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Using Nanoelectronics to Control 1D Wavefunctions

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CINT Thrust Leader

Quantum Transport Group

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Outline

- Semiconductor Materials and Sandia History
- Quantum Transport
  - tunneling between quantum wires
- New Programs

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- **Semiconductor Materials and Sandia History**
- Quantum Transport
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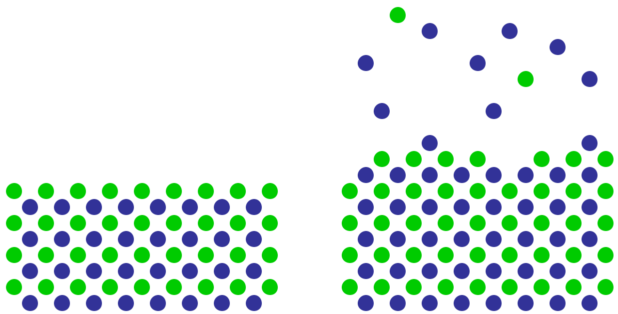
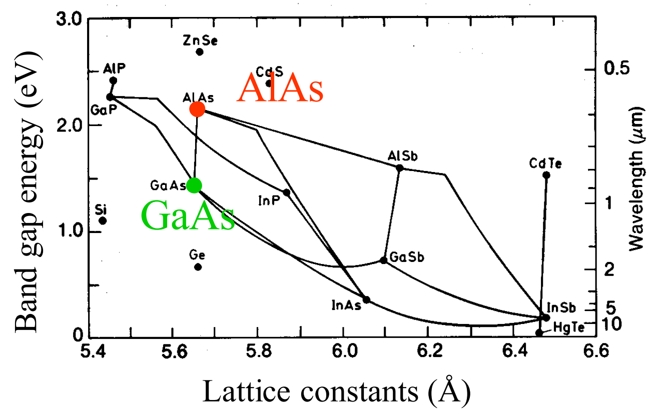
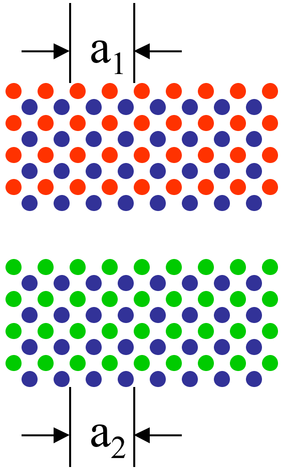
Ultra-low disorder GaAs/AlGaAs

1. Epitaxial growth



2. Lattice matching

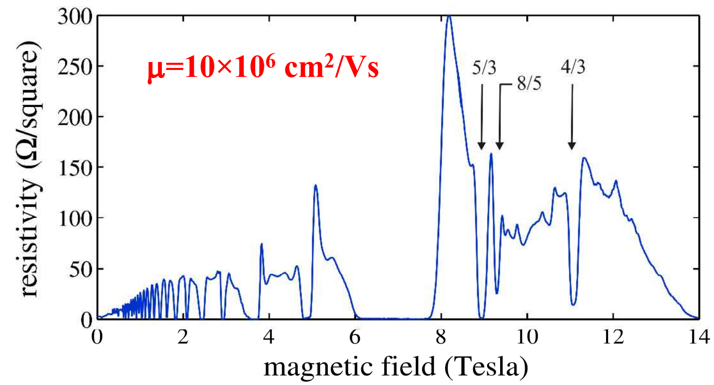




High mobility 2D electrons

Length scales at low temperature

Quantum interference: 100 um
Ballistic transport: 10 um
Size quantization: ~ 500 Å



Material enables science: interaction studies, coherence in nanoelectronics and engineered properties.

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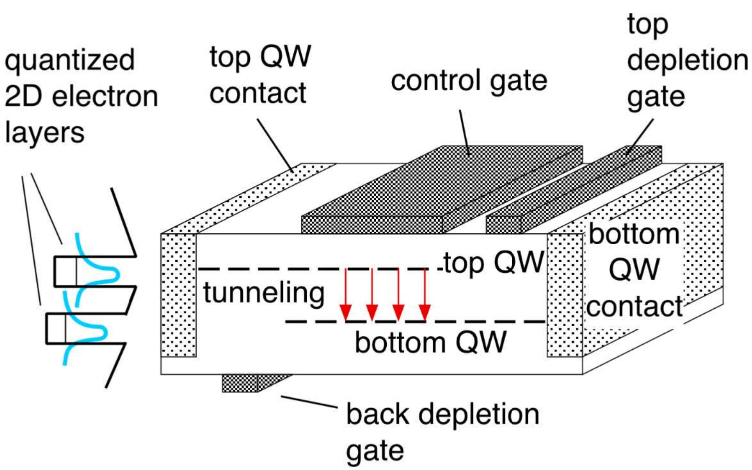
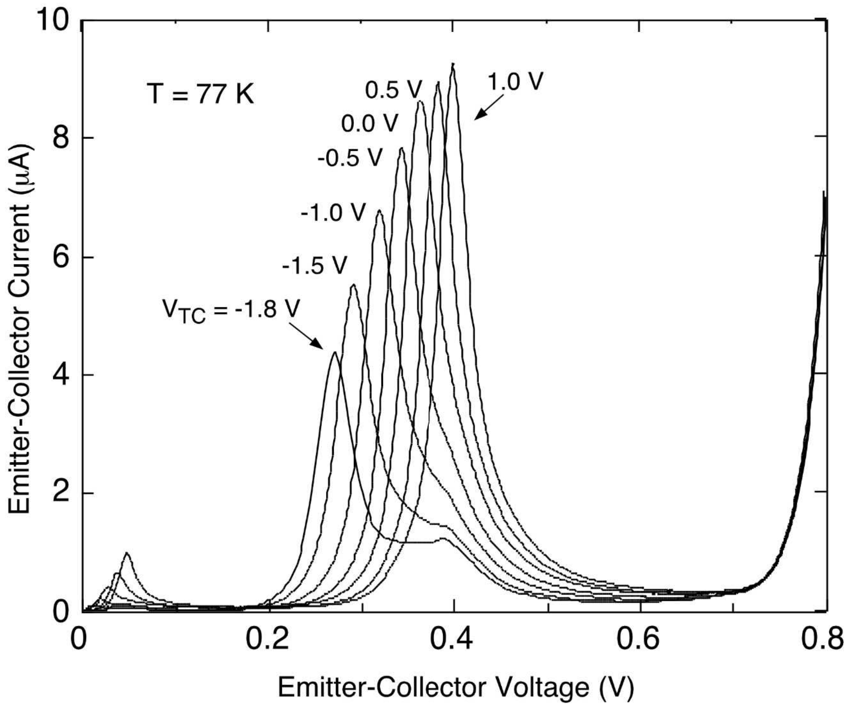
DELTT – tunneling as a fast transistor

- LDRD investments in the 1990s began to study quantum devices for both fundamental science and device applications.





Double electron layer tunneling transistor (DELTT) exhibits gate-controllable resonant tunneling up to ~200K.

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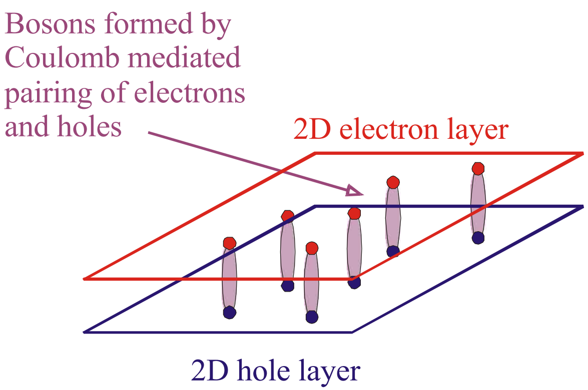
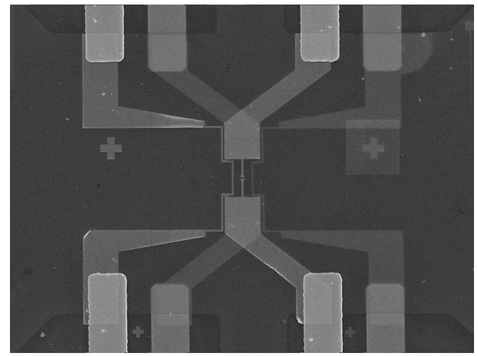
Programs evolving from quantum device research

Present

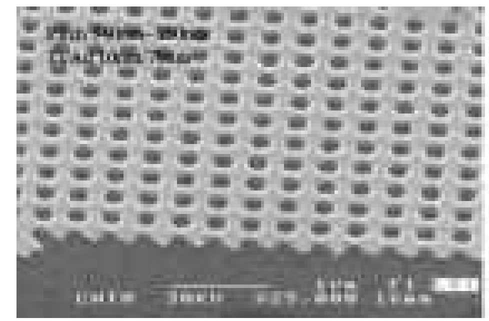
Electron-hole bilayers



Coupled quantum wires



Bloch oscillations



Future directions

- Nanoelectronics at CINT
- Quantum computing
- Next generation molecular beam epitaxy

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Outline

- Semiconductor Materials and Sandia History
- **Quantum Transport**
  - tunneling between quantum wires
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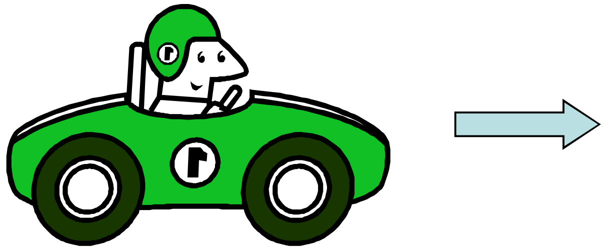
Ballistic conductance

Electrons *do not scatter* in a clean one-dimensional (1D) wire

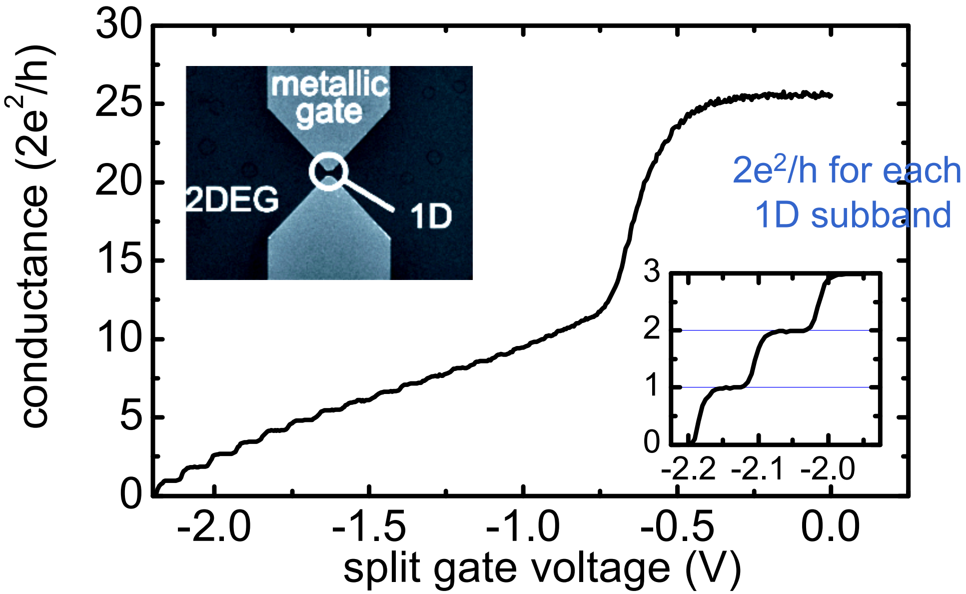
Cartoon

Sunday driving: lots of slow cars,
a few very fast ones (no crashes)



Equation

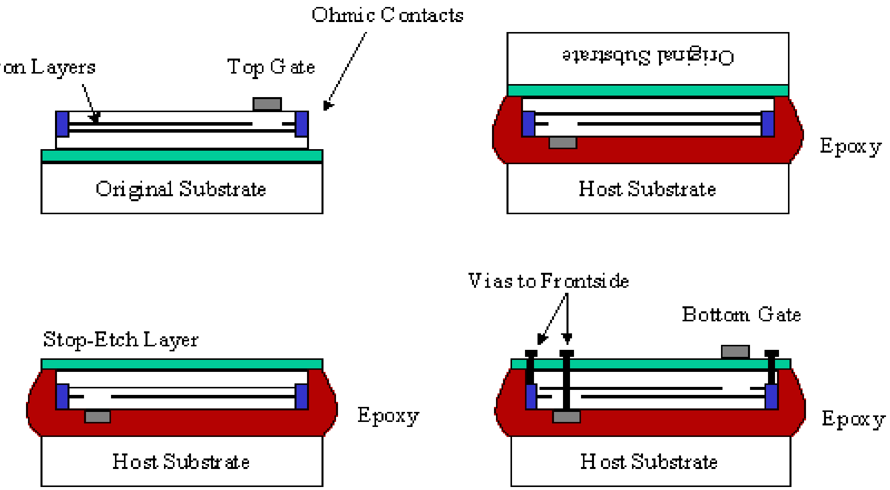
$g \sim v_F N(E)$ → independent of density



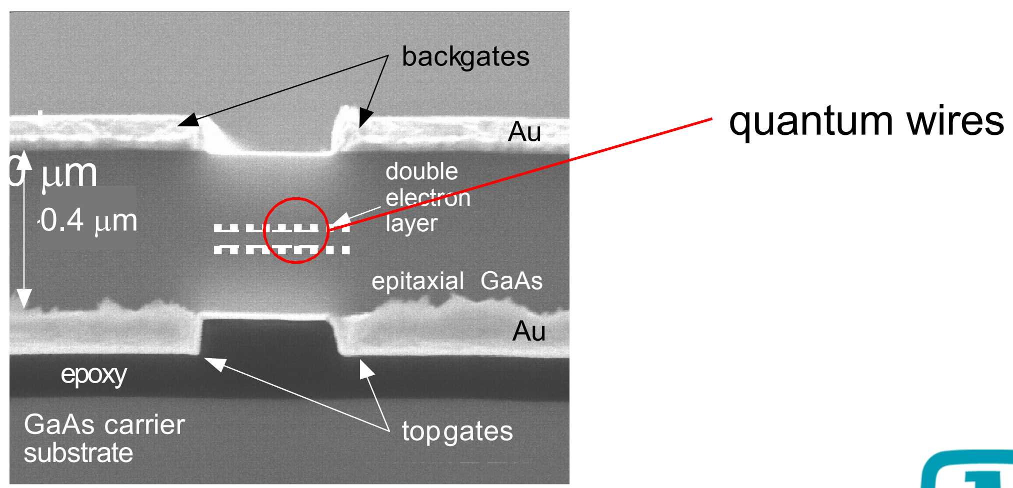
conductance depends on *e*, *h* only

Unique processing: dual-side electron beam lithography

EBASE (Epoxy-Bond-And-Stop-Etch)



(cross-section)



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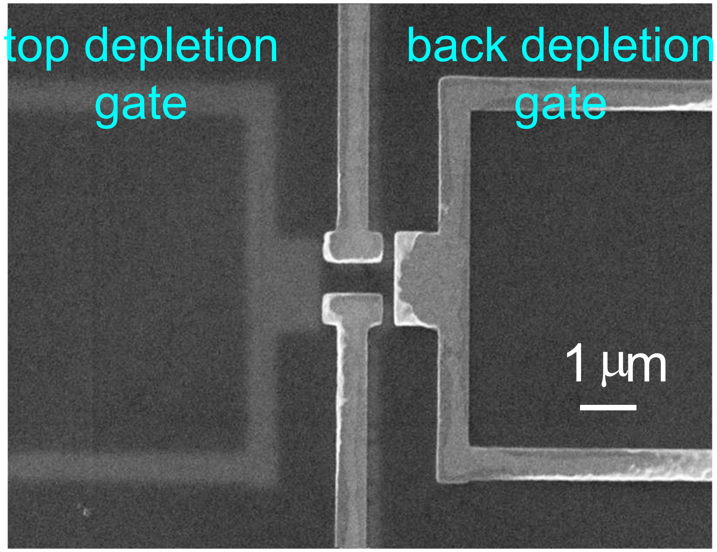
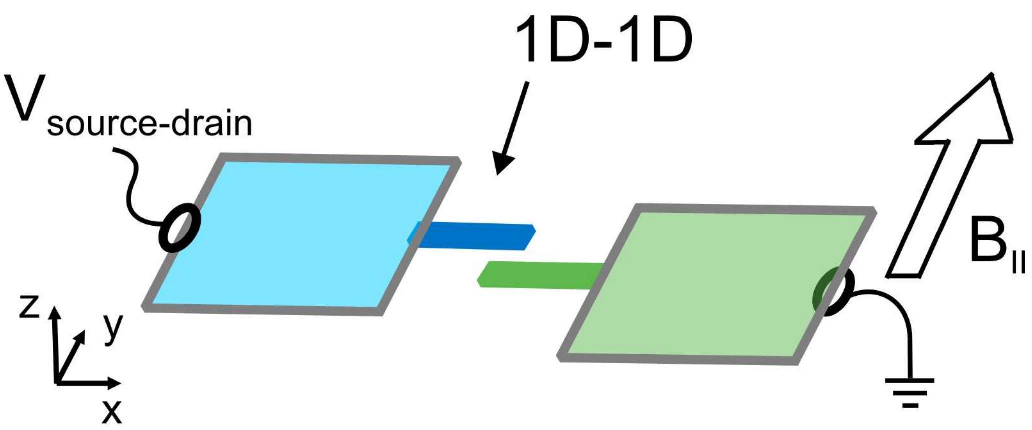
Vertically coupled double quantum wires

- Study nanoelectronic interactions
- Design systems for coherent transport studies





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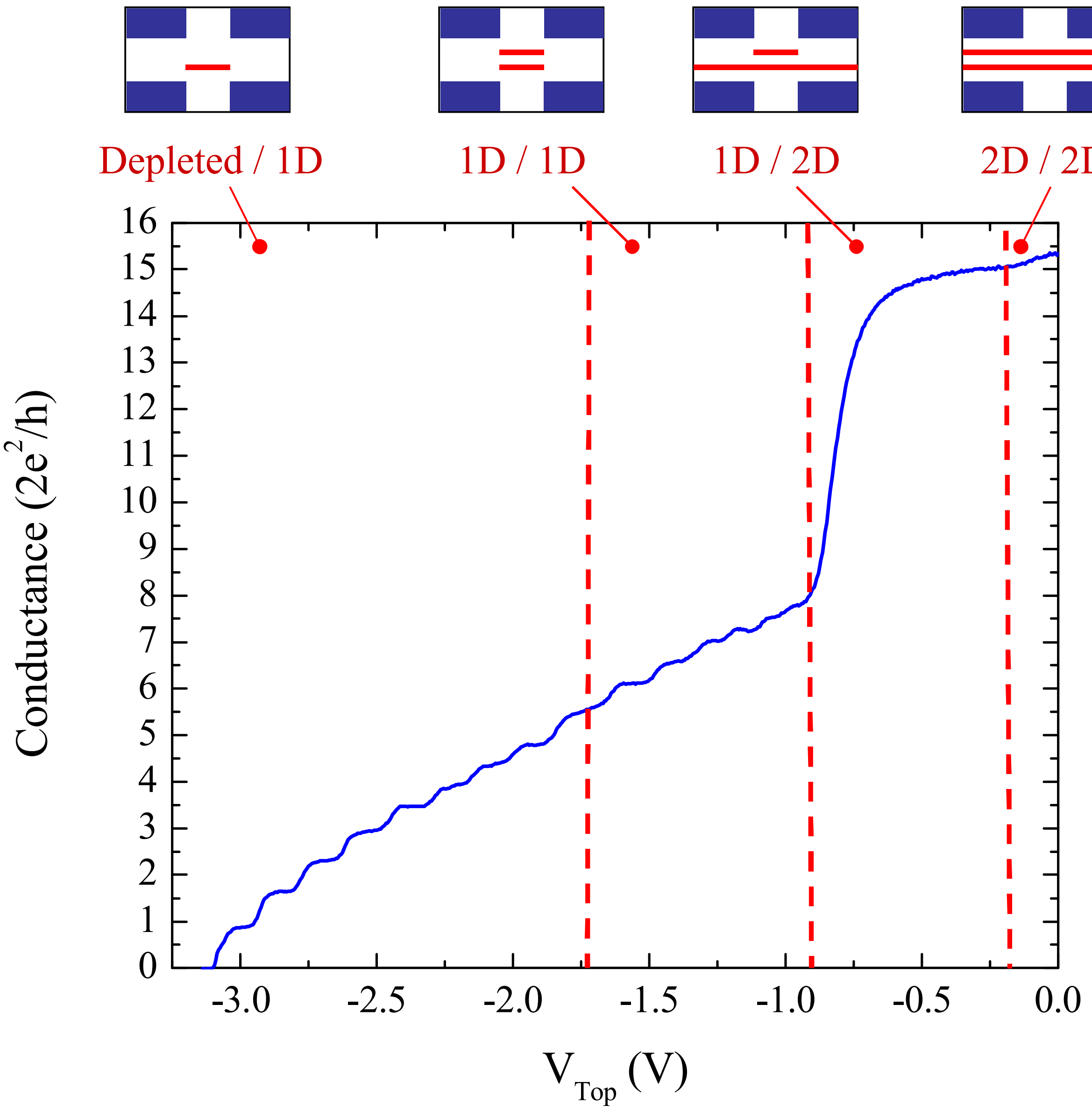
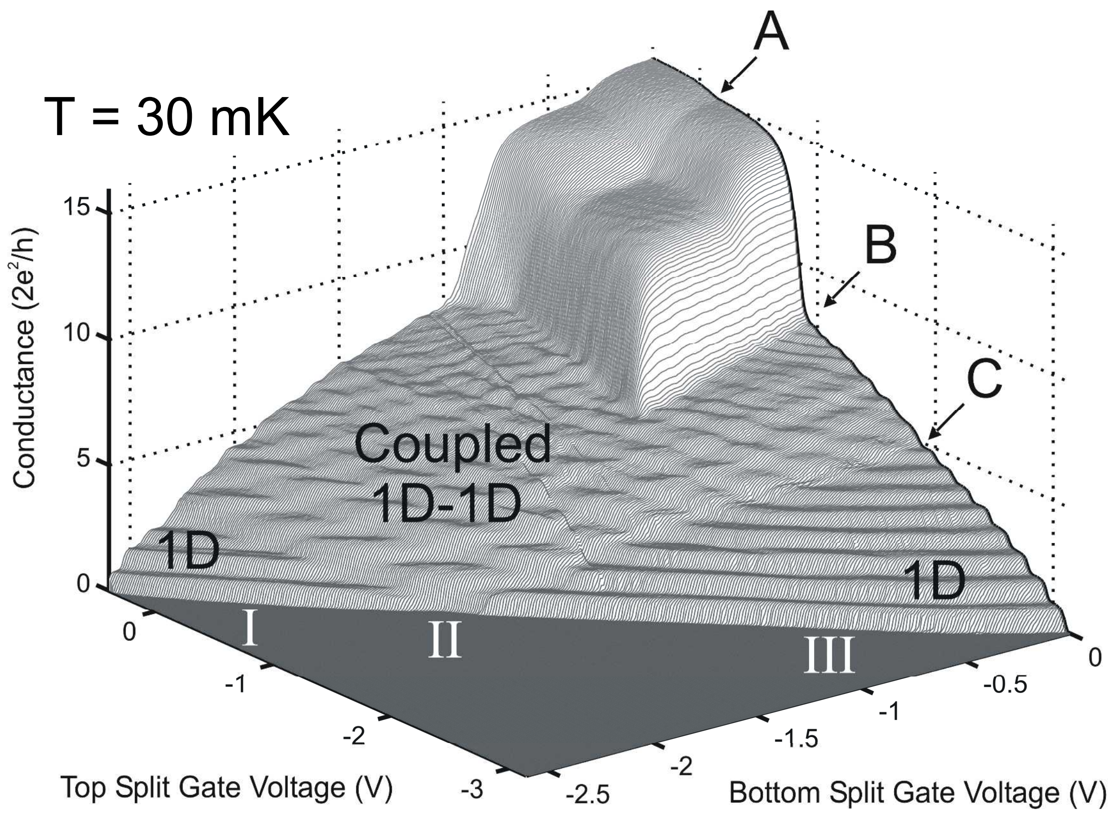
Forming a one dimensional wire



Parallel conductance

Conductance steps in a double wire



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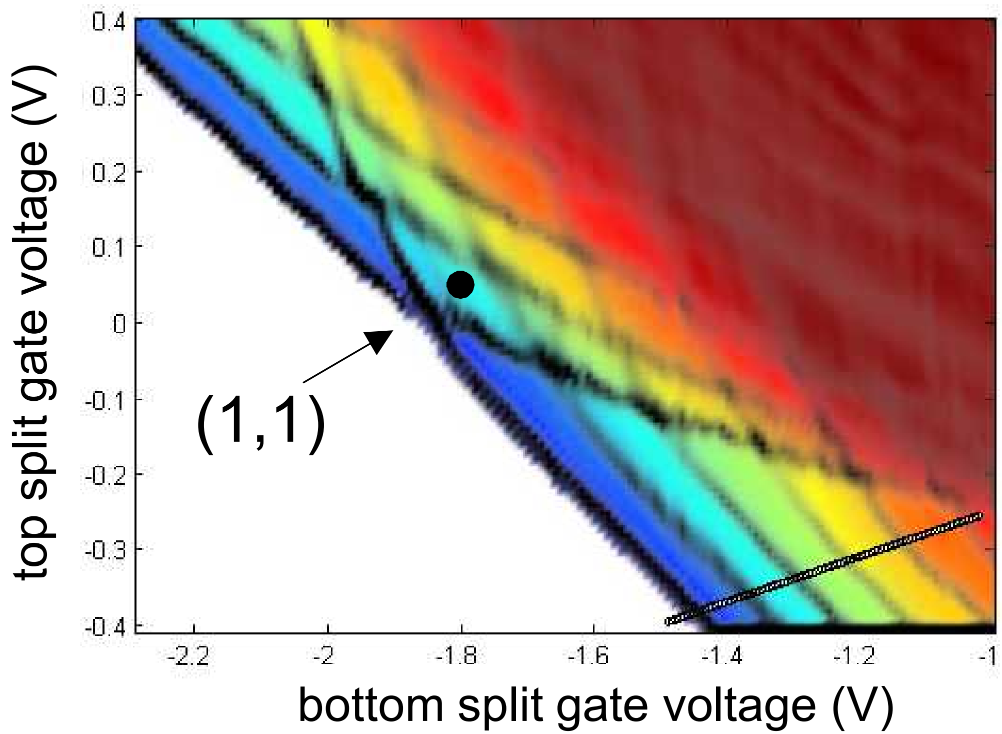
Precise control of the 1D state



- The color scale corresponds to the conductance :

  (2,0), (0,2), (1,1) → $2G_0$

  (3,0), (0,3), (2,1) → $3G_0$

  (6,0), (0,6), (3,3) → $6G_0$

where $G_0 = 2e^2/h$.

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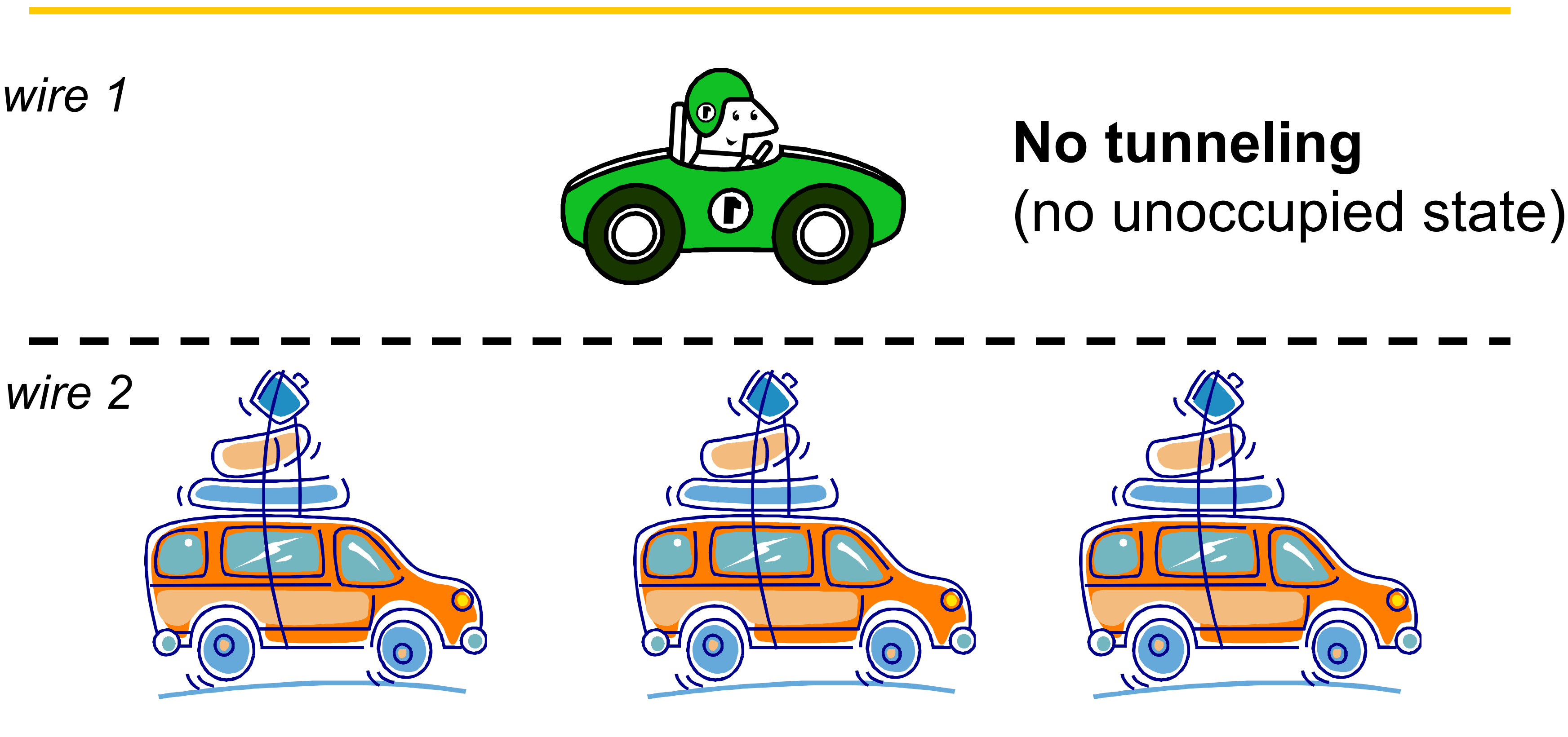
Non-interacting tunneling (cartoon view)

- Tunneling must conserve energy and momentum
- Tunneling must be from an occupied state to an unoccupied state



Non-interacting tunneling (cartoon view)

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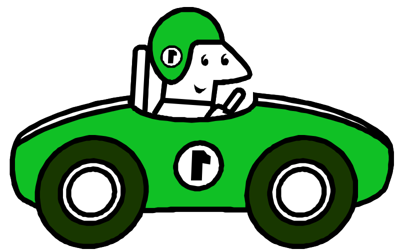
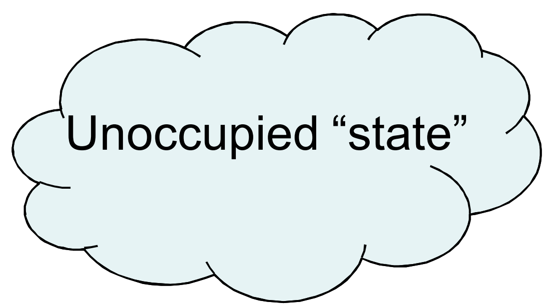
wire 1



No tunneling
(momentum not conserved)

wire 2



Non-interacting tunneling (cartoon view)

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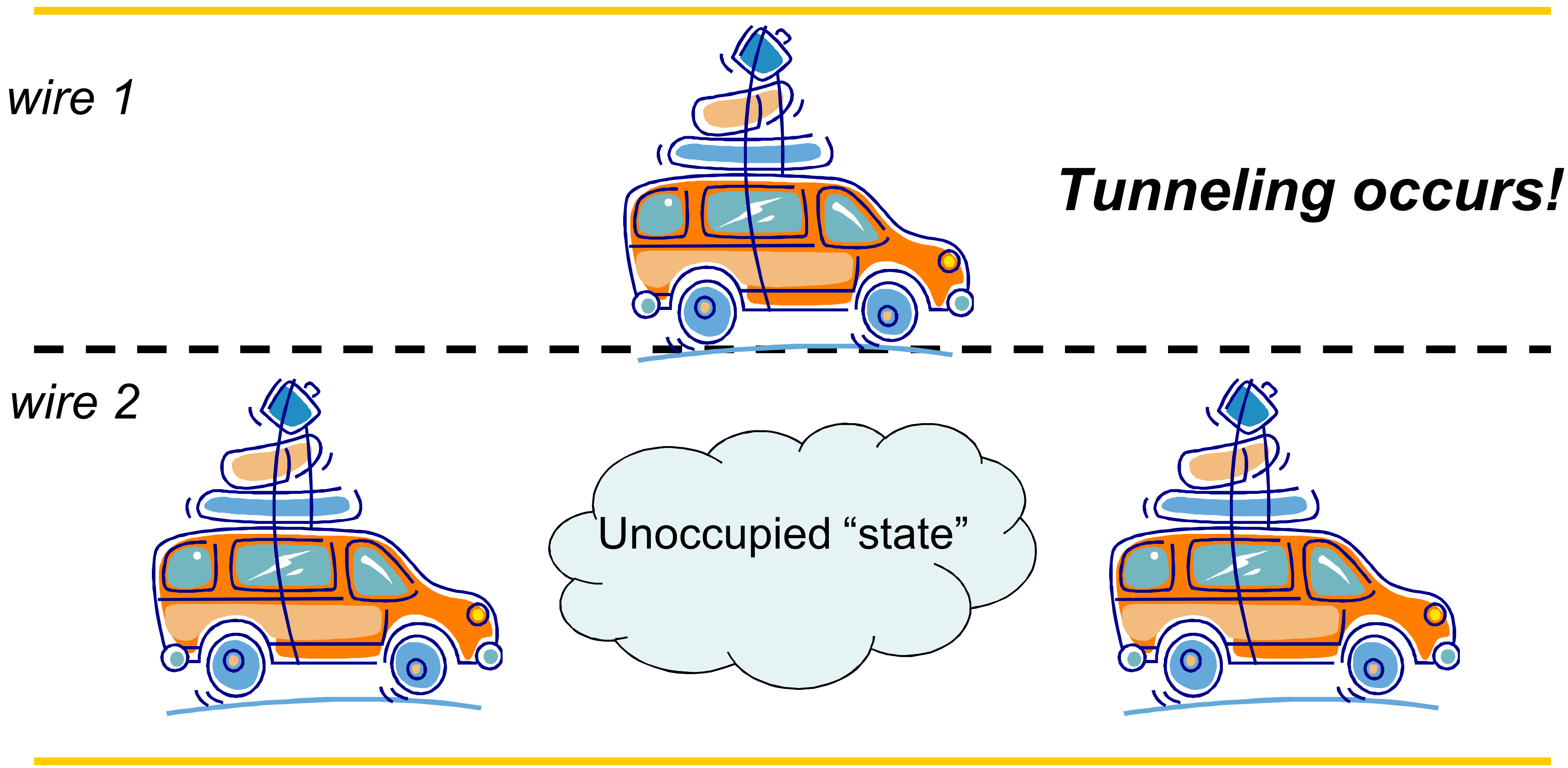
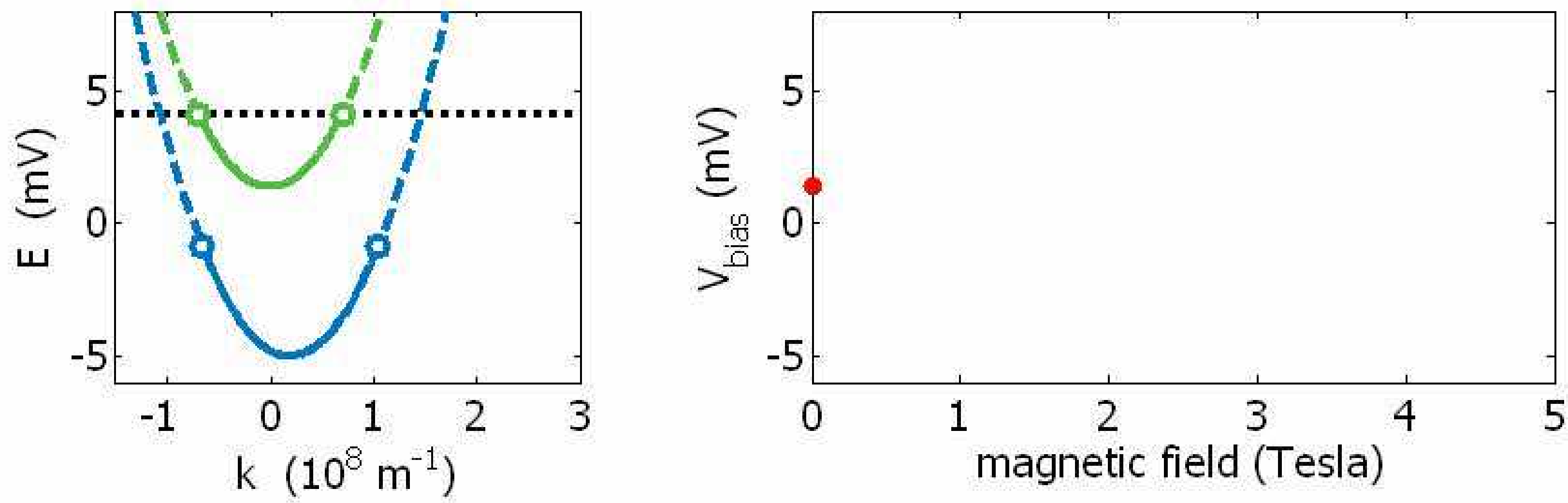


Non-interacting tunneling (graphical view)

- Tunneling must conserve energy and momentum
- Tunneling must be from an occupied state to an unoccupied state



Experiment knobs to tune tunneling

- Vbias shifts dispersion curves in energy
- Parallel field shifts dispersion curves in wavevector

$$p \rightarrow p + \frac{eA_x}{c} \qquad \Delta k = \frac{edB}{\hbar}$$

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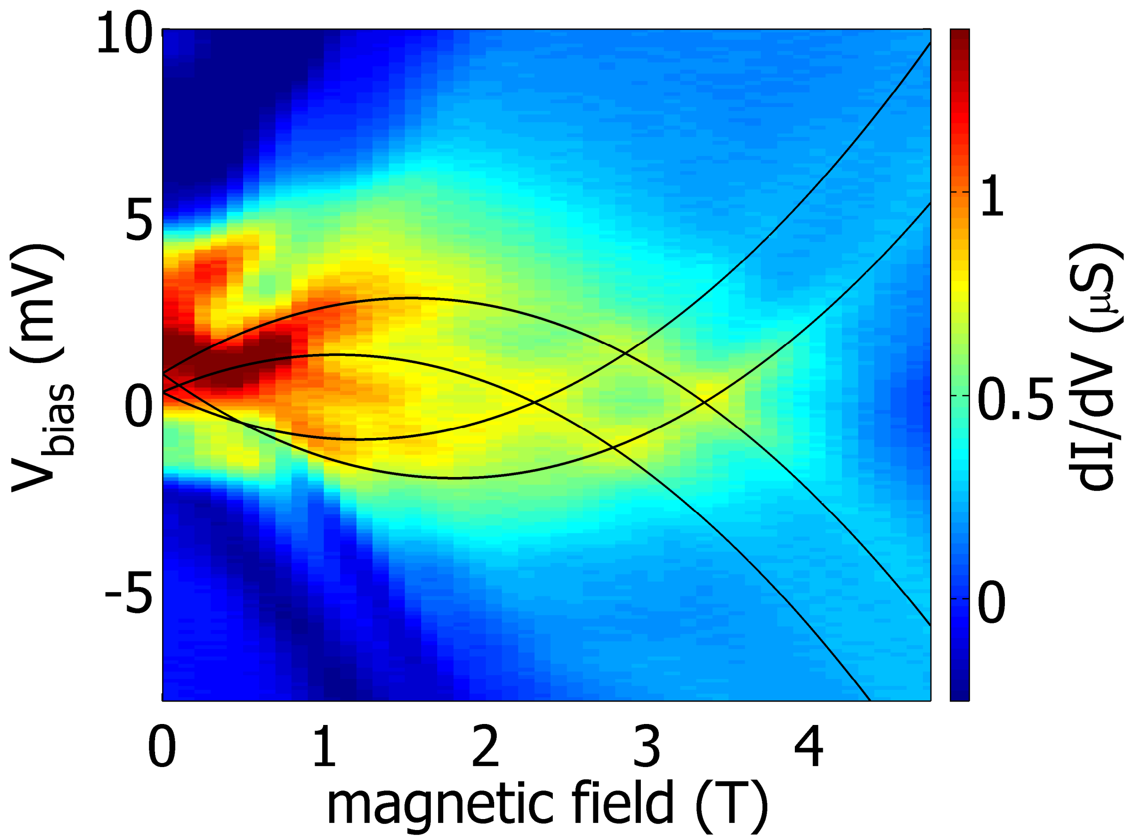
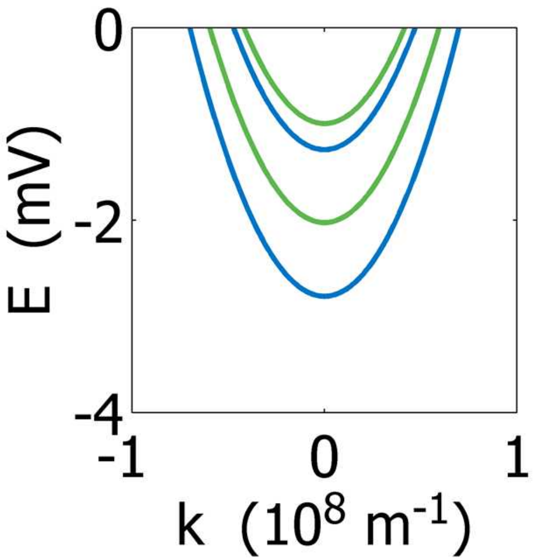
Spectroscopy at (2,2)

Notable features

- Crossing points at high field
- Complicated and broad structure at low field





Non-interacting electron model (lines) provides a good starting point to understand results. Additional features may arise from interactions.

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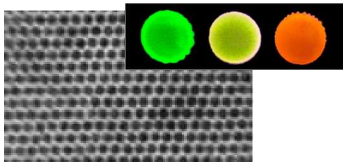
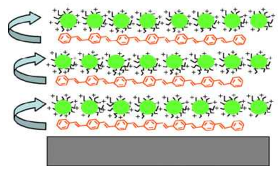
Nanoelectronics at CINT

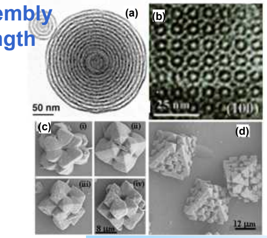
Nanoelectronics & Nanophotonics:
Precise control of electronic and photonic wavefunctions

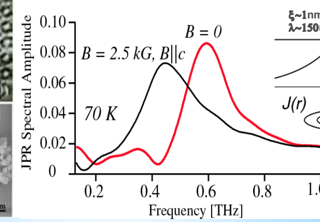


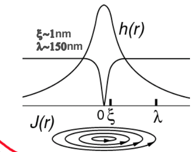


Complex Functional Nanomaterials:
Relationships between synthesis, structure and complex and emergent properties

Self-assembly on all length scales

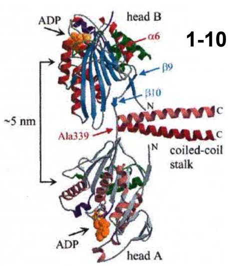




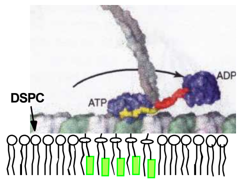


Structure-property relationships

Nano-Bio-Micro Interfaces:
Biological principles & functions imported into artificial bio-mimetic systems



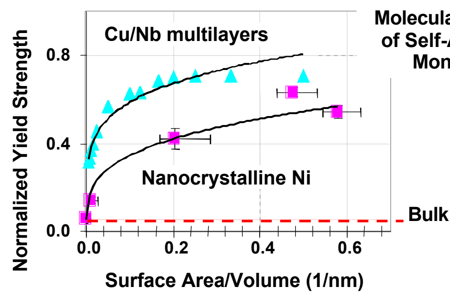
1-10 nm



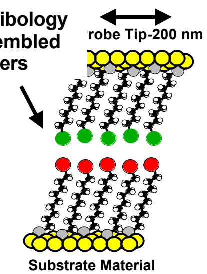
Aggregated receptors

10 -100 nm

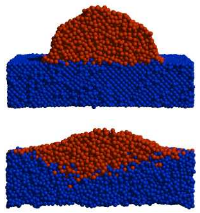
Nanomechanics:
Understanding the mechanical behavior of nanostructured materials

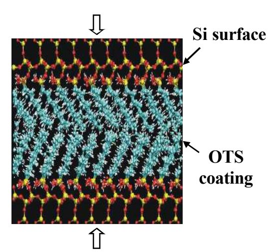


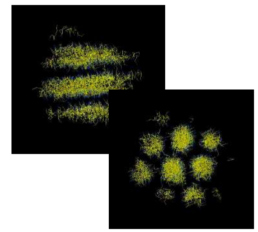
Molecular Tribology of Self-Assembled Monolayers



Theory & Simulation:
Theoretical, modeling and simulation techniques for multiple length and time scales and functionality

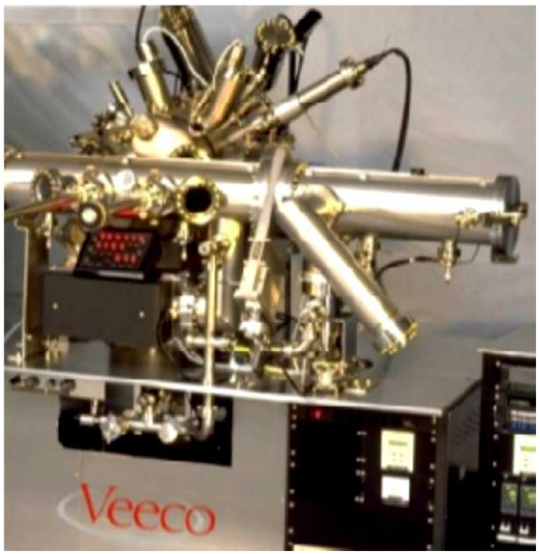






Next generation molecular beam epitaxy

MBE system optimized for ultra-high mobility 2D electrons



- BES mid-scale instrumentation proposal submitted ($5.5M)

National resource for science community

Nanoelectronics, exciton condensation, Bloch oscillation, quantum Hall effects, ...

Non-abelian states for error-free quantum computing


TO BEAT BACTERIA, STOP MUTATIONS • GLOBALIZATION AND POVERTY

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BIZARRE PARTICLES AND SPACETIME BRAIDS SOLVE IMPOSSIBLE PROBLEMS

COMPUTING WITH QUANTUM KNOTS

Cultured Apes and Evolving Intelligence

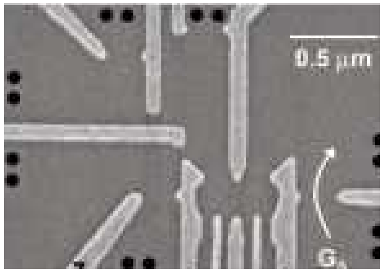
Magnetic Triggers of Solar Flares

Plugged-In Hybrid Cars

Solid State Quantum Computing

- Quantum computing could allow extremely efficient factoring (and a few other things) – **impact**: *cryptography*.
- Quantum computing requires *extreme* control of single electrons.

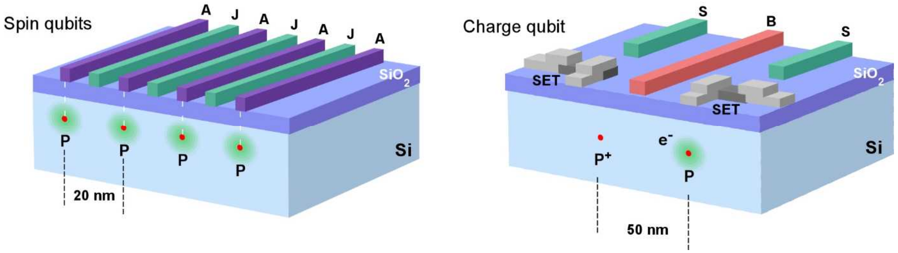
Lateral coupled dots with QPC detector



Petta, J.R., et al., Science, 2005. **309**(5744): p. 2180-2184.

- Design new laterally coupled dots in silicon (many advantages)
- With Mark Eriksson at U. Wisconsin

Integrated Quantum Computer Devices



- Single phosphorus implant in Si with single electron spin or charge detection
- With Clark's group in Australia

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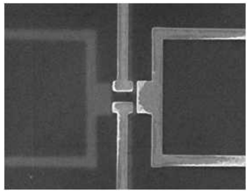
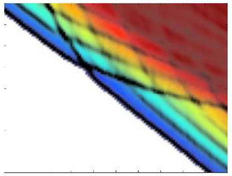
Conclusions

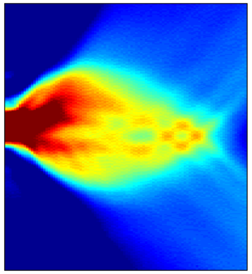
Investment in materials science and semiconductor facilities has enabled world-class basic research.



In a system of coupled quantum wires, we can control the wavefunction of each wires. Our focus is to assess the role of interactions in coupled nanostructures.



We are extending these techniques to impact other areas of nanoelectronics, and developing new programs.



Future directions

World-record high mobility MBE capabilities
Collaborations with CINT scientists and users
Increasing impact in solid state quantum computing

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