Physics of Nanotechnology

What’s new at the nanoscale?

• Quantum confinement
• Surface-to-volume ratio
• Fluctuations and Entropy
Multi-atomic structures have a large density of available energy states. State occupancy is highly peaked near an average energy value.

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

\[ \frac{\sigma_E}{E} \approx \frac{1}{\sqrt{N}} \quad \frac{\sigma_\rho}{\rho} \approx \frac{1}{\sqrt{N}} \]
Scanning Tunneling Microscopy
Scanning Tunneling Microscopy

50nm x 50 nm ACA-templated C₆₀

STM tip with patterned Fe/Si

10μm x 10 μm electromigrated Si

C-nanotube imaged in device
Model System - Pb Crystallites
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 $1/(\text{volume})^{1/2}$
- Surface to volume scales as $1/(\text{volume})^{1/3}$

- At the nanometer scale, individual atomic scale structures rather than average over distribution of structures 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
Repeated STM scans across the same spatial location reveal structure changes as a function of time, $x(t)$. 
Analysis of Fluctuations...

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

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

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

Ranganathan, Dougherty et al, PRL 2005
Modeling

- Local curvature $\kappa$ determines local chemical potential

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

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

- Model first with attachment/detachment kinetics

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

- Begin numerical solution with arbitrary initial shape constrained to join the external circle smoothly.
- Period of 23 minutes is reproduced with $\tau_a = 1.5$ 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

Z_w=-42e
Z_w=-34e
Z_w=-31e

Z_w=-4e
Z_w=-12e

Fa \sim 10^{-7}eV/unit cell

Perturbation of Step Fluctuations

**Step Position, x(t)**

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

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

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

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

EM force causes deviations in correlation of step wandering

P.Rous, to be published
Ag Thin Film with Bias Current

\[ \tau_\eta = 1.7 \times 10^{-8} \text{s} \]

A. Bondarchuk, to be published
Fluctuations and Noise

Known mesoscopic behavior:

\[
\frac{S_I}{I^2} = \frac{1}{f} \frac{\alpha}{N}
\]

1.2-1.8 nm diameter Carbon Nanotube transistors
Nanotube Transistor

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

\[ N = C(V_G - V_T)/q \]

1/A is found to be linear in gate voltage

Carrier density linear in gate voltage

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

*M. Ishigami, et al. submitted 2006*
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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.
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  ➔ Organic monolayers: E. Gomar-Nadal, B. Xu, C. Tao
Experimental Statistical Mechanics at the Nanoscale

Nanoscale structures: fabrication, stability and evolution