Bio – Nano Technology Program at JPL

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NASA’s Nanotechnology Investments

Nano-electronics and Computing
- Molecular electronics & photonics
- Computing architecture
- Assembly

Sensors
- Bio-Chemical Sensors
- Photon Generation and Detection
- Nano Scale Fabrication

Nano-materials and Structures
- Composites
- Multifunctional materials
- Self-healing

- 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

Sonication

Swab assay

Pour or spread plate the sample

Incubation at 32°C for 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
JPL Nano/Bio Technology Program

- 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

Simulation

Characterization

Fabrication

Applications
Nano-scale Device Analysis / Synthesis
Development of a Bottom-Up Nanoelectronic Modeling Tool

** 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.
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.
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


Boxes are 1 x 1 microns
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 /cm²

1) $7 \times 10^{12}$,
2) $6 \times 10^{13}$,
3) $2 \times 10^{15}$,
4) $3 \times 10^{12}$,
5) $6 \times 10^{13}$,
6) $2 \times 10^{14}$
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 $\lambda=620$ 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.

High Voltage

Needle-Shaped Specimen

Image Screen
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)
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)
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

**Diode Sources**
- InGaAsP/InP
- InGaAsSb/GaSb
- Quantum Cascade

**Atmospheric Gases**
- H2, O2, HCl, CO2, CO, NO, NO2, H2O, CH4, HNO3, CH3

**Planetary Gases**
- H2O, CO2, CH4, NH3, HCN, C2H2

**Wavelength (μm)**

Polyimide

Grating

InAsSb QD active region

Au contact
QD Ridge Laser SEM image

Metal contact

4 stack QD active region

GaAs 110 nm

QDs

GaAs 18 nm

GaAs 110 nm

InAs QD laser

Ridge width $W = 5 \, \mu m$
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
- 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.
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

200-inch Hale Telescope, Palomar Observatory

SEEING THE UNIVERSE IN A NEW LIGHT
USING QUANTUM TECHNOLOGY

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

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.

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

ADVANTAGE OF LWIR QWIPs DETECTING COLD HARD BODIES AGAINST HOT PLUME

FIRST DEMONSTRATION OF HAND HELD CAMERA

THERMAL INFRARED IMAGING IS USED TO DETECT FAULTY TRANSFORMERS

PICTURE TAKEN FROM A VISIBLE CCD CAMERA

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.

Features of 640 x 486 QWIP Camera
Array Size = 311,040 pixels
Spectral Bandpass = 8-9 μm
Quantum Efficiency = 4.5%
Operability = 99.98%
NEAT = 16 mK
FPA Uniformity = 99.95%

FIRST DEMONSTRATION OF PALMCORDER SIX QWIP CAM

640 x 486 LWIR QWIP CAM

2000

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

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) 2.5 x 10²⁸ (5.1 x 10²⁸)
(200°C, T = 80K)

NEAT (μK) 23

OPERABILITY (±100 MHz) 98.7% 64%

NONUNIFORMITY 3.25% 0.95%

• 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
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  $D^*$ - $1 \times 10^{12}$ Jons is expected
Nano Sensor Benchmark

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

1. Pd nanowire cyanoacrylate array film (5 x 5 mm)
   - Drawbacks
     - Difficult Fabrication
     - Low reproducibility

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

2. NanoFET nanosensor
   - Drawbacks
     - Post growth assembly
     - Reproducibility?

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

3. Silver contact palladium mesowires silver contact
   - Drawbacks
     - Instrument
     - Small active area

From Penner et al., Science, 293, 2227(2001)
✓ Single Nanowire Fabrication and Sensing
- Hydrogen sensor using single Pd wire
- pH sensor using single Polypyrrole wire

bullet

• Bundled Nanowire Fabrication and Sensing
- Glucose sensor using Pt nanowires
- Hormone sensor using Au nanowires
Fabrication

Deposit low stress Si₃N₄ (or SiO₂) onto Si wafers

Metalize top Si₃N₄ with E-beam evaporation and Lift-off

SiO Deposition

Channel Pattern and Electrodeposition
Electrodeposition
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.
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 Facilities: JPL Microdevices Laboratory, JEOL JBX-9300FS Electron Beam Lithography System, Carbon nanotube and Si nanowire growth systems; Caltech low-noise RF measurement systems

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.

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

Nanotube tunable high-Q resonator

Nanotube bimorph actuator and force sensor

Polymer gel

Carbon nanotube array

DNA

Electric Field

Mobility

Nanotube-Based Electrophoresis System for Biomolecular Analysis
Nanotube Array
RF Filter and RF Filter Bank

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

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

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.
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.