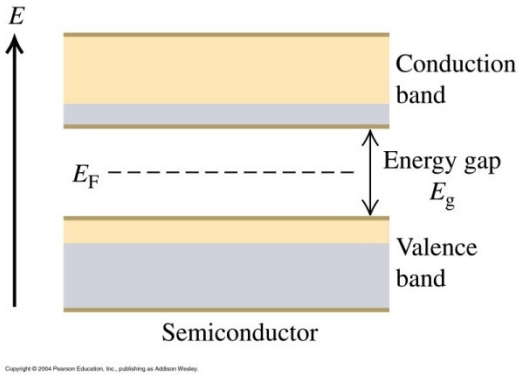
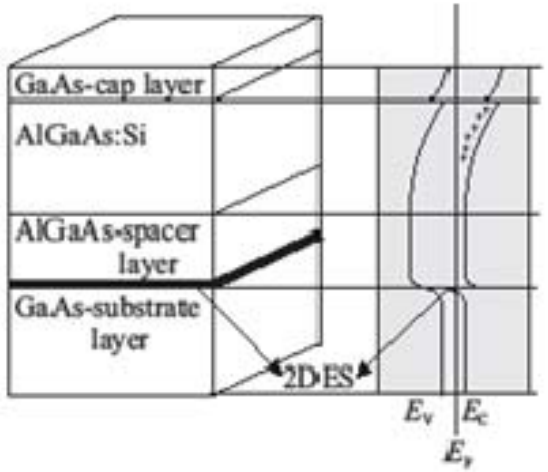
COULOMB EFFECTS IN ULTRA-SMALL ELECTRONIC DEVICES

ANDREI MANOLESCU, ASSOCIATE PROFESSOR
SCOOL OF SCIENCE AND ENGINEERING | RU LECTURE MARATHON

Nanoelectronic devices





GaAs/AlGaAs heterostructure

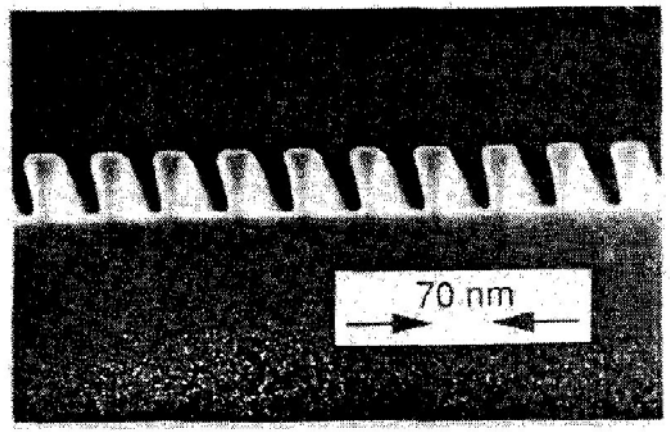
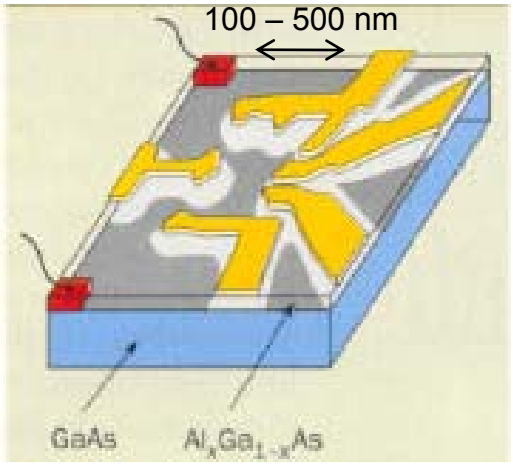


Fig. 2. Cross-sectional view of the reverse-mesa etched QWWs taken by a high resolution SEM.

Quantum wires



Quantum dots

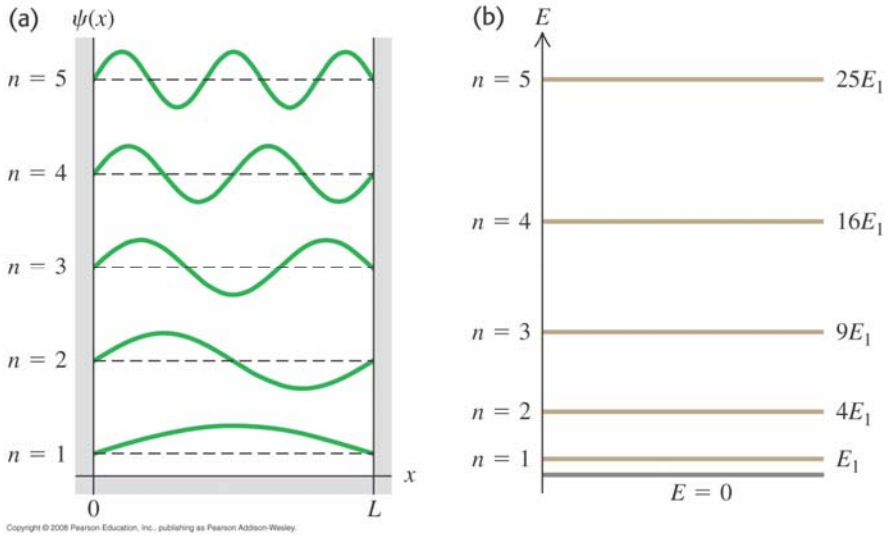
Quantum mechanics

Wave functions: $\Psi(\vec{r},t)$

Schrödinger equation: $i\hbar\dfrac{\partial}{\partial t}\Psi(\vec{r},t)=H(t)\Psi(\vec{r},t)$

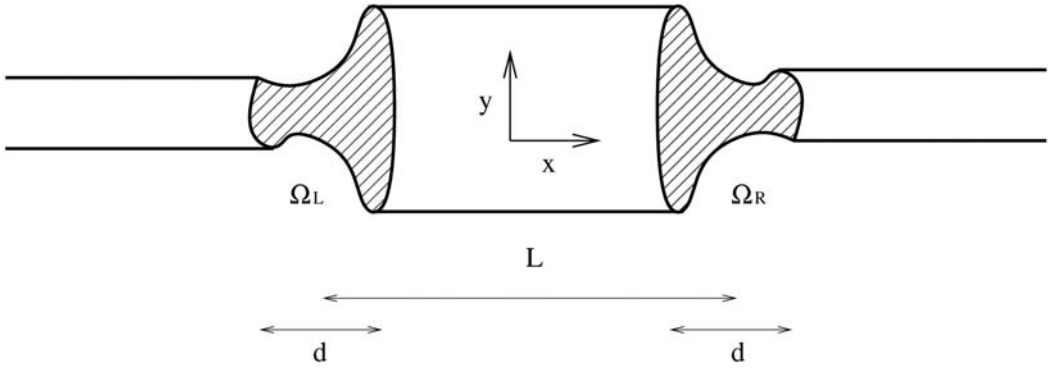
Hamiltonian (energy) operator: $H(t)=-\dfrac{\hbar^2}{2m}\Delta+U(\vec{r},t)$

Example: The quantum well



$$\psi_n(x)=\sqrt{\frac{2}{L}}\sin\frac{n\pi x}{L}\qquad (n=1,2,3,\ldots)$$

Open quantum dots in contact with leads



Unknown wave functions of the electrons in the sample

Statistical description: wave functions ψ_n with probabilities p_n

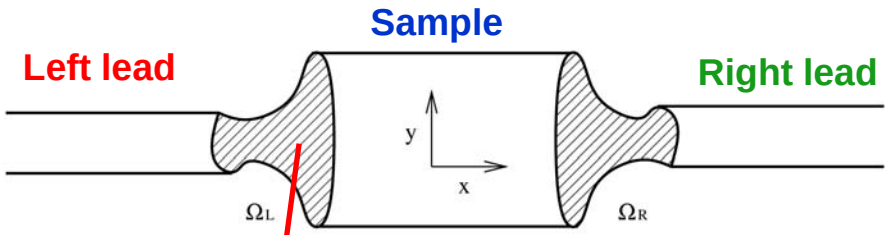
Statistical operator $\rho = \sum_n p_n \mid \psi_n >< \psi_n \mid$

Expected values of physical observables:

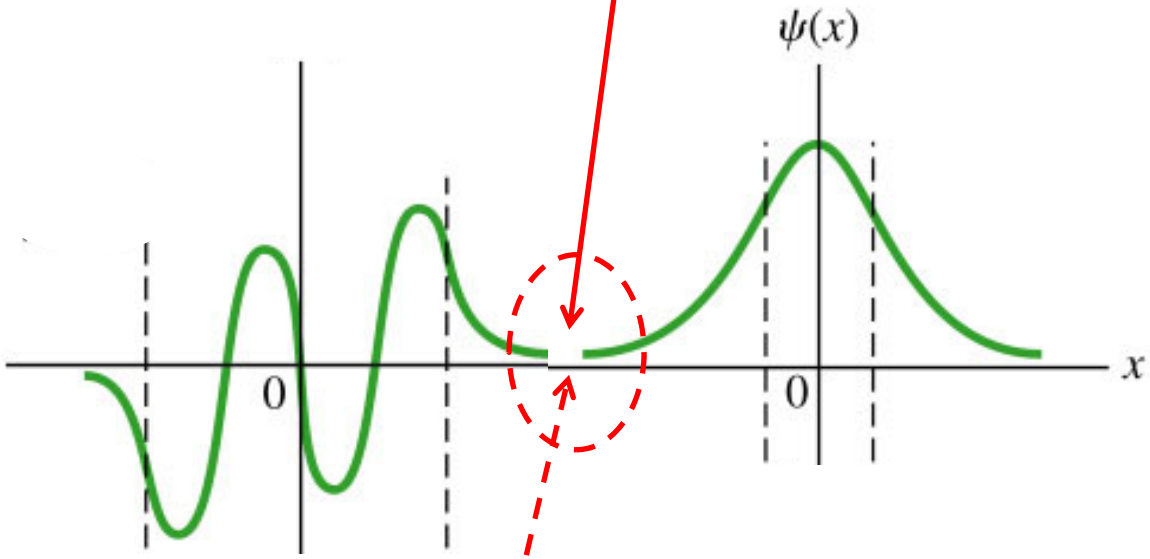
$$< A >_n = < \psi_n \left| A \right| \psi_n > \quad \rightarrow \quad < A > = \sum_n p_n < \psi_n \left| A \right| \psi_n >$$

$$\Rightarrow \quad < A > = Tr\left(A\rho \right) = \sum_n \left(A\rho \right)_{nn}$$

The leads-sample contacts

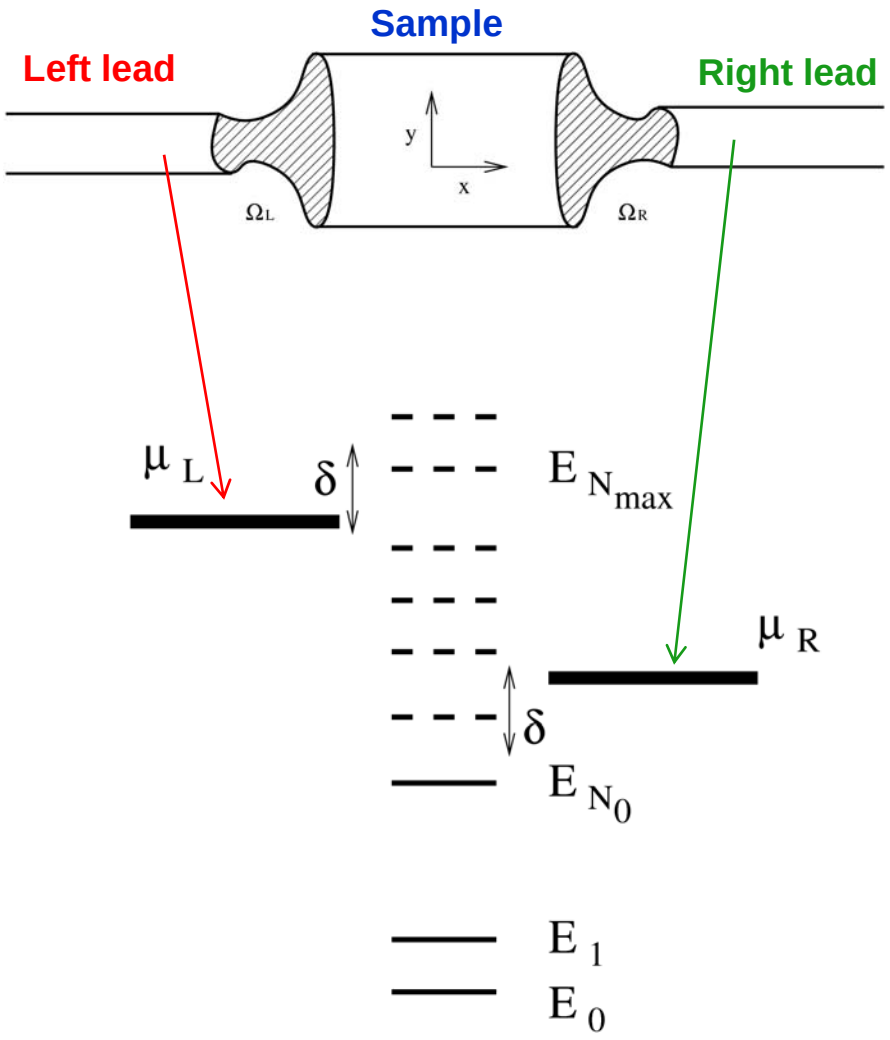


Overalp of wave functions



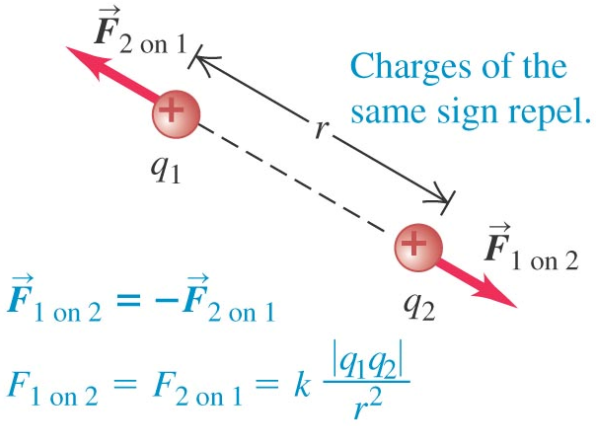
$$T_{qnl} \propto \int_{\Omega_l} d\vec{r} \int_{\Omega_l} d\vec{r}' \psi_{ql}^{*}(\vec{r}) g(\vec{r},\vec{r}') \varphi_n(\vec{r}') \quad \rightarrow \quad \text{Generic form}$$

The external field (bias)



$\mu_{L,R}$ chemical potentials

Coulomb interaction and many-body effects



$$N \text{ electrons in the sample } \Rightarrow H_{Sample} = \sum_n T_n + \frac{1}{2}\sum_{n\neq m}\frac{e^2}{\left|\vec{r}_n - \vec{r}_m\right|}$$

$$V_{nm,pq} = \int d\vec{r}d\vec{r}'\psi^*_n(\vec{r})\psi^*_m(\vec{r}')\frac{e^2}{\left|\vec{r}_n - \vec{r}_m\right|}\psi_p(\vec{r})\psi_q(\vec{r}')$$

The equation for the statistical operator (generalized master equation)

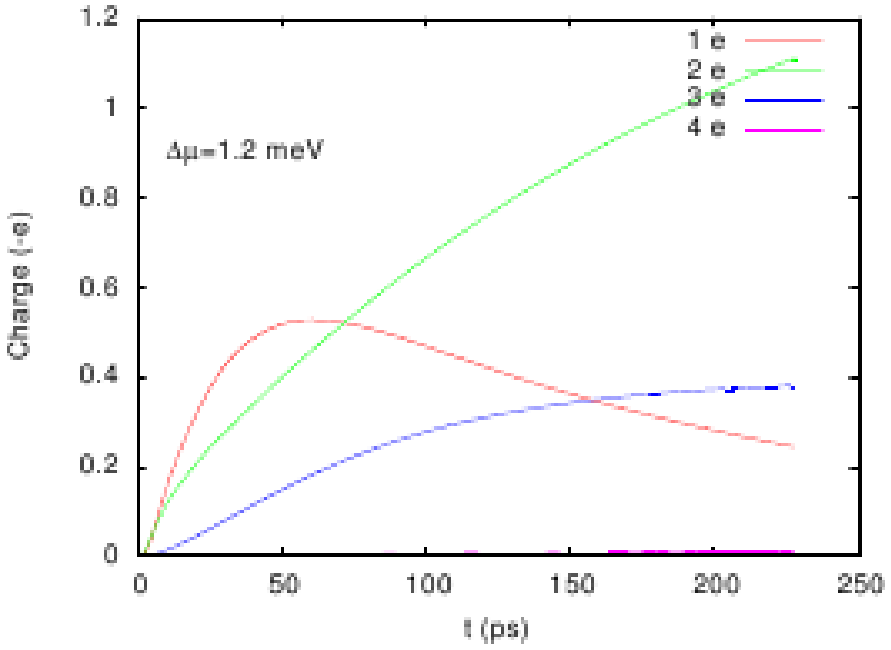
$$\dot{\rho}_S(t) = -\frac{i}{\hbar}\left[H_S, \rho_S\right] - \frac{1}{\hbar^2}\sum_l \int dq\, \chi_l(t)\left\{\left[T_{ql}, \Omega_{ql}(t)\right] + h.c.\right\}$$

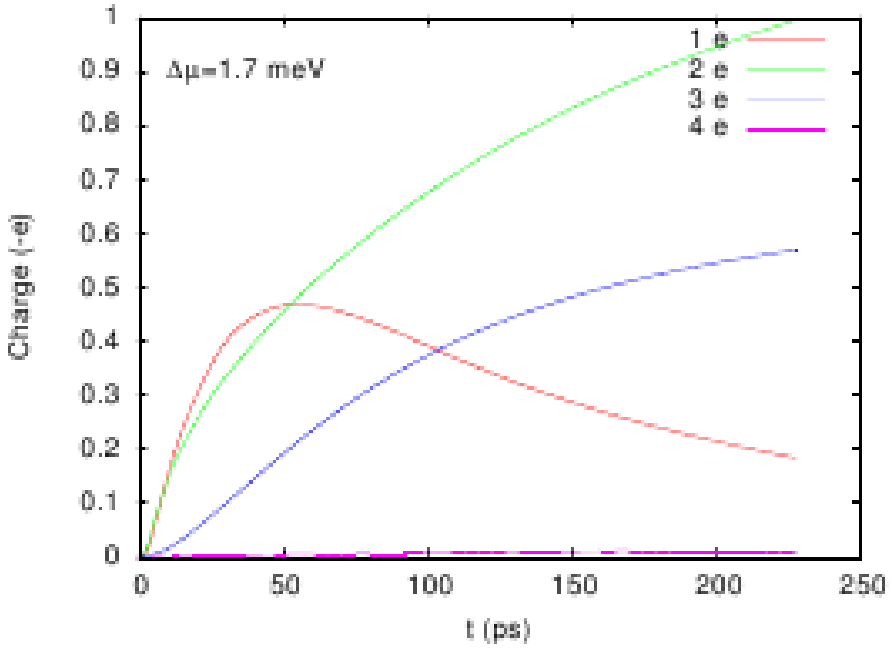
$$\Omega_{ql}(t) = e^{-itH_S/\hbar}\Pi_{ql}(t)e^{itH_S/\hbar}e^{-it\varepsilon_l(q)/\hbar}$$

$$\Pi_{ql}(t) = \int_0^t ds\, \chi_l(s)e^{itH_S/\hbar} \times$$

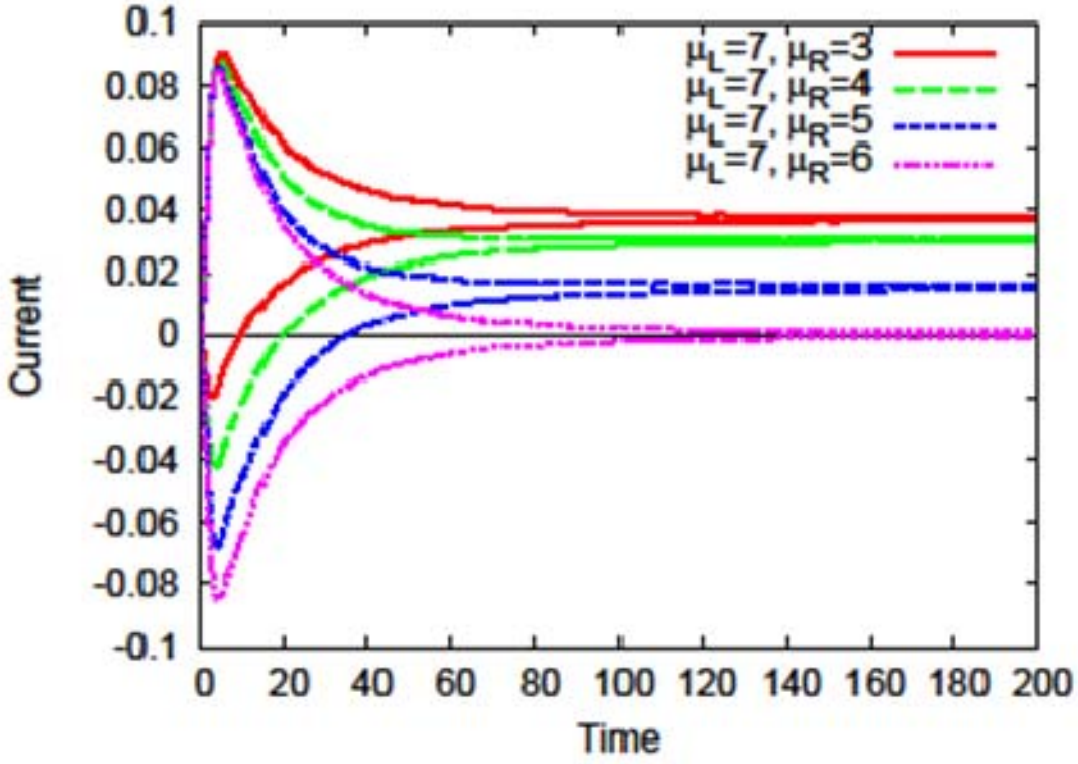
$$\times\left\{T_{ql}^{\dagger}\rho_S(s)\left[1 - f(\varepsilon_l(q)\right] - \rho_S(s)T_{ql}^{\dagger} f(\varepsilon_l(q)\right\}e^{-isH_S/\hbar}e^{is\varepsilon_l(q)/\hbar}$$

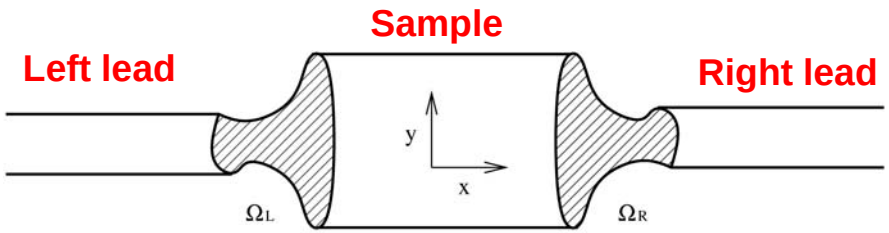
Charging of the sample



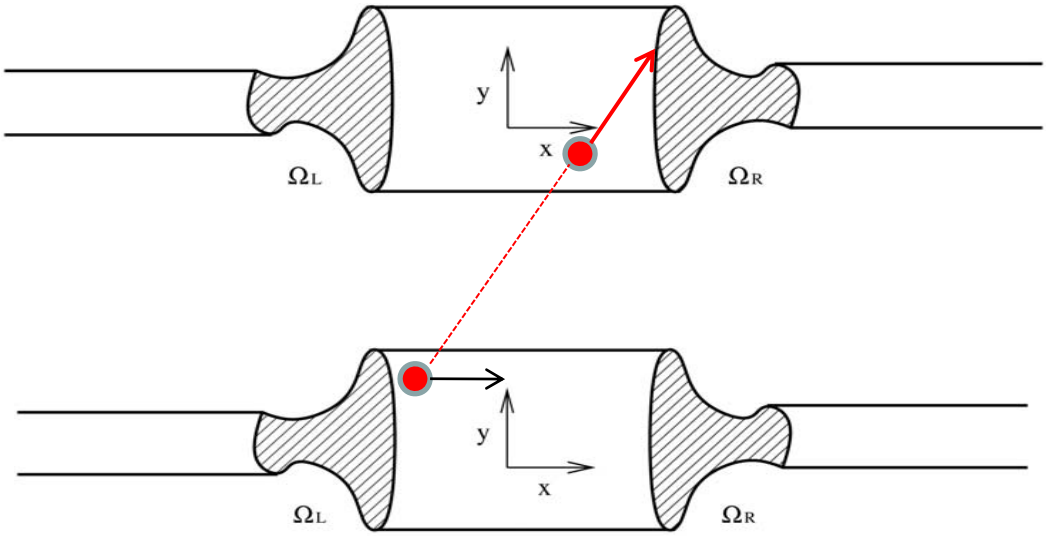


Currents

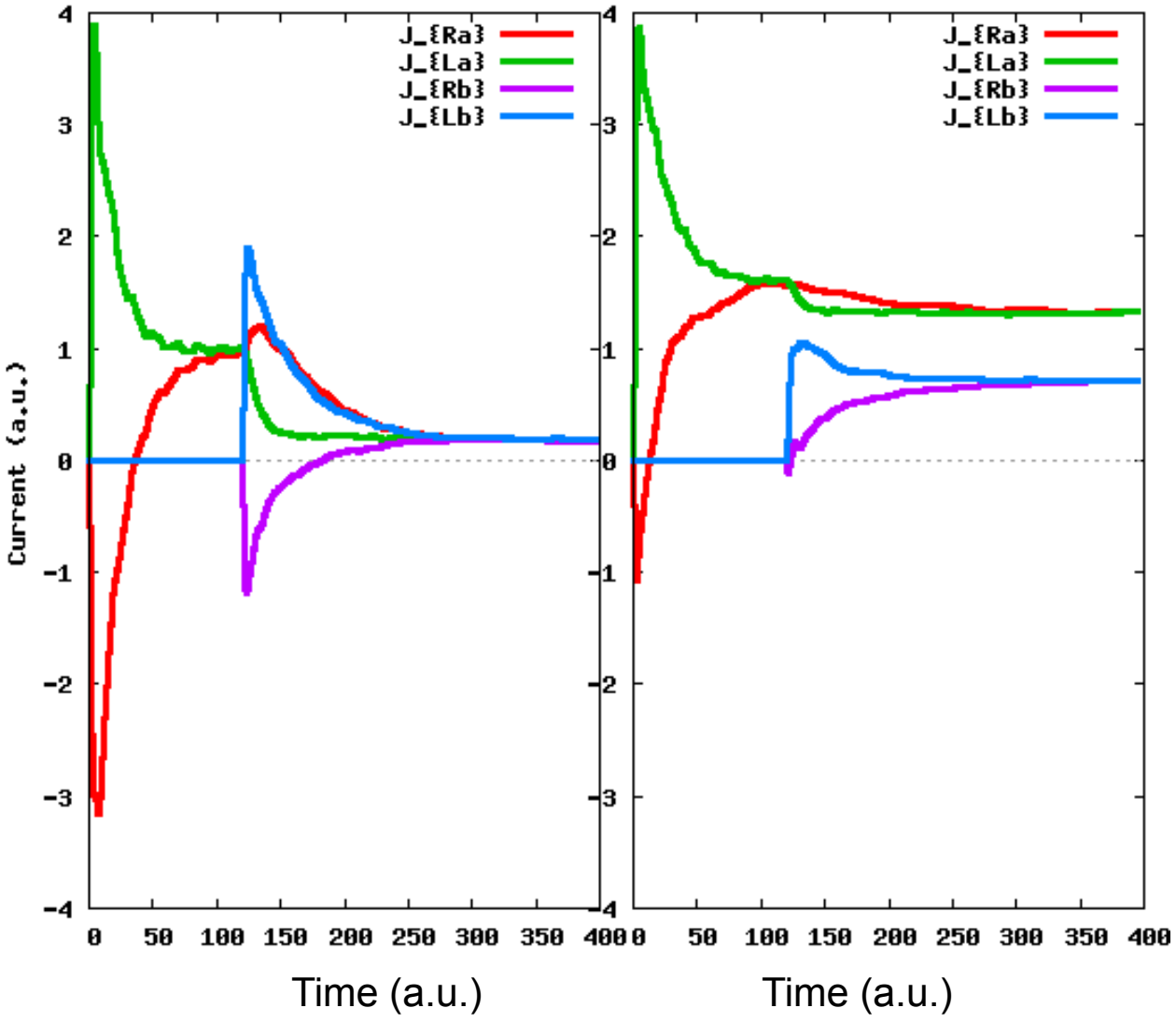

Current
Time
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
0
20
40
60
80
100
120
140
160
180
200
μL=7, μR=3
μL=7, μR=4
μL=7, μR=5
μL=7, μR=6


Sample
Left lead
Right lead
y
x
ΩL
ΩR

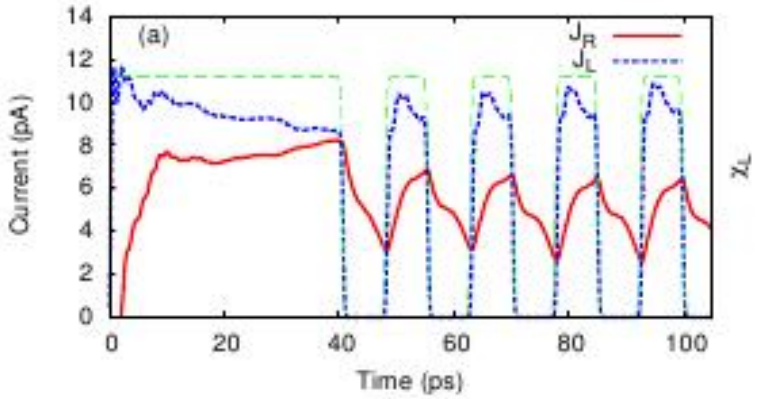
Double system

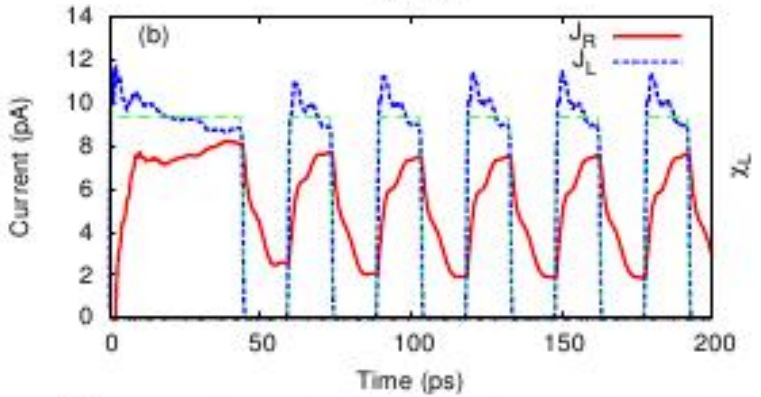


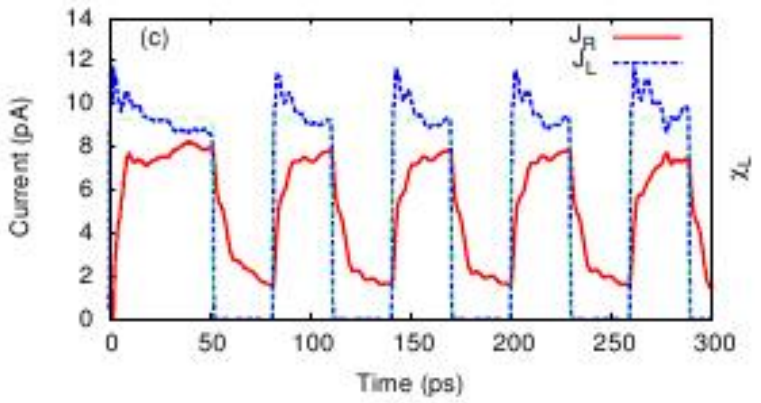
Induced currents

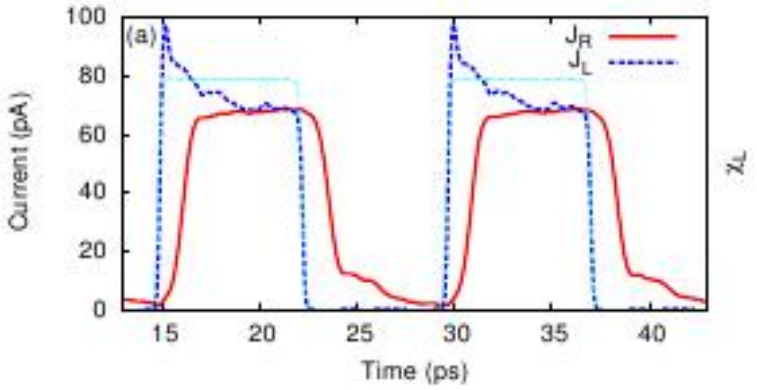


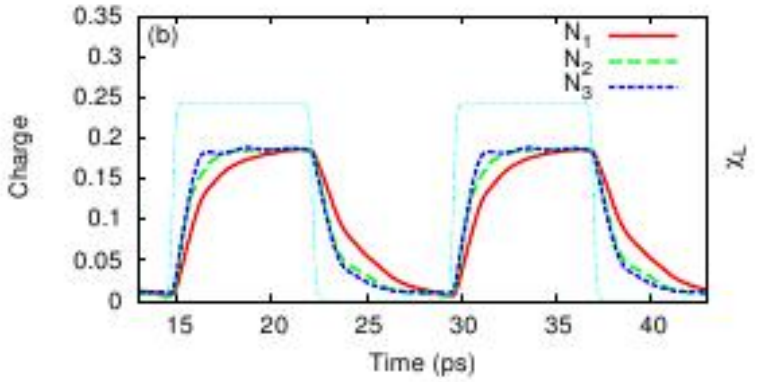
Electric pulses

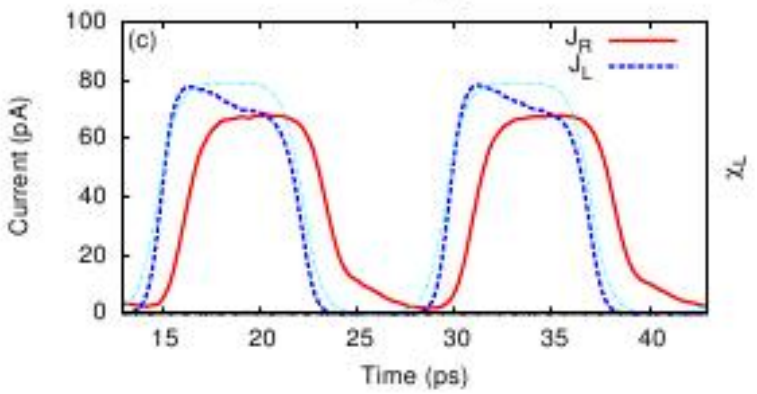












The team

Viðar Guðmundsson,
Professor HÍ

Valeriu Moldoveanu,
Scientist, Romania

Cosmin Gainar,
PhD student HÍ

Kristinn Torfason,
PhD student HR

Andrei, speaker