Microscopic structure of interfaces in condensed matter

A.A. Gorbatsevich

Chair of Quantum Physics and Nanoelectronics

Nanotechnology: flourishing diversity

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Nanotechnologies in MIET:

- **Growth technologies: molecular-beam epitaxy, arc plasma coating, electro-chemical nanostructure formation, porous alumina anodic oxide, Ge nanocluster in Si matrix formation using ion implantation.**
- **Scanning probe technologies: local oxidation based nanolithography, material placing, nanolithography cantilever creation.**

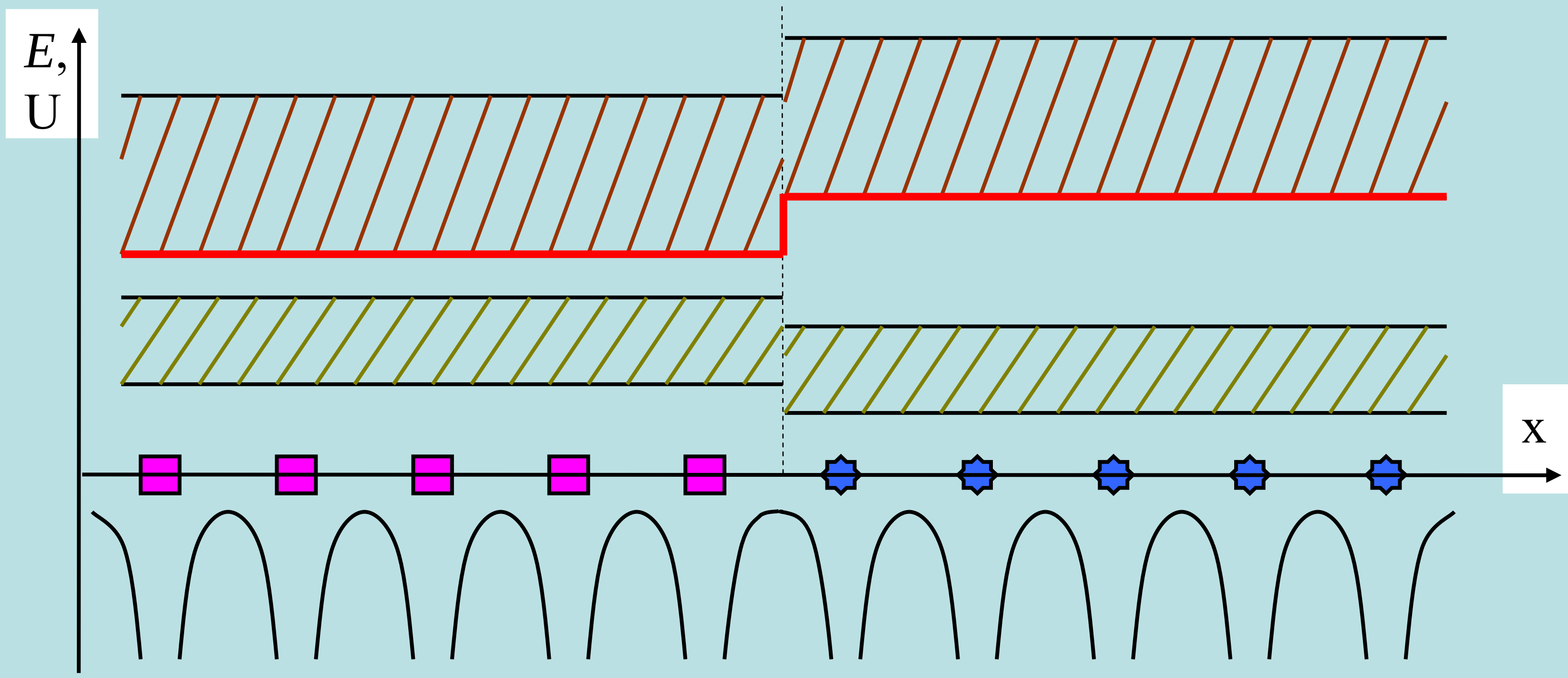
Nanomaterials and nanosctructures for electronics

- semiconductor heterostructures based on A3B5 compounds, including resonant-tunneling heterostructures for ultra-high speed electronics;
- solid nanocoatings for various applications, including coatings for nanolithography, conducting and magnetic coatings for scanning probe microscopy cantilevers;
- carbon nanotubes for studies of quantum transport, development and creation of electronic devices based on quantum conductors;
- Ge quantum dots in Si matrix which were first obtained using ion implantation technique;
- nanoporous alumina oxide for optoelectronic applications as well as for terabit semiconductor memory cell creation;
- quasi-one-dimensional conductor based nanovaristors displaying quantum properties at room temperature, obtained by local anodic and current induced oxidation of various metals (Ti, Ta, Nb, Al)

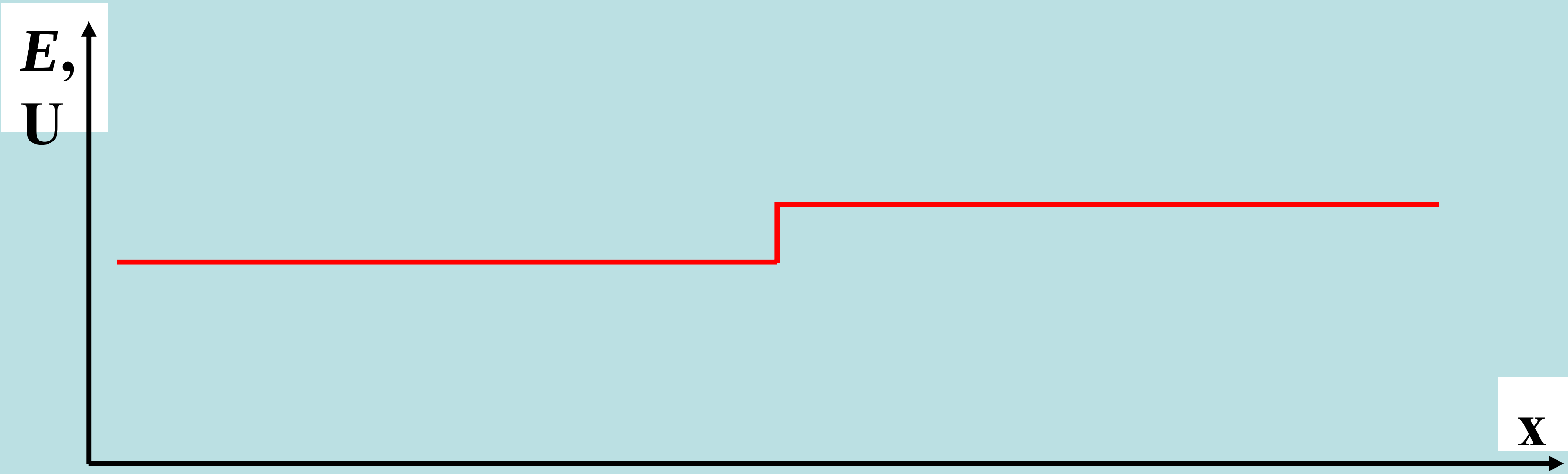
Nanomaterials and nanosctructures for electronics

- semiconductor heterostructures based on A3B5 compounds, including resonant-tunneling heterostructures for ultra-high speed electronics;

Heterojunction

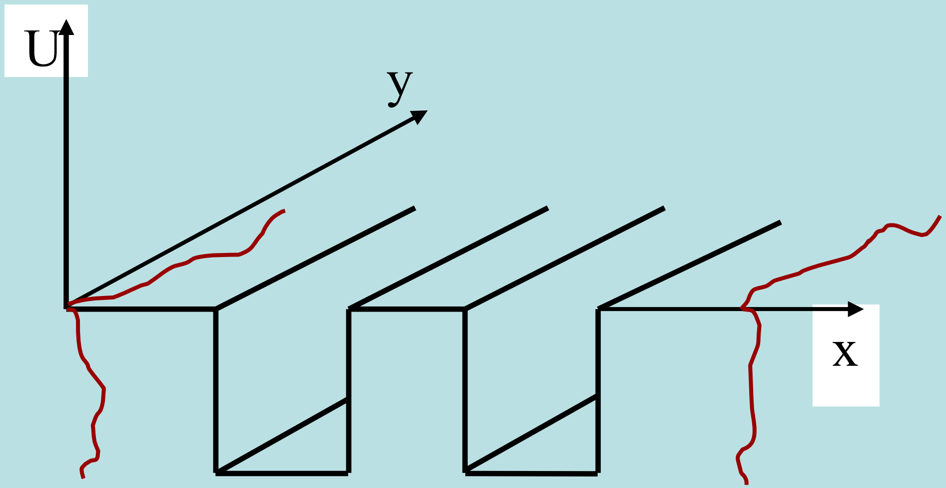


Envelope Function (or Effective Mass) Method

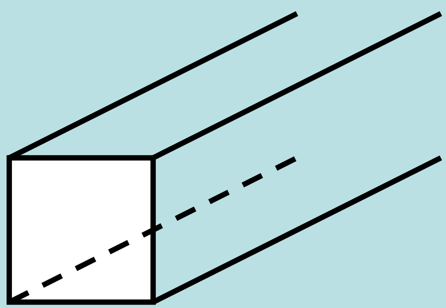


$$\left[-\frac{\hbar^2\nabla^2}{2m^*}+U(r)\right]\psi(\vec{r})=E\psi(\vec{r})$$

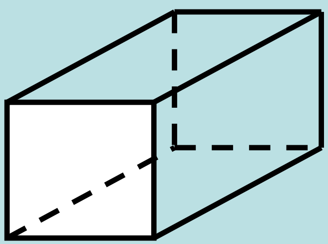
1. Quantum Wells and Superlattices



2. Quantum Wires



3. Quantum Dots

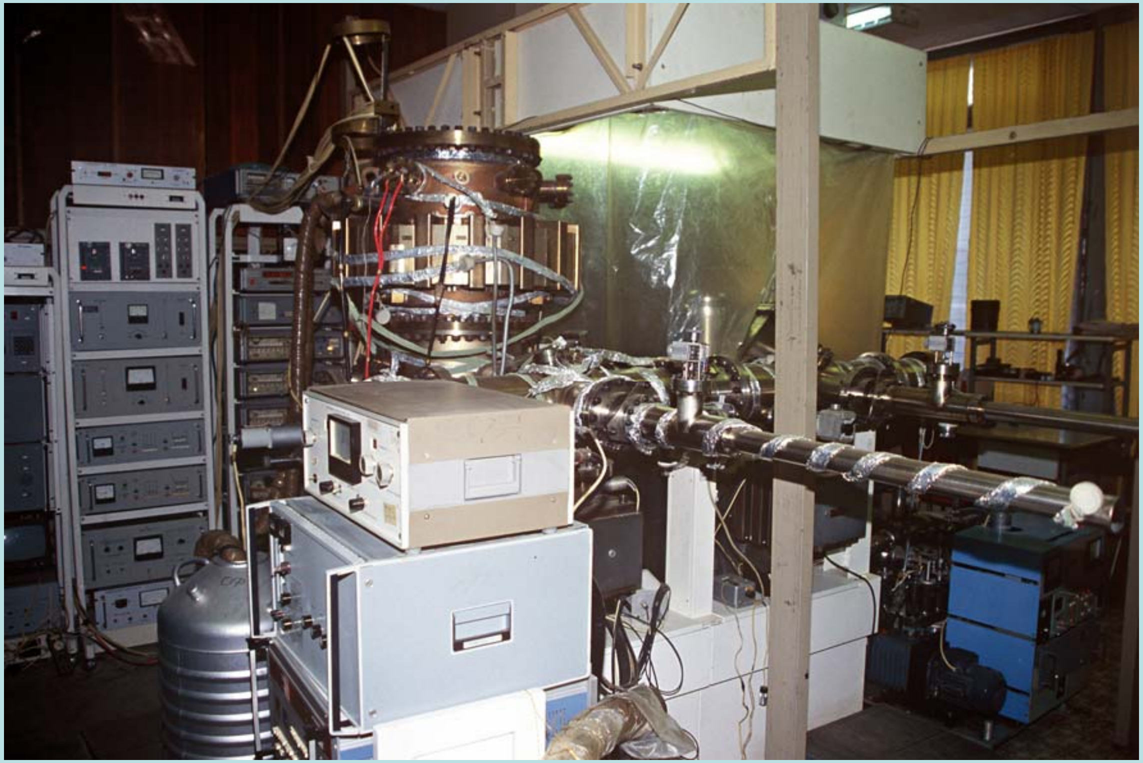


- Heterostructures for high-speed IC applications
- Nanoelectronic elements for ultra-high-speed ICs
- Heterostructures for fundamental researches (microscopic structure of heterojunctions)

- Heterostructures for high-speed IC applications
- Nanoelectronic elements for ultra-high-speed ICs
- Heterostructures for fundamental researches (“dark matter” in crystals)

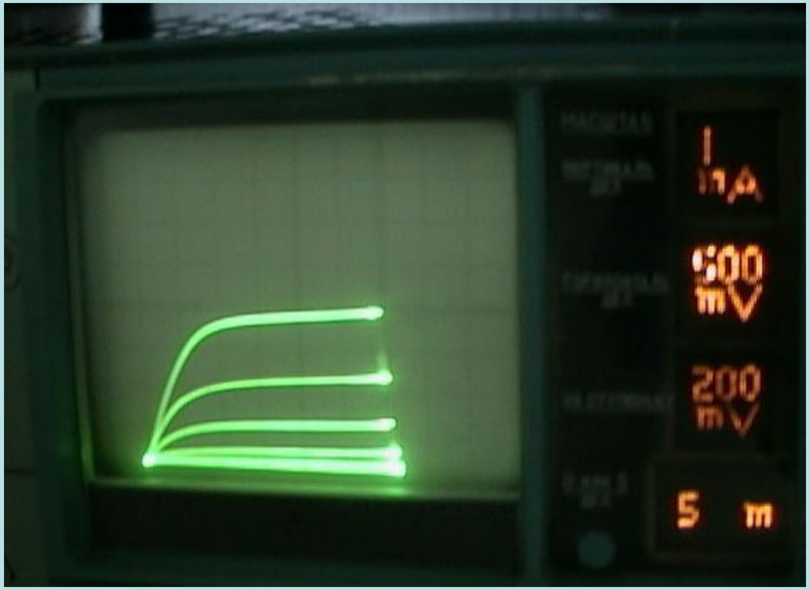
Applications

Molecular-beam epitaxy machine

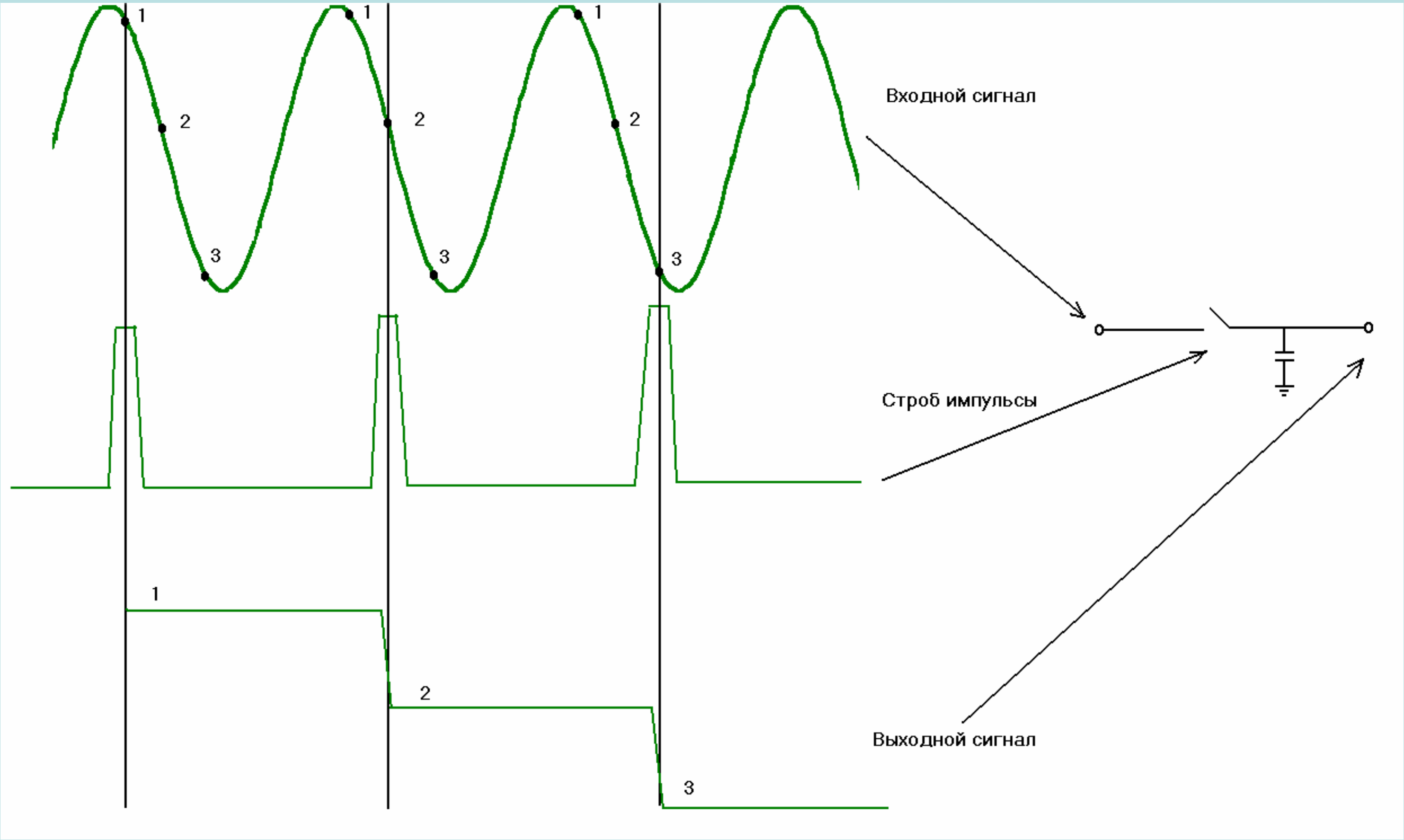


General view of A3B5 compounds technology clean-room facilities

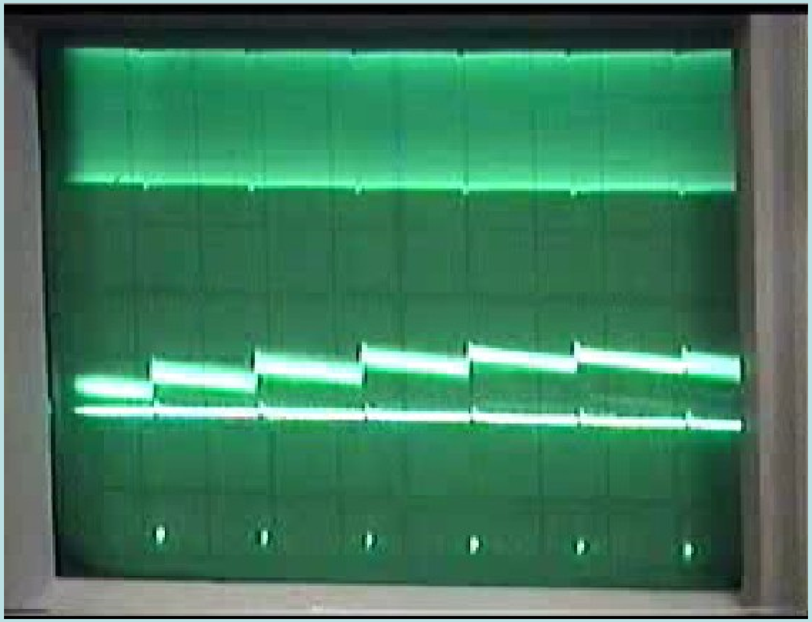
Comparison of FET based on doped epitaxial GaAs structure and heterostructure FET

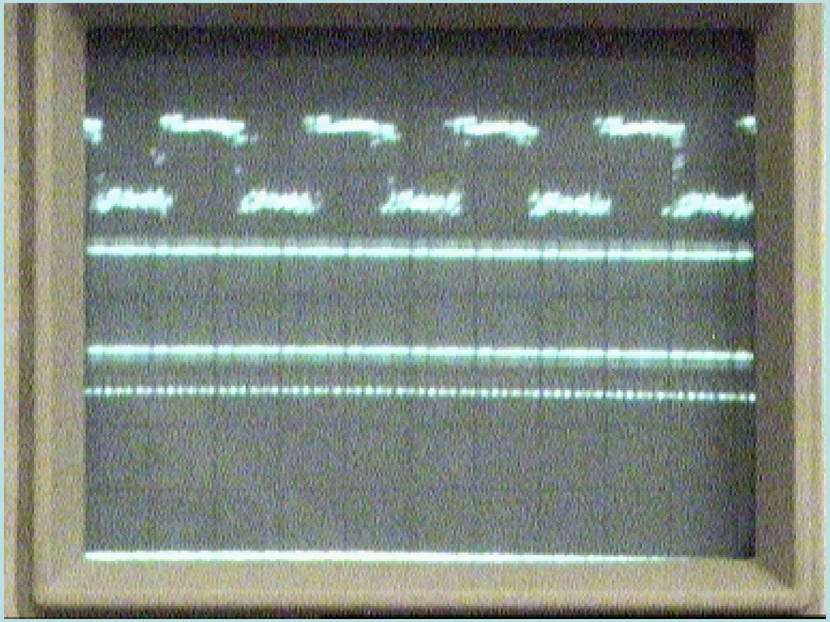


Basic principal of sampler performance

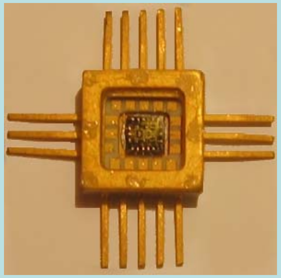


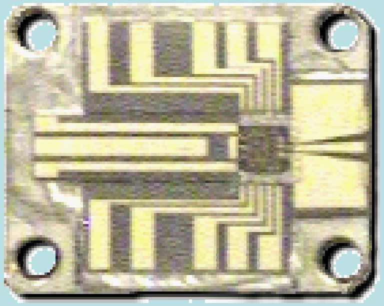
Input signal expansion mode

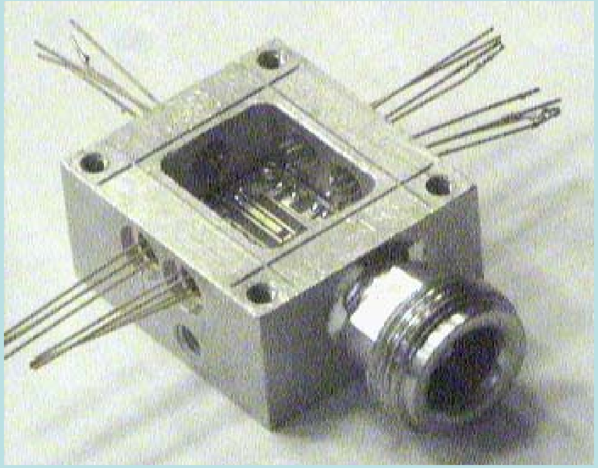




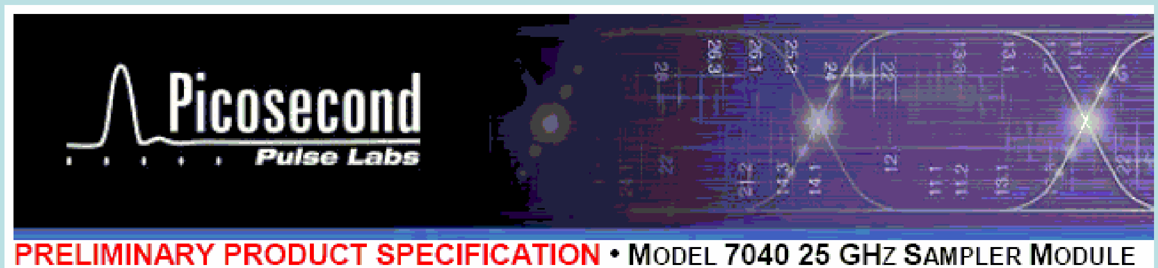
EXAMPLES OF RF ICs AND MODULES





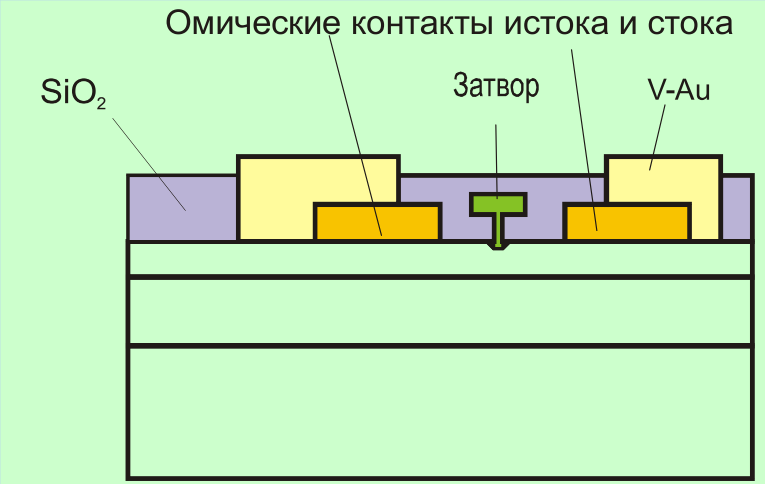


Analogs by Picosecond Pulse Labs 2004-2005 г.

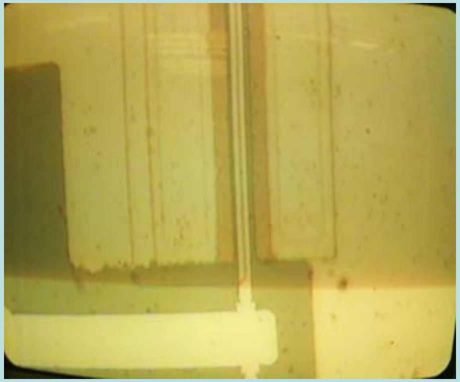


Elements for nanoelectronics

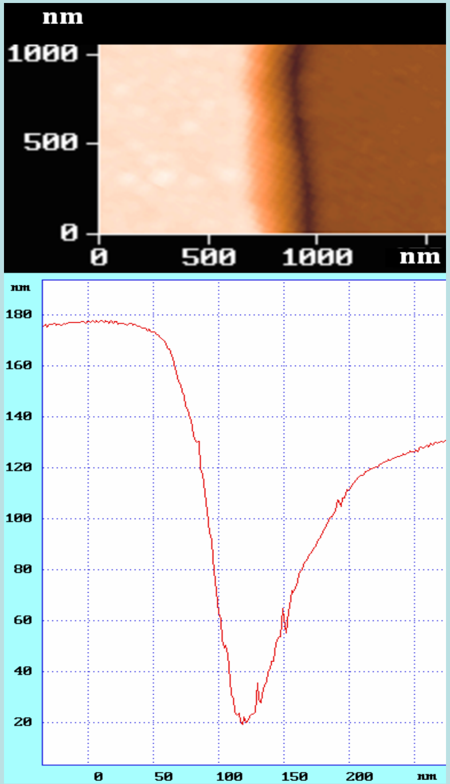
GaAs nano FETs



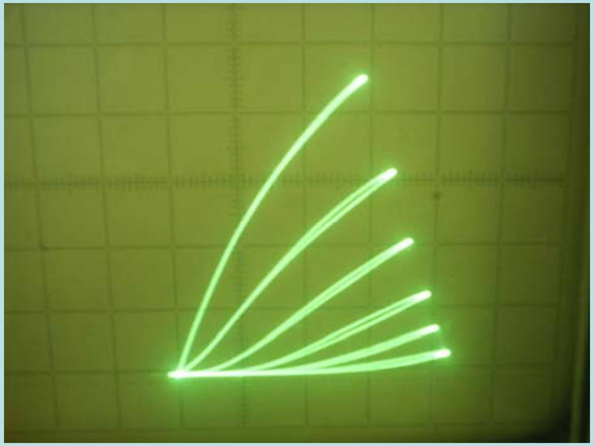
Structure



Optical microscopy image

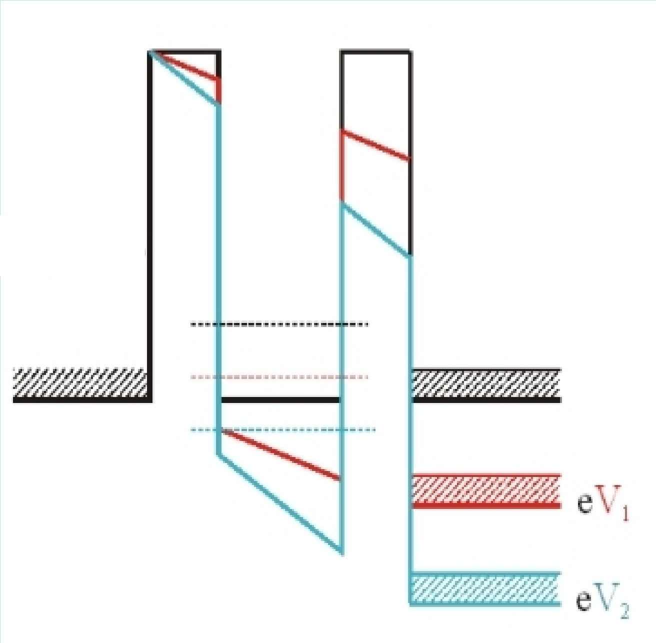


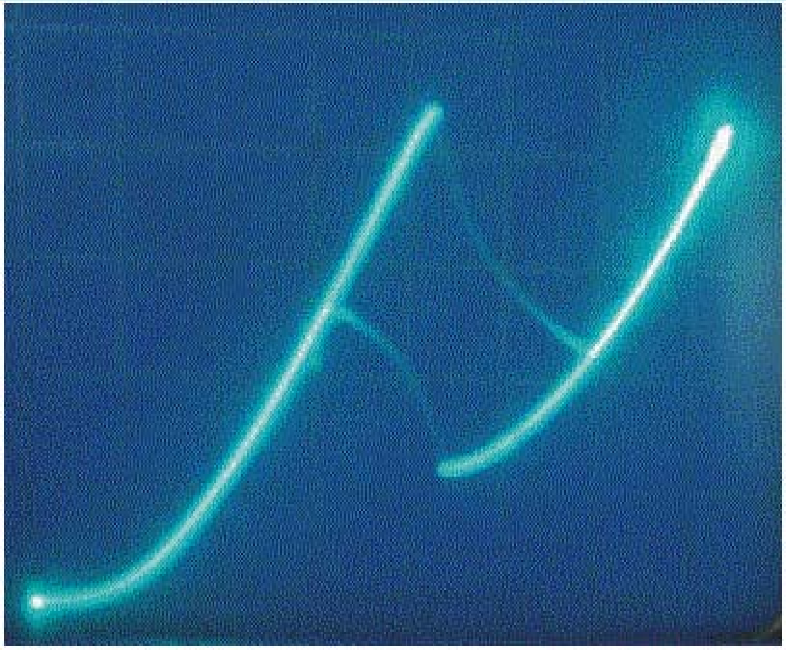
SPM gate image



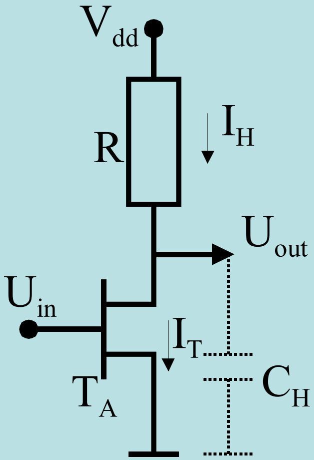
I-V characteristics

Resonant-tunneling diodes (RTD)

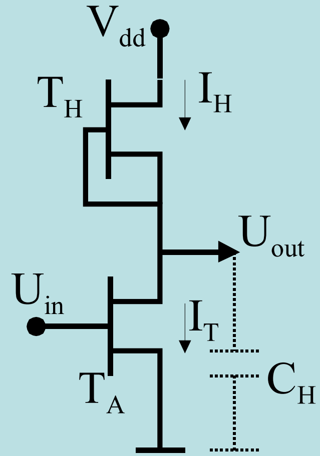




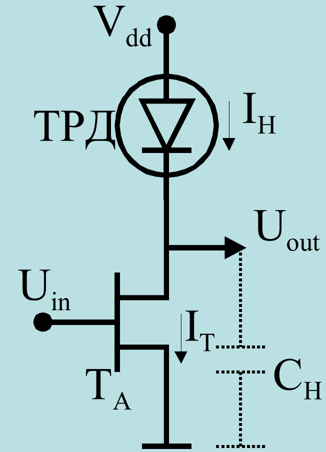
Electric circuits and current-voltage characteristics of basic MESFET inverters



Resistive load

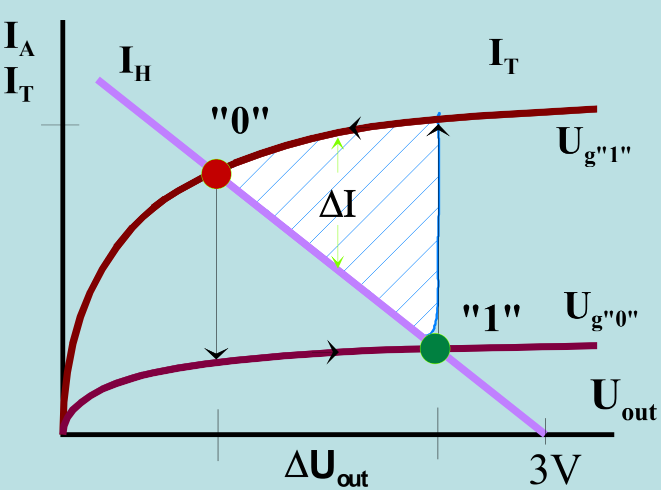


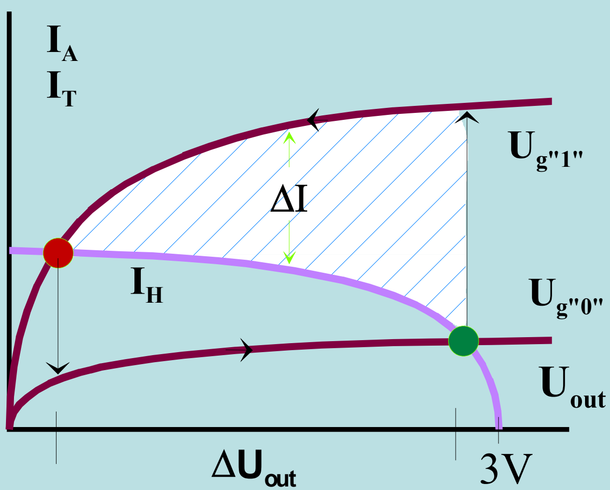
transistor load

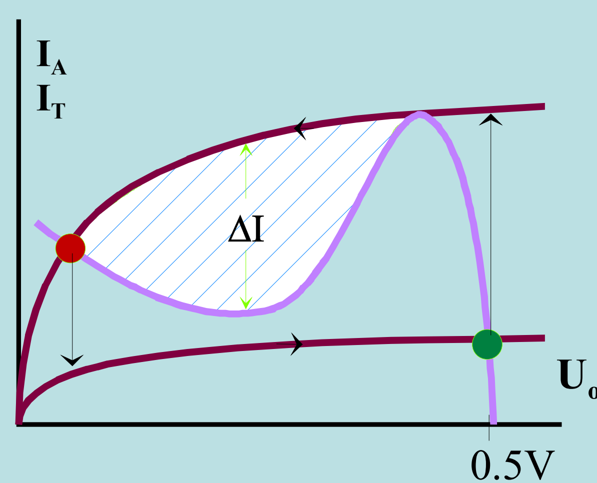


RTD as a load

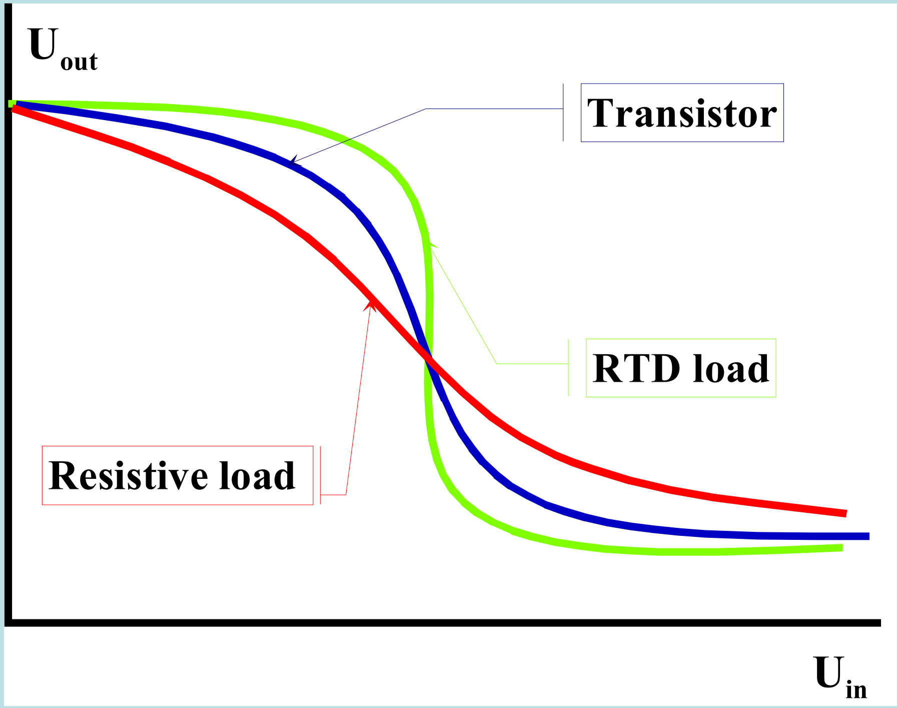
Switching time $\Delta\tau = C_H \Delta U(I)/ \Delta I$, for the RTD at the moment of switching C_H decreases due to the RTD negative capacitance.







Transfer characteristics of inverters



RTD:

1. High speed – up to tens of gigahertzs with lithographic dimensions 0.6-0.8 μm
2. High gain
3. High interference margin
4. Power supply less than 1.5 V
5. Low power consumption

Number of elements necessary to construct logic functions based on different element base types

Circuit	TTL	CMOS	ECL	RTD/ MESFET
Two-stable-state XOR	33	16	11	4
Two-stable-state majority gate	36	18	29	5
Memory element (with 9 states)	24	24	24	5
2NO-OR+trigger	14	12	33	4
2NO – AND + trigger	14	12	33	4

Planarization problem

PERGAMON
Solid-State Electronics 43 (1999) 1355–1365
SOLID-STATE ELECTRONICS

Resonant-tunneling mixed-signal circuit technology

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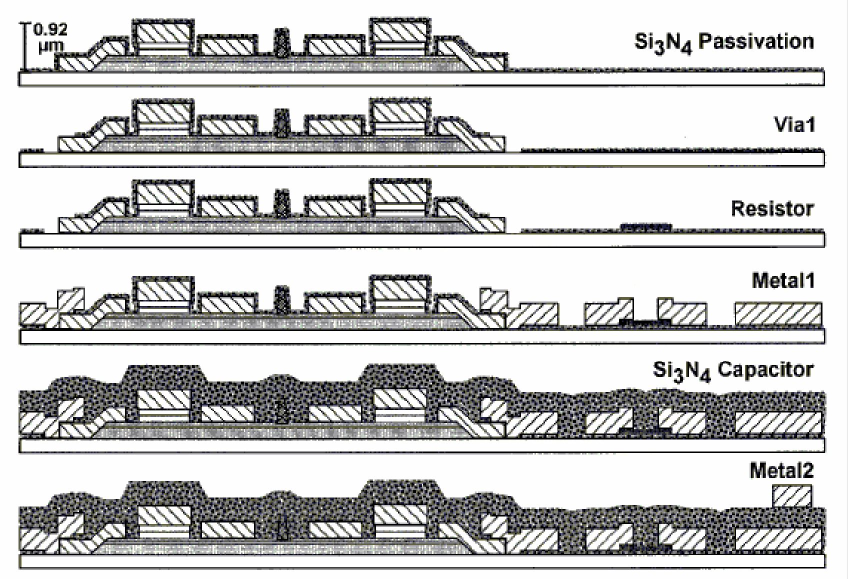
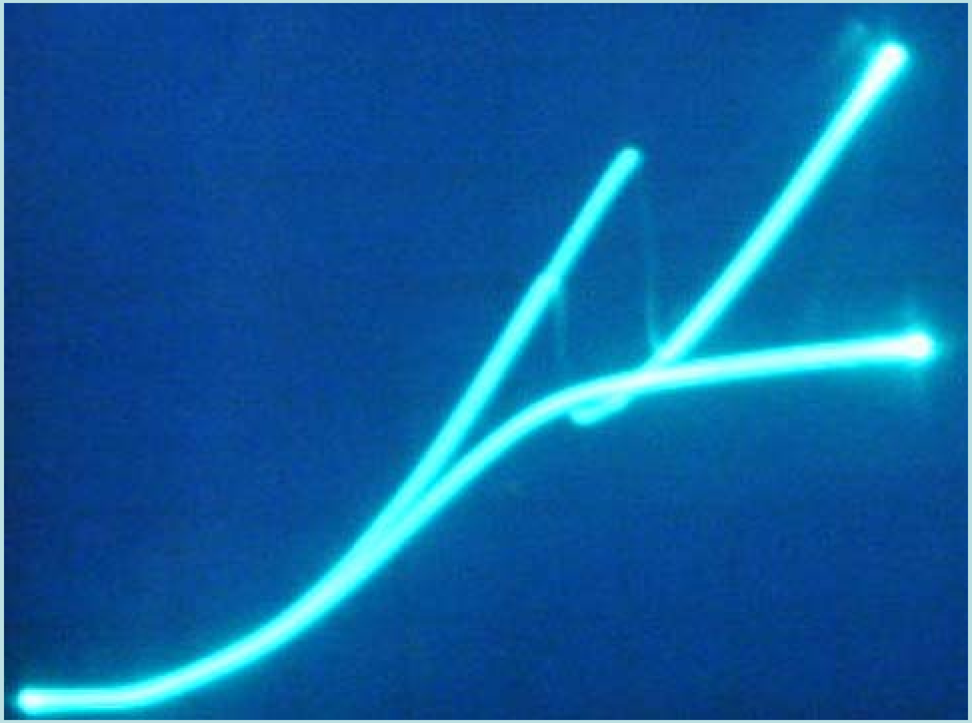
Raytheon Systems Company, P.O. Box 660246, MS35, Dallas, TX 75266, USA



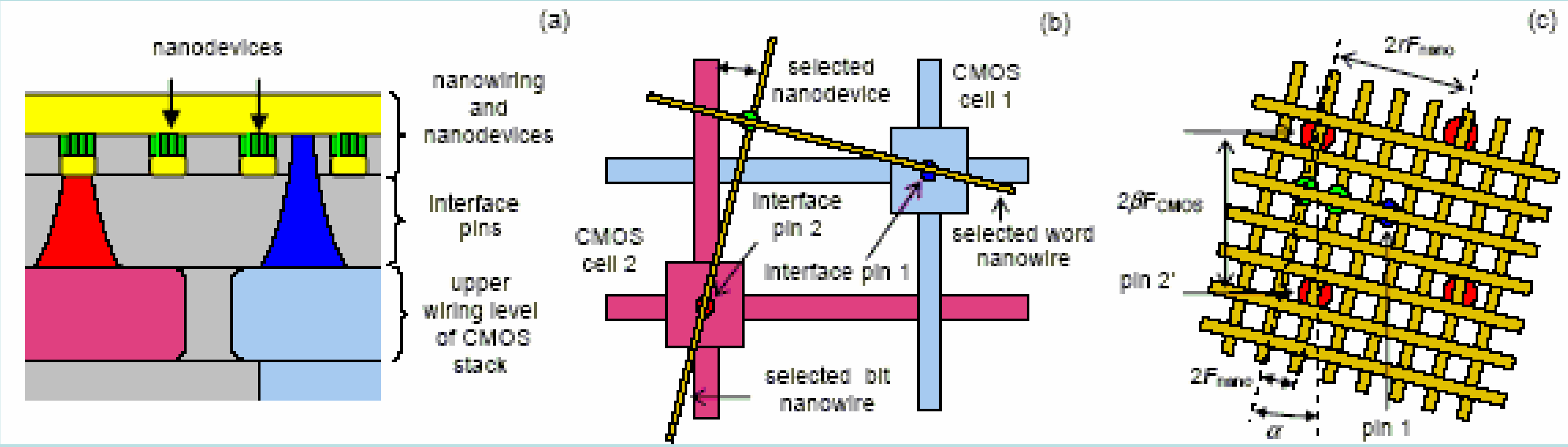
I-V curve of planar RTD+transistor chip



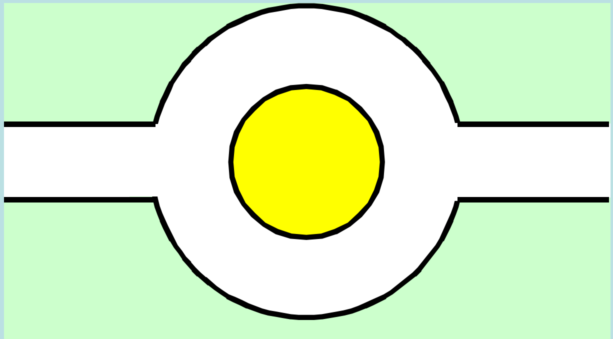
Transistor scaling limits – up to 22nm. And what is below?

May be –
CMOL- electronics or
waveguide nanoelectronics!?

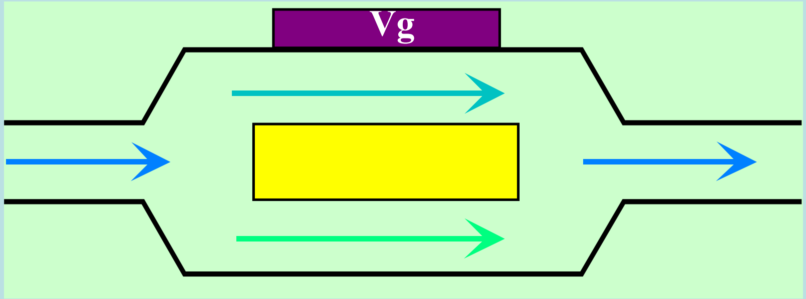
CMOL - electronics



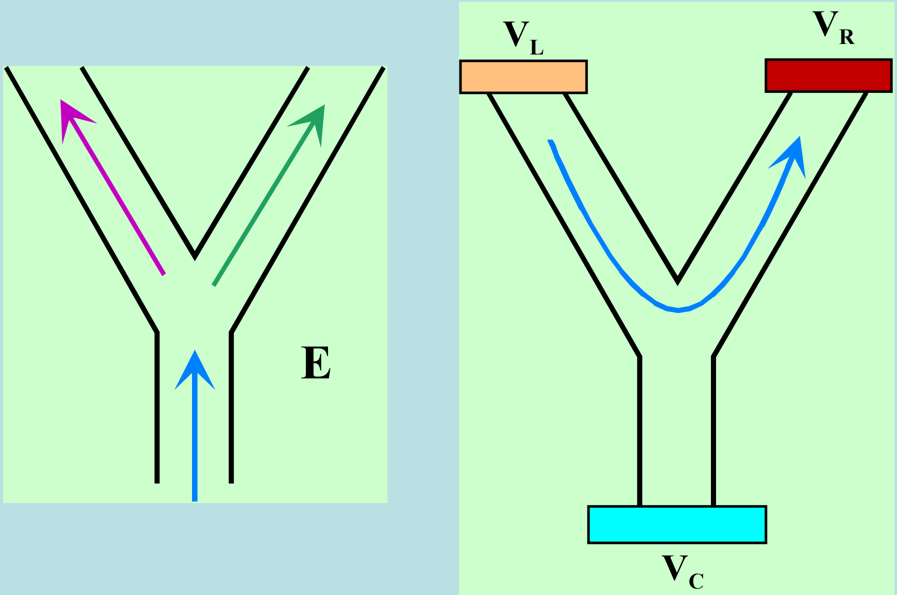
Quantum interference devices

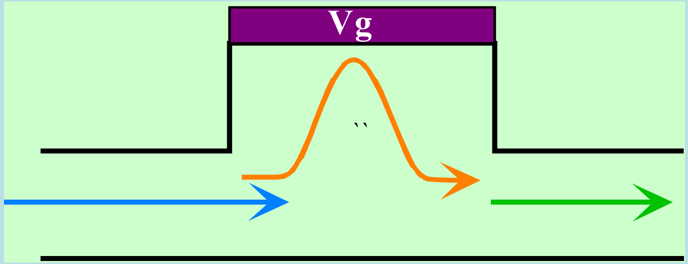


Aharonov-Bohm interferometer

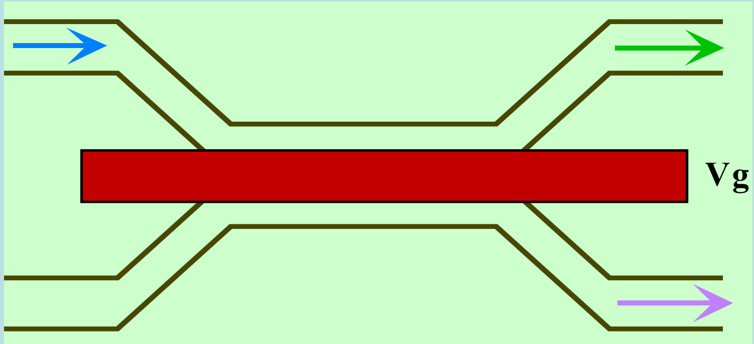


Quantum interference transistor





Quantum T-shaped transistor

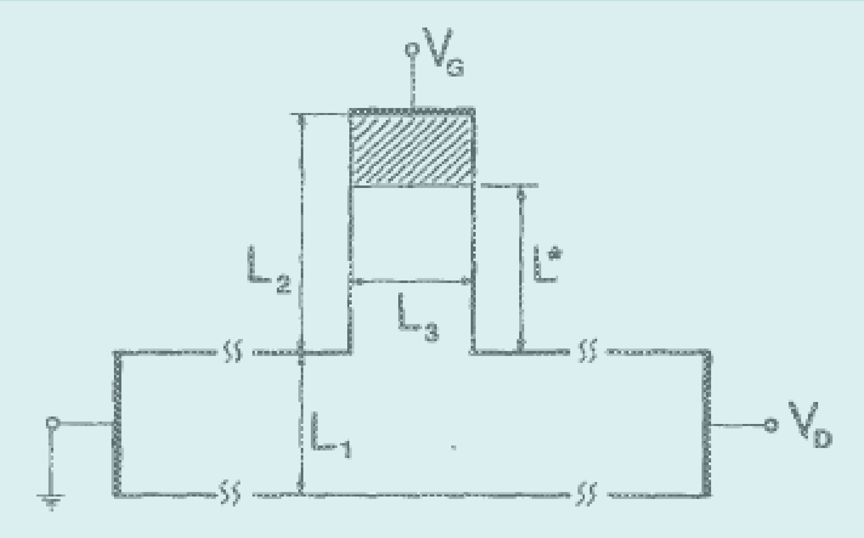


Three-terminal devices with Y-splitters

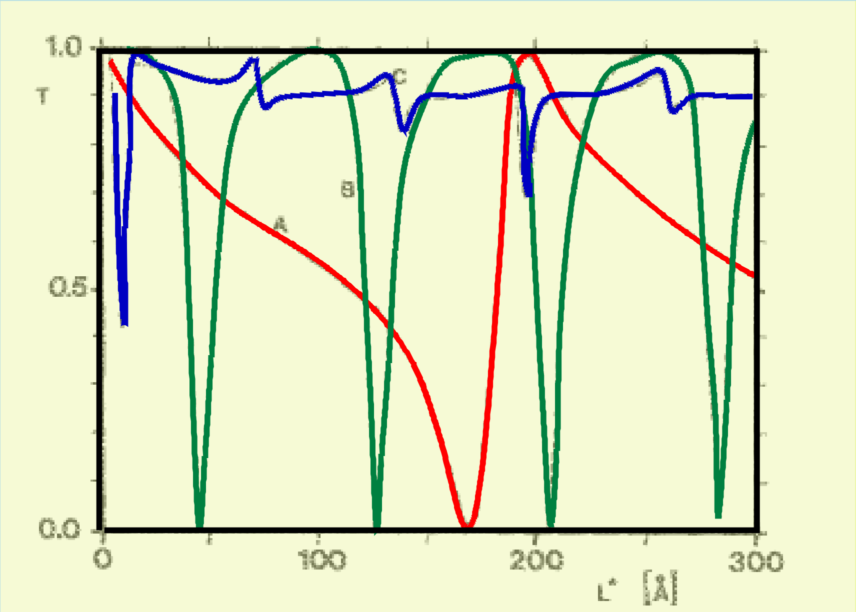
Directional splitter

T-shaped waveguide-like transistor

(F. Sols, M. Macucci, U. Ravaioli, K. Hess, Appl. Phys. Lett. 54 (4), 350, 1989)

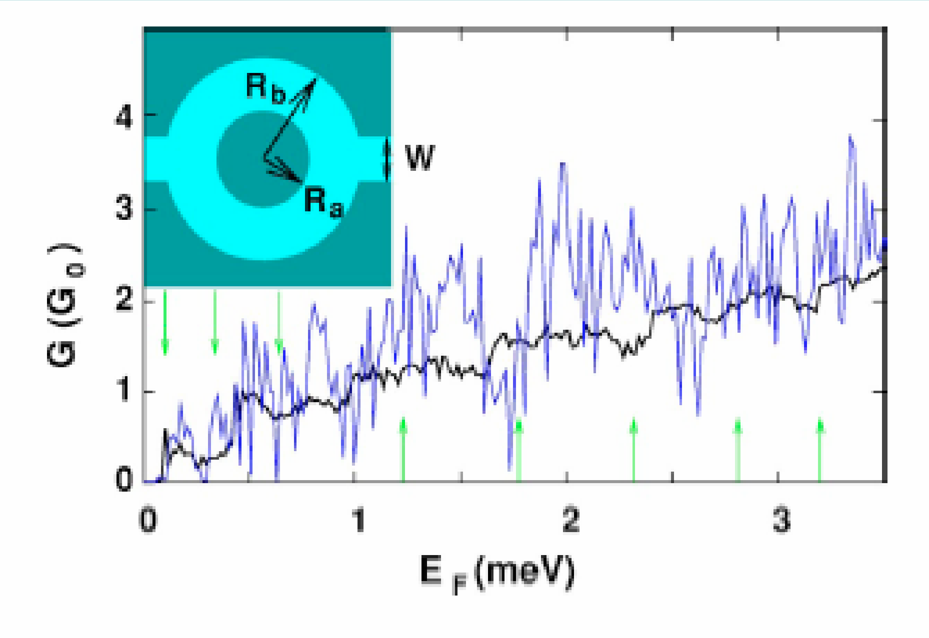


Schematic view of three-terminal structure

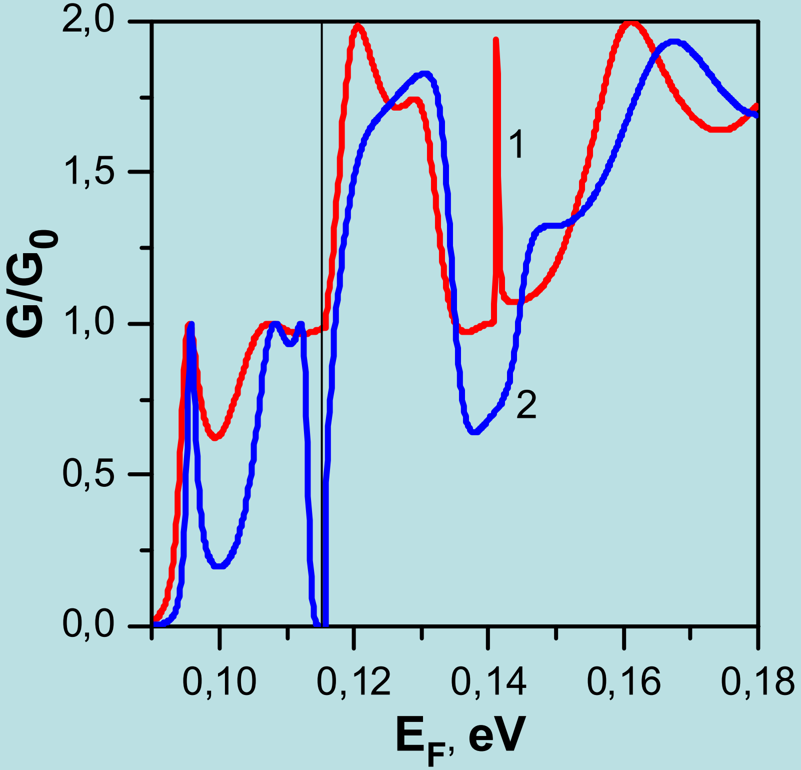


Transmission coefficient as function of the effective length of the stub for energy
E (eV): A – 0.02; B – 0.118; C – 0.199

Complicated structure of conductance



Conductance of the AB ring as a function of the Fermi level of electrons The arrows indicate the energies at which a new conducting channel in the lead is opened. R_a = 350 nm, R_b= is 630 nm. W = 200 nm. G_0 = 2*e*2 /*h*



Phys. Rev. B ***69****, 235304 (2004)*

Quantum Logic Gates based on Coherent Electron Transport in Quantum Wires

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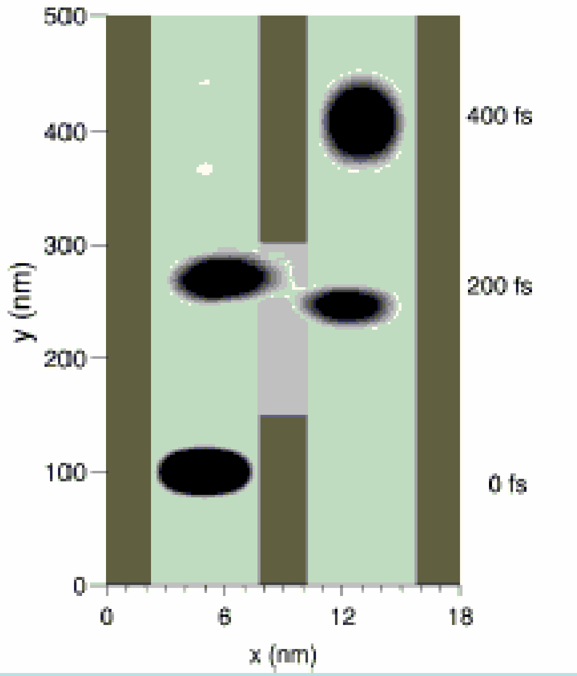
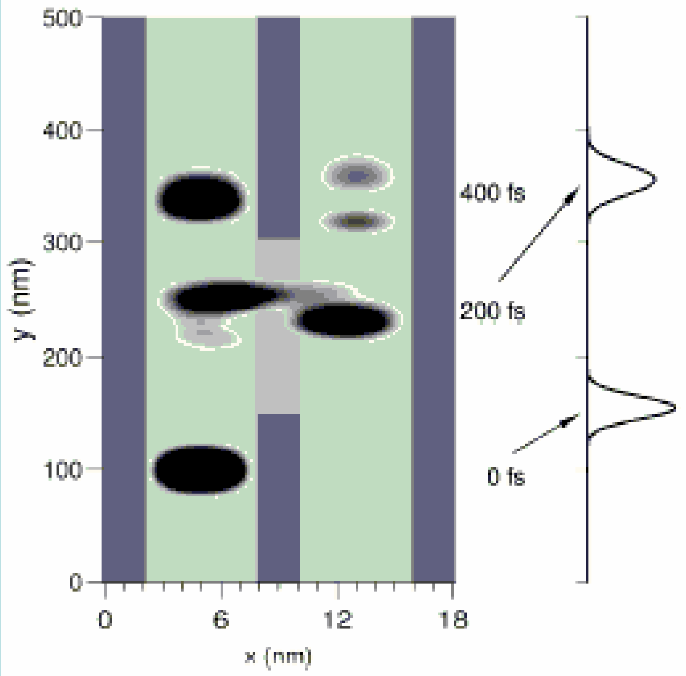
(Received 1 November 1999)





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Magnetically switched quantum waveguide qubit

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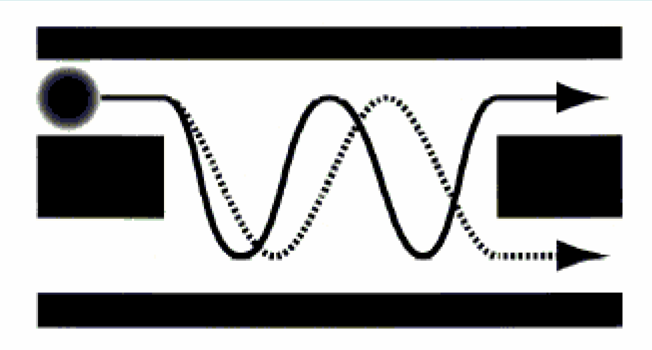
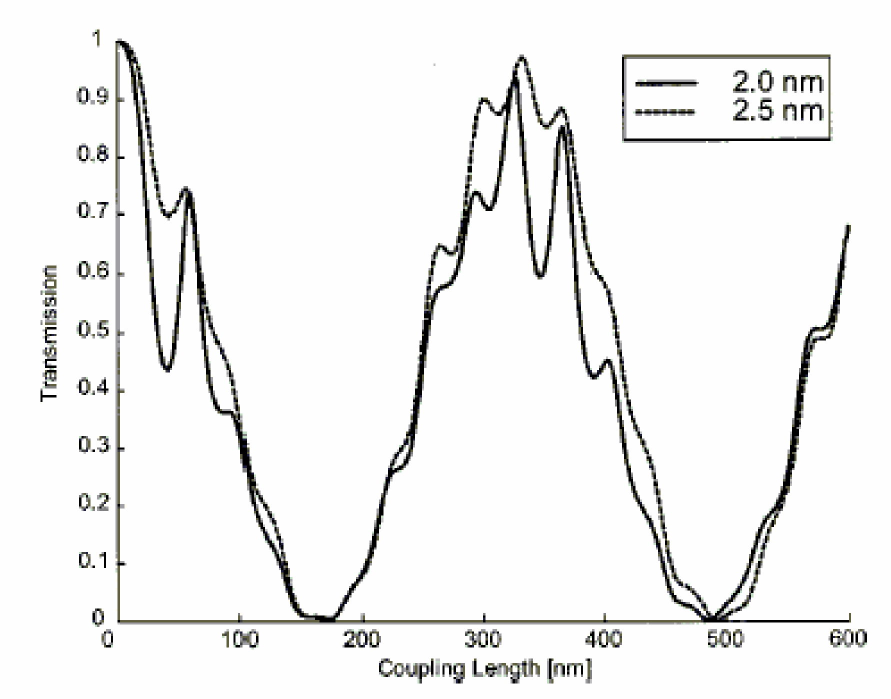
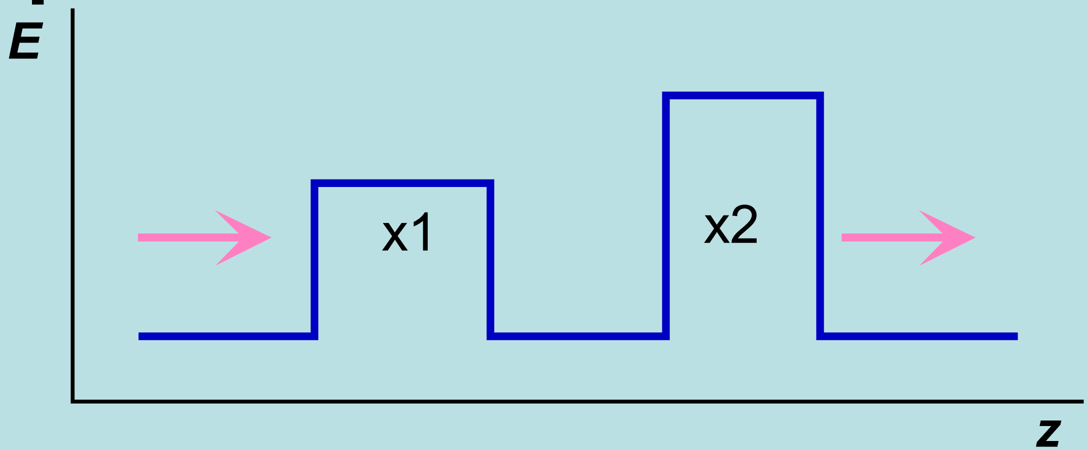
(Received 25 May 2001; accepted for publication 2 August 2001)

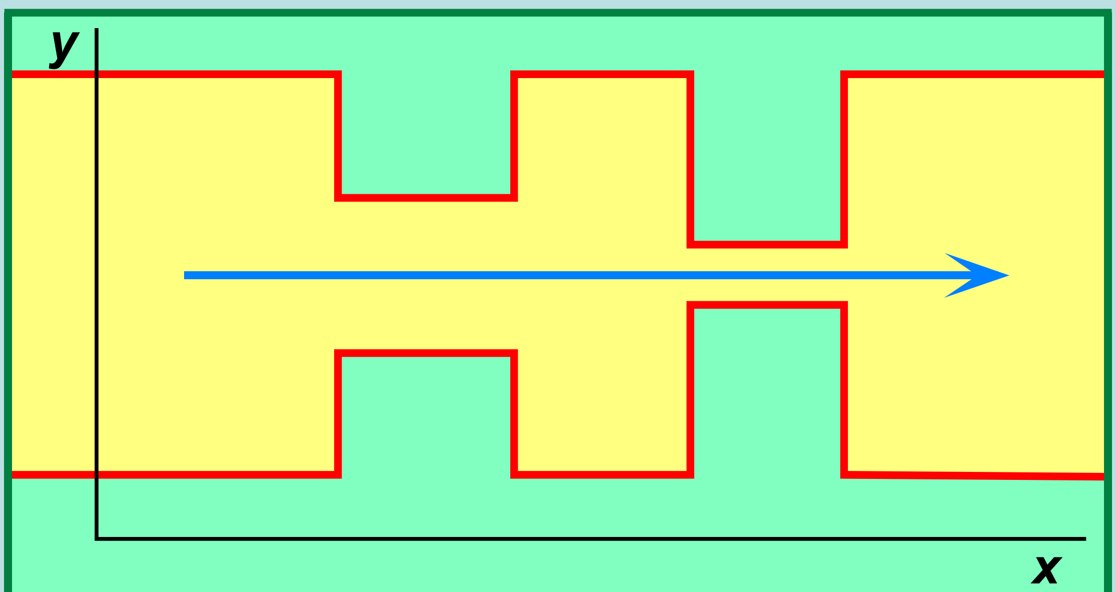




Analogy between electronic transport in semiconductor heterostructures and quantum wires with variable cross-section



Quantum Wells and Quantum Barriers on Heterostructure Potential ($GaAs/Al_xGa_{1-x}As$) – ***Energy Space***



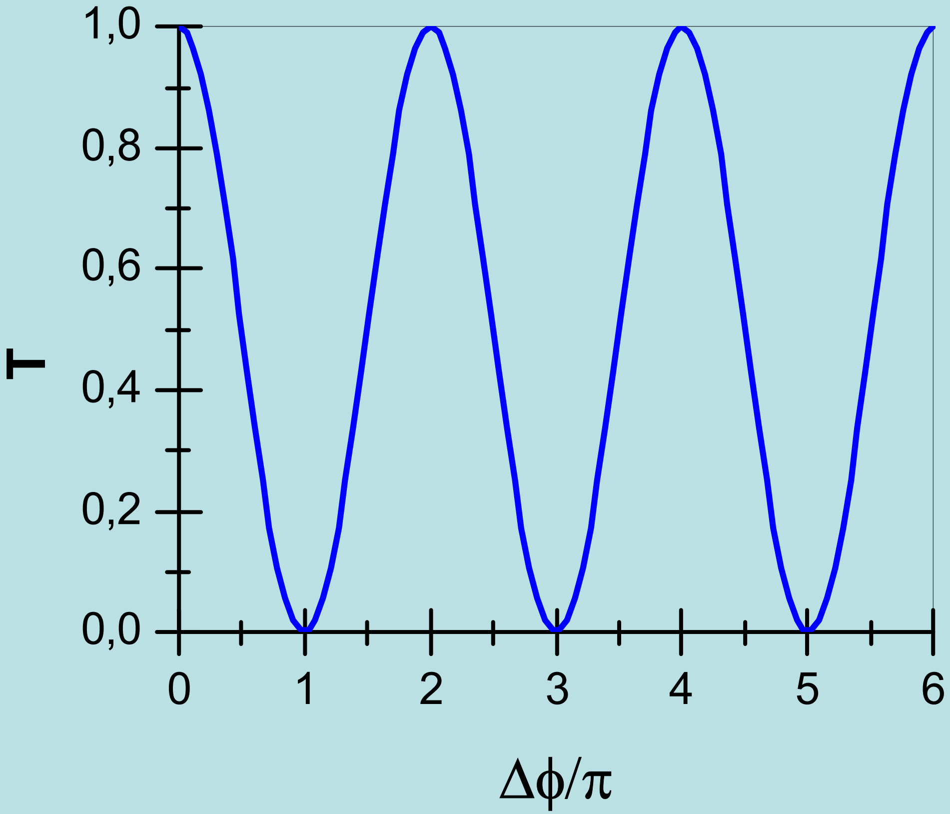
Electronic Waveguide – ***Real Space***

Gated 2D electron gas

Four basic resonances

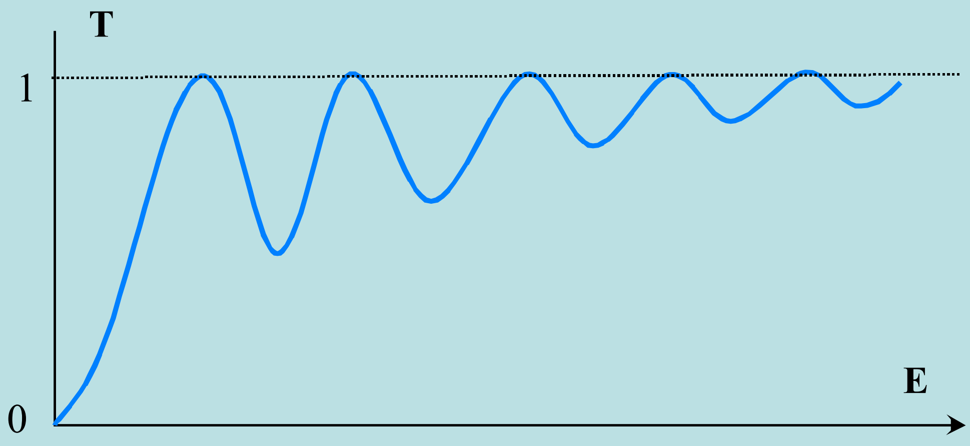
- Resonant tunneling resonance
- Over-barrier (Ramsauer-Townsend-like) resonance
- Fano resonance
- Aharonov-Bohm resonance

Aharonov-Bohm interference



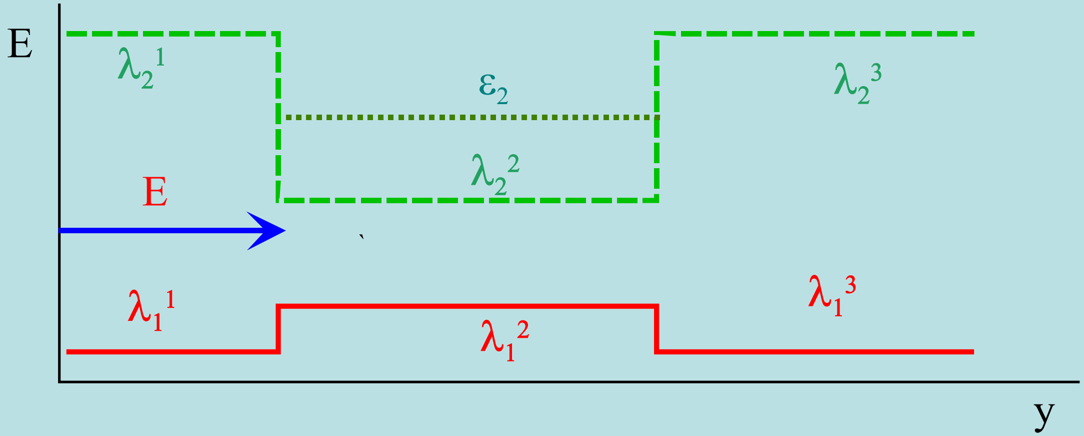
$$\Delta\phi = k_2 L_2 - k_1 L_1$$

Over-barrier resonances (Ramsauer-Townsend-like resonances)

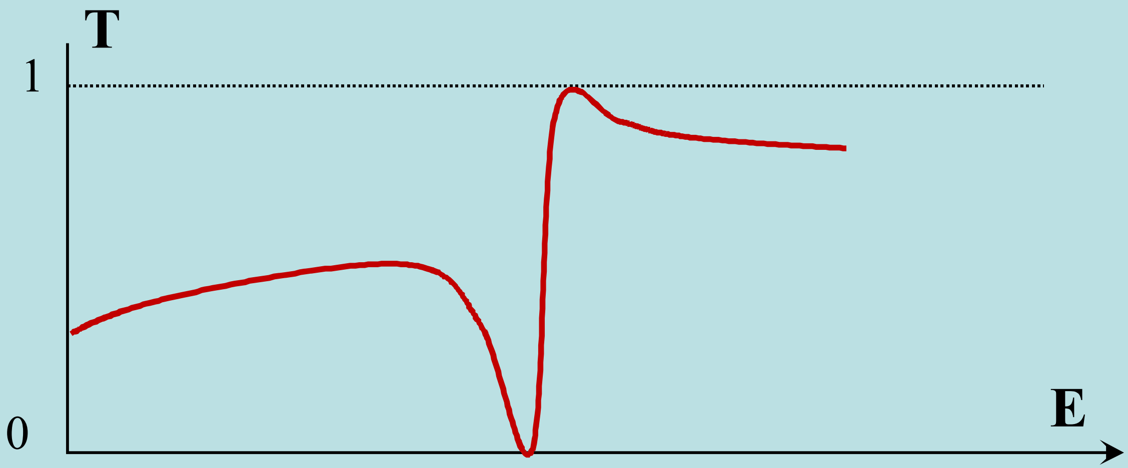


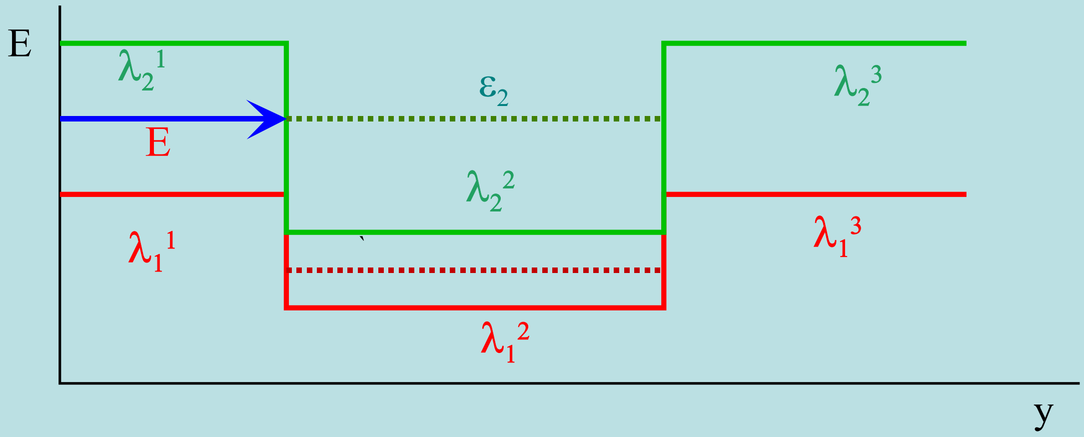
$T = 1$ for $\kappa_n^{(2)} d = n\pi$

where $\kappa_n^{(2)} = \sqrt{\frac{2m}{\hbar^2}\left(E - \lambda_n^2\right)}$

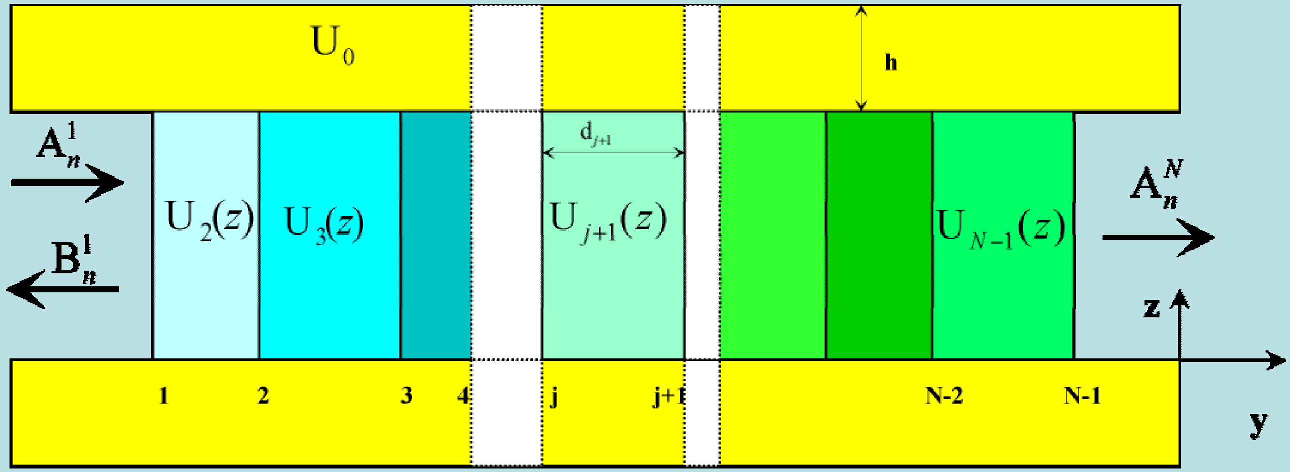


Fano resonance





Solution of a scattering problem for a two-dimensional Schrodinger equation by expansion on waveguide modes



$$\frac{\partial^2\psi(y,z)}{\partial y^2}+\frac{\partial^2\psi(y,z)}{\partial z^2}+\frac{2m}{\hbar^2}(E-U(y,z))\psi(y,z)=0$$

$$\psi_j(y,z)=\sum_n\{A_n^j\exp[i\kappa_n^j(y-y_j)]+\{B_n^j\exp[-i\kappa_n^j(y-y_j)]\}Z_n^j(z)$$

$\kappa_n^j=\sqrt{\frac{2m}{\hbar^2}\left(E-\lambda_n^j\right)}$, λ_n^j - eigenvalues of the one-dimensional Schrodinger equations with a potential $U_j(z)$, $Z_n(z)$ a - corresponding wave functions.

From a continuity condition at $y = y_j$ for ψ and $\partial\psi / \partial y$ we obtain relations

$$A_n^{j+1} = \frac{1}{2}\sum_m \left\{ (1+\frac{\kappa_m^j}{\kappa_n^{j+1}})\mu_{mn}\exp\{i\kappa_m^j d_j\}A_m^j + (1-\frac{\kappa_m^j}{\kappa_n^{j+1}})\mu_{mn}\exp\{-i\kappa_m^j d_j\}B_m^j \right\}$$

$$B_n^{j+1} = \frac{1}{2}\sum_m \left\{ (1-\frac{\kappa_m^j}{\kappa_n^{j+1}})\mu_{mn}\exp\{i\kappa_m^j d_j\}A_m^j + (1+\frac{\kappa_m^j}{\kappa_n^{j+1}})\mu_{mn}\exp\{-i\kappa_m^j d_j\}B_m^j \right\}$$

$$\mu_{mn} = \int Z_m^j(z) Z_n^{j+1}(z)dz$$

In the matrix form

$$\begin{pmatrix} A \\ B \end{pmatrix}^{j+1} = D_j \begin{pmatrix} A \\ B \end{pmatrix}^{j}$$

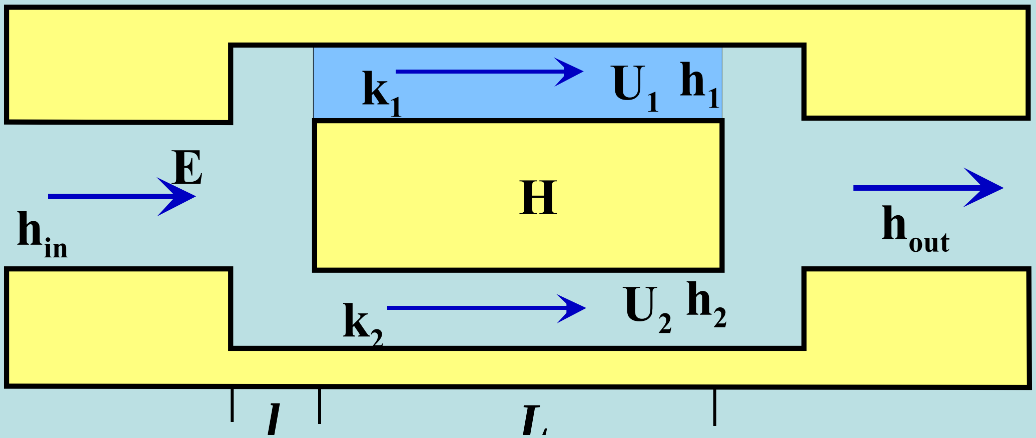
Denoting $A^1 \equiv A;\ B^1 \equiv r;\ A^N \equiv t$ **and sequentially applying, we obtain**

$$\begin{pmatrix} t \\ 0 \end{pmatrix} = D \begin{pmatrix} A \\ r \end{pmatrix}$$

The transfer matrix of the structure

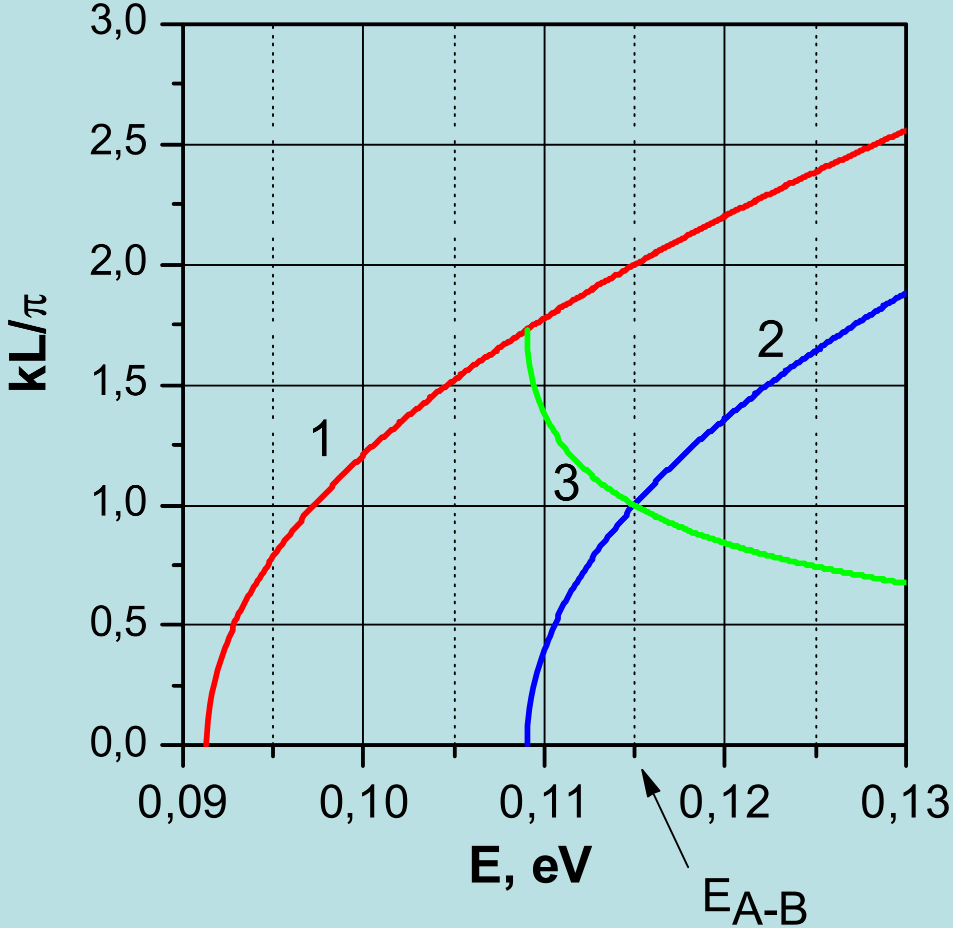
$$D = D_{N-1}D_{N-2}\cdots D_2 D_1$$

Geometry of Aharonov-Bohm interferometer



Step-like transition region

Optimal Channel Length



at $k_2 L_2 = \pi \quad k_1 L_1 = 2\pi$

Over-barrier resonance in each channel and total minimum due to A-B interference

$h_1 = h_2 = 50$ A, L = 309 A

$E_{A\text{-}B} = 0.115$ eV

ΔU=0.02 eV

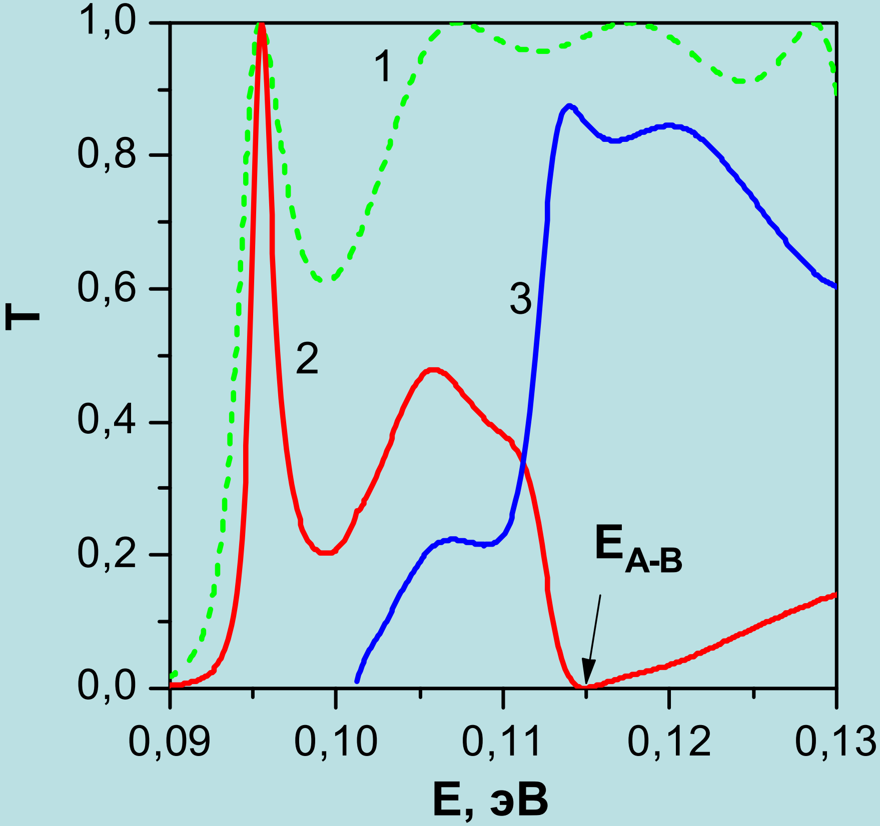
Phase change in channels 1 and 2 and interchannel phase difference (3)

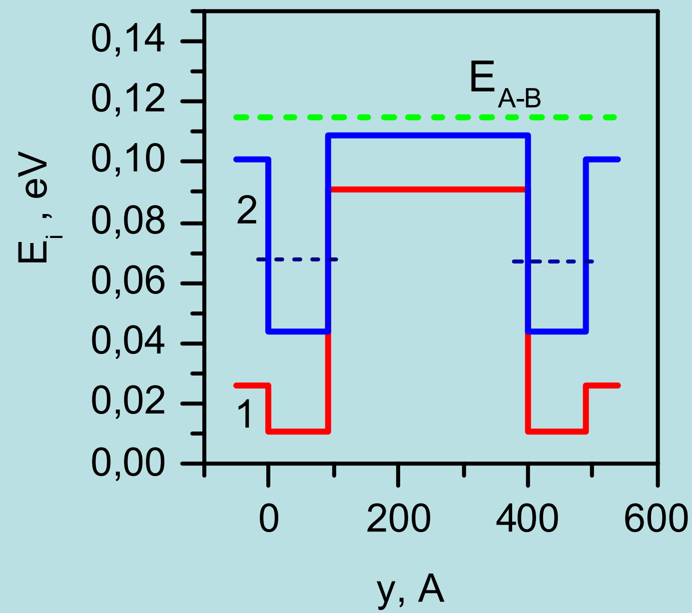
Choice of incoming wave-guide widths

$h_{in} = h_{out} = 120$ Å

Absence of Fano resonance $E_L^2 > E_{in}^2$

But $E_L^2 < E_{A-B}$

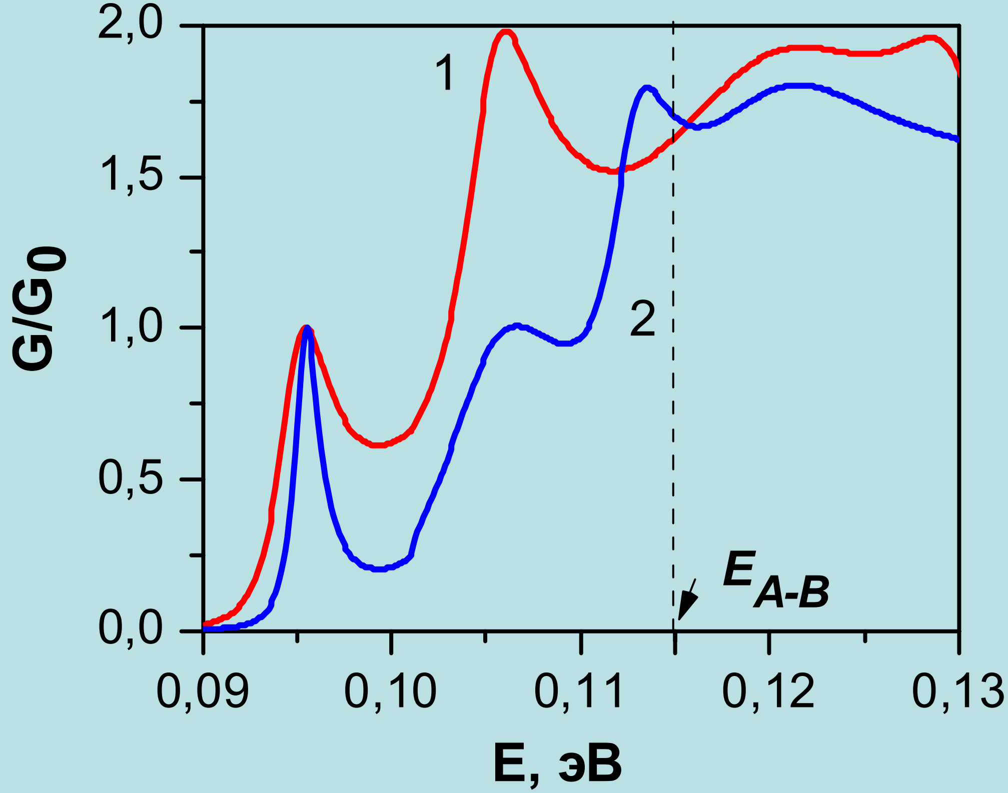




1-st mode transmission at ΔU=0 (1)
1-st (2) and 2-nd (3) modes transmission at ΔU=0.02 eV

Transverse(z) quantization energy position along the direction of the wave-guide (y)

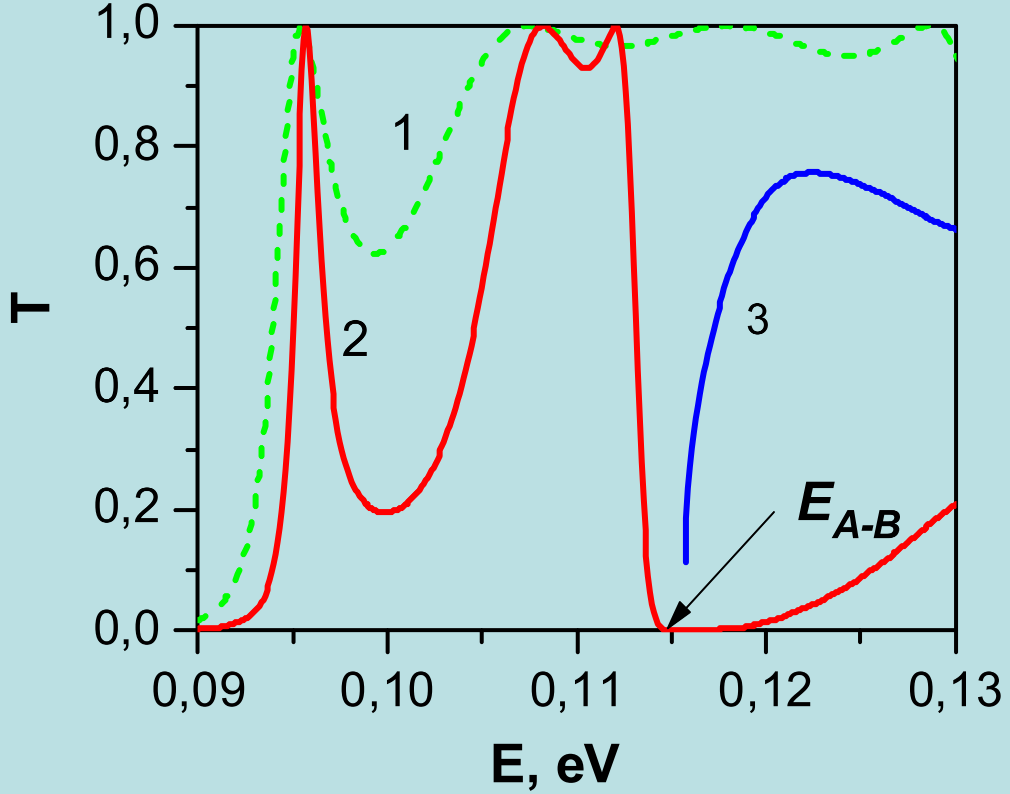
Conductance



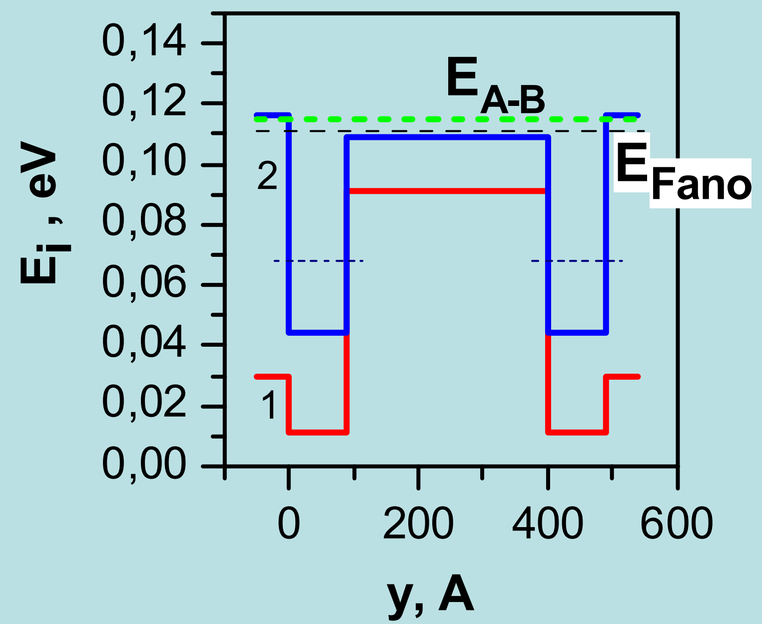
Conductance dependence on Fermi energy for h_{in}= 120 A

1 - ΔU=0 , 2 - ΔU=0.02 eV

Transmittance for h_{in}=110 A

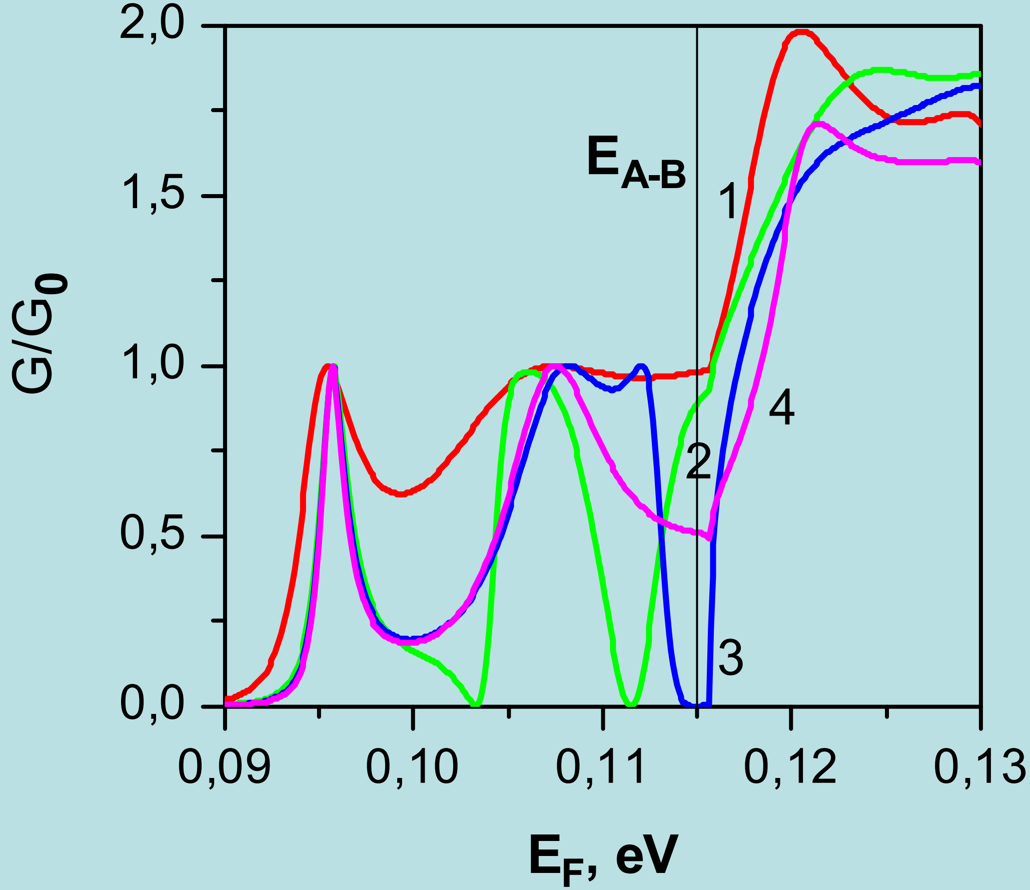


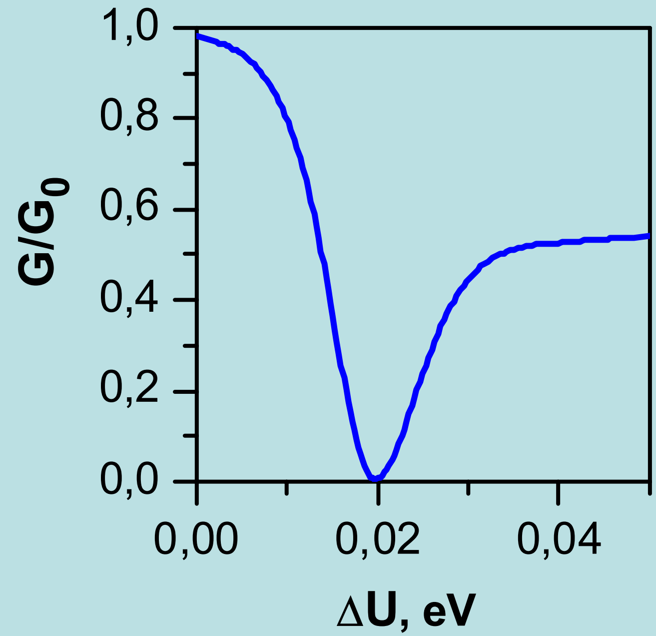
Transmission in 1[st] mode for ΔU=0 (1) and in 1st (2) and 2nd (3) modes for ΔU=0.02 eV



Quantization energy profile along the direction of the wave-guide (y)

Variation of conductance with changing of ΔU for h_{in}=110 A





G(ΔU) curve at E_F = 0.115 eV

1 ΔU (meV): 1 – 0; 2 – 10; 3 – 20; 4 -50

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Quantum Logic Gates based on Coherent Electron Transport in Quantum Wires

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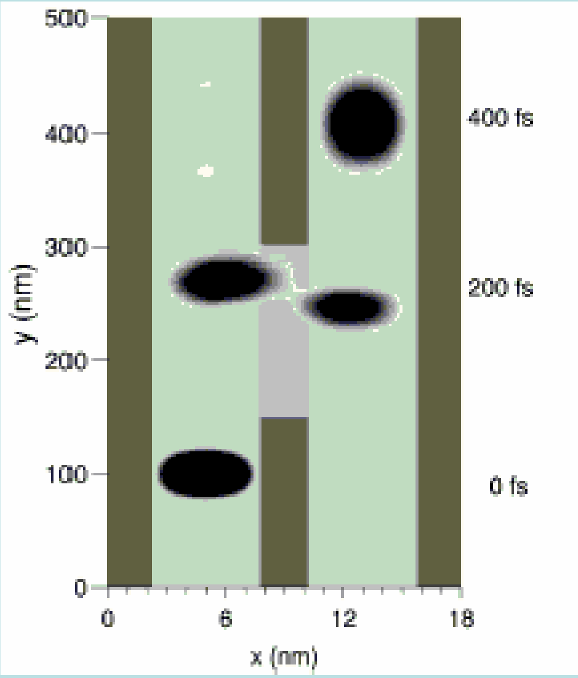
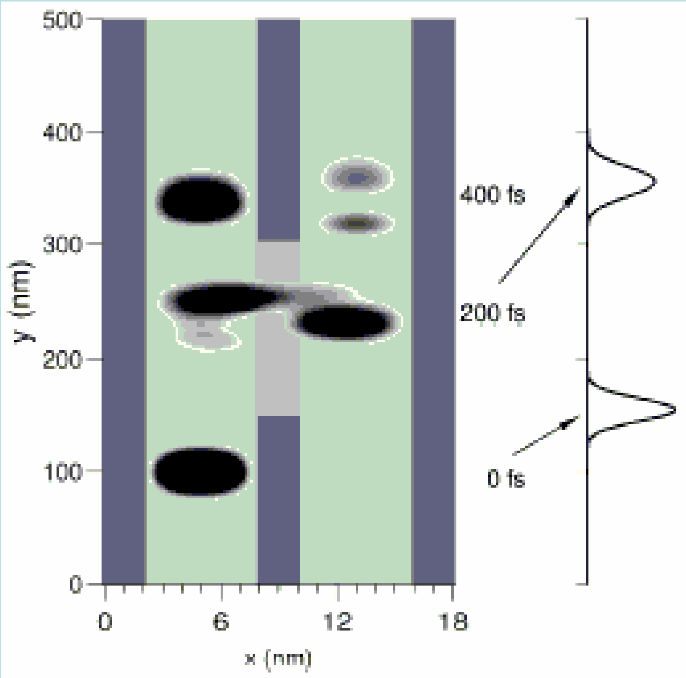
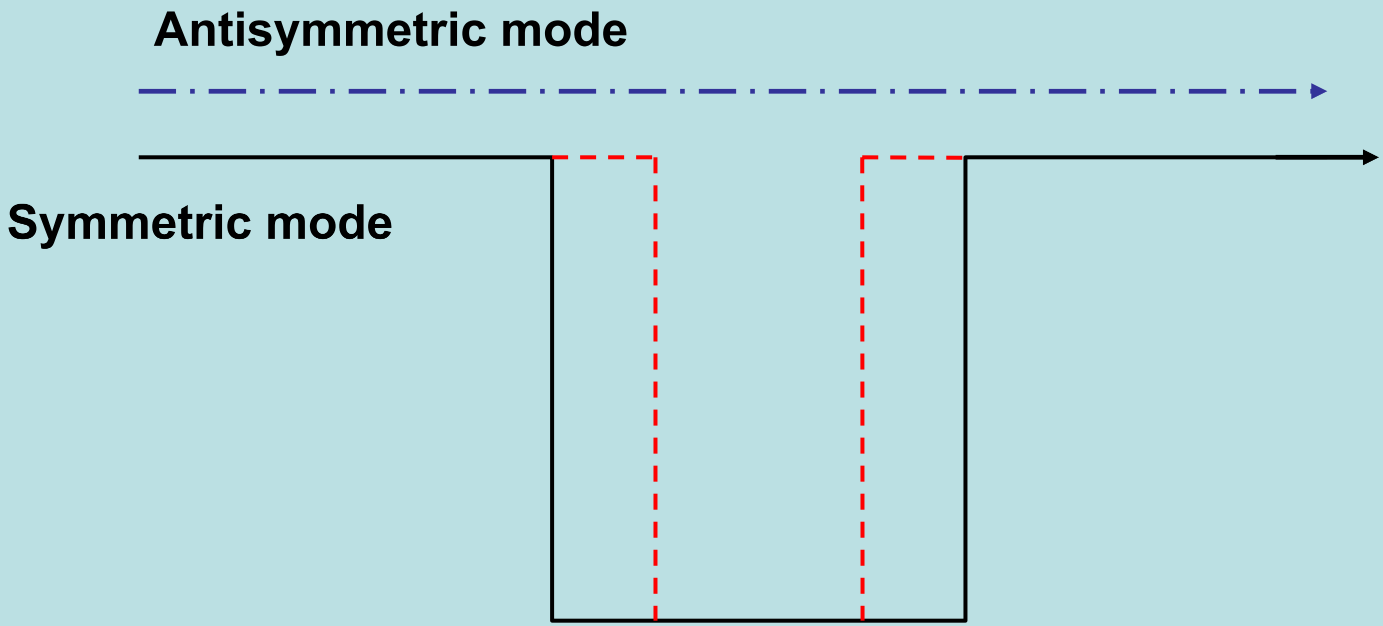




The role of a window in a waveguide barrier

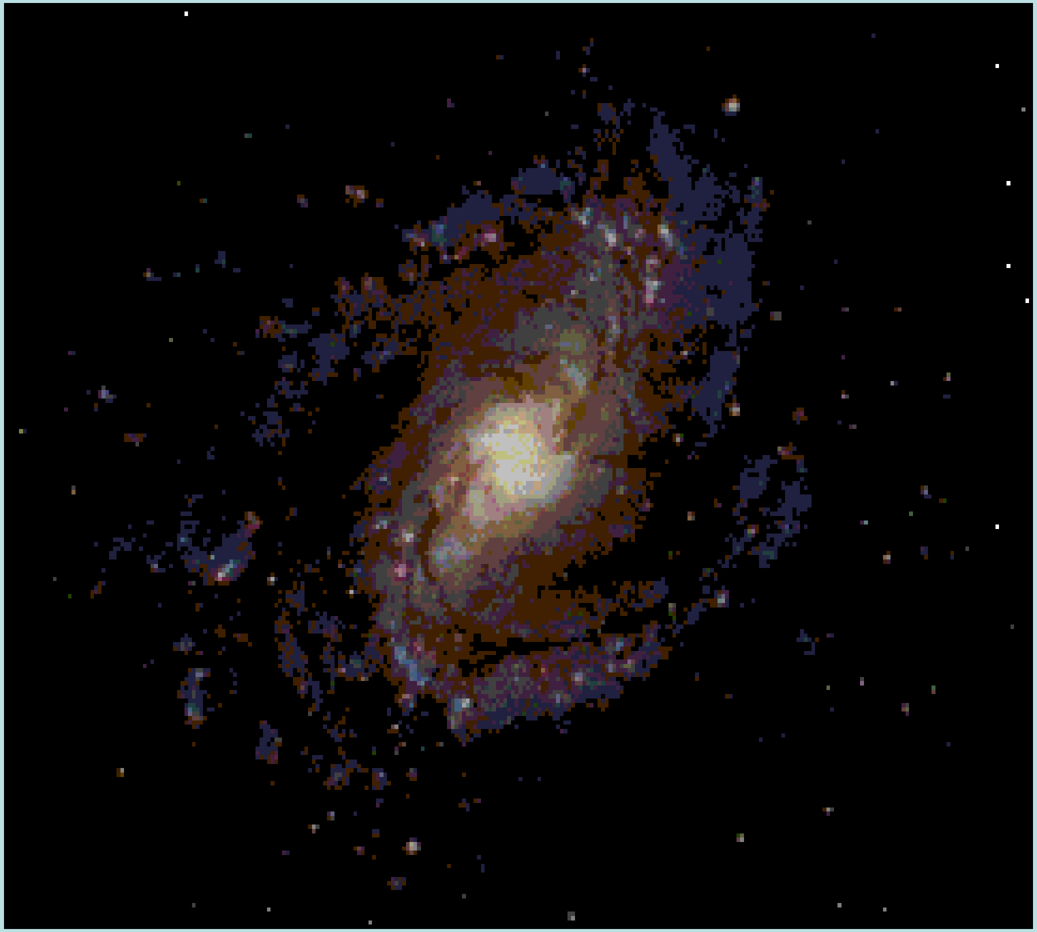


Fundamental problems of physics in low dimensions

The fractional quantum Hall effect …is important …primarily for one:…particles carrying an exact fraction of the electron charge *e* and …gauge forces between these particles, two central postulates of the standard model of elementary particles, can arise spontaneously as emergent phenomena….idea whether the properties of the universe …are fundamental or emergent…I believe…must give string theorists pause…

R.B.Laughlin "Nobel Lecture: Fractional quantization" Rev. Mod. Phys. v. 71, p. 863 (1999)

Dark matter

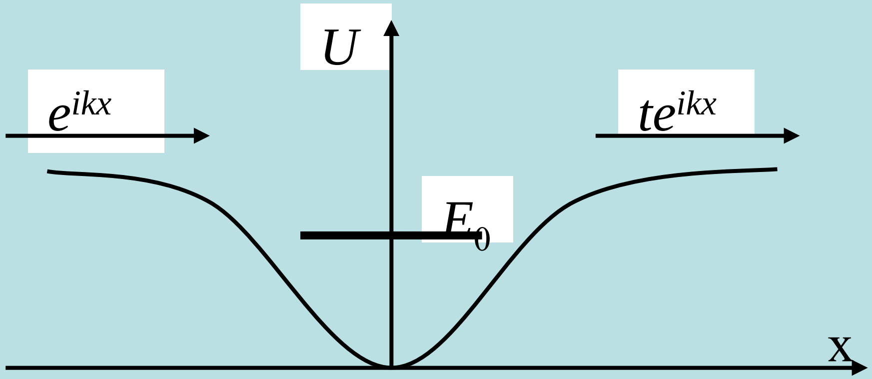


At present it is established that from 88% to 95% of matter in the Universe are of unknown origin

(neutrino mass, new particles etc.?)

Can objects exist in crystal which are invisible?

Reflectionless quantum mechanical potentials



$$U(x) = -U_0 ch^{-2}\alpha x$$

$$1 + (8mU/\hbar^2\alpha^2) = (2n+1)^2$$

$$r \equiv 0, \quad t = e^{i\varphi(k)}$$

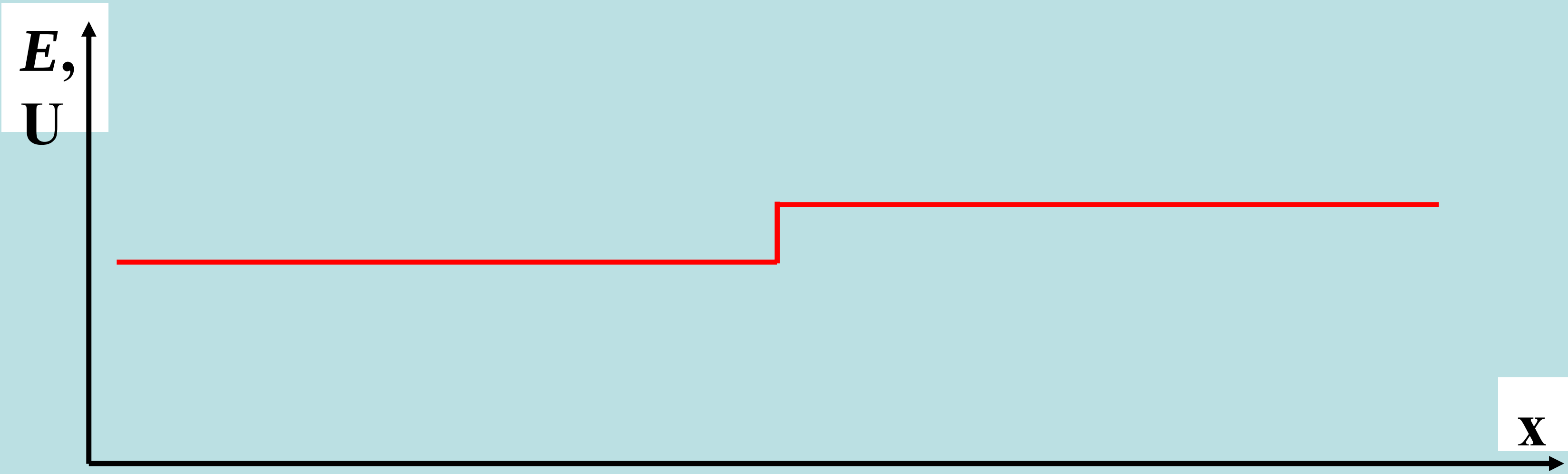
$$E(k) = \frac{\hbar^2 k^2}{2m}, \qquad E_0 = -\frac{\hbar^2 æ^2}{2m}$$

$$\varphi = 2arctg\,\frac{æ}{k}$$

There exist *hidden microscopic objects* in crystals – extended objects which are “invisible” in respect to low-energy electron energy (r≡0 и t≡1 in continuum limit)

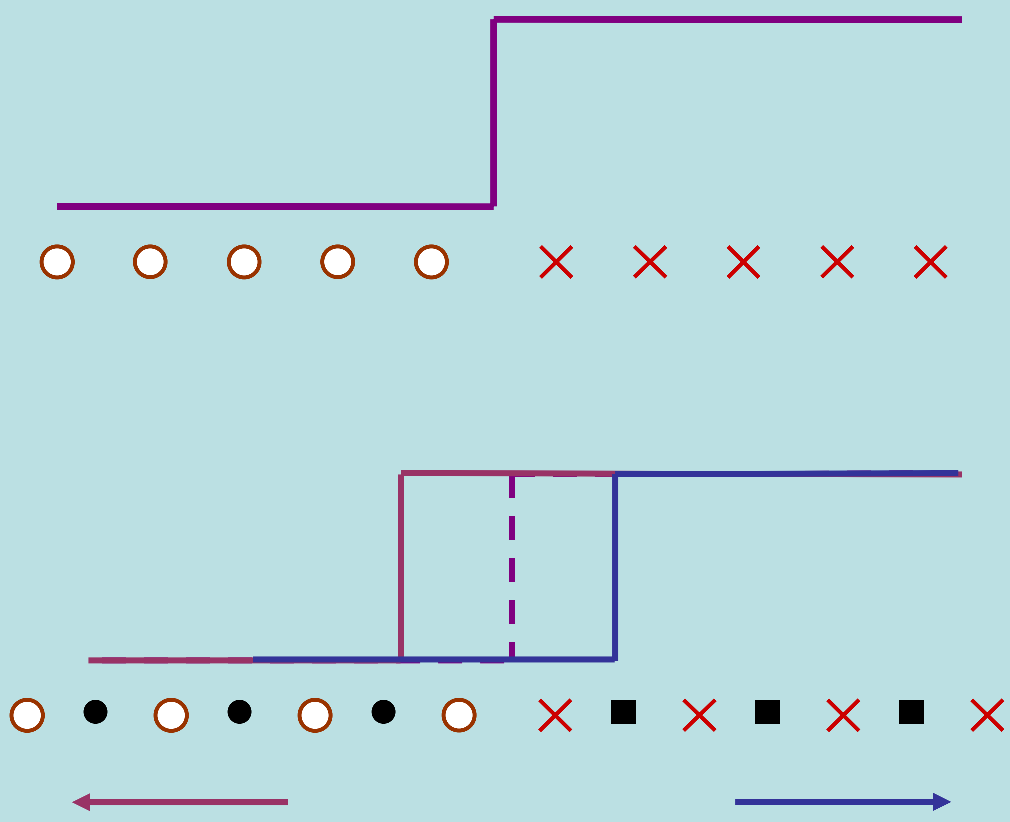
A.A.Gorbatsevich “Hidden Defect Pairs: Objects invisible in low energy electron scattering” e-print cond-mat/0511054 (2005)

Envelope Function (or Effective Mass) Method

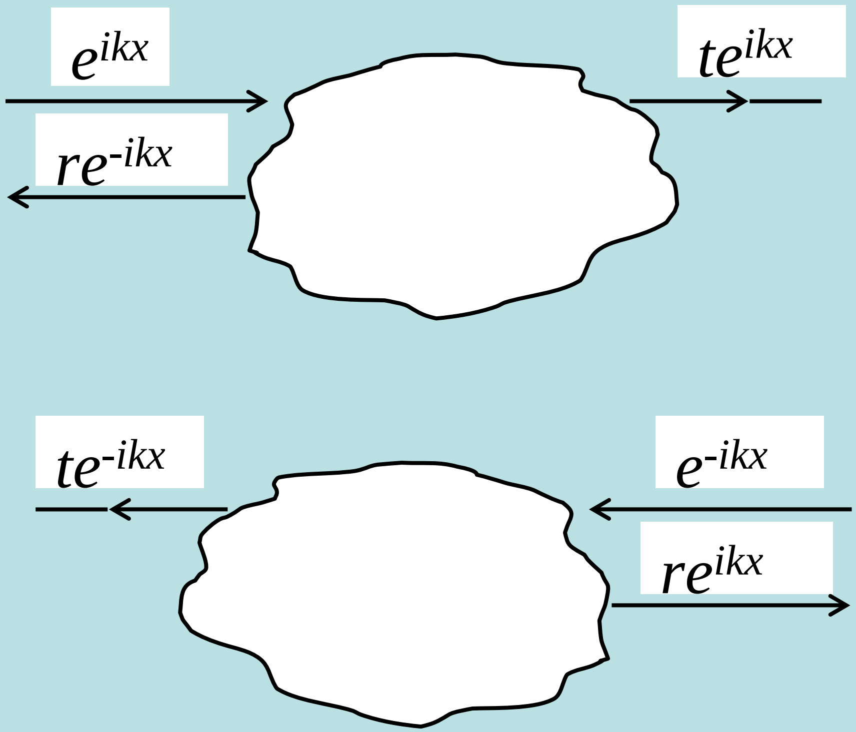


$$\left[-\frac{\hbar^2\nabla^2}{2m^*}+U(r)\right]\psi(\vec{r})=E\psi(\vec{r})$$

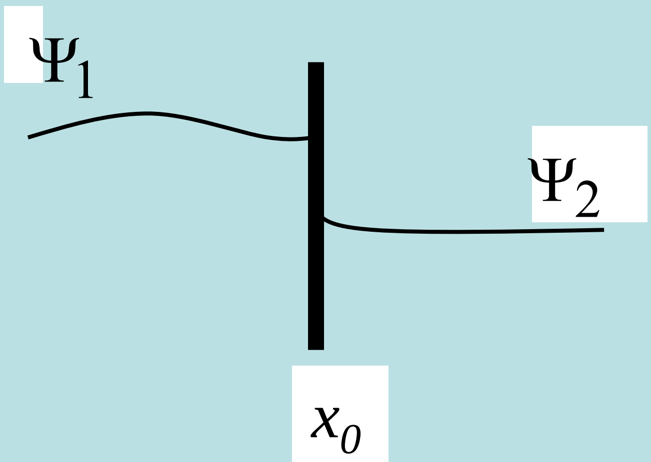
Location of heterointerface can be determined exactly!



Scattering data



Generalized Boundary Conditions



$$\begin{pmatrix} \Psi \\ \nabla\Psi \end{pmatrix}_{x_{0\,+}} = \hat{T}\begin{pmatrix} \Psi \\ \nabla\Psi \end{pmatrix}_{x_{0\,-}} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}\begin{pmatrix} \Psi \\ \nabla\Psi \end{pmatrix}_{x_{0\,-}}$$

Extraction procedure

$$\psi = \begin{cases} e^{ik_1(x-\delta_1)} + re^{-ik_1(x-\delta_1)}, x < x_{0.} \\ te^{-ik_2(x-\delta_2)}, x > x_{0.} \end{cases}$$

$$r = e^{2ik_1(x_0-\delta_1)} \frac{k_1T_{22} - k_2T_{11} - iT_{21} - ik_1k_2T_{12}}{k_1T_{22} + k_2T_{11} + iT_{21} - ik_1k_2T_{12}}$$

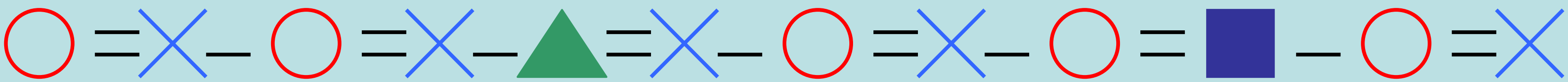
$$t = e^{i[k_1(x_0-\delta_1)-k_2(x_0-\delta_2)]}\sqrt{\frac{m_2}{m_1}} \frac{2k_1}{k_1T_{22} + k_2T_{11} + iT_{21} - ik_1k_2T_{12}}$$

$$r \approx e^{2ik_1Na}\left[1-2\frac{k_2}{k_1}T_{11}^2-4ik_2T_{11}^2\left(\Delta x_0-\delta_1\right)+\ldots\right],$$

$$r' \approx -e^{-2ik_2Na}\left[1-2\frac{k_2}{k_1}T_{11}^2-2ik_2\left(\Delta x_0-\delta_2-T_{12}T_{11}\right)+\ldots\right],$$

$$t^{-1} \approx \frac{1}{2}e^{i\left(k_2-k_1\right)Na}\sqrt{\frac{m_1}{m_2}}T_{22}\left[1+{k_2}/{k_1}\,T_{11}^2-ik_2[(T_{11}T_{12}+T_{11}^2\left(\Delta x_0-\delta_1\right)-\Delta x_0+\delta_2]+\ldots\right]$$

Model



$$\vec{r} \nrightarrow -\vec{r}$$

$$\hat{H} = \sum_{j=1,2 \quad n_1, n_2} \left[\varepsilon_j C^{+}_{j \; n_j} C_{j \; n_j} - C^{+}_{1 \; n_1} \left(t_{+} C_{2 \; n_1+1} + \right.\right.$$

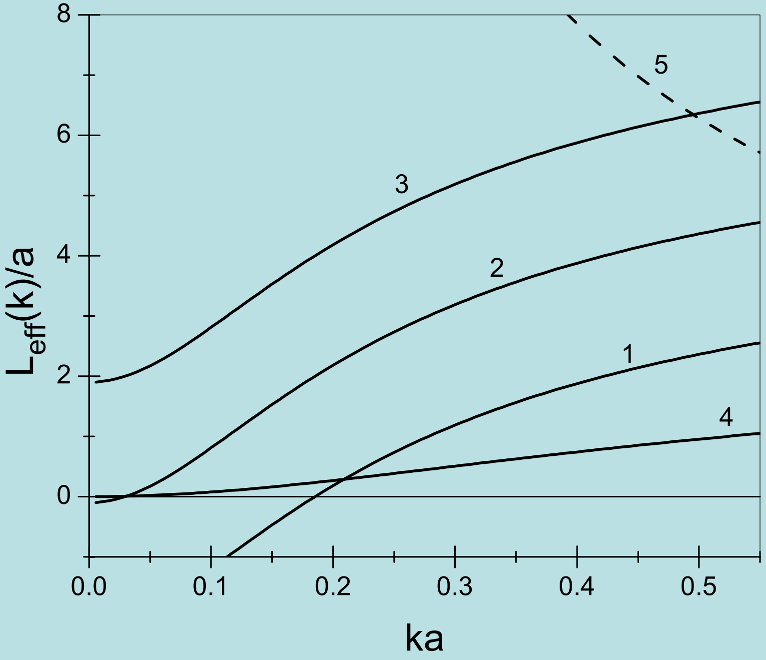
$$\left.\left. + t_{\_} C_{2 \; n_1-1} \right) + \varepsilon^{*}_{j} C^{+}_{M_j} C_{M_j} + h.c. \right]$$

Scattering data in the model

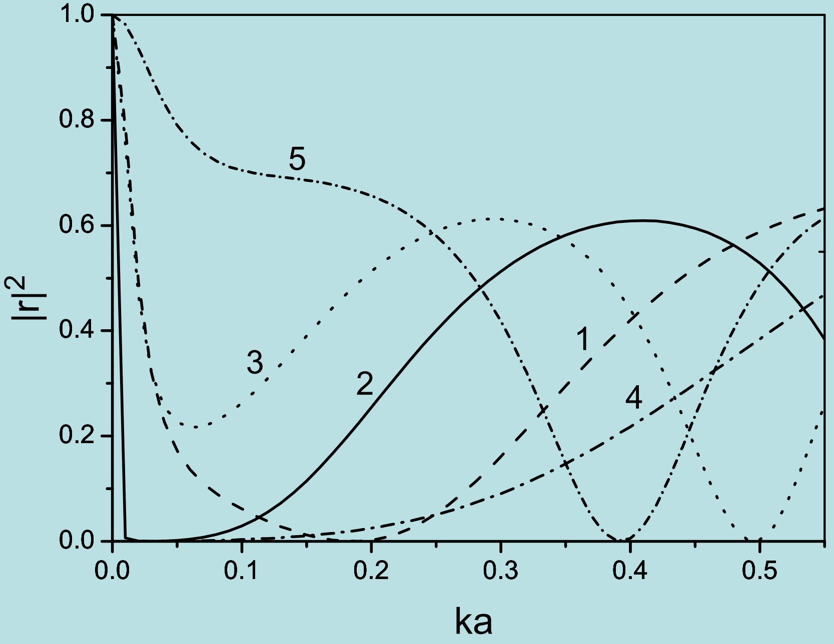
$$r = -e^{2ikM_1 - 2i\varsigma_a} \frac{\left(\Delta_1\Delta_2 u_k v_k + i\Delta_{k-} U_k\right)\sin\left[L_{eff}(k)k\right]}{\Delta_1\Delta_2 u_k v_k \sin\left[L_{eff}(k)k\right] - \left(\Delta_{k+} + 2iu_k v_k U_k\right)U_k e^{-iL_{eff}(k)k}}$$

$$t = -e^{-iLeff(k)k} \frac{2iu_k v_k U_k^2}{\Delta_1\Delta_2 u_k v_k \sin\left[L_{eff}(k)k\right] - \left(\Delta_{k+} + 2iu_k v_k U_k\right)U_k e^{-iL_{eff}(k)k}}$$

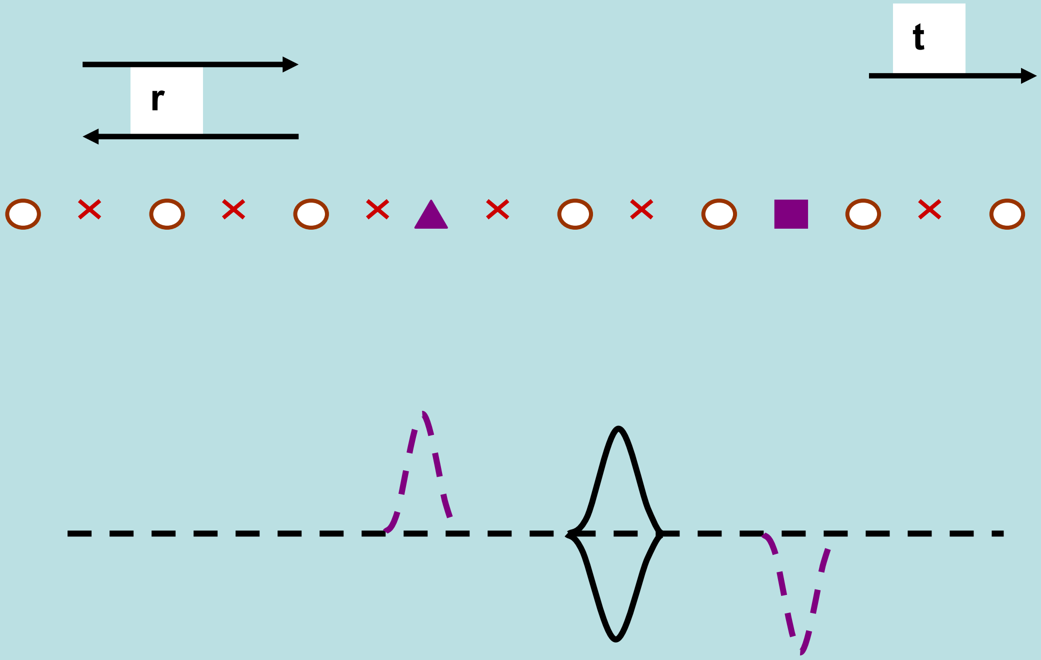
Dependence of effective interdefect distance on wave-vector



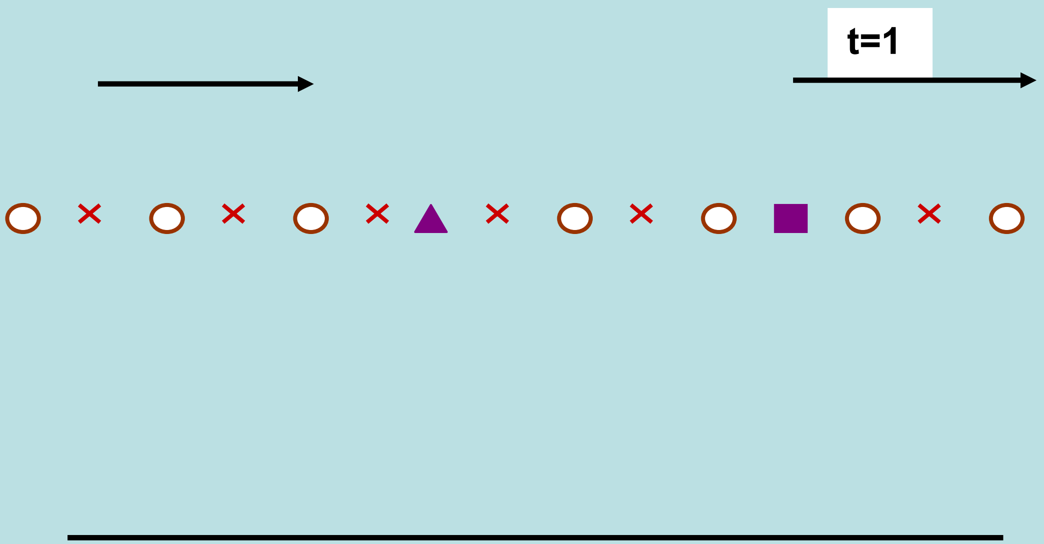
Dependence of reflection coefficient on wave-vector



Hidden Defect Pair



In continuum limit – homogeneous structure



Other examples of “dark matter” objects in systems without inversion center:

- **HDP in the models with continuum potentials (generalized Kronig-Penney model, pseudopotentials)**
- **Quantum well with defects located at the heterointerfaces**

There’s is Plenty of Room at the Bottom.

R.Feinman, 1959

Nanotechnology – a lot of applications and economics, science and new knowledge, and some room for…game!