, *Nature physics*, 1, 57 (2005)

Microfabricated devices in which
electric, magnetic and optical fields
can confine, control and manipulate cold atoms or BEC.



- neutral atoms are trapped a few μm from the AC surface in microtraps (< 500 nm)
- t~ 100 nK despite a room temperature of AC
- control field forces
- nice isolation, small BEC: strong quantum effects
- quantum states live 10-100 s
- control of both atom motion and internal excitations
- integrated optical elements: atom-photon coupling
- versatile technology for quantum measurements and quantum information processing

Quantum optimal control in BEC

Bose-Einstein condensate in traps

New exper. setup: atomic chips

Abilitiy of laser fields!!!

New theory (quantum optimal control):

- transitionless quantum driving,
- invariant-based inverse engineering,
- …

New physics:
BEC interfierometry,
small BECs: spin squeezing and entanglement,
Einstein-Podolsky-Rosen entanglement
……

quantum information

BEC in cosmology

BEC: different kinds

^{4}He BEC

Trapped ultracold gases:
- Bose atoms
- Fermi atoms → dimmer molecules, Cooper pairs

2003: molecular BEC

Spin BEC

Dipole BEC

Exciton BEC

Polariton BEC

Photon BEC

} Physics of trapped ultracold atoms and molecules

Variety of nanosystems

Nanocages
Nanocomposites
Nanofibers
Nanoflakes
Nanoflowers
Nanofoams
Nanomeshs
Nanofilms
Nanorings
Nanorods
Nanoshells
....

Conclusions

Multidisciplinary area

- atomic, molecular physics
- condensed matter
- thermodynamics
- laser physics
- superconductivity
- chemistry
- DFT, …
- quantum transport

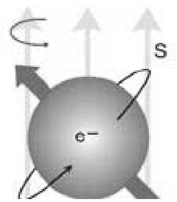
} Promises new discoveries!

Fantastic perspectives for **fundamental physics** and **APPLICATIONS !!!**

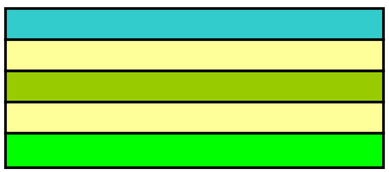
The countries with NT will be leaders in a future world. Others will be their raw-supplies.

Thank you
for the attention

Spintronics

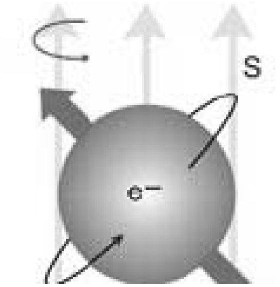


Geterostructures



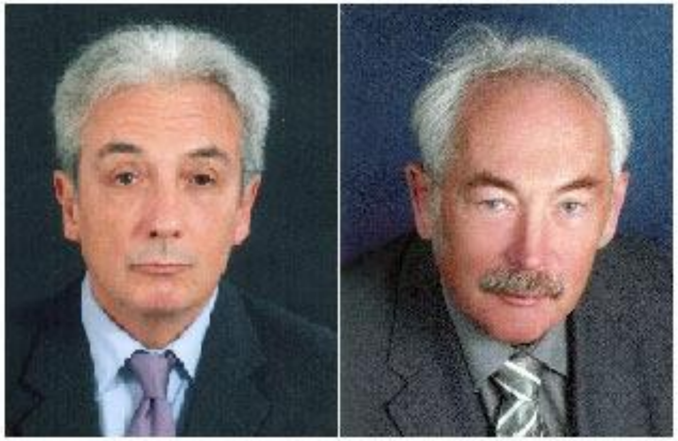
Spintronics = spin electronics

Electronics: currents, charges; spin of electrons does not matter.
Spintronics: manipulation with spin of electrons;
- currents of polarized electrons, non-uniform spin distributions.
- other factors come to play: spin-orbital interaction,…



Si-based microelectronics ⟶ Spintronics

2007 Nobel Prize in physics:



Albert Fert (France)   Peter Grunberg (Germany)

… for discovery of the phenomenon of "giant magnetoresistance", in which weak magnetic changes lead to big differences in electrical resistance.

First Nobel Prize in physics for nanotechnology!

GMR: discovered in 1988

The discovery has allowed industry to develop sensitive reading tools to pull data off hard drives in computers and other digital devices.

↓

Radical miniaturization of hard disks last years.

Onset of

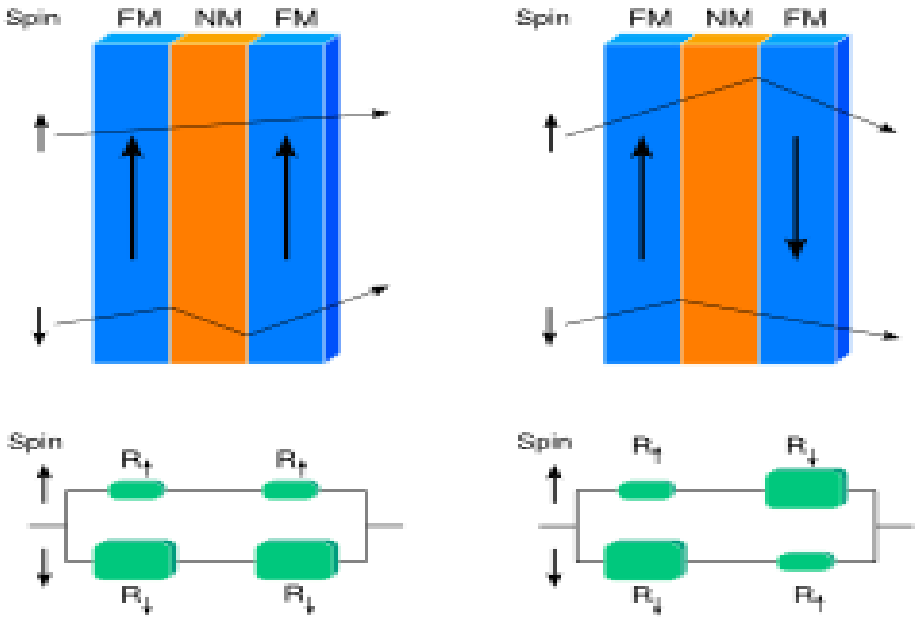
SPINTRONICS!

Applications:

- **IBM 1997: reading data off CD,**
- **angle, position velocity spin sensors (ABS: Antiblock Braking System)**
- **Motorola: MRAM (Magnetoresistance Random access Memory)**
- **HDTV, DVD recorders, …**

Geterostructures: giant magnetoresistance

Spin-valve GMR (layers ~ 3nm)



- Multilayer structures, e.g. Fe/Cr/Fe, with very thin 3-50 layers (~ 100 nm altogether)

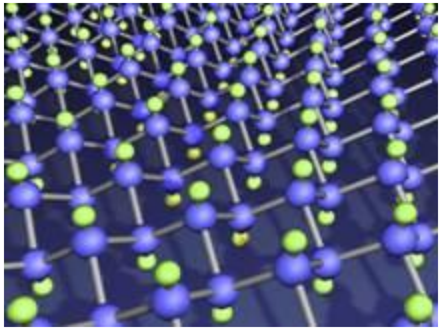
- Possibility to change essentially electric resistance by small varying magnetic field

- Electron-spin-based effect.

SPINTRONICS!

Si-based microelectronics ⟶ Spintronics ???

Fluorographene   Andre Geim, Konstantin Novoselov



- **к каждому атому углерода добавлен атом фтора**
- **напоминает:**
  полупроводник с широкой запрещенной зоной → наноэлектроника
  или изолятор → сверхтонкие изоляторы для дисплеев
- **3-я комбинация графена с другим веществом (другие с кислородом и водородом были неравномерны по структуре и неустойчивы к большим температурам)**
- **напоминает двумерный тефлон**
- **высокая термическая (до 400 градусов) и химическая устойчивость**
- **прочнее стали в 1.5 раза → покрытия**
- **сложная технология получения**

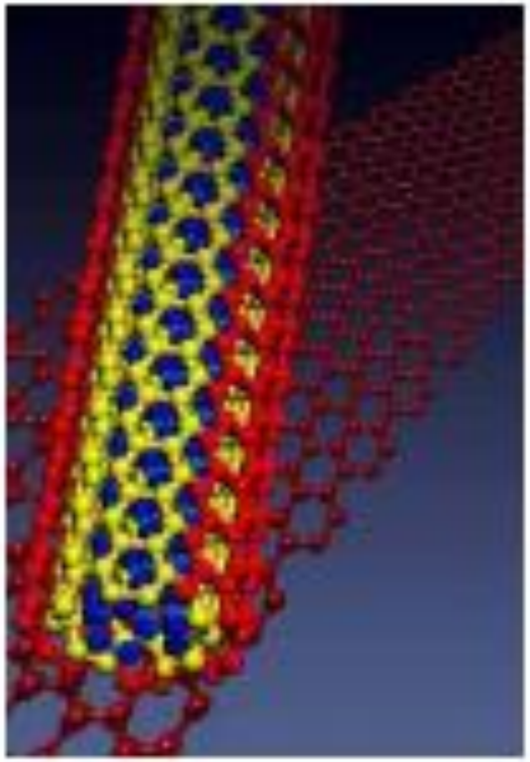
- фторографит: смесь графита с фтором, твердая смазка
- тефлон: одномерные цепочки атомов углерода с присоединенными атомами фтора

Unzipped carbon nanotubes

Nature, 15.04.2009

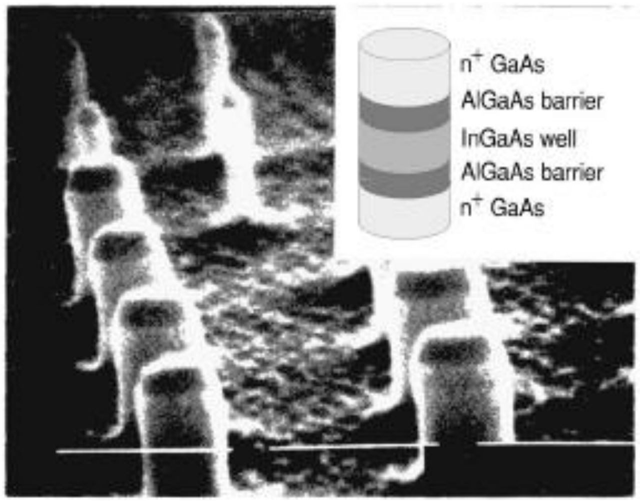
Stanford Univ., USA

- to make graphene ribbons
- possible applications from computers to solar cells
- previous techniques used chemicals or ultrasound to chop graphene into ribbons
- now the tubes are stuck to polimer film and then etched along

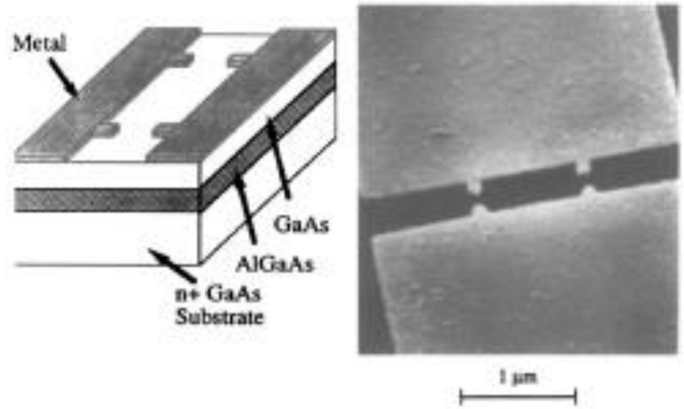


Quantum dots (2): images

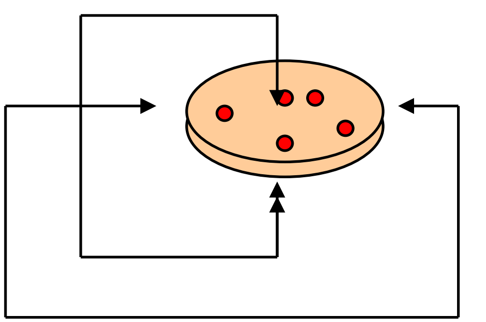
Vertical quantum dots



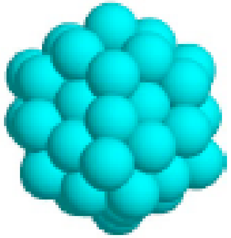
Lateral quantum dot at a surface



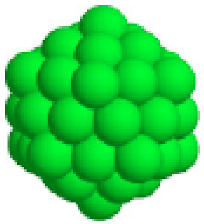
gate voltage → to regulate the confinement well



bias voltage → to regulate transport window, …



Metal clusters (Na, K, Li, Rb, Cz, Au, Ag):
quantum shells (!) , similarity with atomic nuclei, supershells!



Noble gas clusters (Ne, Ar, Kr, …):
no quantum shells, geometric shells, many applications

^{4}He, ^{3}He clusters and cryostats for embedded atoms and molecules

C_{60}
"Buckminster-Fulleren"

Fullerenes: clusters from carbon atoms

4th carbon state in addition to graphite, diamond, soot.

New systems:

- atomic nuclei — $10^{-15}\ m$
- atomic clusters
- fullerene, graphene, carbon tubes
- quantum dots
- geterostructures

} $10^{-9}\ m$ ← nano

- optical lattice
- Bose-Einstein condensate

} $10^{-3} - 10^{-6}\ m,\ \ 10^{-9}\ m$

- …..

$10^{-6} = micro$
$10^{-9} = nano$
$10^{-12} = pico$
$10^{-15} = femto$
$10^{-18} = atto$

New effects and processes:

- Hall effect (>5 variants),
- quantum transport
- spintronics, …..

New experimental set-up:

- intense fs lasers
- new kinds of microscopes, …
- atomic chips, …

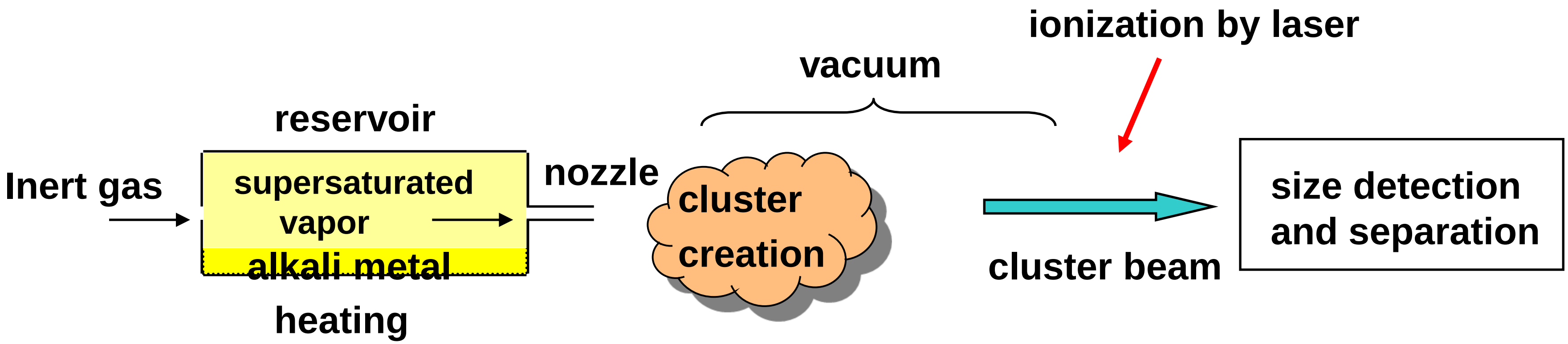
The main point is not the system size itself but:

New systems, effects, set-up } → to appear 0 - 20 years ago

Cluster production

1. W.D. Knight, et al, PRL 52, 2141 (1984) -- experiment
2. W. Ekardt, PRB, 1558 (1984) -- theory

Seeded supersonic nozzle source



- heating of the material in reservoir to get the supersaturated vapor,
- mixture with a beam of high-pressure inert gas,
- supersonic expansion of the mixture to vacuum,
- sudden expansion, cooling and condensation of atoms into clusters,
- ionization of neutral clusters in beam by laser,
- detection and separation of clusters with a given number of atoms,
- experiments in a beam of size-separated clusters.

Alternative sources: creation of supersaturated vapor by intense laser, growing cluster in solutions, …

Intense fs lasers

New generation of pulse lasers:

-- pulse duration 1-100 fs,

-- intensity up to $10^{20}\ W/cm^2$ **,**

earlier { ns; 10^{6}-$10^{9}\ W/cm^2$ }

It is possible to investigate chemical reactions in real time scale !

Regimes of photoionization of clusters:

-- thermal (enough time for e-e and e-i couplings), ← **ns**

-- electron bath (enough time for e-e coupling), ← **ps**

-- direct knock-down of electrons. ← **fs (new!)**

The chance to investigate:

-- mean field spectra of valence electrons,

-- maximal ionization and Coulomb explosion.

1 fs = 10^{-15} s
1 ps = 10^{-12} s
1 ns = 10^{-9} s

Attosecond lasers

P. Agostini and L. Di Mauro,
Rep. Prog. Phys., 67, 813 (2004)

- **ultrashort pulses:** $1as = 10^{-18}$ s **(the time the light takes to travel trough atomic distances!)**
- **breakthrough in metrology,**
- **control of dynamical processes in sub-fs and sub-** $\dot{A}$ **scales,**
- **now we can trace in real time most of atomic processes!**