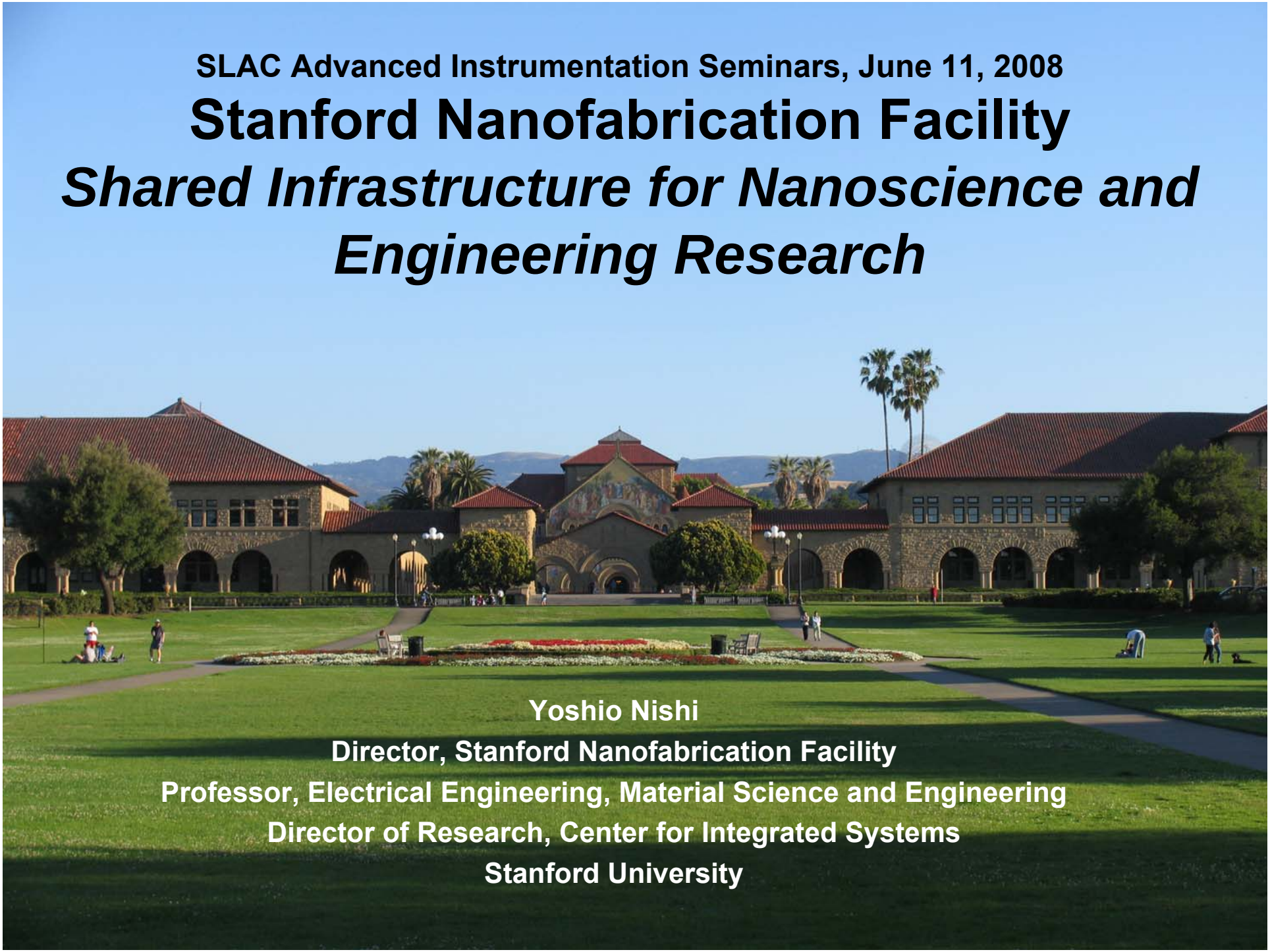
SLAC Advanced Instrumentation Seminars, June 11, 2008

Stanford Nanofabrication Facility

Shared Infrastructure for Nanoscience and Engineering Research



Yoshio Nishi

Director, Stanford Nanofabrication Facility

Professor, Electrical Engineering, Material Science and Engineering

Director of Research, Center for Integrated Systems

Stanford University

Outline

- ***National Nanotechnology Infrastructure Network***
- Research Infrastructure at Stanford
- Areas of Research
- Future Challenges
- Summary

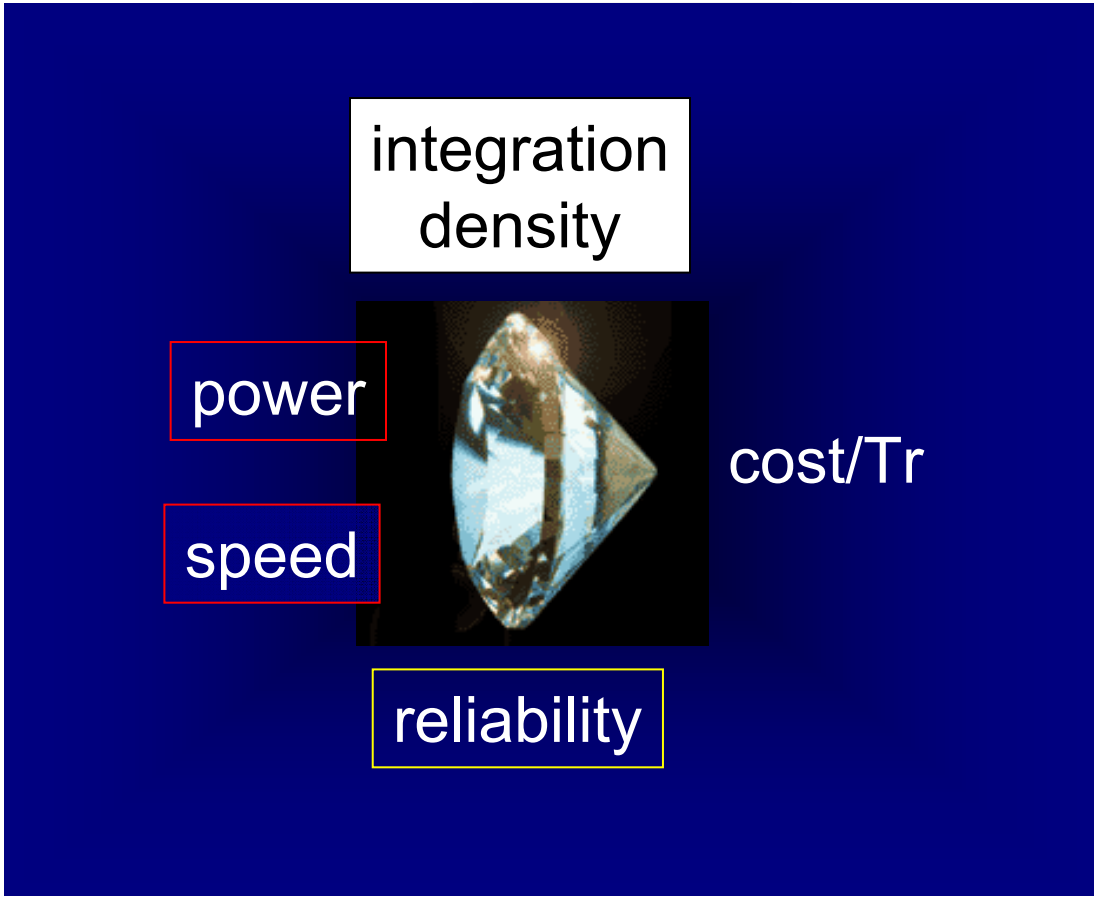
Nanoscience and Nanotechnology

- "Evolutionary" Nano (mm → nm)
- "Revolutionary" Nano (quantum and nano devices, organic (and perhaps molecular) electronics …)
- Nanomaterials
- Biology, and Biological Nanomachines
- Progress on all fronts will require a mixture/portfolio of technologies: top-down lithographies, bottom-up synthesis, self-assembly, templating, bio and biomimetic!
  - Biomedicine: Bioanalysis
  - National Security: Sensors, Materials

The happy scaling: for how long?

R. Dennard © IEEE

dimensions t_{ox}, L, W	**$1/\alpha$**
doping	**α**
voltage	**$1/\alpha$**
integration density	**α^2**
delay	**$1/\alpha$**
power dissipation/Tr	**$1/\alpha^2$**



Smaller = better

M. Brillout, FTM2006

Evolutionary "Nanoelctronic" Devices have been used already.

Question is what "Revolutionary"Nanoelectronic Materials and Devices could provide us.

- Carbon nanotubes
- Nanowires
- Molecular/organic electronics
- Nonvolatile memories/materials
- Spintronics
- Fusion with NEMS, Bioelectronics etc

Revolutionary "Nano"

- Replacing silicon CMOS?
- Inventing new functionality?
- Multidisciplinary cross fertilization?
- Top-down patterning vs. self-assembly
- Energy and environment
- Bio/medical for drug delivery, medical imaging etc

National Nanotechnology Infrastructure Network

Mission:

Enable rapid advancements in science, engineering

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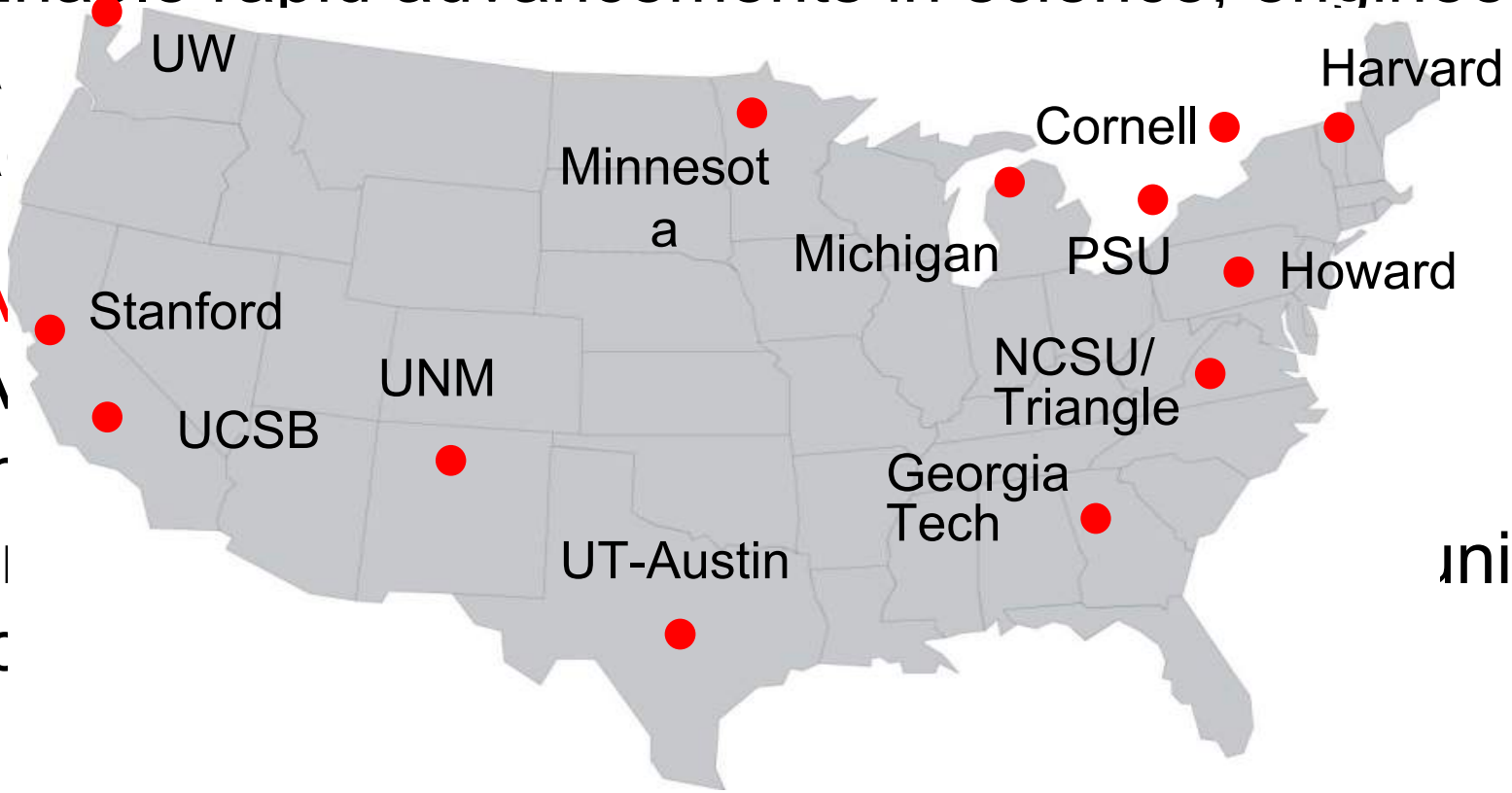

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New NNIN

11 existing sites
3 new sites

Colorado
University of Colorado at Boulder

Precision engineering
Energy
Local connections to NIST and NREL
Local high technology companies

ASU
Arizona State University

Organic/inorganic interfaces
Biosciences
Flexible Electronics
Local high technology companies
Large Hispanic and Native American population

Washington University in St. Louis

Nanoinstrumentation for health and environment
Nanomaterials
Highly rated
- Environmental Engineering
- Medicine and Life Sciences
- Public Health

Experimental Research Support Strategy

Provide comprehensive science and engineering resources

Research Requirements

Graduate Students
- Large Research Universities: Specialized resources
- Small Universities: Broad technical support

Undergraduate Students
- Nanotechnology introduction

Large Companies
- Specialized resources

Small Companies
- Broad range of resources

National Laboratories
- Specialized resources and technical exchange

Technology
Expertise
Processes
Equipment
Process Support

National, Complete and Accessible
Geographically diverse
Distributed technical specialization
Complex integration
Responsive open culture

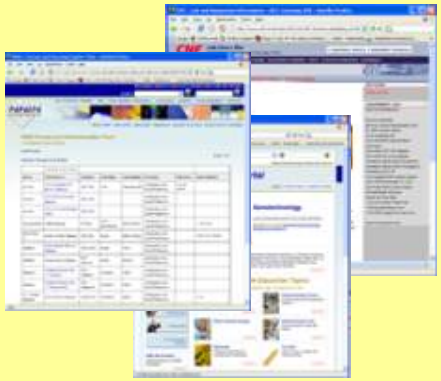
Affordable
On-site and remote usage

NNIN Resources & Output

Equipment
800 major tools

People
~150 FTE

Information
Processes and expertise

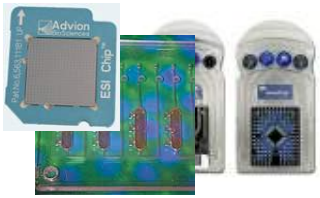


Discipline and User-centric Culture

Education

Research

Development



Society & Ethics

Outline

- National Nanotechnology Infrastructure Network
- ***Research Infrastructure at Stanford***
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Stanford Nanofabrication Facility Vision

To be one of the top fabrication infrastructures for nanotechnology research and education in the world measured in terms of quality and quantity of work in nanotechnology.

Raith 150 electron beam system

SVG resist coat track

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SNF Mission

To provide a fabrication infrastructure which helps both academic and industrial users accomplish their experimental research goals.

To provide an environment in which users can try innovative ideas for scientific research, engineering research, and development of innovative products.

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SNF Strategy

- to provide user operated experimental capabilities with advanced equipment and effective training in order to maintain a safe working environment.
- to acquire, in a timely manner, necessary equipment and process capabilities.
- to balance the budget with NSF/NNIN funding and user fees while establishing a process for new equipment acquisition.
- to enable close coupling and information exchange between academic and industrial users.
- to strengthen resources as necessary in order to meet the demand for new technical knowledge and new skills.
- to increase the use of nanofabrication in non-traditional areas.
- to provide an incubator facility for start-up companies.

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The Nanofab's Philosophy

- the lab is open to all – Stanford academic, non-Stanford academic and industrial users.
- there is a dynamic community of researchers who support one another. There is an active problem discussion list.
- there are consultants who work with users that don't want to come to Stanford to get their project done in the lab.

Tylan furnace

wet bench

- each user is responsible for his or her own intellectual property.
- by terms of the NSF agreement only R&D can be done, no manufacturing.
- it is a cost effective and efficient way to try out new ideas.

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User's Perspective on SNF's Value

- the SNF plays a vital role in the incubation of new technologies
  - most foundries have $50k+ barrier to entry - access gap
  - flexibility to try non-conventional processes
  - variety of equipment
  - hands-on opportunities appealing to Ph.D. founder types
  - home turf advantage to [Stanford] grads
  - SNF's secret weapon: today's academic users are tomorrow's industrial users
- excellent work environment
  - friendly and knowledgeable staff
  - supportive learning environment
  - collegial atmosphere
  - most users are good citizens

Dr. Alissa Fitzgerald
A. M. Fitzgerald & Associates, LLC
655 Skyway Rd., Suite 118, San Carlos, CA 94070
www.amfitzgerald.com

The Stanford Nanofabrication Facility

- SNF is part of the infrastructure of Stanford's Center for Integrated Systems, but does not receive direct funding from CIS.
- there is 10.5k ft^2 (1k m^2) of class 100 cleanroom space with separate floors for fan deck and support equipment.
- primarily 4" wafer processing although some 6" equipment is available.
- over 200 active labmembers in any given month. 130 Stanford academic users, 20 non-Stanford academic users, and 50 industrial users.
- industrial users are primarily from small, local startups, but also several large companies (Intel, HP, IBM, Applied Materials, Hitachi, and others).

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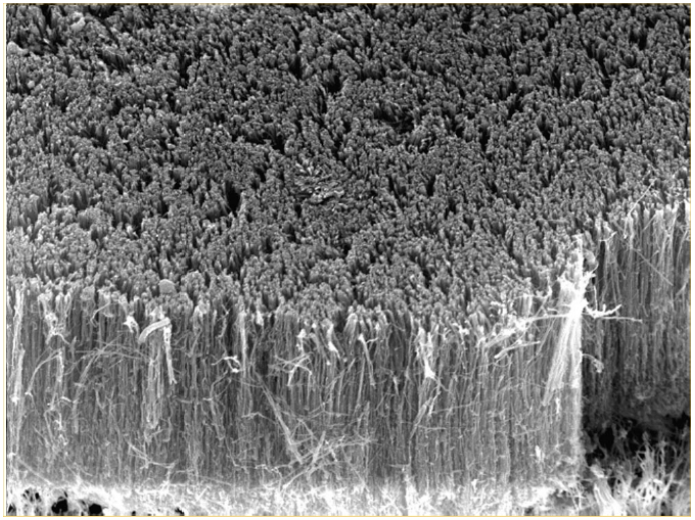
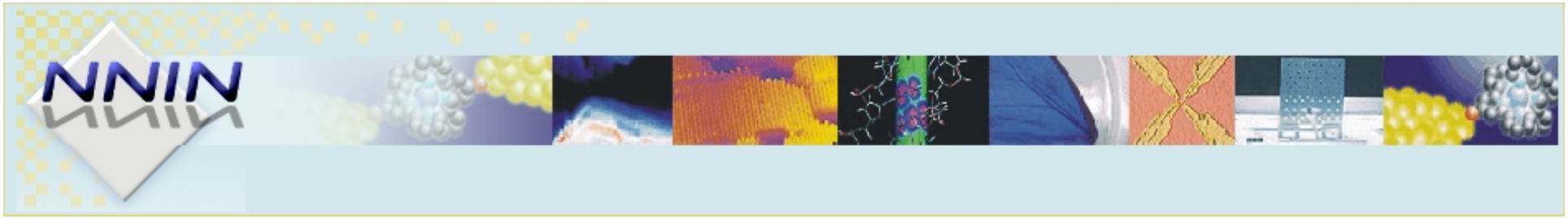
Interdisciplinary Workshops/Symposia

- BioMEMS
- E-Beam Lithography for Nanostructure Fabrication
- DNA Microarray Workshop
- Nanosafety - Dec. 2, 2004 at Georgia Tech
- Nanofacility Workshop with National Nanofab Center of Korea
- Foundry Day – Prototype to Product – October 20, 2005 at Stanford
- UGIM Lab Managers Workshop – June 25, 2006 at Stanford



carbon nanotubes



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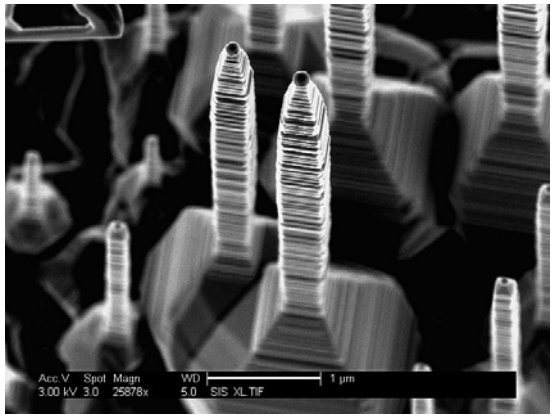
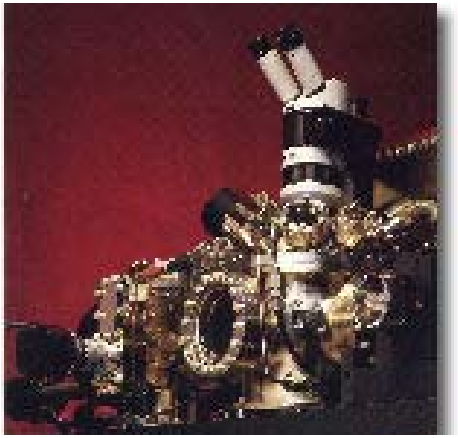
Stanford Nanocharacterization Laboratory (SNL)

contacts – Ann Marshall, Richard Chin, Professor Robert Sinclair

- associated with SNF through NNIN grant
- high resolution scanning electron microscopes (SEM)
- focussed ion beam (FIB)
- high resolution transmission electron microscope (TEM)
- high resolution Auger electron spectroscopy (AES)
- x-ray photoelectron spectroscopy (XPS)
- secondary ion mass spectroscopy (SIMS)
- specimen preparation equipment
- x-ray diffraction laboratory



nanowires – Professor Yoshio Nishi and H. Jagannathan, Stanford



SSI S-Probe monochromatized XPS spectrometer

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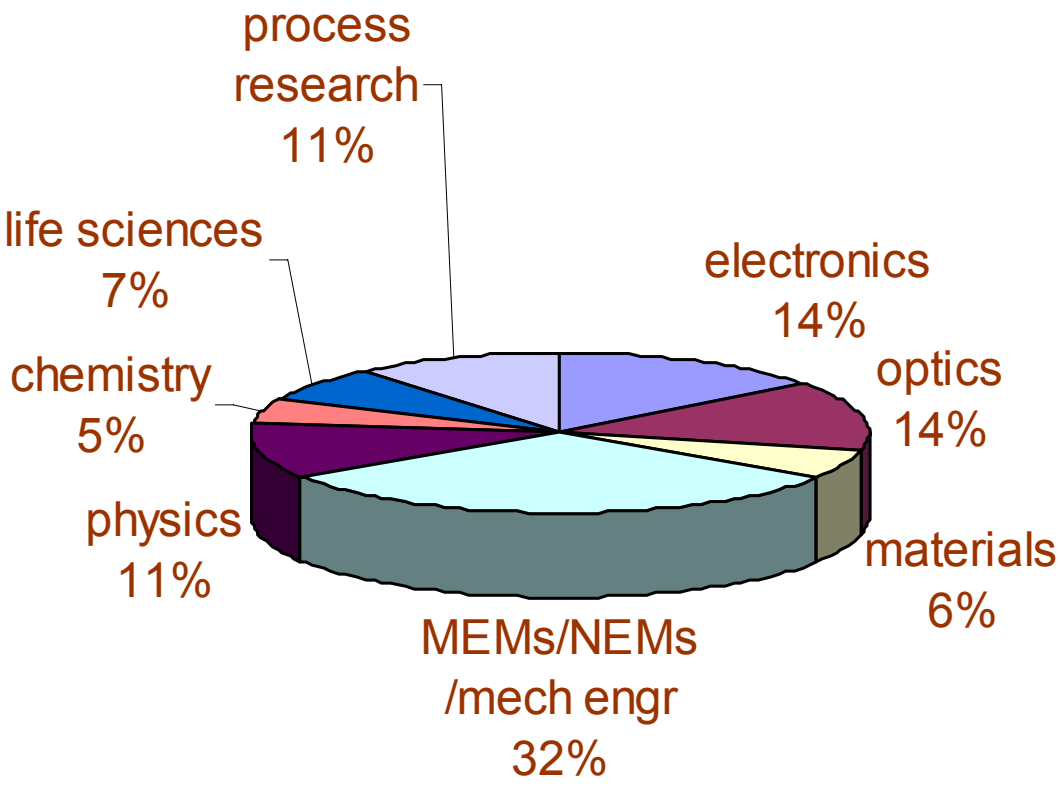
Areas of Research at SNF



data for calendar year 2004

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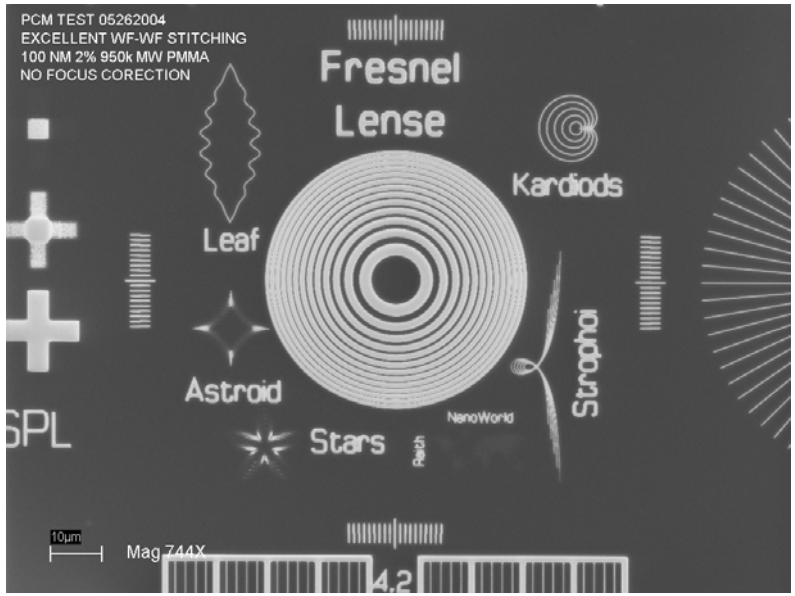
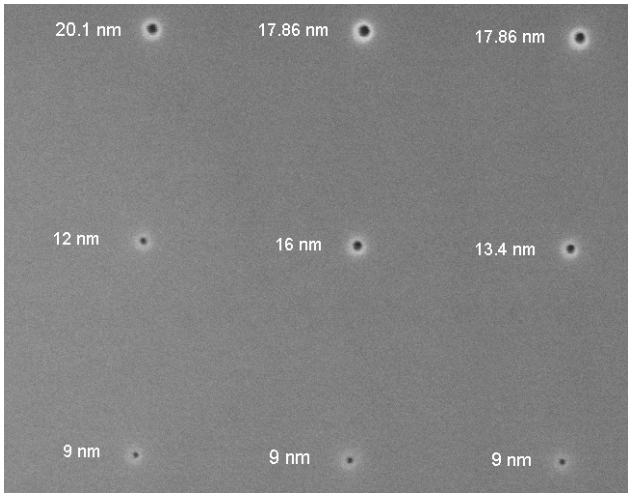
E-Beam Lithography Resources

- Hitachi HL 700F direct-write electron beam system.
  - medium throughput
  - resolution limited to ~150 nm
- Raith direct-write electron beam system.
  - low throughput
  - high resolution down to 10 nm



Raith resolution test pattern



9 nm holes imaged on Raith

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Optical and Imprint Lithography Resources

- optical steppers - Nikon body 4 and body 9 (5:1), two Ultratech 1000s (1:1)
- contact printers with backside alignment - two Karl Süss MA-6 systems, EV Group 620 aligner
- EV Group nano-imprint system
- in-house maskmaking - Micronic Laserwriter
- SVG spin/develop track, DNS spin/develop track, manual spinners
- suite of resist processes

Nikon Body 4

Nikon Body 9

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Etch Resources

Gasonics resist stripper

- silicon/poly etch - Lam Research TCP 9400
- nitride/oxide/silicon/polymer – Applied Materials 8100
- metals/oxide/nitride/silicon/resist strip - Applied Materials 5000 cluster tool.
- GaAs/films etch – PlasmaQuest ECR etcher.
- miscellaneous materials – three Drytek 100 etchers.
- resist strip – Matrix and Gasonics

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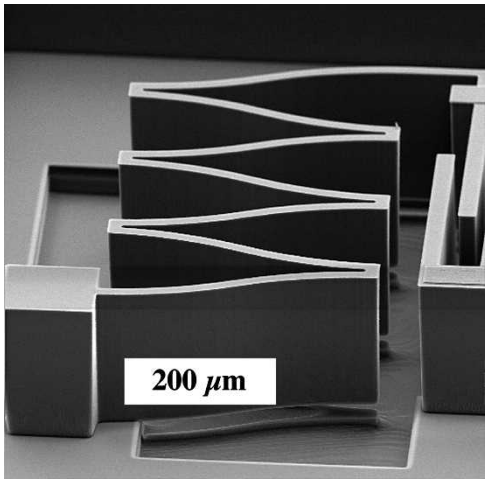
snf

MEMs Etch Resources

STS etcher



spring transducer
Klaasen, et al.,
Stanford

- deep silicon etch – two STS Multiplex ICP reactive ion etch systems.
- Xactix XeF_2 isotropic silicon etcher

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Thin Films Resources

- gate oxide growth
- LPCVD of poly, nitride,
- low temperature oxide
- low-stress nitride
- low stress PECVD of dielectrics
- AG4100, AG4108 rapid themal annealers
- 2 – AG210 rapid thermal annealers
- metal sputtering and evaporation - Cu, Al, AlSi, W, Ti, Au, Cr, Pt, NiCr
- sputtering of some dielectrics and ferromagnetic materials

AG4100 rapid thermal annealer

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Advanced Films Resources

home built atomic layer deposition system
for Al2O3

ASM Epsilon II single wafer epitaxial reactor
- silicon, silicon/germanium, germanium

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Analytical Tools

- scanning electron microscopes
  Hitachi S-800 – out of fab
  Hitachi 4160 – in fab
- Digital Instruments atomic force microscope
- Zygo optical profilometer
- ellipsometer, profilometers
- spectrophotometer
- resistivity mapping
- film stress gauge

Zygo optical profilometer

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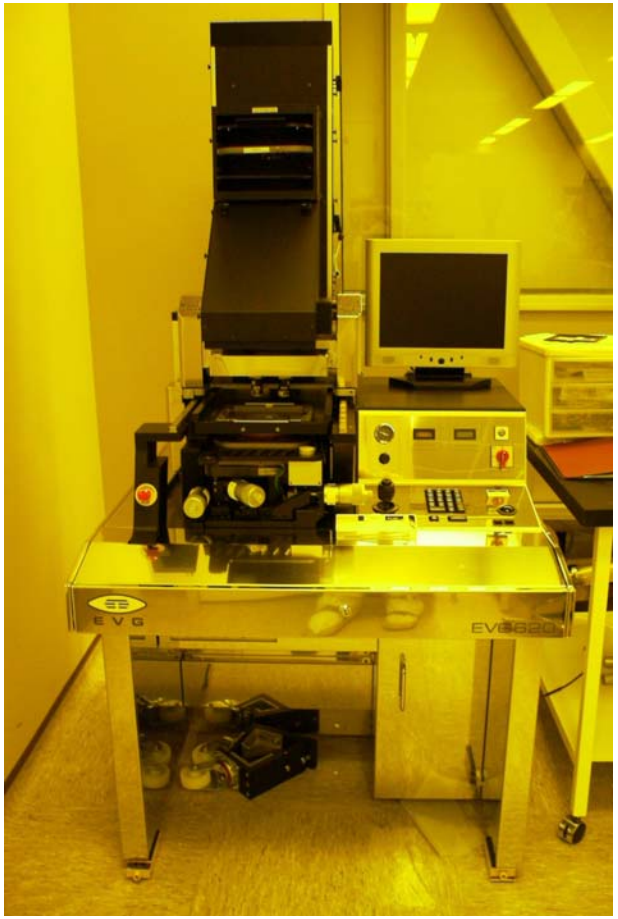
Miscellaneous Equipment

- wafer aligner/bonder - EV Group, Karl Süss
- Tousimis critical point dryer
- HF vapor etch
- thermal bonding
- wafer saw
- chemical mechanical polishing for dielectric materials



EVG 620 Nanoimprint system

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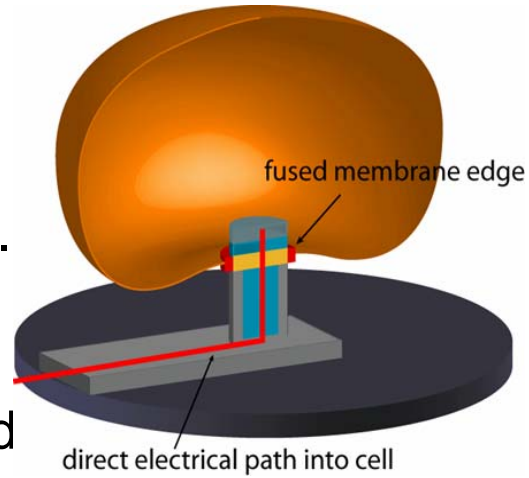
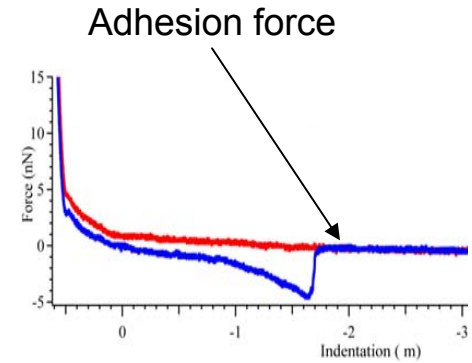
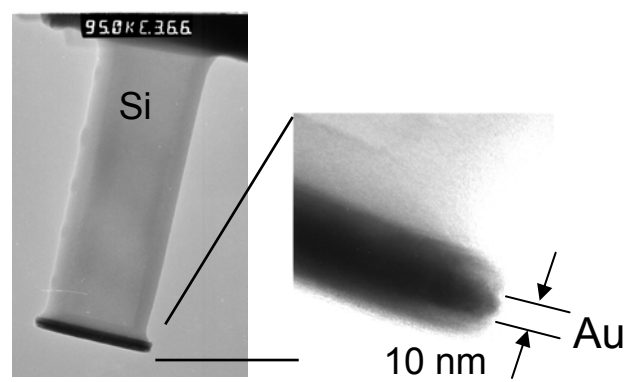
Integration of Electronics into Cells

- nanoscale-functionalized probes at the end of AFM cantilever tips that can directly integrate into a cell membrane.
- “stealth electrodes” do not cause membrane damage, and specifically attach to the core of the lipid bilayer.
- future work will involve fabrication of planar arrays of the devices for on-chip electrophysiological measurements.





AFM force measurements of the tip interaction with the bilayer.

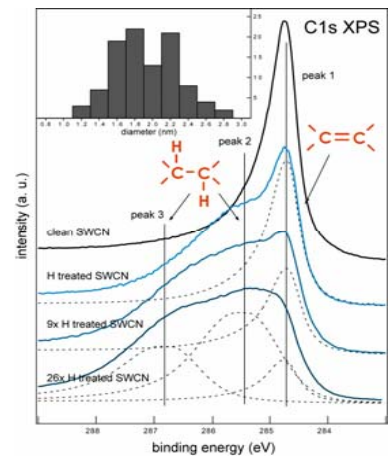


A nanoprobe tip.

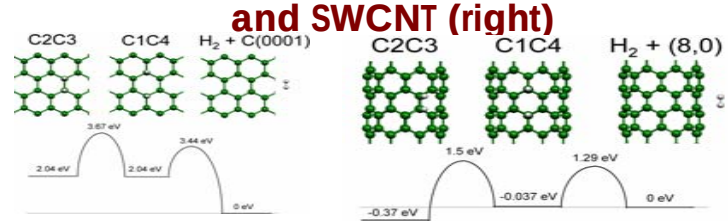
Professor Nicholas Melosh,
Department of Materials Science and Engineering, Stanford University

Hydrogen Storage in Carbon Nanotube Composite Material

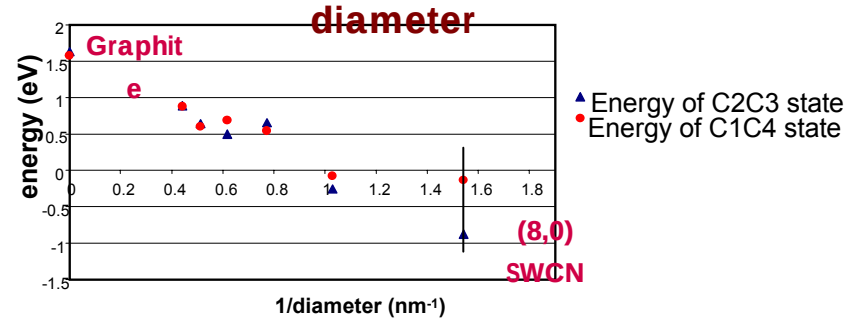
- carbon nanotubes can be hydrogenised to store up to 7% by weight of hydrogen, meeting the Department of Energy requirement.
- computational studies have determined the optimal hydrogenation/dehydrogenation pathways.
- this explains the experimentally observed optimal carbon nanotube diameter ranges for maximum hydrogen storage.



H desorption pathways on graphite (left) and SWCNT (right)



Dependence of energies on SWCNT diameter



Professor H.J. Dai, Chemistry, Professor Anders Nilsson, Photon Science, Professor K.J. Cho, Mechanical Engineering, Dr. Zhiyong Zhang, Chemical Engineering, and Anton Nikitin, Applied Physics, Stanford University

60 mV/decade Switching of Carbon Nanotube Transistors with Ultra-thin ALD High-k HfO_2 Dielectric

- 60 mV/decade switching of carbon nanotube transistors with an ultra-thin HfO_2 dielectric has been demonstrated.

- single wall nanotubes were functionalized with a coating of DNA necessary to achieve a uniform dielectric thickness of 2 to 3 nanometers.

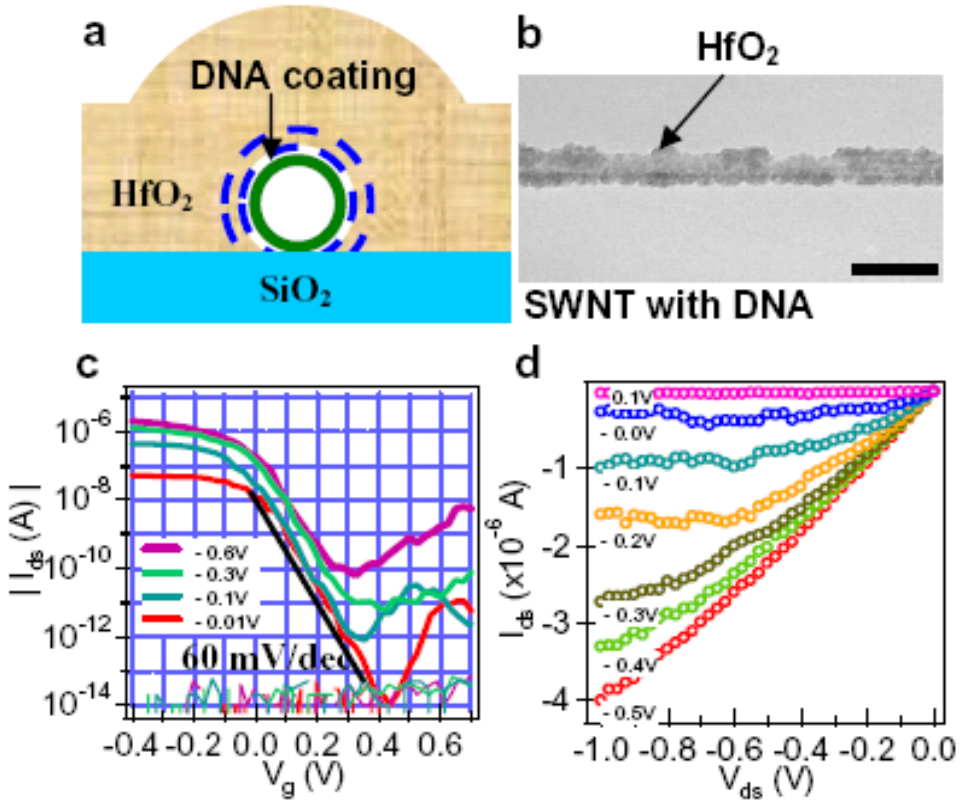
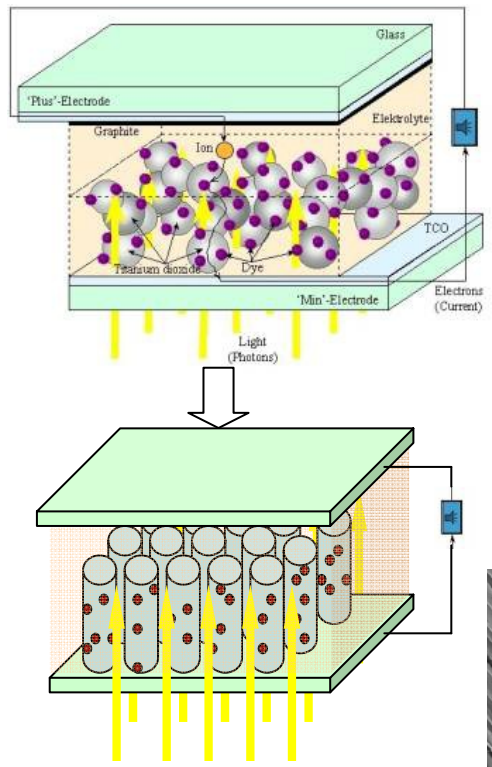


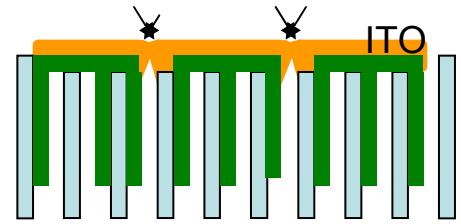
Figure . (a) A schematic of conformal HfO_2 coating on a DNA functionalized SWNT. (2) A TEM image. (c) Transfer characteristics of a SWNT FET (MOSFET-like, with contact regions P-doped by back-gating) with 2-3nm HfO_2 gate oxide. (d) I-V characteristic.

Professor Yoshio Nishi, Electrical Engineering, Professor H.J. Dai and Yuerui Lu, Chemistry, Stanford University

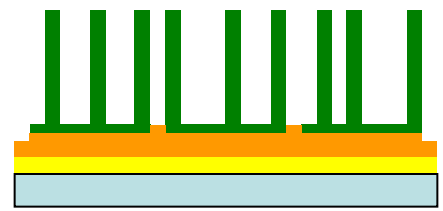
Nanowire Dye-Sensitized Solar-Cells

- nanowire arrays are used to provide a large collection surface area as well as the electrical conducting path to achieve a large surface area and low intrinsic resistance.
- this is one key to improving energy conversion efficiency.
- a fabrication method that minimizes grain boundaries in the nanowires to keep electrical resistance low has been developed.

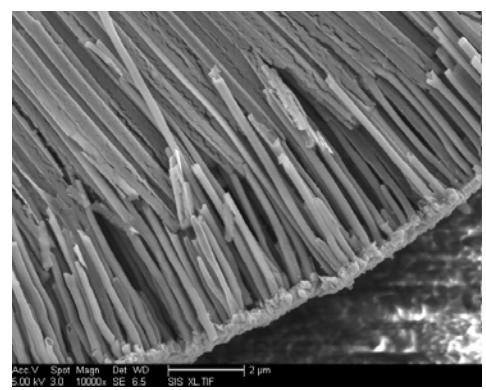




Sputtering ITO

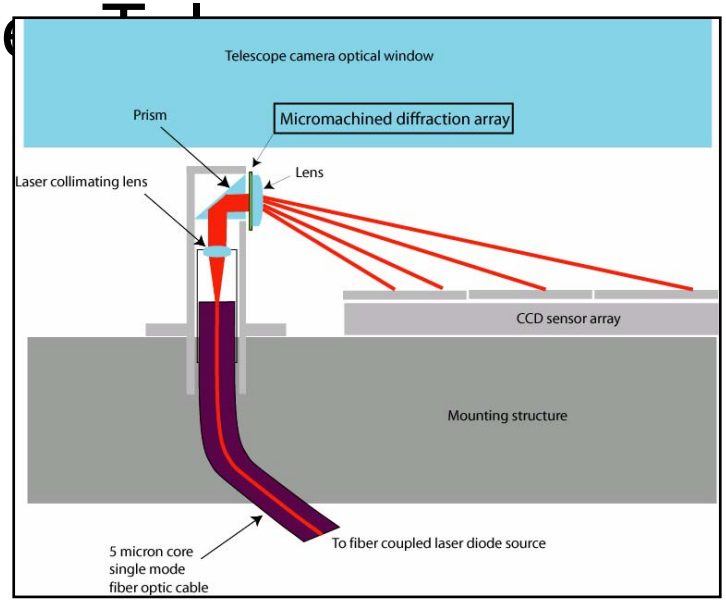


After Dissolving Template

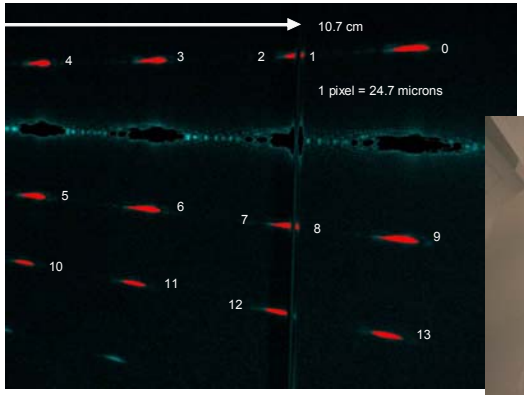


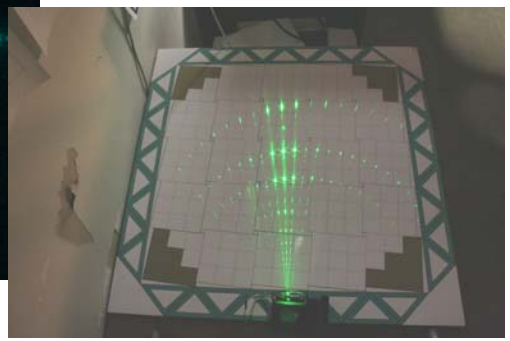
Professor Yoshio Nishi, and Ms. Ying Chen Electrical Engineering, Stanford University

Micromachined Diffractive Optical Element for the Large Synoptic Surve



- a diffractive optical element MEMs device to align the 201 CCD elements in the Large Synoptic Survey Telescope was fabricated.
- various prototype diffractive grids were fabricated using electron beam, laser direct-write and standard optical lithography and the best methodology was determined.
- this work was supported in part by a Center for Integrated Systems grant.

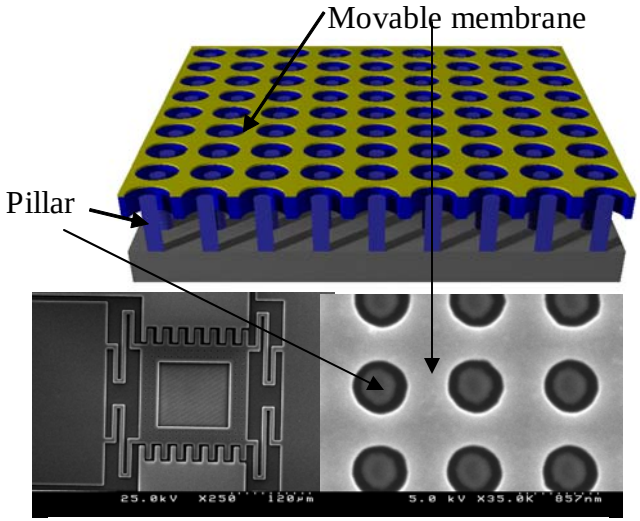


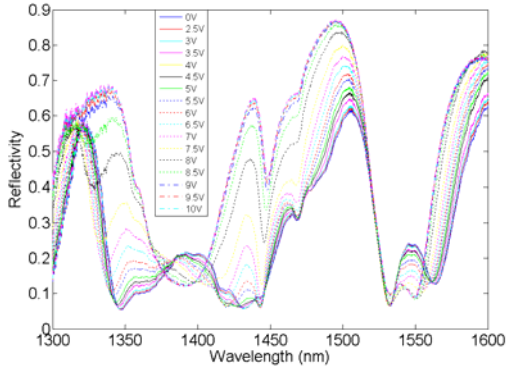


Dr. Chris Kenney, Molecular Biology Consortium, Professors Martin Perl and Rafe Schindler, Dr. Eric R. Lee, Stanford Linear Accelerator, Stanford, CA

New Structures Magnify Interfacial Effects in Photonic Crystals

- mechanically tunable photonic crystal displacement sensors have been developed.
- these devices are fabricated using SNF's epitaxial reactor.
- this is a breakthrough for fast crystal fabrication since single crystal, hydrogen anneal of these devices was possible.



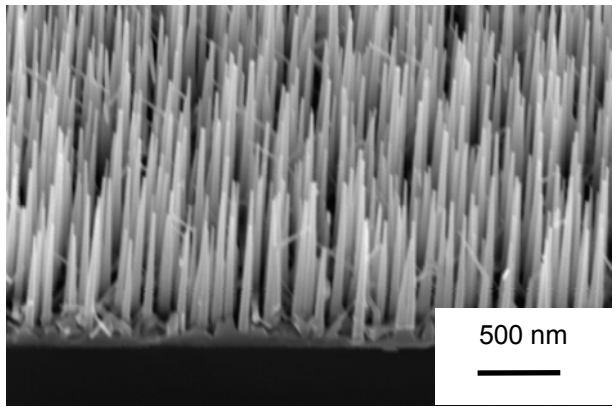


Gary Yama, Robert Bosch Corporation, Professor Tom Kenny, Mechanical Engineering, Professor Roger Howe and Dr. J. Provine, Electrical Engineering, Stanford University

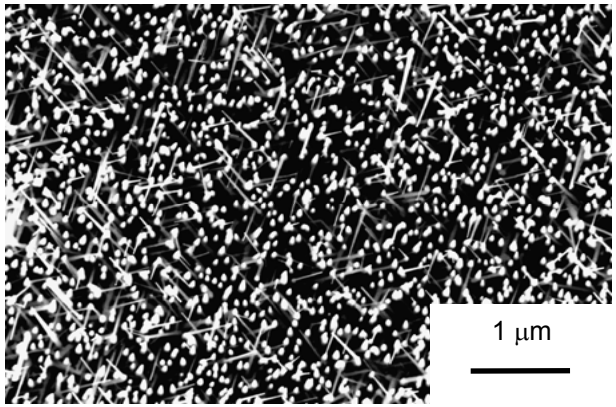
Controlling Nanowire Synthesis

Orientation Control

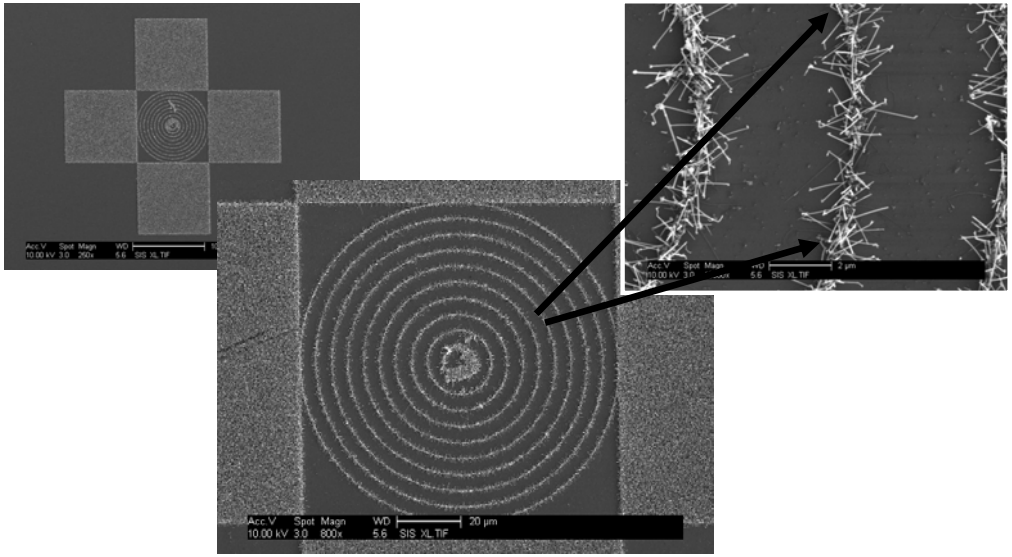
An array of ordered perpendicular germanium nanowires on silicon (111) surface



Cross section SEM



Plane view SEM

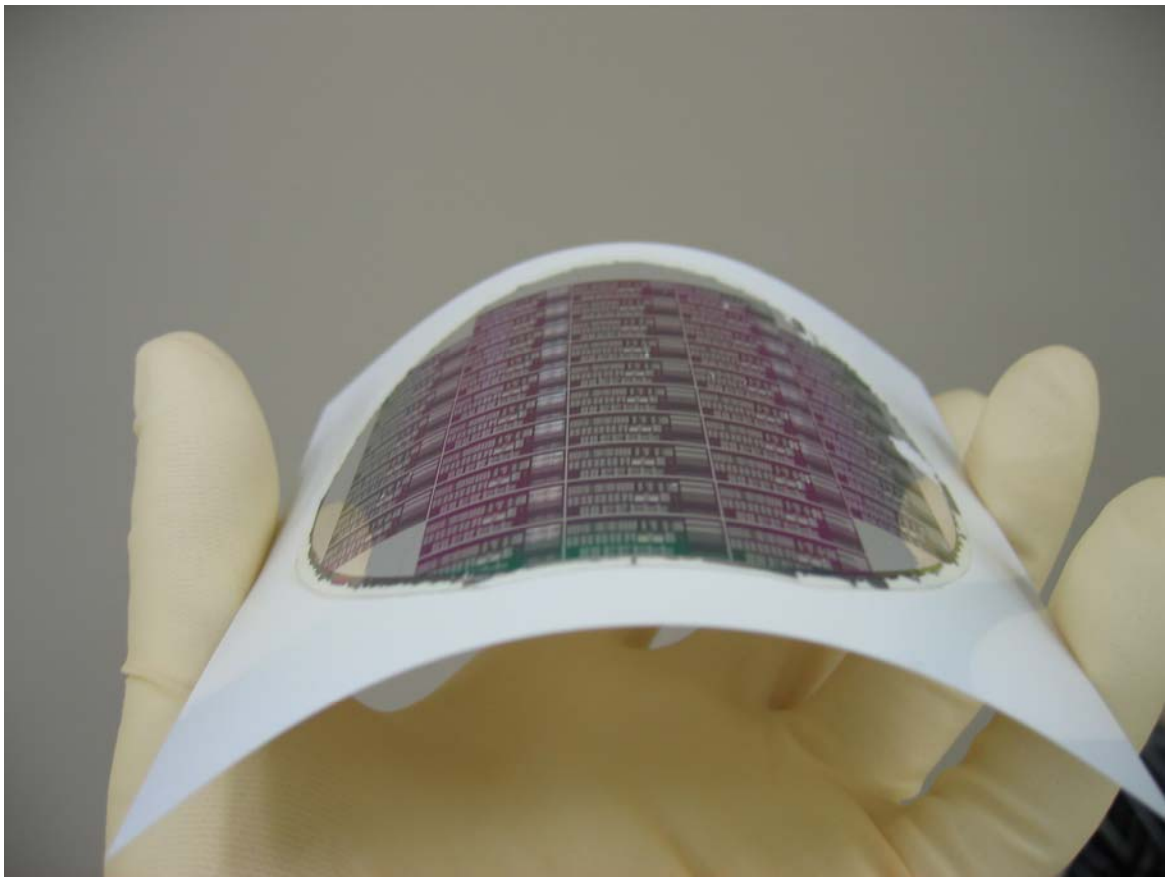


Position Control

Nanowires restricted to areas with patterned gold. Gold patterns defined using e-beam lithography and liftoff

H. Jagannathan, Yoshio Nishi,

Active device layer Transfer



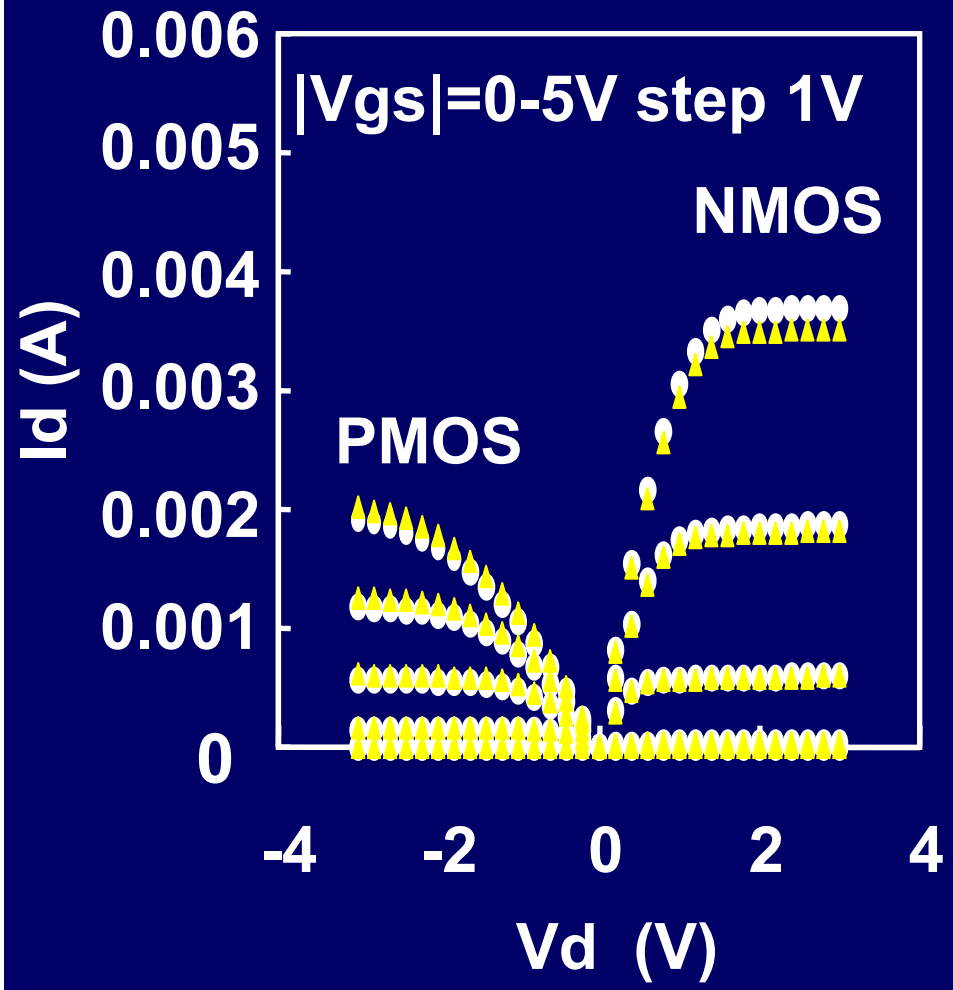
Sanda, McVittie, Nishi, IEDM05

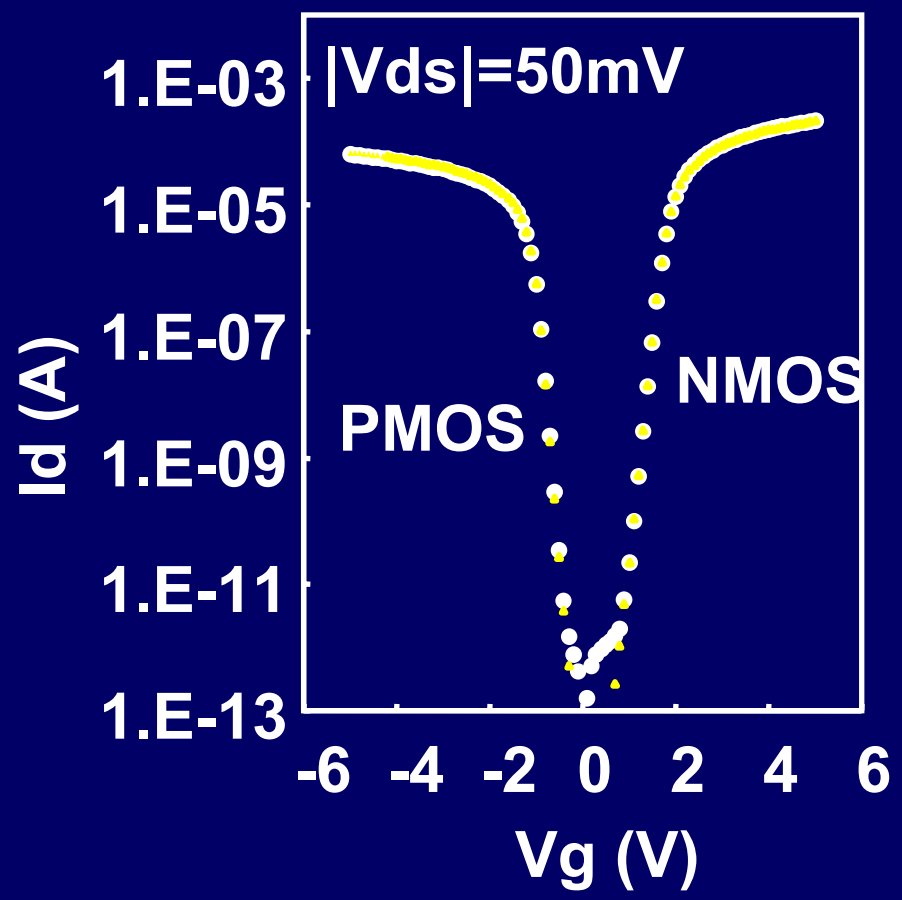
Id-Vd, Id-Vg before/after transfer

T_{epi}:1.5μm

• before transfer

▲ after transfer



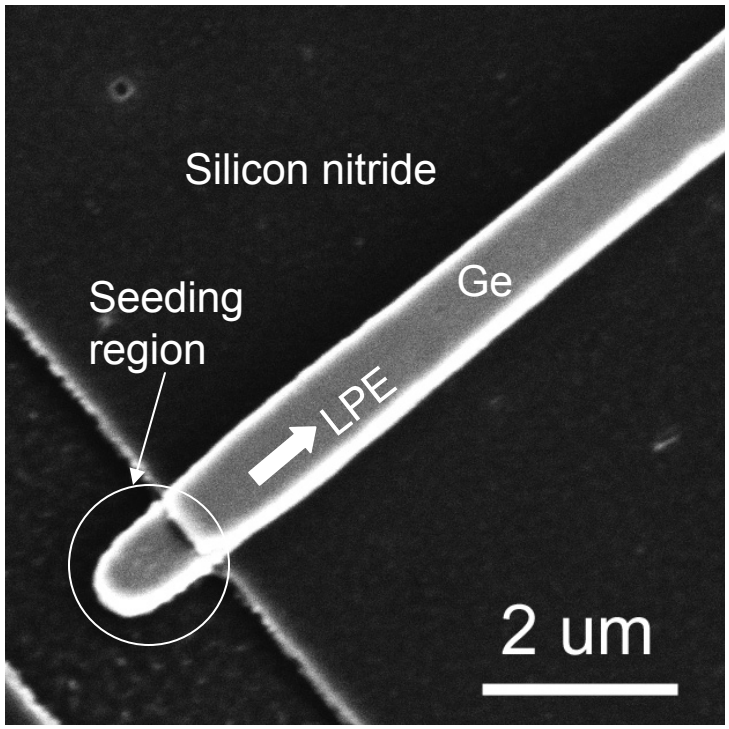


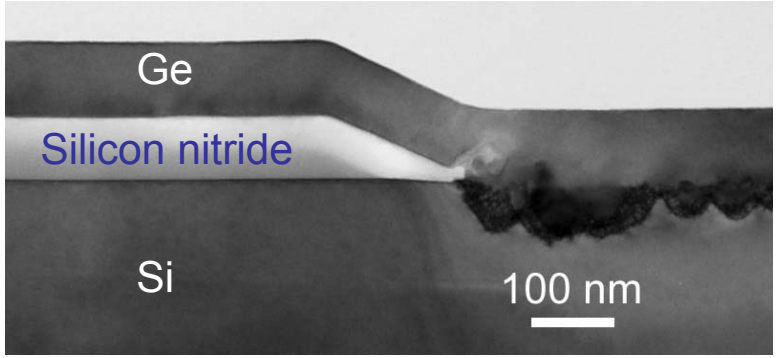
W/L=100 μm /10 μm

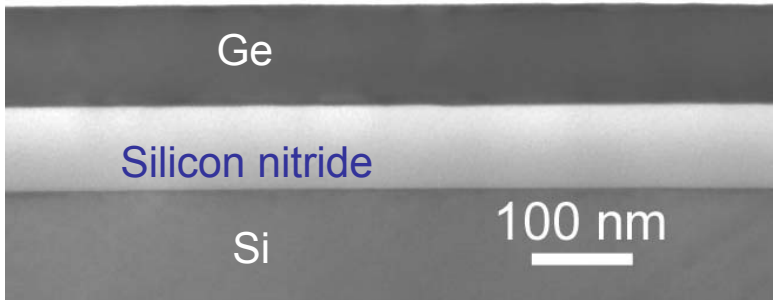
• DLT Research, H. Sanda, J. McVittie, Y. Nishi, IEDM05

Germanium on Insulator by Rapid Melt Growth

Yaocheng Liu and Professor James D. Plummer, Stanford



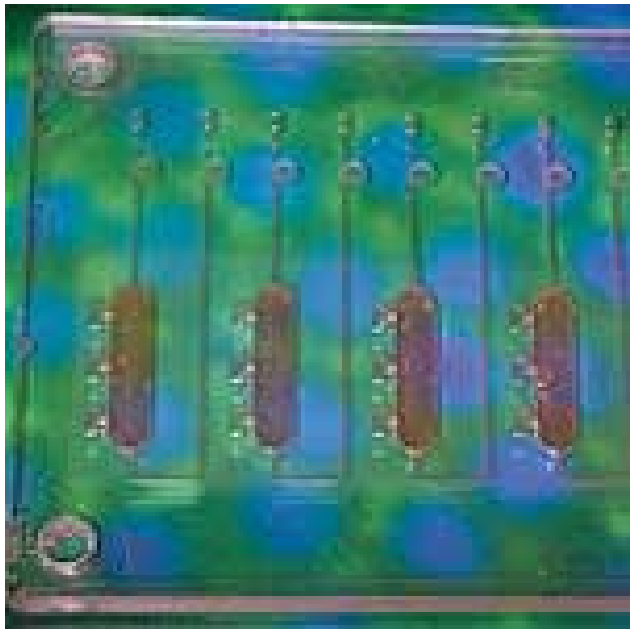


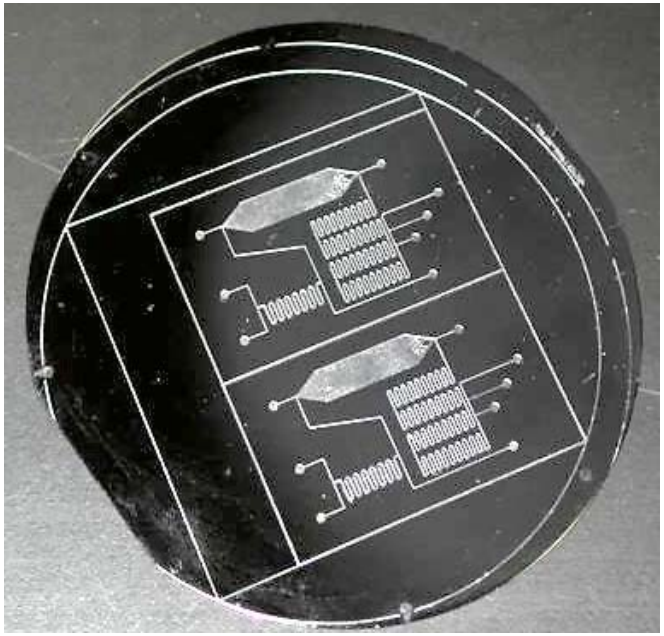


- more than 50μm long single crystal - large enough for multiple devices.
- the germanium film is relaxed and defect free in device regions.
- process is robust and repeatable and devices have been demonstrated.

Parallel Biopharmaceutial Process

Anne Heibel, Lawrence Fama, Neville Mehenti, Brett Schreyer, Andrey Zarur, BioProcessors Corporation



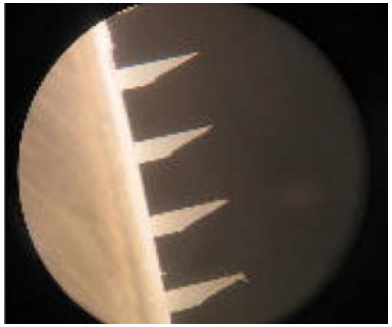


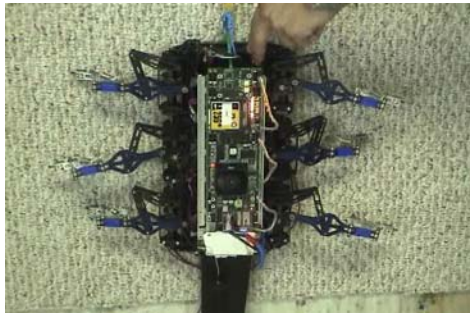
- scale up of protein drug manufacture is tedious and done by varying individual environmental conditions in cultures of increasing size.
- BioProcessors has developed microfermenters which can be used in parallel to manufacture drugs.
- they have reported optimization of production of an antibody in one month for $1M – this would typically take one year and $25M.

NNIN

Anisotropic Dry Adhesives for Climbing Robots

Aaron Parness and Professor Mark Cutkosky





- need to create a controllable adhesive force.
- difficult to detach once foot needs to move.
- adhesive stalks 1.4 mm high by 0.4 mm wide.
- considering carbon nanotubes for adherence to rough surfaces.

Outline

- National Nanotechnology Infrastructure Network
- Research Infrastructure at Stanford
- Areas of Research
- ***Future Challenges***
- Summary

Future Challenges

- How can such nanotechnology infrastructures keep upgrading their capabilities to fulfill even more demanding needs for better controlled environment for experimental research
- Technology transfer from/to
- Progressive flow of prototyping to larger “manufacturing” like environment
- Broader multi-disciplinary collaborations

Summary

- Nanotechnology opportunities have quite a large range in terms of application areas, timelines and risks involved
- Relatively low hanging fruits do exist in non-traditional areas
- Large potentials in Nano-MEMS and bio-Nano
- It will require break-through improvement in “engineering aspect” for possible integration with existing Si-based CMOS integrated circuits applications
- NNIN and a variety of university owned infrastructures have contributed a lot for nanoscience and engineering research, and productization of new ideas
- Multidisciplinary and global collaborations are essential