SAND2009-1772P

What is MBE? Why is It at a Nanotechnology Center?

John Reno
Center for Integrated Nanotechnologies
Sandia National Laboratories
To be presented at Taylor University
March 5, 2009

MBE is a technique that is about 40 years old and uses large pieces of equipment yet is a major part of the Center for Integrated Nanotechnologies (CINT). A brief explanation of what CINT is will be presented first, followed by what MBE is and what it can do. Examples of the range of nanotechnology that are being impacted by the MBE system at CINT will then be presented.

This work was performed in part at the US Department of Energy, Center for Integrated Nanotechnologies, at Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-AC04-94AL85000).

What is MBE?
Why is at a Nanotechnology Center?

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Distributed Facilities to Meet National Needs

Albuquerque, New Mexico

Kauai Test Facility, Hawaii

Tonopah Test Range, Nevada

Yucca Mountain, Nevada

WIPP, New Mexico

Pantex, Texas

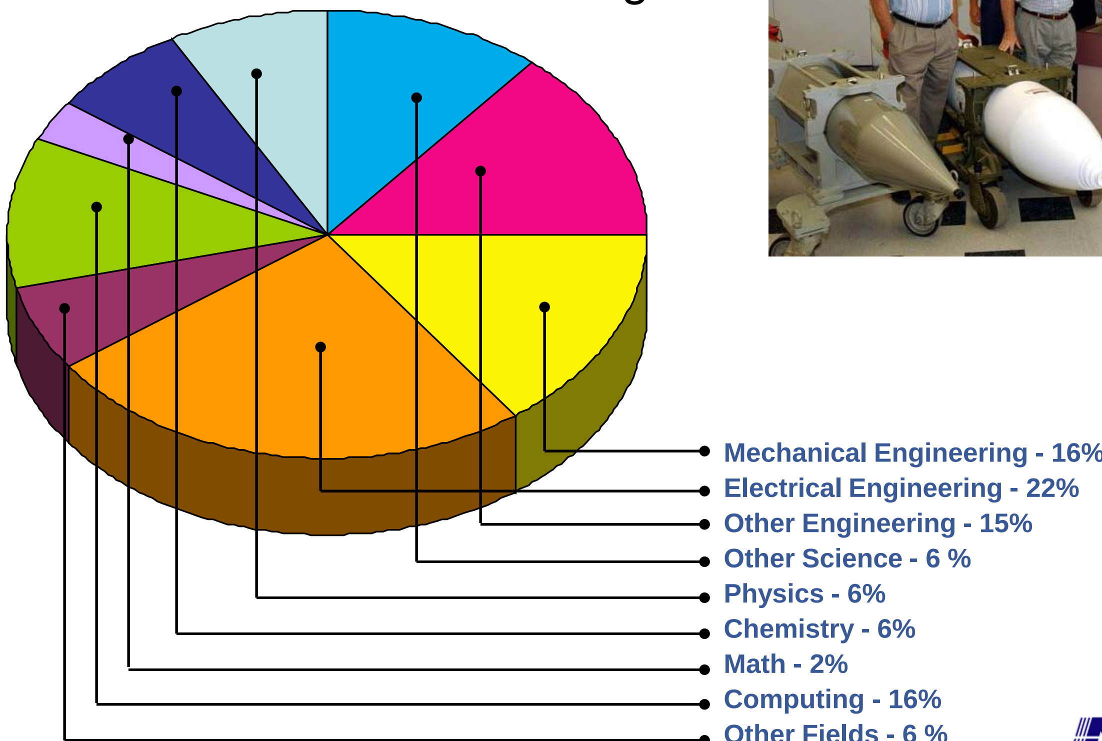
Livermore, California

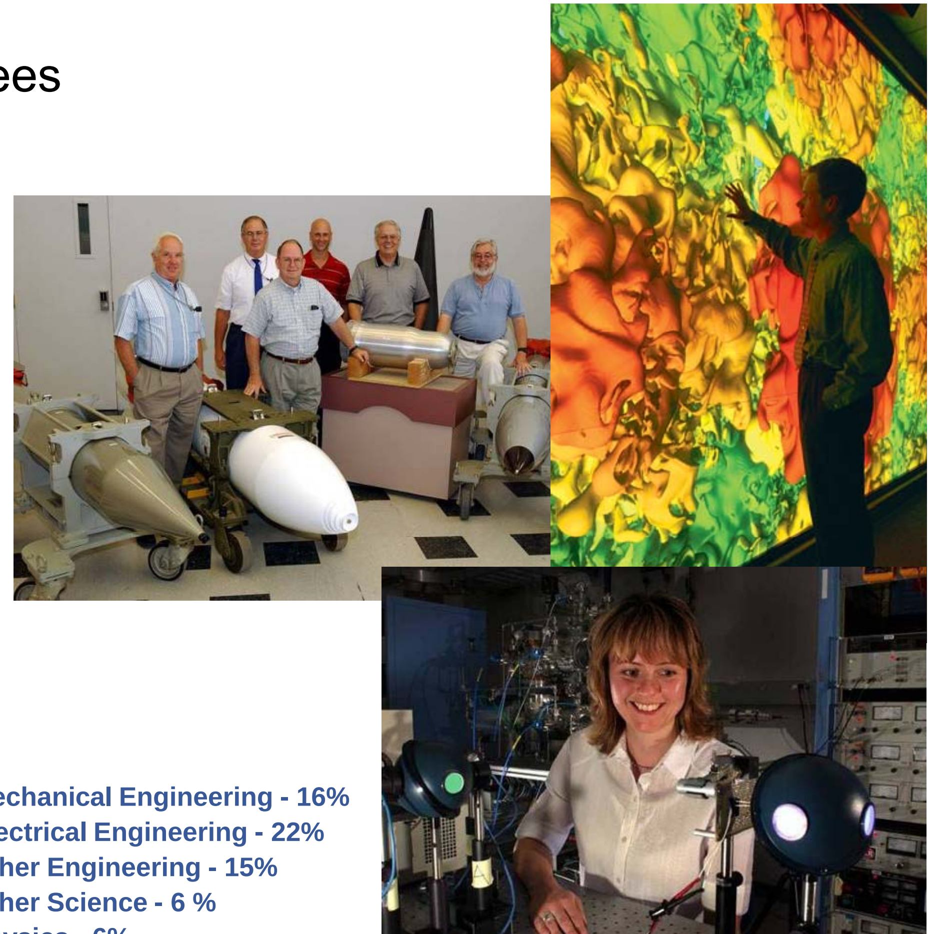
NNSA National Nuclear Security Administration

Sandia National Laboratories

Highly Skilled Workforce

- More than 8,600 full-time employees
- More than 1,500 PhDs and 2,700 MS/MAs
- 2,200 on-site contractors
- $2.33 billion FY06 total budget





NNSA National Nuclear Security Administration

Sandia National Laboratories

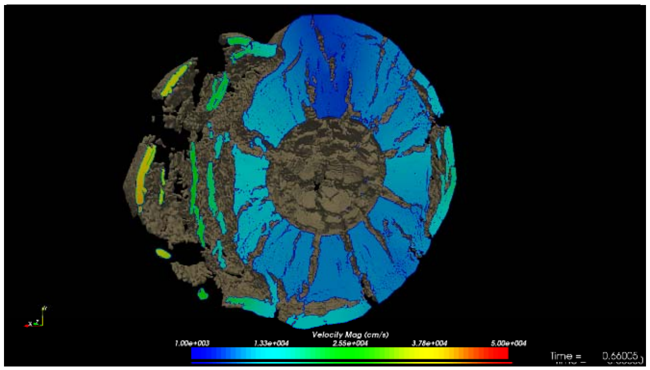
Our Business: National Security

- Core Purpose: to help our nation secure a peaceful and free world through technology.
- Highest Goal: to become the laboratory that the United States turns to first for technology solutions to the most challenging problems that threaten peace and freedom for our nation and the globe.

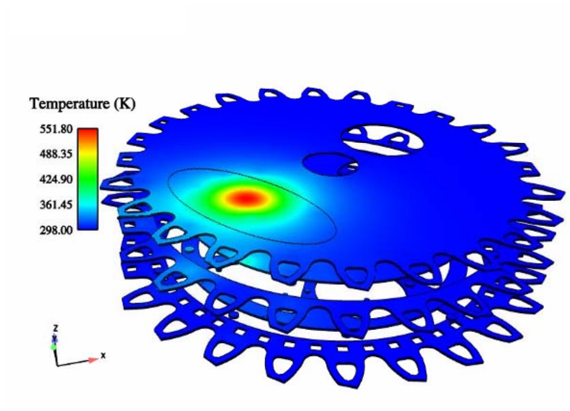
NNSA
National Nuclear Security Administration

Sandia National Laboratories

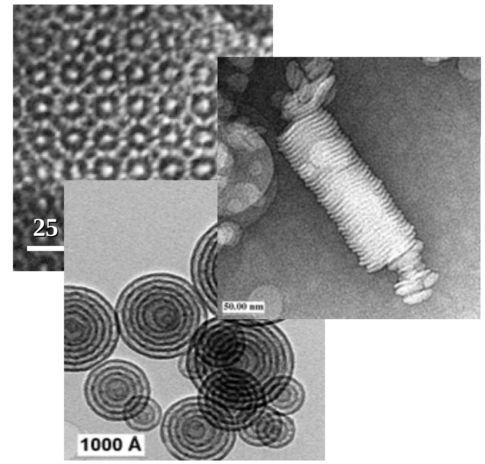
Our Mission Focus Relies on Strong Science and Engineering



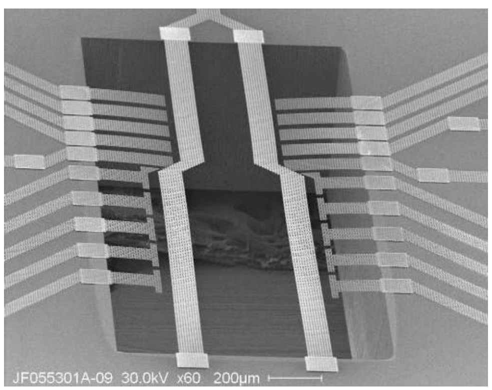
Computational and Information sciences



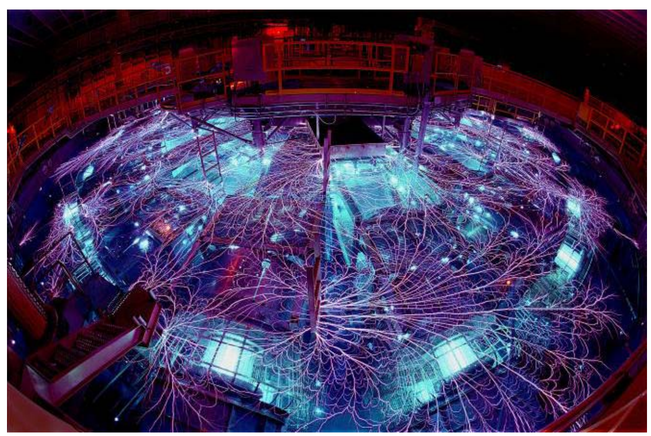
Engineering Sciences



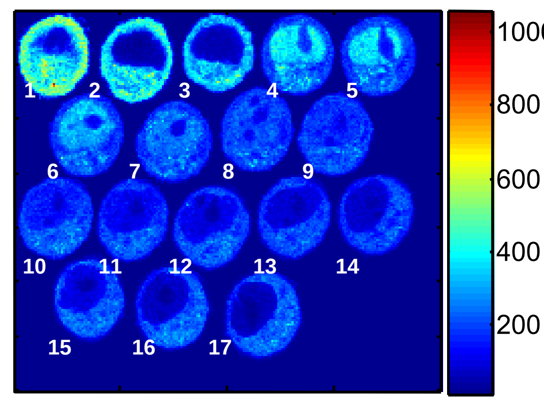
Materials Science and Technology



Microelectronics and Photonics



Pulsed Power



Bioscience

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Sandia's Primary Mission: *Support the Nuclear Deterrent*

Ensure that the stockpile, the infrastructure, and the people are fully capable of supporting our nation's deterrence policy

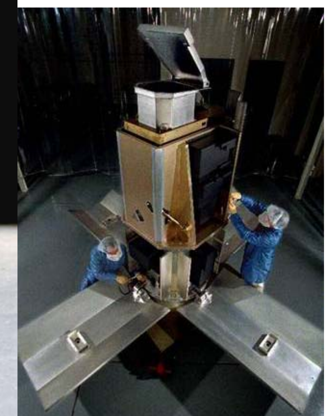
Computer modeling of B61 tail assembly

National Nuclear Security Administration

Sandia National Laboratories

Four Mission Areas

- Nuclear Weapons
- Defense Systems and Assessments
- Energy, Resources, and Nonproliferation
- Homeland Security and Defense



NNSA National Nuclear Security Administration

Sandia National Laboratories

Provide Exceptional Systems Engineering and Programmatic Support for the Stockpile

- Research, Design, and Development of Non-Nuclear Components (96% of Total NW Parts)
- Life Extension of Nuclear Weapons
- Neutron Generator (NG) Manufacturing
- Stockpile Support – maintenance, military liaison, surveillance, dismantlement, logistics
- Nuclear Materials Protection

Trident Submarine

C4/D5 Missile

National Nuclear Security Administration

Sandia National Laboratories

Defense Systems & Assessments Programs

- Proliferation Assessment
- Remote Sensing and Verification
- Surveillance, and Reconnaissance
- Integrated Military Systems

Shuttle Heat Shield Inspection

Future Combat System Integrated Support Team

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Energy, Resources, and Nonproliferation

Energy, Water, and Security Enabled by Science & Technology

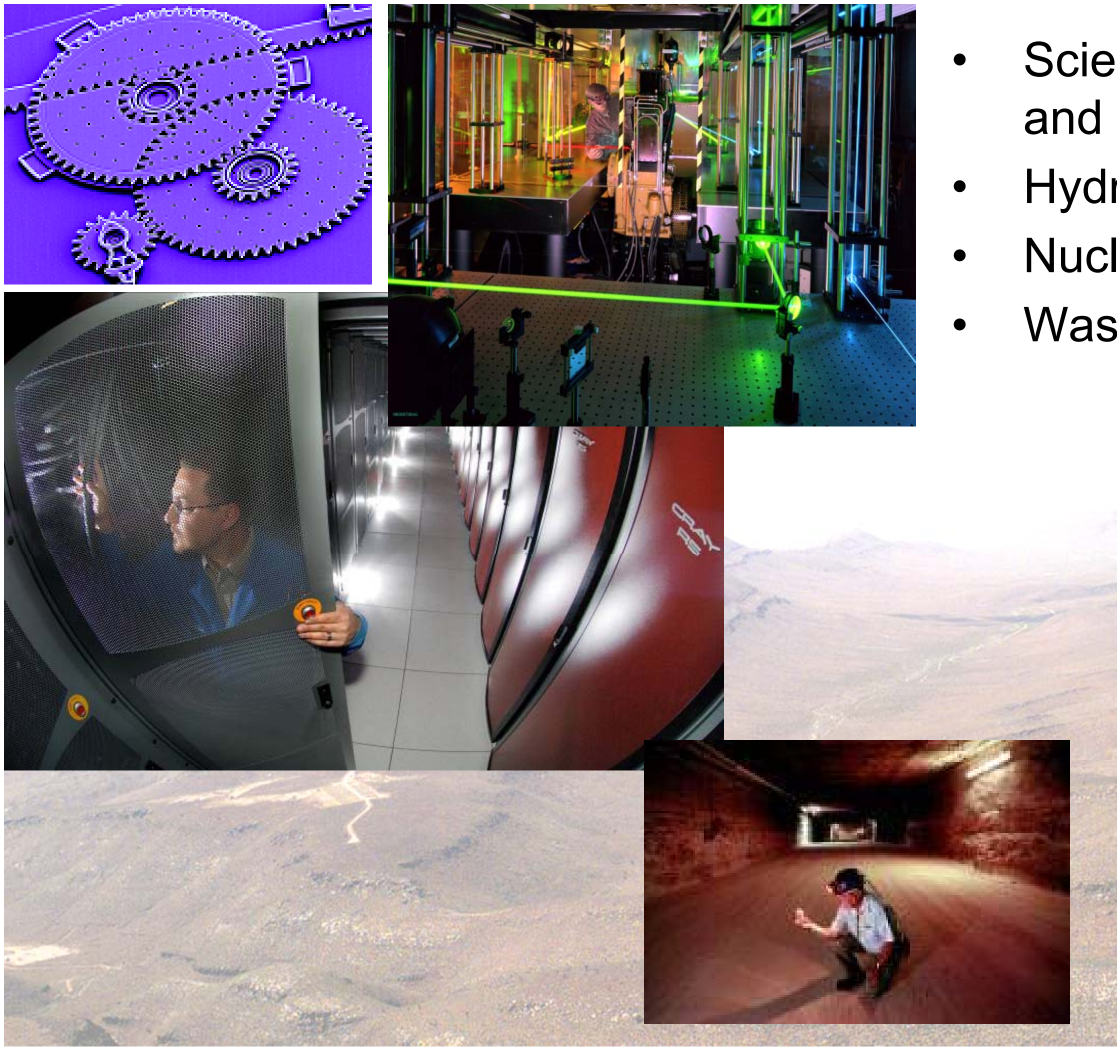
- Secure energy supplies for national security
- Clean, abundant and affordable energy
- Water research
- Infrastructure protection

National Nuclear Security Administration

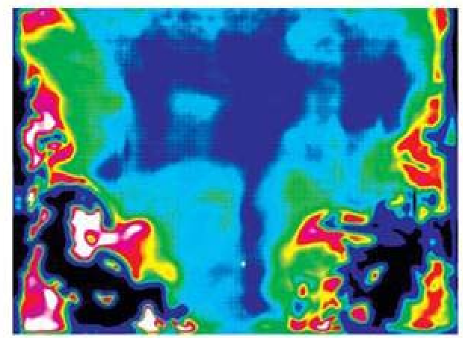
Sandia National Laboratories

Energy, Resources, and Nonproliferation

Making the World a Safer Place



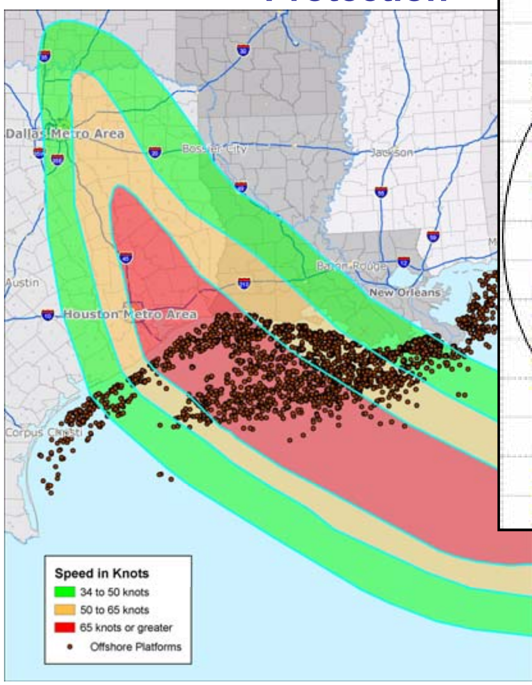
- Science, Technology, and Engineering Base
- Hydrogen Research
- Nuclear Power Research
- Waste Management

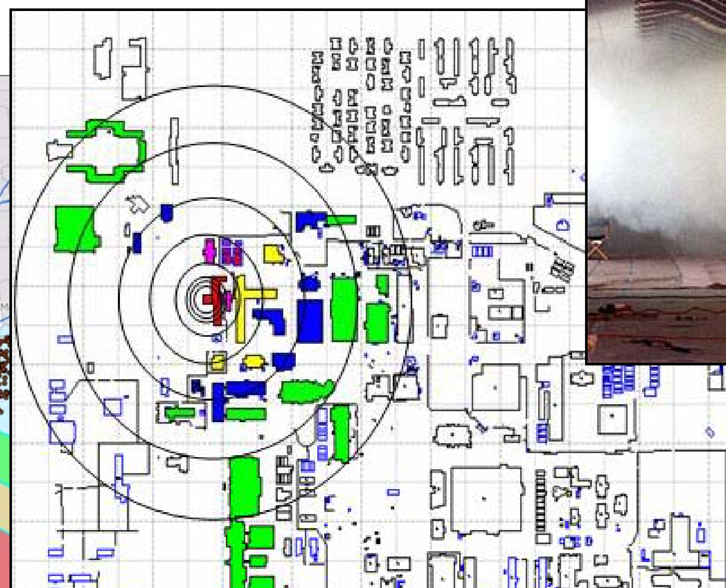


Homeland Security and Defense

Mitigating the risk of catastrophic events and enhancing the nation's ability to respond and recover

Risk Management and Infrastructure Protection





Homeland Defense and Force Protection

Catastrophic Event Mitigation

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Catastrophic Event Mitigation

- Chemical and Biological Countermeasures
- Radiological and Nuclear Countermeasures
- Explosives Countermeasures
- Information Analysis
- Red Teaming
- Border and Transportation Security
- Systems Analysis

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The DOE Center for Integrated Nanotechnologies (CINT)

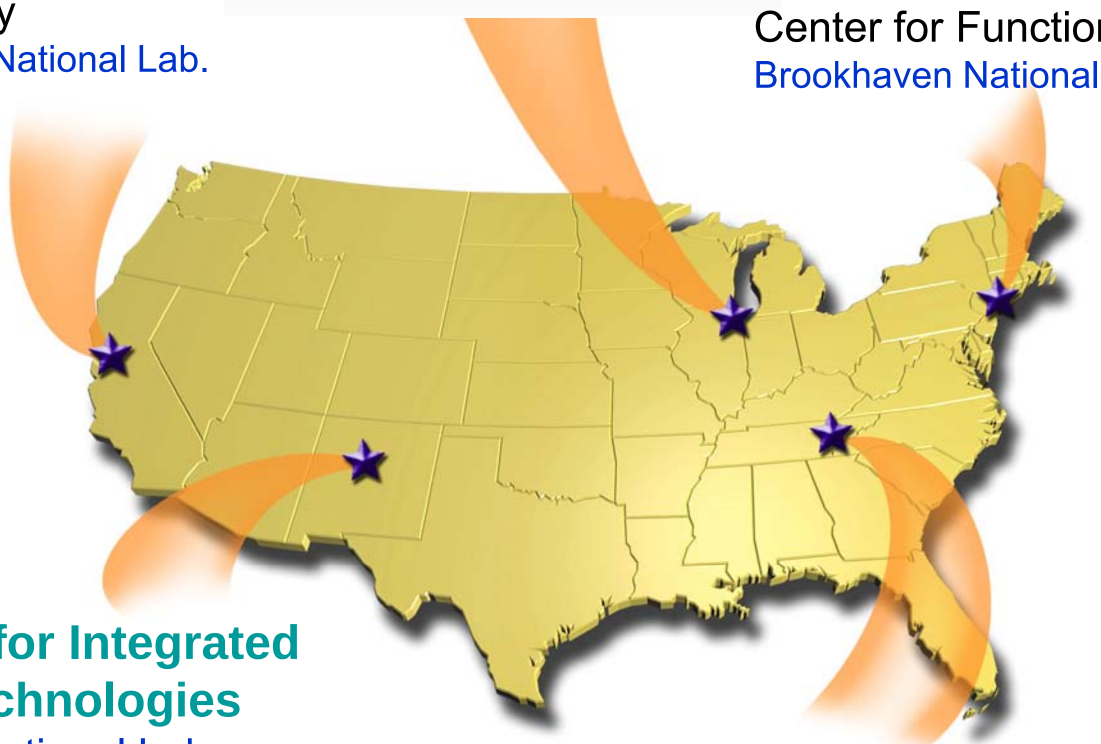
DOE Center for Integrated Nanotechnologies
Sandia National Laboratories
Albuquerque, NM 87185-1315

CINT is one of five U.S. Dept. of Energy Nanoscience Centers

Center for Nanoscale Materials
Argonne National Lab.

Molecular Foundry
Lawrence Berkeley National Lab.

Center for Functional Nanomaterials
Brookhaven National Lab.



Center for Integrated Nanotechnologies
Sandia National Labs.
Los Alamos National Lab.

Center for Nanophase Materials Sciences
Oak Ridge National Lab.

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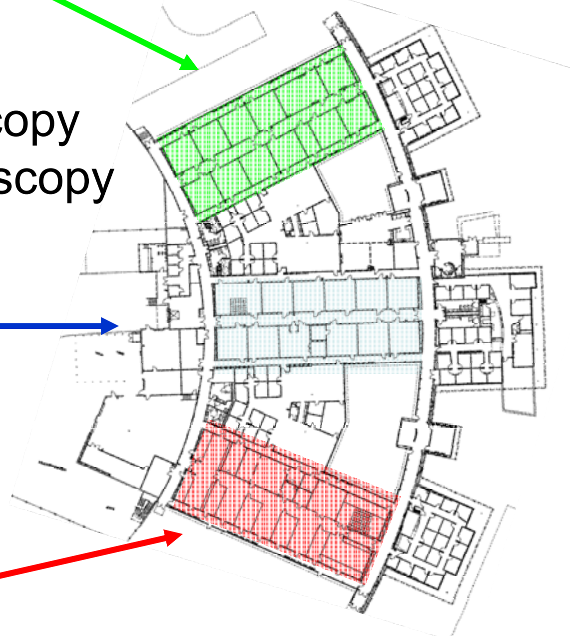
CINT has capabilities for synthesis, characterization and integration

Core Facility

Characterization Wing
- TEM, SEM
- Low Temp Transport
- Scanning Probe Microscopy
- Ultra-fast Laser Spectroscopy

Synthesis Wing
- Molecular Beam Epitaxy
- Chem & Bio labs
- Molecular films

Integration Lab
- E-beam lithography
- Photolithography
- Deposition & Etch
- SEM/FIB



Gateway to Los Alamos
- NSOM, AFM
- Environmental SEM
- Nano-indenter
- Pulsed Laser Dep.
- Ultra-fast Spectroscopy
- Computer Cluster
- Visualization Lab

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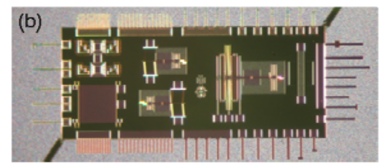
Science Thrusts

Nanophotonics & Optical Nanomaterials

Synthesis, excitation and energy transformations of optically active nanomaterials and collective or emergent electromagnetic phenomena (plasmonics, metamaterials, photonic lattices)

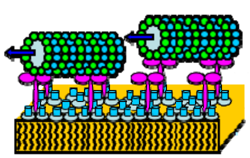
Nanoscale Electronics and Mechanics

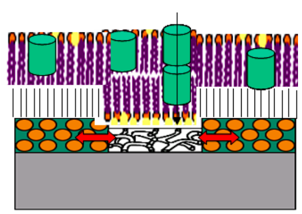
Control of electronic transport and wavefunctions, and mechanical coupling and properties using nanomaterials and integrated nanosystems



Soft, Biological, & Composite Nanomaterials

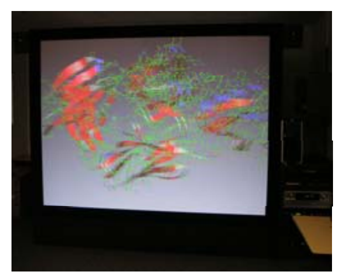
Solution-based materials synthesis and assembly of soft, composite and artificial bio-mimetic nanosystems





Theory & Simulation of Nanoscale Phenomena

Assembly, interfacial interactions, and emergent properties of nanoscale systems, including their electronic, magnetic, and optical properties



Sandia National Laboratories

CINT is a DOE/BES National User Facility

- **No-fee access based on scientific quality**
- **Fee required for proprietary work**
- **Collaborative research or access equipment**
- **Short & long term projects (1 year, renewable)**
- **Rapid Access Proposals**
- ***Spring Call for User Proposals is now open through March 16!***

http://CINT.sandia.gov **or** http://CINT.lanl.gov

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CINT has attracted widespread interest

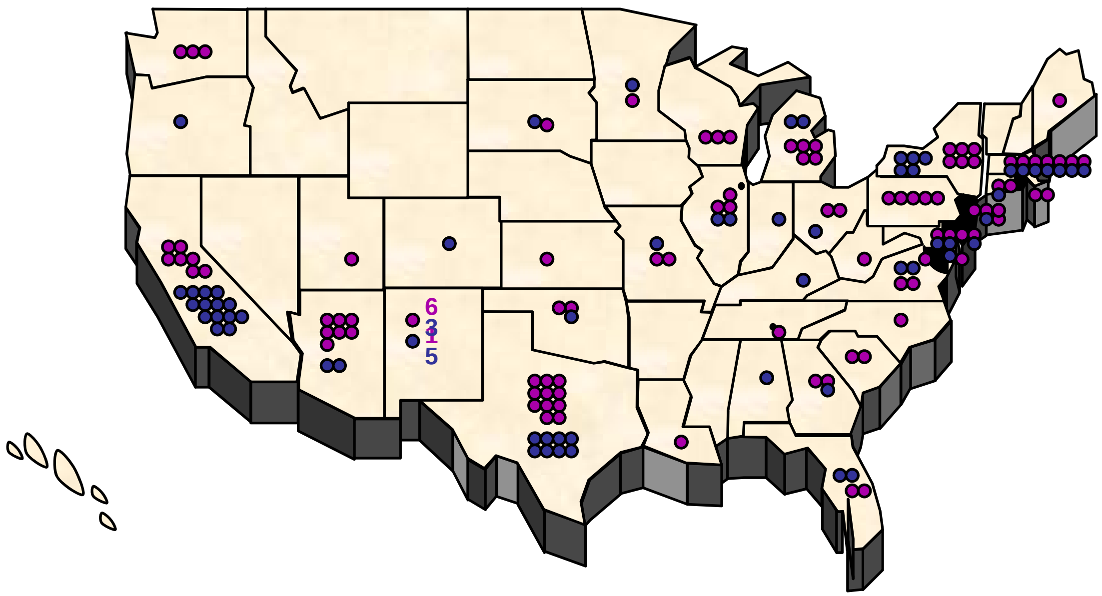
<u>User Proposals</u>

175 submitted; 130 accepted (74%) in 2006

101 submitted;   79 accepted (78%) in 2007 (+13 Rapid Access)

172 submitted; 160 accepted (93%) -- Spring 2008 (+13 Rapid Access)

119 submitted; 107 accepted (90%) -- Fall 2008



425 researchers involved in current projects, representing 36 States and 14 Foreign Countries

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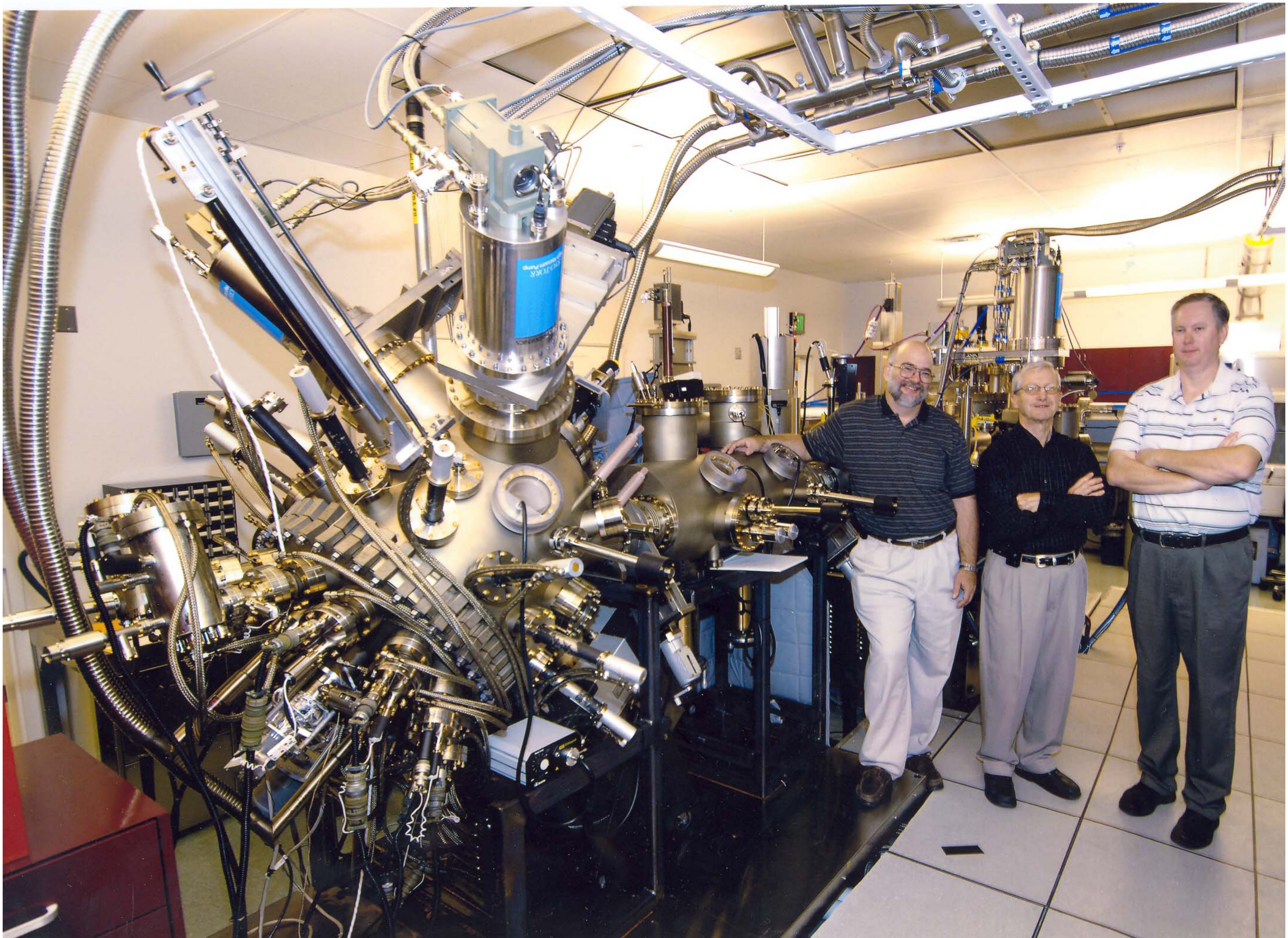
31.07.2007



What Is MBE?

- Clearly not "nano"
- Not a new technique (~1970)

Molecular Beam Epitaxy

Molecular Beam Epitaxy

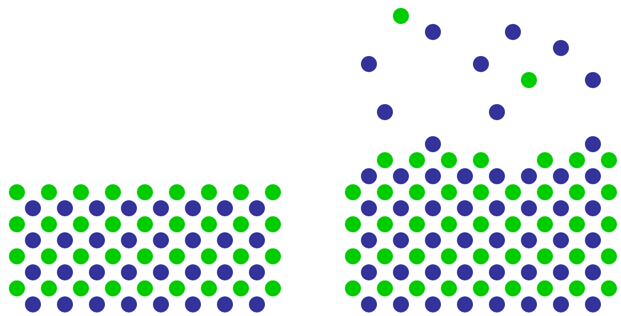
Elemental
- Al
- Ga
- As_4

- Directional
- UHV => no scattering
- Mechanical Shutter
  start and stop
- Change Materials

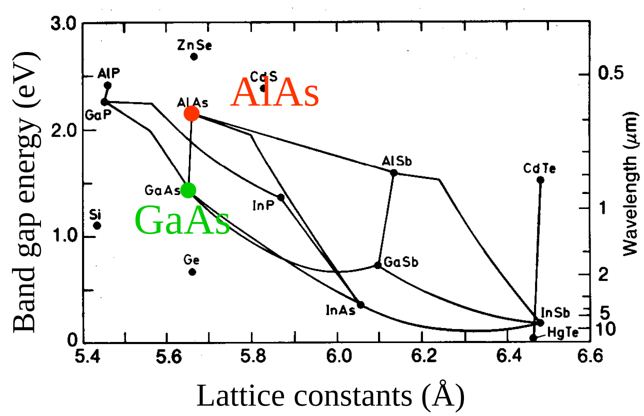
Same crystal structure as substrate

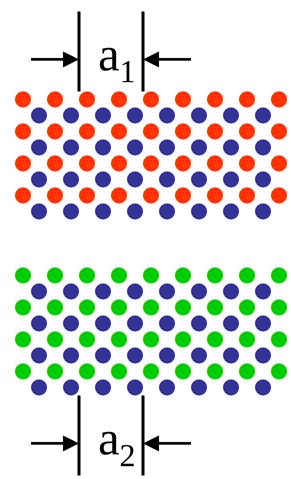
Ultra-low disorder GaAs/AlGaAs

1. Epitaxial growth

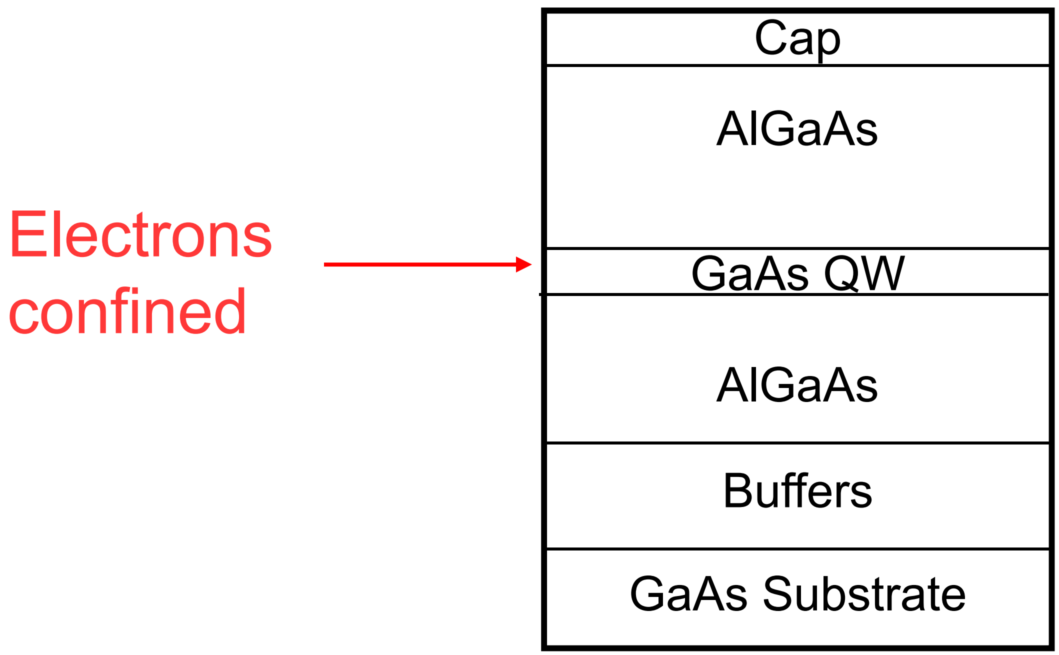


2. Lattice matching

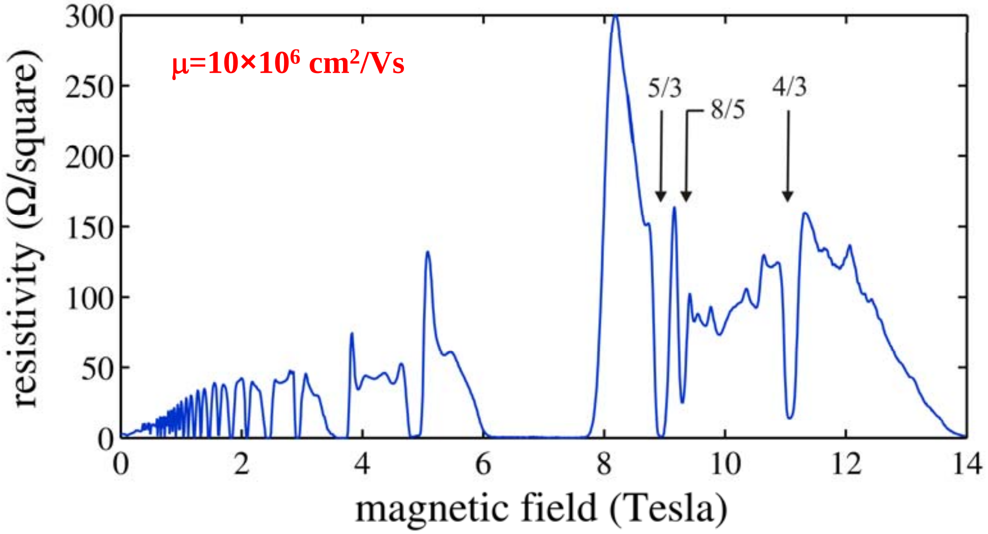




Typical High Mobility Structure



Low Temperature Transport
High mobility 2D electrons



Quantum Hall Effect
Fractional Quantum Hall effect

Length scales at low temperature

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

Nano scales but
not technically nanomaterials

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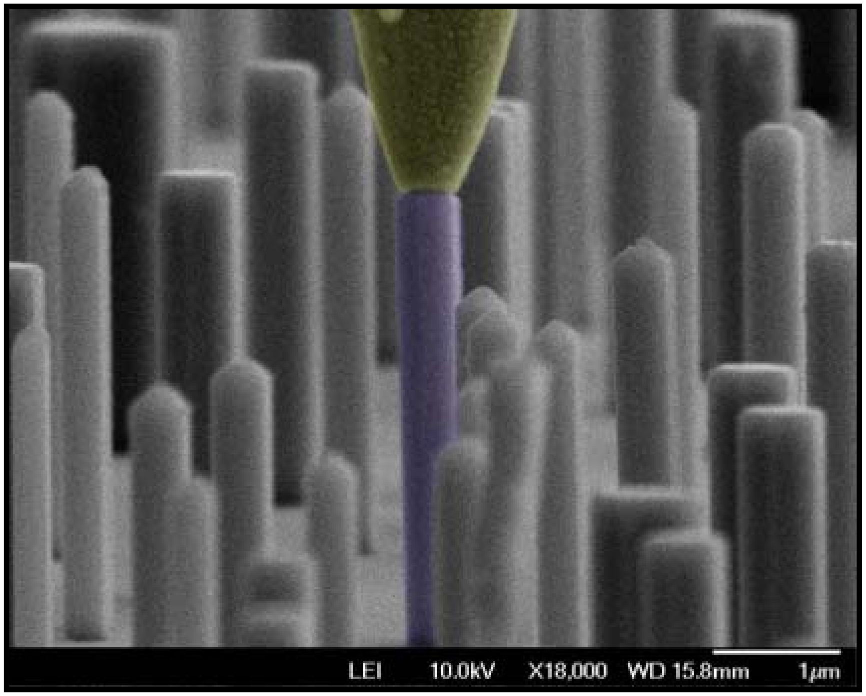
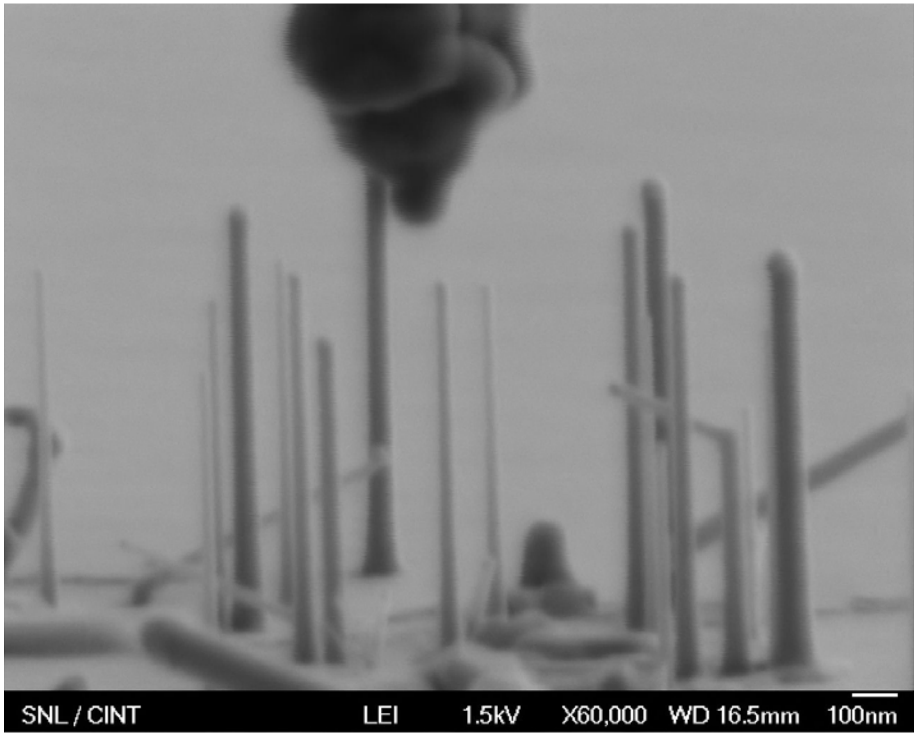
Nanowires

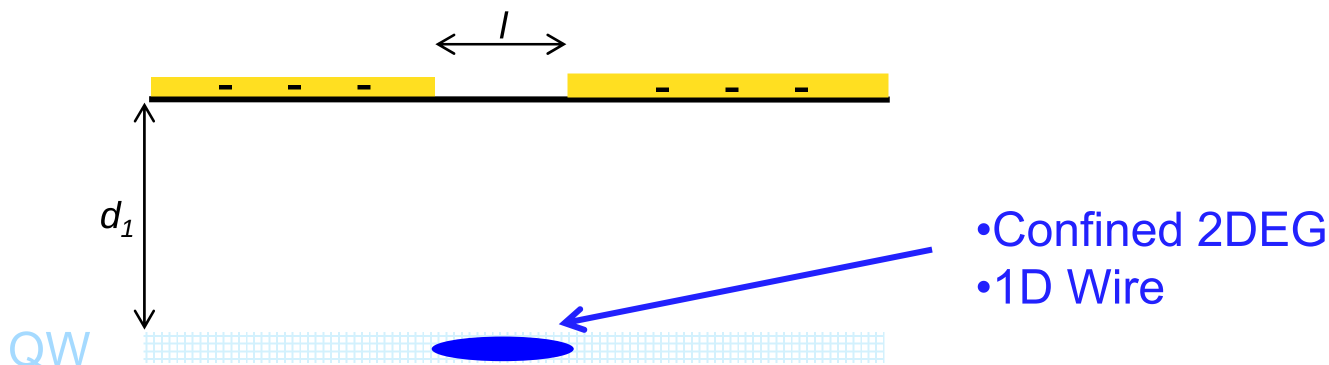


GaN rods ~0.5μm diameter

Ge nanowires <100nm diameter

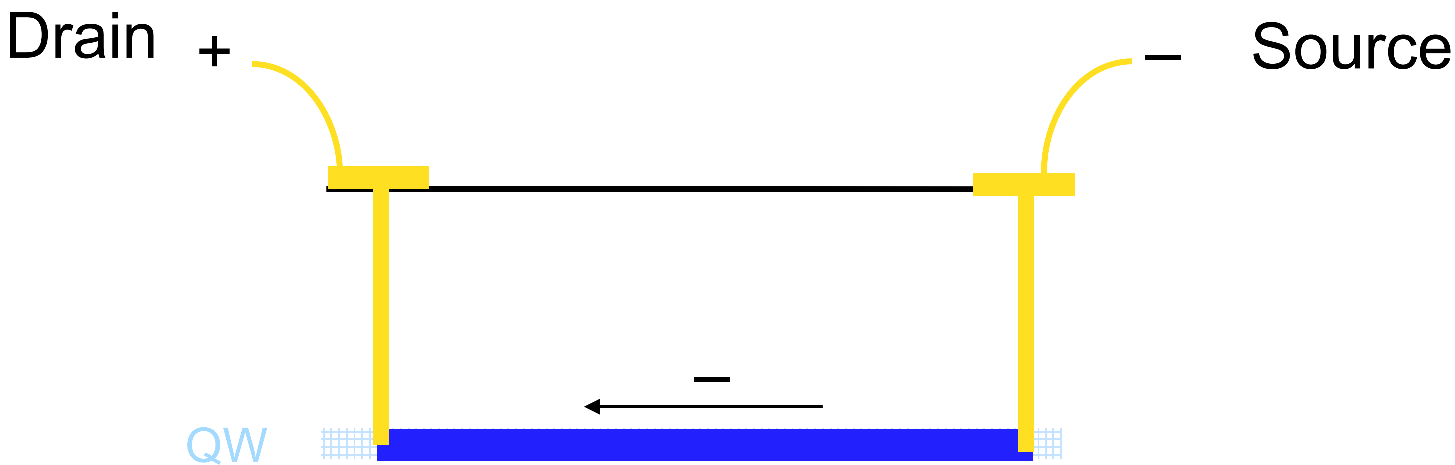


Gated Electronic Structures



•Gate dimension (*l*) of ~100nm can be achieved

Quantum Wires

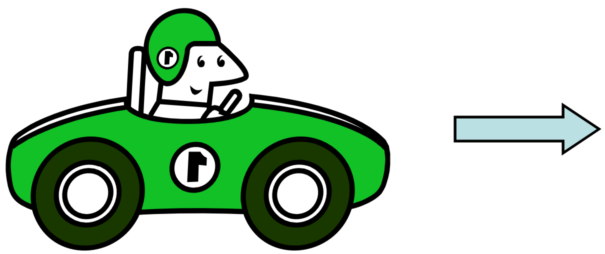


Ballistic conductance

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

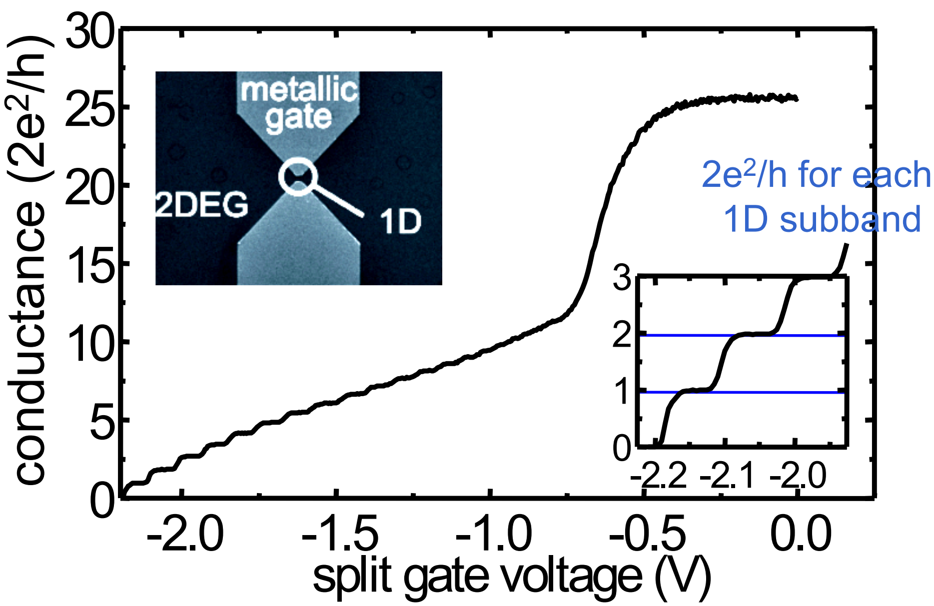
Cartoon

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



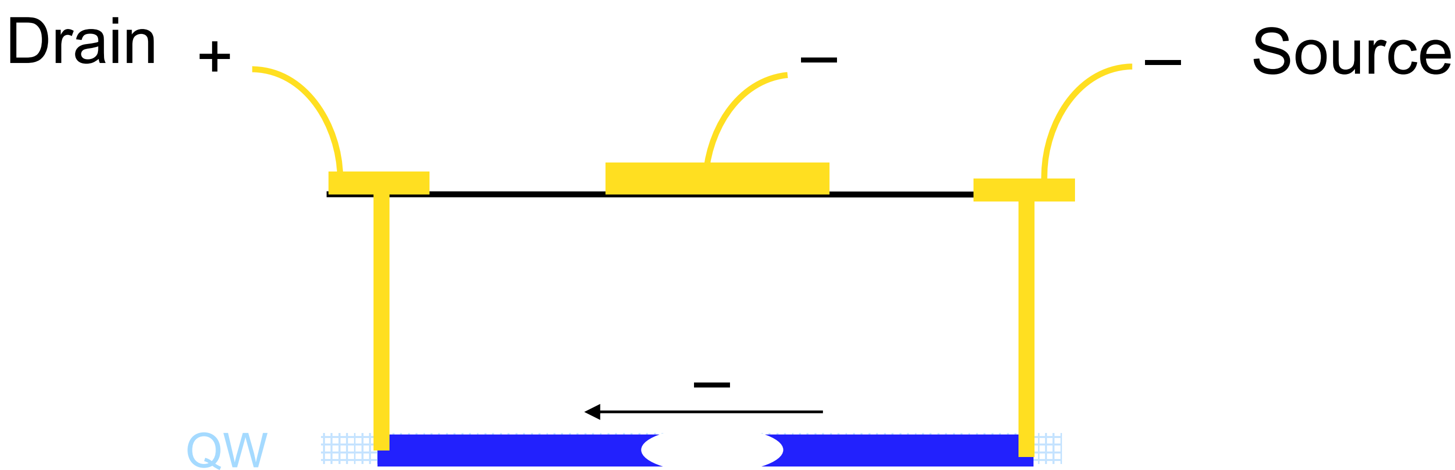
Equation

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



conductance depends on *e*, *h* only

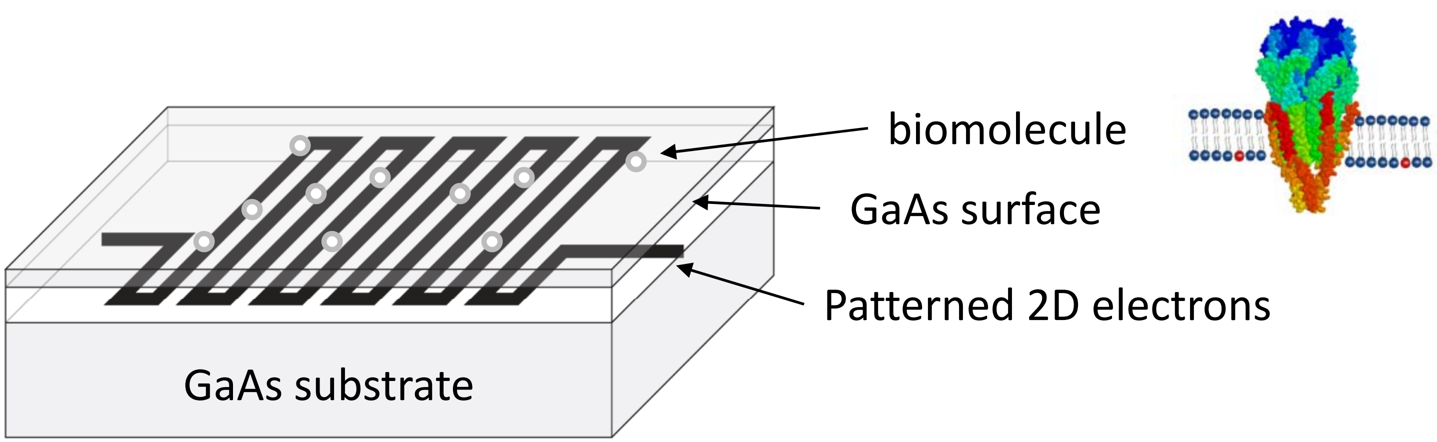
Uses of Gated Electronic Structures



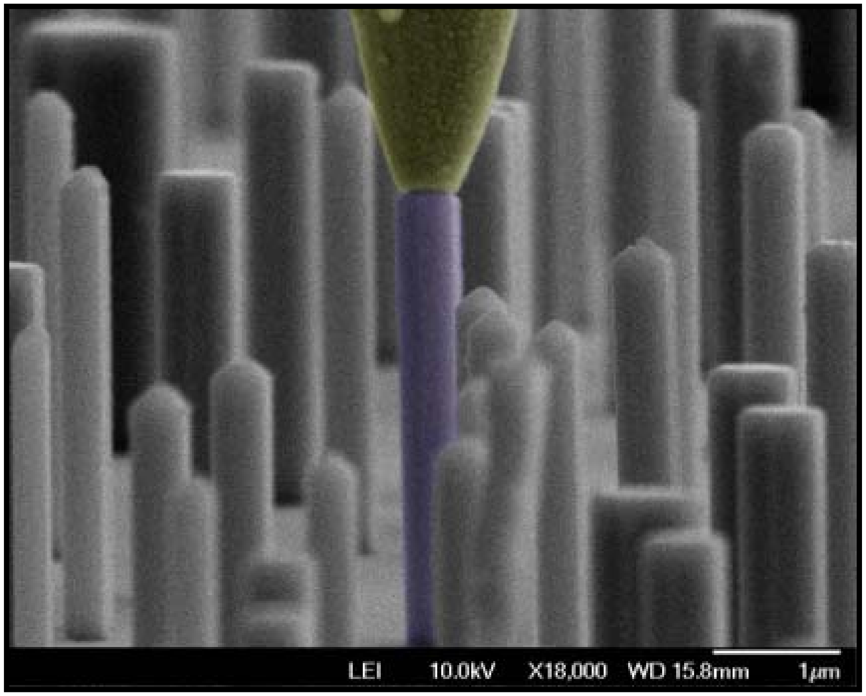
Charge on the Gate Affects Current Flow

Semiconductor biosensor for charged proteins

- GaAs quantum wells create a two-dimensional electron gas below the surface of the semiconductor.
- The resistance of the 2D electrons will depend on the electric fields.
- Changes in the charge state of a biomolecule (e.g. membrane protein) on the surface will lead to changes in the local resistance.
- Initial device structure will be a meander line to maximize resistance changes
- Processed surface will be buried under 1 micron of GaAs to expose a uniform surface

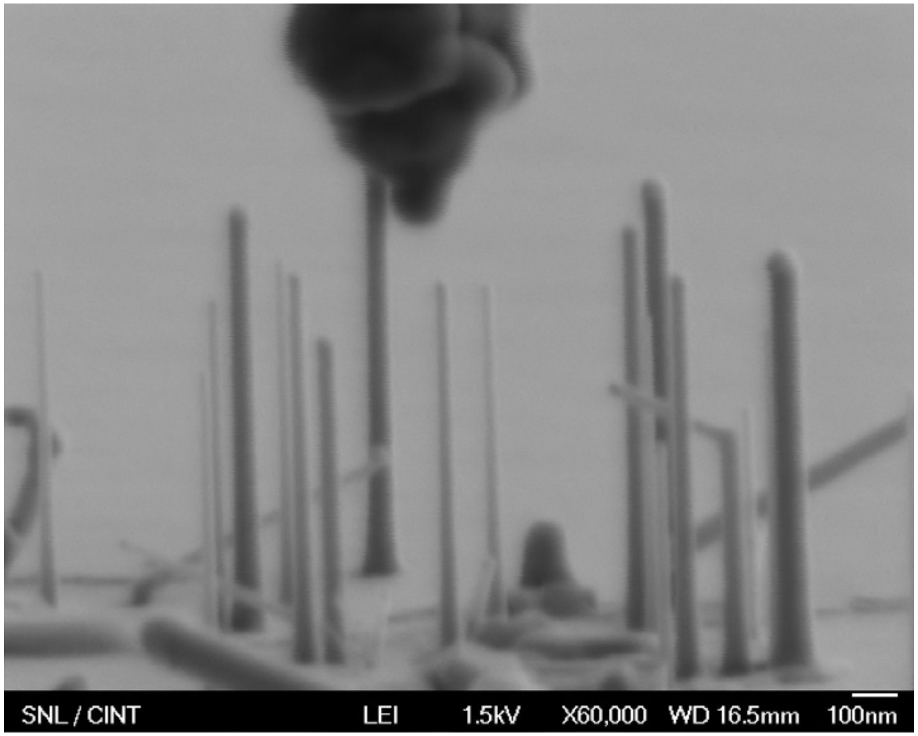


Nanowires

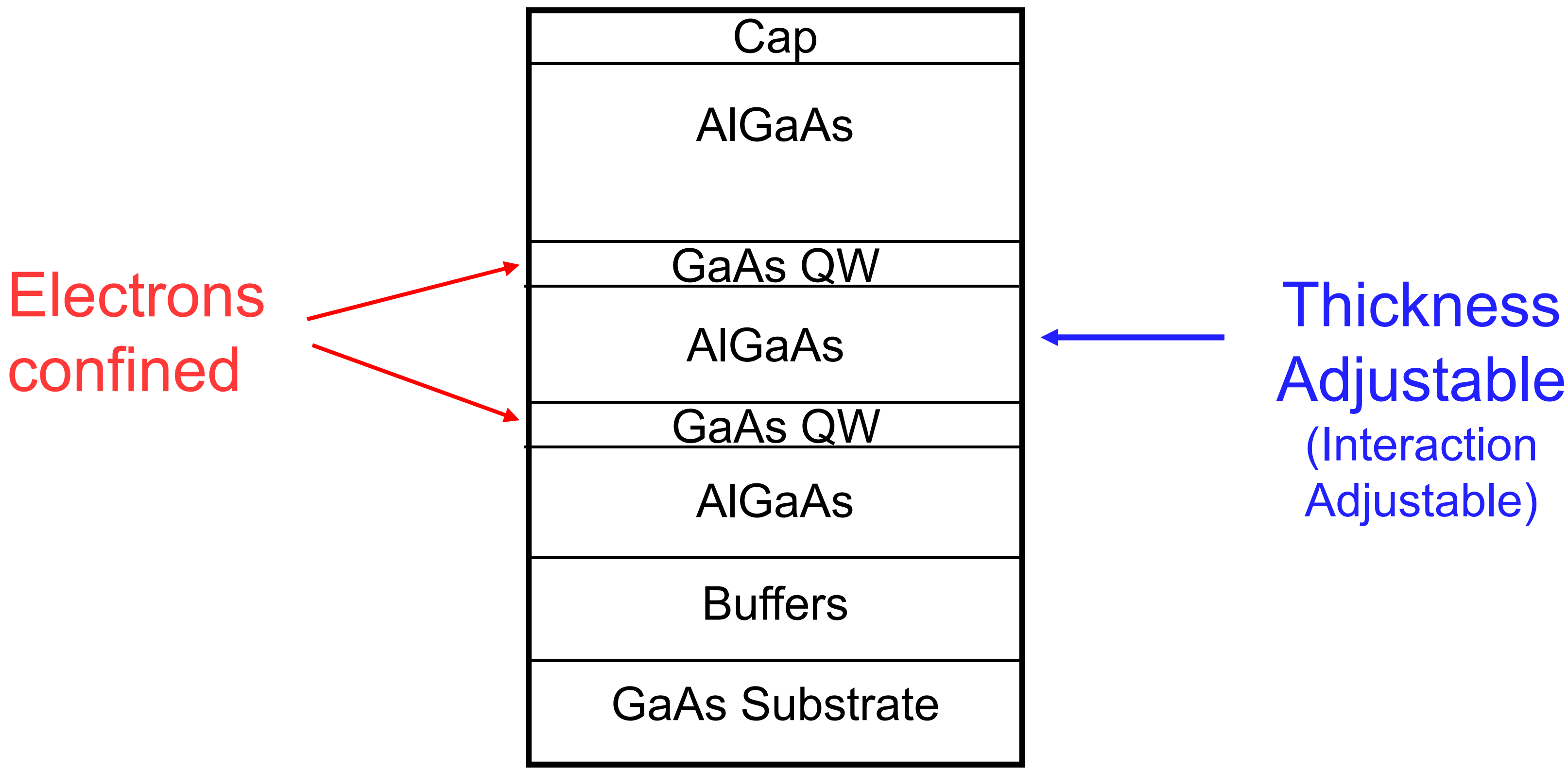


GaN rods ~0.5μm diameter

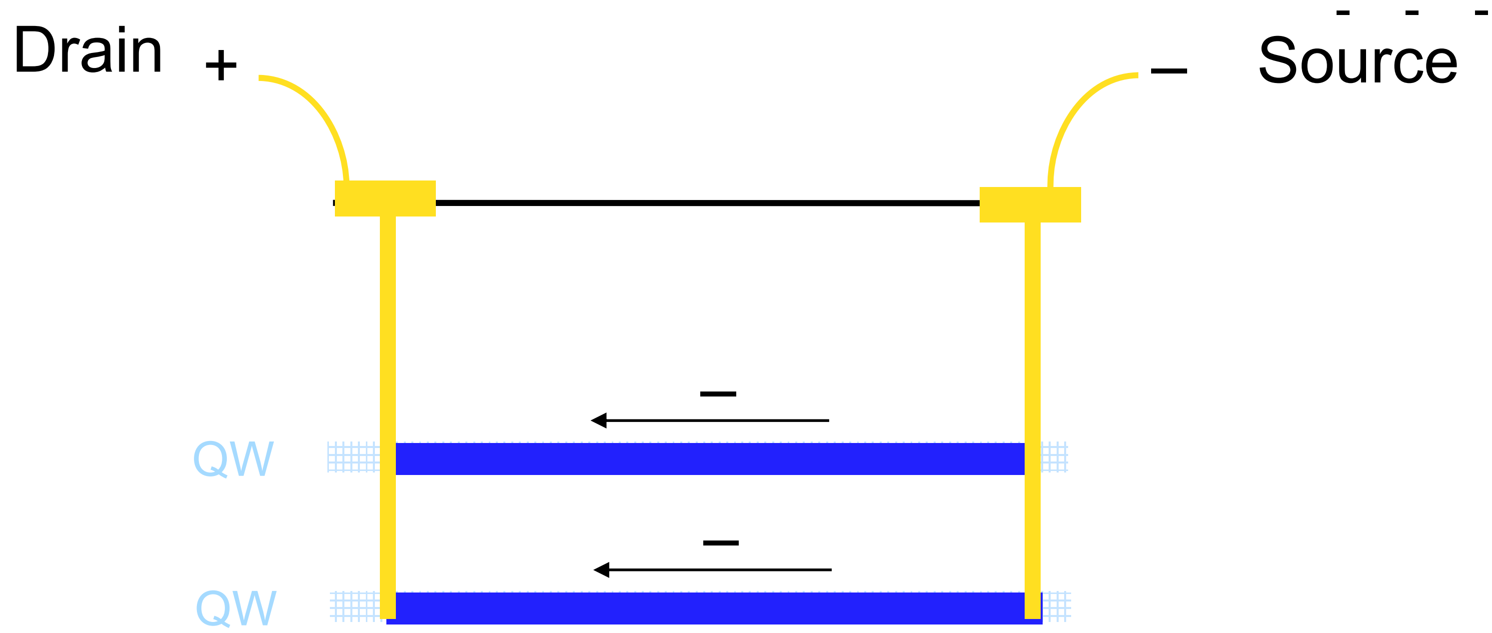
Ge nanowires <100nm diameter

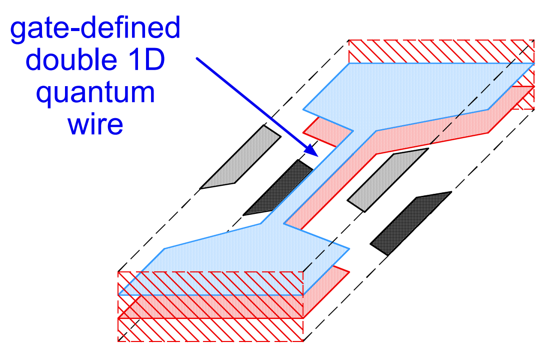


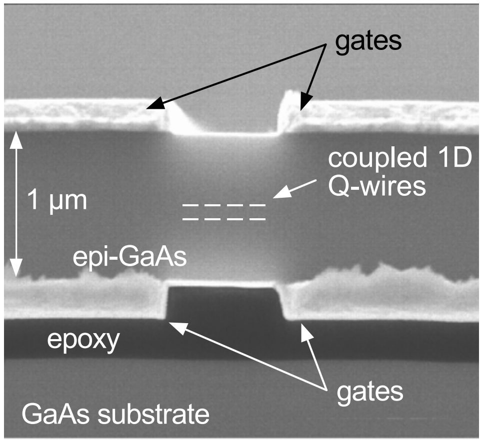
Two Wire Structure



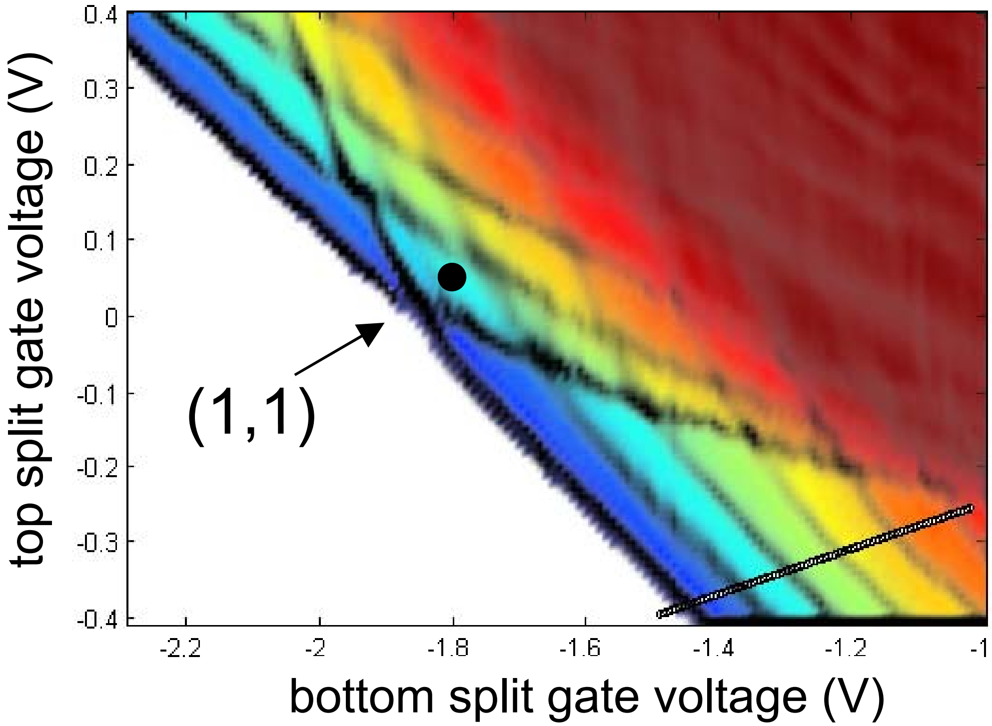
Double Quantum Wires







Precise Control of the 1D states w/ No Interaction



- The color scale corresponds to the conductance :

(2,0), (0,2), (1,1) → $2G_0$

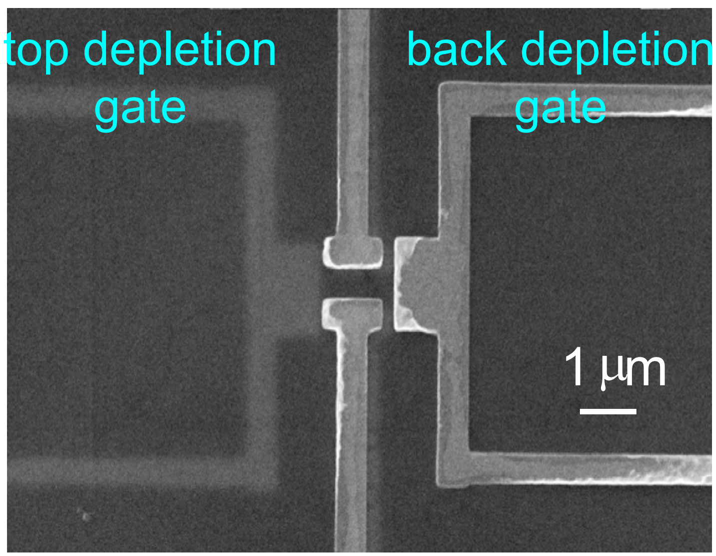
(3,0), (0,3), (2,1) → $3G_0$

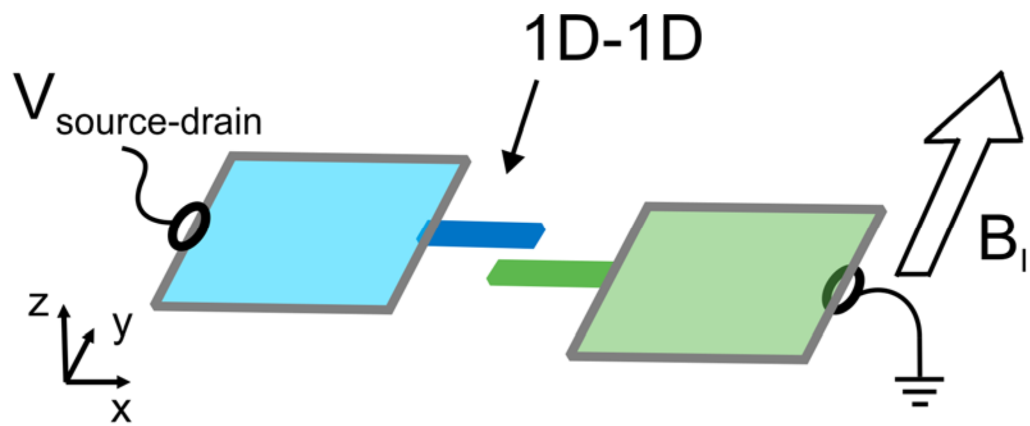
(6,0), (0,6), (3,3) → $6G_0$

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

Vertically coupled double quantum wires

- Study nanoelectronic interactions
- Design systems for coherent transport studies





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Interactions Can Lead to Tunneling (cartoon view)

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

wire 1

No tunneling
(no unoccupied state)

wire 2

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Interactions Can Lead to Tunneling (cartoon view)

- Tunneling must conserve energy and momentum
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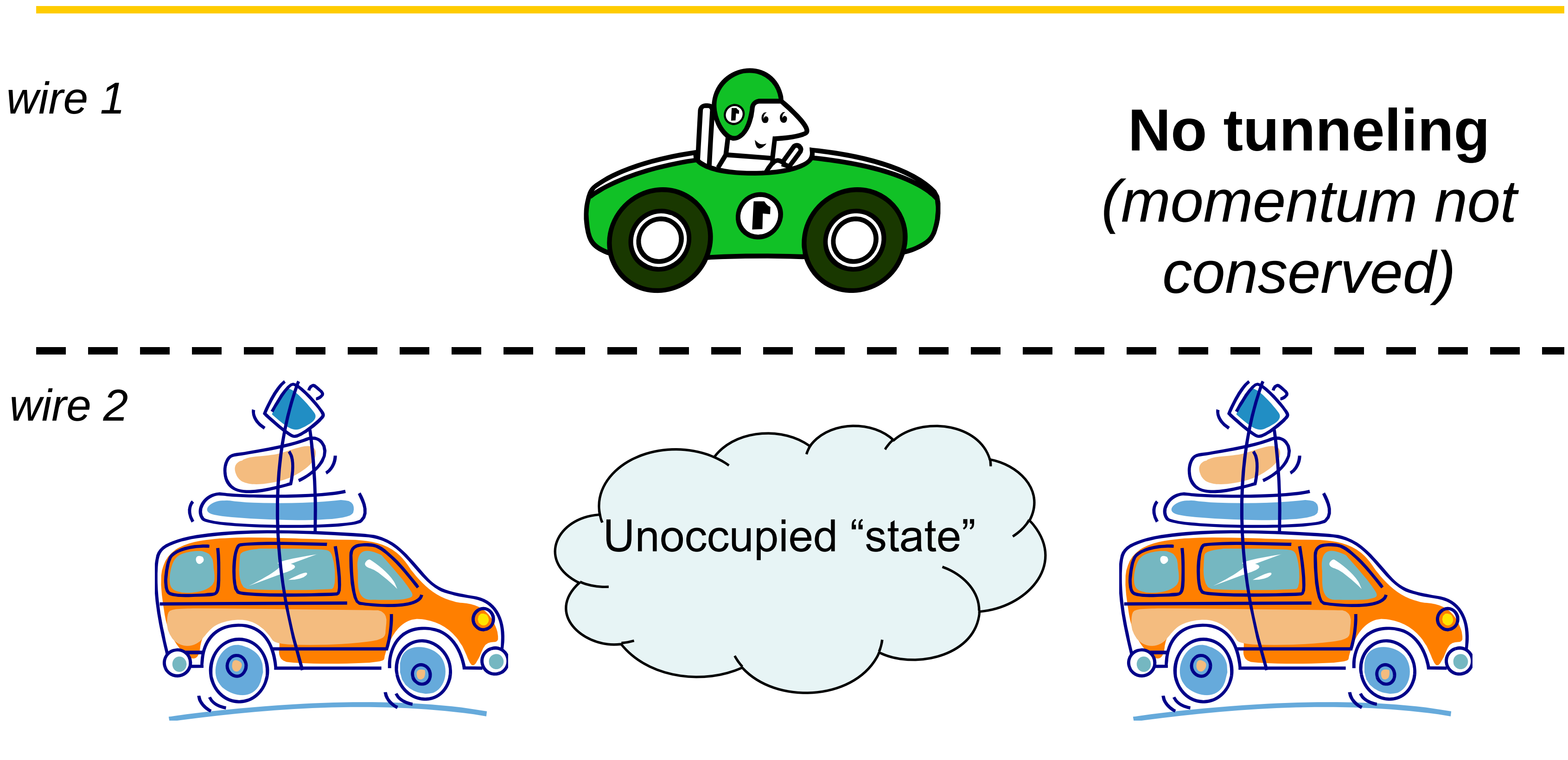

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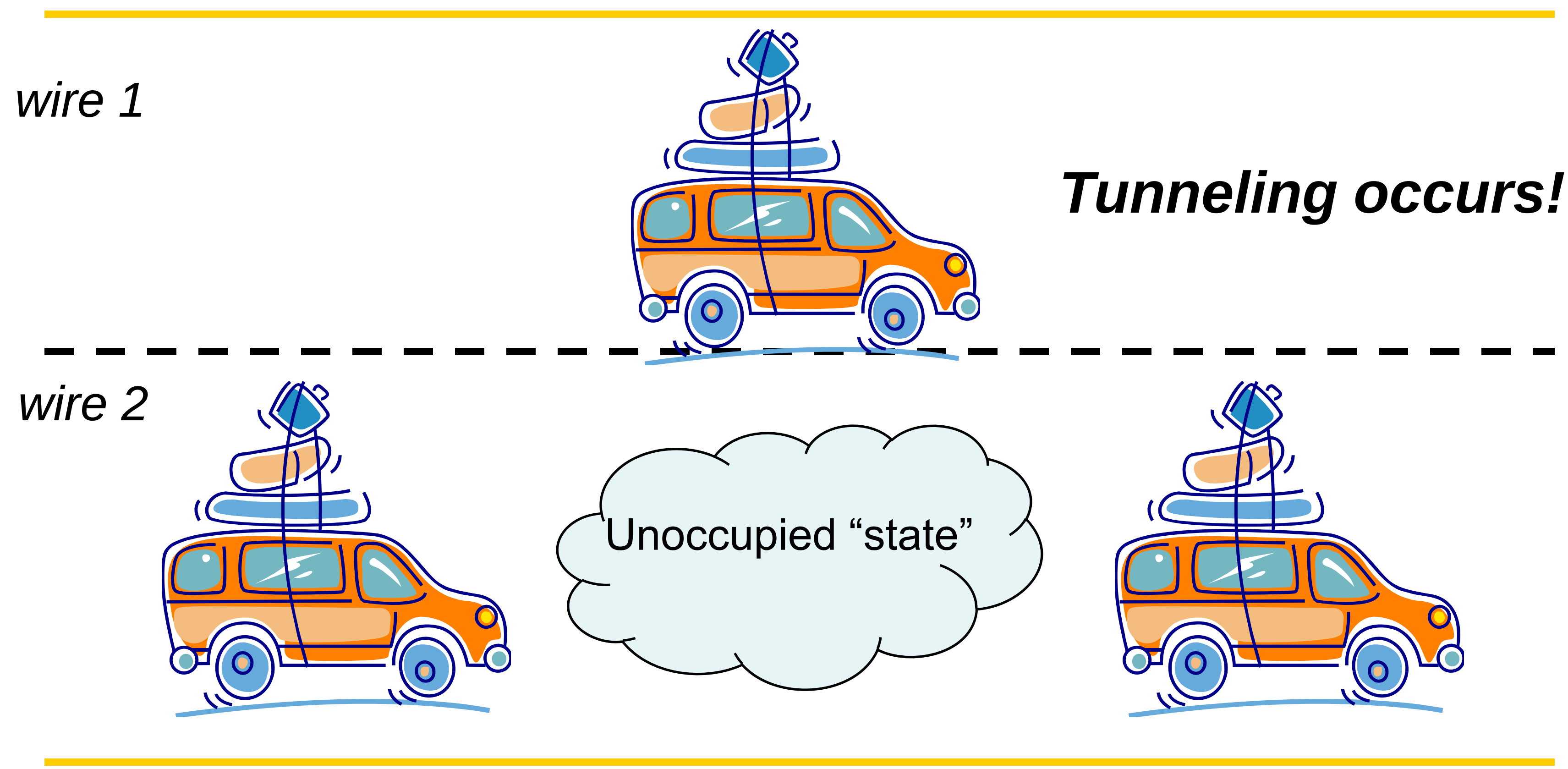

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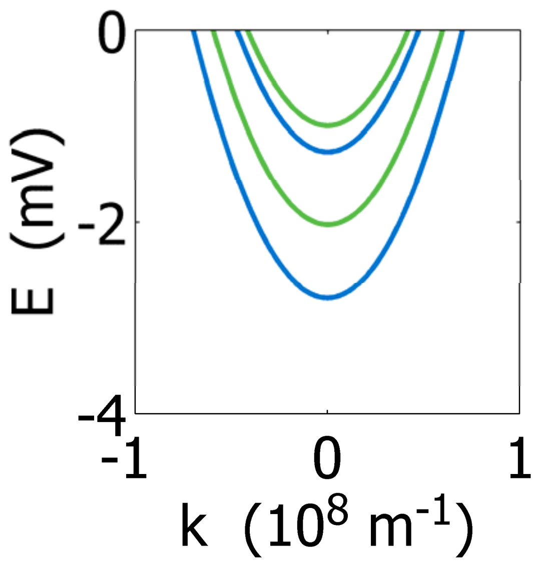
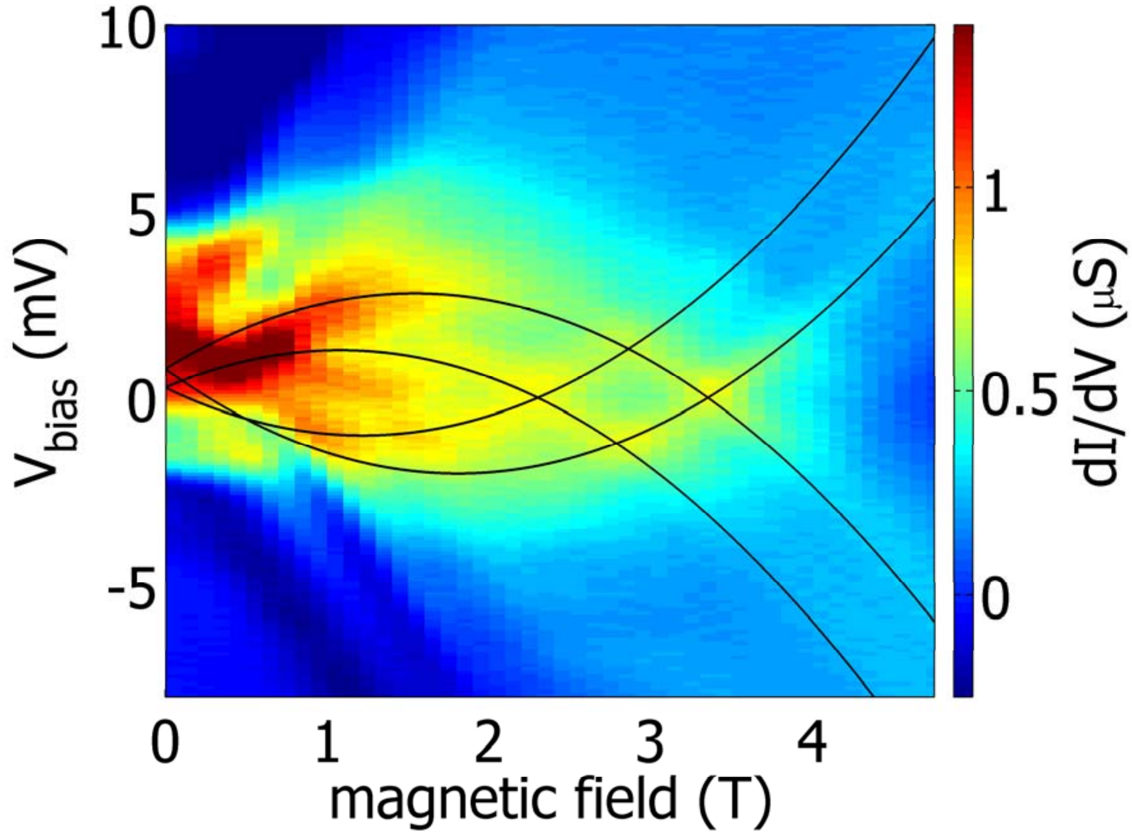
Spectroscopy at (2,2)

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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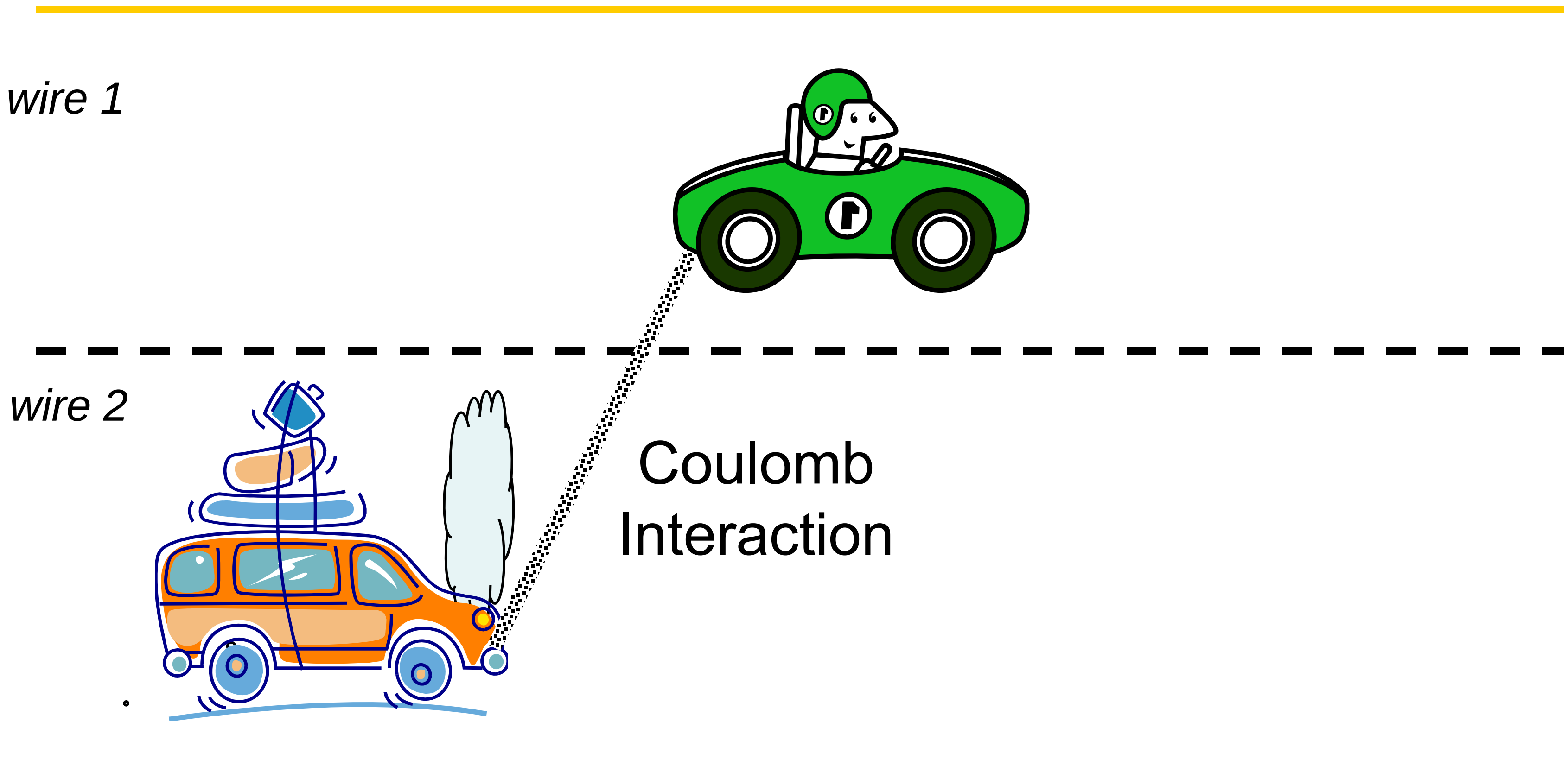
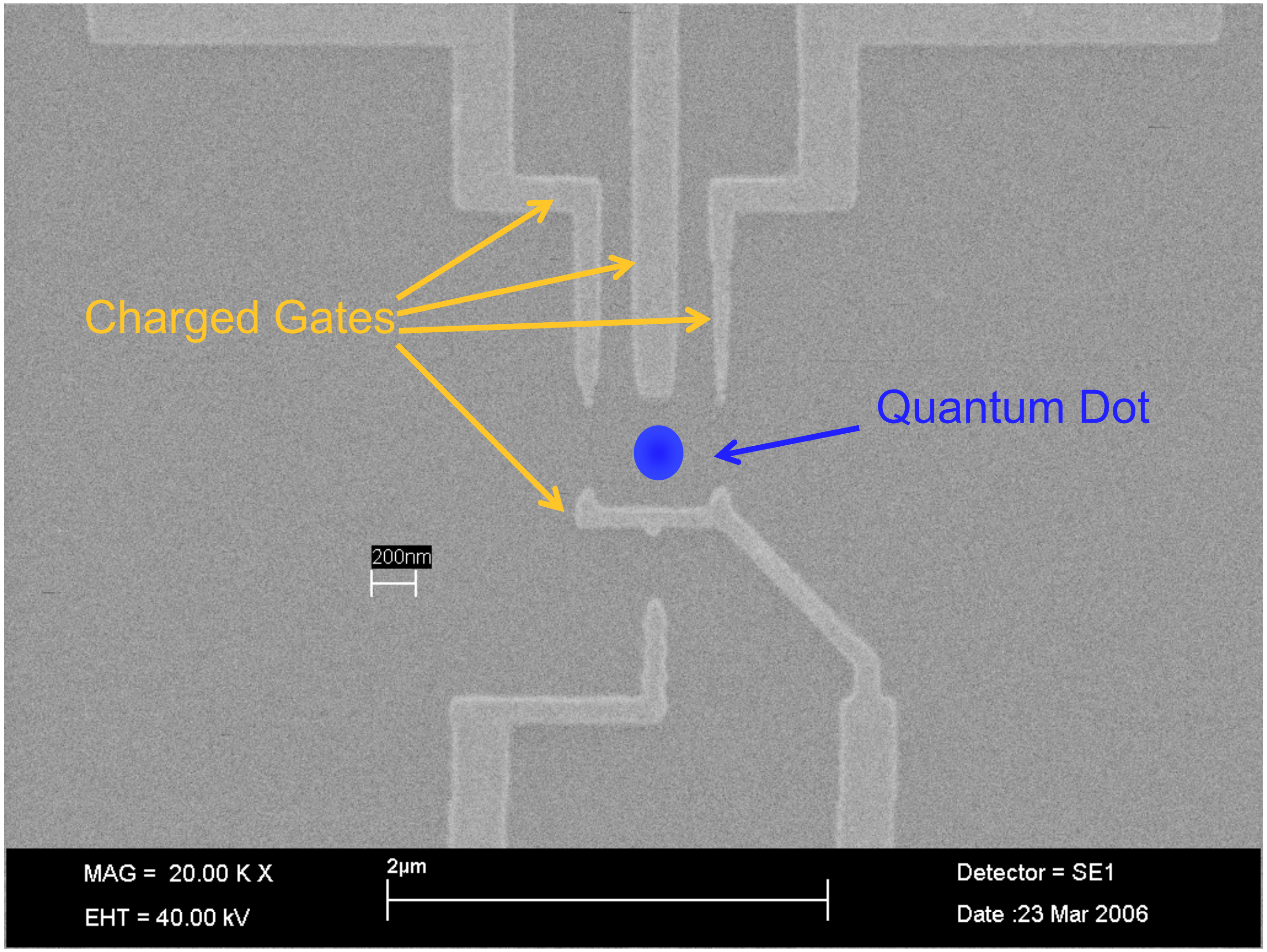
Interactions Can Lead to Coulomb Drag(cartoon view)

- No voltage on wire 2 so carriers (cars) not moving
- Moving carriers in wire 1 can drag those in 2 by Coulomb interactions



Quantum Dot w/ Charge Sensor



For the Chemists

- Standard Optical Techniques to Identify Chemical
  - Adsorption, Luminescence, Transmission,…
- Need Laser (gas lasers are not small)

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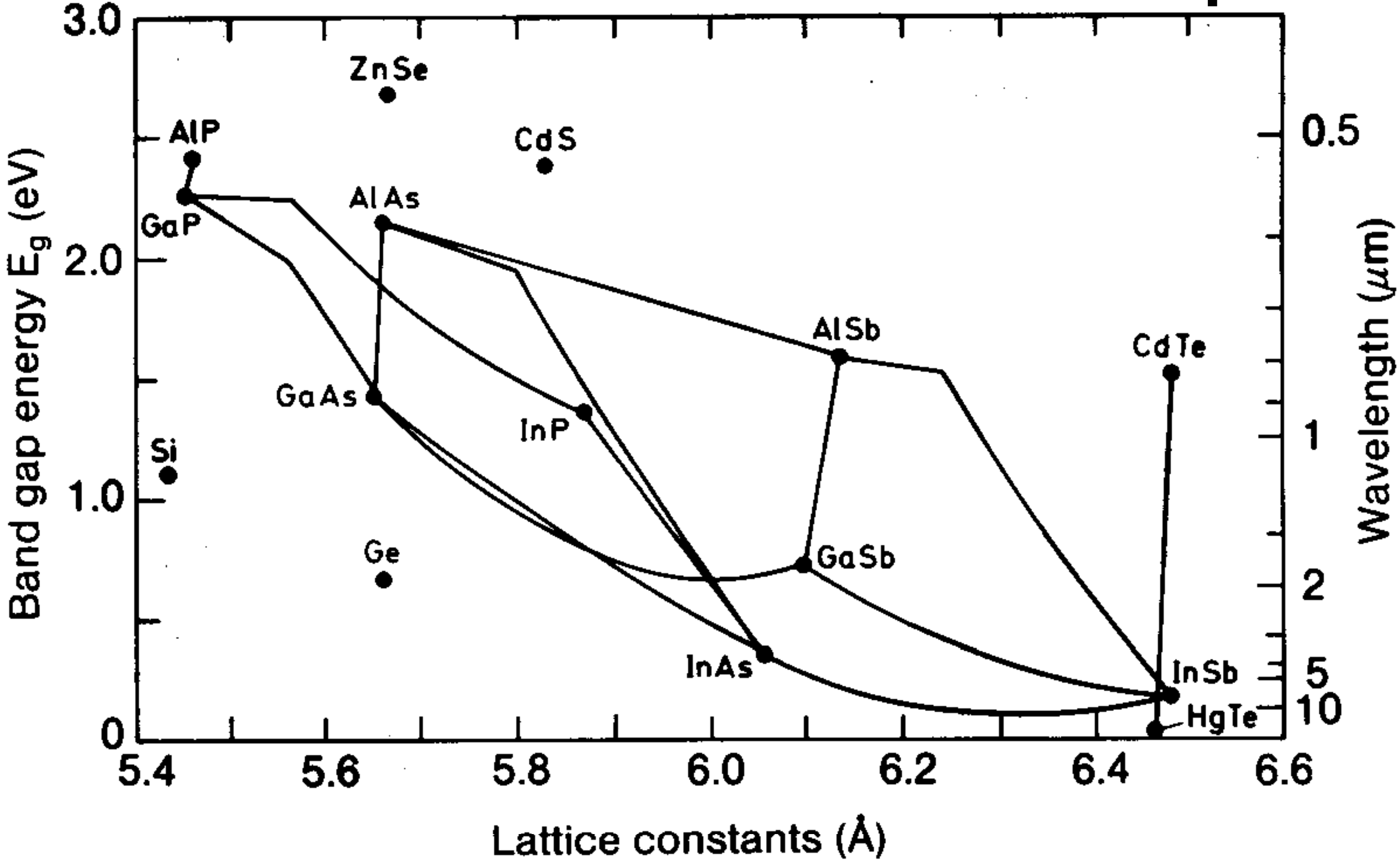
Gas Laser

For the Chemists

- Standard Optical Techniques to Identify Chemical
  - Adsorption, Luminescence, Transmission,…
- Need Laser
  - (gas lasers are not small)
- Semiconductor lasers
  - (not new but are limited)

Semiconductor Roadmap



For the Chemists

- Standard Optical Techniques to Identify Chemical
  - Adsorption, Luminescence, Transmission,…
- Need Laser
  - (gas lasers are not small)
- Semiconductor lasers
  - (new but are limited)
- New Approach - Quantum Cascade Lasers

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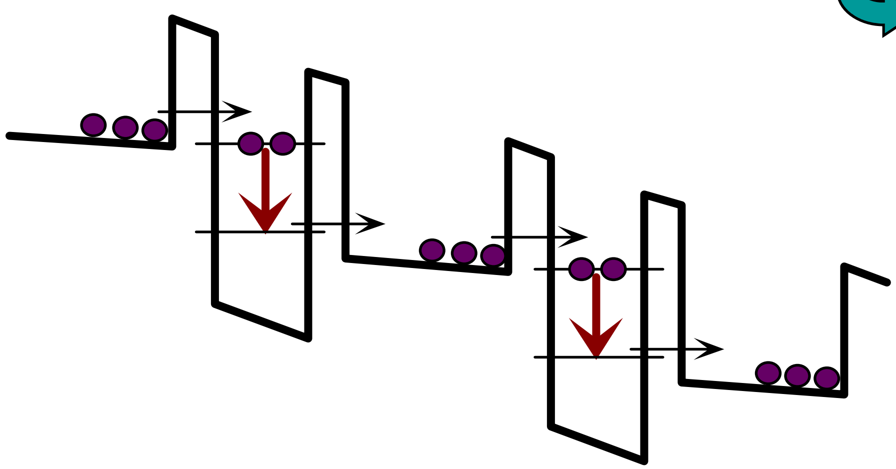
What is a QCL

QCL - Quantum Cascade Laser

- Semiconductor laser (unipolar)
  - Frequency defined by layer thickness
    - Tens to thousands of MBE layers
      - Watts of power
        - Broad wavelength range
          - 2.1 to 150 microns



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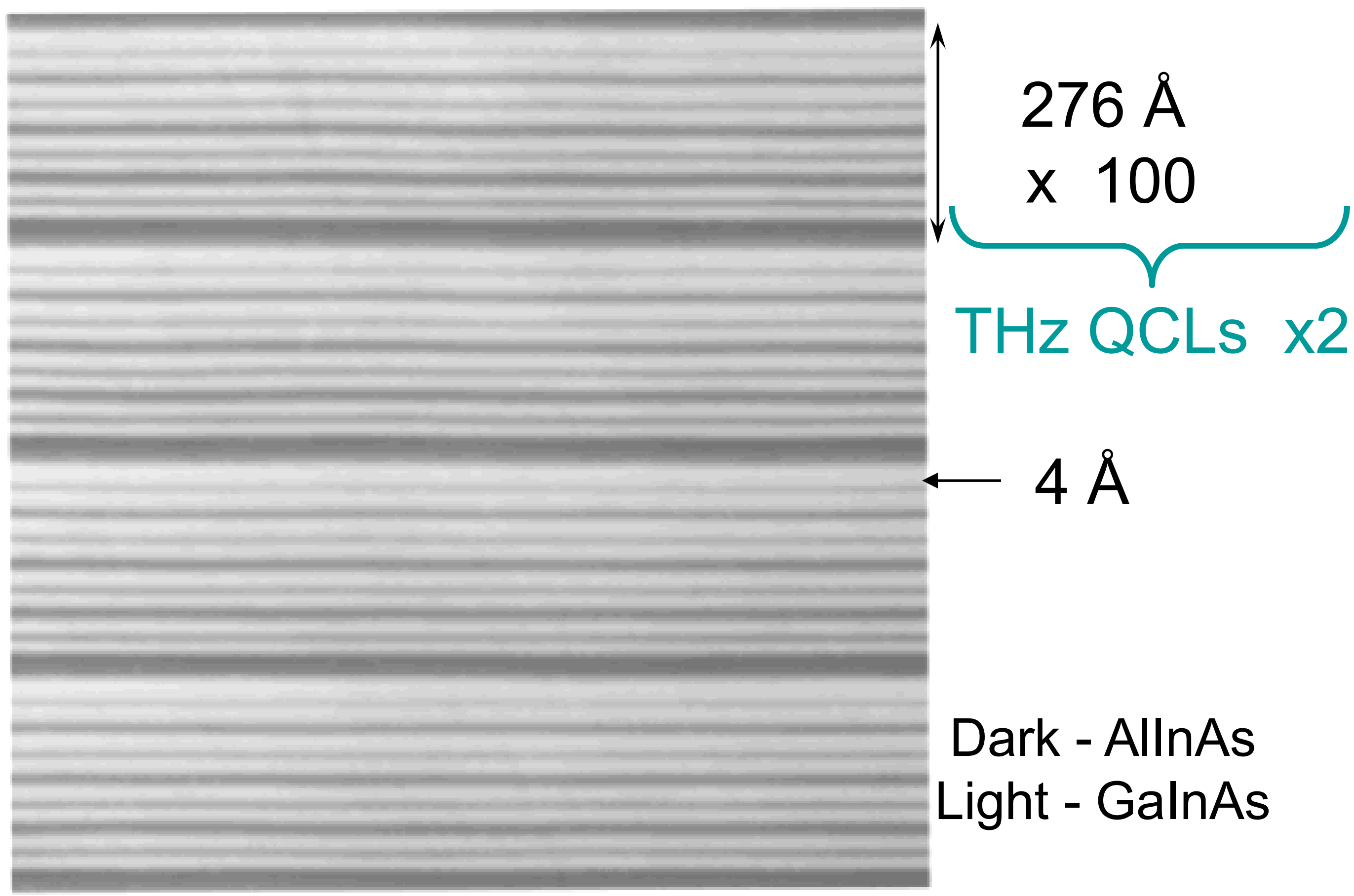
Why You Need to be NICE to Your Grower



Courtesy of
Claire Gmachl et al

Lucent Technologies
Bell Labs Innovations

Sandia National Laboratories

THz QCL Example Structure

GaAs	**LTG (250 C)** cap layer	35 A
GaAs	$5x10^{19}$ cm^{-3}	100 A
GaAs	$5x10^{18}$ cm^{-3}	500 A
$Al_{0.15}Ga_{0.85}As$	undoped	33.9 A (12 ML)
GaAs	$1.9x10^{16}$ cm^{-3}	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	31.1 A (11 ML)
GaAs	undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48.0 A (17 ML)
GaAs	undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	11.3 A (**4 ML**)
GaAs	undoped	53.7 A (19 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	14.1 A (**5 ML**)
GaAs	undoped	45.2 A (16 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	11.3 A (**4 ML**)
GaAs	undoped	48.0 A (17 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	33.9 A (12 ML)
GaAs	**$1.9x10^{16}$ cm^{-3}**	161.0 A (57 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	31.1 A (11 ML)
GaAs	undoped	96.1 A (34 ML)
$Al_{0.15}Ga_{0.85}As$	undoped	48.0 A (17 ML)
GaAs	$3x10^{18}$ cm^{-3}	0.8 µm
$Al_{0.55}Ga_{0.45}As$	undoped	0.1 µm
S. I. GaAs substrate		

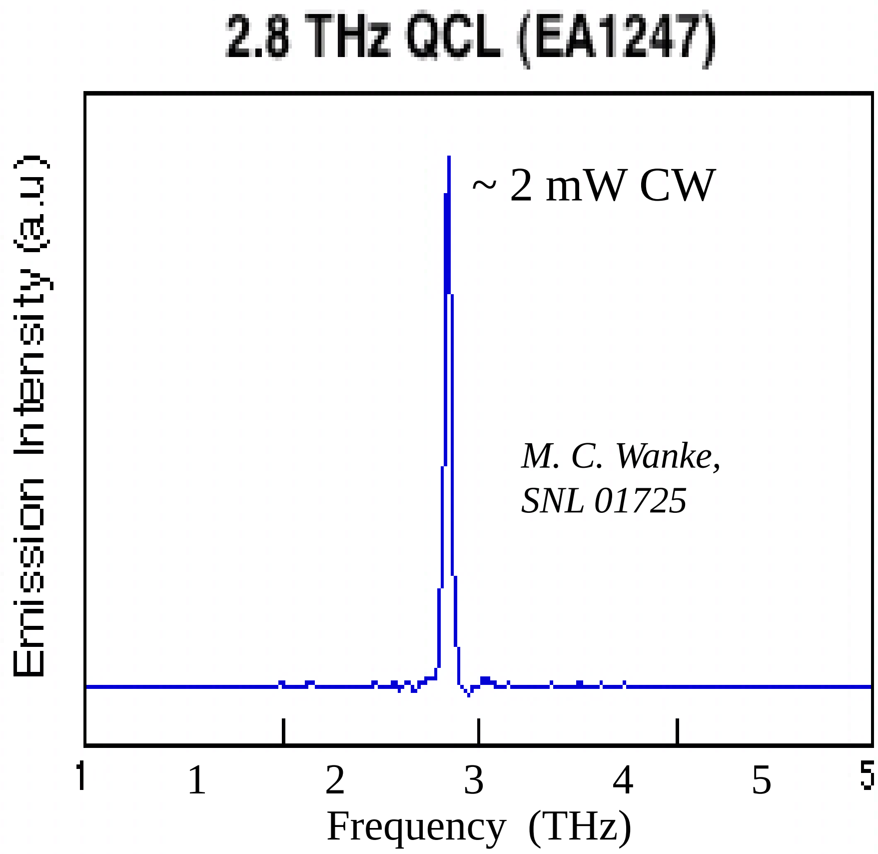
Many Layers

Repeat **163** times

Thin Accurate Layers

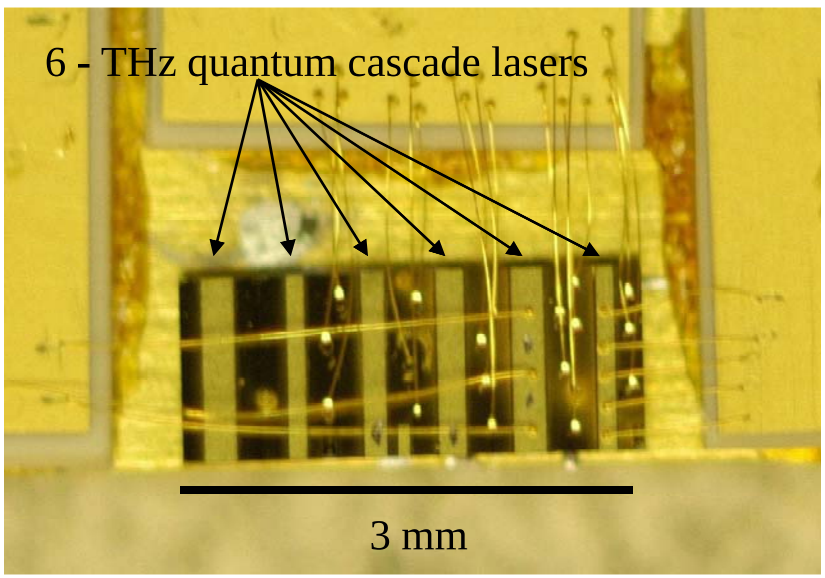
Total Active Thickness ~10 µm

QCL Output


2.8 THz QCL (EA1247)
~ 2 mW CW
M. C. Wanke,
SNL 01725
Emission Intensity (a.u.)
1
2
3
4
5
Frequency (THz)

Which do want for a Satellite?

Coherent/DEOS molecular gas tube THz laser



Mounted chip with 6 THz lasers (1.5 x 3 mm)

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Conclusion

MBE is a powerful technique with many applications in nanotechnology

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