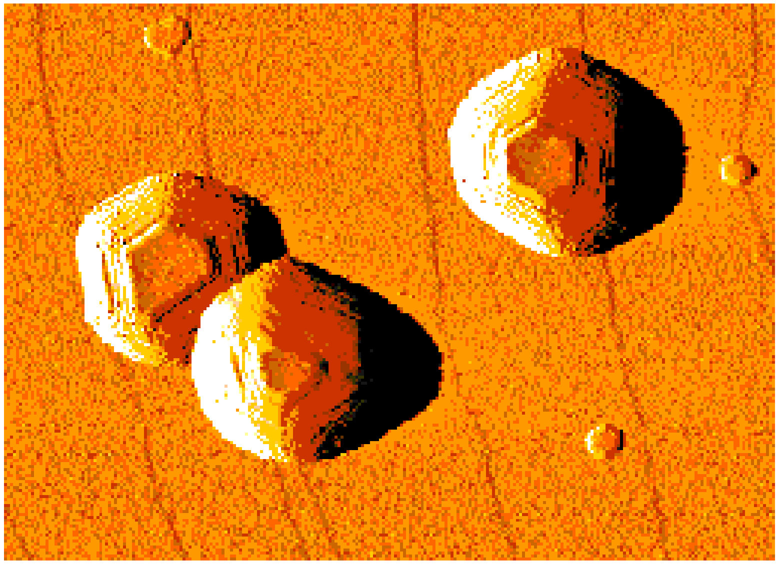
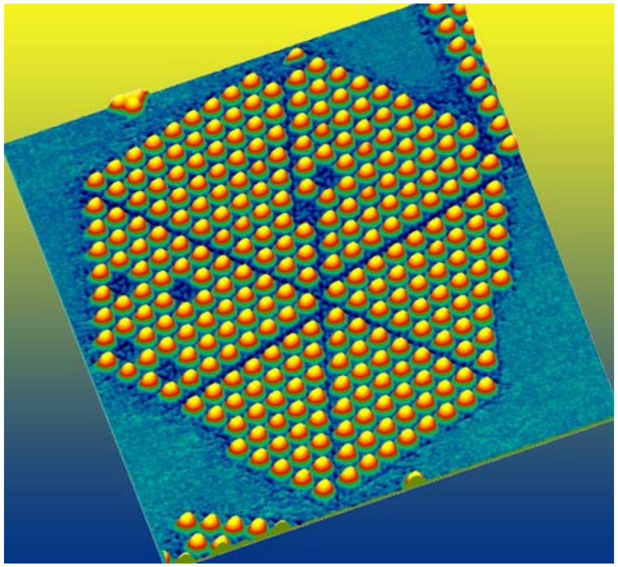
Physics of Nanotechnology

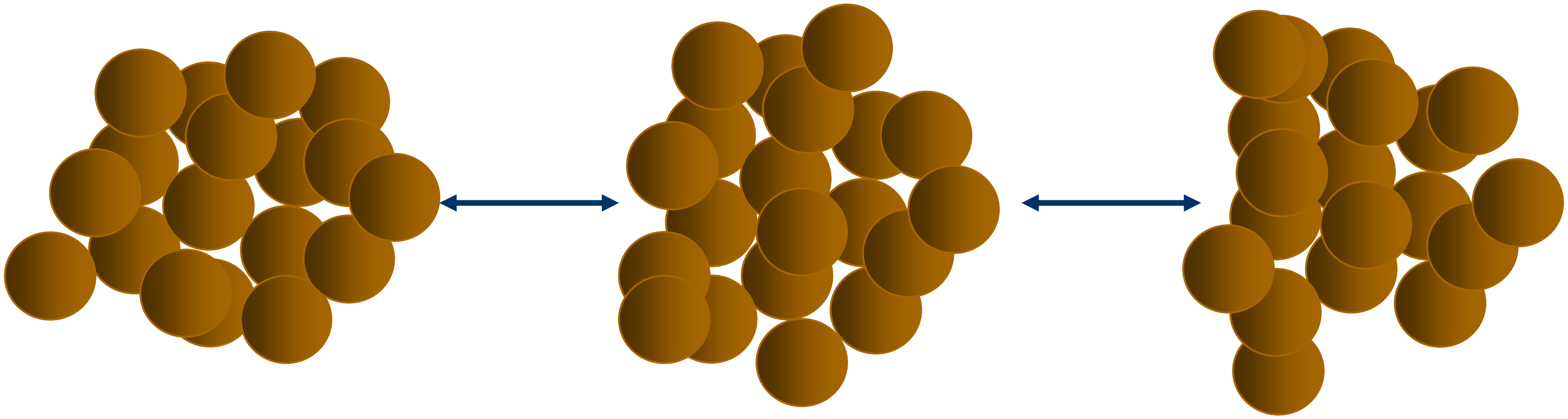
What's new at the nanoscale?

- Quantum confinement
- Surface-to-volume ratio
- Fluctuations and Entropy





10^5 *vs.* 10^{23}

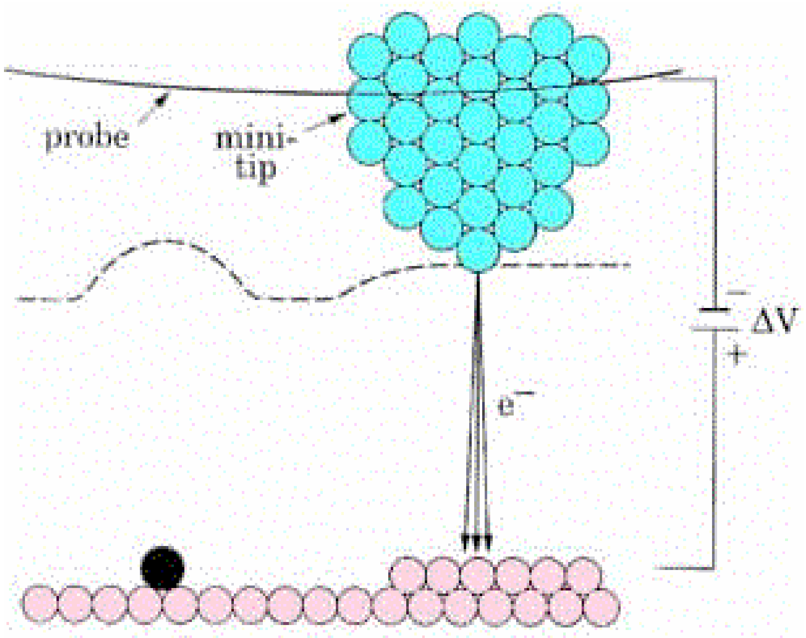


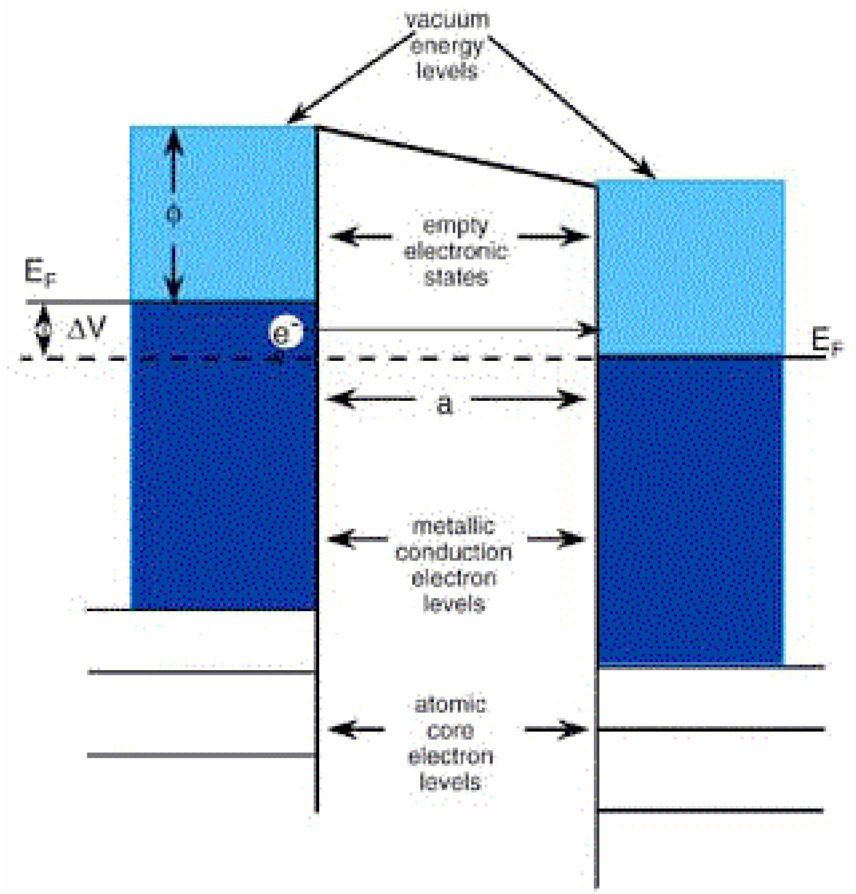
Multi-atomic structures have a large density of available energy states. State occupancy is highly peaked near an average energy value.

$$N(E) = N(\bar{E})\exp\left\{-\frac{(E-\bar{E})^2}{2kT^2C_V}\right\} \approx N(\bar{E})\exp\{-1/N\}$$

$$\frac{\sigma_E}{\bar{E}} \approx \frac{1}{\sqrt{N}} \qquad \frac{\sigma_\rho}{\rho} \approx \frac{1}{\sqrt{N}}$$

Scanning Tunneling Microscopy





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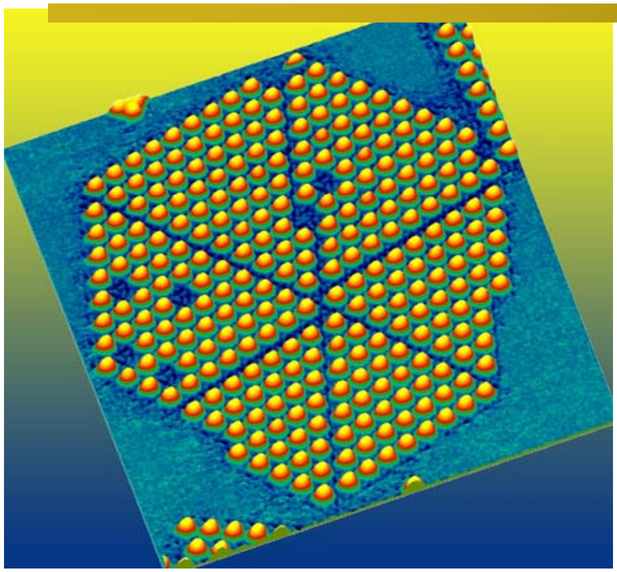
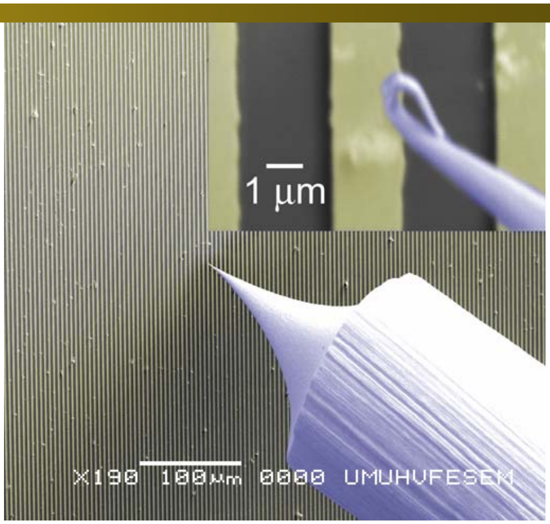
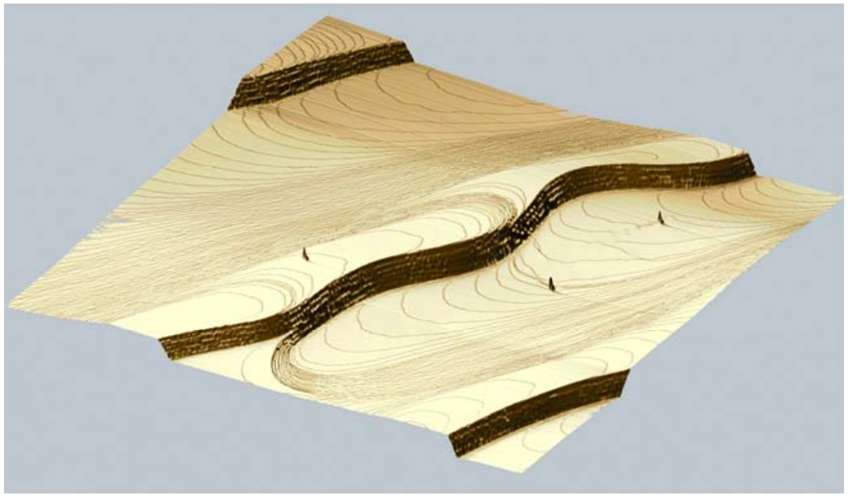


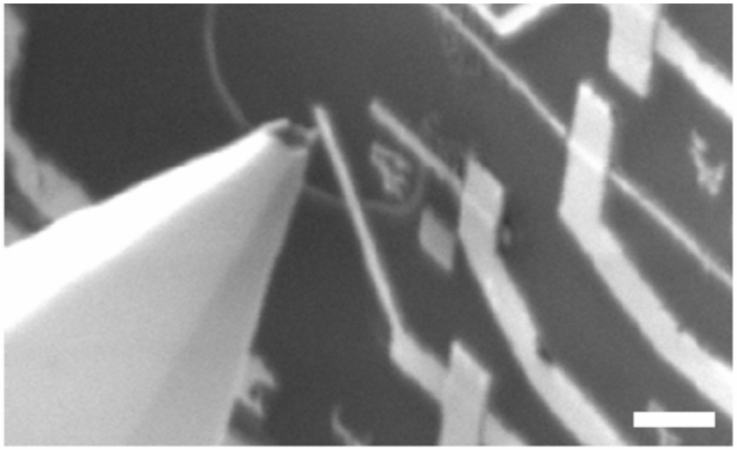
50nm x 50 nm ACA-templated C_{60}



STM tip with patterned Fe/Si



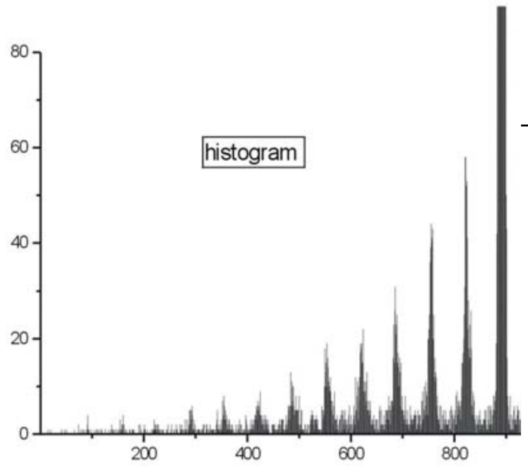
10µm x 10 µm electromigrated Si

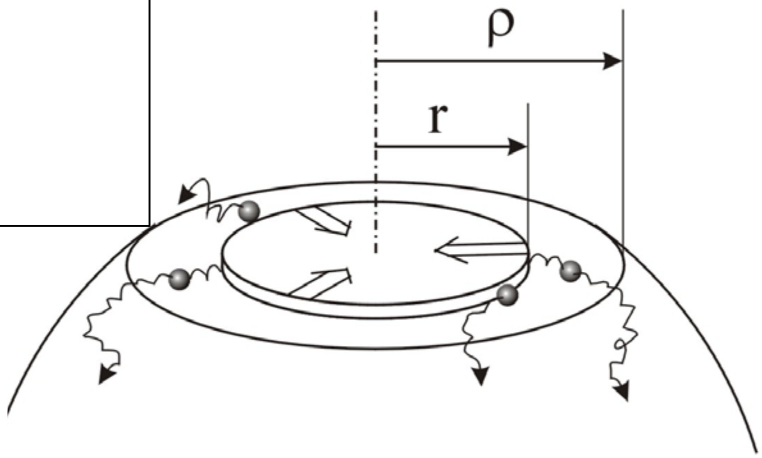


C-nanotube imaged in device

Model System - Pb Crystallites

QuickTime™ and a
decompressor
are needed to see this picture.





Nano-Physics

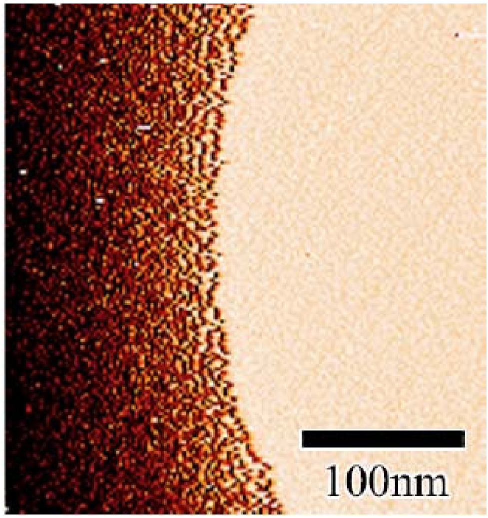
- Atoms at the surface are relatively free to move around - mass transport to fabricate and modify nanoscale structure and functional properties can be controlled at the surface
- Fractional fluctuation scales as 1/(volume)$^{1/2}$
- Surface to volume scales as 1/(volume)$^{1/3}$

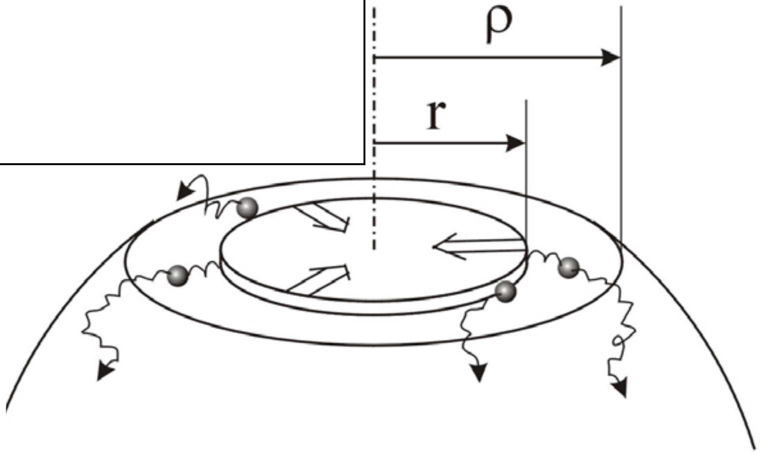
↓

- At the nanometer scale, individual atomic scale structures rather than average over distribution of stuctures will determine functional behavior of individual nanostructures and nanodevices
- This may be good or bad, but in all cases….

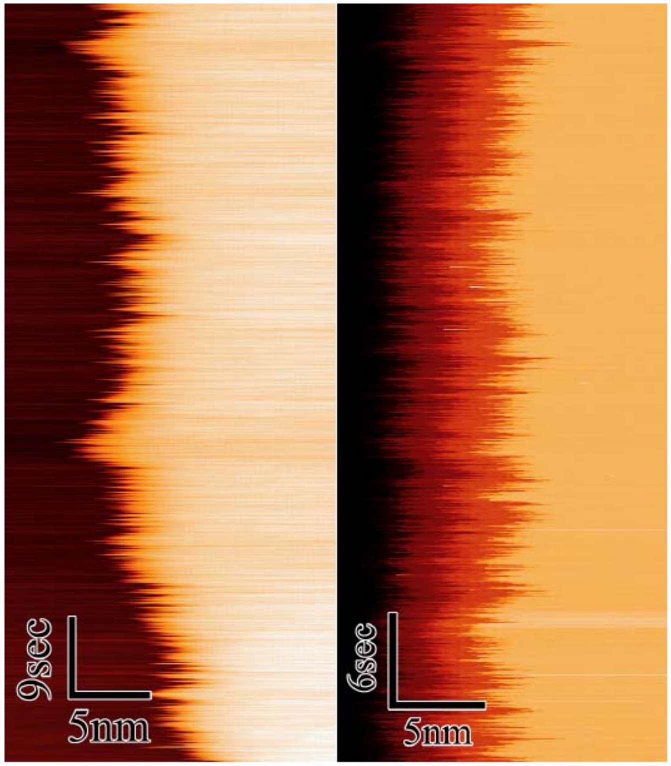
  it will be interesting

Spatial Images - Edge boundaries



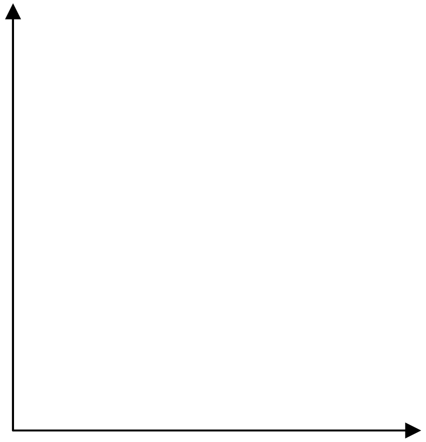


Time - Images



free step

step at crystal edge



t, seconds

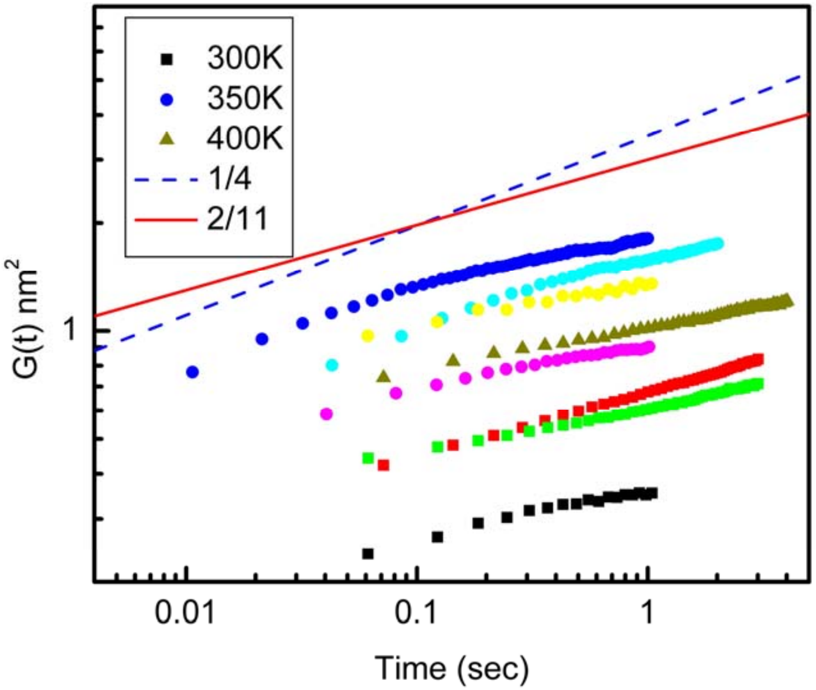
time at which position recorded

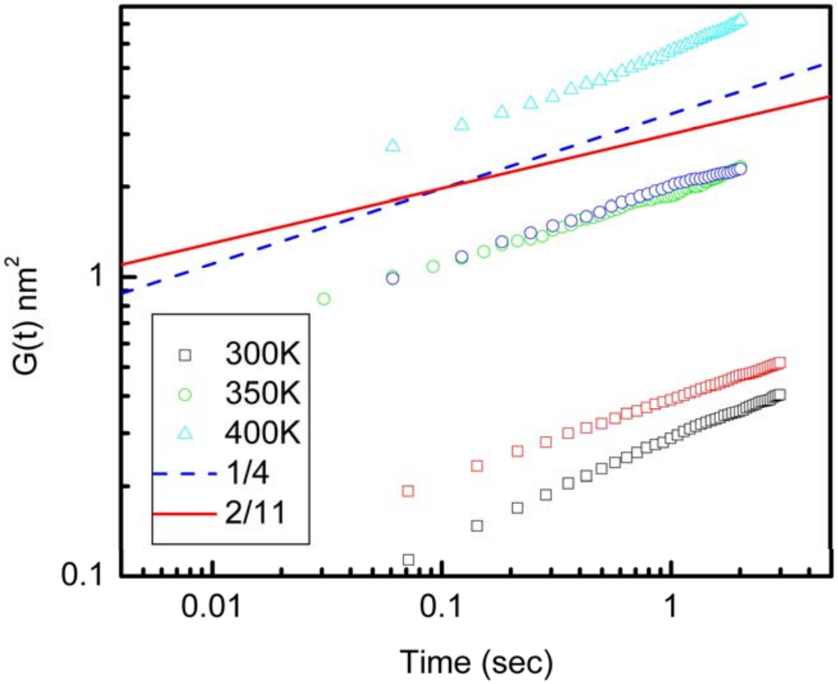
x, nm

position of step edg

- Repeated STM scans across the same spatial location reveal structure changes as a function of time, x(t)

Analysis of Fluctuations…





$$G(t)=\left\langle \left(x(t)-x(0)\right)^{2}\right\rangle=\left(\frac{2\Gamma(1-1/n)}{\pi}\right)\left(\frac{kT}{\tilde{\beta}}\right)^{\frac{n-1}{n}}\left(\Gamma_{n}t\right)^{1/n}$$

- Yields mechanism, local chemical potential and time constant governing fluctuations
- Next step - predict mass transport

Nano-confined structure evolution

QuickTime™ and a
decompressor
are needed to see this picture.

930 nm

Ranganathan, Dougherty et al, PRL 2005

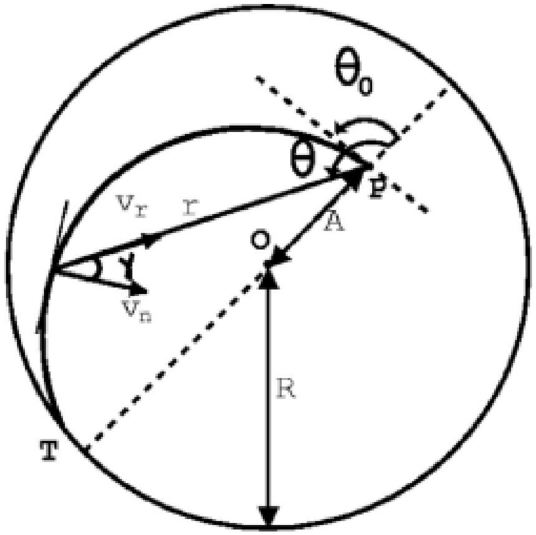
Pb Crystallite

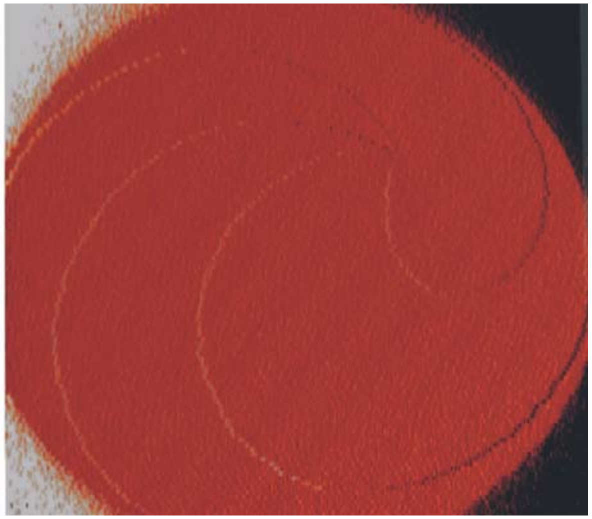
- Temperature 390K
- Period of rotation 23 min
- Screw is unwinding - mass transfer from dislocation step edge to edges of the crystallite
- Screw core is offset by about 1/2 the radius

Screw Dislocations

- Standard growth defect
- Unconfined growth reaches steady state with spiral winding at constant angular speed

Modeling





- Local curvature κ determines local chemical potential

$$\mu(\kappa)=\Omega\tilde{\beta}\kappa$$

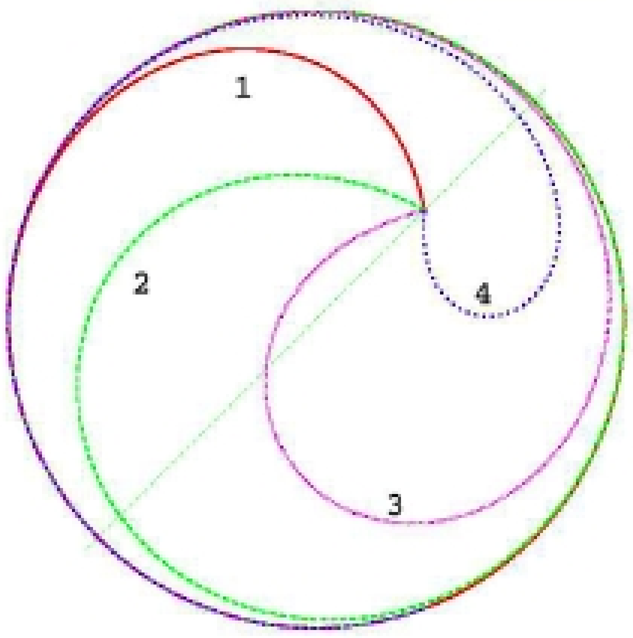
$$\kappa(r)=\frac{r^2+2r'^2-rr''}{\left(r^2+r'^2\right)^{3/2}}$$

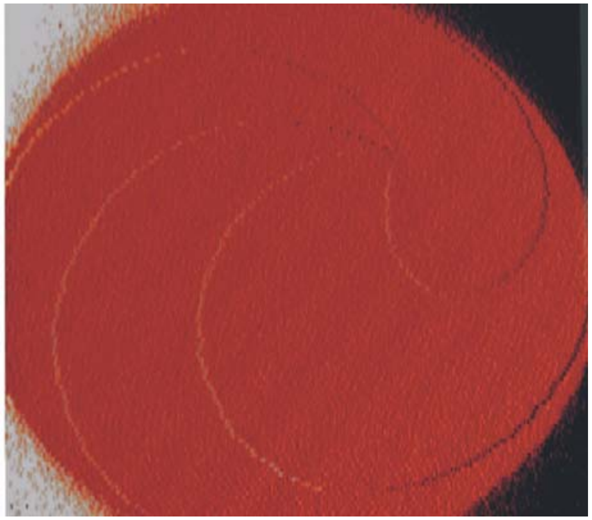
- Model first with attachment/detachment kinetics

$$v_n(\kappa)=\frac{a^3}{\tau_a}\frac{\tilde{\beta}}{kT}\left[\kappa(r)-1/R\right]$$

Unconstrained solution

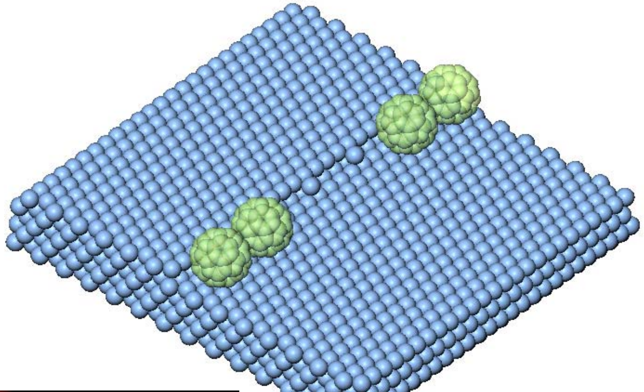
- Begin numerical solution with arbitrary initial shape constrained to join the external circle smoothly
- Period of 23 minutes is reproduced with τ_a = 1.5 ms
- Solutions requiring SED alone cannot reproduce shape evolution

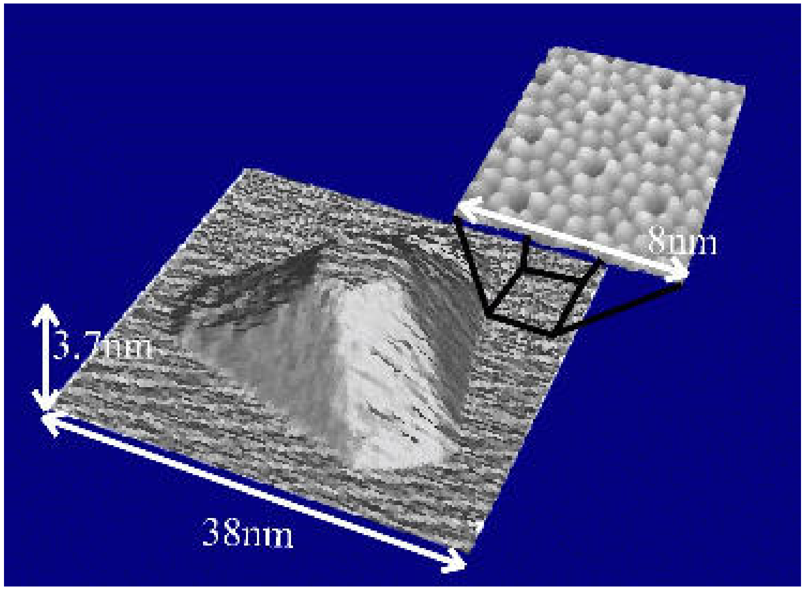


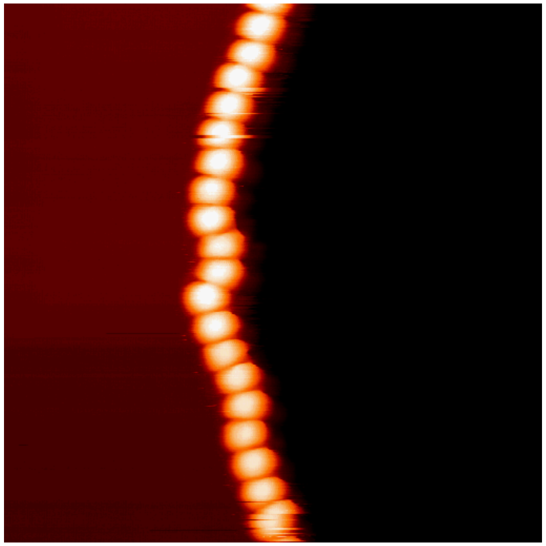


Structure assembly

- Fluctuation analysis yields parameters needed for quantitative prediction of mass transport
  - Single steps
  - Cooperative motion of 3-d structures
  - Confined structures

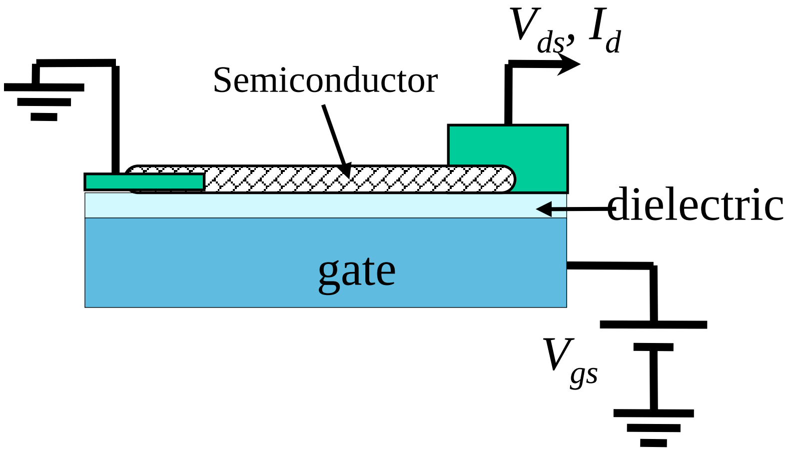




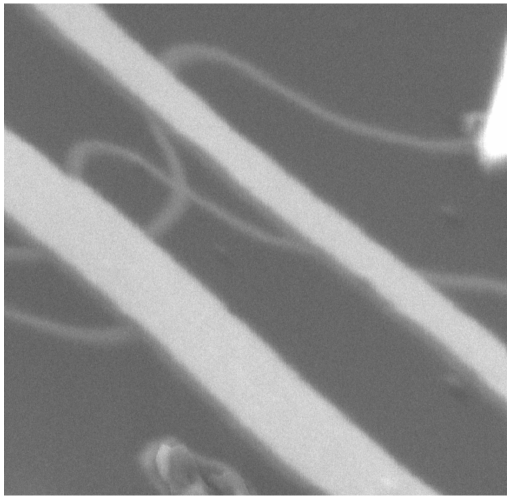


Fluctuations in Nanoelectronics

Generic Thin Film Transistor



Real Nanotube Transistor



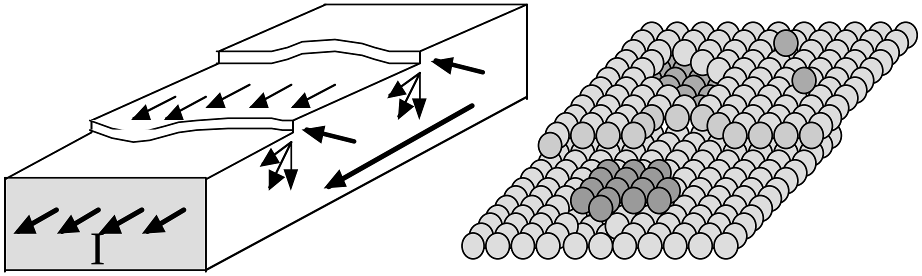
Nanoelectronics - consider nanoscale semiconductor structures such as nanotubes, or even individual molecules as the working functional for new applications in electronics

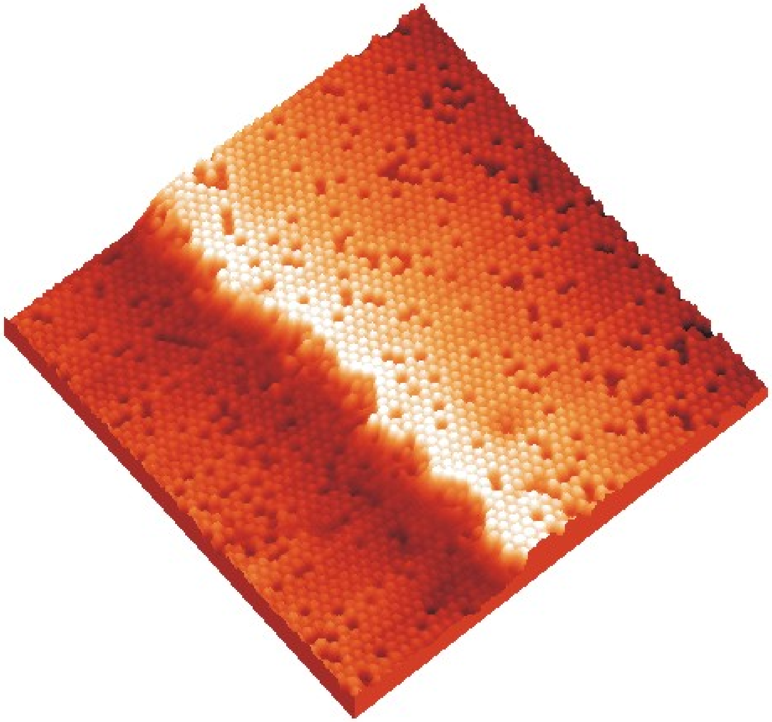
Fluctuations and Electrical Transport

Current variance $S_I(f)$ $$\frac{S_I}{I^2} = \frac{1}{f}\frac{\alpha}{N}$$

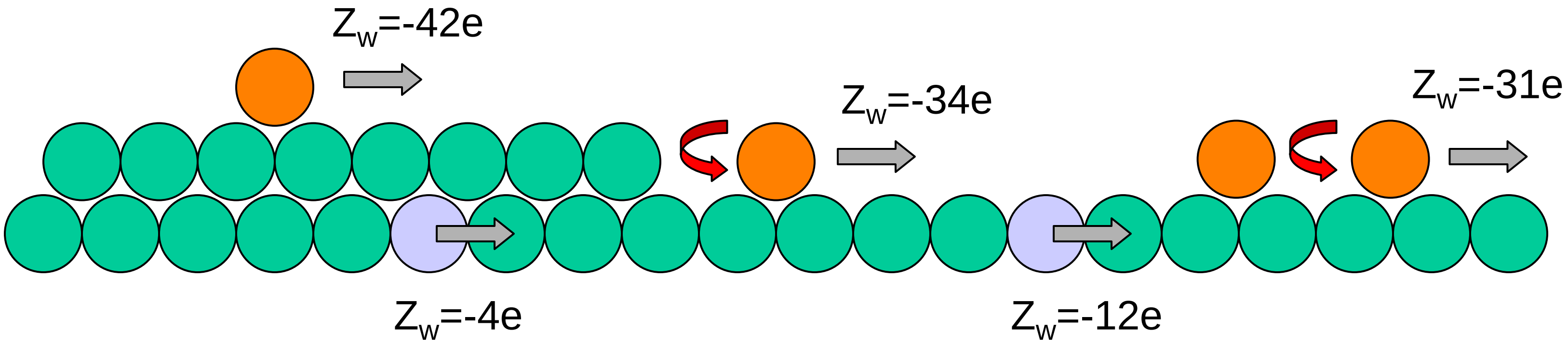
- Signal noise scales with size according to the same rules as structure fluctuations

Fluctuating surface steps affect and are affected by internal scattering from surface/interface

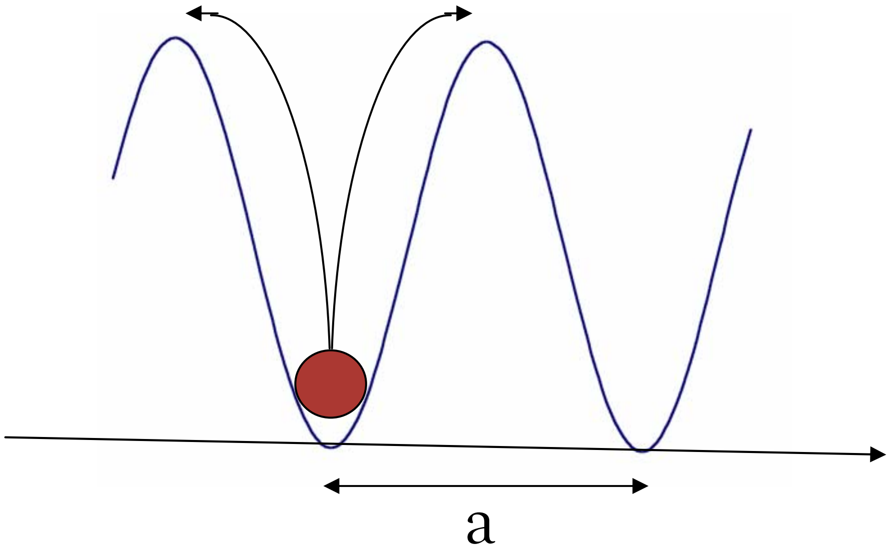




The Force of Electrical Current



P.J. Rous, “Electromigration force at stepped Al Surfaces,” Physical Review B59, 7719, 1999.



Fa ~10^{-7}eV/unit cell

Perturbation of Step Fluctuations

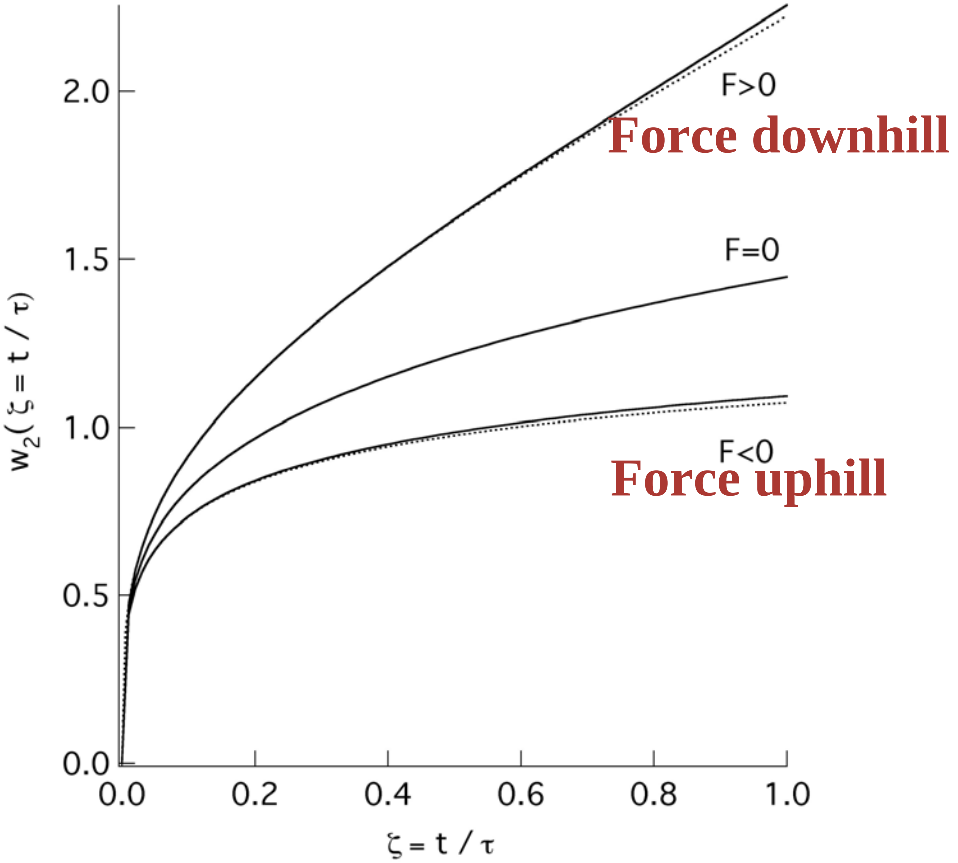
Step Position, x(t)

$$G(t) = \left\langle \left(x(t) - x(0) \right)^2 \right\rangle$$

$$G_{eq}(t) = \left(\frac{2\Gamma(3/4)}{\pi} \right) \left(\frac{kT}{\tilde{\beta}} \right)^{3/4} (\Gamma_h t)^{1/4}$$

$$\tau_{EM} = \frac{kT\tilde{\beta}}{(Fa)^2} \tau_h$$

$$G_{EM}(t) \approx G_{eq}(t) \left[1 \pm \left(\frac{t}{\tau_{EM}} \right)^{1/2} \right]^{-1}$$



Force downhill

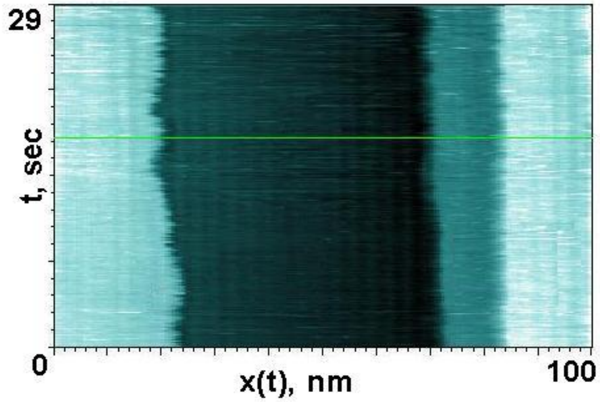
Force uphill

EM force causes deviations in

correlation of step wandering

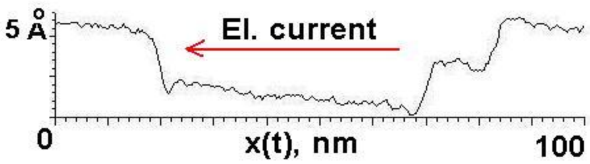
P.Rous, to be published

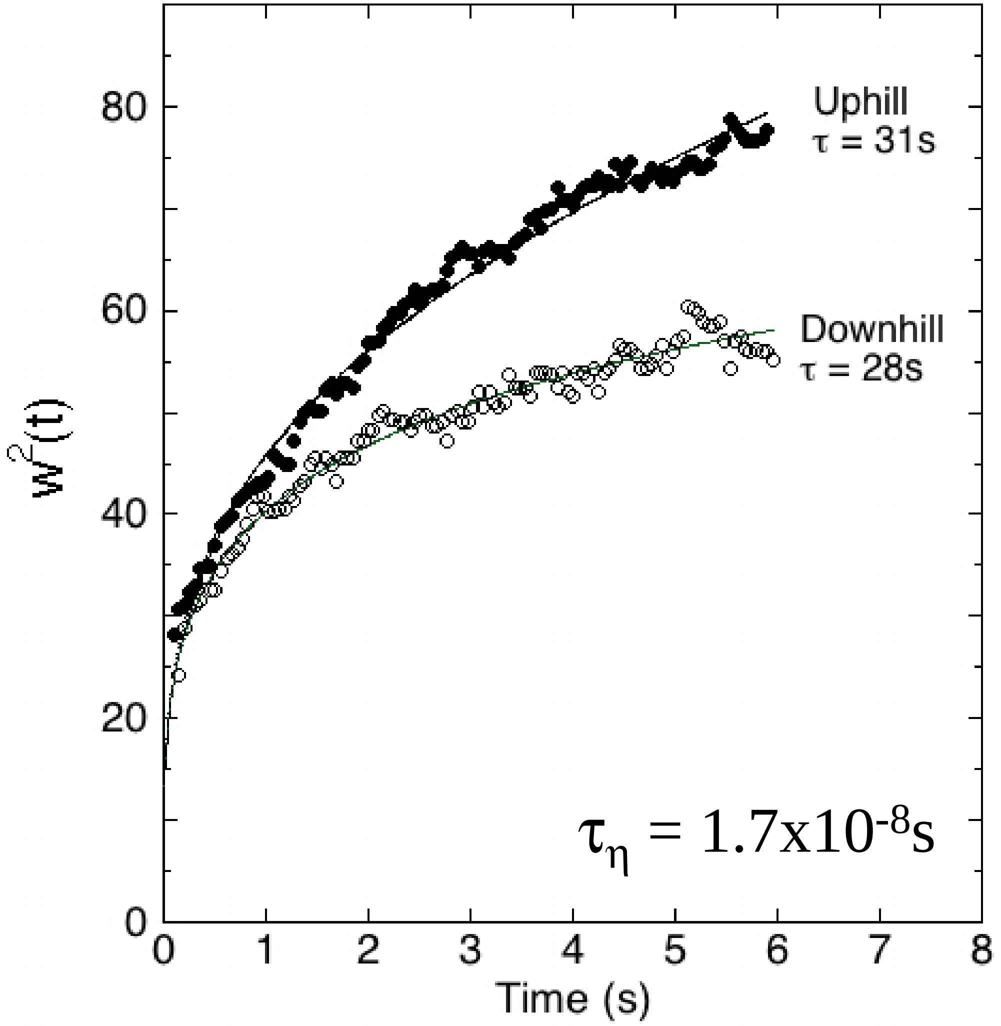
Ag Thin Film with Bias Current



Uphill and Downhill steps

Horizontal Cross Section





$\tau_\eta = 1.7 \times 10^{-8}$s

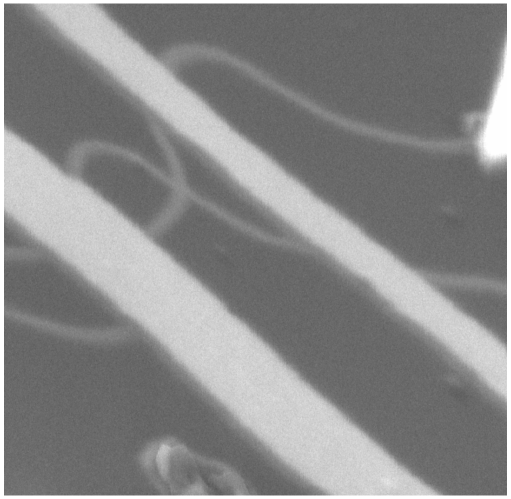
A. Bondarchuk, to be published

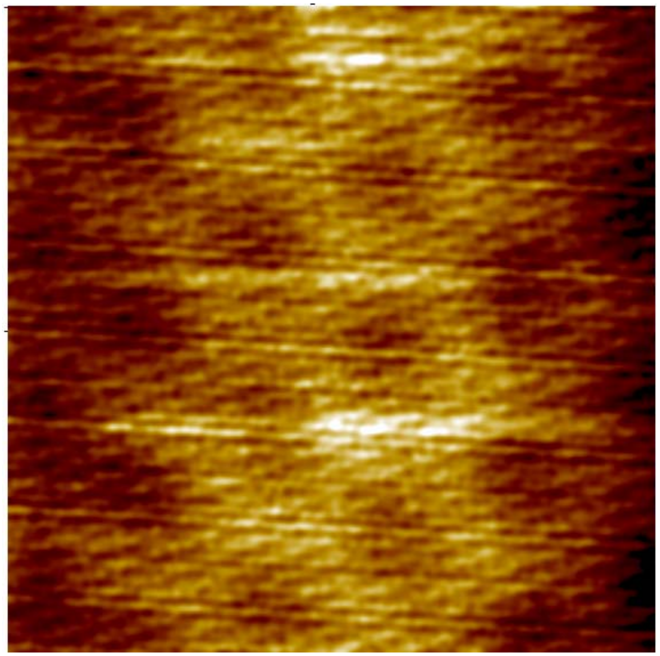
Fluctuations and Noise

Known mesoscopic behavior:

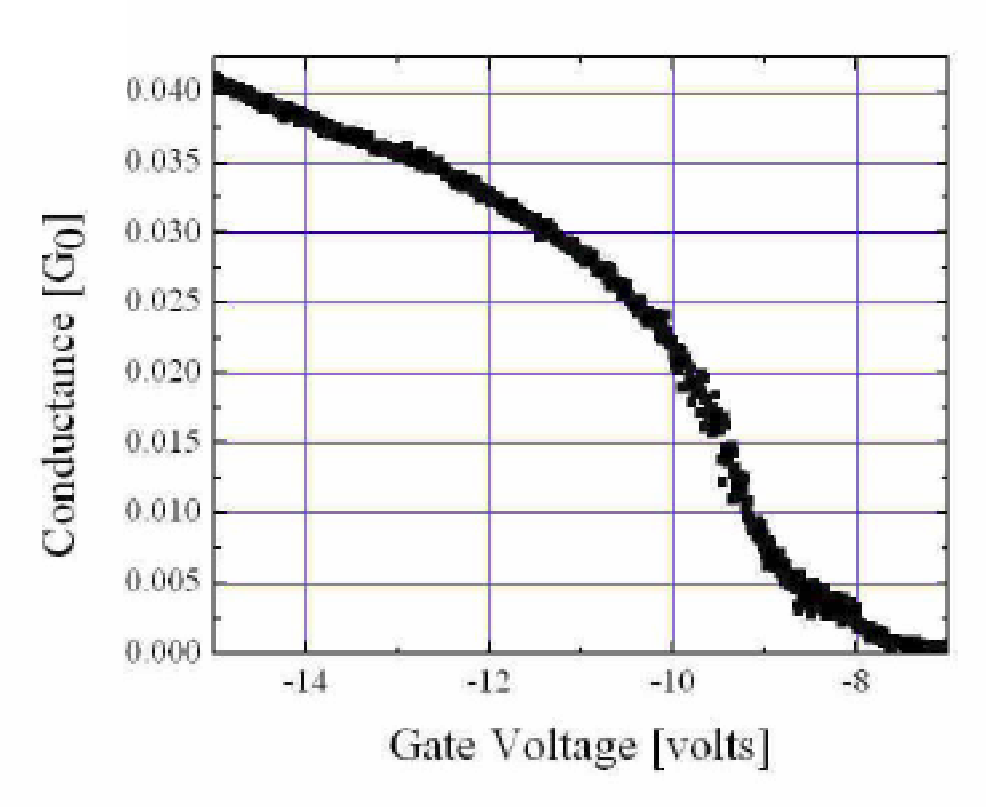
Current variance $S_I(f)$ $$\frac{S_I}{I^2} = \frac{1}{f}\frac{\alpha}{N}$$

1.2-1.8 nm diameter Carbon Nanotube transistors

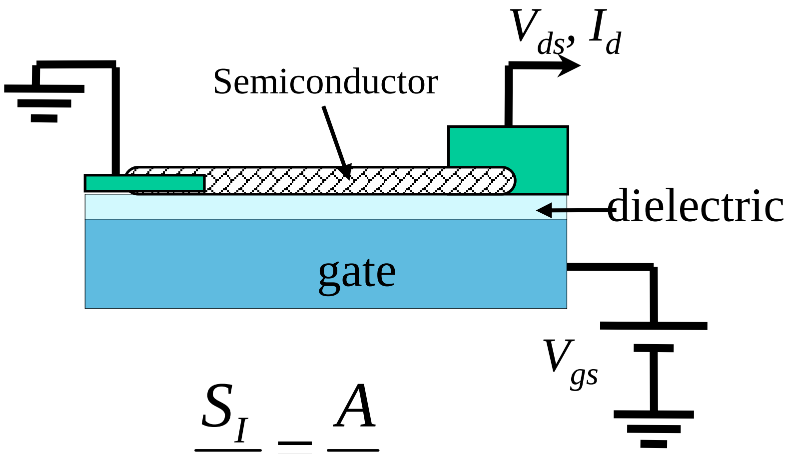




Nanotube Transistor



Gate voltage mediates the number of current carriers in the nanotube:



$$\frac{S_I}{I^2} = \frac{A}{f}$$

1/A is found to be linear in gate voltage

Carrier density linear in gate voltage $N = C(V_G - V_T)/q$

Current variance scales as 1/N for the CNT transistor!

***M. Ishigami, et al. submitted 2006**

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- Surface to volume scales as 1/(volume)$^{1/3}$

- At the nanometer scale, individual atomic scale structures rather than average over distribution of stuctures will determine functional behavior of individual nanostructures and nanodevices
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  it will be interesting

Implications

- Modern solid state electronics requires manufacturing perfection, material system stability
- Biology works in the regime of fluctuation-dominated systems. Error correction is ubiquitous in biological systems.
- Nanotechnology is at the borderline of these two behavior regimes. The challenge is to capture the best of both.

Acknowledgments

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- Collaborators: T. Einstein, J. Reutt-Robey, J.D. Weeks, W.C. Cullen, M. Fuhrer, P. Rous
- Post-docs and Students:
  - Pb system: K. Thuermer, M. Degawa, D. Dougherty, M. Ranganathan
  - Electron force and C60/Ag: C. Tao, A. Bondarchuk, T. Stasevich
  - Noise in Transistors: M. Ishigami, W. Yan
  - Organic monolayers: E. Gomar-Nadal, B. Xu, C. Tao

Experimental Statistical Mechanics at the Nanoscale

Nanoscale structures: fabrication, stability and evolution