Lecture 3

Quantum dots
Quantum transport
Bio-medical applications

Quantum dots

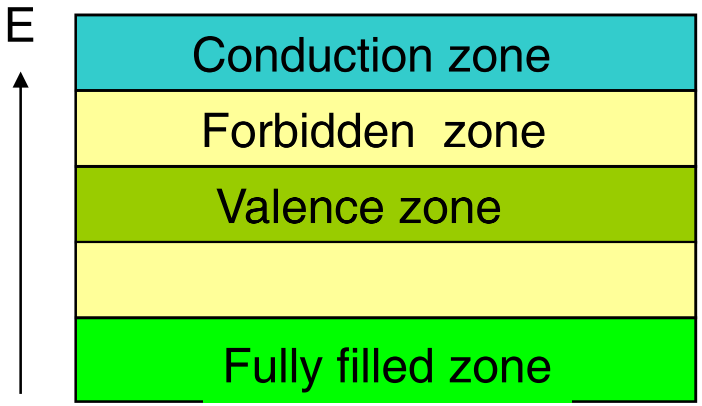
- definition
- production
- quantum shells
- Wigner crystallization
  Wigner molecules
- Coulomb blocade
- spintronics

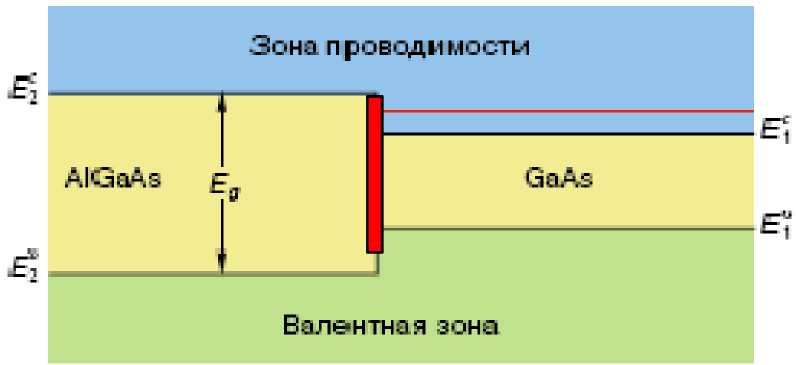
Quantum dots

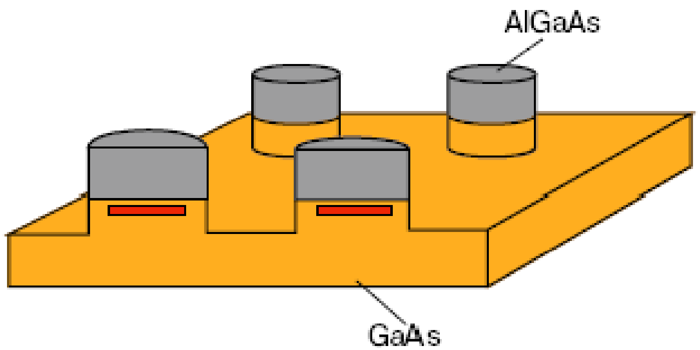
Quantum dot is a semiconductor nanostructure that confines motion of electrons (holes, excitons) in a limited 2D space.

2D electron gas at semiconductor interface

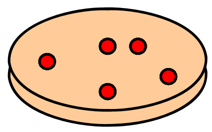
Zone structure in semiconductor







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



New kind of a finite 2D Fermi-system !

Harmonic confinement

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

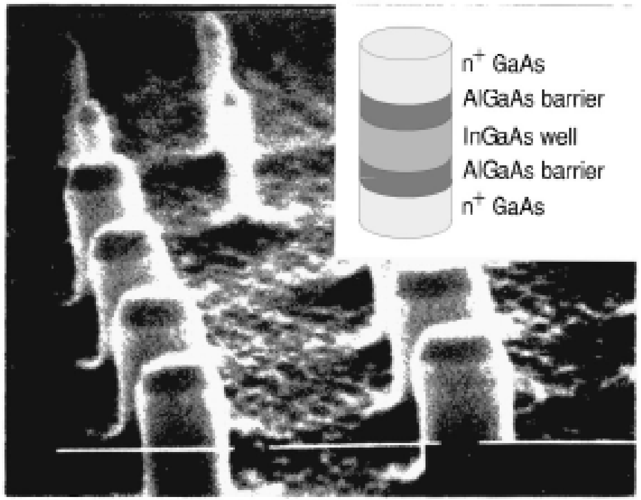
← Electrons move at 2D oscillator mean field

Various applications:

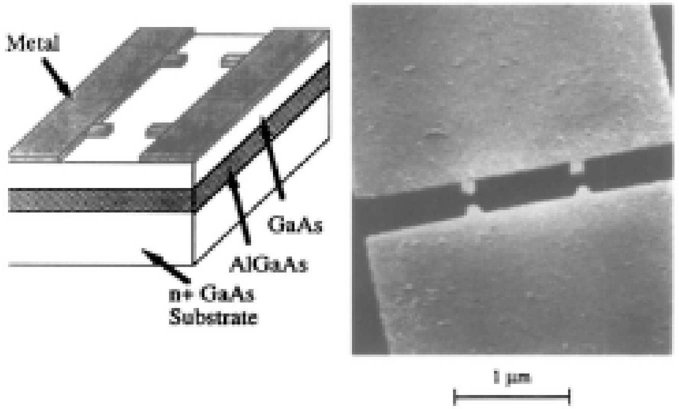
- **Energy spectrum of QD can be engineered by controlling its size and shape as well as the confinement potential:** **nano-electronics**
- **It is rather easy to connect QD by tunnel barriers to conductive leads:** **electronic and spin transport**

Quantum dots (2): images

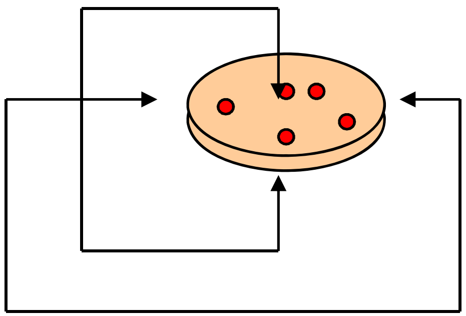
Vertical quantum dots



Lateral quantum dot at a surface



gate voltage → to regulate the confinement well



bias voltage → to regulate transport window, …

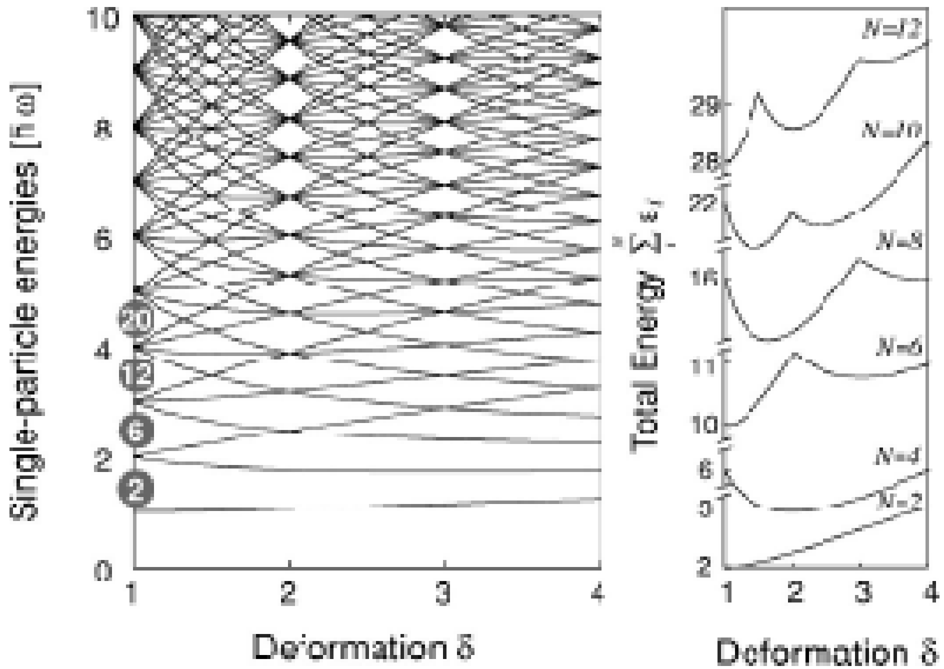
Quantum dots : physics around

✓ **- Quantum shells for electrons:**

- magic numbers 2, 6, 12, … are magic numbers of 2D oscillator

✓ **- Wigner molecules**

QD: quantum shells



quantum shell number:

$$N_0 = n_x + n_y = 0,1,2,...$$

shell degeneracy:

$$N_0 + 1$$

parabolic confinement:

$$V_{conf}(x,y) = \frac{1}{2} m^* (\omega_x x^2 + \omega_y y^2)$$

↓

$$V_{conf}(x,y) = \frac{1}{2} m^* \omega^2 (\delta x^2 + \frac{1}{\delta} y^2)$$

$$\omega^2 = \omega_x \omega_y, \quad \omega_x = \omega\sqrt{\delta}, \quad \omega_y = \frac{\omega}{\sqrt{\delta}}$$

deformation (Jahn-Teller effect):

$$\delta = \frac{\omega_x}{\omega_y} = \begin{cases} \delta = 1 & \text{circular QD} \\ \delta > 1 & \text{elliptic QD} \end{cases}$$

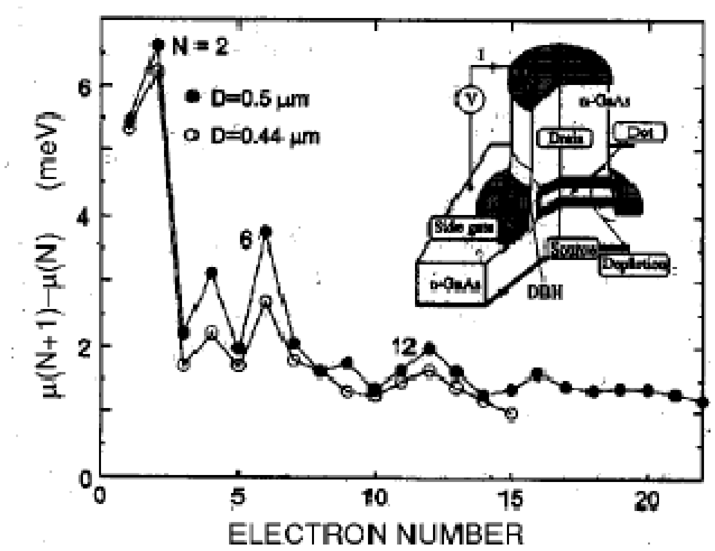
spectrum:

$$E = \hbar\omega[(n_x + \frac{1}{2})\sqrt{\delta} + (n_y + \frac{1}{2})\frac{1}{\sqrt{\delta}}]$$

magic numbers in circular QD:

N=2,6,12,20,24,…

Experimental observation of magic numbers in circular QD (Tarucha et al, 1996).



Wigner crystallization

Prediction of Wigner (1934):
3d and 2d electron gas at low densities is crystallized and form a lattice

Reason → Coulomb dominates at low densities!

Wigner-Seitz radius r_s ⟵ average distance between electrons $\rho_s = (\frac{4\pi}{3} r_s^3)^{-1}$

Effective Bohr radius

$$a_B^* = \frac{\hbar^2 (4\pi\varepsilon\varepsilon_0)}{m^* e^2}$$

$a_B^* \approx 9.8$ nm **in GaAs**

Critical r_s to form Wigner molecules:	
homogeneous 3d	$r_s > 100 a_B^*$
homogeneous 2d	$r_s > 37 a_B^*$
QD	$r_s > 7.5 a_B^*$

QD is a good candidate!

QD: Wigner molecules

$$R_W = \frac{V_{Coul}}{V_{trap}}$$

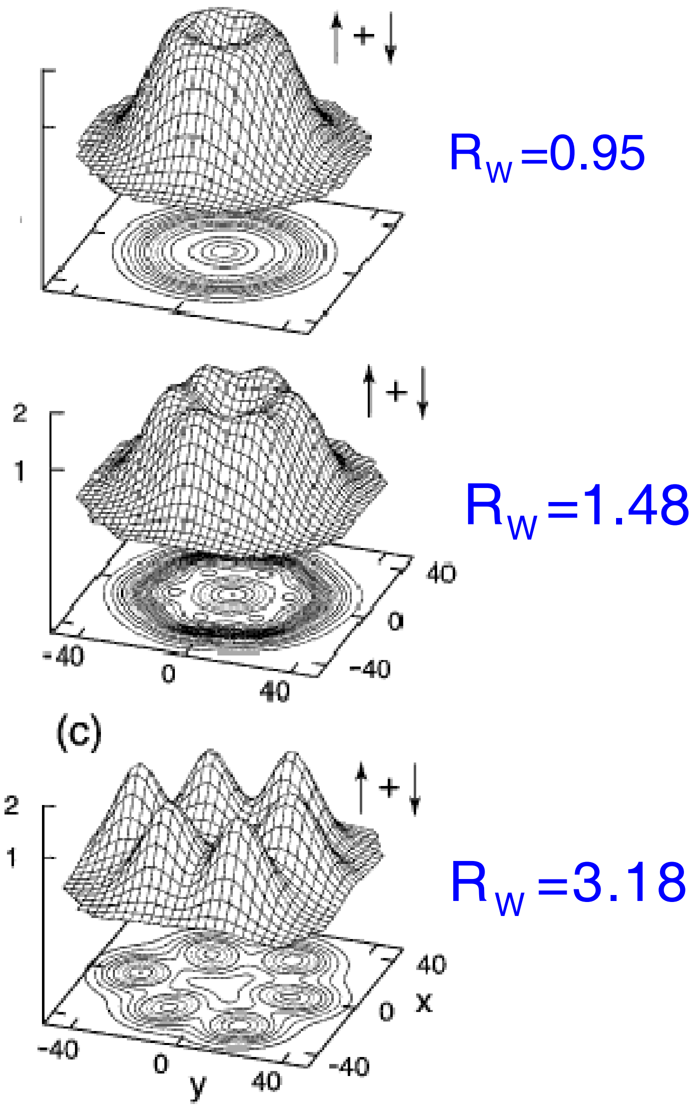
$$R_W \approx \frac{1}{k\sqrt{\omega_0}}$$ can be varied through the choice of material and strength of the confinement

k - dielectric constant

By monitoring the circular confinement field, we can make it weaker than Coulomb interaction: $R_W > 1$
Then we have:
- **strict localization of electronic w.f. (formation of a Wigner molecule),**
- **spontaneous breaking rotation symmetry of the circular confinement field.**

Not still observed in QD …

QD: 6e

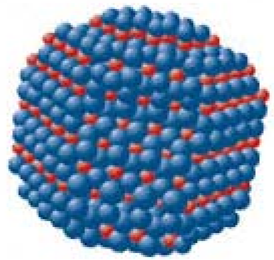


C. Yannouleas, U. Landman, PRL, 1999

3D quantum dots

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

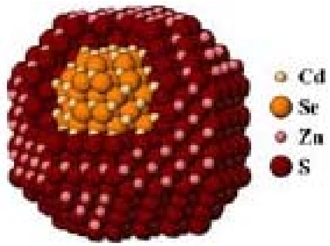
3D quantum dot CdSe



3D quantum dots are similar to atomic clusters

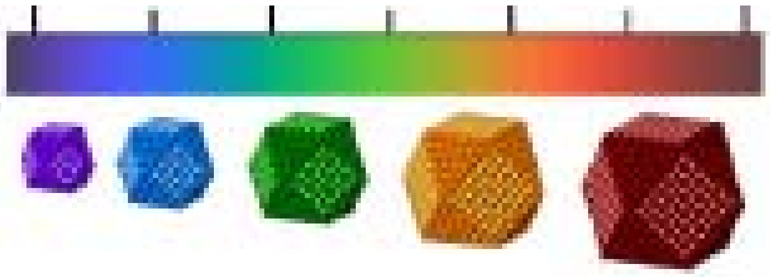
High fluorescence in narrow (~30nm) wave range: depends on QD size and structure:

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



← GeteroQD

400 nm | 500 nm | 600 nm | 700 nm



UV
< 400 nm

Visible light
400-700 nm

IR
> 700 nm

References: quantum dots, spintronics

1) **S.M. Reinmann and M. Manninen,**
"Electronic structure of quantum dots",
Rev. Mod. Phys., 74, 1284 (2002).

2) **I.Zutic, J. Fabian, S. Das Sarma,**
"Spintronics: fundamentals and applications",
Rev. Mod. Phys., 76, 323 (2004).

3) **R. Hanson et al,**
"Spins in few-electron quantum dots",
Rev. Mod. Phys., 79, 1217 (2007).

4) **«Нанотехнологии в ближайшем десятилетии»,**
под ред. М.Роко. М.. Мир. 2002.

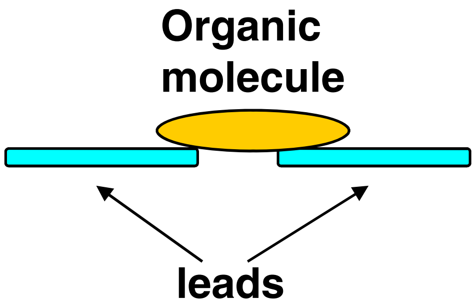
5) **R.G. Nazmitdinov,**
"Magnetic field and symmetry effects in small quantum dots",
Phys. Part. Nucl. , 40, n.1, 71-92 (2009).

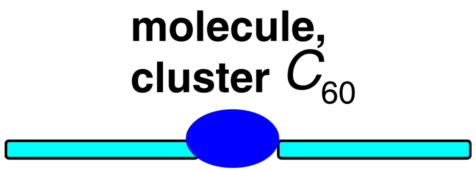
Quantum transport

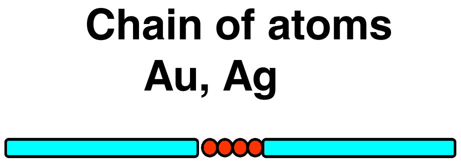
- variety of quantum transport
- Landauer equations

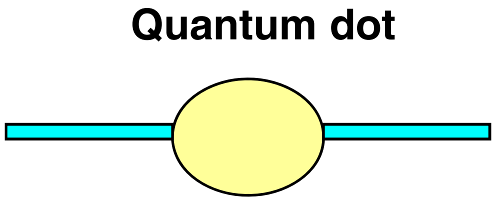
Quantum transport

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

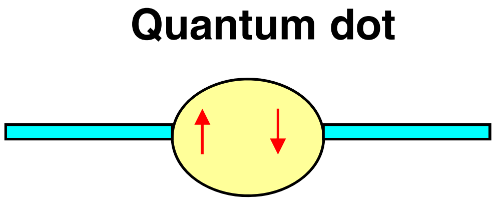




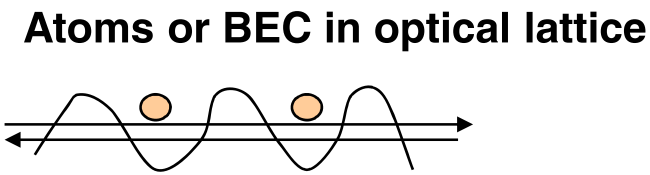




Transport of electrons



Transport of spin

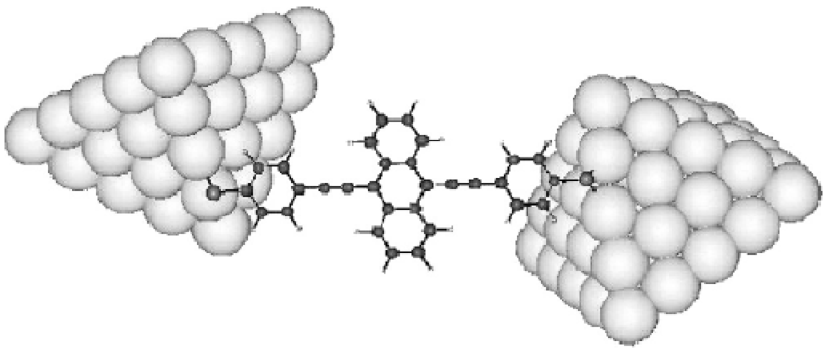


Atoms or BEC in multi-well traps

Transport of atoms

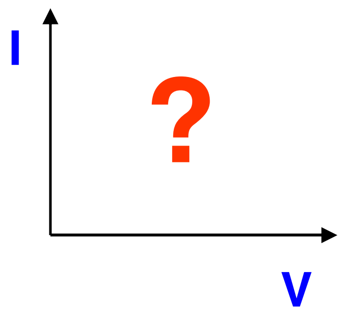
Examples:

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, …)

Low temperature, low bias ⟶ basic transport features
(electrons at the Fermi energy)

Room temperature, high bias ⟶ practical applications

We will consider

basic transport features!

Mainly planar semi-conductor systems like
GaAs – AlGaAs
(gallium arsenide – aluminium gallium arsenide)

References:

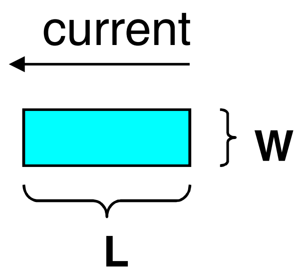
- **S. Datta, "Electronic transport in mesoscopic systems", (Cambridge Univ. Press, Cambridge, 1995)**
- **S. Datta, "Quantum transport: atom to transistor", (Cambridge Univ. Press, Cambridge, 2005)**

Mesoscopic transport

Ohmic:

$U = IR$

$\frac{1}{R} = \frac{I}{U}$



Ohmic behavior for macroscopic conductors:

Conductance: $G = \frac{1}{R} = \sigma W / L$

Principle question:
How small can we make the dimensions before the ohmic behavior breaks down?

The system demonstrates 'ohmic' behavior if

$$W, L >> \lambda_B, \overline{r}_D, \overline{r}_{Phase}$$

λ_B - **de Broglie wavelength**

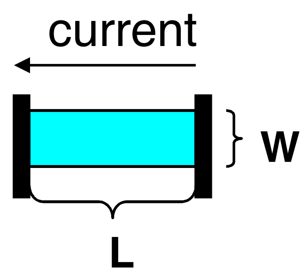
$\overline{r}_D$ - **mean free path** **(the distance that electron travels before its initial momentum is destroyed)**

$\overline{r}_{Phase}$ - **phase-relaxation length**

Mesoscopic systems:
- larger than microscopic objects (atoms, …),
- but not large enough to be 'ohmic',
- typical dimensions: $nm \div \mu m$ or $10^{-9} - 10^{-4}\, m$

→ **Mesoscopic transport!**

Landauer formalism



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

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

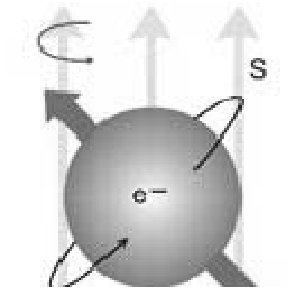
Mesoscopic transport:

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

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.
- unlike electrical charge, "spin charge" is not conserved and depends on several factors: spin-orbital interaction,…

Change of electron spin direction by using its precession in magnetic field:
- **low energy effort and heating**
- **prompt (~ ps =** $10^{-9} s$**)**
- **long-living**



Si-based microelectronics ⟶ Spintronics

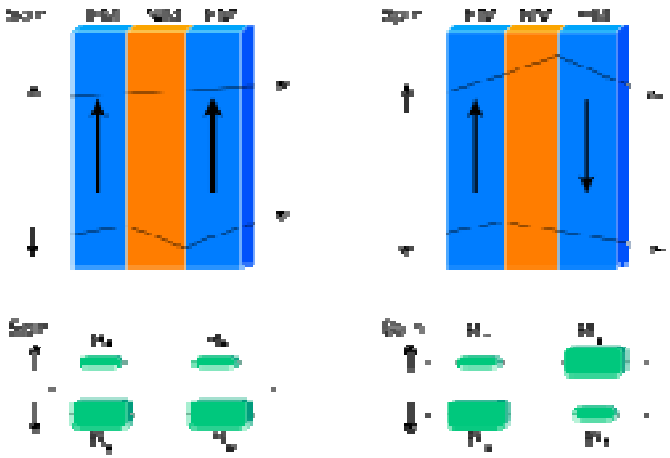
Best perspectives:

- quantum computer
- spin field-effect transistor
- spin memory, 8 registers

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

- Effect via spins of electrons. Hence

SPINTRONICS!

References: quantum transport

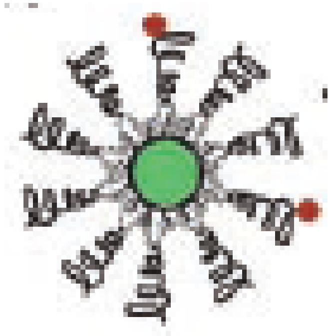
1) S. Datta, "Electronic transport in mesoscopic systems",
(Cambridge Univ. Press, Cambridge, 1995)

2) S. Datta, "Quantum transport: atom to transistor",
(Cambridge Univ. Press, Cambridge, 2005)

Bio-medical applications of nanosystems

Nanoparticles for bio-medical aims (1)

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



- functionalization
- bioconjugate

Main applications:

- targeted drug delivery
- biomarkers, diagnostics
- photo-thermolise → using of plasmon

Main candidates:

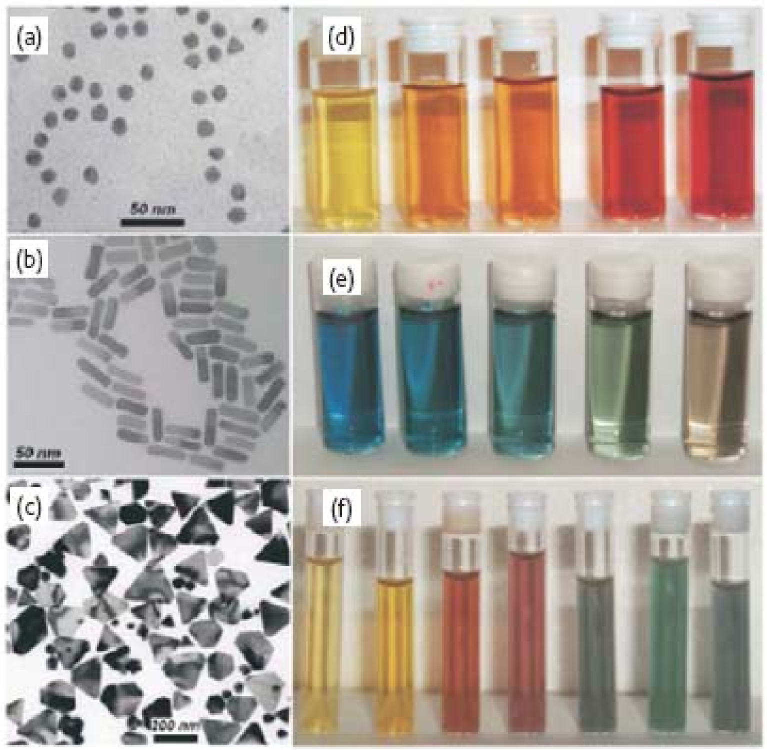
- semiconductor QD CdSe (toxic!)
- Au and Ag nanoclusters

Problems of traditional sensors

(organic dyes):

- weak signal
- rapid photobleaching
- subtle spectra differences
  for normal and deceased cells
- low possibility to change the plasmon
  frequency

Nanoparticles can solve these problems!

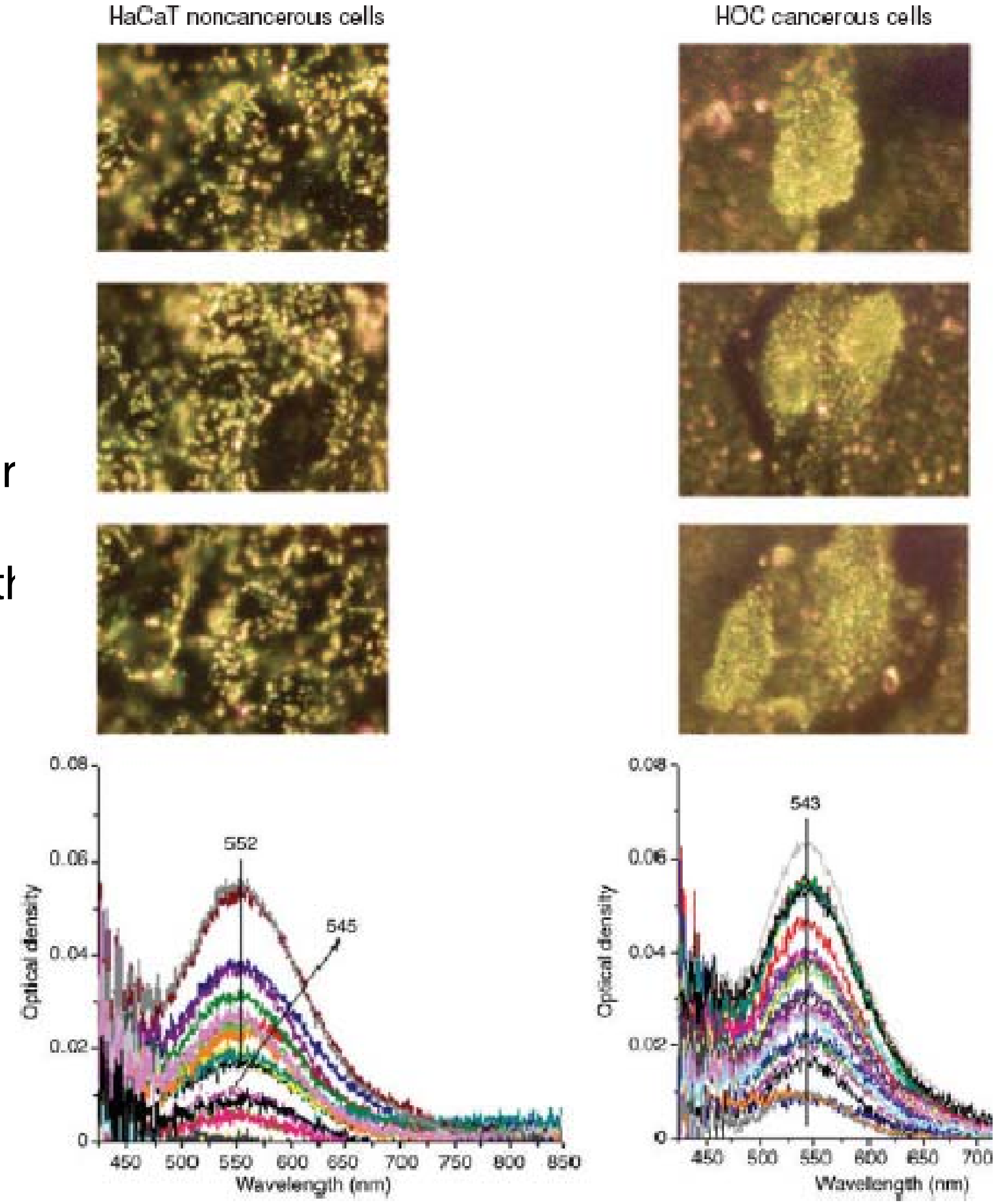


Nanoparticles for bio-medical aims (2)

Colloidal Au:

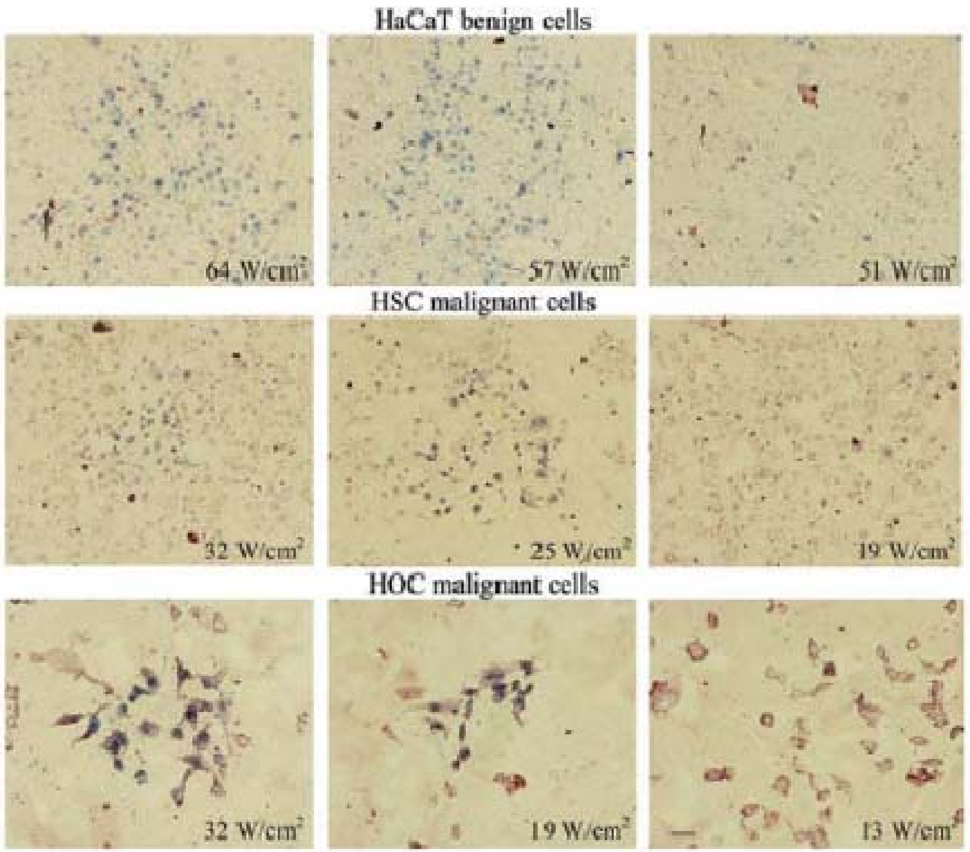
- known already in ancient Egypt,
- nanoparticles of the size 4-80 nm
- biocompatible, notoxic
- strong binding affinity
- optical cross-section is $10^4 - 10^5$ higher than for conventional dyes
- the ratio absorption/scattering rises with particle size

- Au nanoparticle ~ 35 nm
- anti-EGFR/Au nanoparticle conjugate
- light scattering images
- microabsoption spectrometry (shift ~ 9nm)



Selective photothermal cancer therapy

- rapid (~ 1 ps) conversion of absorbed light into heat
- $10^4 - 10^5$ times more effective absorption



- 4 min exposition of weak CW laser, visible light 530 nm

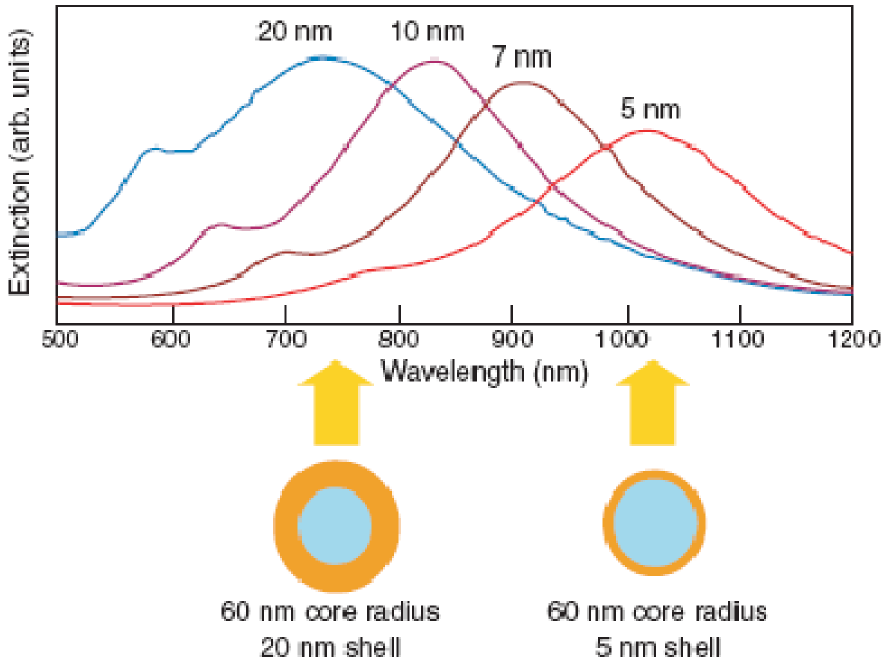
Targeted cells:
- healthy HaCaT die at 57 W/cm^2
- malignant HSC die at 25 W/cm^2
- malignant HOC die at 19 W/cm^2

Non-targeted cells
- survive up to 76 W/cm^2

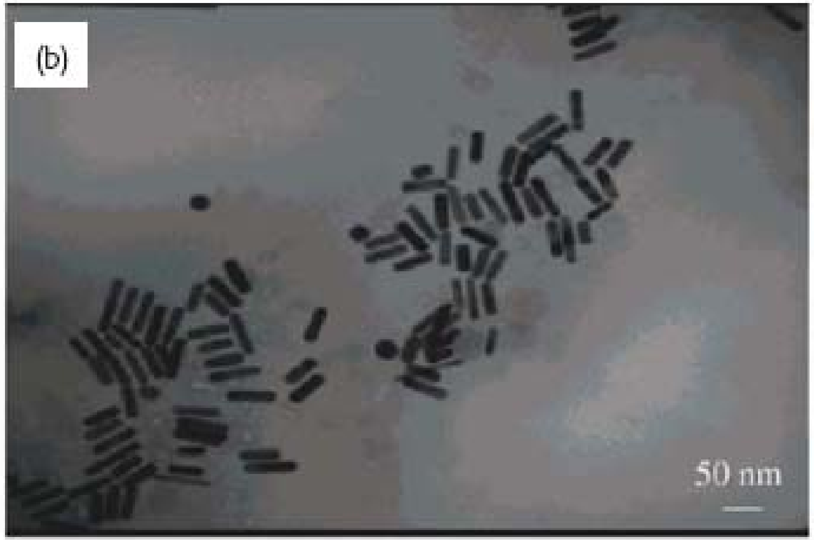
Transparency window for tissue: 800-1000 nm >> visible light

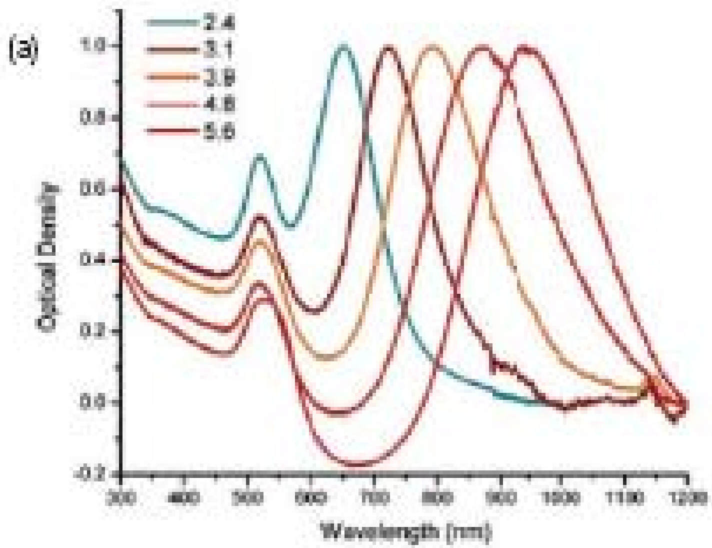
- infrared irradiation:
- **diagnostic and therapy *in vivu***
- **biological NIR window 650-900 nm, (maximal transmissivity for hemoglobin and water)**
- **penetration: few cm.**

Silica-core Au-shell nanoparticles



Nanorods with different aspect ratio





REFERENCES: BIO-MEDICAL APPLICATIONS

1) Н.Г. Хлебцов, В.А. Богатырев, Л.А. Дыкман, Б.Н. Хлебцов "Золотые наноструктуры с плазмонным резонансом для биомедицинских исследований", Российские нанотехнологии, т.2 (3-4), 2007 (www.nanorf.ru)

2) A.O. Govorov and H.H. Richardson, "Generating heat with metal nanoparticles" NanoToday, 2, n.1, 30 (2007)

3) P.K. Jain et al, "Au nanoparticles target cancer", NanoToday, 2, n.1, 18 (2007)

Thank you for your attention!