ECE606: Solid State Devices
Lecture 26
The Single Atom Transistor
Future Transistors
New Modeling Tools (NEMO)
nanoHUB: Cloud Computing - Software as a Service

Gerhard Klimeck
gekco@purdue.edu

1965
Gordon Moore
http://www.intel.com/technology/mooreslaw
Intel in 2012

Device Size:
Tens of nanometers

Stanford SUPREM

Device Integration:
>2 Billion
Berkeley SPICE

Berkeley
Simulation Program with Integrated Circuit Emphasis.

from: Larry Nagel, BCTM ‘96
- Started as a class project
- Developed as a teaching tool
- Quality control: pass Pederson
- Dissemination:
  - Public domain code
  - Pederson carried tapes along
  - Students took it along to industry and academia
  - Released 1972
Stanford University Process Modeling

- Stanford wanted to mimic Berkeley success
- Combine various existing models
- Dissemination:
  - Public domain code
  - Community workshops
  - Students took it along to industry and academia

Birth of an Industry

Intel Capitalization: $85B
Total Industry: $280B
What’s Next? New Nano Modeling Tools

Nano Initiatives

Research

Electronics

Materials

Photonics

Mechanics

Bio/Medicine

What’s Next?

New Nano Modeling Tools

Device Size

nano-scale structures

Billions of nano structures

Years

Transistors

Billions of nano structures

Years
nanoHUB: A Science Simulation Cloud

- Services:
  - Modeling and Simulation Software
  - Seminars, tutorials, classes
- Goals:
  - Knowledge transfer
    - Use in class rooms
  - Knowledge generation
    - Use in research
    - Use by experimentalists
  - Economic impact
    - Use in Industry
  - Professional Development / Community building
- Software as a service - A new delivery mechanism

Device Simulation coming of Age

- 60’s-80’s: analytical expressions
- 90’s: “Today’s tools simulate yesterday’s transistors”, Steve Hillenius, Bell Labs
- Today: highly parameterized drift diffusion
- Tomorrow: atomistic materials and devices by design
Device Simulation coming of Age

Device Simulation?

Tomorrow: atomistic materials and devices by design

Key Messages

Today:
• Drift Diffusion fit to atomistic model
Tomorrow:
• Quantum at the core
• 5nm transistors with metals by design
Future:
• Wires: 1 atom tall, 4 atoms wide
• Transistor made of one P atom
• Quantum computing

Today:
• Software as a service delivered to thousands in an open science gateway
• No code rewrite needed
Tomorrow:
• Vendors embrace software as a service
The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

Moore’s Law Forever?

Number of transistors: Moore’s law is continuing

http://jai-on-asp.blogspot.com
2005: free lunch is over, updated 2009
CPU’s are not getting faster!

Number of transistors: Moore’s law is continuing

Clock speed: no longer scaling

Power is the Limit!

Number of transistors: Moore’s law is continuing

Clock speed: no longer scaling

Power: today’s limitation ~100W

http://jai-on-asp.blogspot.com

2005: free lunch is over, updated 2009
Limited Performance Improvements

Number of transistors: Moore’s law is continuing

Clock speed: no longer scaling

Power: today’s limitation ~100W

Performance Gain: limited

Supply voltage (Vdd) stopped scaling at around 2003

What is Special about 100W?

Power: today’s limitation ~100W
**Intel Projection from 2004**

How do we burn power?
Switching Circuits & Leakage => Transistors

![Power Density Chart]

---

**CMOS Inverter**

**Dynamic / Switching Power:**
- Charging a capacitor network

$$P \propto f \, C_L \, V_{dd}^2$$

- Reduce frequency 😞
- Reduce capacitance
- => device size 😊
- Reduce voltage 😊

**Static Power:**
- Leakage through transistors

$$P \propto I_{OFF} \propto \frac{1}{\exp(V_{dd})}$$ 😞
“Fundamental” Limit

\[ V_{gd} \geq 60 \text{ mV/dec} \]

Threshold

\[ S \geq 60 \text{ mV/dec} \]

\[ \log I_d \]

\[ S = 2.3m(k_B T/q) \text{ mV/dec} \]

\[ m = (1 + C_D/C_{ox}) \geq 1 \]
Device Scaling for Performance

Dynamic / Switching Power:
- Charging a capacitor network
  \[ P \propto f C_L V_{dd}^2 \]
- Reduce supply voltage

Static Power:
- Leakage through transistors
  \[ P \propto I_{OFF} \propto 1/\exp(V_{DD}) \]
Device Scaling for Performance

Static Power:
➢ Leakage through transistors

\[ P \propto I_{OFF} \propto \frac{1}{\exp(V_{DD})} \]

Need a Different Switch

Static Power:
➢ Leakage through transistors

\[ P \propto I_{OFF} \propto \frac{1}{\exp(V_{DD})} \]
The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
    – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

Ultra-Thin-Body (8nm) InAs BTBT Device

Source  Gate (40nm)  Drain

p+  InAs  n+

Substrate

- Do not need phonons for direct current
- Highly non-parabolic conduction band
- Realistic valence band features
UTB Band Edges

- 1D quantization
  => Bandgap raised from bulk
  0.37eV => ~0.6eV
- Realistic Poisson Solution
  Doping 1x10^{18}/cm^3
- High doping regions flat bands
- Central gate region good control

UTB: Current Hotspots in Energy

- 1D quantization
  => Bandgap raised from bulk
  0.37eV => ~0.6eV
- Realistic Poisson Solution
  Doping 1x10^{18}/cm^3
- High doping regions flat bands
- Central gate region good control

Bandgap “narrow” at
  » Certain energies
  » Certain biases
**UTB Current Density in Energy**

- 1D quantization
  - Bandgap raised from bulk
  - $0.37 \text{eV} \Rightarrow \sim 0.6 \text{eV}$
- Realistic Poisson Solution
  - Doping $1 \times 10^{18}/\text{cm}^3$
- High doping regions flat bands
- Central gate region good control
- Bandgap “narrow” at
  - Certain energies
  - Certain biases
- 2 energy regions of current flow
  - Low Ec / high Ev
  - High Ec / low Ev

**UTB Current as a function of Gate Voltage**

- Current vs. Gate Voltage

`Gerhard Klimeck`
Strong Energy Dependence in $T(E,k=0)$

• Strong energy dependence in $T(E,k=0)$

Application to pin InAs UTB and Nanowire

Single-Gate UTB

$N_A = N_D = 5 \times 10^{19} \text{ cm}^{-3}$
$t_{ox} = 1 \text{ nm}$

Double-Gate UTB

GAA Nanowire

Purdue University
Nanowires can deliver very steep turn-offs!

Benchmarking by industry: Charge-devices continue to shine
D. Nikonov, I. Young (Intel)
Power Problem: Tunneling Transistors to the Rescue!

For a little while!

The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum => finite atoms

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org
Today: non-planar 3D devices
Better gate control!

Intel 22nm finFET

Today: non-planar 3D devices
Better gate control!

22nm = 176 atoms
8nm  = 64 atoms


Atomistic Modeling
=>
NEMO

Roadmap of finite atoms!

<table>
<thead>
<tr>
<th>nm Node</th>
<th>Node atoms</th>
<th>Critical atoms</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>176</td>
<td>64</td>
<td>160-190</td>
</tr>
<tr>
<td>14</td>
<td>122</td>
<td>44</td>
<td>64-80</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>29</td>
<td>30-38</td>
</tr>
<tr>
<td>7</td>
<td>56</td>
<td>20</td>
<td>18-23</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>14</td>
<td>11-15</td>
</tr>
</tbody>
</table>

Roadmap of finite electrons!

<table>
<thead>
<tr>
<th>nm Node</th>
<th>Node atoms</th>
<th>Critical atoms</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>176</td>
<td>64</td>
<td>160-190</td>
</tr>
<tr>
<td>14</td>
<td>122</td>
<td>44</td>
<td>64-80</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>29</td>
<td>30-38</td>
</tr>
<tr>
<td>7</td>
<td>56</td>
<td>20</td>
<td>18-23</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>14</td>
<td>11-15</td>
</tr>
</tbody>
</table>
Quantum Dot Research

![Graph showing number of electrons vs. node size with ITRS and Intel data points.]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Node atoms</td>
<td>22</td>
<td>14</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Critical atoms</td>
<td>64</td>
<td>44</td>
<td>29</td>
<td>20</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>160-190</td>
<td>64-80</td>
<td>30-38</td>
<td>18-23</td>
<td>11-15</td>
<td></td>
</tr>
</tbody>
</table>

Roadmap of finite electrons!

How should one think about finite number electron transport?

Can this be seen in today’s devices?

![Graph showing number of electrons vs. node size with ITRS and Intel data points.]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Node atoms</td>
<td>176</td>
<td>122</td>
<td>80</td>
<td>56</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Critical atoms</td>
<td>64</td>
<td>44</td>
<td>29</td>
<td>20</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>160-190</td>
<td>64-80</td>
<td>30-38</td>
<td>18-23</td>
<td>11-15</td>
<td></td>
</tr>
</tbody>
</table>
FinFETs with finite electrons

How should one think about finite number electron transport?

- IMEC & Delft & Purdue & Melbourne
- Single impurity / electron effects
- Each device has a specific fingerprint –> Metrology of As vs P impurities

Objective:
- Understand impurity spectroscopy Expt.

Questions:
- How deep are the impurities?
- Are the impurities “As” or “P”?

Results / Impact:
- Understand state hybridization
- Understand depth and identify As

Metrology with multimillion atom simulations
Excited States are Critical!

How should one think about finite number electron transport?
The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

Transport through single electron states

1) Apply $V_{DS}$ bias
2) Apply $V_{D}$ bias
3) First electron
4) First + second electron
5) First electron trapped
6) First + second electron trapped
"The I-V curve of atomic transistors"

Conductance G vs. $V_{\text{DS}}$ and $V_{\text{G}}$

1 = Transistor on (current flow)
0 = Transistor off (no current flow)

Charge Stability Diagram

Experimental Data

A single-atom transistor,
M. Fuechsle et.al.
*Nature Nanotechnology, 2012*
A designed single electron transistor!
How did we get there?
The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

A designed single electron transistor!
How did we get there?
Experimental Efforts: STM Lithography

**Objectives**
- Precise donor placement
- Place “many” donors in ultra-scaled region

**Scanning Tunneling Microscopy**
- Device surface imaging
- Control/pattern at atomic scales
  
  *Eagler et al., Nature (1990)*
- Densely P δ-doped Si (Si:P) device
  - Doping control ~ 5x10^-10(m)
  - Up to 1/2.9ML (1 P atom per every 2.9 Si atoms)

Fabricating single ML thick P doped planes using STM lithography

---

**Si:P System**

- **Densely Phosphorus δ-doped Si (Si:P) device**
  - Thin densely P doped layer in low-doped/intrinsic Si bulk
  - Electrons strongly confined in P doped layer

- **Prototype: Novel Structures/ Nanoscale Devices**
  - 2-D electron reservoirs (Shallow Junctions)
  - Ultra-narrow NW channel (Interconnector)
  - Single donor device with NW leads
Collaboration with UNSW: Experimental Devices

Si:P Systems

Modeling

Experiment, Theory

Questions, questions, questions

Single impurity device?
• Explain the coupling of the channel donor to the Si:P leads
• “quantify” the controllability of planar Si:P leads on the channel confinement
• Why does the Coulomb diamond extend into the D-regime?
• Why are there the conductance streaks at the Coulomb diamond edges?
Answers.... Some...

- 2d layers - quantum well
  - Detailed bandstructure
  - Validate methodology against other theories
  - Overall potential landscape
  - Robustness against disorder
  - S. Lee et al, Phys. Rev. B 84, 205309 (2011)

- Si:P Nanowires
  - Ohmic conduction
  - Spatial details
  - B. Weber
  - Si:P Single
    - D̄ and D̅
    - Validate single impurity
    - M. Fuechsle et al.

- Ohm’s Law Survives to the Atomic Scale
  - B. Weber et al, Science 335, 64 (2012)

- A single-atom transistor
  - Martin Fuechsle, Jiri A. Misev, Sudhanshu Mahapatra, Oliver Warchol, Lloyd C. L. Hohenberg, Genham

A multi-scale modeling procedure

1. Contact modeling
   - Atomistic modeling on the leads
   - Charge-potential self-consistency
   - Semi-metallic, DOS profile

2. Potential profile
   - Semi-classical potential profile
   - Superpose w. donor potential

3. Charge filling
   - Potential profile → Hamiltonian
   - Compute eigenstates w.r.t. E_F at every V_G
   - Transition, charging energy and gate modulation
A multi-scale modeling procedure

1. Contact modeling
   • Atomistic modeling on the leads
   • Charge-potential self-consistency
   • Semi-metallic, DOS profile

2. Potential profile
   • Semi-classical potential profile
   • Superpose w. donor potential

3. Charge filling
   • Potential profile → Hamiltonian
   • Compute eigenstates w.r.t $E_F$ at every $V_G$
   • Transition, charging energy and gate modulation

4. Coulomb diamond
   • DOS profile of S/D and Charge filling information
   • Rate equation formalism

The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org
Industrial Device Trends and Challenges

Observations:
- 3D spatial variations on nm scale
- Potential variations on nm scale
- New channel materials (Ge, III-V)

Questions / Challenges
- Strain?
- Quantization?
- Crystal orientation?
- Atoms are countable; does granularity matter? Disorder?
- New material or new device?

Assertions of importance
- High bias / non-equilibrium
- Quantum mechanics
- Atomistic representation
  - Band coupling, non-parabolicity, valley splitting
  - Local (dis)order, strain and orientation

NEMO5 - Bridging the Scales
From Ab-Initio to Realistic Devices

Ab-Initio

Goal:
- Device performance with realistic extent, heterostructures, fields, etc. for new / unknown materials

Problems:
- Need ab-initio to explore new material properties
- Ab-initio cannot model non-equilibrium.
- TCAD does not contain any real material physics

Approach:
- Ab-initio:
  - Bulk constituents
  - Small ideal superlattices
  - Map ab-initio to tight binding (binaries and superlattices)
  - Current flow in ideal structures
  - Study devices perturbed by:
    - Large applied biases
    - Disorder
    - Phonons
NEMO 3-D Multi-Scale Modeling

- Atom Positions: ~10-50 million atoms
- Valence Electrons: ~0.5-10 million
- e-e interactions: Few States

- Geometry Construction
- Atomistic Relaxation
- Strain
- Piezoelectric Potential
- Hamiltonian Construction
- Electrical / Magnetic field
- Single Particle States
- Optical Prop. Electronic Str
- Many Body Interactions
- Optical Prop. Electronic Str

- Valence Force Field (VFF) Method
- Piezoelectric eff. Pol. charge density
- Empirical tight binding
- sp^3d^5s^* + spin orbit
- SCP: Poisson + LDA
- Slater Determinants

Quantum Transport far from Equilibrium

- Macroscopic dimensions: Diffusive, Ballistic, Quantum
- Drift / Diffusion
- Boltzmann Transport
- Unified model
- Non-Equilibrium Green Functions
- Non-Equilibrium Quantum Statistical Mechanics

- Unified model
- Macroscopic dimensions: Diffusive, Ballistic, Quantum
- Drift / Diffusion
- Boltzmann Transport
- Unified model
- Non-Equilibrium Green Functions
- Non-Equilibrium Quantum Statistical Mechanics

- Unified model
- Macroscopic dimensions: Diffusive, Ballistic, Quantum
- Drift / Diffusion
- Boltzmann Transport
- Unified model
- Non-Equilibrium Green Functions
- Non-Equilibrium Quantum Statistical Mechanics
### A Journey Through Nanoelectronics Tools

#### NEMO and OMEN

<table>
<thead>
<tr>
<th></th>
<th>NEMO-1D</th>
<th>NEMO-3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Dim.</td>
<td>1D</td>
<td>any</td>
</tr>
<tr>
<td>Atoms</td>
<td>~1,000</td>
<td>50 Million</td>
</tr>
<tr>
<td>Crystal</td>
<td>[100] Cubic, ZB</td>
<td>[100] Cubic, ZB</td>
</tr>
<tr>
<td>Strain</td>
<td>-</td>
<td>VFF</td>
</tr>
<tr>
<td>Multi-physics</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Parallel Comp.</td>
<td>3 levels 23,000 cores</td>
<td>1 level 80 cores</td>
</tr>
</tbody>
</table>
## A Journey Through Nanoelectronics Tools
### NEMO and OMEN

<table>
<thead>
<tr>
<th>NEMO-1D</th>
<th>NEMO-3D</th>
<th>NEMO3Dpeta</th>
<th>OMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dim.</td>
<td>1D</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>Atoms</td>
<td>~1,000</td>
<td>50 Million</td>
<td>100 Million</td>
</tr>
<tr>
<td>Crystal</td>
<td>[100], Cubic, ZB</td>
<td>[100], Cubic, ZB</td>
<td>[100], Cubic, ZB, WU</td>
</tr>
<tr>
<td>Strain</td>
<td>-</td>
<td>VFF</td>
<td>VFF</td>
</tr>
<tr>
<td>Multi-physics</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel Comp.</td>
<td>3 levels 23,000 cores</td>
<td>1 level 80 cores</td>
<td>3 levels 30,000 cores</td>
</tr>
</tbody>
</table>
## A Journey Through Nanoelectronics Tools

<table>
<thead>
<tr>
<th></th>
<th>NEMO-1D</th>
<th>NEMO-3D</th>
<th>NEMO3D-peta</th>
<th>OMEN</th>
<th>NEMO5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Yes</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dim.</td>
<td>1D</td>
<td>any</td>
<td>any</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>Atoms</td>
<td>~1,000</td>
<td>50 Million</td>
<td>100 Million</td>
<td>~140,000</td>
<td>100 Million</td>
</tr>
<tr>
<td>Crystal</td>
<td>[100] Cubic, ZB</td>
<td>[100] Cubic, ZB</td>
<td>[100], Cubic,ZB, WU</td>
<td>Any</td>
<td>Any</td>
</tr>
<tr>
<td>Strain</td>
<td>-</td>
<td>VFF</td>
<td>VFF</td>
<td>-</td>
<td>MVFF</td>
</tr>
<tr>
<td>Multi-physics</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>Spin, Classical</td>
</tr>
<tr>
<td>Parallel Comp.</td>
<td>3 levels</td>
<td>1 level</td>
<td>3 levels</td>
<td>4 levels</td>
<td>4 levels</td>
</tr>
<tr>
<td></td>
<td>23,000 cores</td>
<td>80 cores</td>
<td>30,000 cores</td>
<td>220,000 cores</td>
<td>100,000 cores</td>
</tr>
</tbody>
</table>

### Core Code / Theory Development

- **NEMO-1D** *(Texas Instruments ’94-’98, JPL ’98-’03)*
  - Roger Lake, R. Chris Bowen, Dan Blanks

- **NEMO-3D** *(NASA JPL, Purdue, ’98-’07)*
  - R. Chris Bowen, Fabiano Oyafuso, Seungwon Lee

- **NEMO3D-peta** *(Purdue, ’06-’11)*
  - Hoon Ryu, Sunhee Lee

- **OMEN** *(ETH, Purdue, ’06-’11)*
  - Mathieu Luisier

- **NEMO5** *(Purdue, ’09-’12)*
  - Michael Povolotsky, Hong-Hyun Park, Sebastian Steiger, Tillmann Kubis, Jim Fonseca, Arvind Ajoy, Bozidar Novakovic, Rajib Rahman
Compute Intensive: NEMO/OMEN

18 years development
• Texas Instruments
• NASA JPL
• Purdue

• Peta-scale Engineering

18 years development
• Texas Instruments
• NASA JPL
• Purdue

• Peta-scale Engineering
Atomistic Device representation

- Deemed by many too computationally intensive

**Compute Intensive: NEMO/OMEN**

- 18 years development
- Texas Instruments
- NASA JPL
- Purdue
- Peta-scale Engineering
- Gordon Bell

**ACM Gordon Bell Prize**

Honorable Mention

Mathieu Lusier, Timothy B. Boykin, Gerhard Klimke, Wolfgang Fichtner

*Atomic Scale Nano-electronic Device Engineering with Sustained Performance up to 1.4 TFlops*:

**Ohm’s Law Survives to the Atomic Scale**

- B. Weber, S. Borkar, H. Epl, S. Lec, G. Klimke, C. G. Hallenberg

A single-atom transistor

Martin Fourche, Jill A. Mixon, Sudhadanta Mohapatra, Oliver Warschkow, Lloyd C. L. Hollenberg, Gerhard Klimke
Atomistic Device representation
• Deemed by many too computationally intensive
  Compute Intensive: NEMO/OMEN
  Powers 8 Tools:
  >12,300 Users
  >187,000 Simulation Runs
  18 years development
  • Texas Instruments
  • NASA JPL
  • Purdue
  • Peta-scale Engineering
  • Gordon Bell
  • Science, Nature Nano

224 classes w/ 2044 students
62 citations
Powers 8 Tools:
>12,300 Users
>187,000 Simulation Runs

NEMO Funding and Leverage
Industrial Use
Tunneling Transistors
Contacts, HEMTs
Quantum Computing
NSF-NCN
12,000 users
Peta-Scale Computing
NSF-NEB
A single-atom transistor
11/28/2012
The single-atom transistor
Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

 nanoHUB
World’s Largest Nano User Facility

Activities on http://nanoHUB.org in 172 countries

New Registrations
Simulation Users
Tutorial / Lecture Users

nanoHUB.org usage 2012-02-03 00:00:00

Total Users
The single-atom transistor

Presentation Outline

• Why?
  – A power problem
  – Near term solution
  – Continuum invalid
    => finite atoms/electrons

• What is it?
  – Coulomb diamond
  – How is it built?

• How to model this?
  – NEMO

• Where to study this?
  – nanoHUB.org

Teaching Moments

CMOS: fundamental limit 60mV/dec

\[
\log I_0
\]

\[
I_{ON} \quad S<<60 \text{ mV/dec}
\]

\[
I_{OFF} \quad S\geq60 \text{ mV/dec}
\]

Coulomb Diamonds

Fingerprint of single electrons
Key Messages

Today:
• Drift Diffusion fit to atomistic model
Tomorrow:
• Quantum at the core
• 5nm transistors with metals by design
Future:
• Wires: 1 atom tall, 4 atoms wide
• Transistor made of one P atom
• Quantum computing

What are the implications?....

Single Atom Transistor: Future Implications

Other limits to Moore’s Law (real world issues)
• Mass production
  – Not today
  – Zyvex maybe “tomorrow”
• Room temperature operation
  – Not today
  – Need other impurity
• Single Electron circuit architectures
  – Research available
  – Stray charges

Research Today:
• Atomic physical limit of Moore’s law (not accidental)
• Wires: 1 atom tall, 4 atoms wide
• Transistor made of one P atom
• Goal / funding:
  Quantum computing
• NEMO5 calibration
  – Atomistic, discrete
  – Realistically extended
Thank You!

Research Group
@Purdue
@NASA JPL 1998-2003
@Texas Instruments 1994-1998

Collaborators:
Michelle Simmons, Sydney
Lloyd Hollenberg, Melbourne
Alan Seabaugh, Notre Dame

Thank You!