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Mesoscopic Nano-Electro-Mechanics of Shuttle Systems

Robert Shekhter

University of Gothenburg , Sweden

- Lecture1: Mechanically assisted single-electronics
- Lecture2: Quantum coherent nano-electro-mechanics
- Lecture3: Mechanically assisted superconductivity

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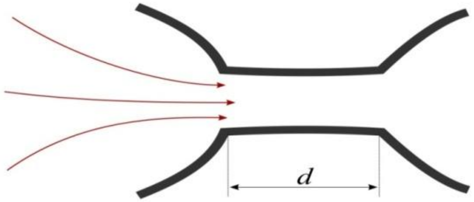
Electric Weak Links (EWL)

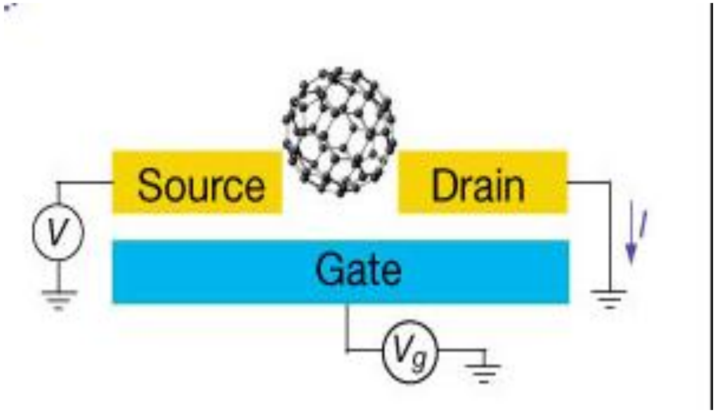
Electronic transmission through small regions of material determines electric transport between bulk conductors

Microbridges – EWL with
current concentration



$J \approx 10^9 A/cm^2$

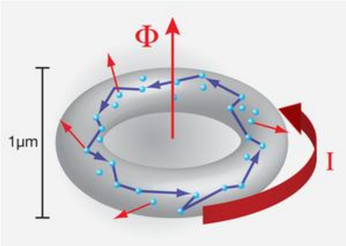
Coulomb Blockade structures –
EWL with electric
charge concentration



Mesoscopic Phenomena (Examples)

Persistent currents (in the ground state)

-Microscopic scale: Electrons move in atomic orbitals,
may generate net magnetization
-Macroscopic scale: No current in the ground state of bulk sample
-Mesoscopic scale: Persistent currents in the ground state



Josephson effect (supercurrent passing through SNS-region)

-A supercurrent may flow between two superconductors separated by a non-superconducting region of mesoscopic size

Coulomb blockade (due to discreteness of electronic charge)

-Microscopic scale: Electrons have finite charge *e*, Coulomb interactions
give rise to large ionization energies of atoms
-Macroscopic scale: Electron liquid, charge discreteness not important
-Mesoscopic scale: Coulomb blockade of tunneling through granular samples

Mesoscopic samples contain a large number of atoms but are small on the scale of a temperature-dependent ”coherence length”. On such scales electronic and mechanical phenomena coexist: ***Mesoscopic Nanoelectromechanics***

References

Book: **Andrew N. Cleland: Foundation of Nanomechanics**
Springer,2003 (Chapter7,esp.7.1.4, Chapter 8,9);

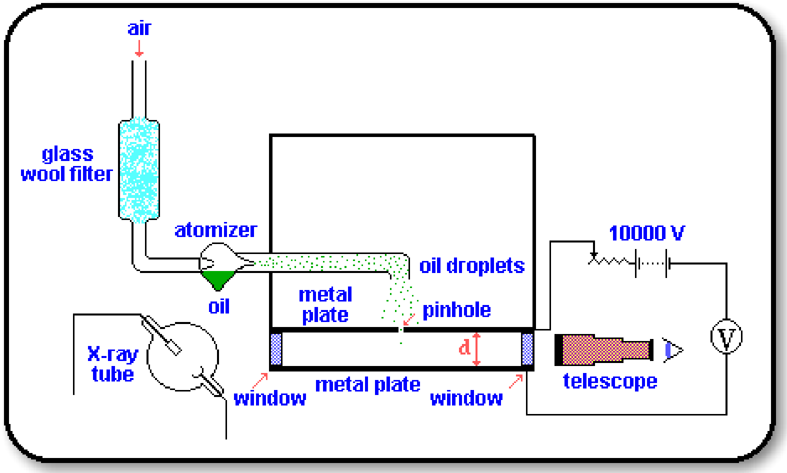
Reviews: **R.Shekhter et al.: Low.Tepmp.Phys. 35, 662 (2009);**
J.Phys. Cond.Mat. 15, R 441 (2003)
J. Comp.Theor.Nanosc., 4, 860 (2007)

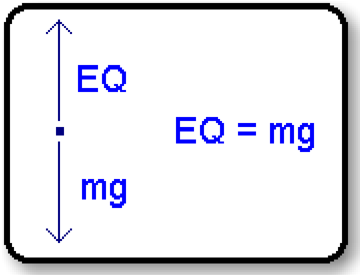
Lecture 1
Mechanically Assisted Single Electronics

Outline

- Electric charge quantization in solids (important historical events)
- Nanoelectromechanical coupling due to tunneling of single electrons
- Shuttling of single electrons in NEM-SET devices

Millikan's Oil-Drop Experiment (Nobel Prize in 1923)





$EQ = mg$

$E = V/d$

hence $Q = dmg/V$

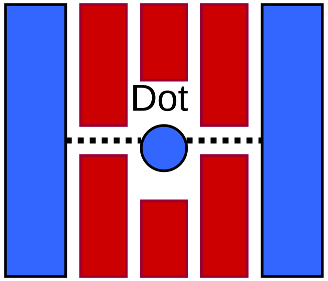
The electronic charge as a discrete quantity:

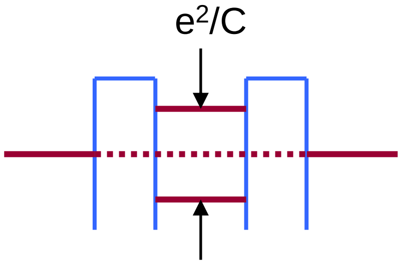
In **1911**, Robert Millikan of the University of Chicago published* the details of an experiment that proved beyond doubt that charge was carried by discrete positive and negative entities of equal magnitude, which he called electrons.

The charge on the trapped droplet could be altered by briefly turning on the **X**-ray tube. When the charge changed, the forces on the droplet were no longer balanced and the droplet started to move.

*Phys. Rev. **32**, 349-397 (1911)
See also *http://nobelprize.org/physics/laureates/1923/press.html*

Electrically Controlled Single-Electron Charging





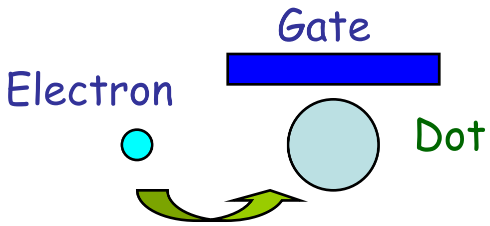
Experiment:

L.S.Kuzmin, K.K.Likharev, JETP Lett. **45**, 495(1987):
T.A.Fulton, C.J.Dolan, PRL, **59**,109(1987);
L.S.Kuzmin, P.Delsing, T.Claeson, K.K.Likharev, PRL,**62**,2539(1989);
P.Delsing, K.K.Likharev, L.S.Kuzmin & T.Claeson, PRL, **63**, 1861, (1989)

Theory:

R.Shekhter., Soviet Physics JETP **36**, 747(1973);
I.O.Kulik, R.Shekhter, Soviet Physics JETP **41**, 308(1975);
D.V.Averin, K.K.Likharev, J.Low Temp.Phys. **62**, 345 (1986)

Coulomb Blockade

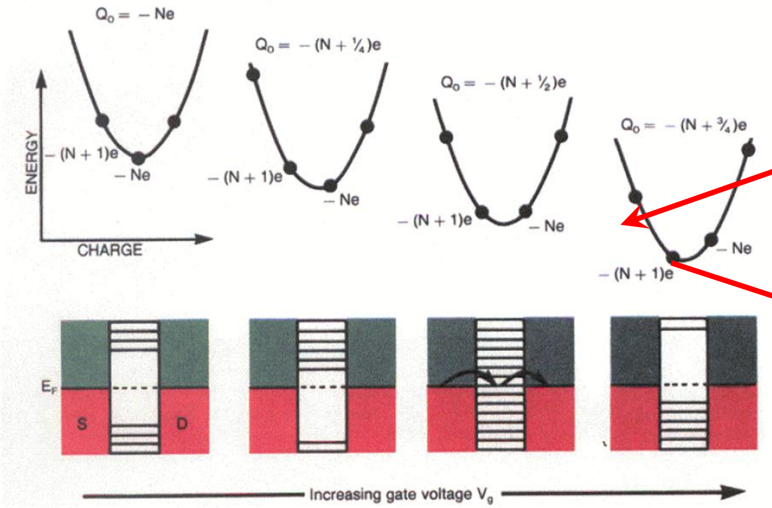


$$Q = -Ne$$

Repulsion at the dot

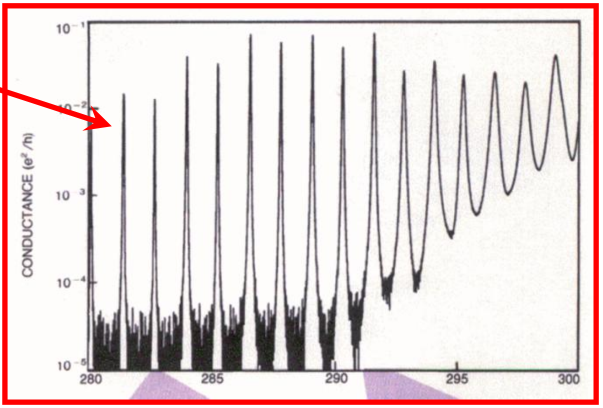
Cost $$E = QV_g + \frac{Q^2}{2C}$$

Attraction to the gate



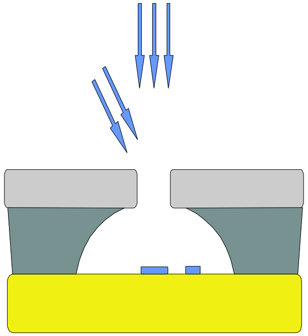
At $$V_g = -\left(N + \frac{1}{2}\right)\frac{e}{C}$$

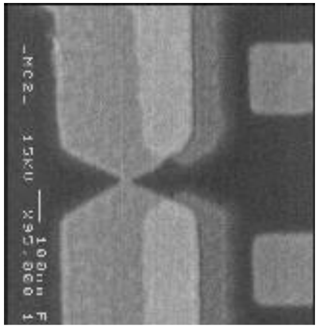
the energy cost vanishes !

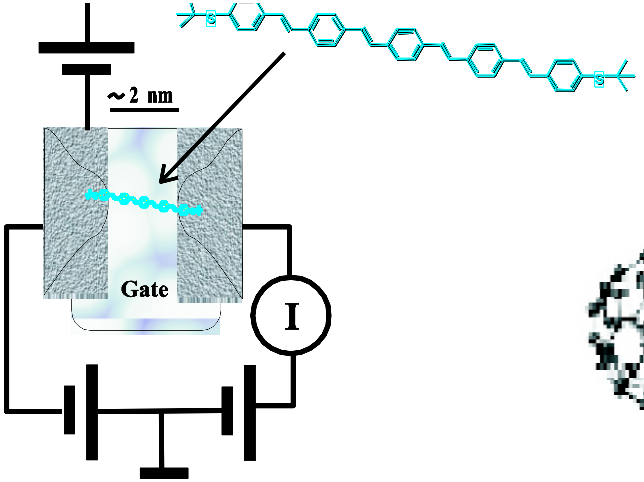


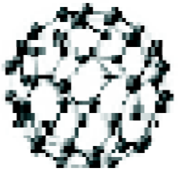
Single-electron transistor (SET)

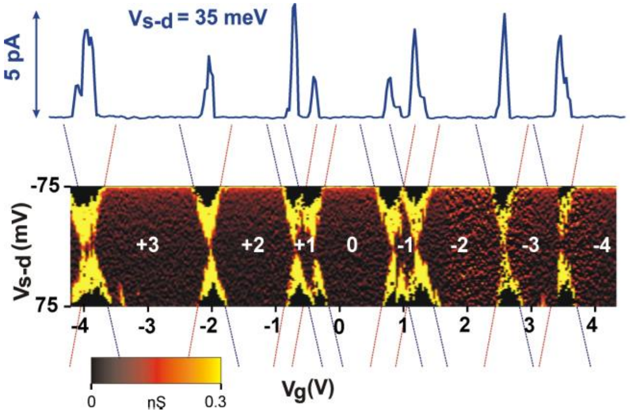
Single Molecular Transistors with OPV5 and Fullerenes







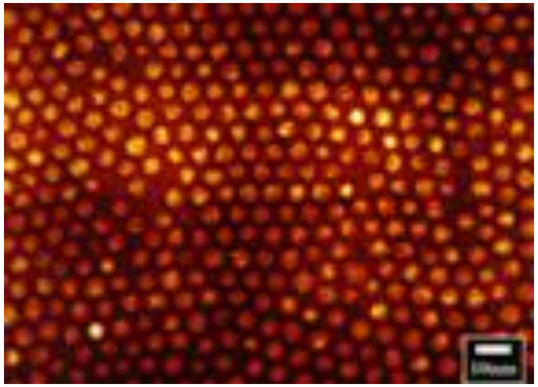




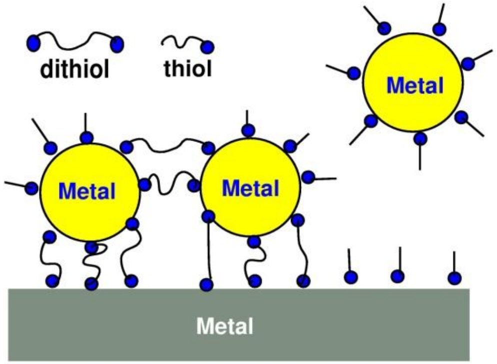
Nature **425**, 628 (2003)

Self-Assembled Metal-Organic Composites

Molecular manufacturing – a way to design materials on the nanometer scale



Encapsulated **4nm Au** particles self-assembled into a **2D** array supported by a thin film, Anders *et al*., 1995



Scheme for molecular manufacturing

Basic Characteristics

Materials properties:

Electrical – heteroconducting

Mechanical – heteroelastic

Electronic features:

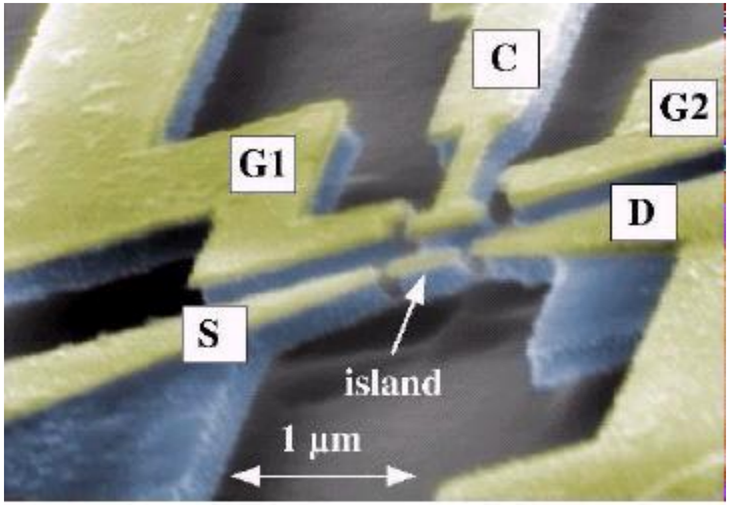
Quantum coherence

Coulomb correlations

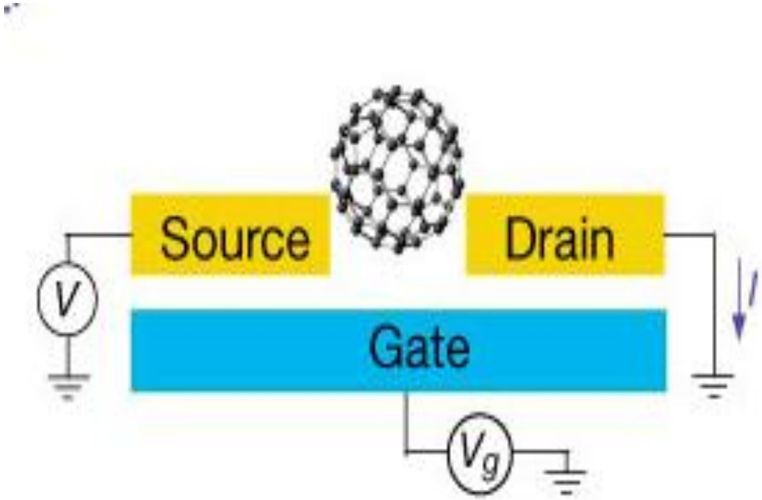
Electromechanical coupling

Nanoelectromechanical Devices

Quantum ”bell”



Single $\mathbf{C_{60}}$ Transistor



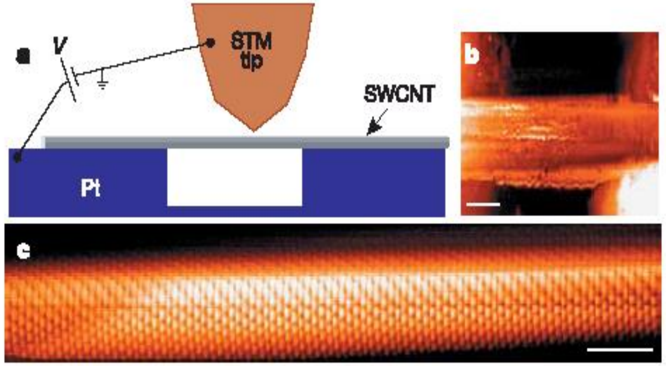
A. Erbe *et al*., PRL **87**, 96106 (2001);
D. Scheible *et al*. NJP **4**, 86.1 (2002)

H. Park *et al*., Nature **407**, 57 (2000)

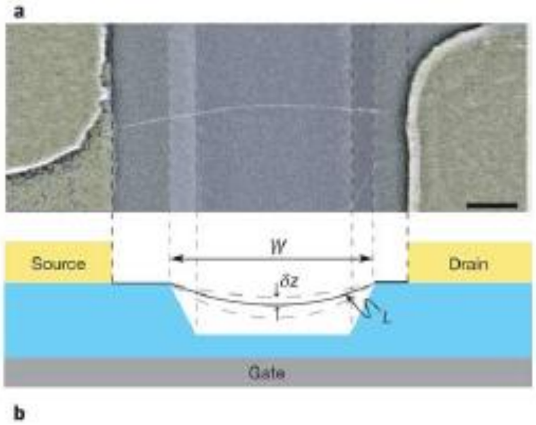
Here: Nanoelectromechanics caused by or associated with single-charge tunneling effects

CNT-Based Nanoelectromechanics

A suspended **CNT** has mechanical degrees of freedom **=>** study electromechanical effects on the nanoscale.

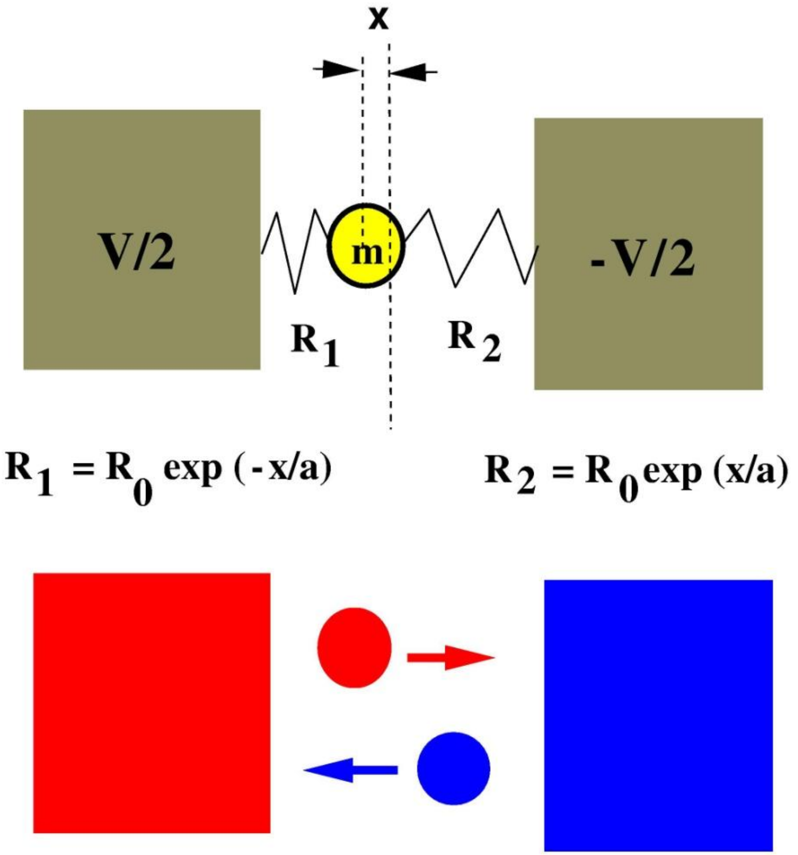


B. J. LeRoy et al., Nature **432**, 371 (2004)



V. Sazonova et al., Nature **431**, 284 (2004)

Millikan’s Set-up on a Nanometer Length Scale



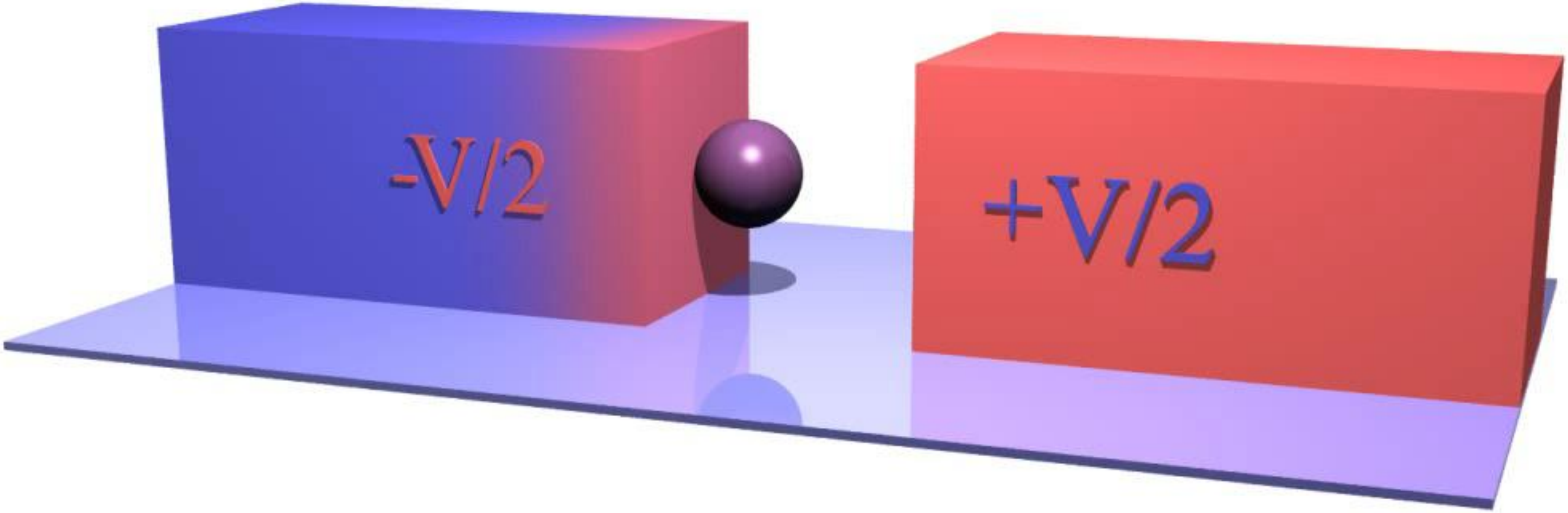
$R_1 = R_0 \exp(-x/a)$ $R_2 = R_0 \exp(x/a)$

Velocity direction is correlated with the charge sign

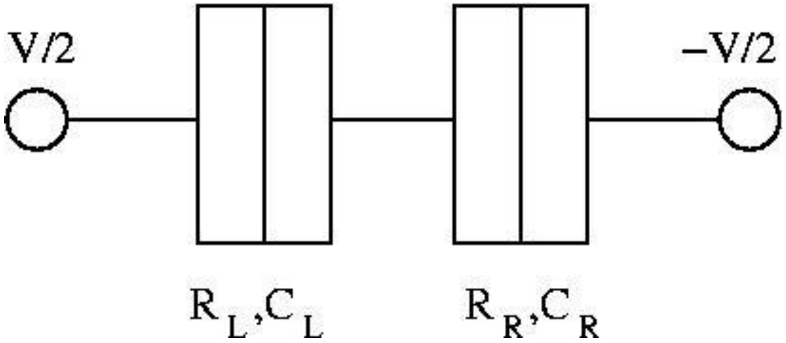
If **W** exceeds the dissipated power an instability occurs

Gorelik et al., PRL, **80**, 4256(1998)

The Electronic Shuttle



Circuit Model for the Shuttle



Electrostatic energy of the charged grain

$$E_n = Q_n^{\,2}/2C + \frac{V}{2} Q_n \frac{C_L - C_R}{C},$$

$$Q_n = ne$$

$$C = C_L + C_R$$

Electronic tunneling rate:

$$G^{s}_{n'n} = \frac{1}{e^2 R_s(x)} \frac{E_{n'} - E_n - eV_s(n'-n)}{1 - \exp \beta\{E_n - E_{n'} - eV_s(n-n')\}}, \qquad s = L, R$$

$$R^{-1}_{L(R)}(x) = R_0^{-1} \exp\left\{\pm \frac{x}{\lambda}\right\}$$

Formulation of the Problem

$$\boxed{p_n = Sp\{\hat{\rho}\}_n}$$

$$\boxed{Q(x) = e\sum_n n p_n}$$

$$\boxed{\frac{\partial p_n}{\partial t} = \sum_{\substack{n' = n\pm 1\\ s=1,2}} \{G^s_{n'n}(x)\,p_{n'} - G^s_{nn'}(x)\,p_n\}}$$

$$\boxed{\frac{d^2x}{dt^2} = -\omega^2 x - \gamma\frac{dx}{dt} + \frac{Q(x)E}{M}}$$

Nanoelectromechanical Instability

$$\frac{dQ}{dt} = I_L + I_R \quad \Rightarrow \quad \frac{dQ}{dt} = \frac{Q}{C}\left(\frac{1}{R_L} + \frac{1}{R_R}\right) + \frac{V}{C}\left(\frac{C_R}{R_L} - \frac{C_L}{R_R}\right)$$

$$R^{-1}{}_{R,L} = R_0^{-1}\left(1 \pm \frac{x(t)}{\lambda}\right)$$

$$\frac{d^2x}{dt^2} = -\omega^2 x - \gamma\frac{dx}{dt} + \frac{Q(x)E}{M}$$

Weak electromechanical coupling:

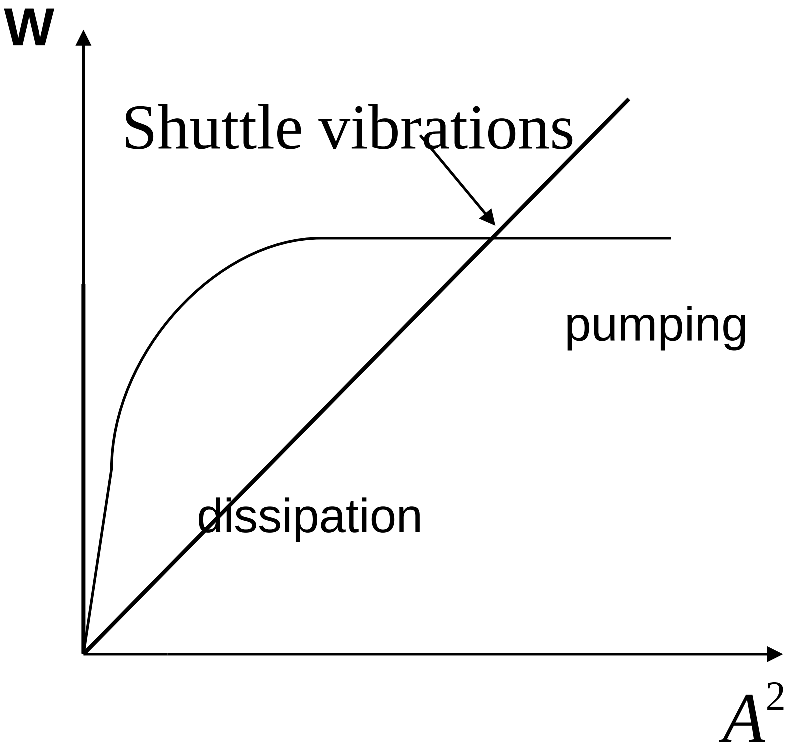
$$\eta = \frac{CVE\lambda}{2M\lambda^2\omega^2} << 1$$

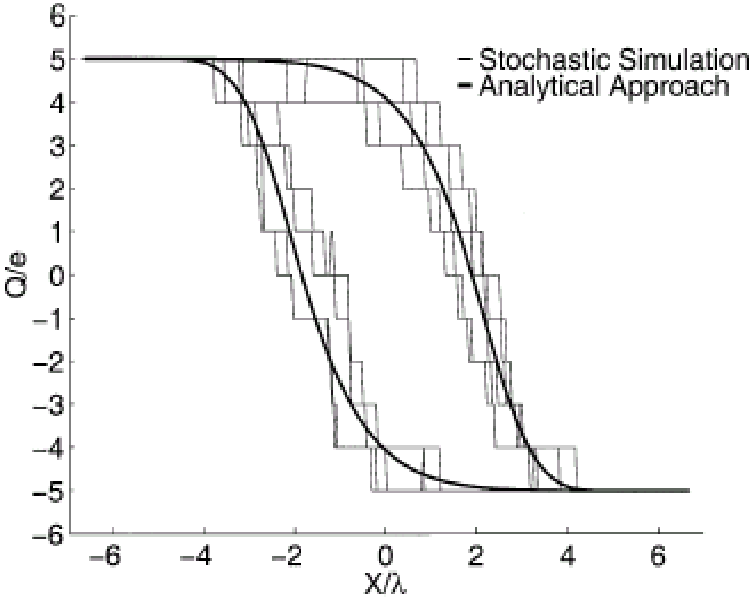
$$x(t) = x_0 \exp\{i\omega t + \alpha t\}$$

$$\alpha = \frac{1}{2}\{\gamma_{thr} - \gamma\}$$

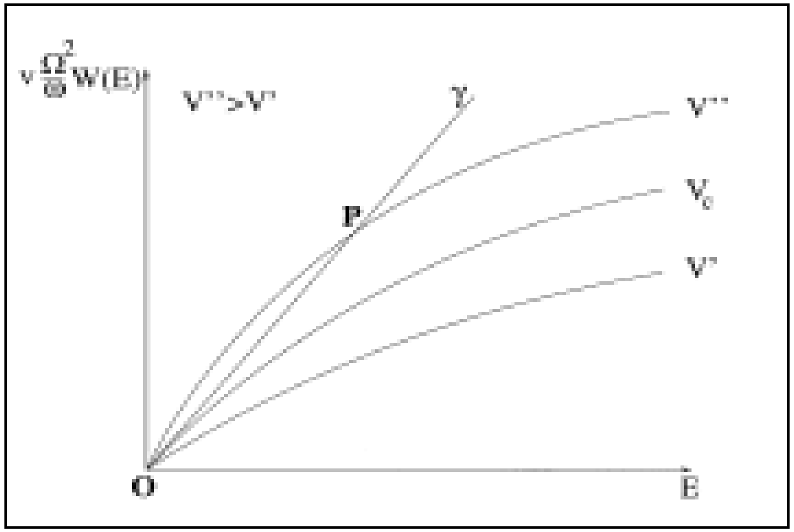
$$\gamma_{thr} = \frac{\eta\omega}{2} f(\omega_R/\omega); \quad \omega_R{}^{-1} = R_0 C; \quad f(x) = \frac{x}{x^2+1}$$

Stable Shuttle Vibrations

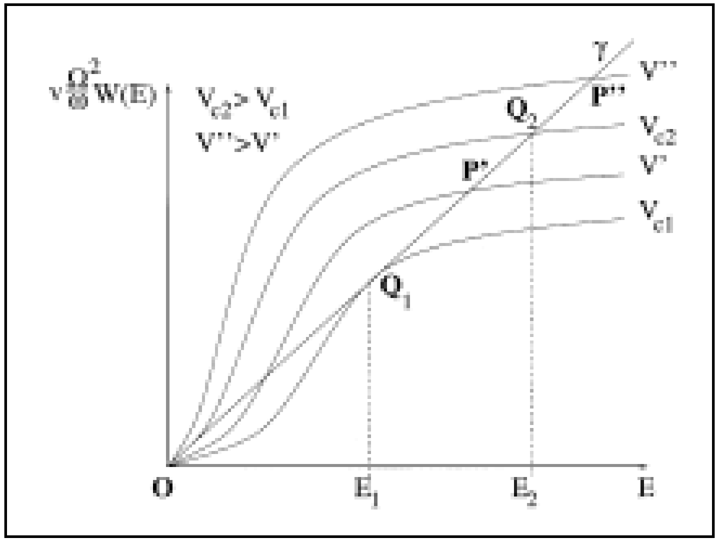




Different Scenarios for a Shuttle Instability



”SOFT” instability

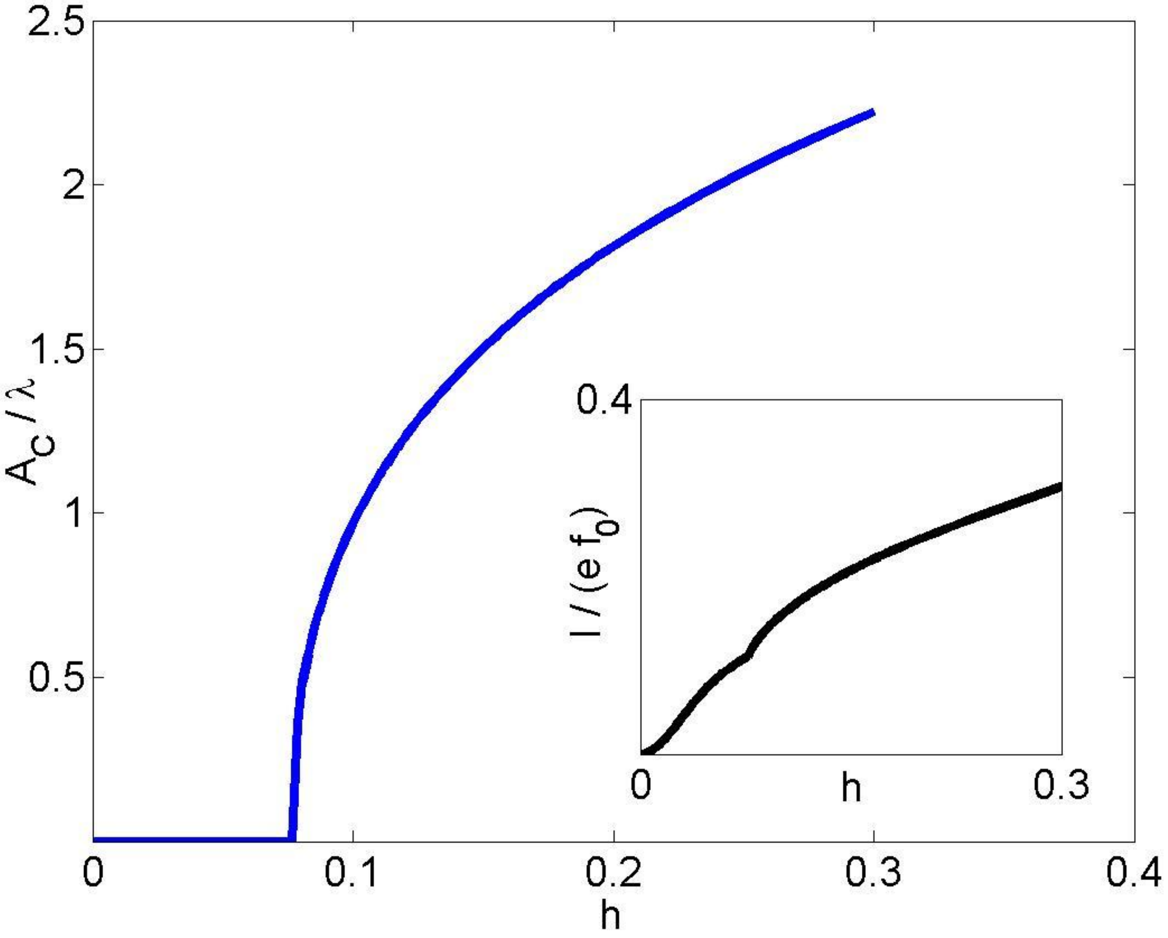


”HARD” instability

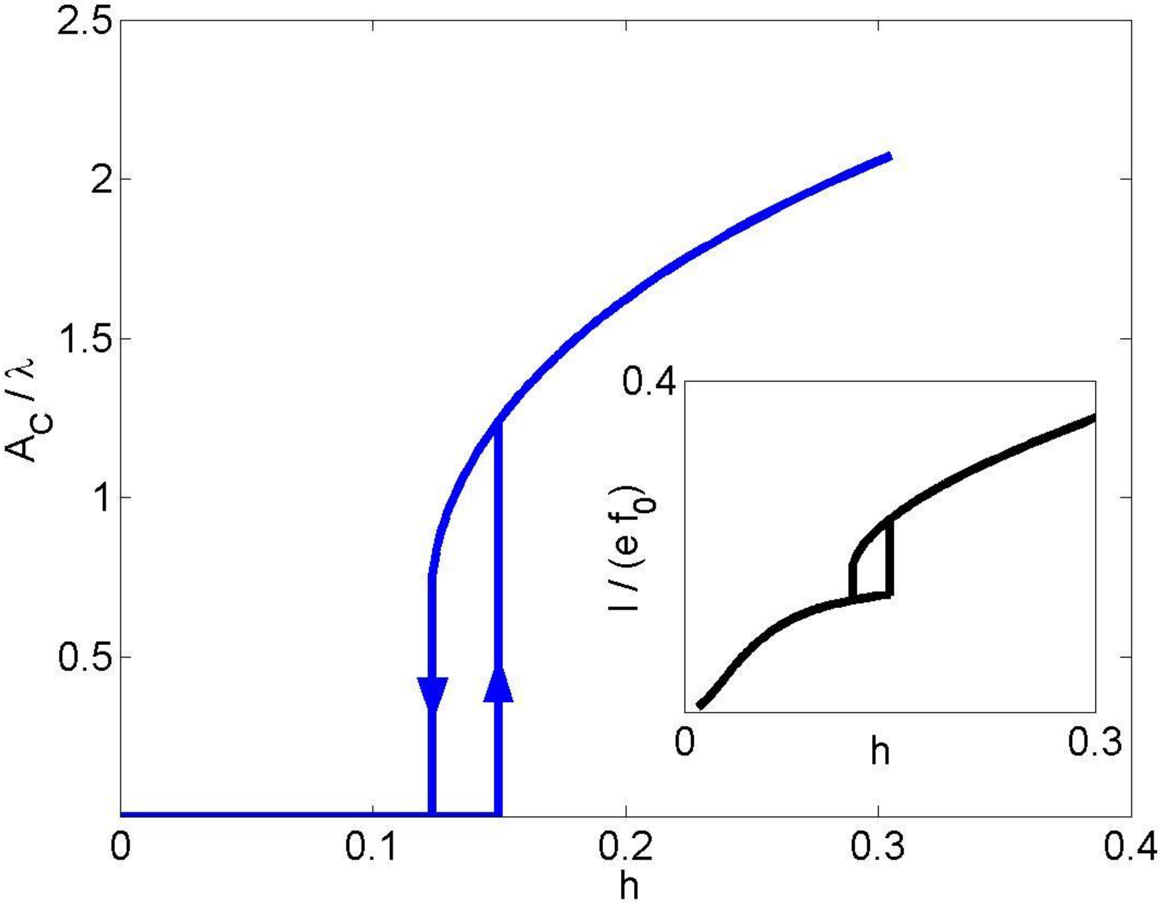
$\boxed{\omega/\omega_R < \frac{\sqrt{3}}{2}}$ *Only one stable mechanical regime is possible*

$\boxed{\omega/\omega_R > \frac{\sqrt{3}}{2}}$ *Two regimes of locally stable mechanical operations*

”Soft” Onset of Shuttle Vibrations



”Hard” Onset of Shuttle Vibrations



Shuttling of Electronic Charge