Bio – Nano Technology Program at JPL

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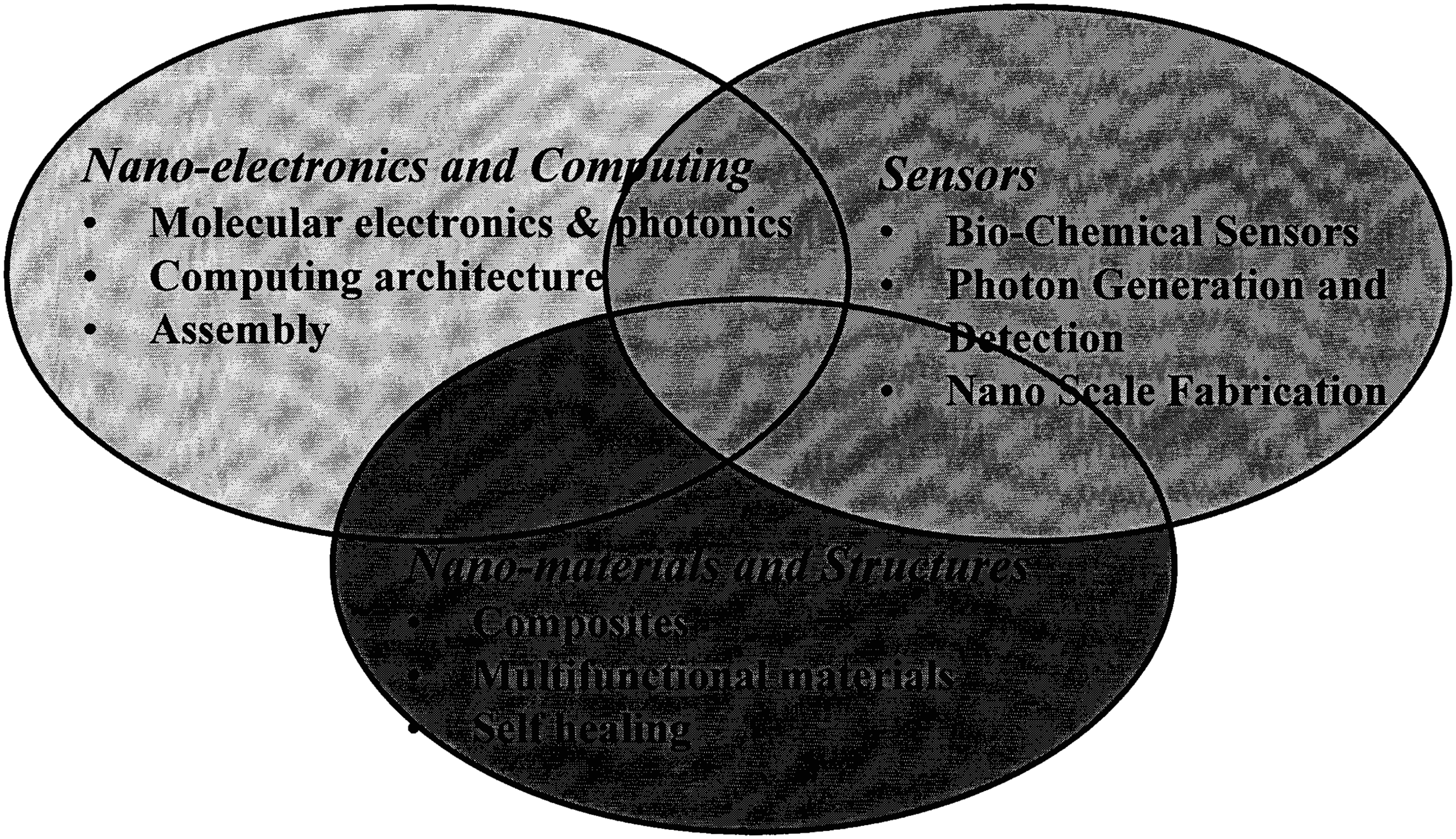
NASA's Nanotechnology Investments



- Emphasis on 'bio-inspired' approach
- Guidance from modeling and simulation

OBJECTIVES

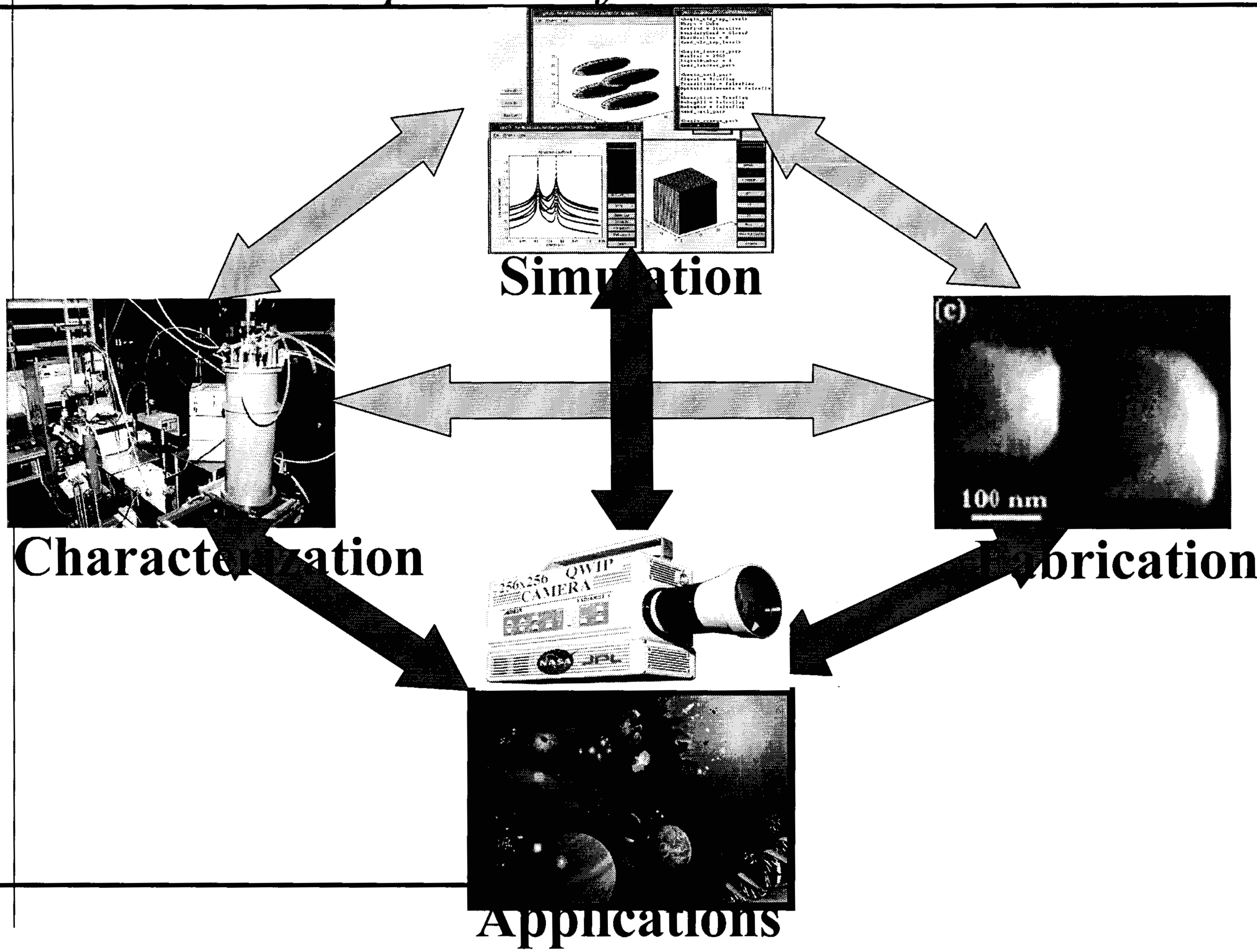
- **Focusing on unique sensing methods to support Space and Earth Science as well as Biological and Physical Research**

  - **Develop novel, nanotechnology-based chemical, biological, and physical sensors for *in situ* and remote sensing**

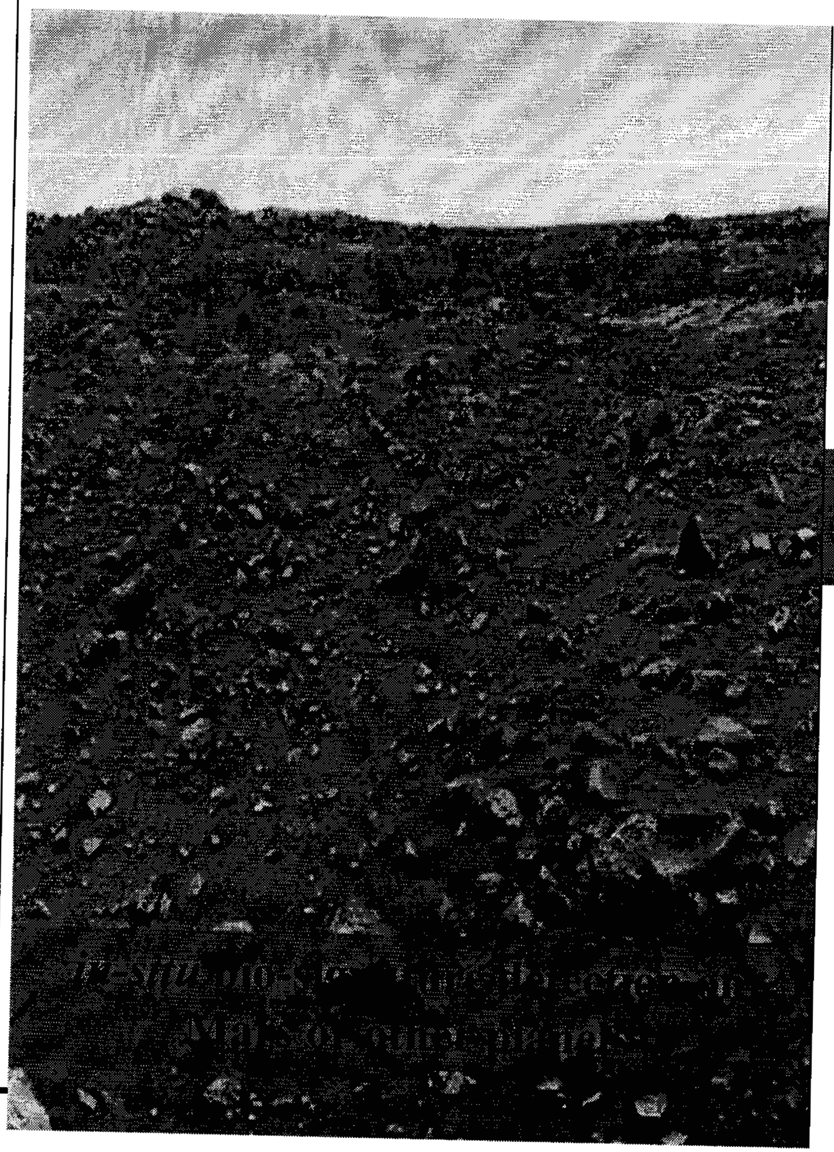
Why Nano

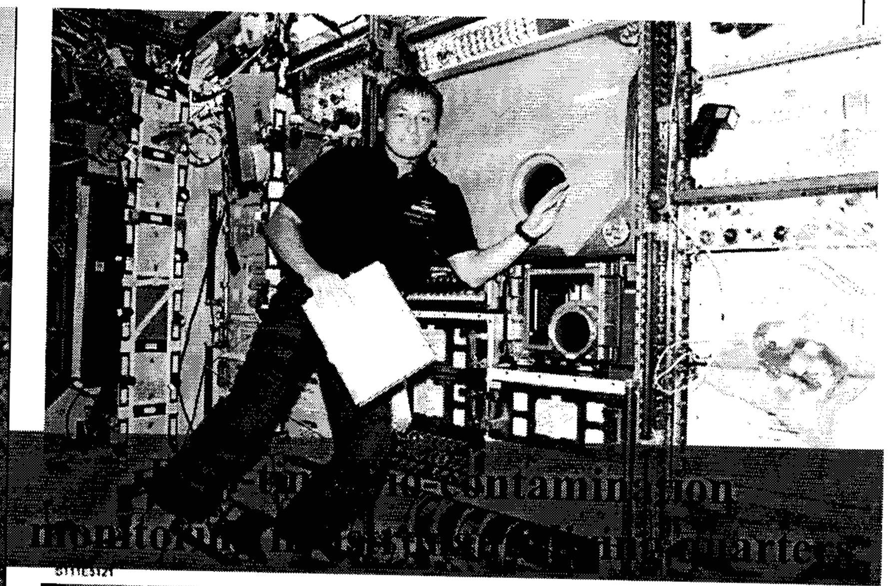
- Unique capabilities/Higher performance
  - Advancing future missions
- Greater integration
  - Lower mass, volume and power
    - Essential for NASA's resource constrained missions

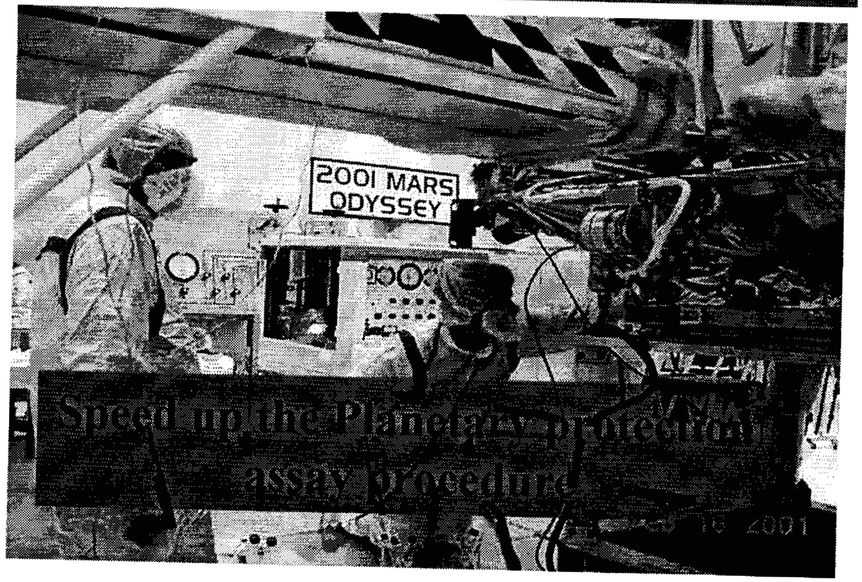
Modeling, Characterization and Fabrication are inseparable for nanoscale devices



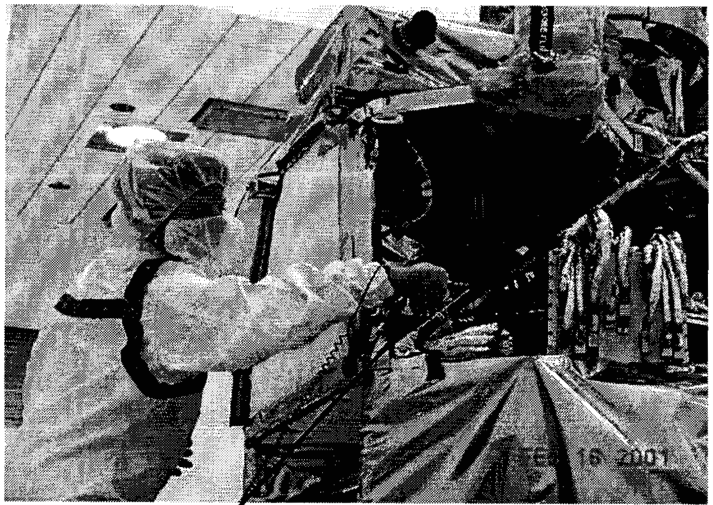
Applications of Bio-Nano technology

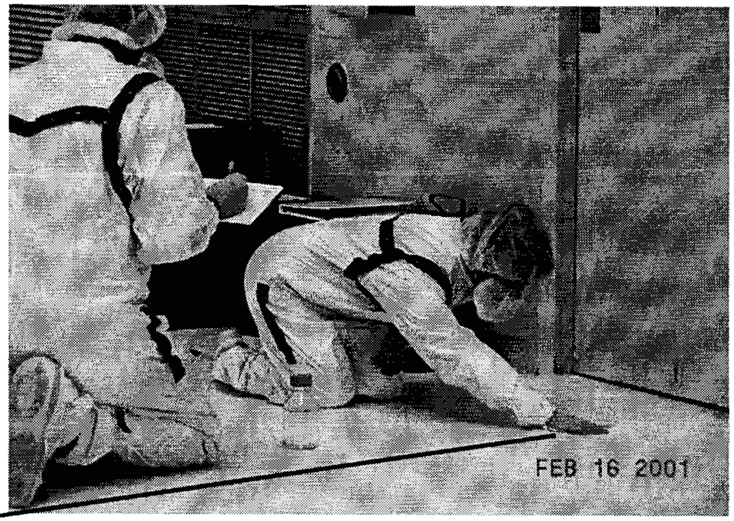


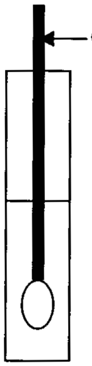




Planetary Protection







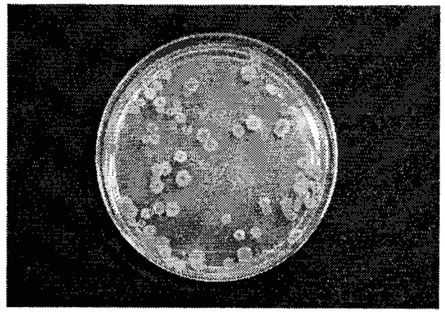
Cotton or polyester swabs

Swab assay

Sonication

Pour or spread plate the sample

Incubation at 32°C
3 days later



Counting
colonies

Science Measurement Needs

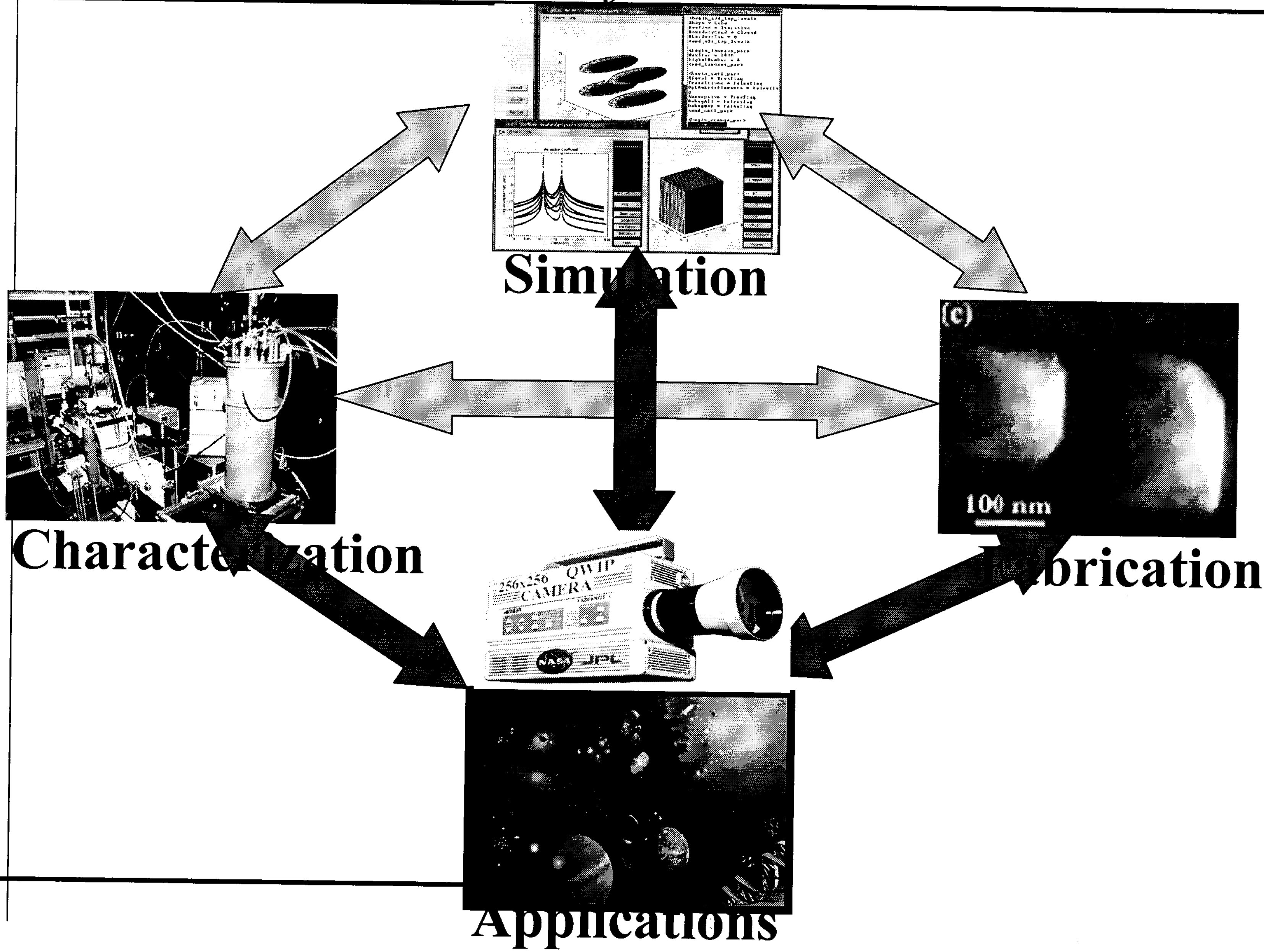
- **In-Situ (non-orbital based) locations**
- **Harsh Environments**
- **Long-duration monitoring**

- In-Situ Signatures:
  - Physical
    - IR Spectroscopy
  - Biological
    - UV Fluorescent
    - Micro Fluidic
  - Chemical
    - Mass-spectroscopy
    - E-nose
- **Remote Sensing:**
  - **Thermal IR**
  - **Sub-mm Radiometer**
  - **Radar**
  - **Lidar**

- Advanced nano-scale sensor and components development

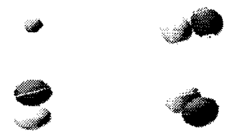
  - Focal Planes
  - In-situ bio/chem. Sensors
  - THz Sources
  - RF Filters
  - Rad-hard Computing & Memories

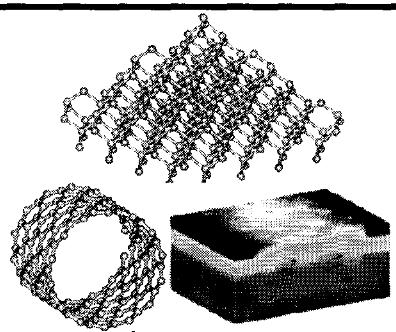
Modeling, Characterization and Fabrication are inseparable for nanoscale devices



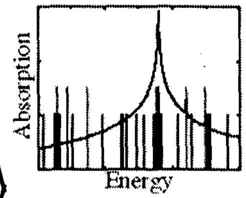
Nano-scale Device Analysis / Synthesis

Development of a Bottom-Up Nanoelectronic Modeling Tool



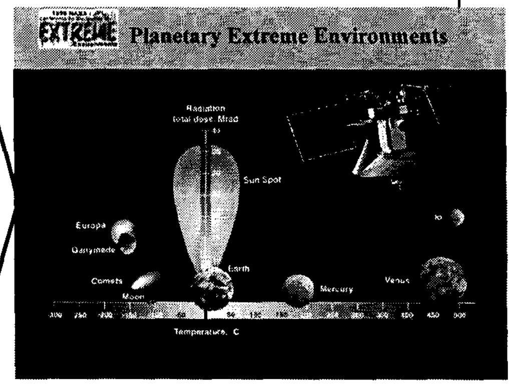


Atomic Orbitals size: 0.2nm + Nanoscale Structures (~20nm)



New Devices for Sensing and Computing

Analyze Devices: Environment and Failures



Assertions / Problems:

- Nanoscale structures are built today! The design space is huge: choice of materials, compositions, doping, size, shape
- Radiation on today's sub-micron devices modifies the electronics on a nanoscale.

Approach:

- Deliver a 3-D atomistic simulation tool
- Enable analysis of arbitrary crystal structures, particles, atom compositions and bond/structure at arbitrary temperatures and ambient electric and magnetic fields.

Collaborators:

- U. of Alabama, Ames, Purdue, Ohio State, NIST

NASA Relevance:

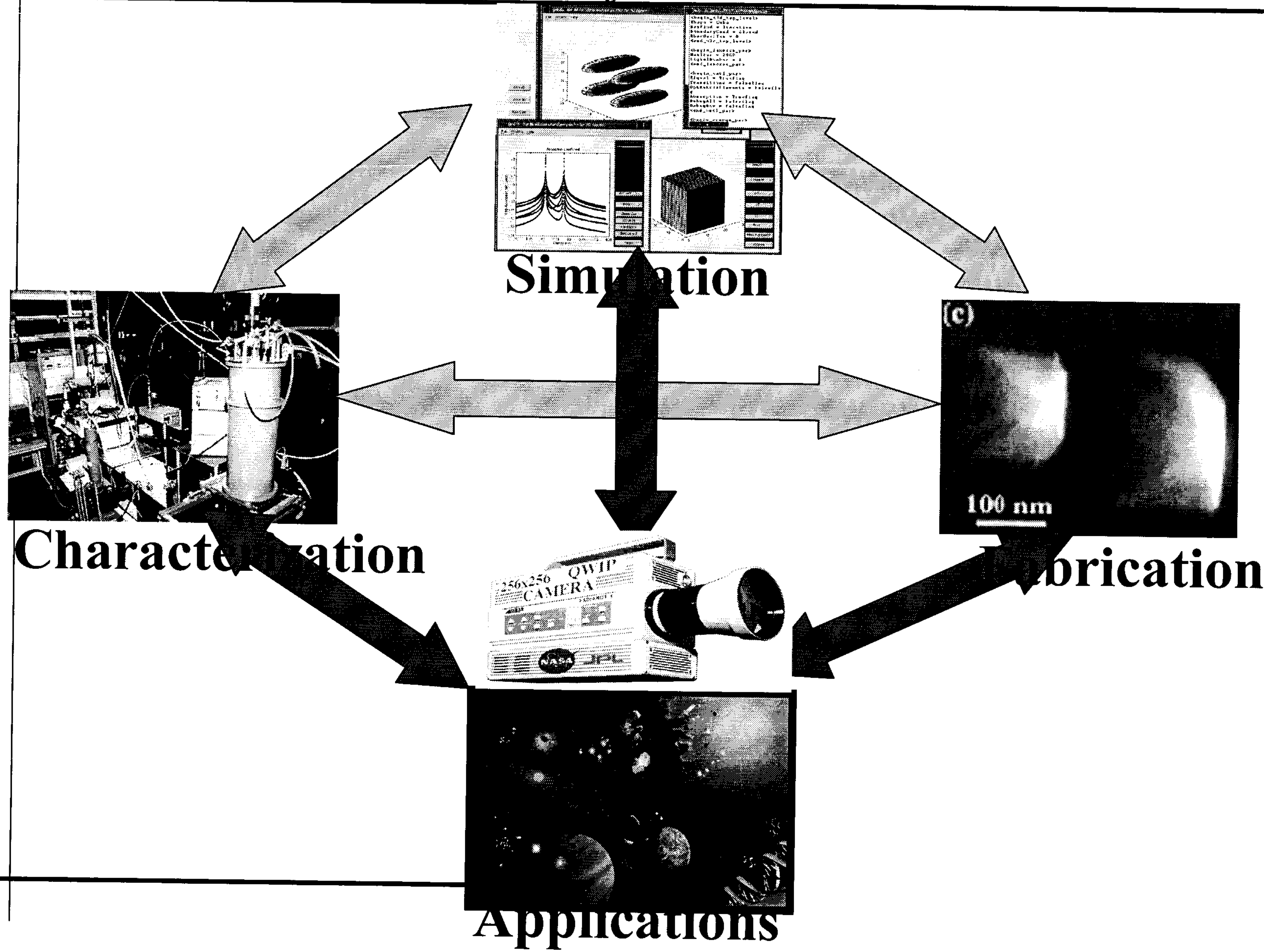
- Enable new devices needed for NASA missions beyond existing industry roadmap:
  - Water detection -> 2-5μm Lasers and detectors.
  - Avionics -> High density, low power computing.
- Analyze state-of-the-art devices for non-commercial environments:
  - Europa -> Radiation and low temperature effects. Aging and failure modes.
  - Jovian system -> Magnetic field effects
  - Venus -> high temperature materials: SiGe

Impact:

- Low cost development of revolutionary techn.

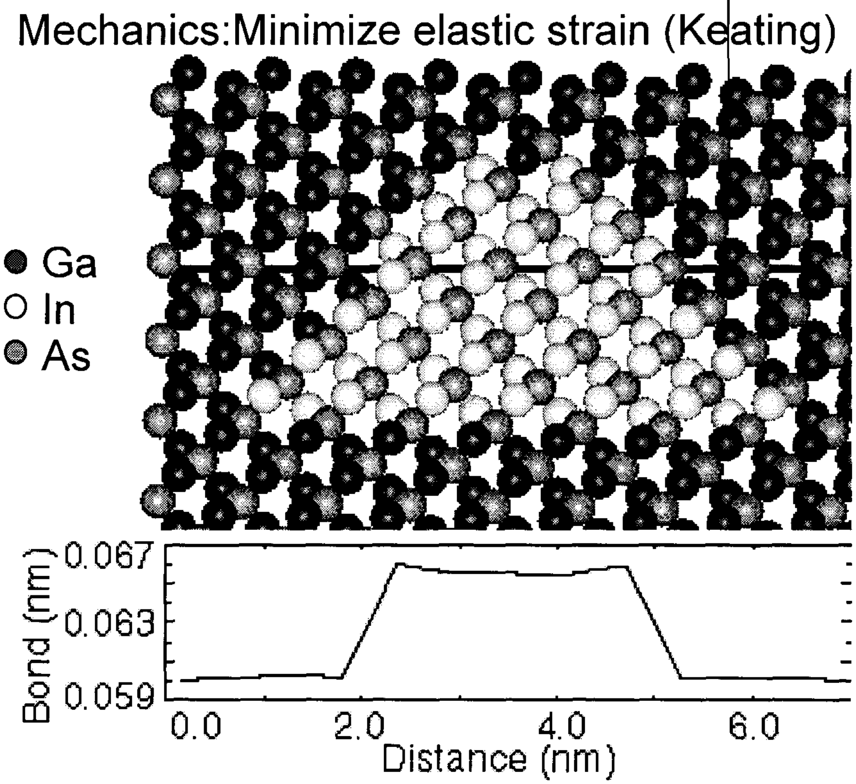
[redacted]

Modeling, Characterization and Fabrication are inseparable for nanoscale devices

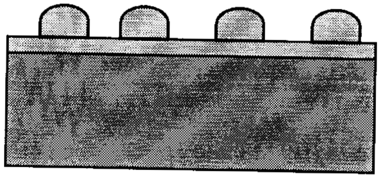


Quantum Dots

- Quantum Dots (QDs) are solid state structures made of semiconductors or metals that confine a countable, small number of electrons into a small space.
- The confinement of electrons is achieved by the placement of some insulating material(s) around a central, well conducting region.
- If the insulation of the QD is strong enough and if the QD is small enough quantum mechanical effects due to the discrete electron charge and/or discrete electron energies can be observed macroscopically.
- QDs have therefore also been called artificial atoms. Neighboring, weakly coupled QDs have been called artificial molecules.



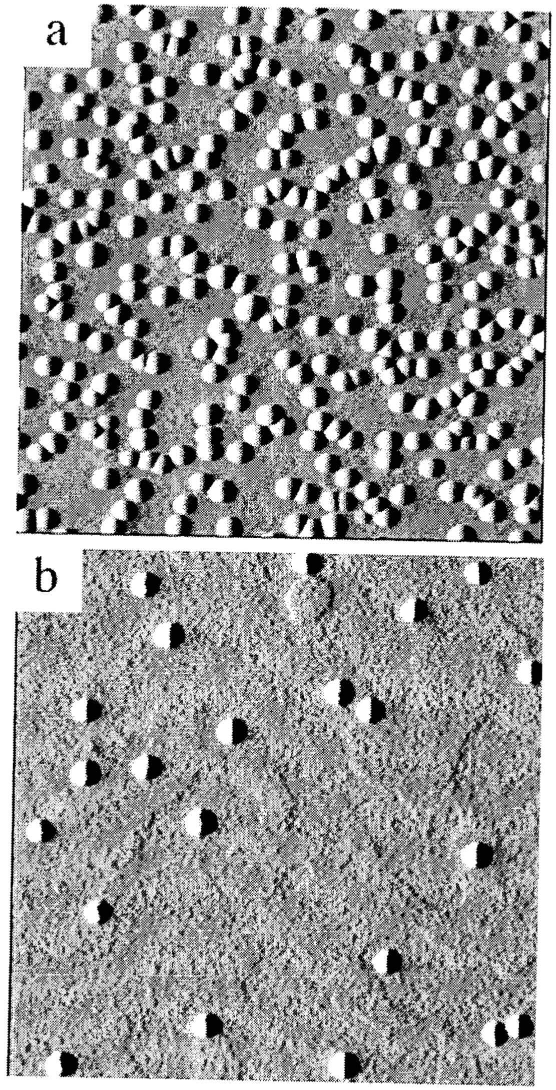
Stranski-Krastanow Quantum Dots



This type of growth occurs for crystals of dissimilar lattice parameters but low interfacial energy, like **Ge on Si** and **InAs on GaAs**. After an initial layer-by-layer growth, islands form spontaneously, leaving a thin "wetting layer" underneath.

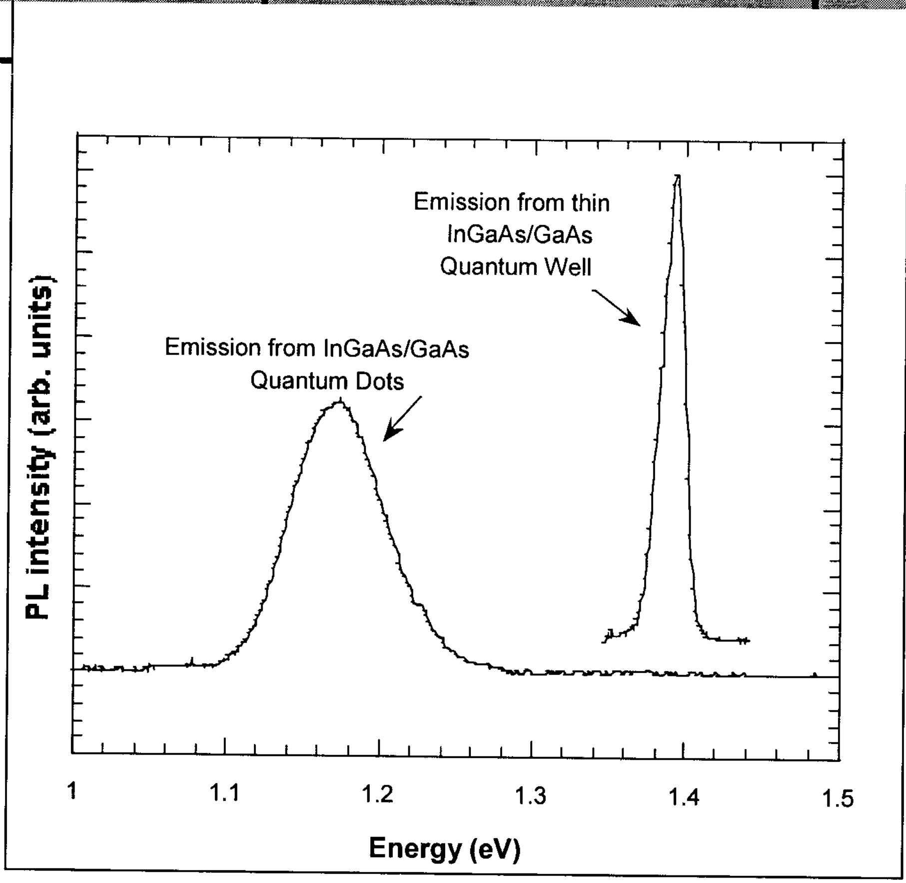
Self-forming InGaAs/GaAs QDs surface coverage range from 5% to 25%, depending on growth conditions

[R. Leon, C. Lobo, J. Zou, T. Romeo, and D. J. H. Cockayne, *Phys. Rev. Lett.* **81**, 2486 (1998)]



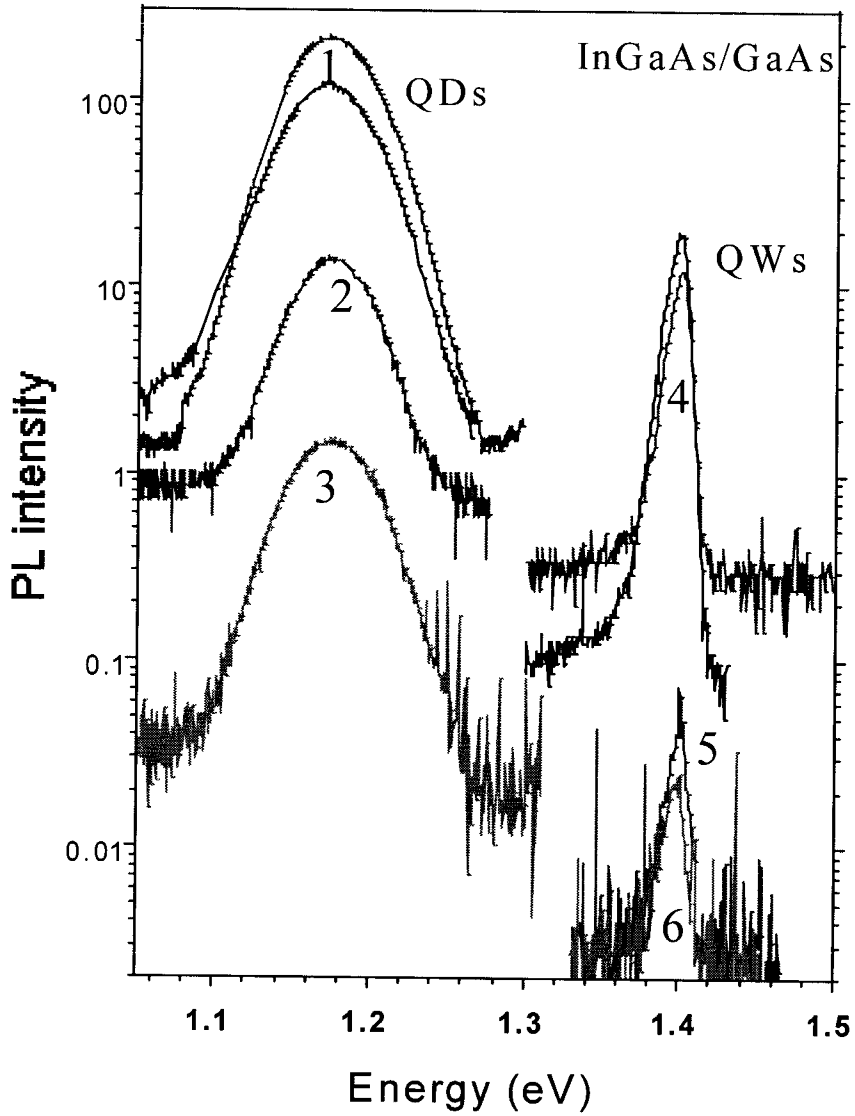
Boxes are 1 x 1 microns

Low temperature (77 K) photoluminescence spectra for InGaAs/GaAs quantum wells and quantum dots



Differences in the PL emission prior to proton radiation:

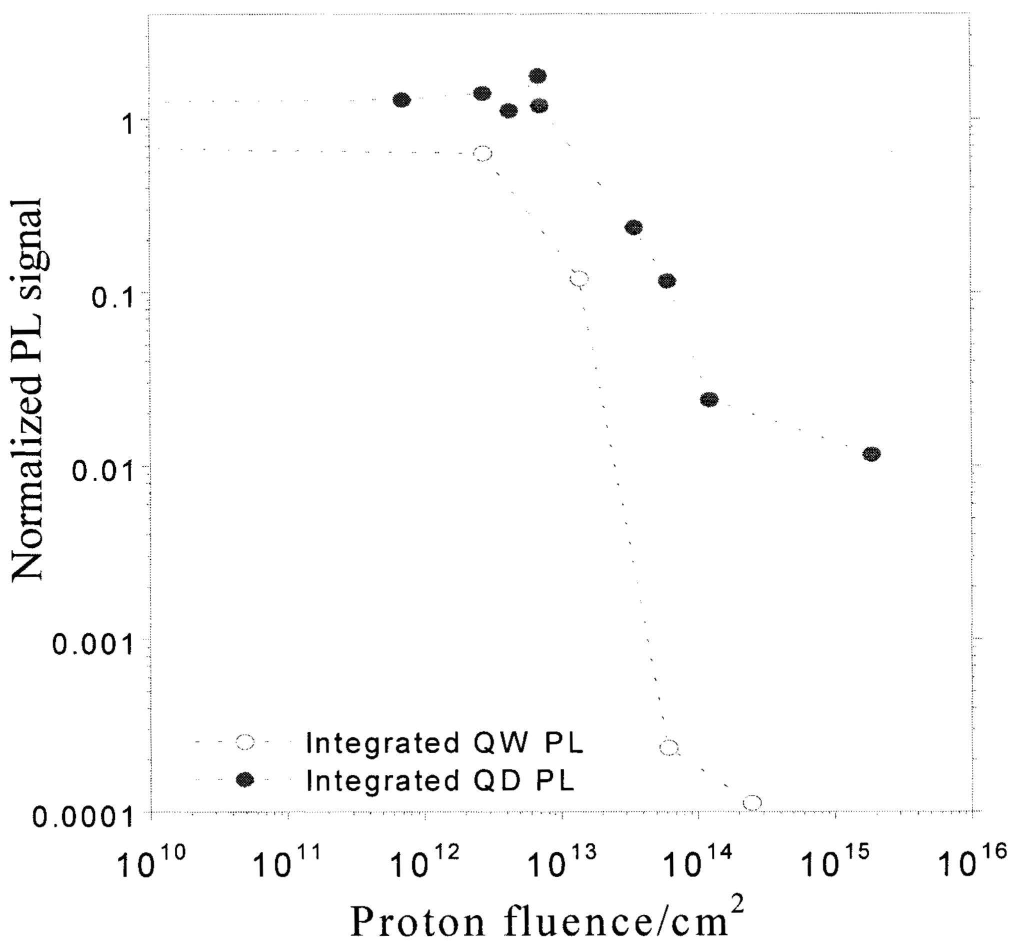
- Peak from QW is at higher energy (very thin ~ 1nm)
- Peak from QD is broader:
  1. Because of slight size fluctuations
  2. Because of positional disorder in dense dot ensembles



1.5 MeV protons /cm^2

1) 7 x 10^{12},
2) 6 x 10^{13},
3) 2 x 10^{15},

4) 3 x 10^{12},
5) 6 x 10^{13},
6) 2 x 10^{14}



From: Changes in Luminescence Emission Induced by Proton Irradiation: InGaAs/GaAs Quantum Wells and Quantum Dots, R. Leon, G. M. Swift, B. Magness, W. A. Taylor, Y. S. Tang, K. L. Wang, P. Dowd, and Y. H. Zhang, submitted for publication.

Results for Quantum Dot Lasers

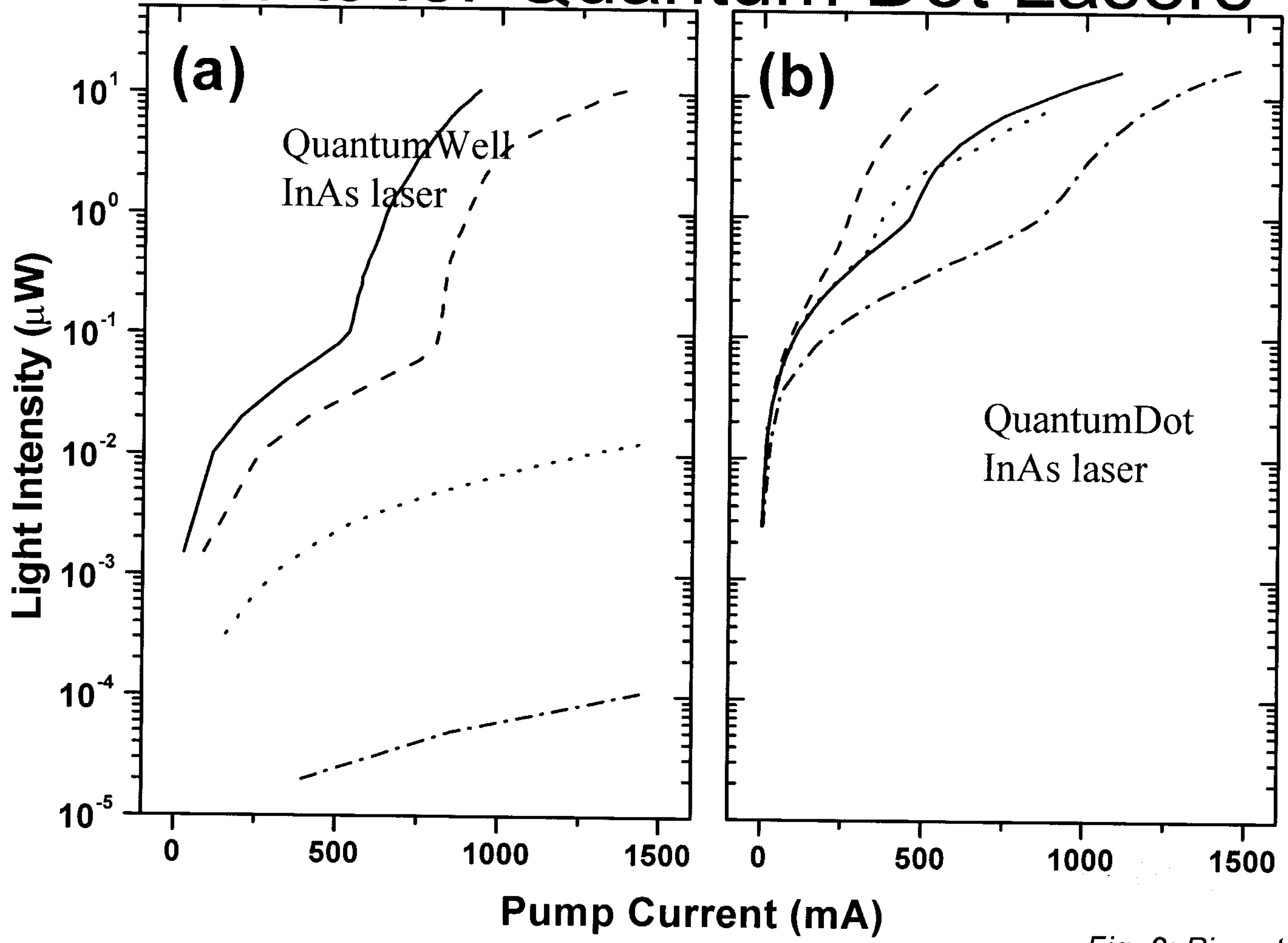


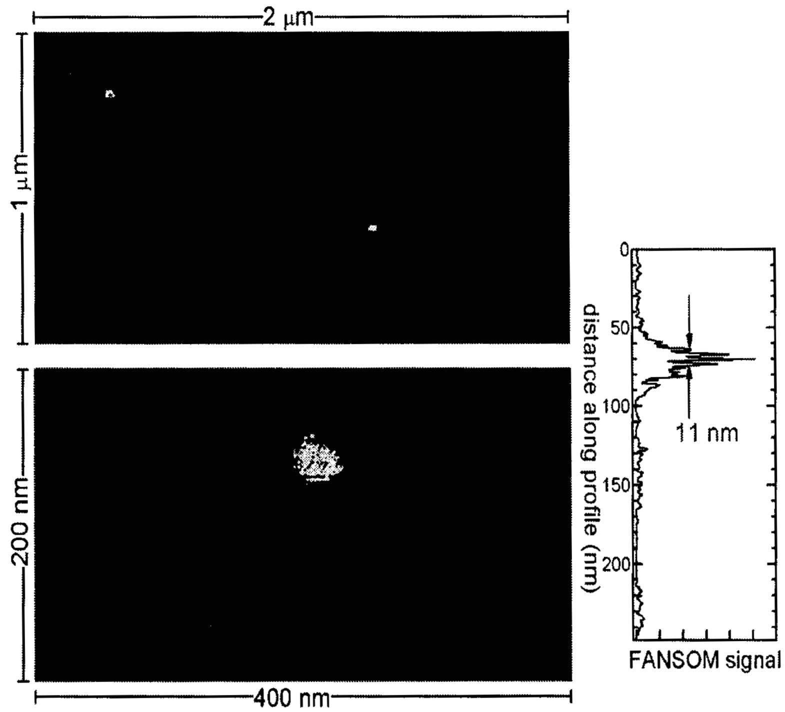
Fig. 2: Piva et al.

~~Solid,~~ dashed, dotted, and dash-dotted, lines correspond to as-grown, and 10^8, 10^9, and 10^{10}, per cm^{-2} irradiated samples, respectively.

Results obtained with 8.5 MeV Phosphorus ions - for more information see: Enhanced Degradation Resistance of Quantum Dot Laser Diodes and Detectors to Radiation Damage, *by ~~P.G. Piva, R.D. Goldberg, I.V. Mitchell, D.~~ Labrie, R. Leon, S. Charbonneau, Z.R. Wasilewski, and S. Fafard, Appl. Phys. Lett.* 77, 624 (2000).

Imaging Single Molecules and Nanostructures <10 nm Optical Resolution!

- Microscope simultaneously takes topographic and spectroscopic/optical images with single molecule sensitivity and unprecedented resolution
- Unique ability to identify, study and characterize single organic molecules one-by-one
- Development led by L. Wade (JPL) and J. Gerton, S. Quake (Caltech)



Large FoV and zoomed in images of 4 nm CdSe/ZnS quantum dots demonstrate sub-10 nm optical resolution at λ=620 nm

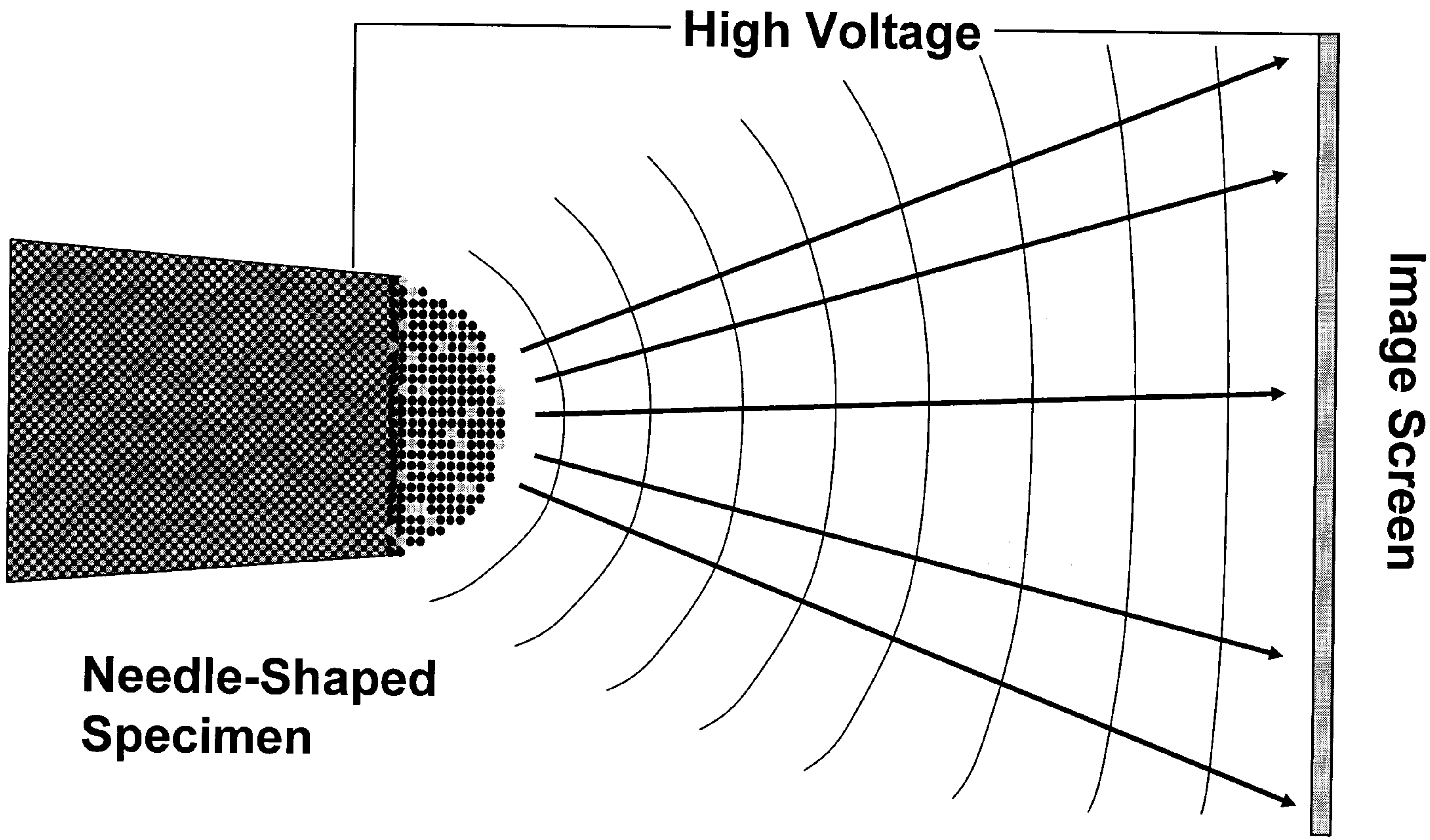
~25 times better than diffraction limit!!

Science Goals

- Dynamic, molecular-scale **observation** of biology
  - Membrane-imbedded protein complexes
  - Protein-mediated membrane fusion
  - Interactions between proteins and chromosomes
- Precise **control** of cellular activity
  - Biochemically functionalize FANSOM probes
  - Investigate interconnectivity of signaling pathways
    - Use FANSOM to identify target receptors
    - Induce local stimulus
    - Monitor cellular response via fluorescence
- Characterization of molecular function: the fragments of life

Atom Probe Operation

In situ three-dimensional microscopy of poorly conducting materials with near atomic spatial resolution and mass spectroscopy with high mass resolution.



Advantages of LEAP

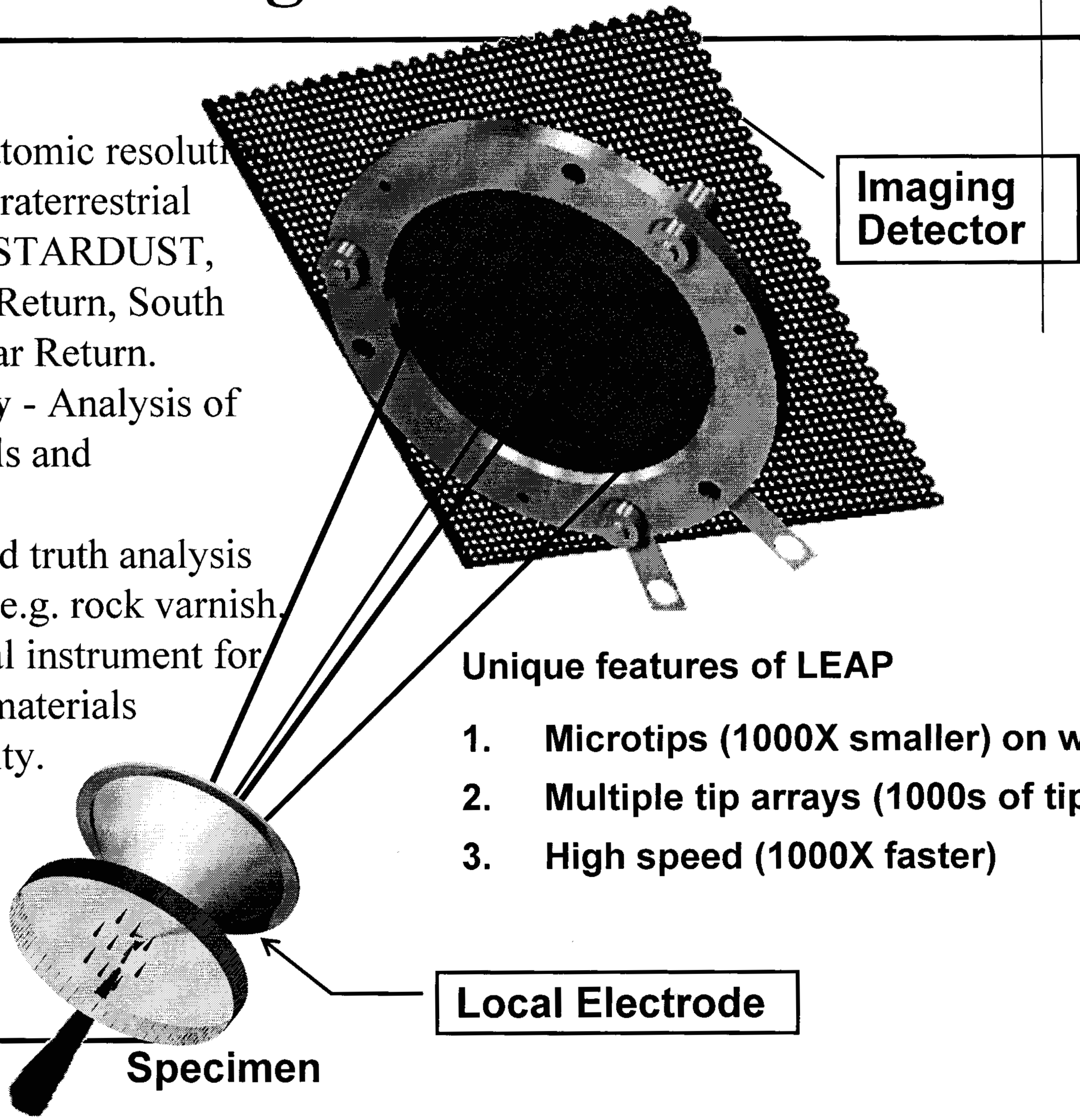
Enterprise Needs:

Space Science - Near atomic resolution analysis of returned extraterrestrial materials, e.g. Apollo, STARDUST, Genesis, Mars Sample Return, South Pole Aitken Basin Lunar Return.

Aerospace Technology - Analysis of nanostructured materials and microelectronics

Earth Science - Ground truth analysis of terrestrial materials, e.g. rock varnish.

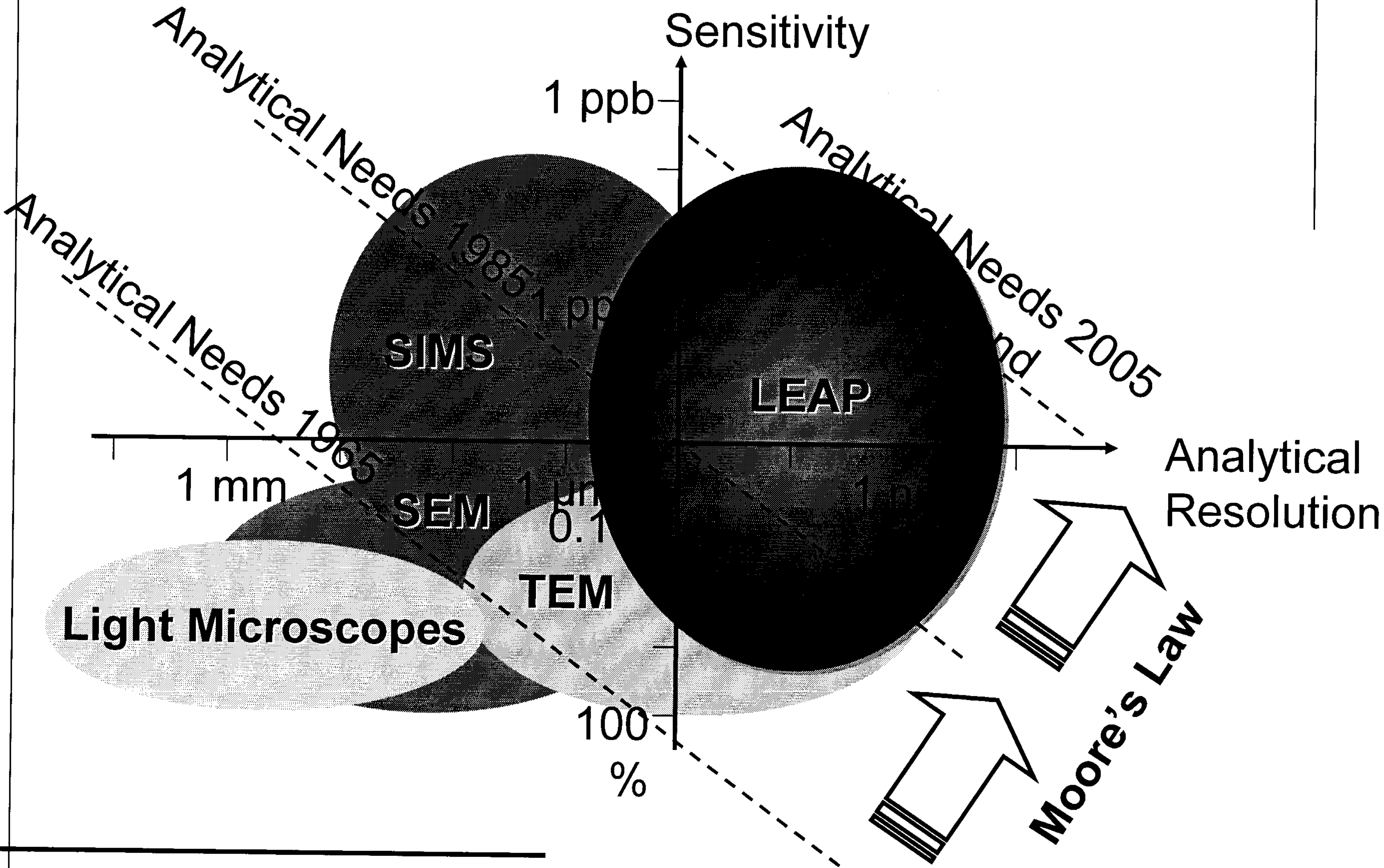
Space Flight - Potential instrument for on-Station analysis of materials produced in microgravity.



Unique features of LEAP

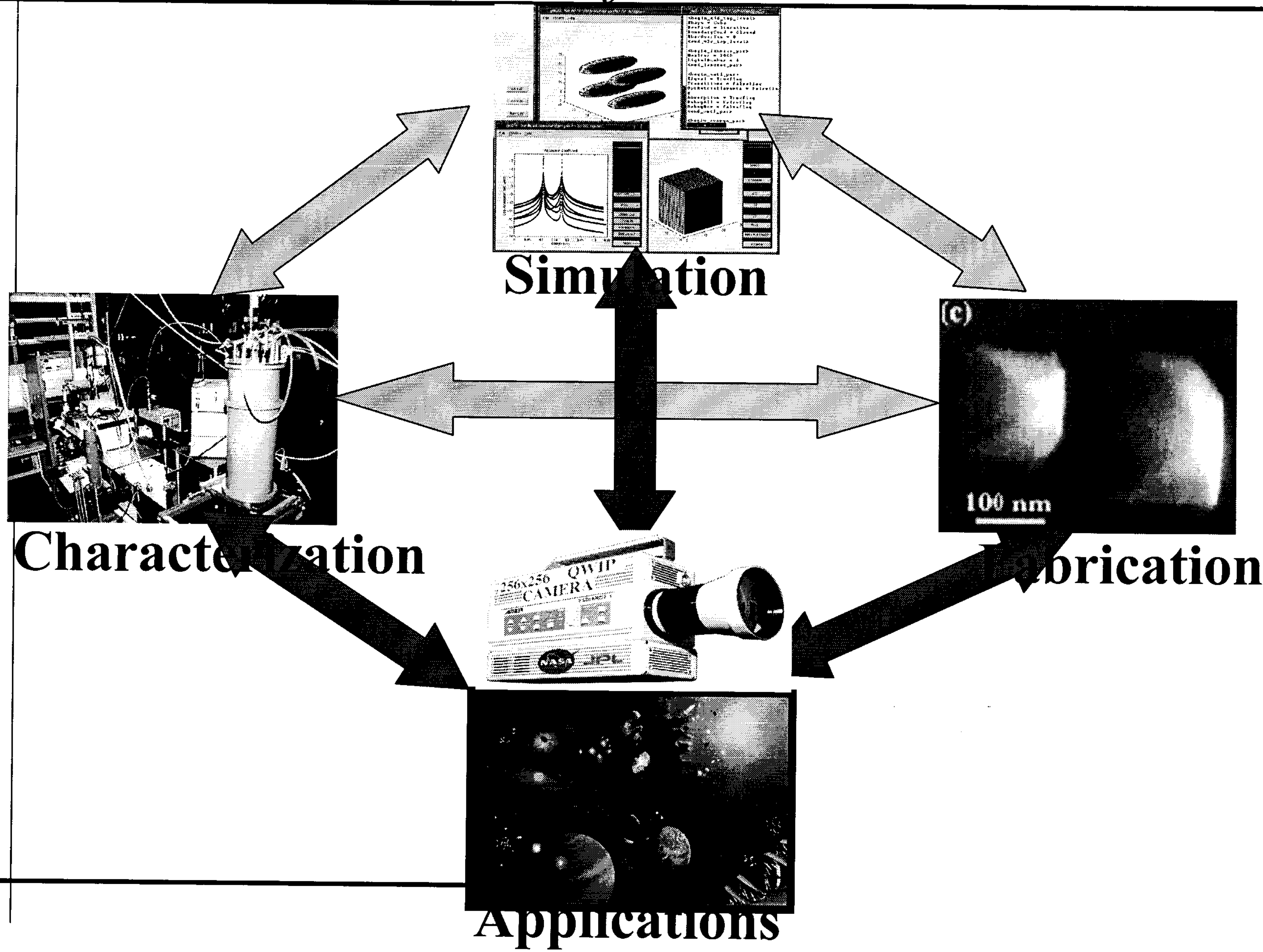
1. **Microtips (1000X smaller) on wafer**
2. **Multiple tip arrays (1000s of tips)**
3. **High speed (1000X faster)**

Benchmarks



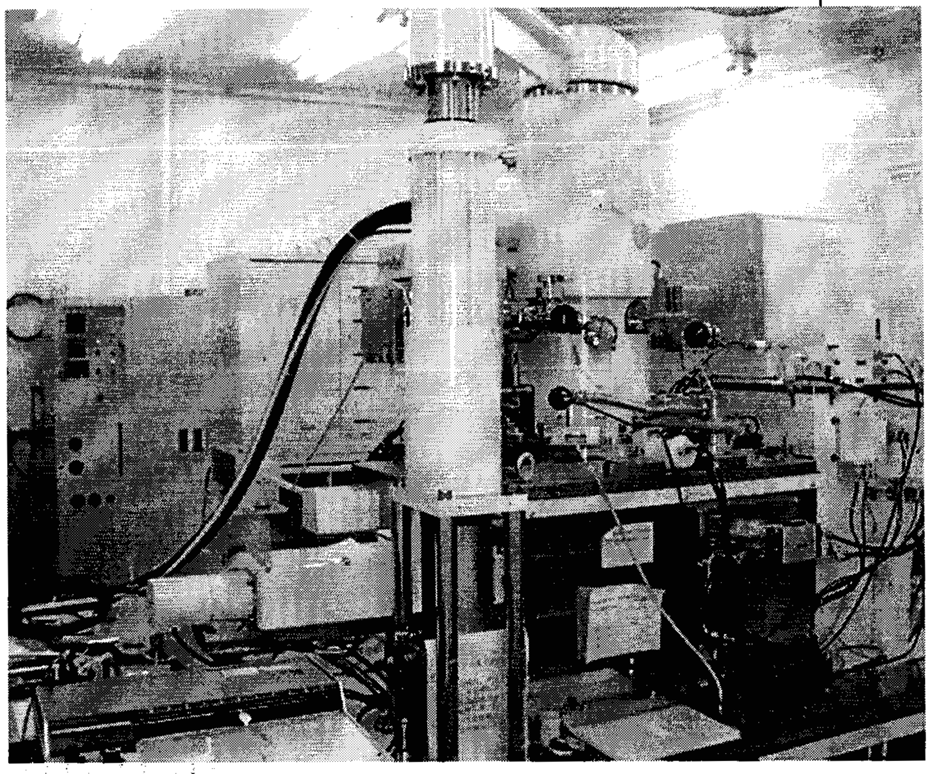
Sensitivity
1 ppb
Analytical Needs 1985
Analytical Needs 1965
Analytical Needs 2005
SIMS
LEAP
SEM
TEM
Light Microscopes
1 mm
100
%
Analytical
Resolution
Moore's Law

Modeling, Characterization and Fabrication are inseparable for nanoscale devices



Nano - Lithography

- Reliable fabrication of nanoscale features (< 100 nm) is challenging. We aim to push the limits of electron-beam lithography for nanoscale device and materials fabrication.
- Develop a set of reliable techniques (recipes) for nanoscale patterning of device materials (metals and semiconductors).
- Will enable the success and increase the efficiency of many tasks (bio-nano, quantum electronics, photonics) by providing the key step in the fabrication of their proposed devices.



JPL's JEOL 9300FS E-Beam Lithography System
(currently the most advanced commercial system in the world)

Reliable Nano-Lithography Techniques

Objective

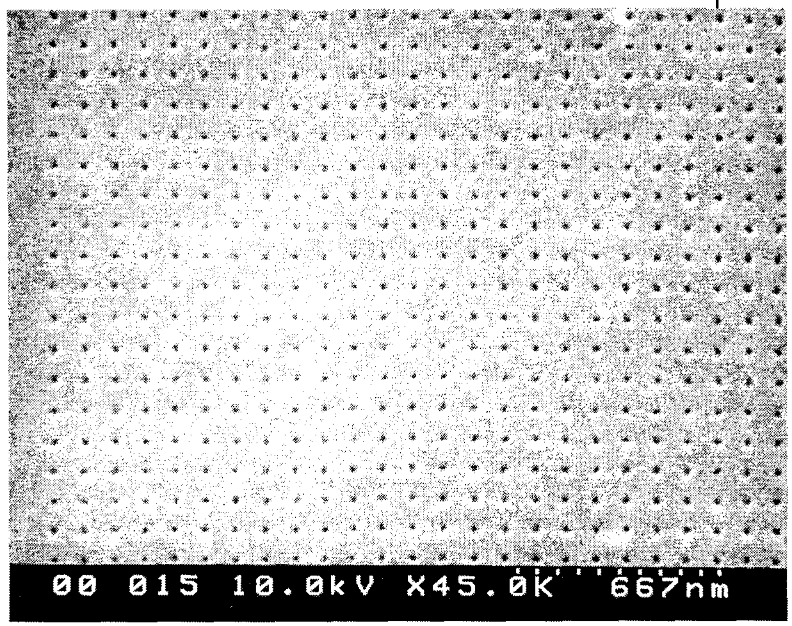
- **Develop reliable electron-beam lithography processes for fabricating nanoscale structures (<20 nm dots, lines, and patterns) in device materials**
  - **Arrays of sub-10 nm etched pits in semiconductors for fabrication of patterned quantum dots.**

Major Products

- Quantum Dots Based Infrared Detectors
- Quantum Dots Based Lasers
- Optical Waveguides

Unique Facilities:

- JEOL 9300FS electron-beam lithography system in the Microdevices Laboratory at JPL is currently the most advanced system in the world.



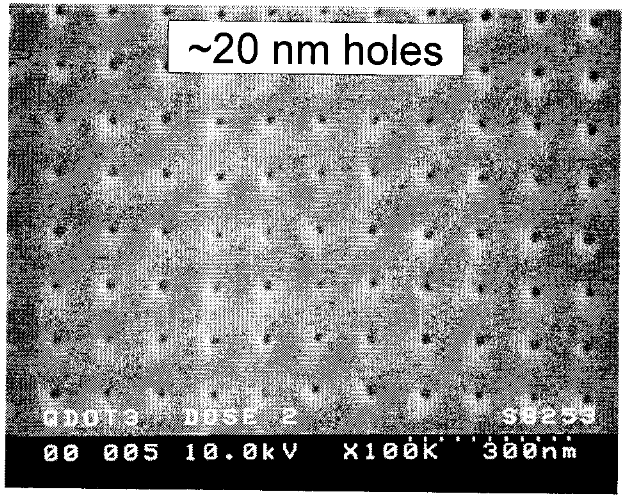
Array of sub-20 nm holes in electron-beam resist. Need to develop techniques for making metal and semiconductor structures at this size scale.

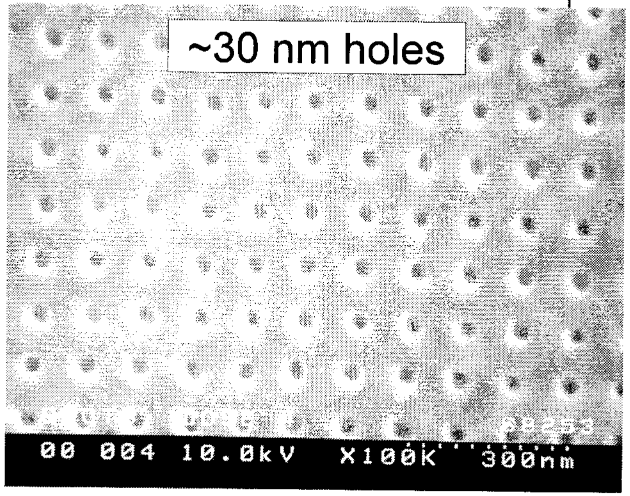
Accomplishments to Date

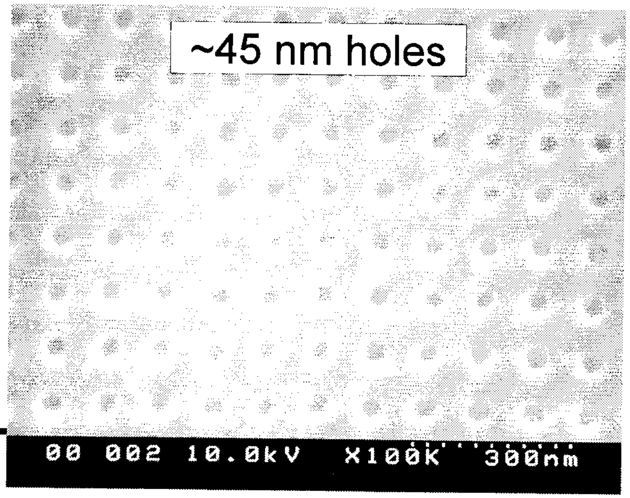
Hole arrays in ZEP-520 resist for positive-tone etching

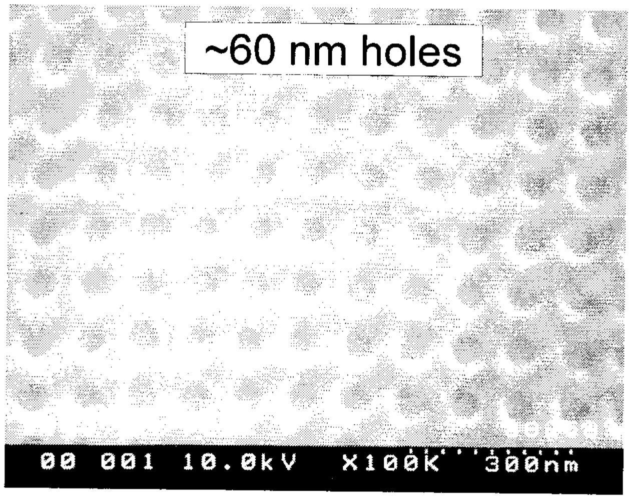
- ZEP-520 has good RIE etch resistance and is much more E-beam sensitive than PMMA
- Application: controlled quantum dot growth

Single-shot E-beam exposures with varying dwell time (each hole is imprint of E-beam spot, after development)





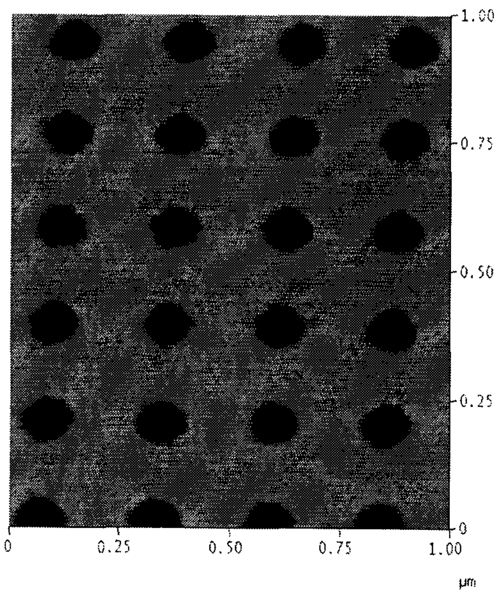




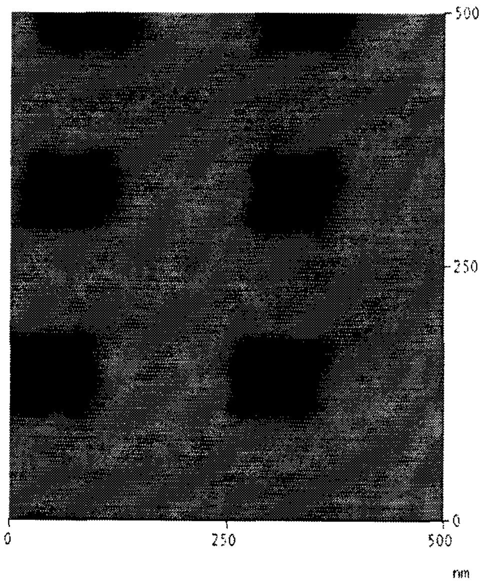
Accomplishments to Date

Shaped holes in ZEP-520 resist for positive-tone etching

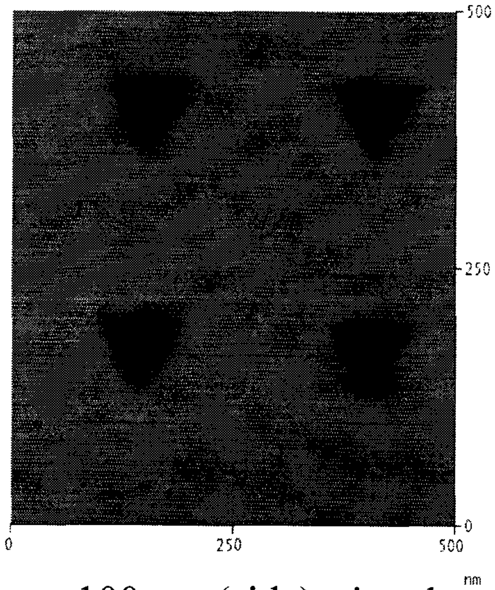
- Shape feature preservation gives indication of resolution



100 nm circles

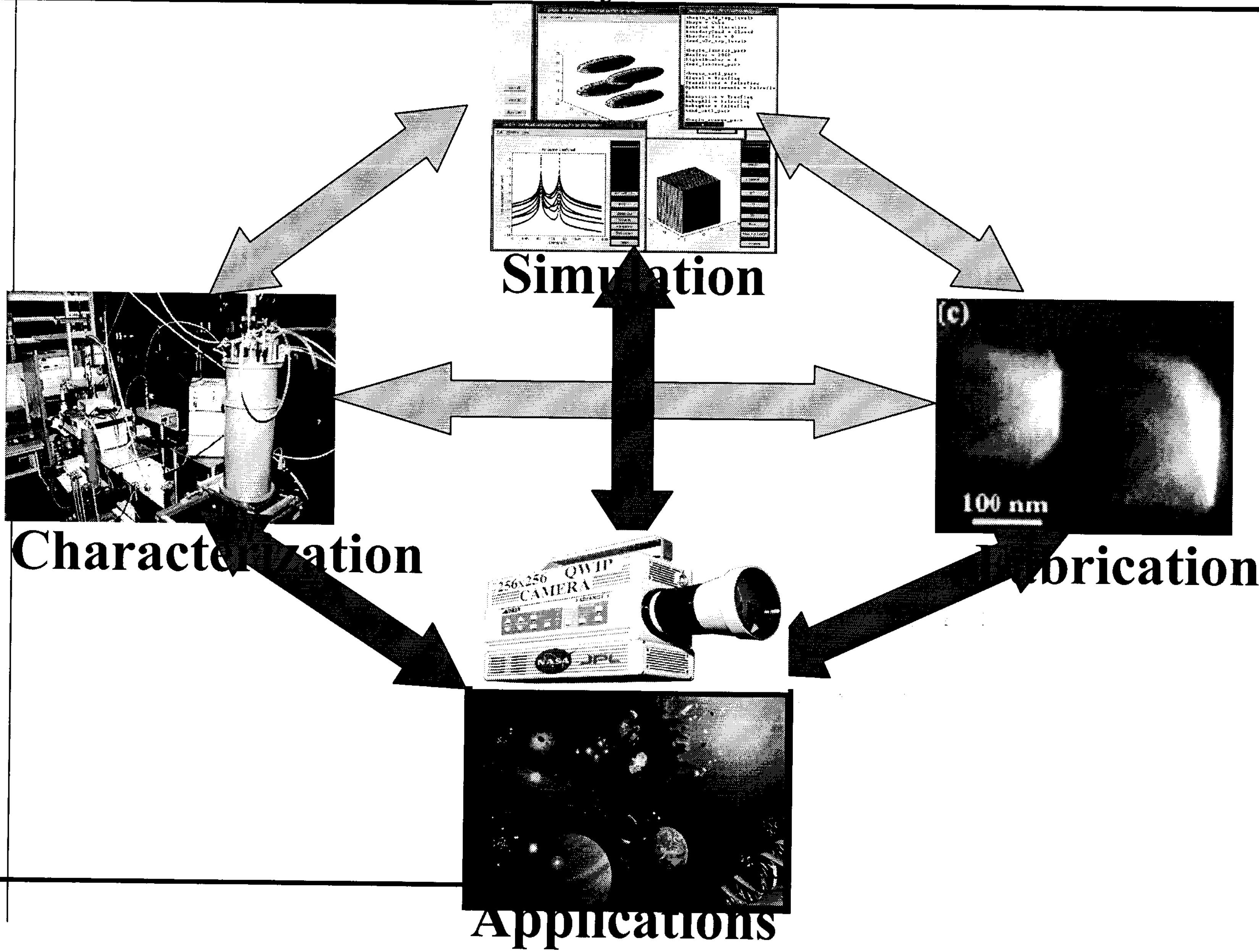


100 nm squares



100 nm (side) triangles

Modeling, Characterization and Fabrication are inseparable for nanoscale devices



QDs Optoelectronic Devices

Objective:

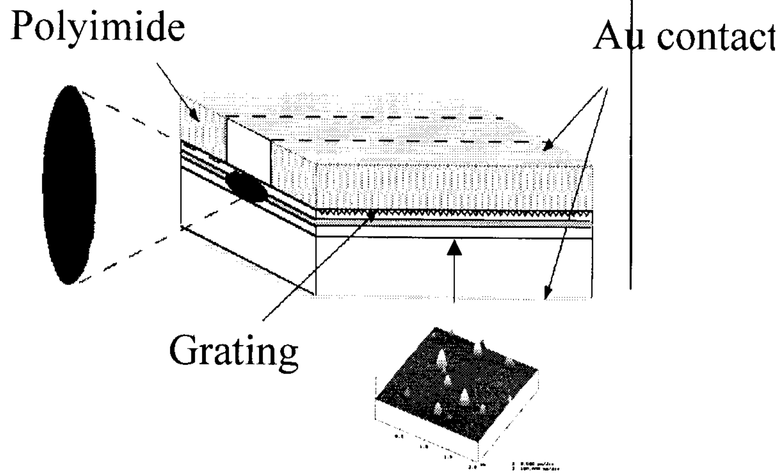
Design and fabricate high efficient, low power consumption, radiation hard QD based optoelectronic devices, such as QD lasers

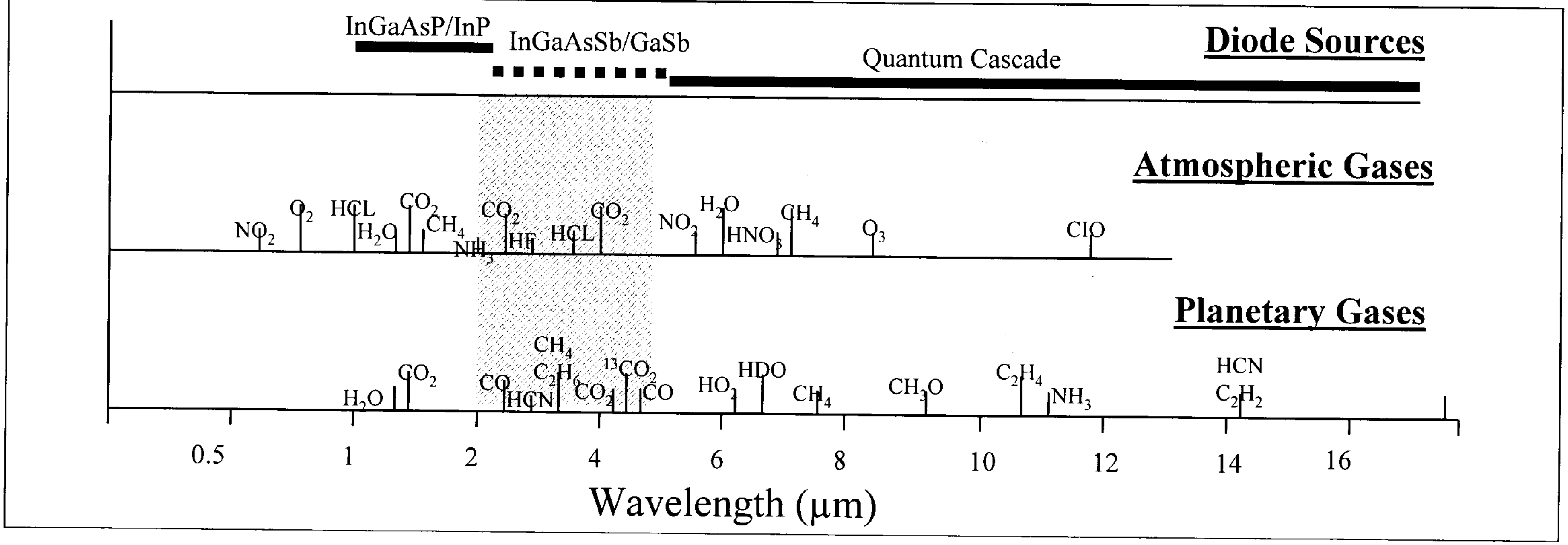
- ultralow threshold current density
- temperature insensitive .

NASA applications:

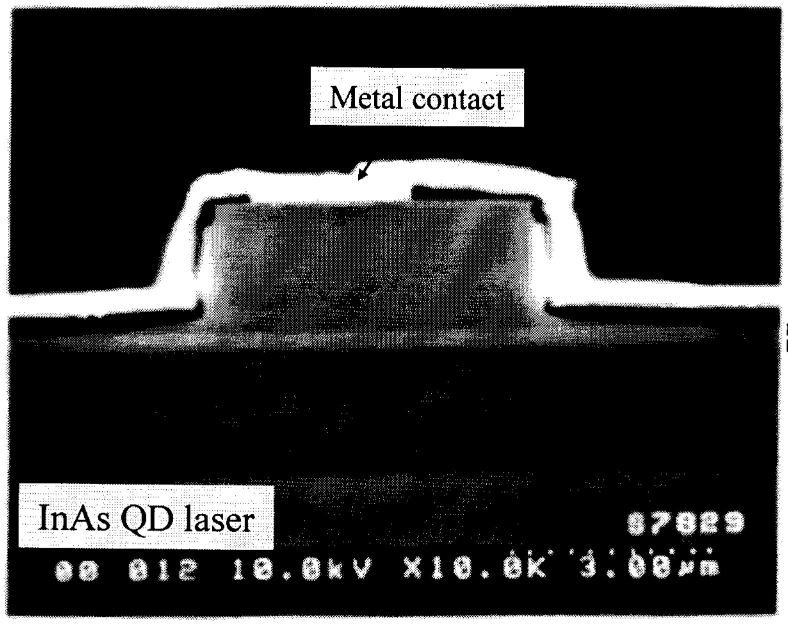
Broad area of applicability:

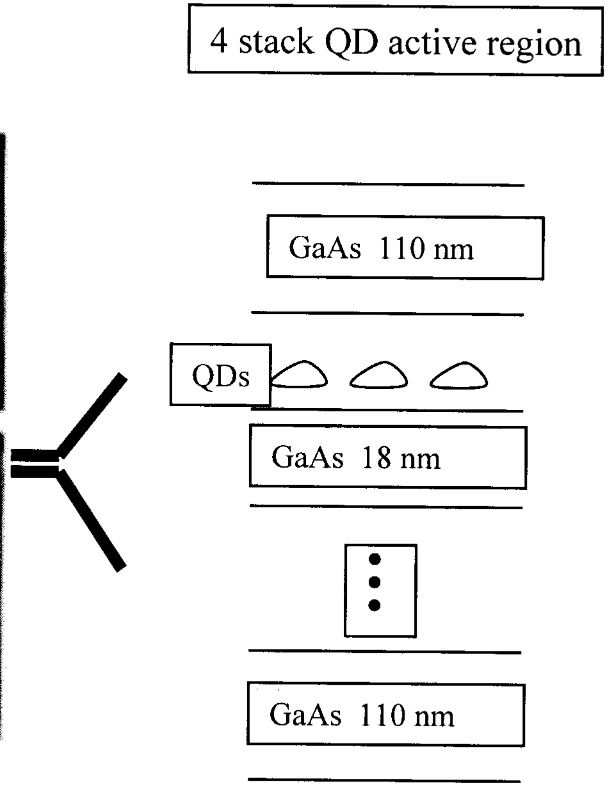
Spectroscopy especially 2-5 μm,
Communications
Microinstruments, LIDAR and
Interferometry





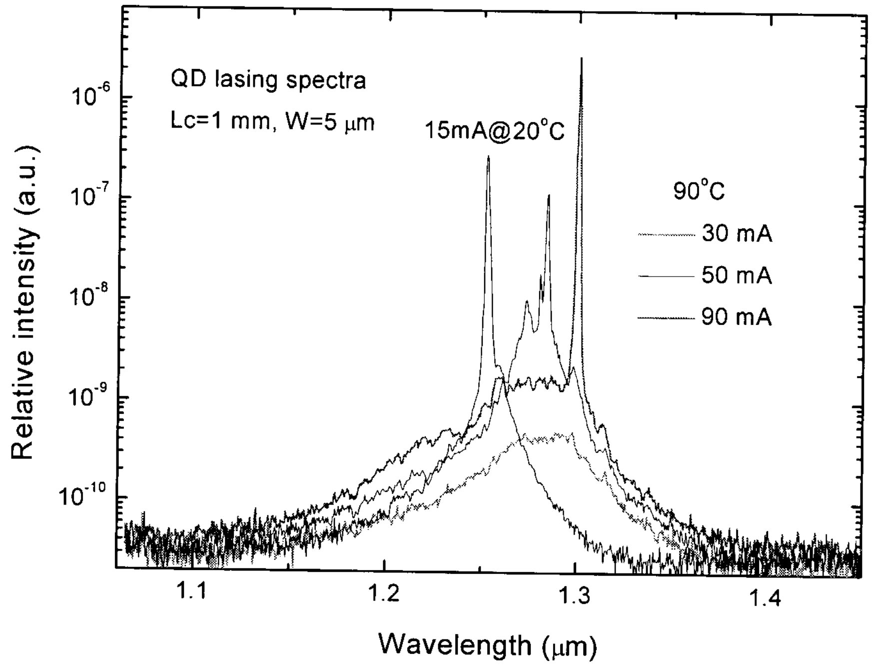
QD Ridge Laser SEM image





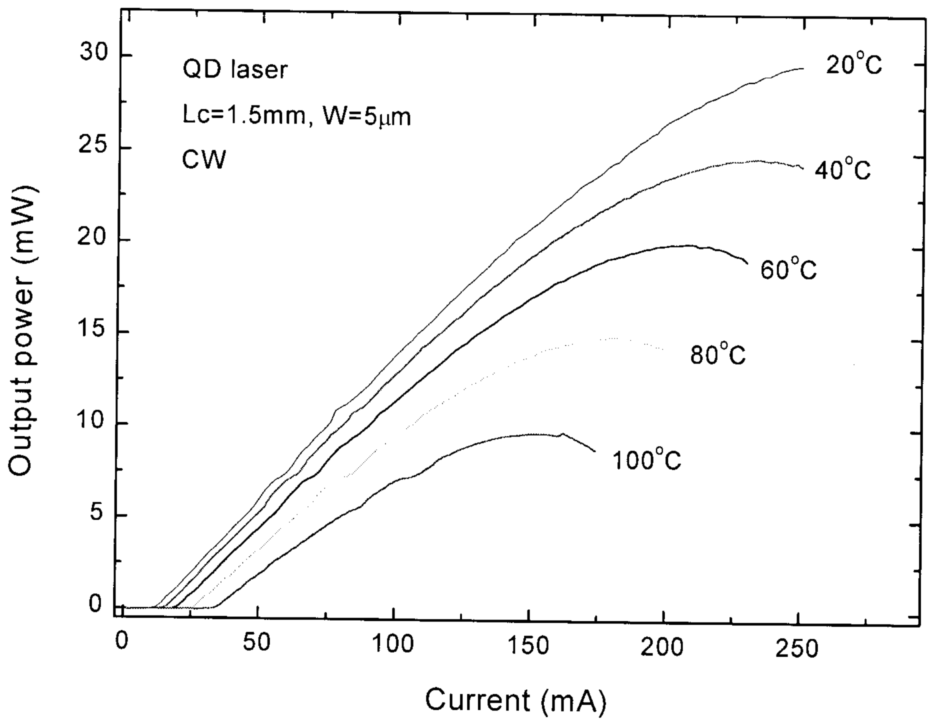
Ridge width W= 5 μm

QD Lasing Spectra



- Cavity length 1 mm, 1.5 mm, ground state lasing up to 100°C.
- Cavity length 500 μm, 750 μm, lasing switching from ground state to excited state.
- Wavelength temperature dependence: 3.7 Å/K

Light Output vs Current



- For 1.5 mm cavity length Ground state lasing up to 100°C, which is the limit of the setup.
- At 20°C, single facet output power >30 mW, differential quantum efficiency about 37%.
- At 100°C, output power ~ 10 mW.

Quantum Dots based Lasers

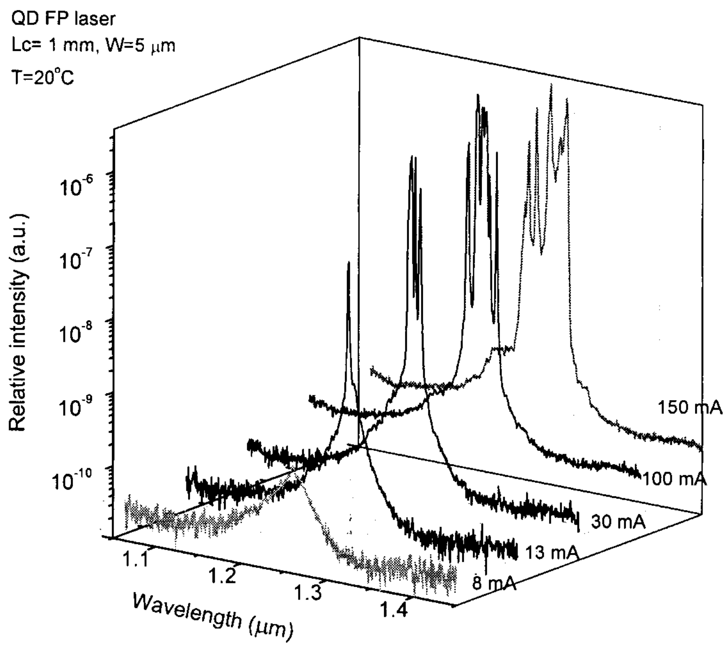
Goal: To develop advanced quantum-dot based semiconductor lasers at wavelengths of interest to Code S.

Applications:

- Spectroscopy
- Interferometry and LIDAR
- Microinstruments
- Communications
- Medical and life support

Advantages:

- Radiation hard
- Low power consumption
- Temperature stable
- Narrow linewidth

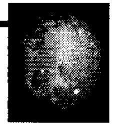


QD FP laser lasing spectra

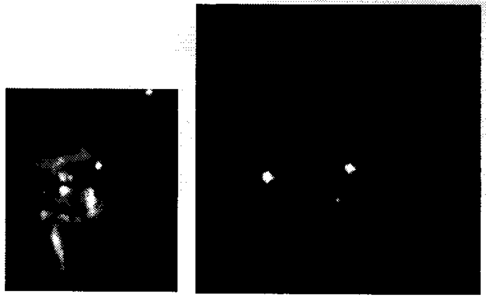
ADVANCES IN QWIP TECHNOLOGY

SEEING THE UNIVERSE IN A NEW LIGHT
USING QUANTUM TECHNOLOGY

Total Eclipse of the Moon
taken with QWIP Camera
20 January 2000



Courtesy: Arnold Goldberg
Army Research Laboratory

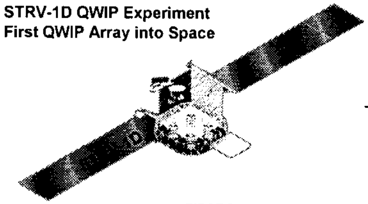


8.5 μm mid-infrared image, obtained with a QWIP focal plane array at primary focus of the Palomar 200-inch Hale telescope.

The S106 region displays vigorous star-formation obscured behind dense molecular gas and cold dust, and extended nebular emission from dust heated by starlight. QWIP-infrared images are used to assess the prevalence of warm dusty disks surrounding stars in such regions. Formation of these disks are an evolutionary step in the development of planetary systems.

200-inch Hale Telescope, Palomar Observatory

STRV-1D QWIP Experiment
First QWIP Array into Space



2001

FIRST DEMONSTRATION O
AND 14-1
DUALBAND QWIP CA

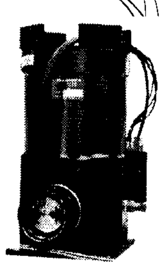
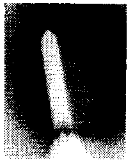
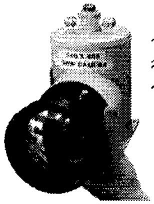


IMAGE OF DELTA II
LAUNCH TAKEN
WITH 8-9 μm JPL
QWIP CAMERA



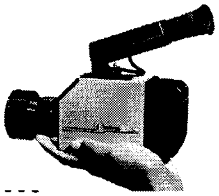
ADVANTAGE OF LWIR QWIPs
DETECTING COLD HARD BODIES
AGAINST HOT PLUME

640 x 486 LWIR
QWIP C

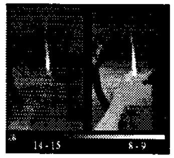


2000

FIRST DEMONSTRATION
OF
PALMCORDER
SIZE QWIP CAMERA

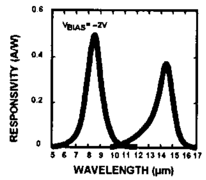


1999



SIMULTANEOUS 8-9
AND 14-15 μm
DUALBAND IMAGE
OF A FLAME

SIMULTANEOUSLY MEASURED RESPONSIVITY
SPECTRUMS OF A DUALBAND DETECTOR



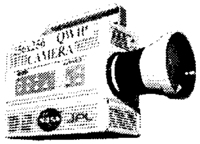
DUALBAND FOCAL PLANE ARRAY DATA

DETECTIVITY (cm√Hz/W) (300K BACKGROUND WITH f/2 STOP, T = 40K)	2.9 x 10^{10}	1.1 x 10^{10}
NEΔT (mK)	29	44
OPERABILITY (<100 MK)	99.7%	98%
NON-UNIFORMITY	0.03%	0.05%

FIRST DEMONSTRATION OF
15 MICRON 128 X 128
QWIP FOCAL PLANE
ARRAY CAMERA

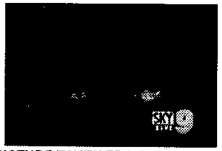
19

FIRST DEMONSTRATION OF
HAND-HELD CAMERA



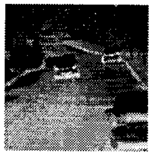
96

QWIP CAMERA SCANS MALIBU FIRES



PICTURE TAKEN FROM A VISIBLE CCD
CAMERA

640 x 486 QWIP
IMAGE

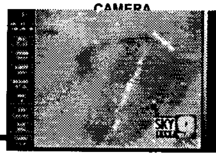


Features of 640 x 486
QWIP Camera

Array Size = 311,040 pixels
Spectral Bandpass= 8-9 μm
Quantum Efficiency= 4.5%
Operability = 99.98%
NEΔT = 36 mK
FPA Uniformity= 99.95%

THERMAL INFRARED IMAGING
IS USED TO DETECT FAULTY
TRANSFORMERS

Courtesy of QWIP Technology



LONG-WAVELENGTH ALLOWS THE
QWIP CAMERA TO SEE THROUGH
SMOKE AND PINPOINT LINGERING
HOTSPOTS (PICTURE ON LEFT)
WHICH ARE NOT NORMALLY
VISIBLE (PICTURE ON TOP)

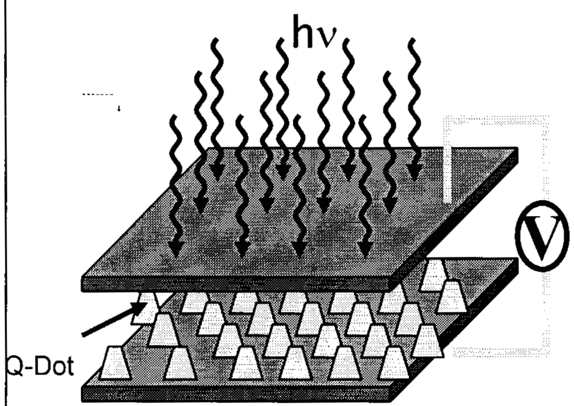
THE EVENT MARKED THE QWIP CAMERA'S
DEBUT AS A FIRE OBSERVING DEVICE.

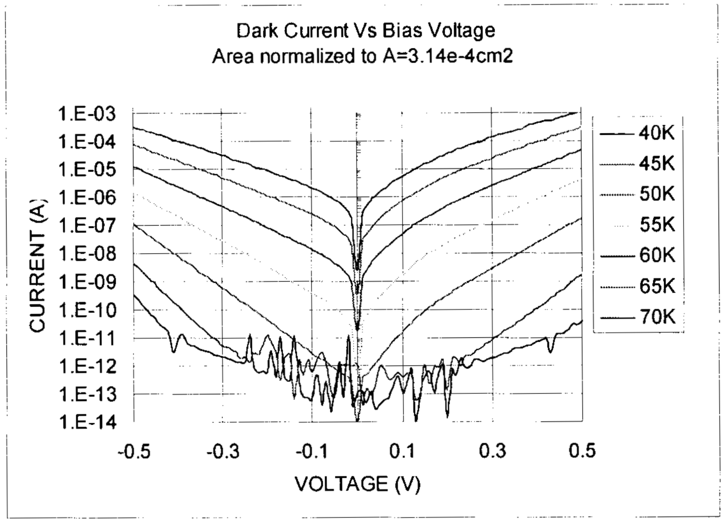
- OVER 100 PUBLICATIONS IN QUANTUM AND NANO TECHNOLOGY
- ORGANIZED QWIP 2000 WORKSHOP
- 18 PATENTS FILED (4 APPROVED, 14 PENDING)
- DELIVERED OVER 100 FOCAL PLANE ARRAYS

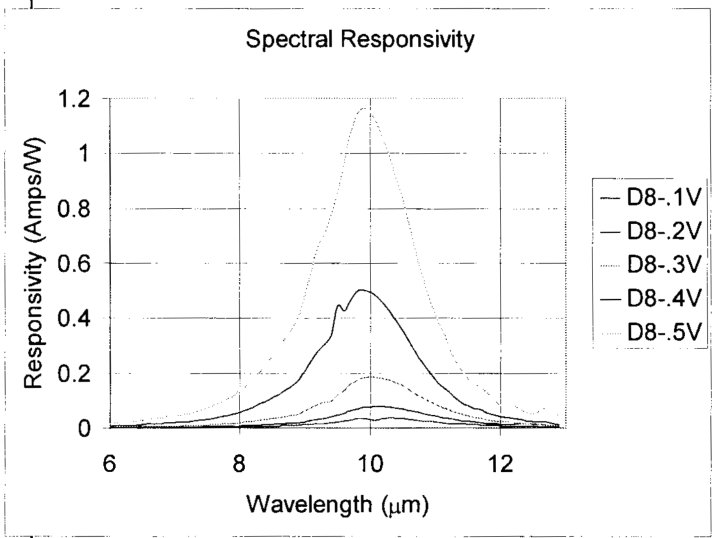
Reference: Sarath D. Gunapala, et al.,
IEEE Trans. Electron Devices,
44, pp. 45-57, 1997; 45, 1890 (1998);
47, pp. 326-332, 2000; **47**, pp. 963-971, 2000

QUANTUM DOT INFRARED PHOTODETECTOR (QDIP)

Quantum Dot Infrared Photodetector





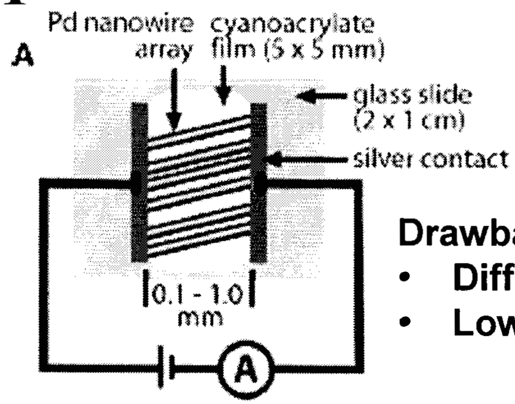


Advantages:

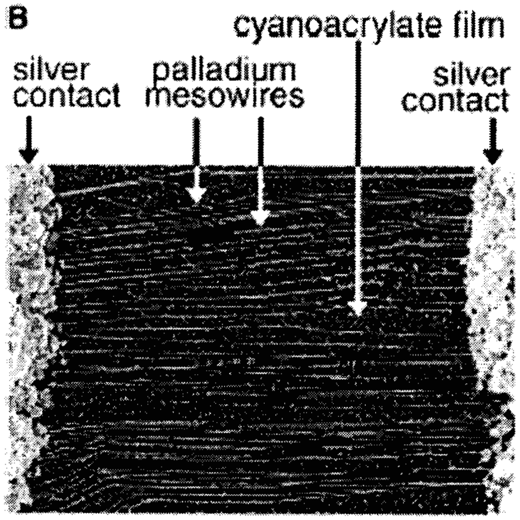
- Normal incidence radiation absorption
- *Near 80% quantum efficiency is achieved.*
- *4 - 300 K wide operating temperature range;*
- *Radiation Hard up to 1.5 M Rads;*
- *High Signal-to-noise Ratio,*
- *detectivity D* - $1x10^{12}$ Jons is expected*

Nano Sensor Benchmark

1

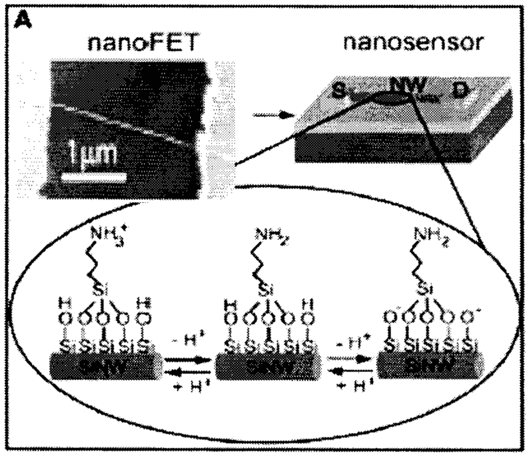


Drawbacks
- Difficult Fabrication
- Low reproducibility



From Penner *et al.*, Science, 293, 2227(2001)

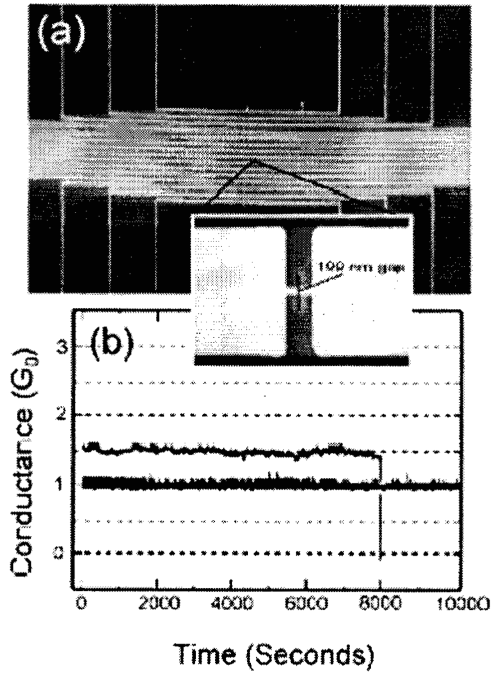
2



Drawbacks
- Post growth assembl
- Reproducibility?

From Lieber *et al.*,
Science,
293, 1289(2001)

3



Drawbacks
- Instrument
- Small active area

From Tao *et al.*,
APL,
76(10),
1333(2000)

✓ Single Nanowire Fabrication and Sensing

-Hydrogen sensor using single Pd wire

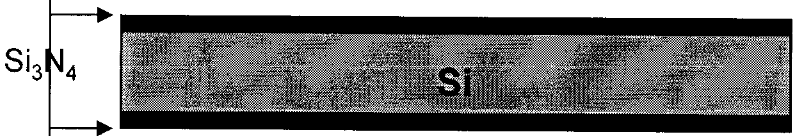
-pH sensor using single Polypyrrole wire

- Bundled Nanowire Fabrication and Sensing

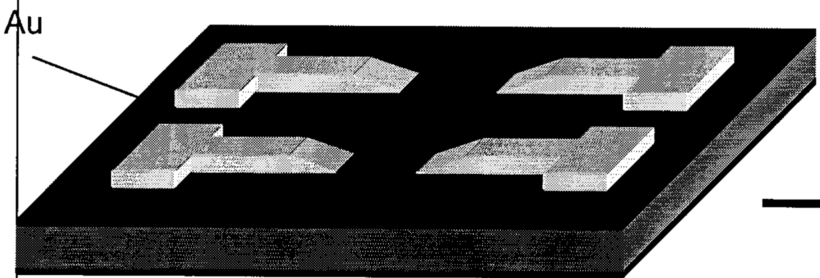
-Glucose sensor using Pt nanowires

-Hormone sensor using Au nanowires

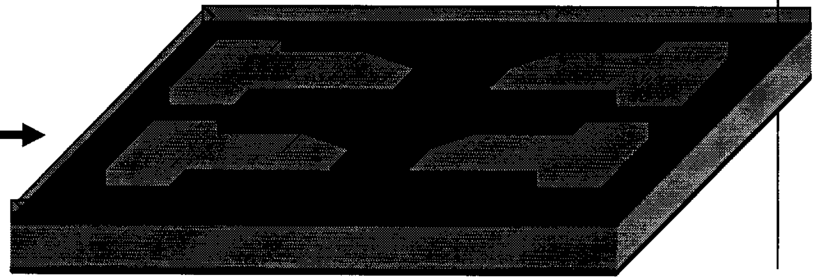
Fabrication



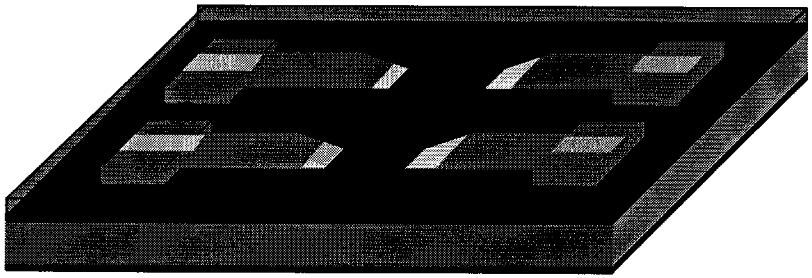
Deposit low stress Si_3N_4 (or SiO_2onto Si wafers)



Metalize top Si_3 N_4 with E-beam evaporation and Lift-off

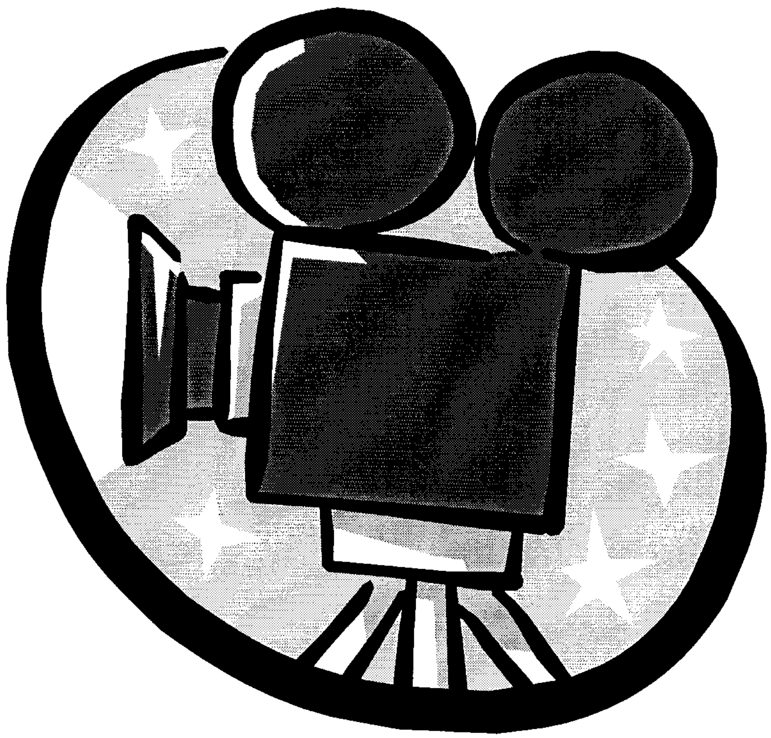


SiO Deposition



Channel Pattern and Electrodeposition

Electrodeposition

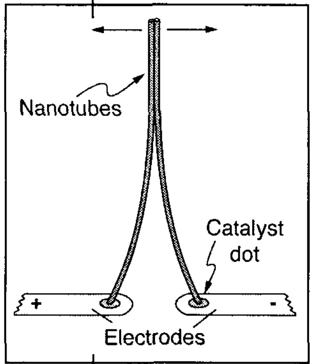


Electrodeposition Summary

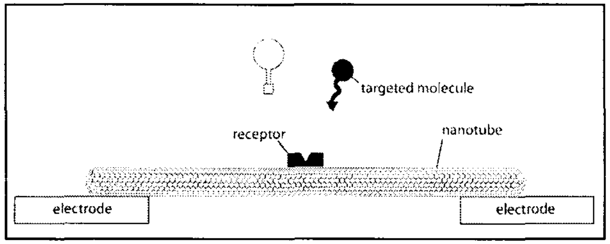
1. We developed a novel process to directly grow a wire between Au electrodes using electrochemical deposition. This method has the potential of fabrication of individually addressable nanowire arrays and could be used for nanoelectronic devices and various sensors.
2. Various bundles of nanowires (e.g. tin, antimony, gold, platinum, and polyaniline) were electrodeposited and characterized for pH, Glucose and Hormone sensors.
3. Using Pd single wire, hydrogen gas was detected with 3.75nW of power consumption and 0.002 second of response time.
4. We have successfully grown single conducting polymer (Polypyrrole) wires with a diameter of 1μm and 500nm and sensed pH.
5. We have developed and improved the sensitivity of glucose detection using Pt bundled nanowires. Pt nanowires show increase in effective surface area and 50 X greater in sensitivity than Pt thin film.
6. T3 hormone was immobilized and detected using Polyaniline thin film, Au thin film, and bundled Au nanowires.

Carbon and Silicon Nanowire Biosensors

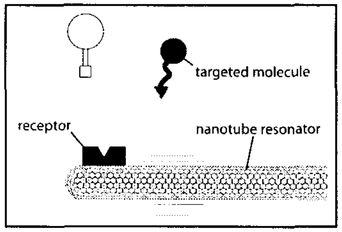
Products: *Nanowire-based sensors, actuators*



Nanotube bimorph



Nanowire biosensor



Nanomechanical resonator

Objective:

- Demonstration of three chemically-functionalized C and Si nanowire devices for NASA biosensing applications: 1) a nanowire molecular sensor based on conductance modulation; 2) a nanowire mechanical resonator which functions as a molecular balance; and 3) a nanowire "bimorph" structure for molecular manipulation and force sensing.

Competition:

- State of the art

Major Products:

- Nanowire biosensor with chiral specificity; nanomechanical resonator molecular balance; nanotube bimorph actuator and force sensor.

Participants

- PI: Brian Hunt, Jet Propulsion Laboratory
- Co-Is: Mike Bronikowski, Michael Hoenk, Anita Fisher, Eric Wong - JPL; Michael Roukes - Caltech

Significance (Customer Relevance)

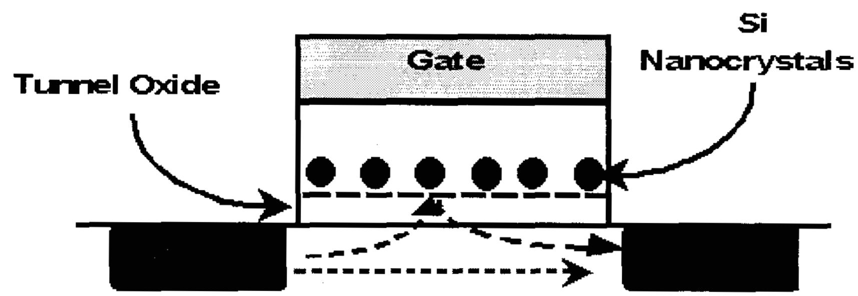
- These devices will enable *chemically-specific single molecule sensing with chiral selectivity.*
- Unique Facilitites: JPL Microdevices Laboratory, JEOL JBX-9300FS Electron Beam Lithography System, Carbon nanotube and Si nanowire growth systems; Caltech low-noise RF measurement systems
- Primary Customer: NASA Space Science Solar System Exploration (S3). Secondary Customer: NASA Human Exploration and Development of Space (HEDS).

Milestones:

- FY03: – Development of growth and processing techniques for fabrication of lateral and vertical carbon nanotube structures. – Begin chemical functionalization studies. TRL 1.
- FY04: – Development of growth and processing techniques for fabrication of lateral and vertical silicon nanowire structures. – Fabricate 1st round of three basic nanowire device structures. TRL 2.
- FY05: – Measurement of 1st round devices. – Fabrication/test of improved devices after initial test feedback. TRL 3-4.

Nanocrystal based Non-Volatile Memory

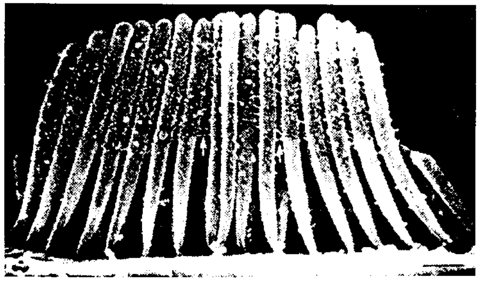
- Code S has unique requirements for computing and memory:
  - Radiation hardness
  - High density,
  - Low power,
  - Small size.



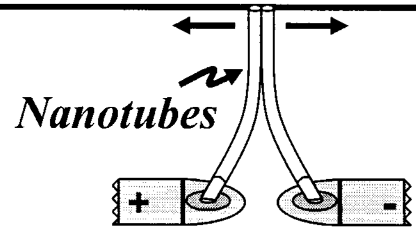
- Emphasize is on Non-volatile memories because power needed only during read/write operations.
  - Conventional DRAM-type memories require continuous power to maintain storage.
- By using nanocrystal ensembles we anticipate that:
  - The distributed nature of a storage element leads to intrinsic fault tolerance and radiation-hardness.
  - Using group-IV technology, *directly integrable* into existing CMOS process lines.
  - dramatically increased write/erase speeds for non-volatile memory.
  - Replacement of volatile with non-volatile memory would *drastically decrease* power requirements.

Order Carbon Nanotube Arrays

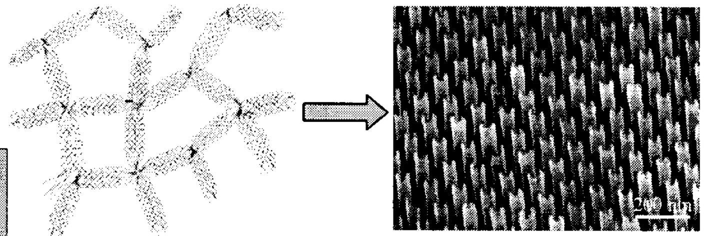
Nanotube based acoustic sensors using biomimetic detection principles

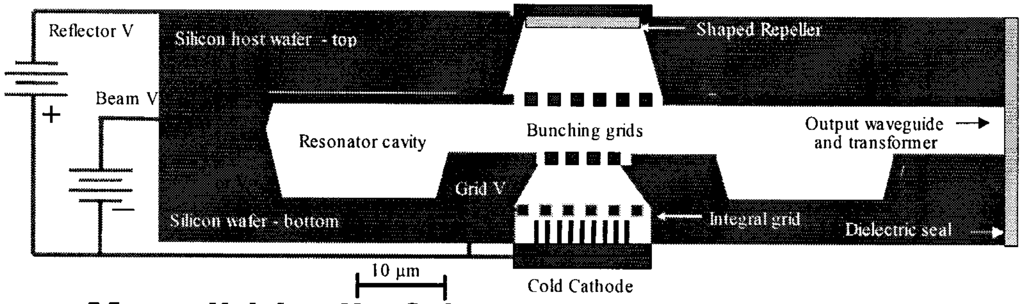


Stereocilia bundle protruding from an inner hair cell of a guinea pig cochlea. Scale bar 500 nm.

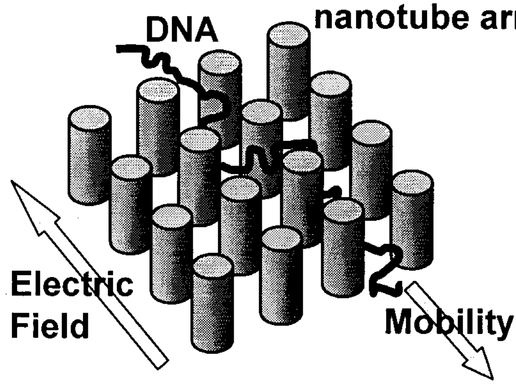


Nanotube bimorph actuator and force sensor

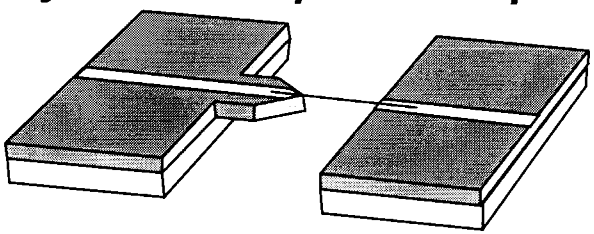




Monolithically fabricated vacuum-tube nano-klystron with power output at THz



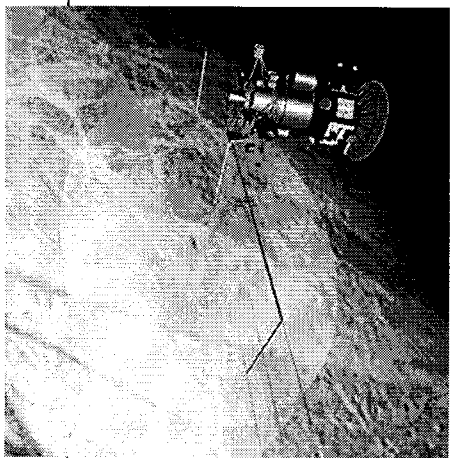
Nanotube-Based Electrophoresis System for Biomolecular Analysis



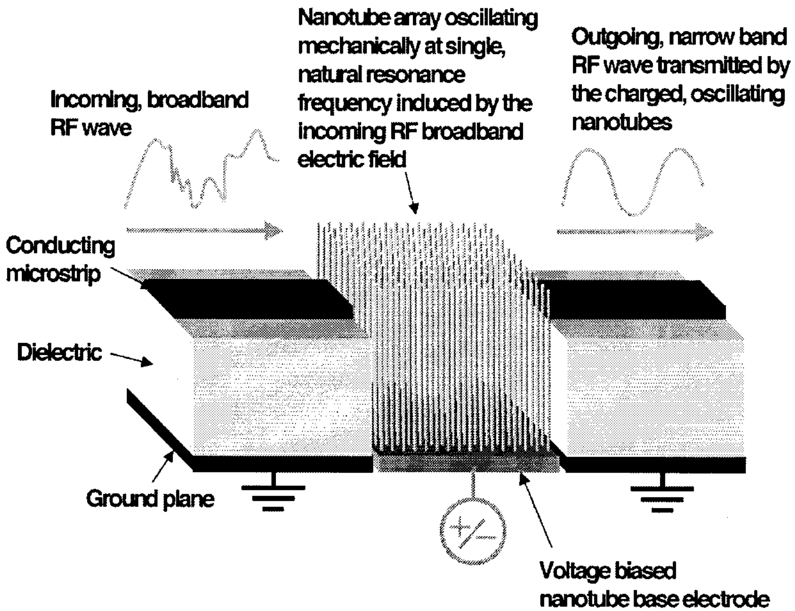
Nanotube tunable high-Q resonator

Nanotube Array
RF Filter and RF Filter Bank

Nanotube mechanical resonators can provide rad-hard high-Q performance from MHz to GHz frequencies



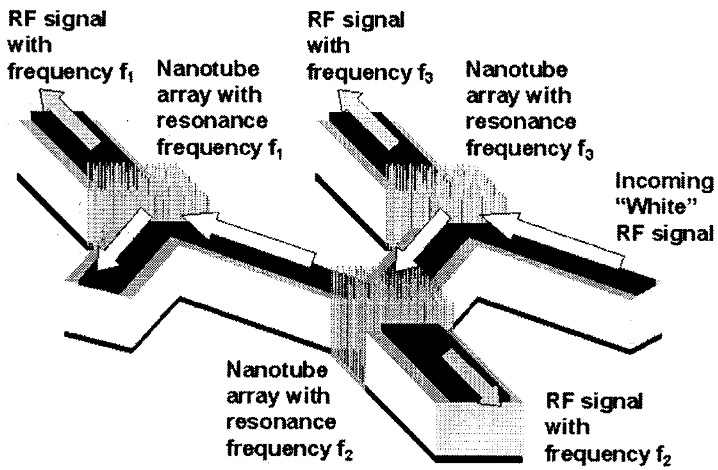
- *Low power*
- *Compact*
- *Rad-hard*



Waveguide-Embedded Nanotube Array RF Filter. A highly uniform nanotube array functions as a narrow band RF filter in a microstrip structure.

Nanotube Arrays

- Provide power handling capacity
- Potential mechanical phase locking can greatly increase Q



Nanotube Array RF Filter Bank

Summary

- We are working synergistically with Code U, Y and S needs in the area of Chem. and Bio sensors
- Several of our technologies have strong applicability to Homeland Defense DoD.