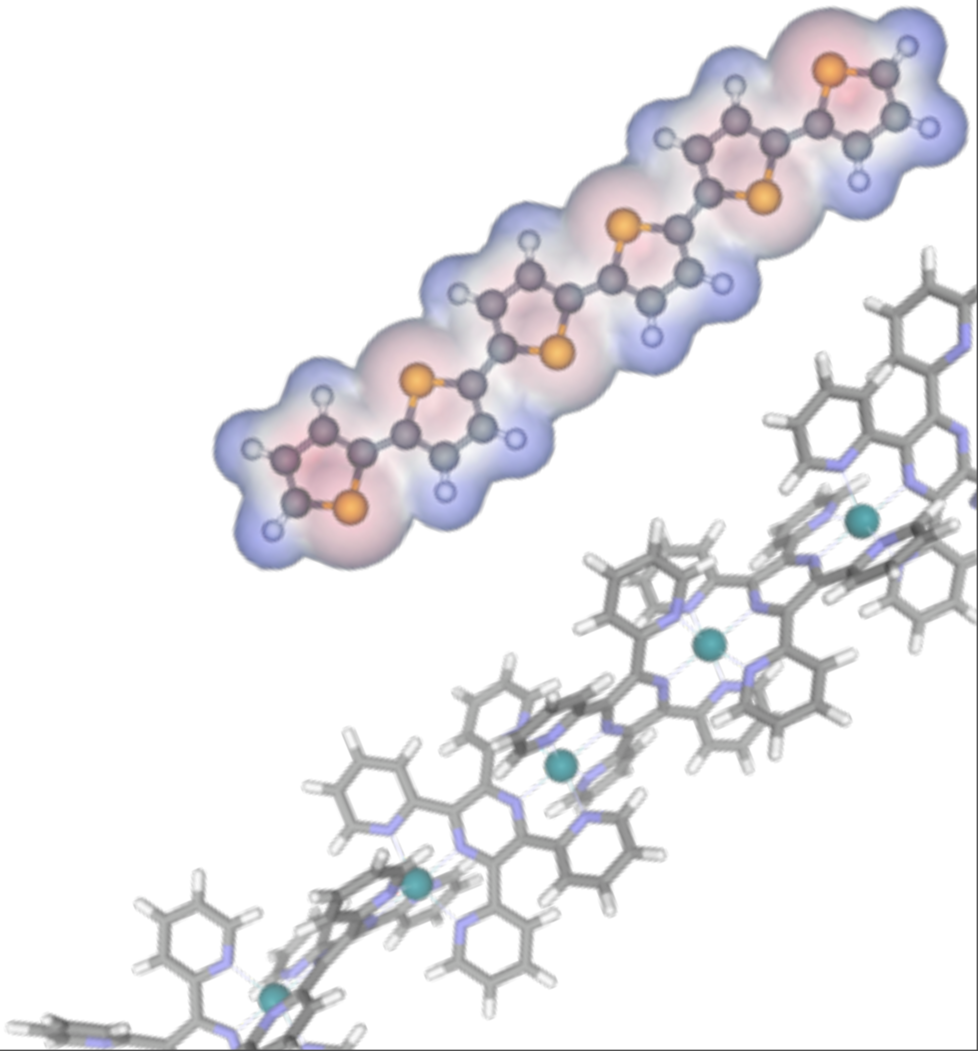
Molecular Electronics For Fun and Profit(?)

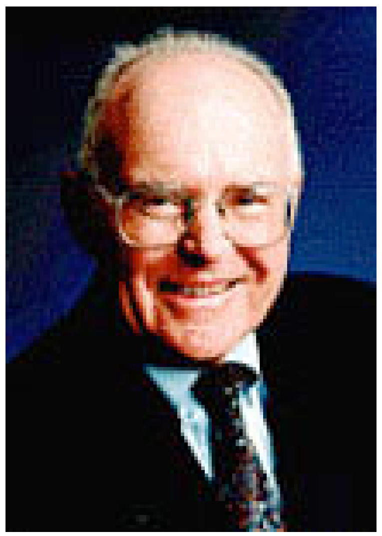
Prof. Geoffrey Hutchison
Department of Chemistry
University of Pittsburgh
geoffh@pitt.edu

July 22, 2009

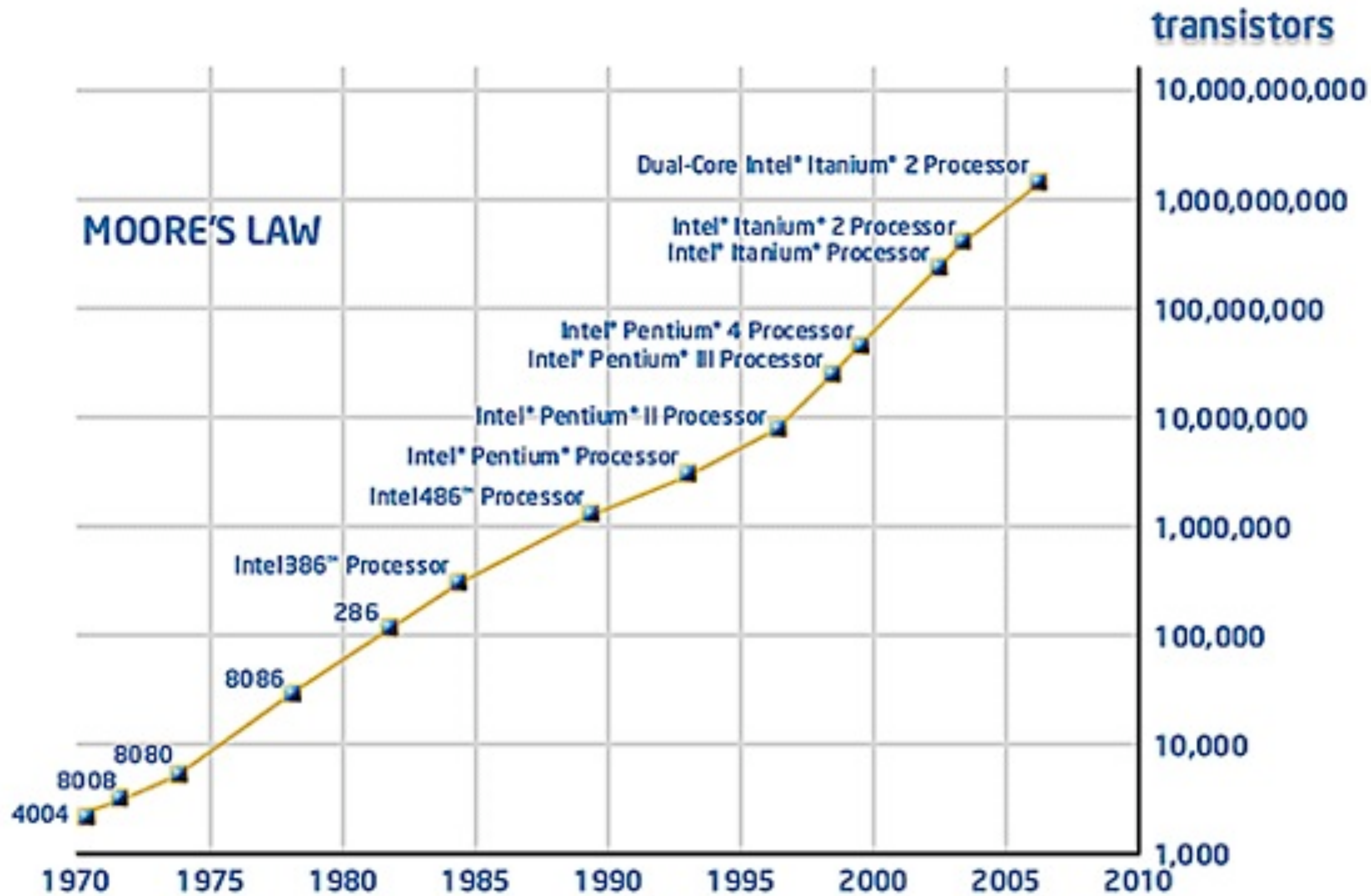


http://hutchison.chem.pitt.edu

Moore's "Law:" Transistor Count Doubles Every 18 Months



Gordon Moore:
Co-founder of Intel



From Intel Corp. circa 2007

Similar trends observed in chip performance, price per peformance, etc.

Moore-San's Law

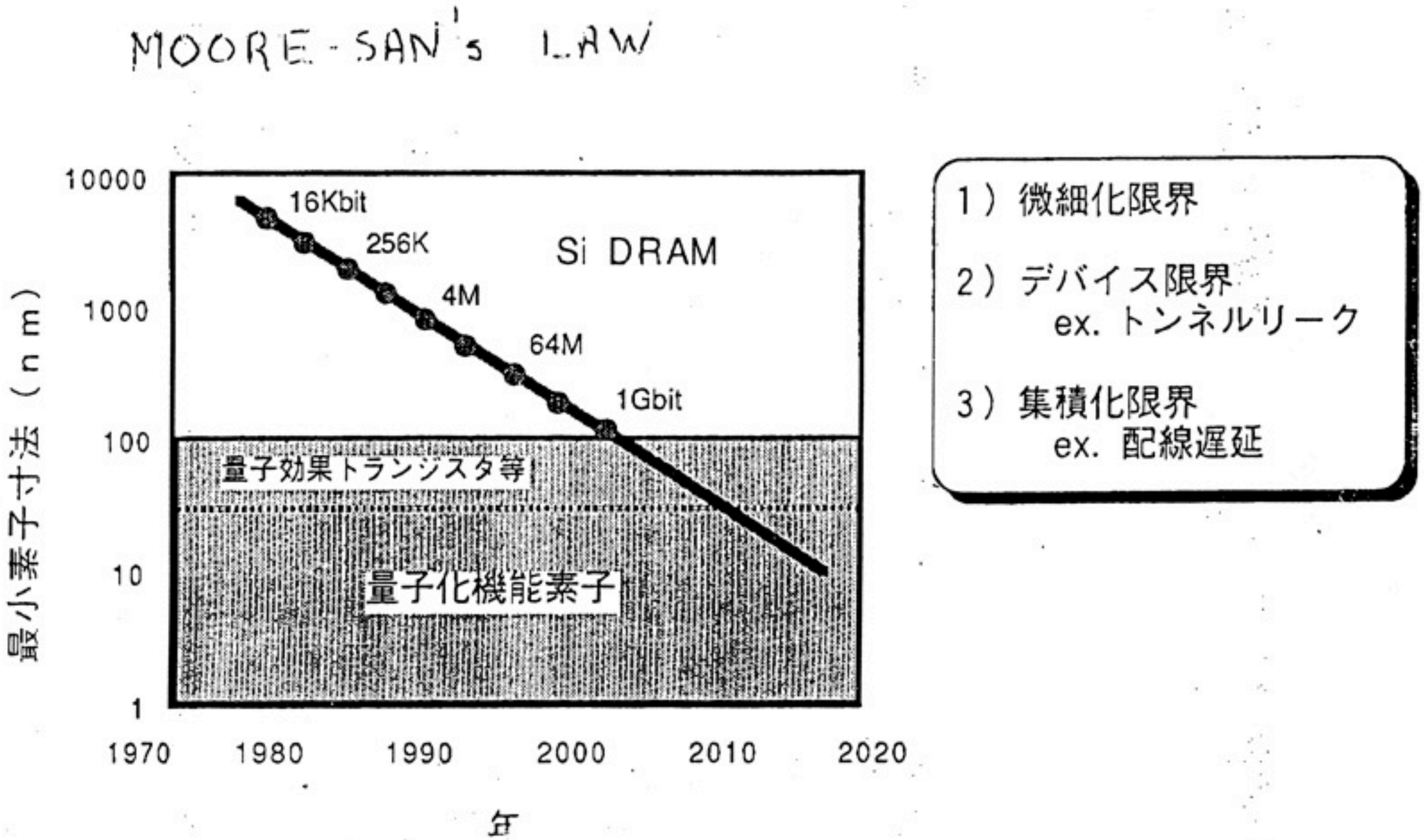
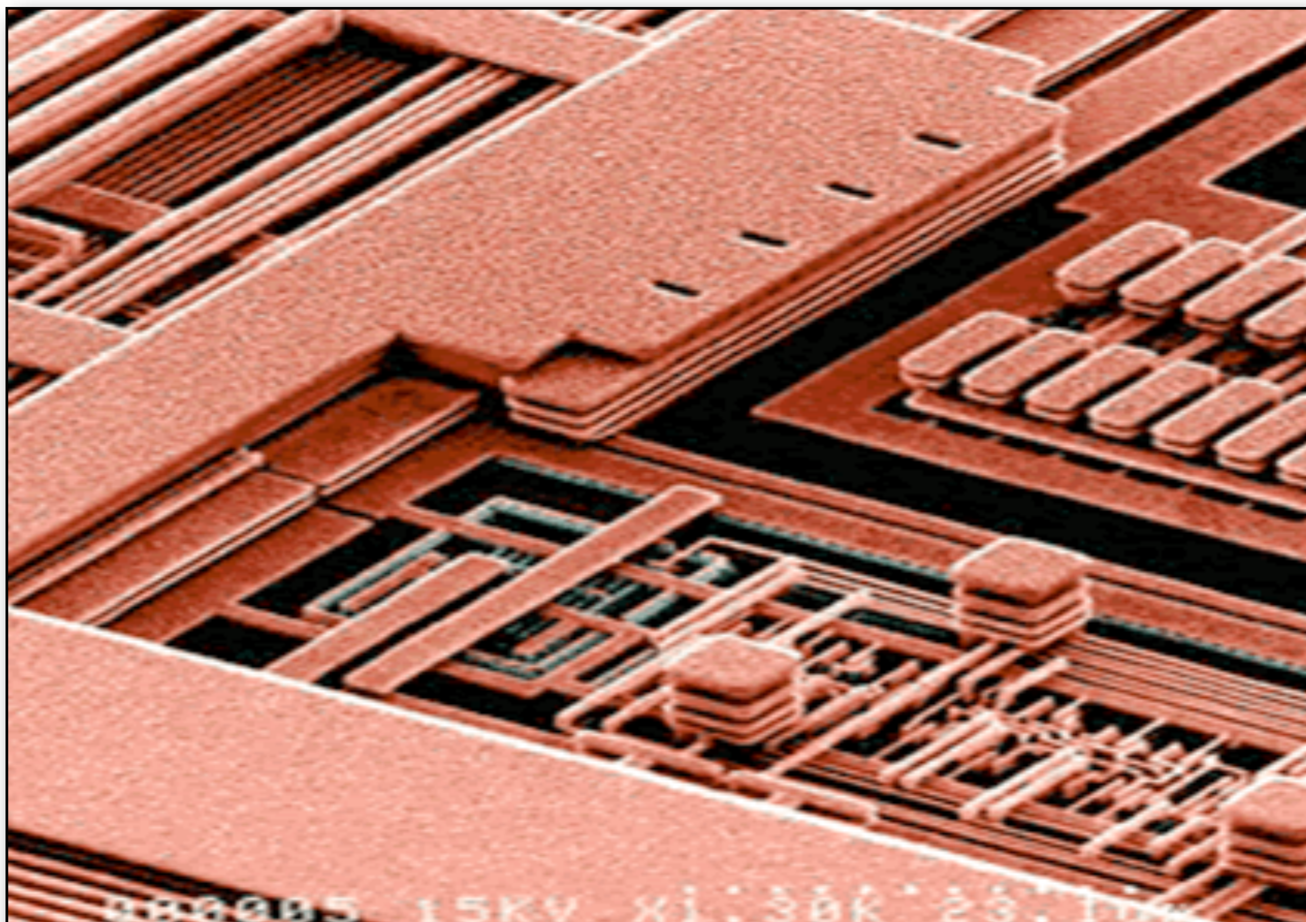


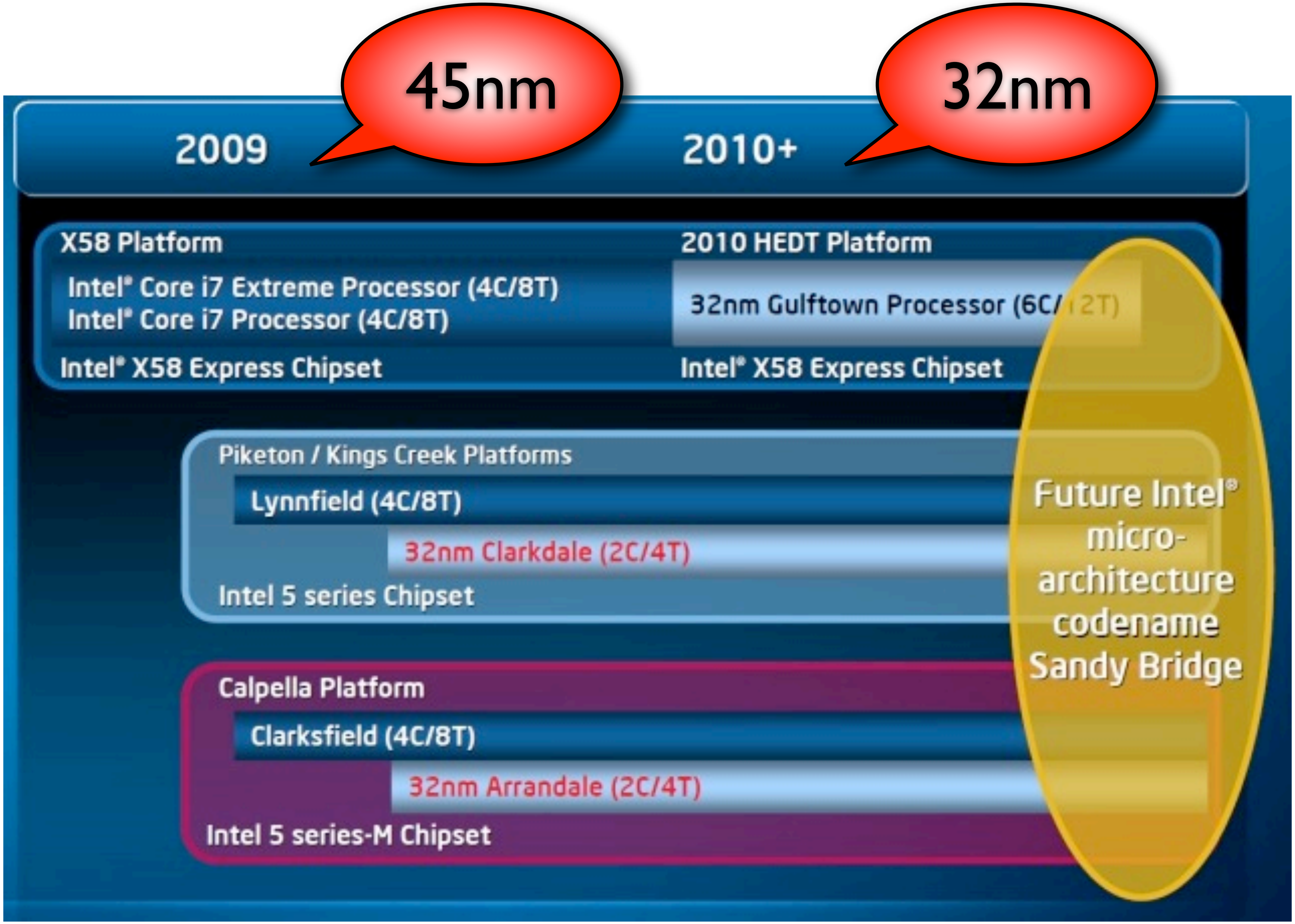
Image courtesy M. Ratner

Don’t Underestimate Silicon...

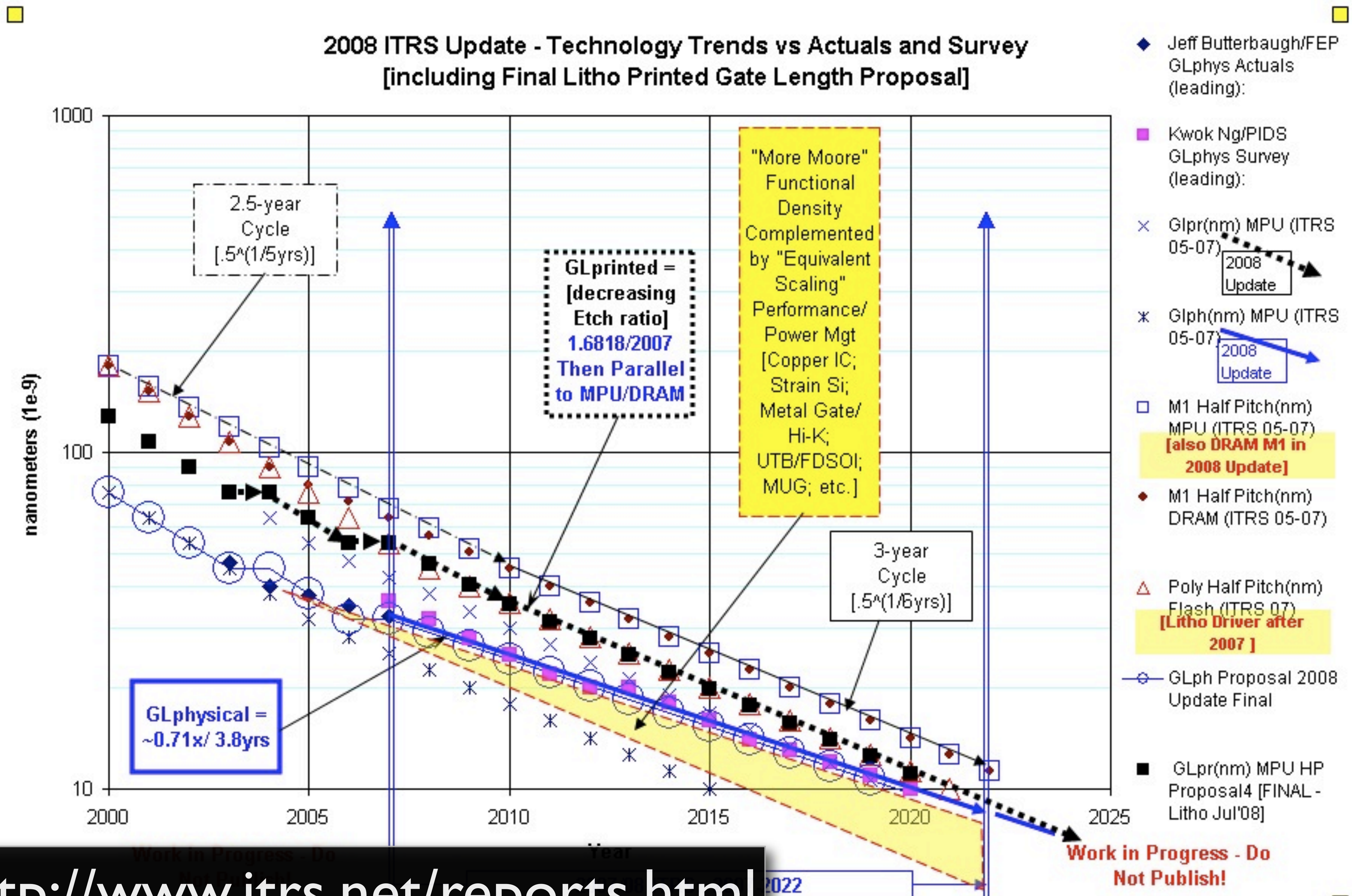


Actually, these are from 1997(!)

Current Intel Roadmap



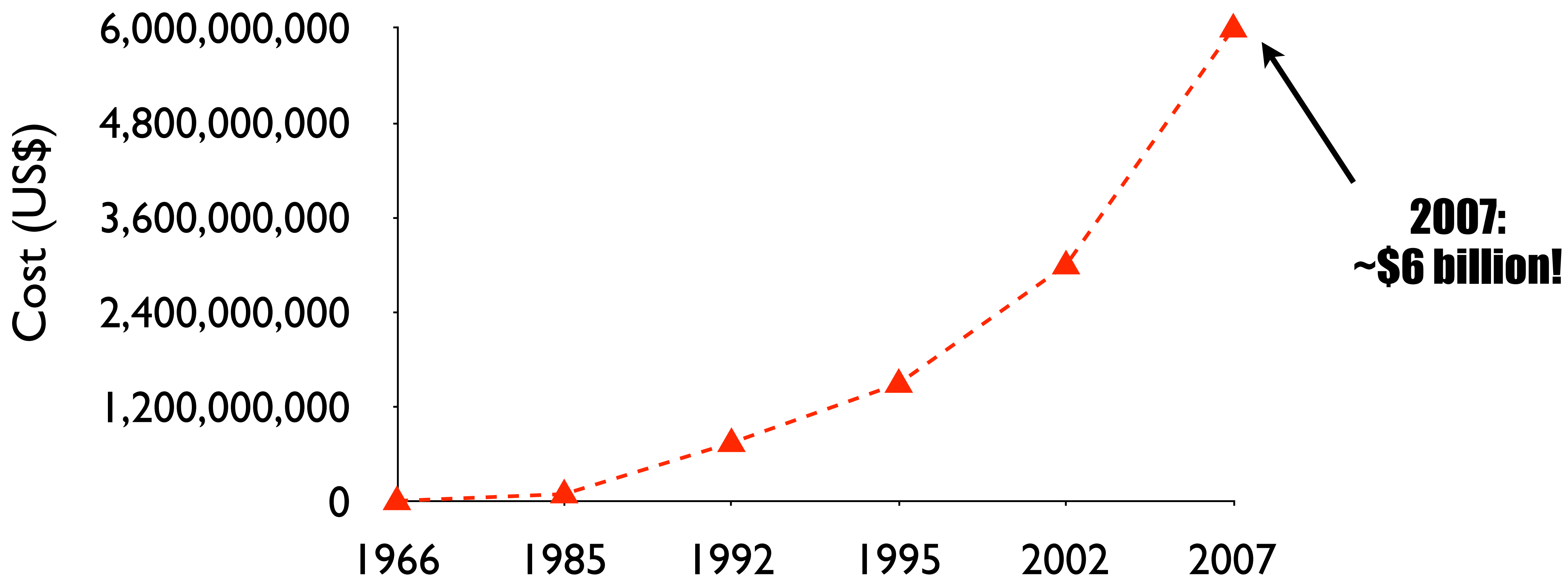
International Technology Roadmap for Semiconductors (ITRS)



http://www.itrs.net/reports.html

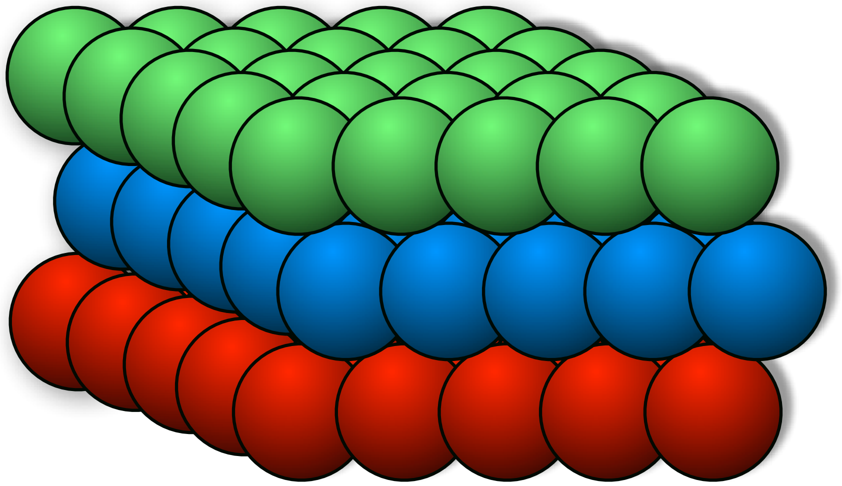
Moore's *Second* Law: Exponential Economics

Cost of a building a new fabrication plant ***doubles*** every 3-4 years:

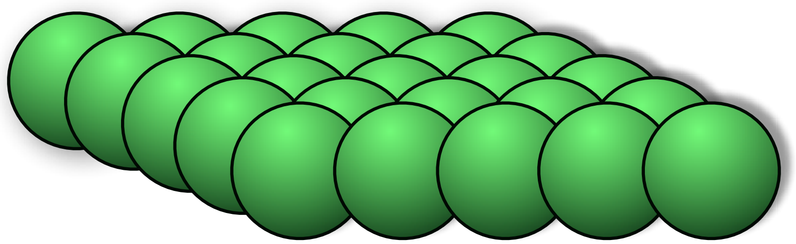


Advances in conventional lithography are quickly becoming cost-prohibitive!

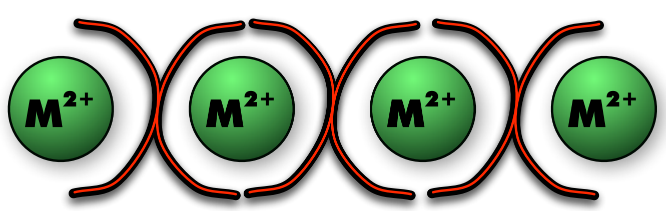
Molecular Electronics: Just Nanoscale?



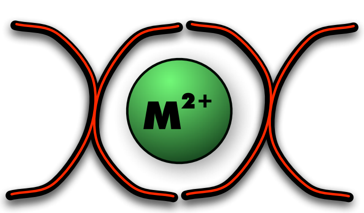
3D: Bulk Films

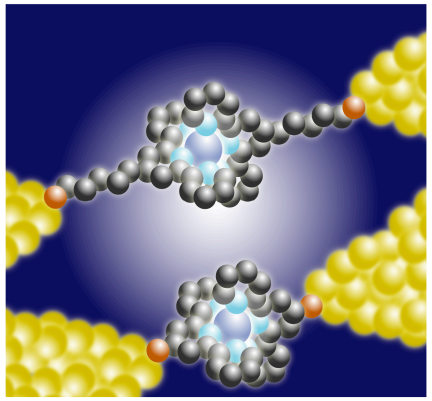


2D: Monolayer



1D: Chains





0D: Individual Molecules

Why Organic Electronics?

Relative to Inorganic Materials:

Pros

- Greater "tailorability" through synthetic chemistry
- "Wet" deposition
    - Wide-area
    - Inexpensive
- Flexible, lightweight
- Synthesis = 6.02×10^{23}

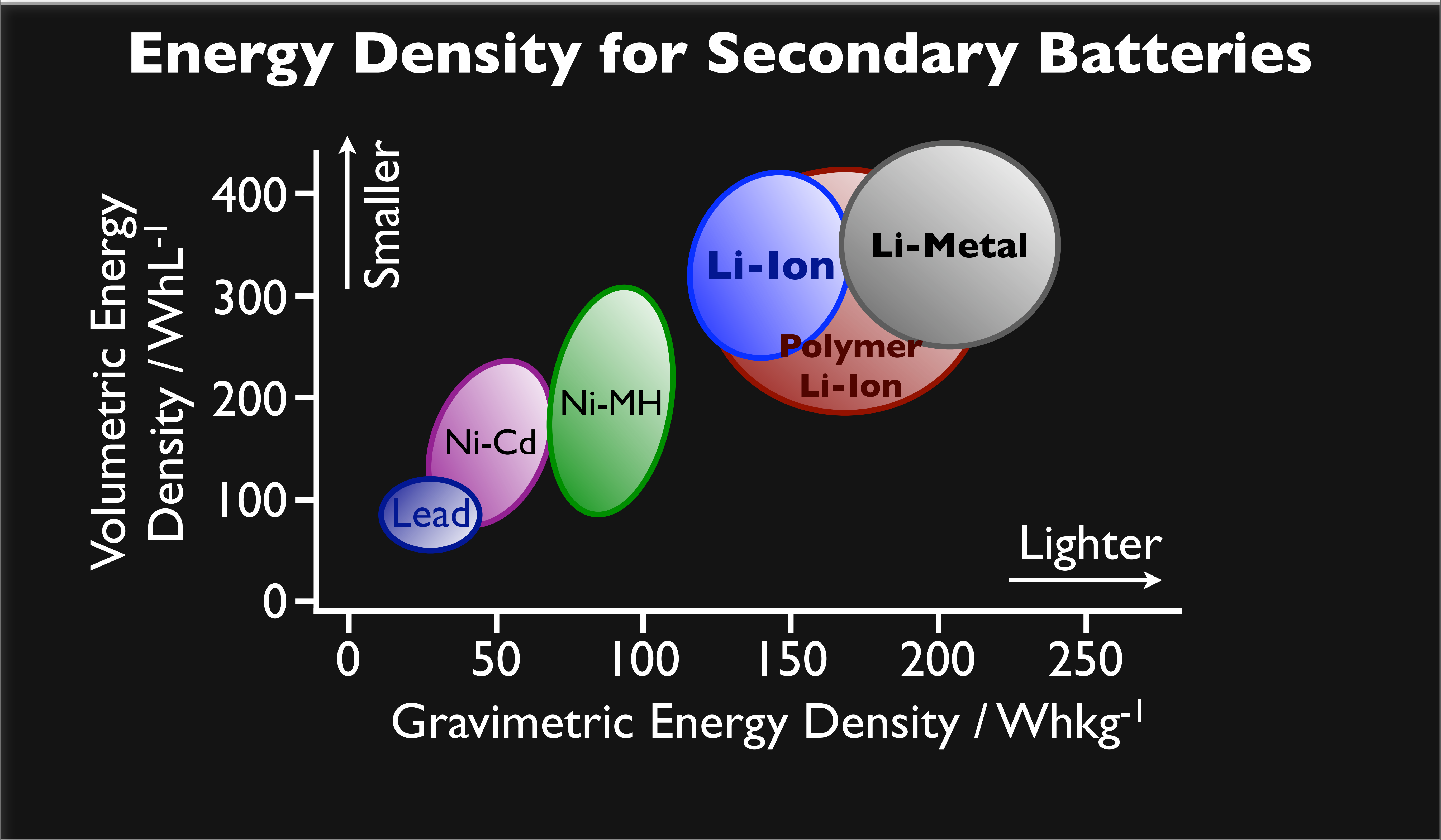
Cons

- Lower electron mobility
- Slower switching speeds
- Hard to obtain complementary *p*/*n* logic
- Integration into industry?

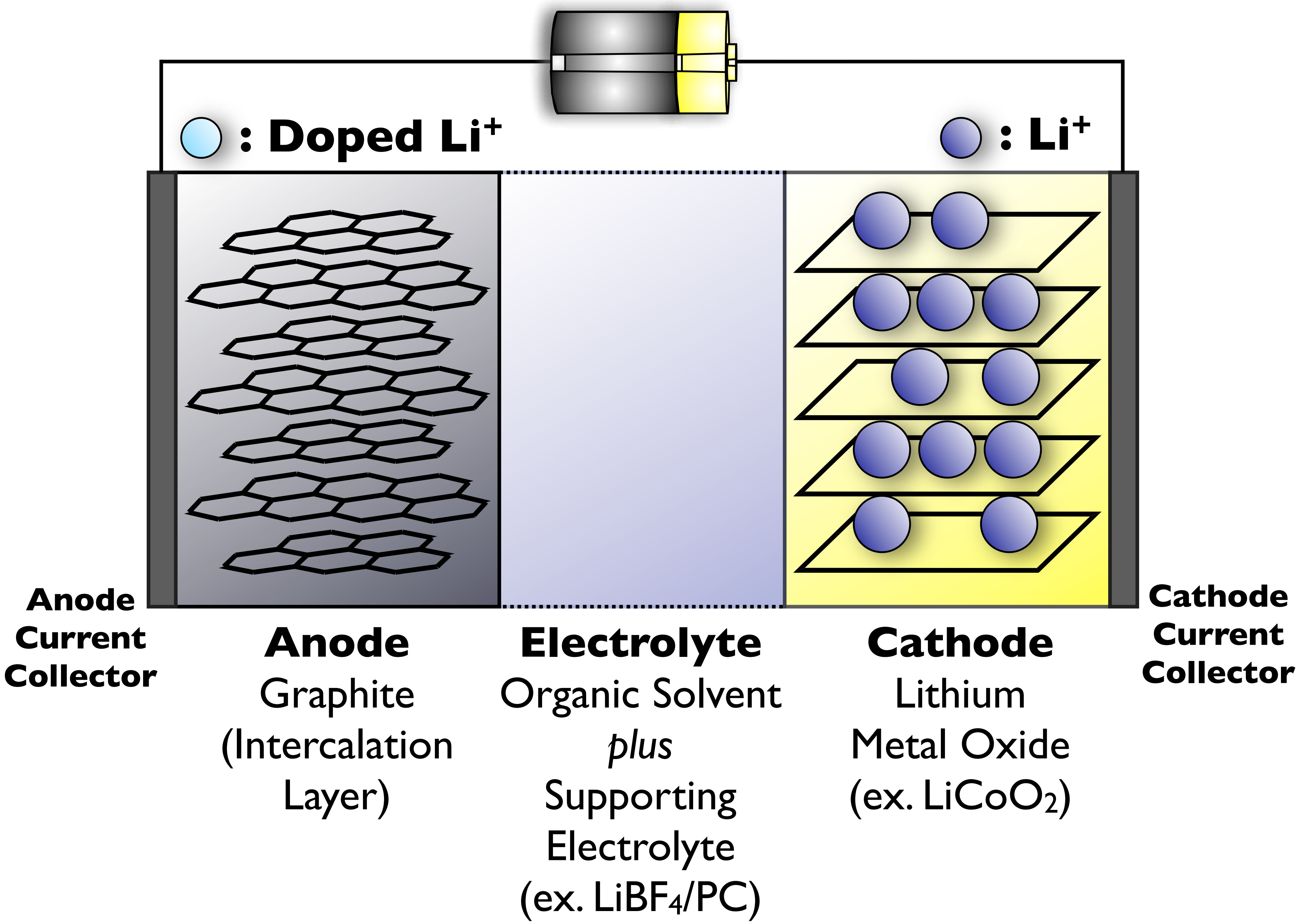
Broad Applications for Molecular Electronic Materials

- Light-Emitting Diodes
  - *Hole transport layers*
  - *Flexible anodes*
- Photovoltaic Devices
- Thin-Film Transistors
  - *Flexible circuits*
- "Smart" Windows
  - *Fast color changes*
- Anti-Static Films
  - *Device fabrication*
  - *Photographic film*

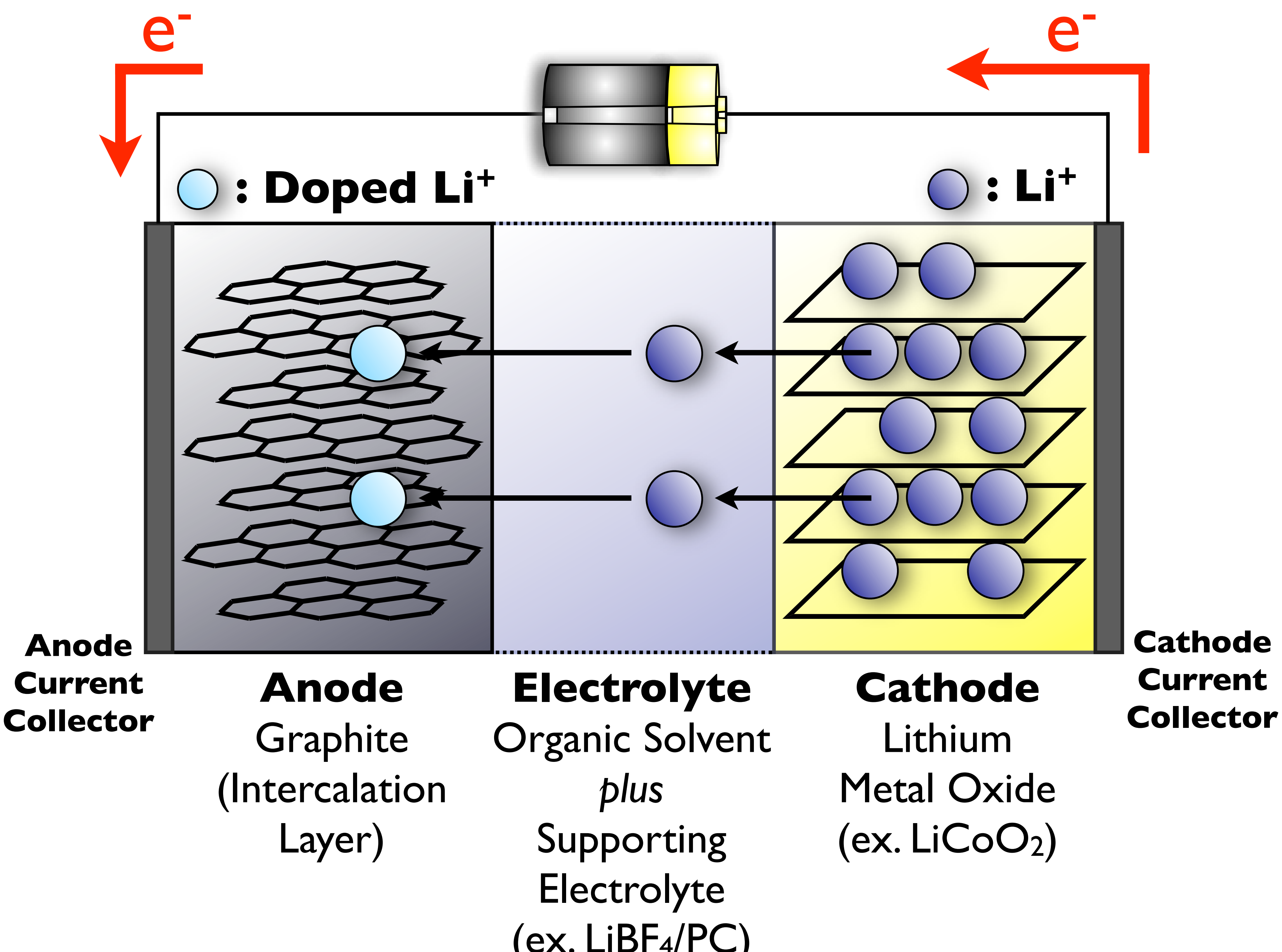
Batteries: Not Just Inorganics...



Reaction Mechanism for LIBs

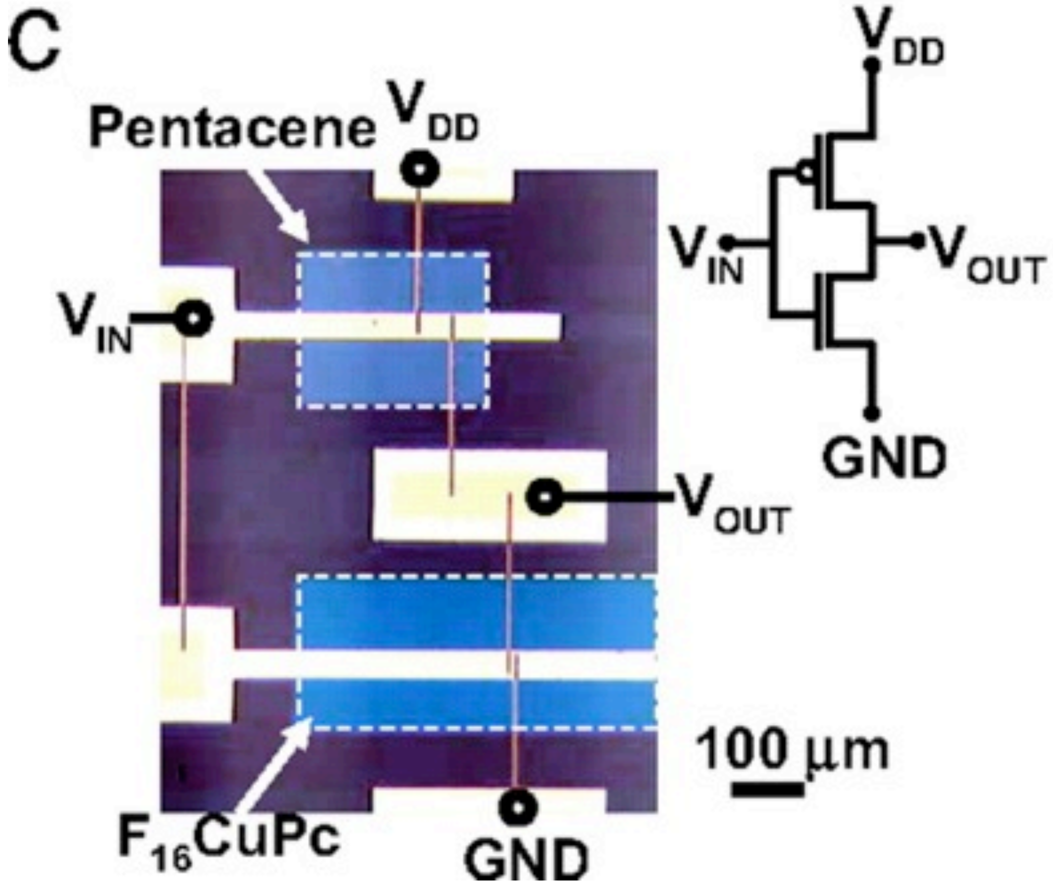


Reaction Mechanism for LIBs



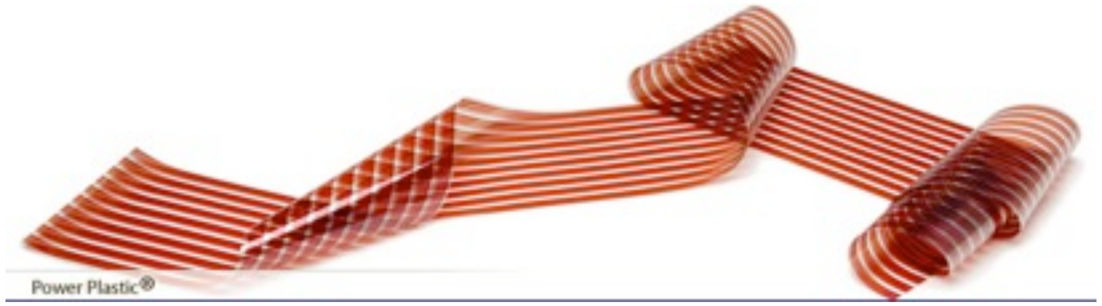
Ink-Jet Printing of Organic Electronics

Ink-Jet Printing Transistors

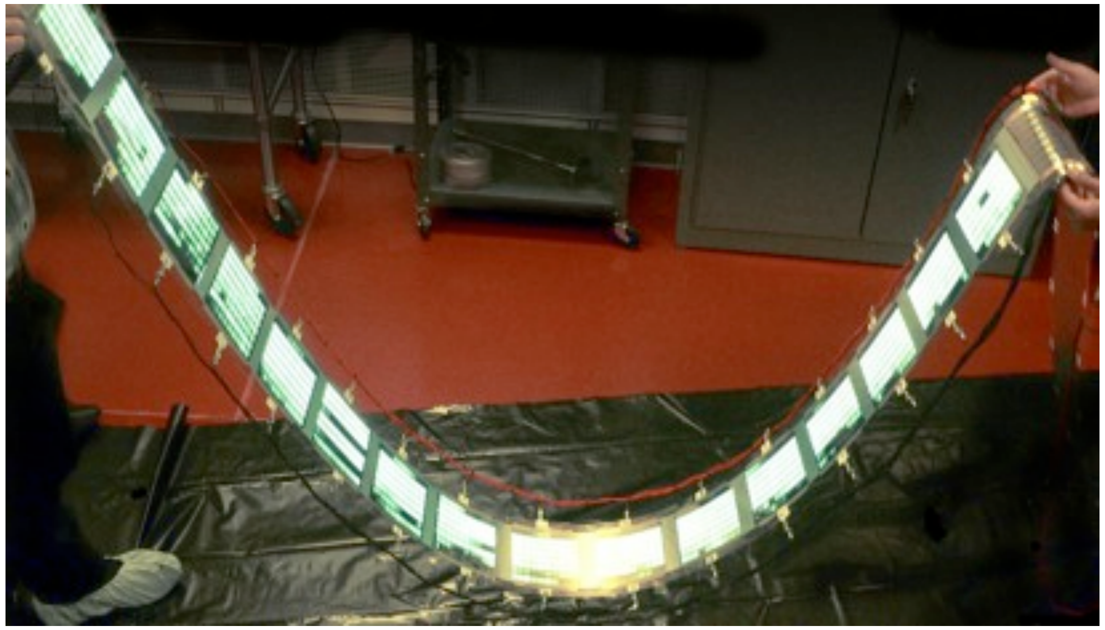


Sekitani *et al. PNAS* **2008** p. 4976

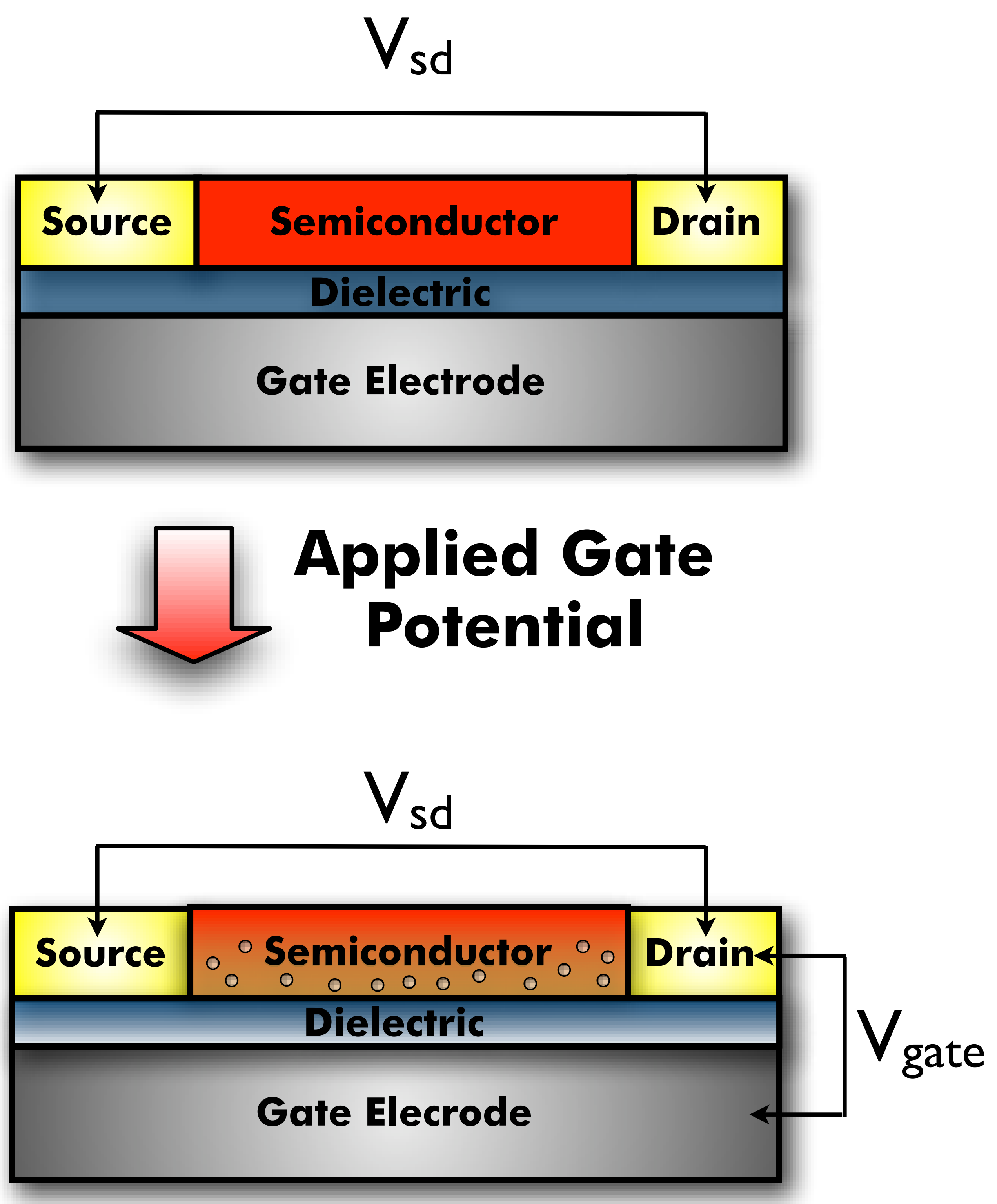
Konarka: Ink Jet Printing for Solar Cells
Mar. 4, 2008



GE: Ink Jet Printing for Displays
Mar. 11, 2008



Organic Field-Effect Transistors

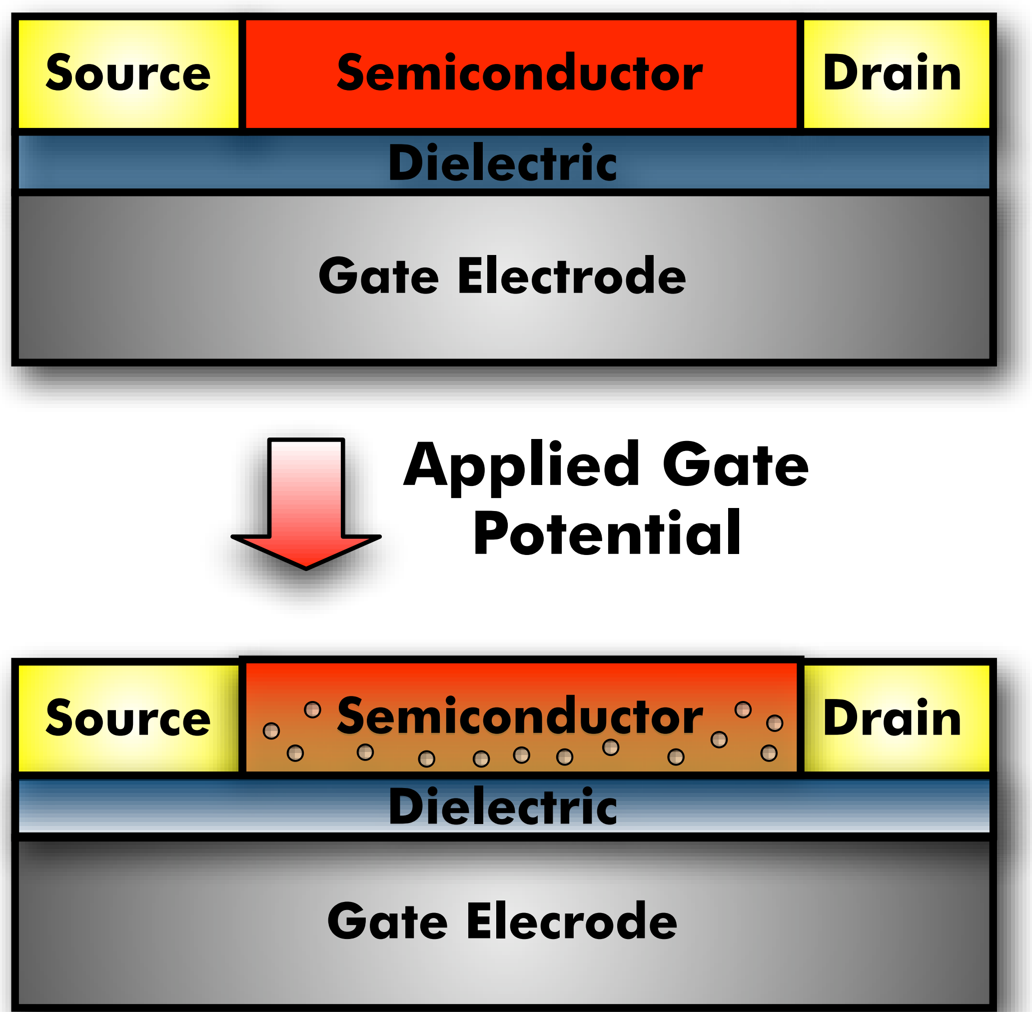


$I_{sd} \sim 0.0$ A “Off”

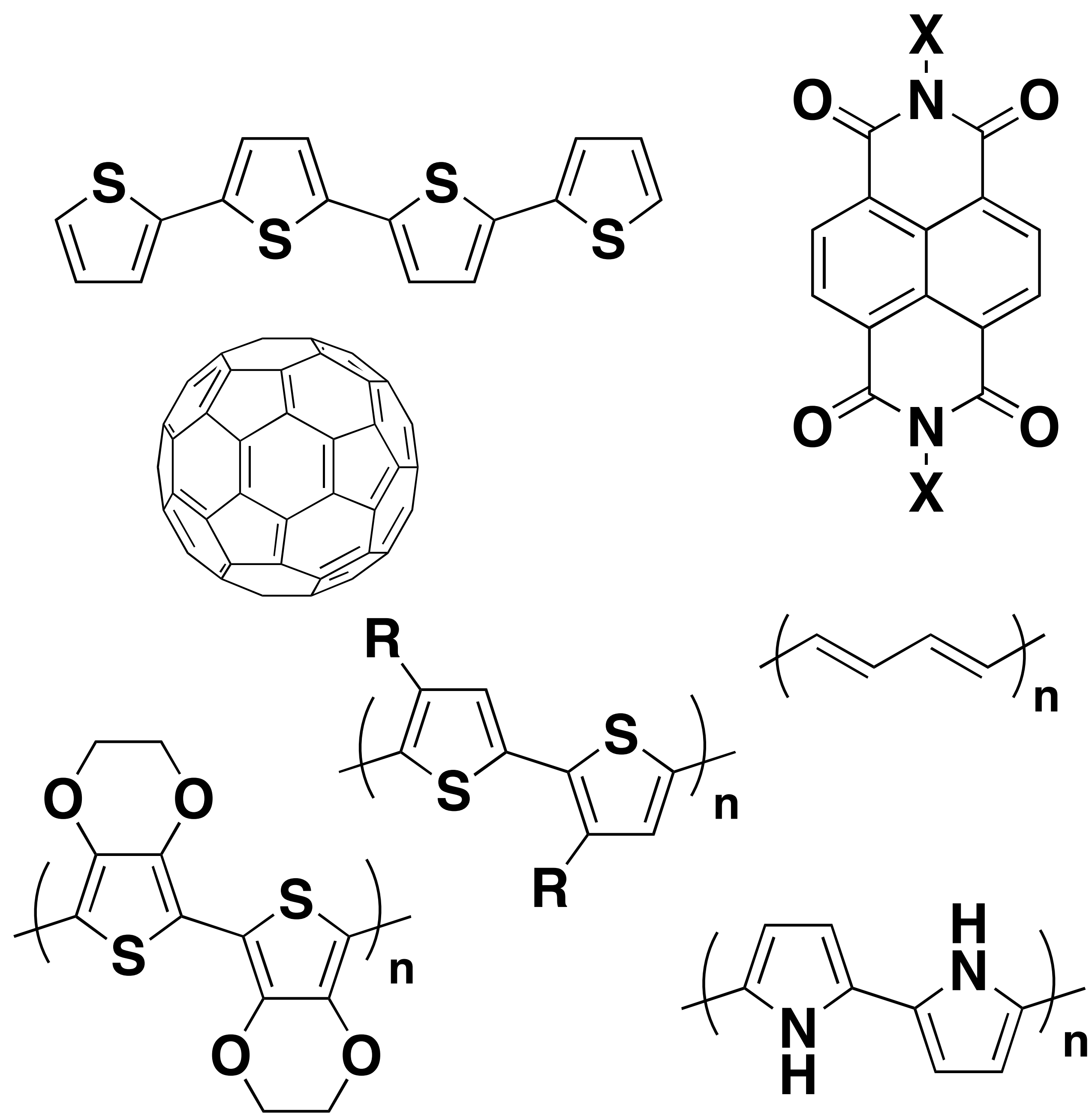
$I_{sd} = 10^x$ A “On”

Organic Field-Effect Transistors

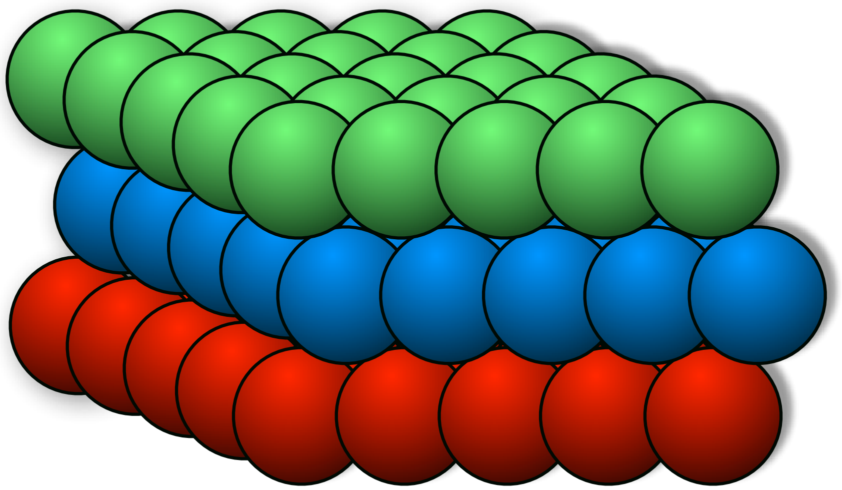
Operation of an Organic Field-Effect Transistor



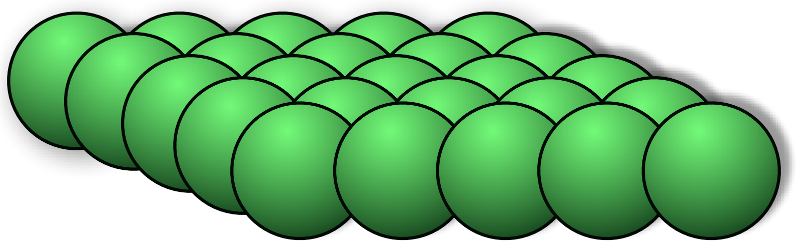
Example Organic Semiconductor Materials



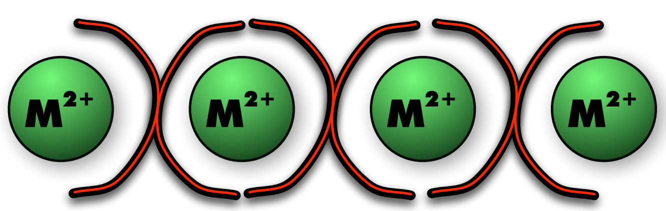
Back to the Nanoscale...



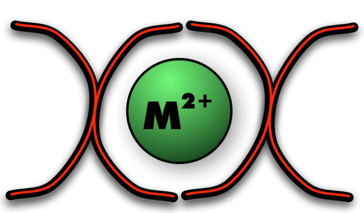
3D: Bulk Films

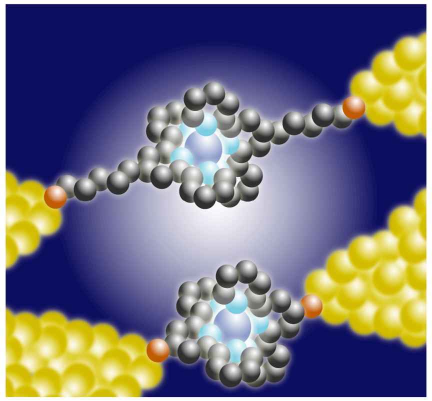


2D: Monolayer



1D: Chains

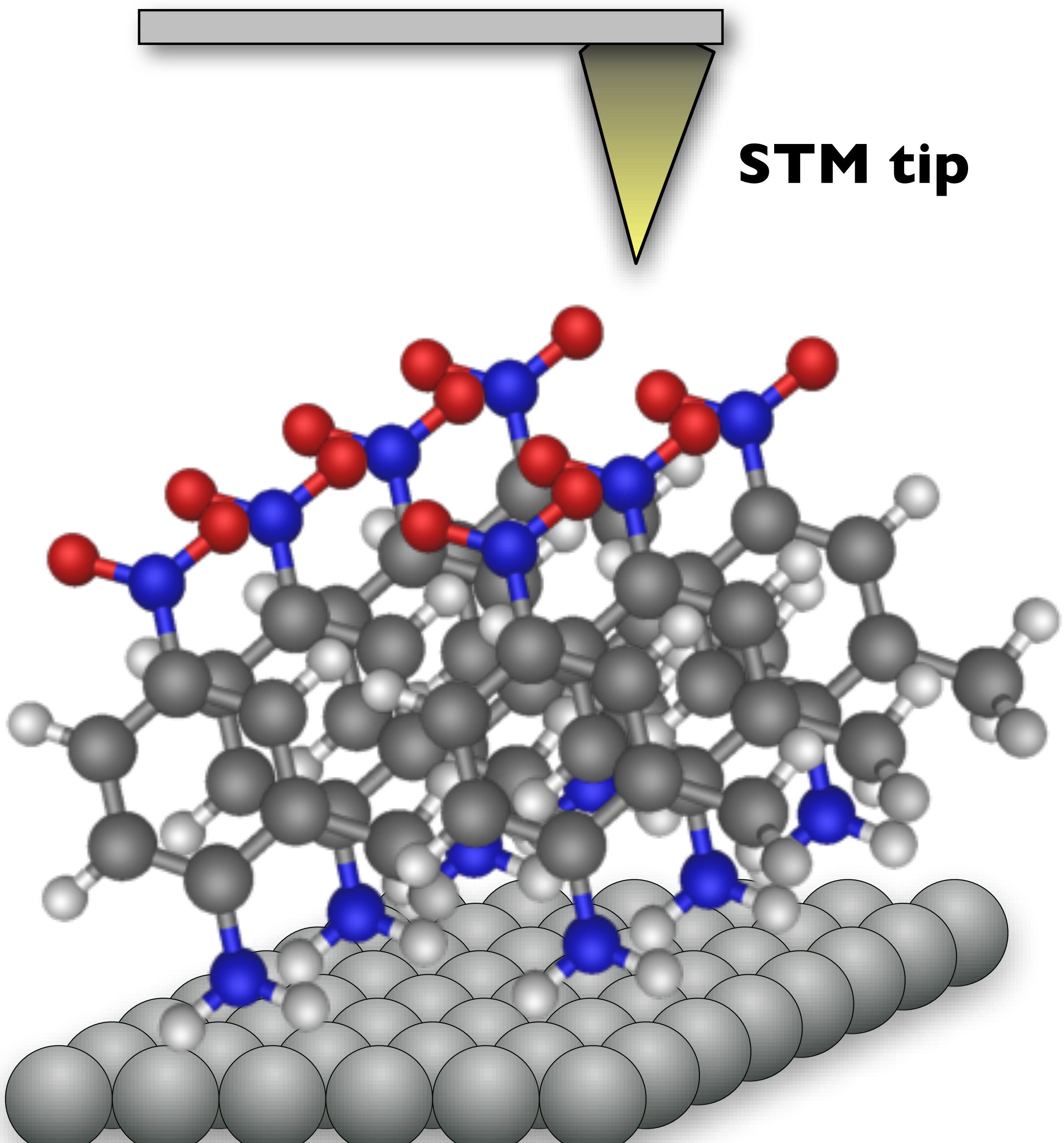


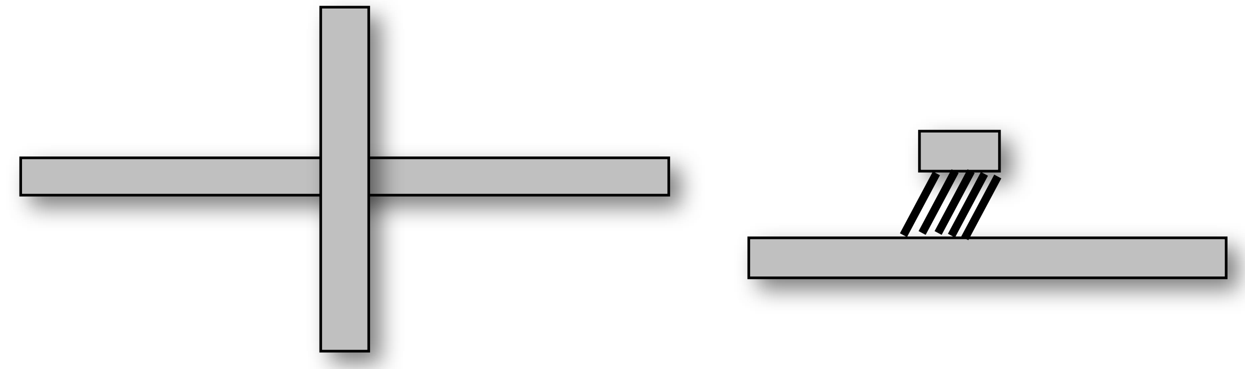


0D: Individual Molecules

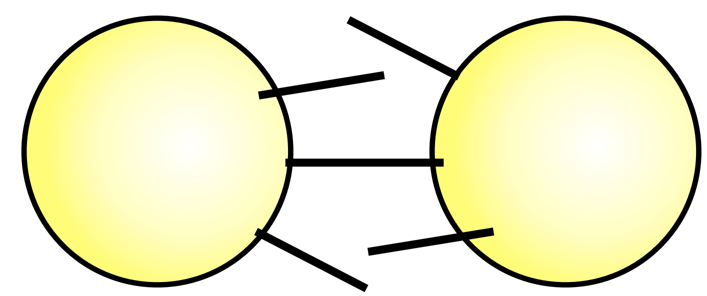
Enough Bulk Conductivity: How Do You Wire Up a Molecule?

Many, Many Methods...



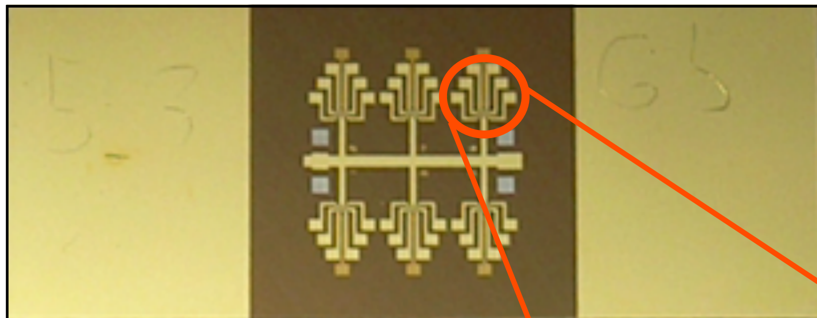


Crossbars

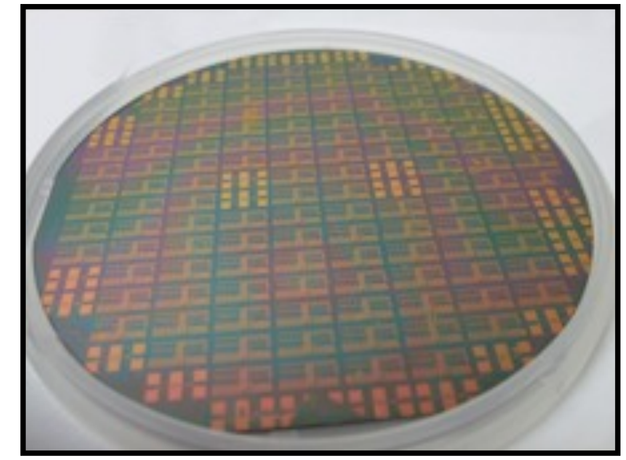


Break Junctions

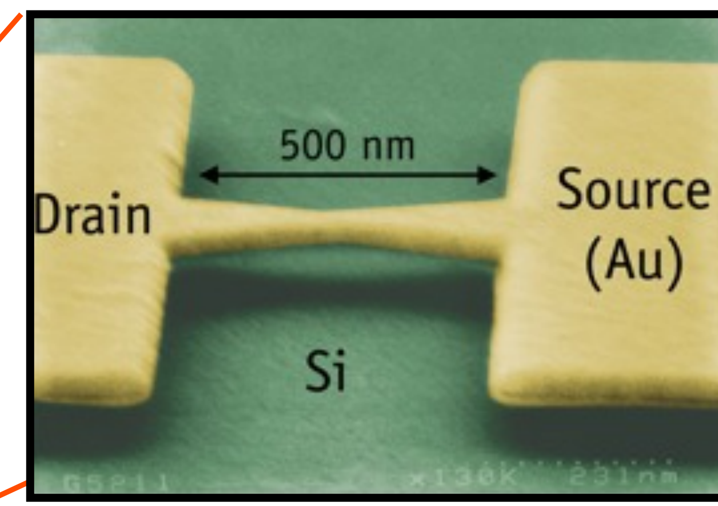
Example: Device Fabrication



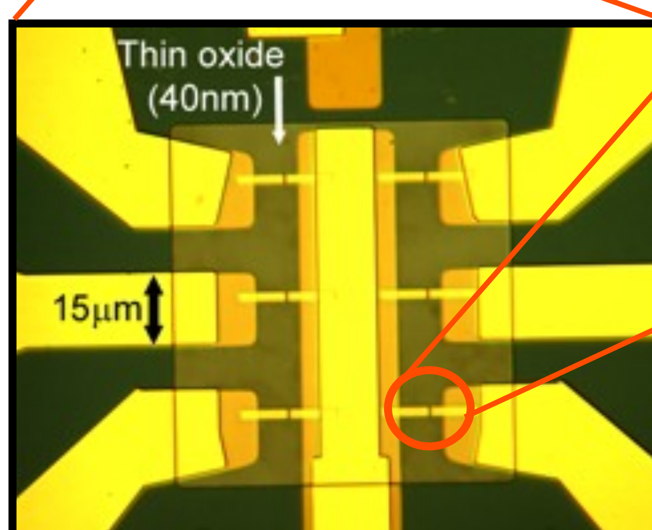
Sixty 15 mm x 6 mm chips are fabricated on a thin (200 μm) Si wafer.



Bonding pads are defined by photolithography.



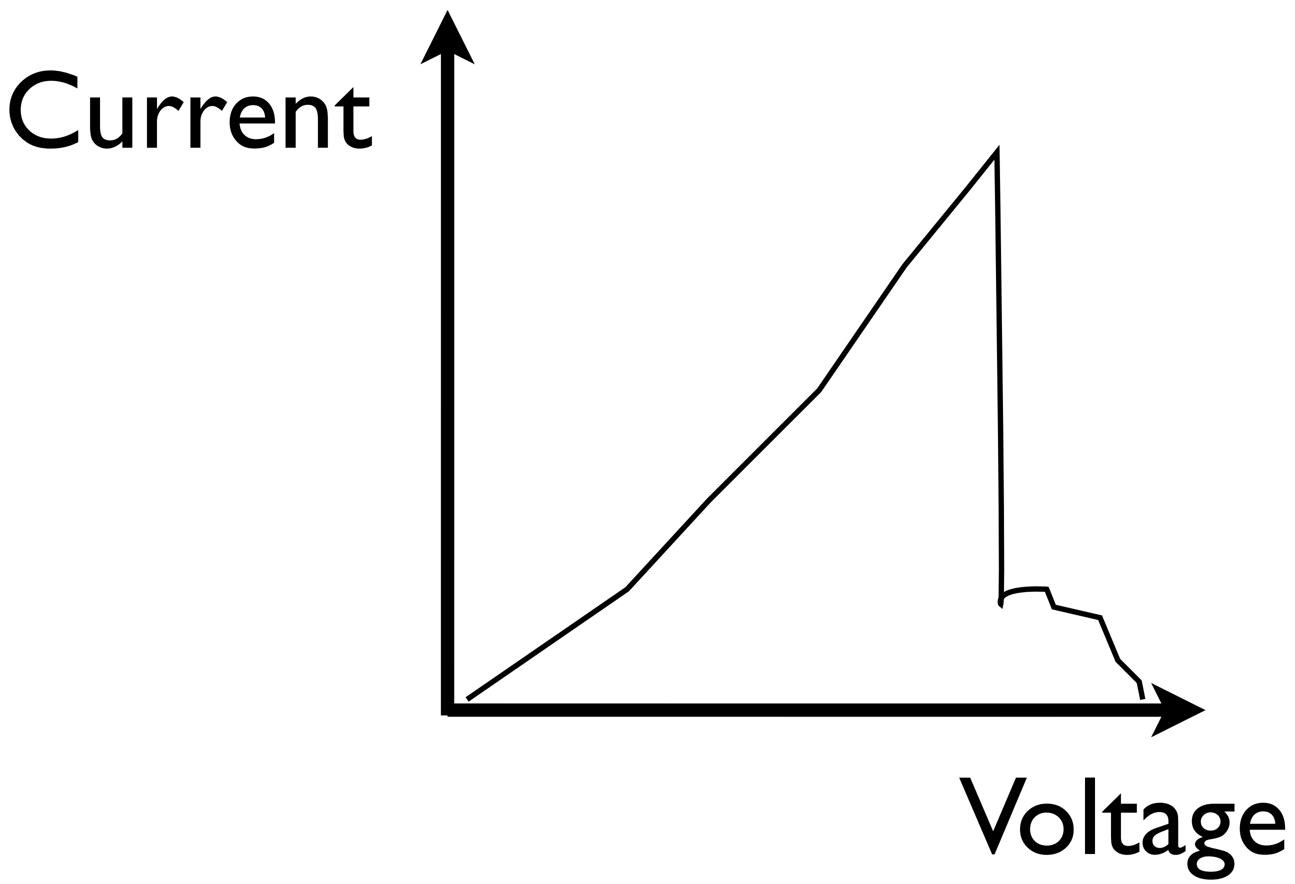
Critical features are defined by e-beam lithography.

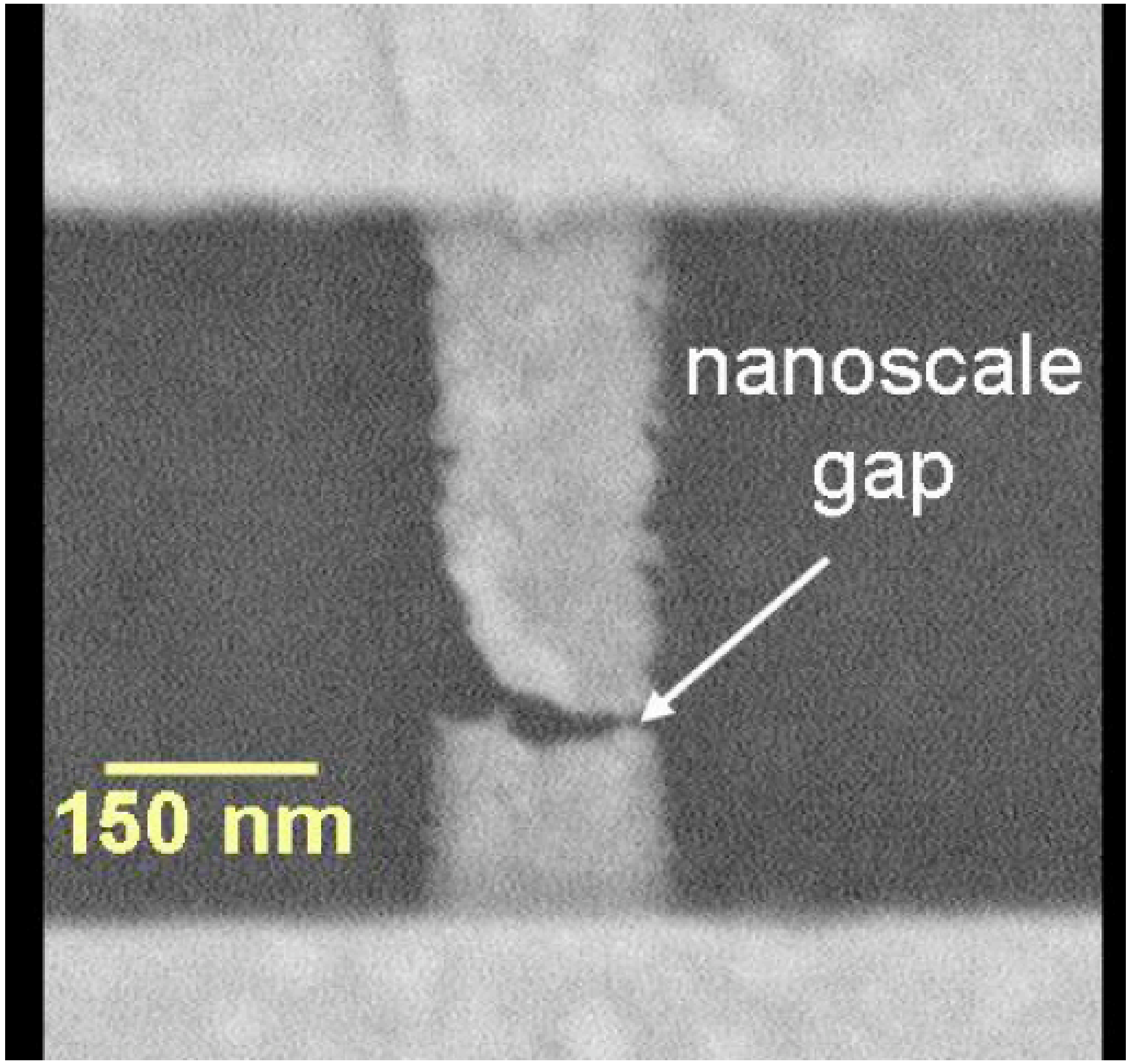


A timed etch is used to suspend the junctions.

Ralph Group, Cornell

Electromigration: Making a 1-3nm Gap

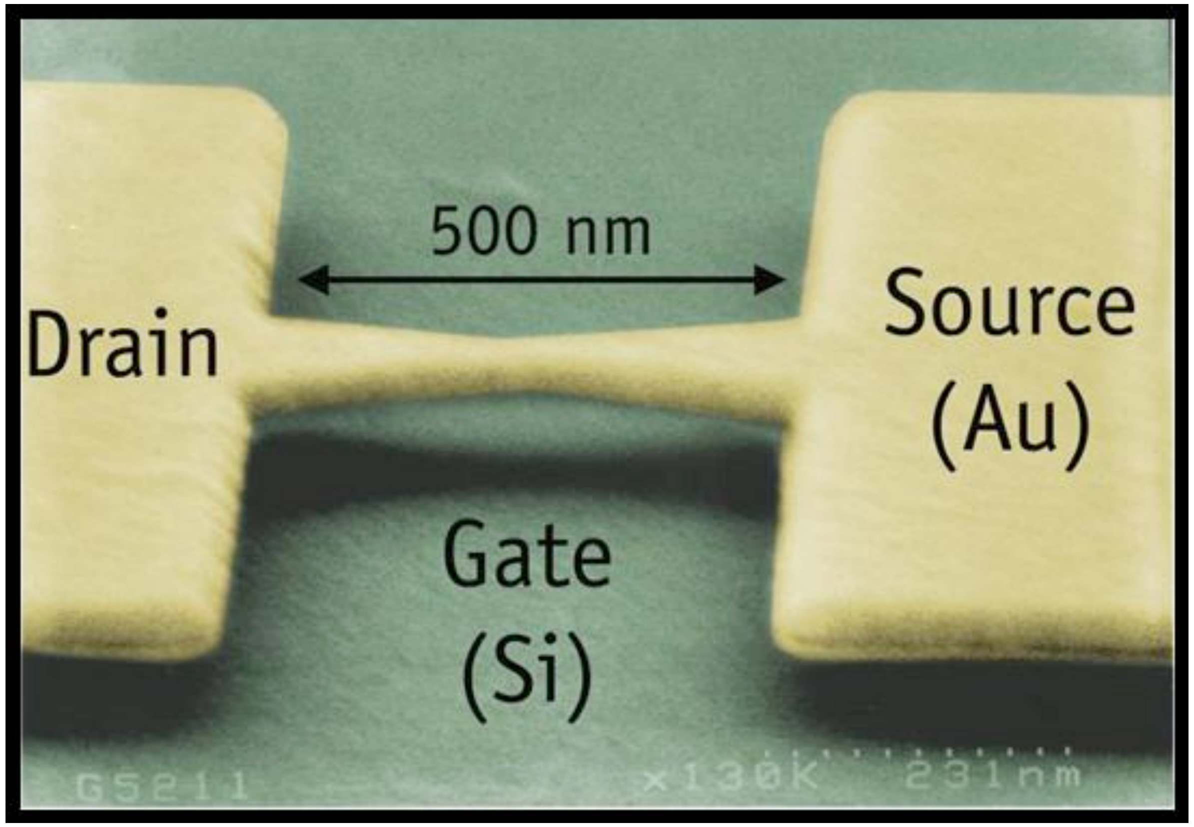


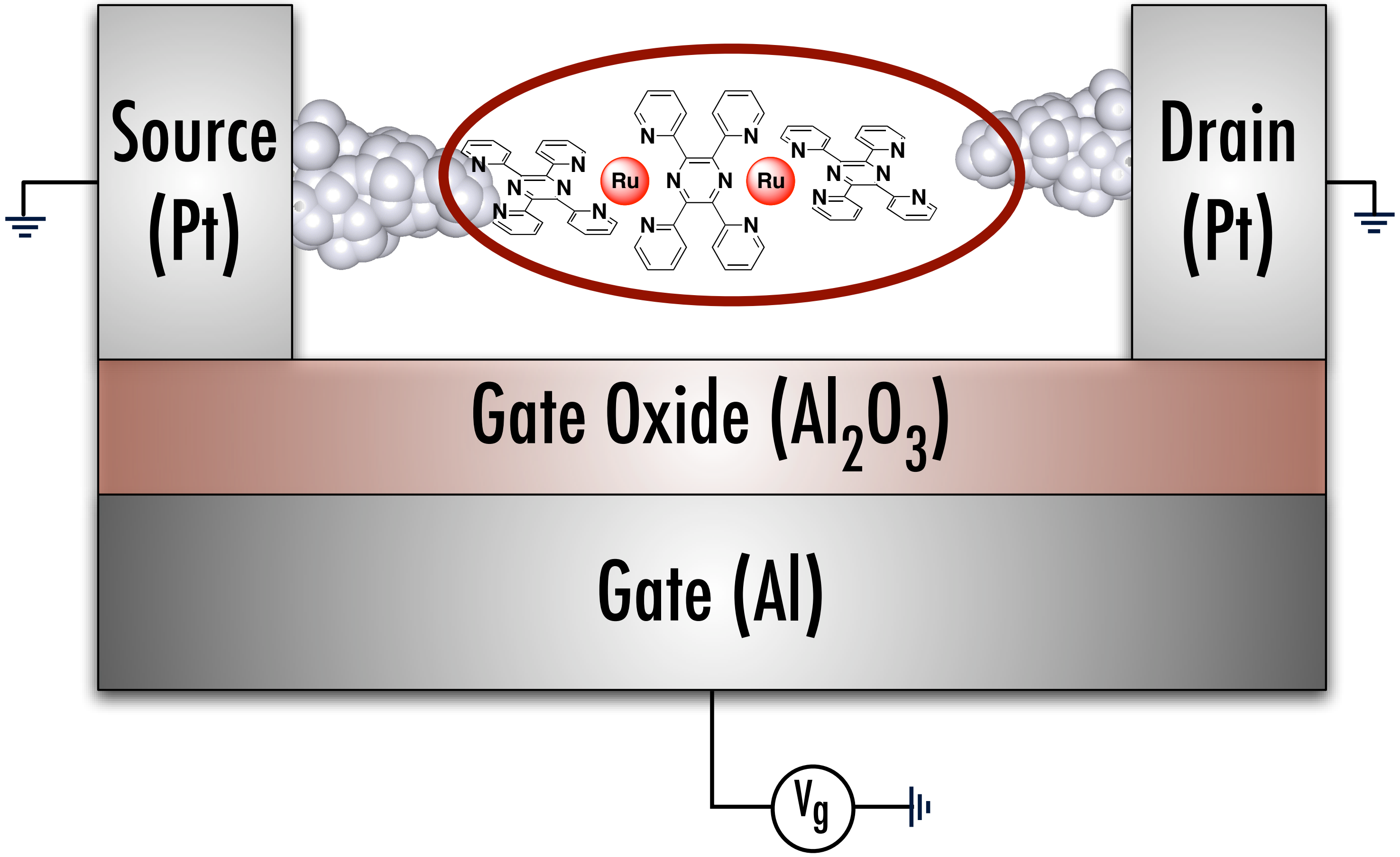


Ralph Group, Cornell

Single Molecule Transistors

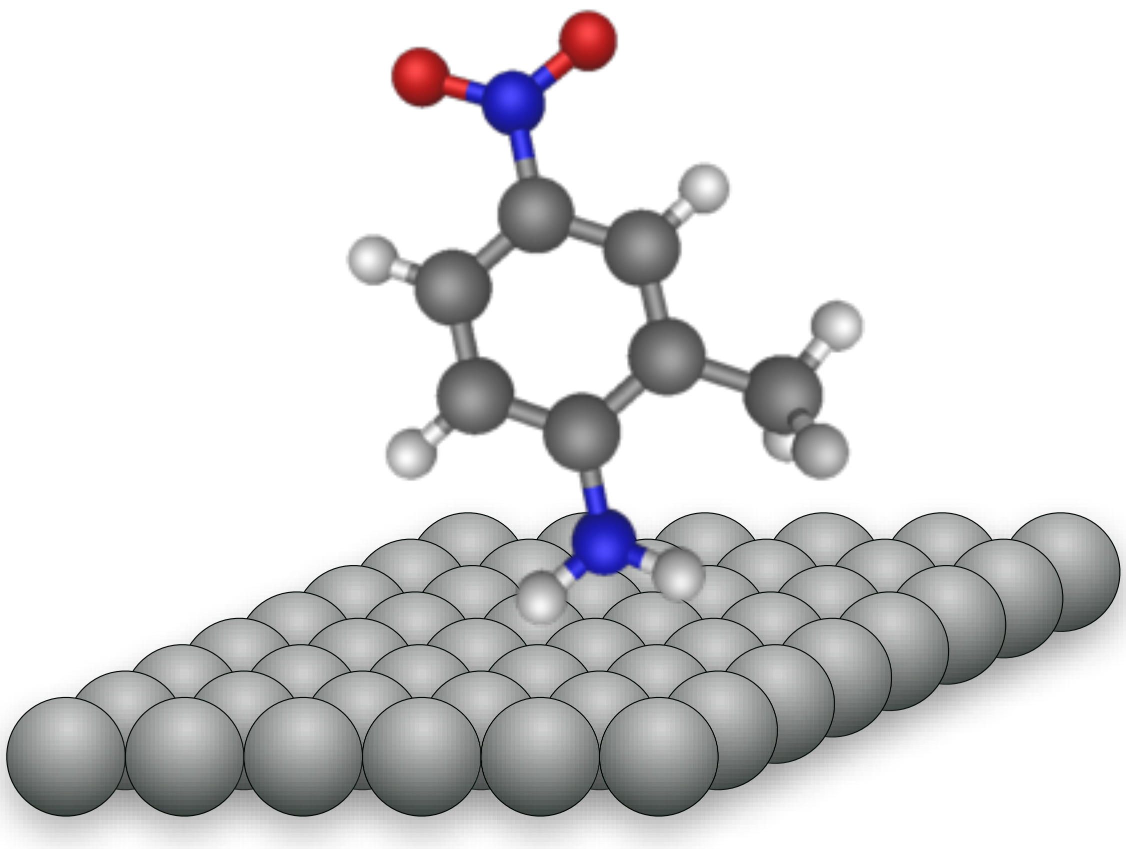
Note: No Guarantee of 2 Connections



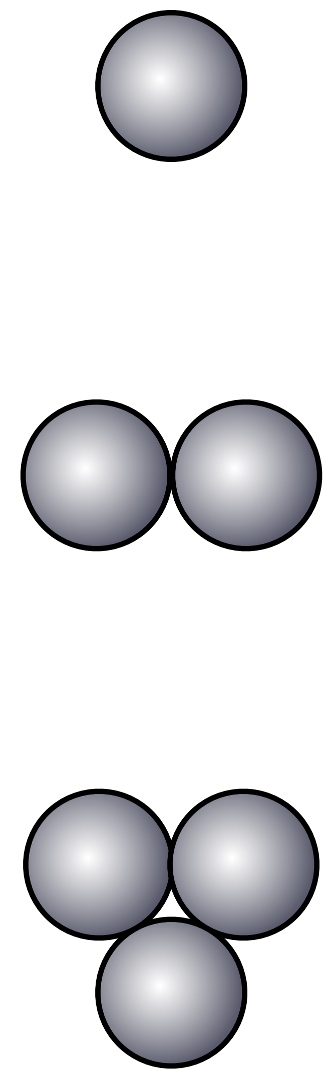


Ralph Group, Cornell

Metal / Molecule Interface



Coordination



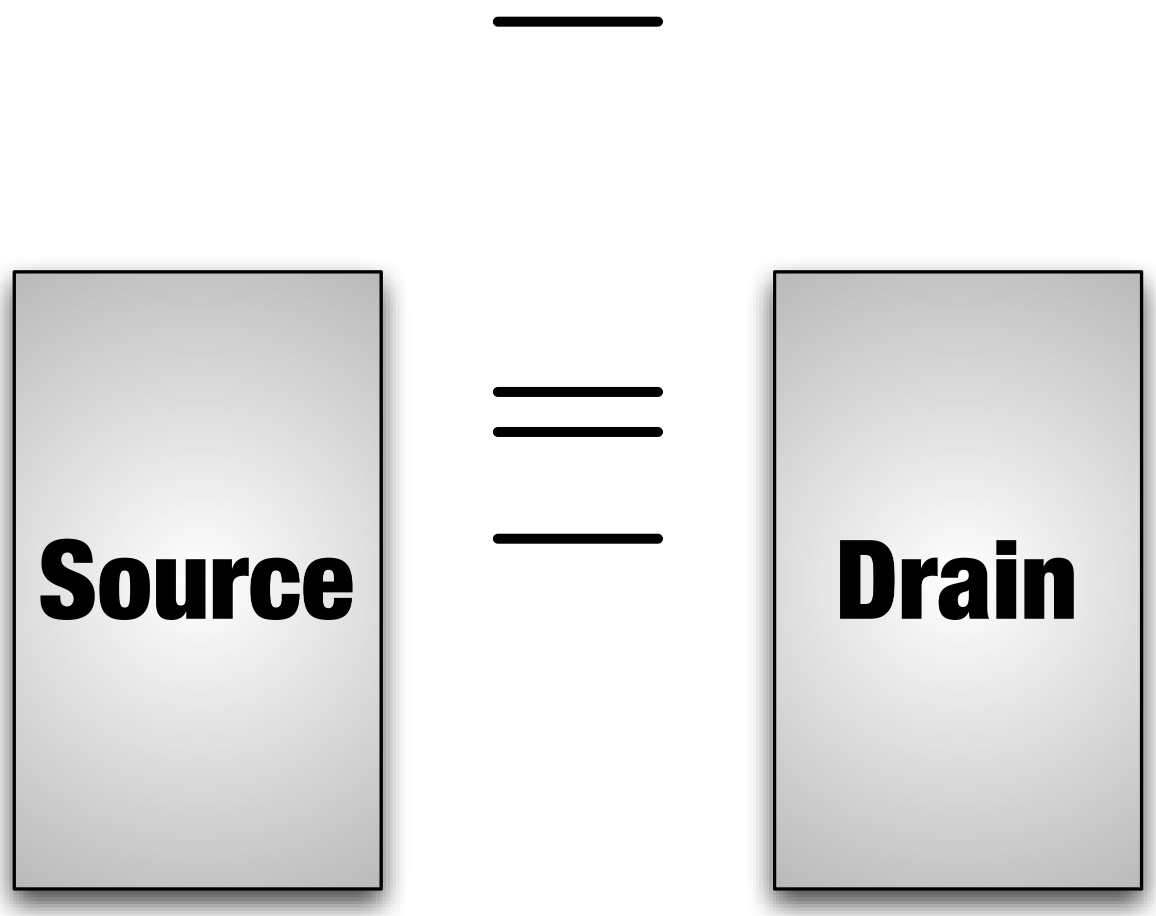
One-Site

“Bridging”

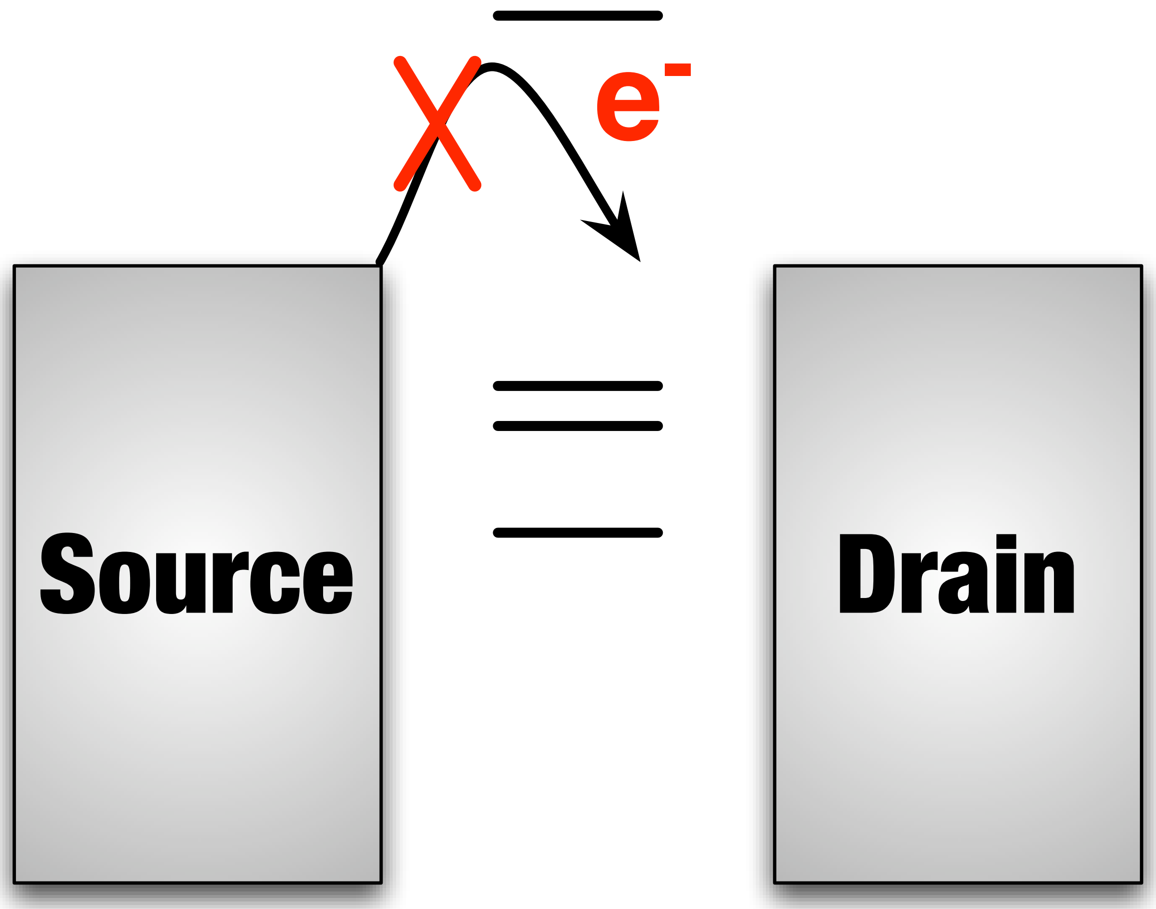
Three-Site

WARNING: PowerPoint Science!

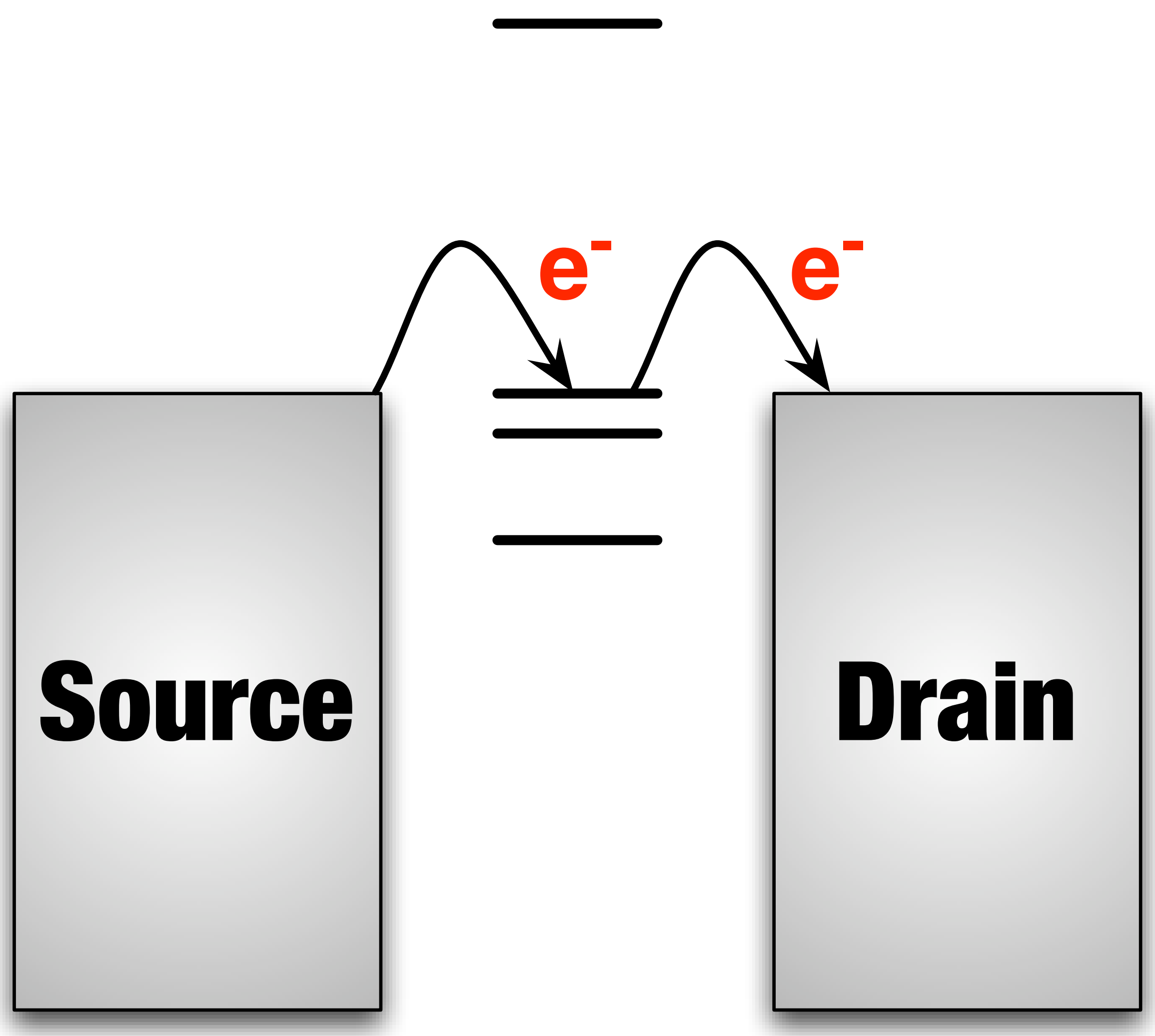
"Coulomb Blockade"



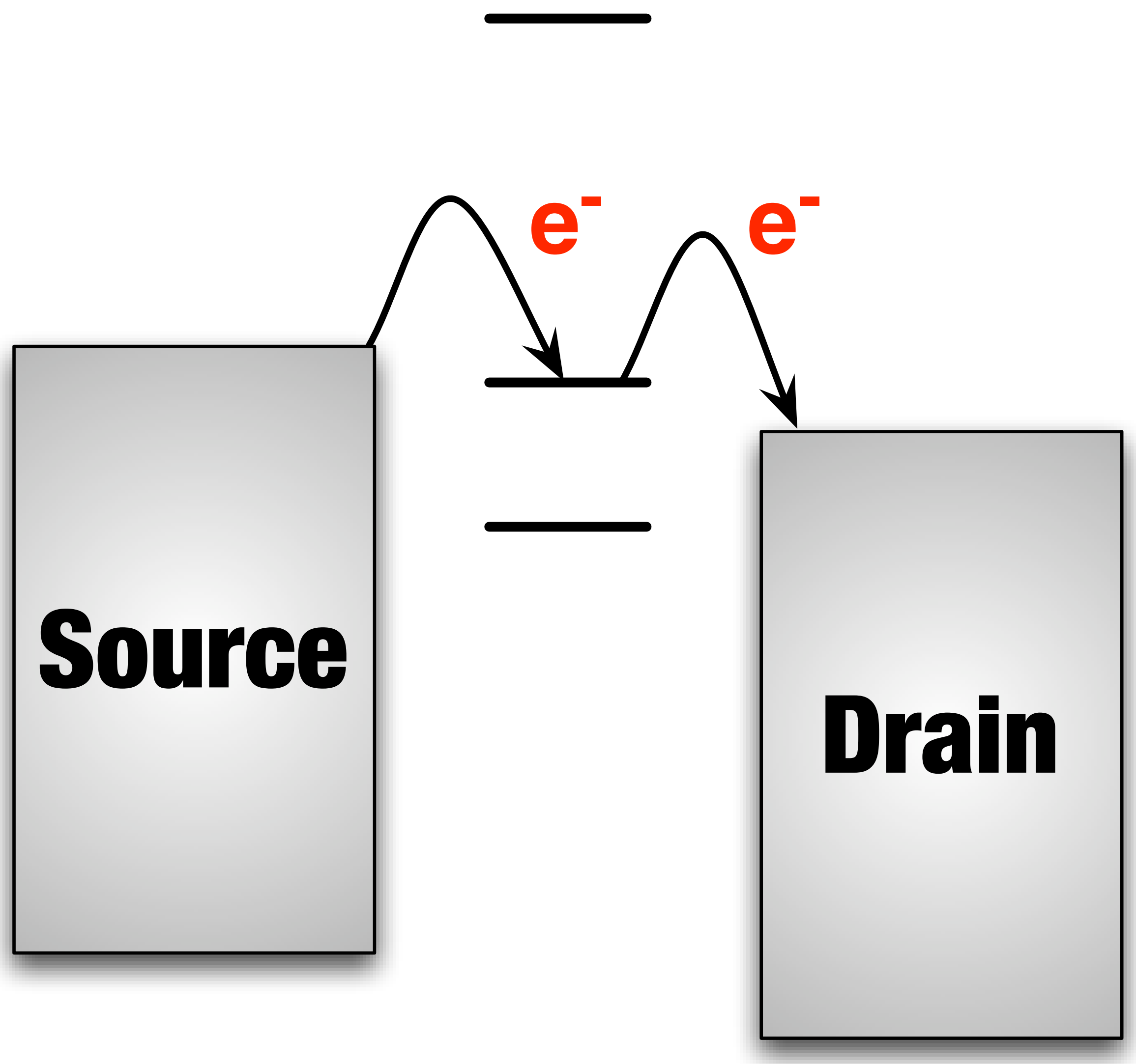
“Coulomb Blockade”



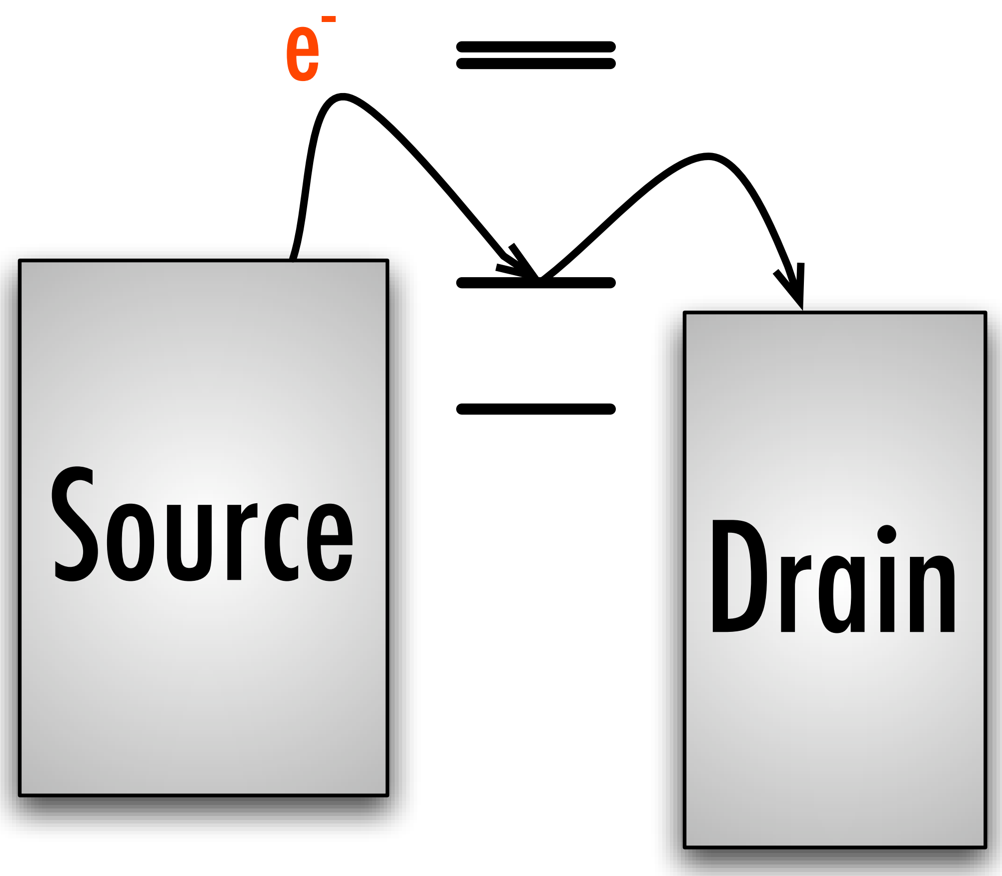
"Coulomb Blockade"



“Coulomb Blockade”

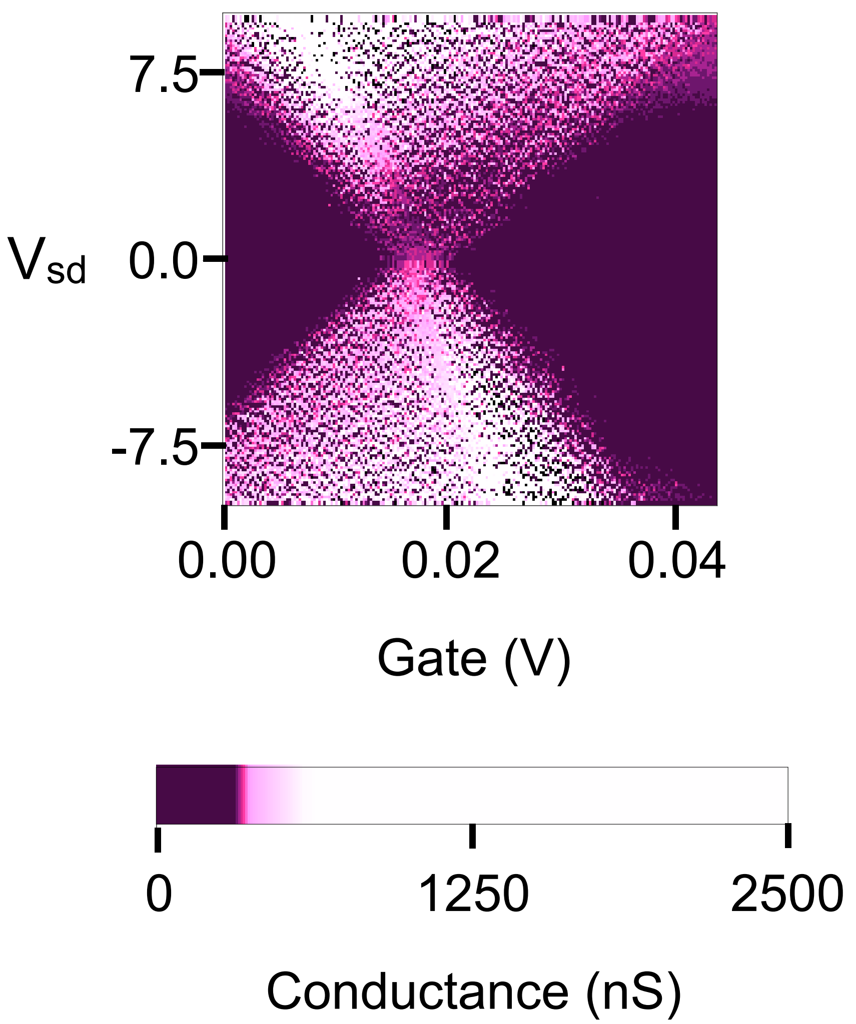


Coulomb Blockade in $[Ru_2(tppz)_3]^{+4}$



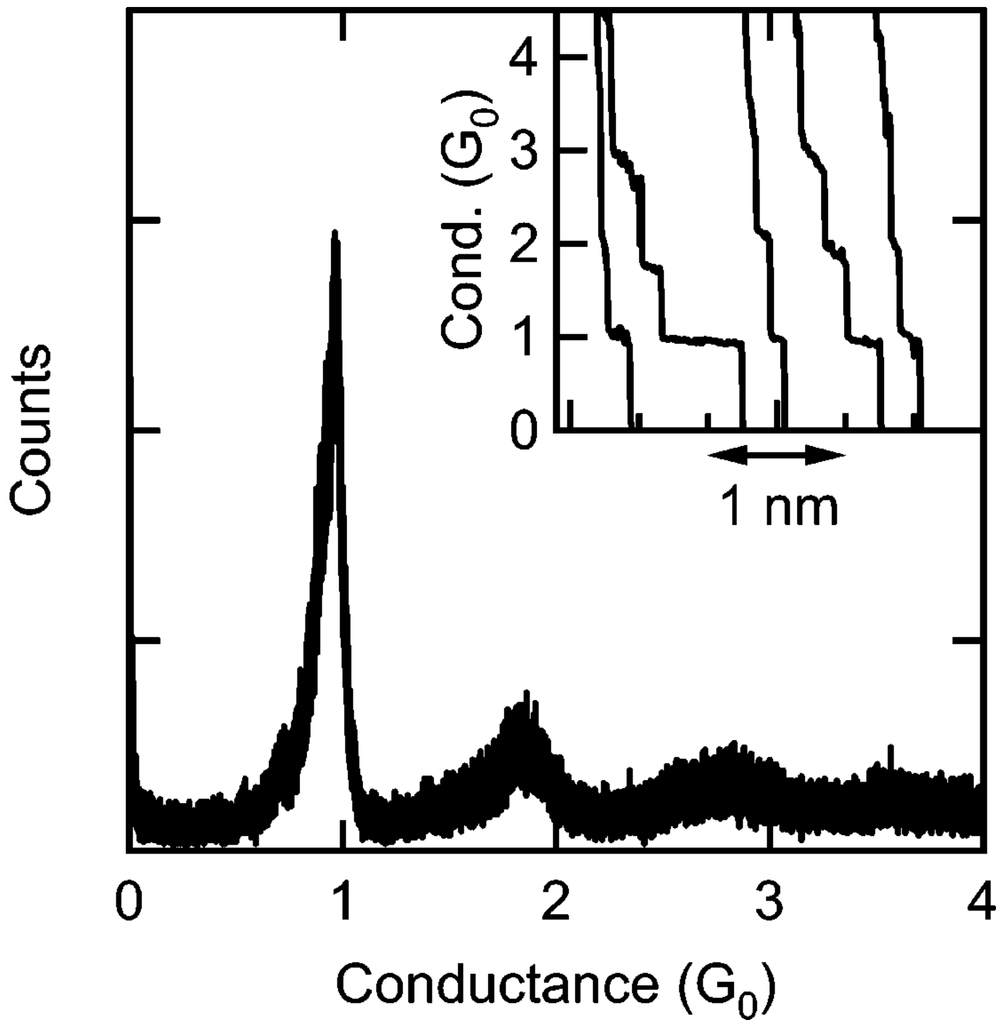
Charge passes when source, drain and molecule bridge electronic states are aligned

4K Temp. Single-Molecule Coulomb Blockade Transistor



Is it ***<u>Really</u>*** Single-Molecule?

- You *<u>must</u>* do statistics....
- You *<u>must</u>* do statistics...
- Careful controls ("no molecules")
- Dilution Experiments



Venkataraman, L. et. al. *Nano Letters* **2006** v. 6, 458-462

Is it ***Really*** A Molecule?

- Is it a nanoparticle?
- What are molecular "signatures?"
- What are control experiments?
- What are our statistics?

WARNING: Be Skeptical!
We can do theory...
But what's the real experiment?

Prospectus

- Statistics, Statistics, Statistics!
- Charge Transport Mechanisms
- More Charge Transport
- Ensembles & Dynamics
- Solar Energy:
  Where things get (more?) complicated