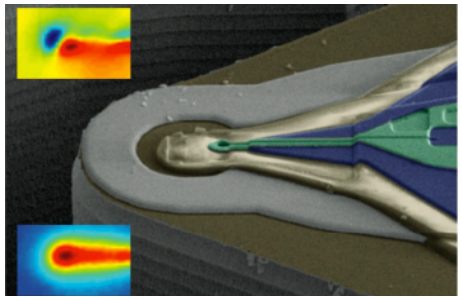
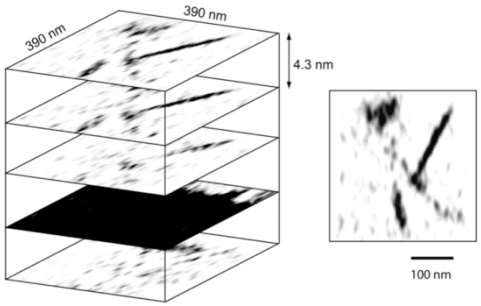
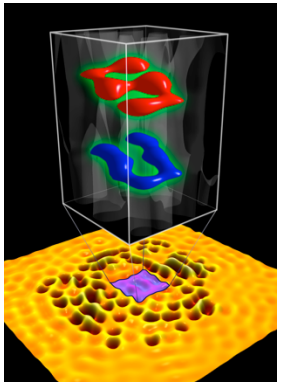
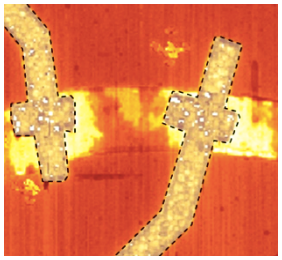
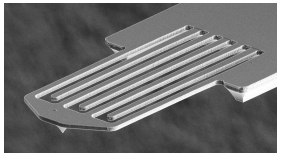
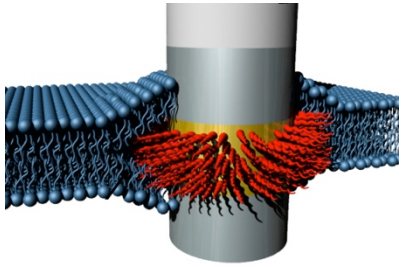
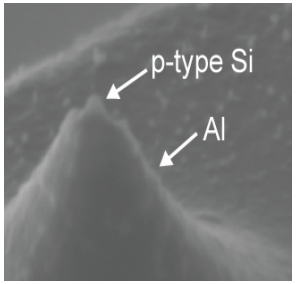
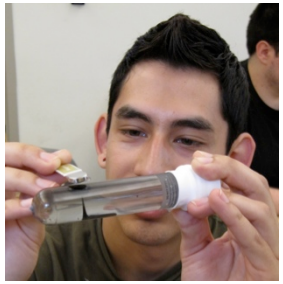
CPN
An NSF Nanoscale Science and Engineering Center



Stanford NSEC Reverse Site Visit Open Session

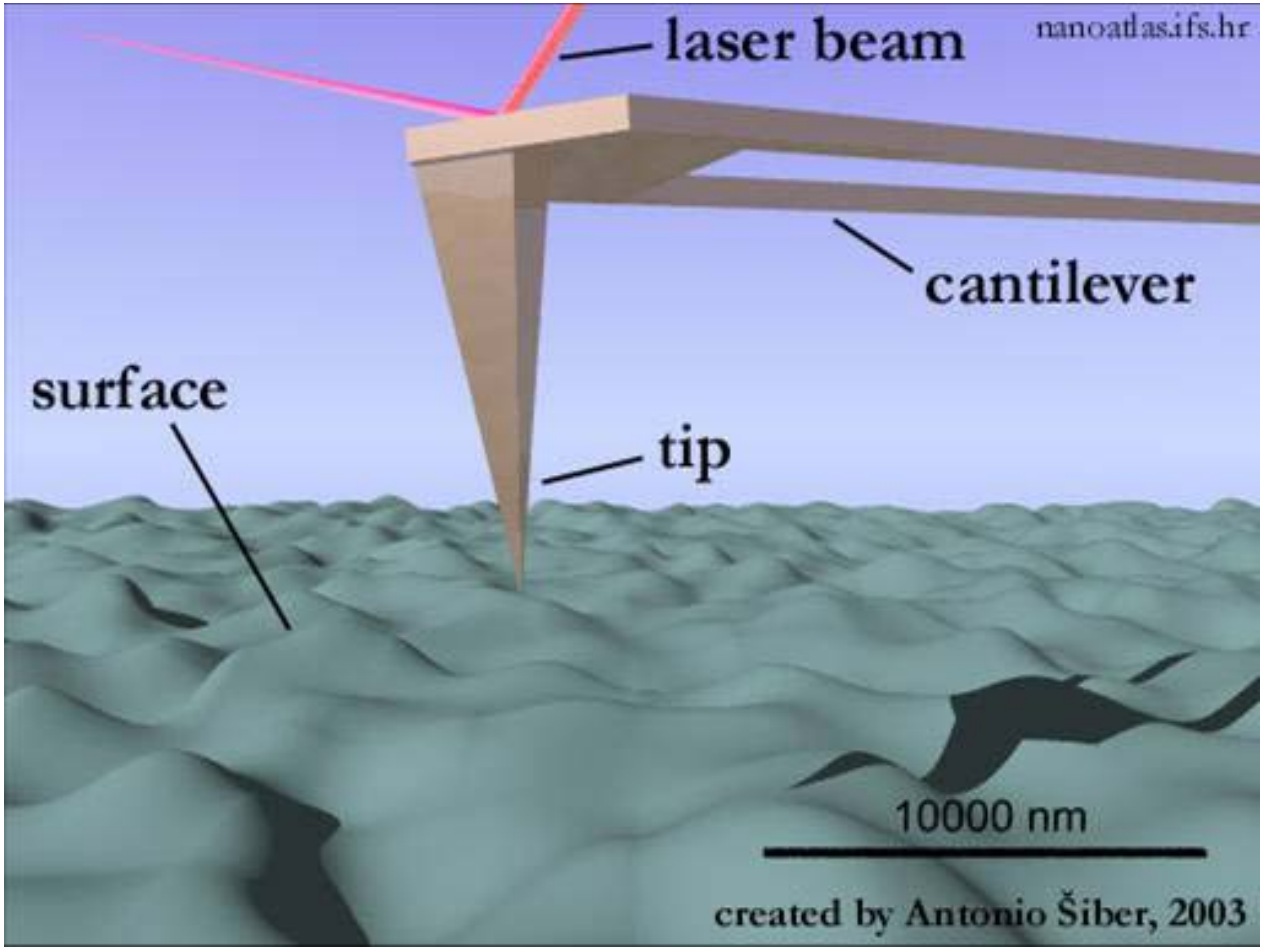
Washington DC, June 10, 2013

CPN is supported by the National Science Foundation under Award PHY-0830228

Overview of Center Activities

Nick Melosh
CPN Deputy Director
Bio-Probes Theme Leader

The Scanning Probe Concept



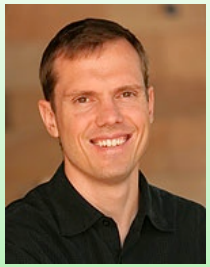
About the Center for Probing the Nanoscale

Goals

- ***To develop novel probes*** that dramatically improve our capability to observe, manipulate, and control nanoscale objects and phenomena.
- ***To educate*** the next generation of scientists and engineers regarding the theory and practice of these probes.
- ***To apply these novel probes*** to answer fundamental questions and to shed light on technologically relevant issues.
- ***To disseminate*** our knowledge and to transfer our technology so that other research scientists and engineers can make use of our advances, and so that corporations can manufacture and market our novel probes.
- ***To inspire*** thousands of middle school students by training their teachers at a Summer Institute.

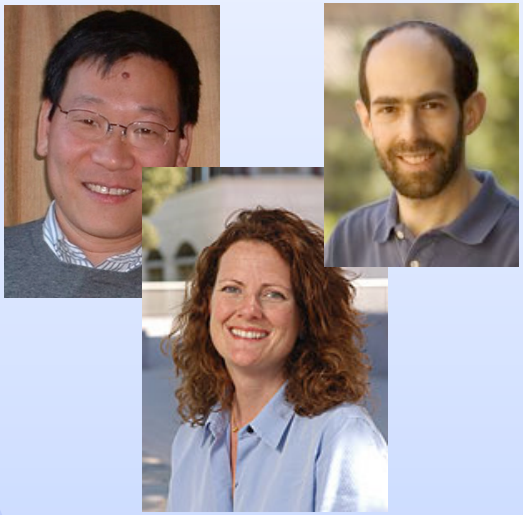
The CPN Team

D. Goldhaber-Gordon


N. Melosh

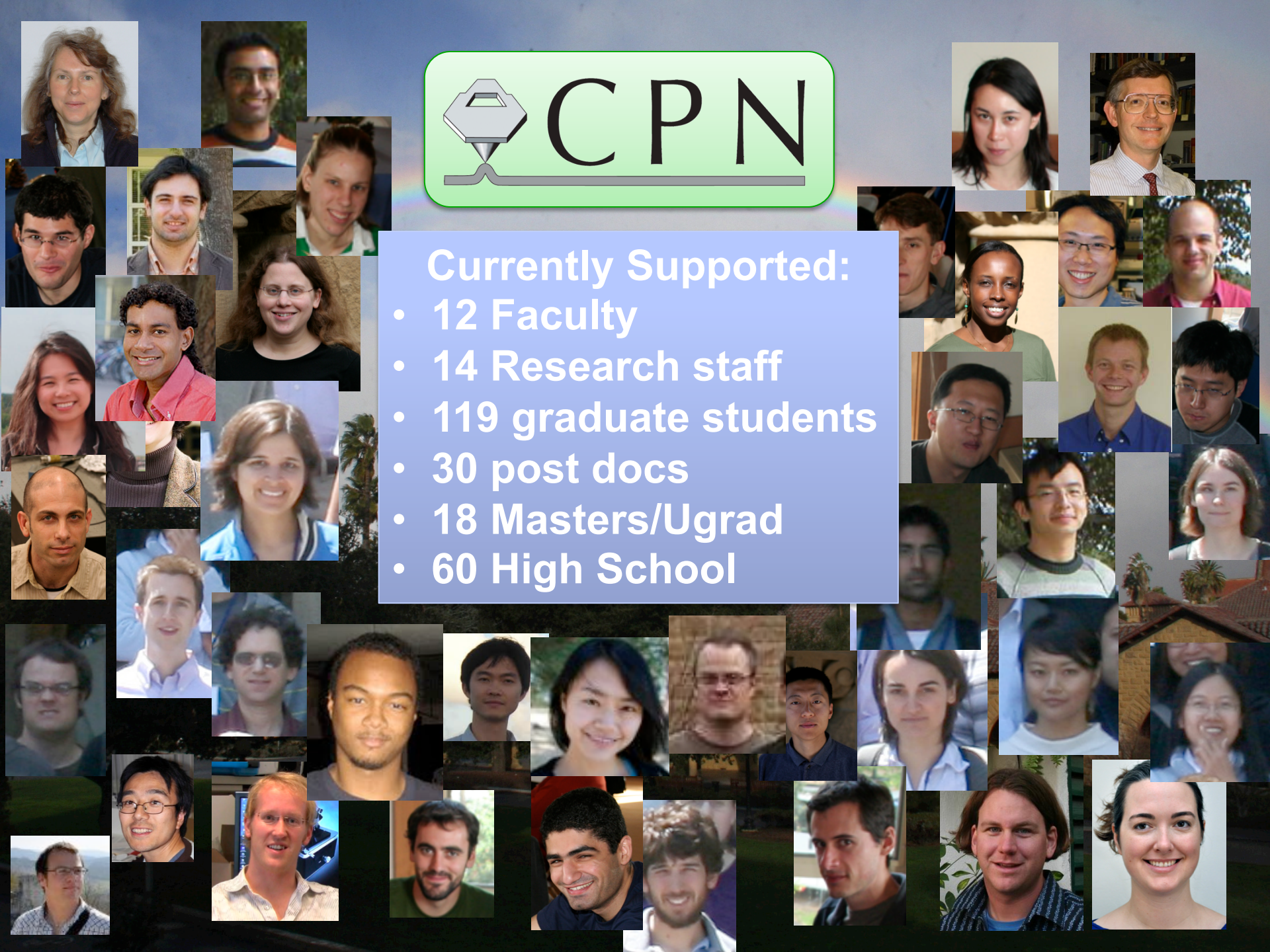
M. Wang

NanoElectronic



NanoMagnetic

NanoBio


CPN
Currently Supported:
• 12 Faculty
• 14 Research staff
• 119 graduate students
• 30 post docs
• 18 Masters/Ugrad
• 60 High School

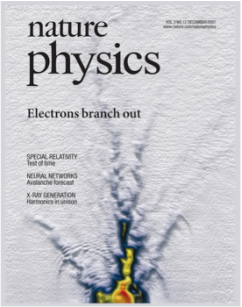
Center Activities

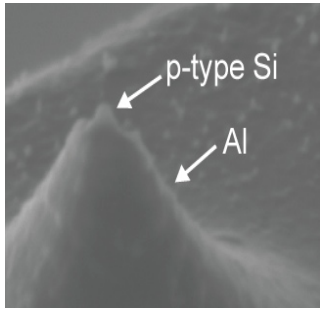
Scientific theme groups

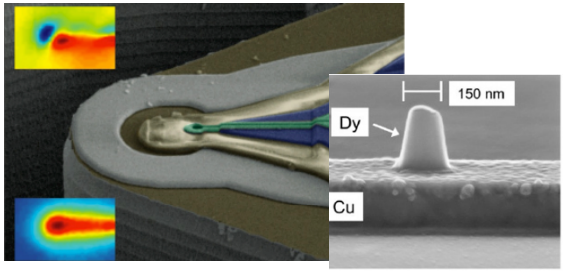
- **Nanoelectric**: Measure electronic properties of materials at the 10-nm scale.

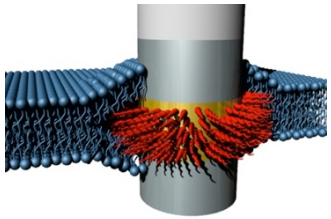
- **Nanomagnetic**: Magnetic sensitivity and spatial resolution for nanomagnet characterization. Molecular structure microscope with chemical sensitivity.

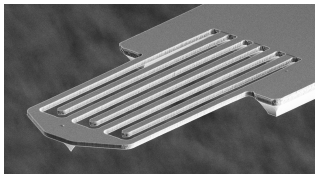
- **Bio-Probes**: Measure forces, mechanical properties and dynamics of biological membranes with critical resolutions of pN, nanometers and microseconds.







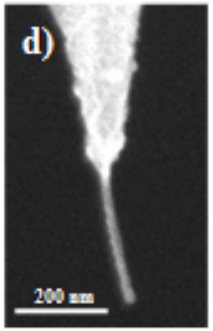


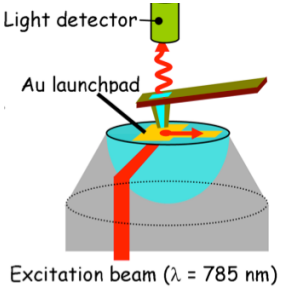


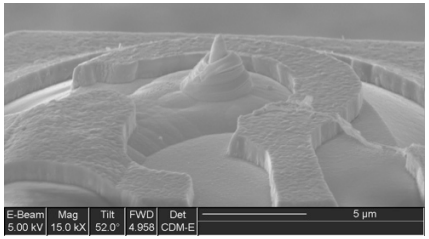
- ***Education and outreach programs*** that translate research into classrooms and that reach a diverse audience, mainly through the Summer Institute for Middle School Teachers.
- ***Seminars and workshops*** to support cross-theme interaction and increase industrial participation.
- ***Courses and professional development workshops*** for students and postdocs.

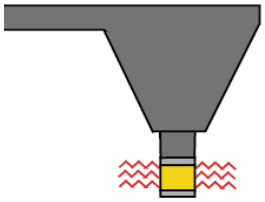
CPN Nanoprobe Development

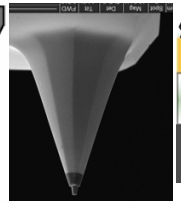
- >20 research projects
- Force microscopy (e.g., AFM, MFM, MRFM)
- Photonic near-field microscopy (e.g, NSOM, MIM)
- Quantum mechanical probes (e.g., STM, nanoSQUID)

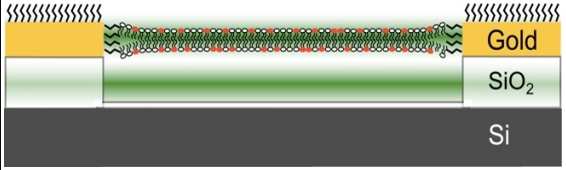


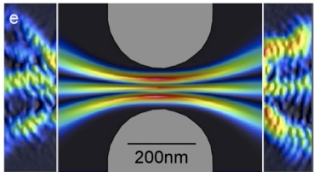


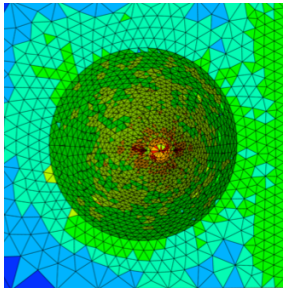


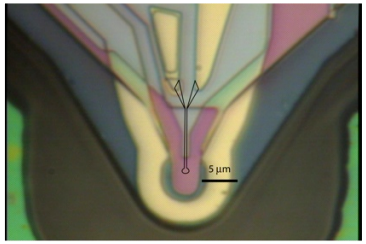


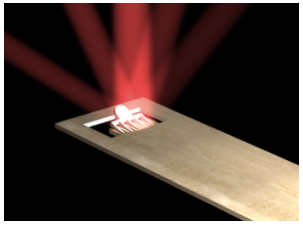


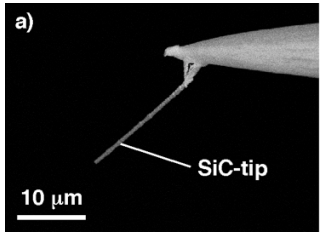


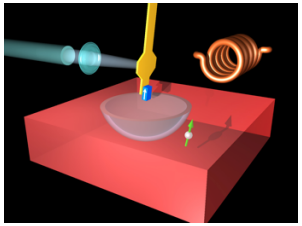


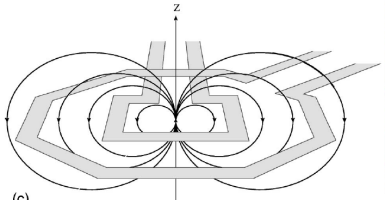


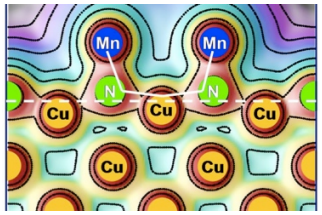


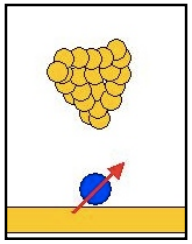


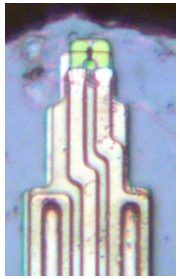


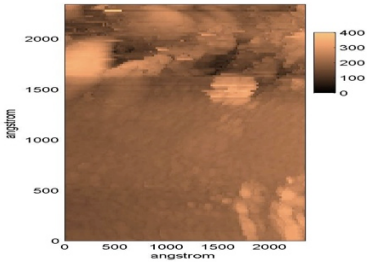


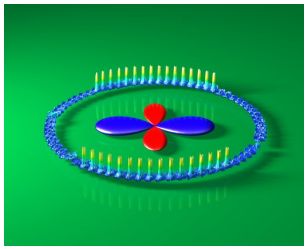








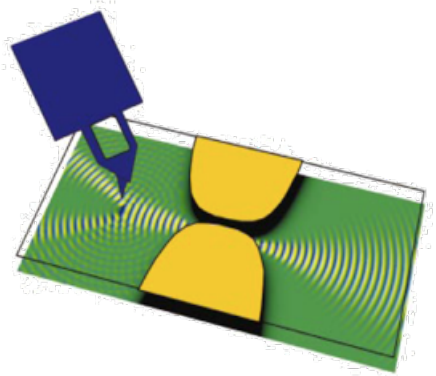


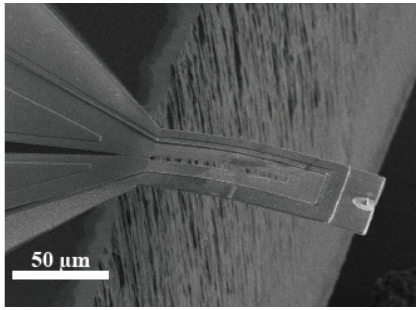


Breadth and Depth of Nanoprobe Science

- Magnetic Resonance Force Microscopy
- Electron Spin Resonance - STM
- Theory of Nanoscale Magnetism
- Scanning SQUID Microscopy
- Scanning Hall Probe Microscopy
- Magnetic Force Microscopy
- Sagnac Microscopy
- Spin Injection
- Scanning Probe Suite for Trace Superconductivity
- Current Imaging with MFM
- NV Centers for nanoMRI
- Optical probes for near-field microscopy
- Scanning Tunneling Potentiometry
- Scanning Gate Microscopy
- Microwave Microscopy
- Raman NSOM
- Dip-Pen nanolithography
- Bowtie Antennas
- Coaxial tip piezoresistive cantilevers
- Coupled Resonator Atomic Force Microscopy
- Modeling Time-Resolved Interactions
- Nanowires for Electrochemical Microscopy
- Biomolecular δ-functionalized probes
- Fluorescence Interferometry
- Coupled Resonator Atomic Force Microscopy
- Cell penetrating peptide mechanical probes
- T-cell receptor probes

Nanoelectric Activities and Intellectual Merit





Activities

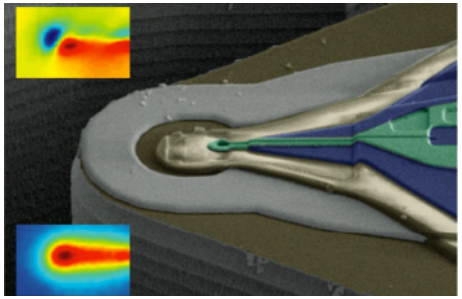
- **Scanning Gate Microscopy** (SGM) to study local charge transport in graphene, complex oxides, and topological insulators.
- **Scanning Microwave Impedance Microscopy** (MIM) to study electronic phase transitions in manganites, 2DEG systems, topological insulators, and ferroelectrics.
- Fabrication of **dual-function, shielded DC/microwave probes** for SGM/MIM

Intellectual Merit

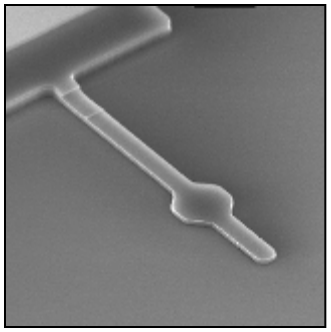
- *Condensed Matter Physics* – Visualize spatial inhomogeneity accompanying electronic phase transitions, study electron scattering mechanisms
- *Nanoelectronics* – Associate device performance with spatial distribution of functional material components (dopants, dielectrics, …)
- *Material Science* – Characterize nanoscale materials in various forms and/or modify the structure with local electric fields
- *Energy* – Probe local ionic vs electronic conduction
- *Biology* – Provide detailed information on different parts of cells/tissues

Nanomagnetic Activities and Intellectual Merit

Activities



- **Scanning Superconducting Interference Device (SQUID) Microscopy**: Extremely sensitive instrument for imaging local magnetic fields.
- **Scanning Sagnac Microscopy**: Interferometric technique for magneto-optic imaging based on the polar Kerr Effect.
- **nanoMRI**: Chemically specific 3D imaging of molecular structures using magnetic resonance force microscopy and nitrogen-vacancy (NV) centers in diamond.



Intellectual Merit

- World-leading sensitivity at low fields
- Improve and extend applications of individual nanomagnets of importance for biotechnology
- Determine molecular structure of proteins that are too large for conventional NMR spectroscopy → understand biological structure and function
- Exploration of new contrast mechanisms

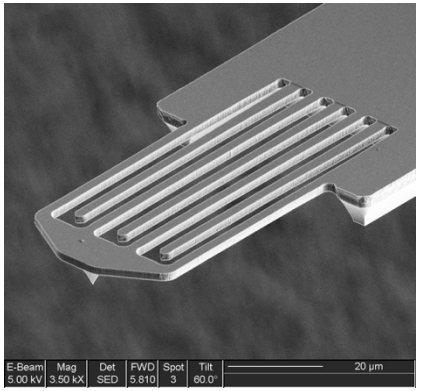
Bio-Probe Activities and Intellectual Merit

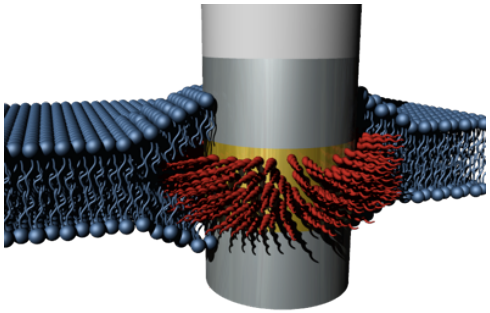
Activities

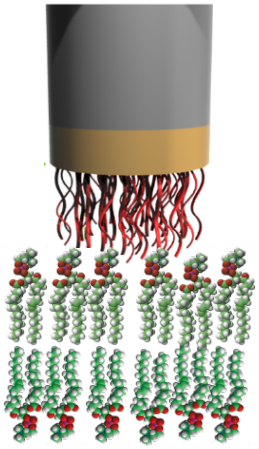
- Fabrication of high-bandwidth, interdigitated AFM probes as **ultrafast sensors**
- Bio-functionalized **"stealth" probes** for insertion into lipid bilayer membranes
- Application of these probes for **T-cell receptor mapping**

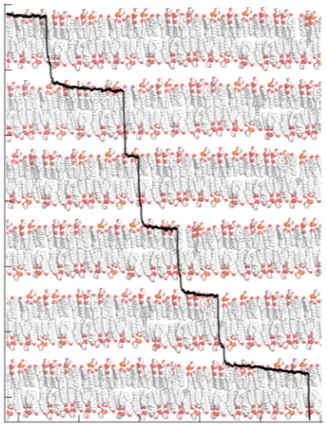
Intellectual Merit

- Understanding biological processes via high-resolution and rapid detection of cell surface events and materials properties
- Insight on designing improved cell-entry agents for drug delivery
- Stimulation and characterization of T-cells to understand immune activation









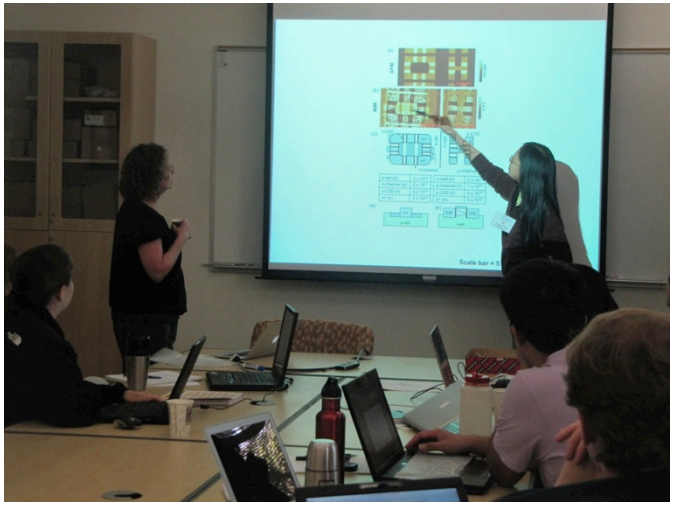
Education and Outreach

- ***To educate*** the next generation of scientists and engineers regarding the theory and practice of these probes.
- ***To disseminate*** our knowledge and to transfer our technology so that other research scientists and engineers can make use of our advances, and so that corporations can manufacture and market our novel probes.
- ***To inspire*** thousands of middle school students by training their teachers at a Summer Institute.

Overview of Education & Outreach Programs

Stanford Education and Mentoring

- Curriculum
  - Probing the Nanoscale (Graduate, AP275)
  - Tools of Nanotechnology (Undergraduate, AP78)
- CPN Fellows enrichment
  - Theme meetings and seminars
  - Industry seminars and field trips
  - Professional development workshops



Community Outreach

- Summer Institute for Middle School Teachers
- Partnerships with formal and informal science education institutions
- Public events for K-12

Annual Nanoprobes Workshop

Industrial Partnerships

Nanoscale Electrical Imaging

Agilent
Asylum Research
Formfactor
Park Systems
Veeco

Nanomagnet Characterization

Asylum Research
Attocube
Park Systems
Texas Instruments

Bio-Probes

Agilent
Asylum Research
Park Systems

Agilent Technologies

attocube systems
explore your nanoworld

Park Systems

Asylum Research
Atomic Force Microscopes

Texas Instruments

Spin-off Companies

Start-up companies founded by CPN researchers

- PrimeNano, Inc. (Mike Kelly)
  - Developing a production version of a Microwave Impedance Microscope system that can be used on existing Atomic Force Microscopes
  - Holds two exclusive licenses from Stanford
- Solum, Inc. (Nick Koshnick)
  - Makes a field-deployable sensor to give farmers immediate answers on soil nutrient needs
- Alion, Inc. (Mark Topinka)
  - Formerly SunPrint, Inc., founded with the goal of making cheap solar cells
- C3Nano (Melbs LeMieux)
  - Developing solution-coated, transparent conductive materials to replace indium tin oxide
- Stealth Biosciences, Inc. (Nick Melosh)
  - Commercializing solid-state patch clamps based on the stealth probe architecture

CPN's Impact on Stanford

- Demonstrated the importance of tool development for scientific research
- Former CPN Director, Kam Moler, and current CPN Director, David Goldhaber-Gordon coordinated the development of the Stanford Nano Center Shared Facility

"*Shared facilities that offer access to state of the art scientific instruments are an essential resource for Stanford's faculty and students*," -- Ann Arvin, Vice Provost and Dean of Research

- Kam Moler and former CPN Associate Director, Tobi Beetz, are now the Director and Associate Director, respectively, of the SNC
- Establishment of a nanoresearch community
- Opportunities to engage with the public through SIMST and other outreach events

NSEC accomplishments since the start of the renewal award and impact on the institution

Beth Pruitt
CPN Investigator, Nanoelectric Theme

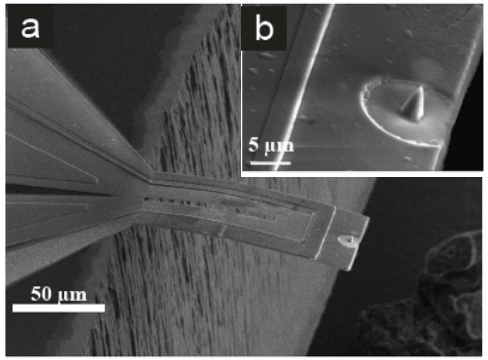
Center Outputs

From March 2009 to March 2013:

- 76 peer-reviewed journal publications
- Patents: 5 filed, 3 awarded, 1 licensed
- 5 spin-off companies
- Highlights at http://www.stanford.edu/group/cpn/about/nuggets.html

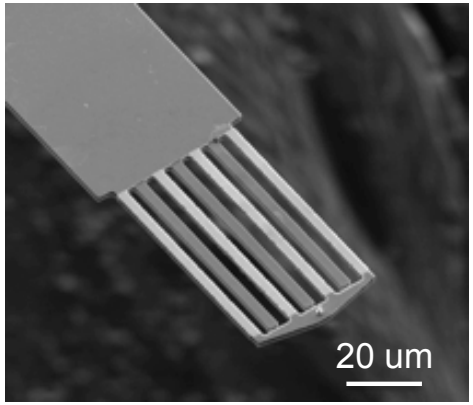
Key Research Accomplishments

- *Nanoelectric*: Coaxially shielded probes with integrated piezoresistor

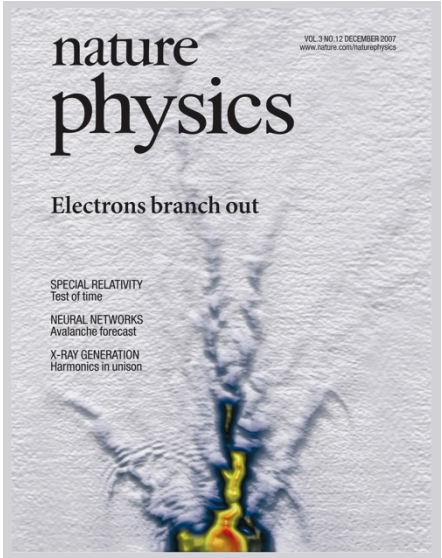


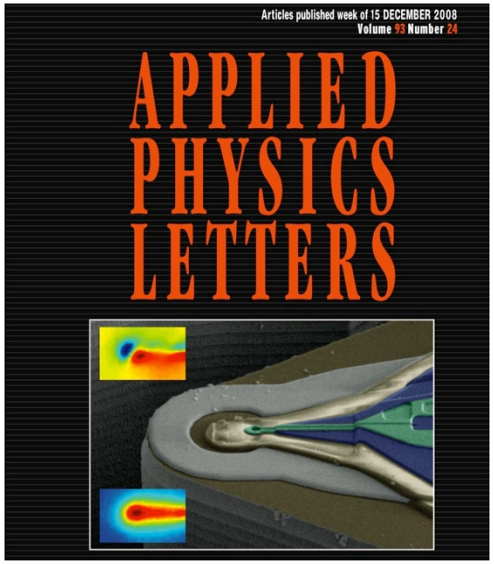
- *Nanomagnetic*: Ultrasensitive SQUID sensors

- *Bio-Probes*: Dual-cantilever probes for ultrafast detection of mechanical properties



Selected CPN Covers

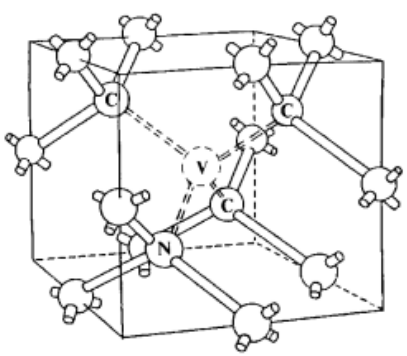


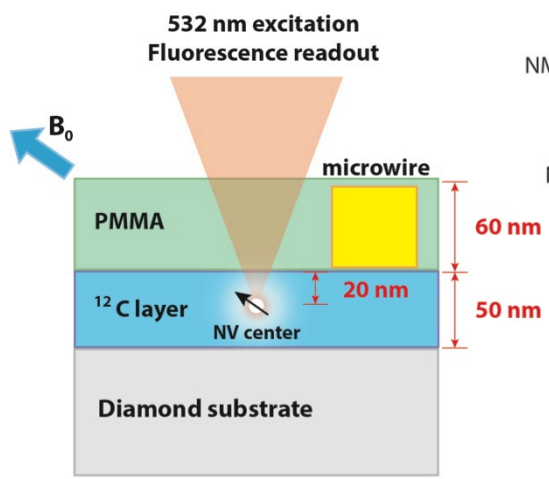


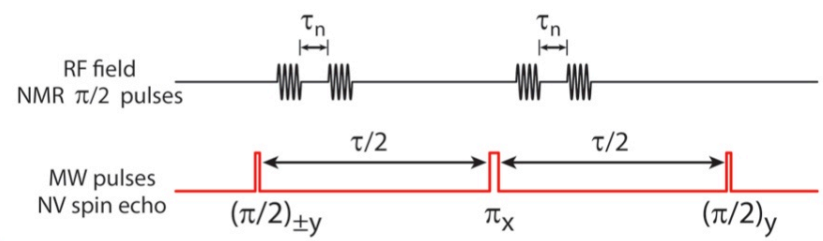
Nitrogen-Vacancy Centers in Diamond for Nano-MRI

- NV centers in diamond are atomic-scale defects with a spin state that can be manipulated by microwave pulses and read out via optical fluorescence
- The spin has remarkably long coherence times, leading to the ability to perform sensitive magnetometry using spin echo techniques
- Demonstrated use of single NV centers to detect nanotesla-field fluctuations from protons in a sample external to the diamond

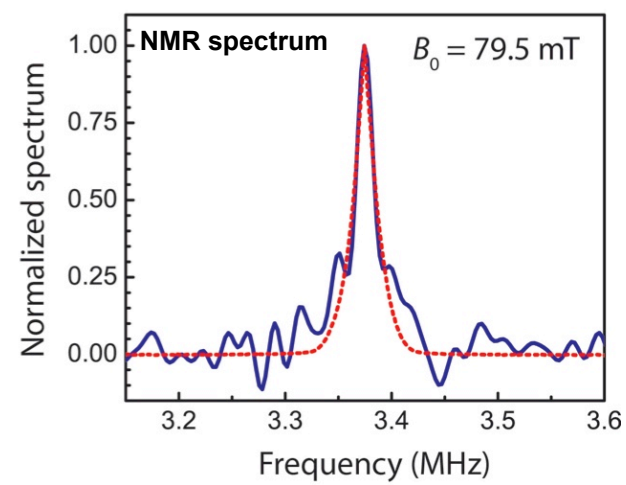
Nitrogen-Vacancy structure







The detection uses an electron spin – nuclear spin double resonance method with optical fluorescence readout.

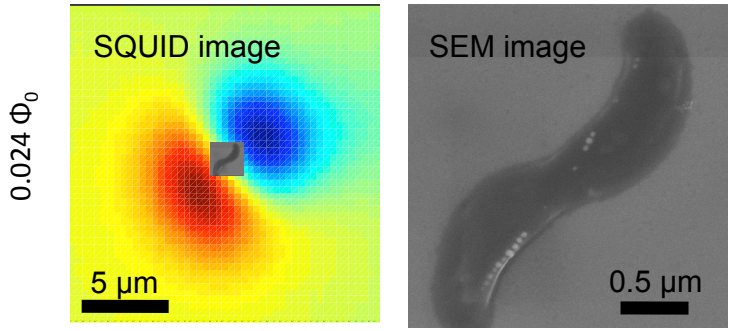


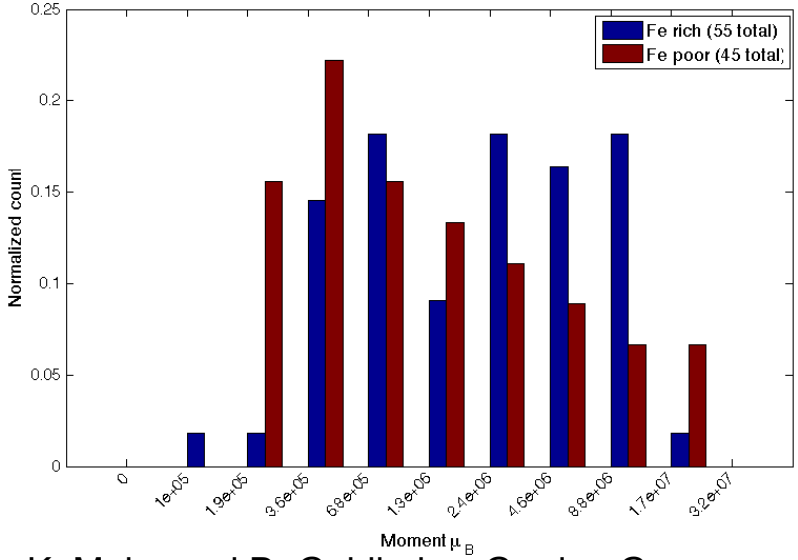
IBM

H.J. Mamin, et al, *Science* 339, 557-60 (2013)

Biological and Physical Applications of Scanning SQUID Microscopy

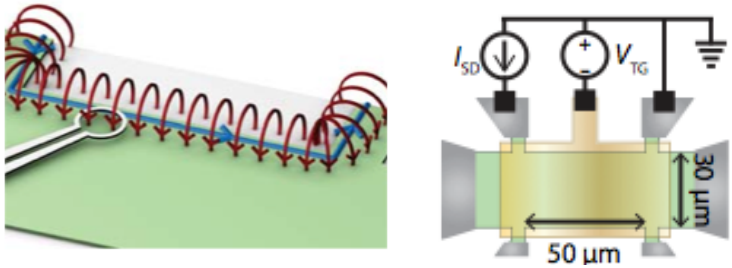
Quantitative analysis of magnetic moments of individual magnetotactic bacteria for biotechnology/MRI applications. On average the magnetic moments are larger for bacteria grown in Fe-rich medium.

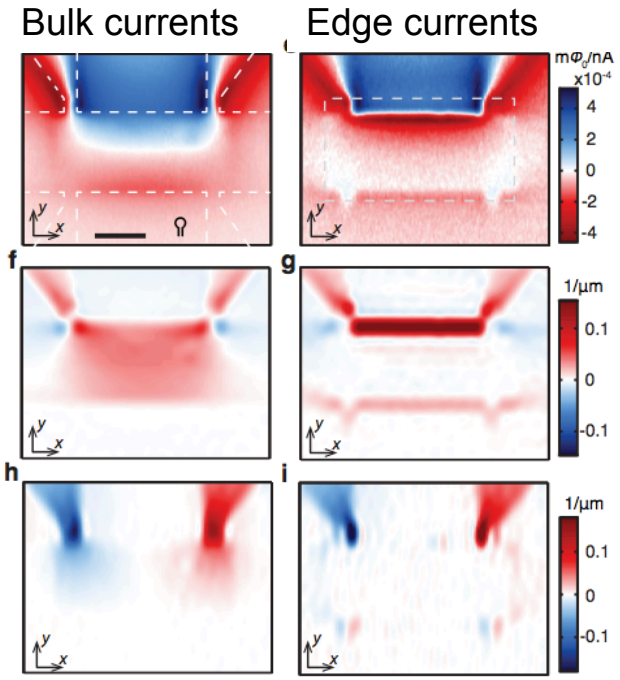




K. Moler and D. Goldhaber-Gordon Groups

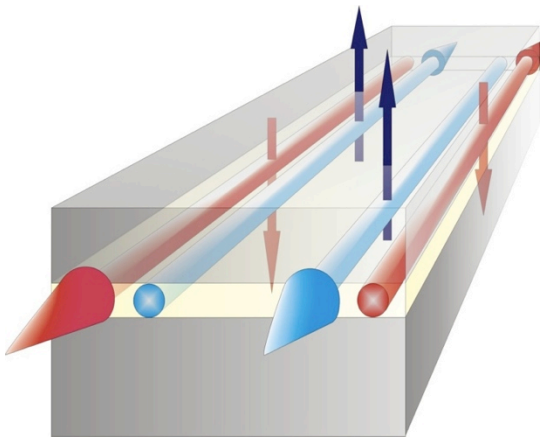
Direct observation of edge currents in a Quantum Spin Hall regime of HgTe quantum wells. Edge channels and bulk transport coexist, providing input on how ballistic transport may be limited in the edge channels.

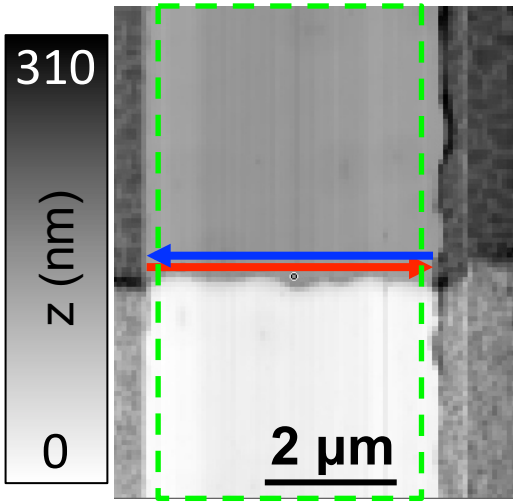


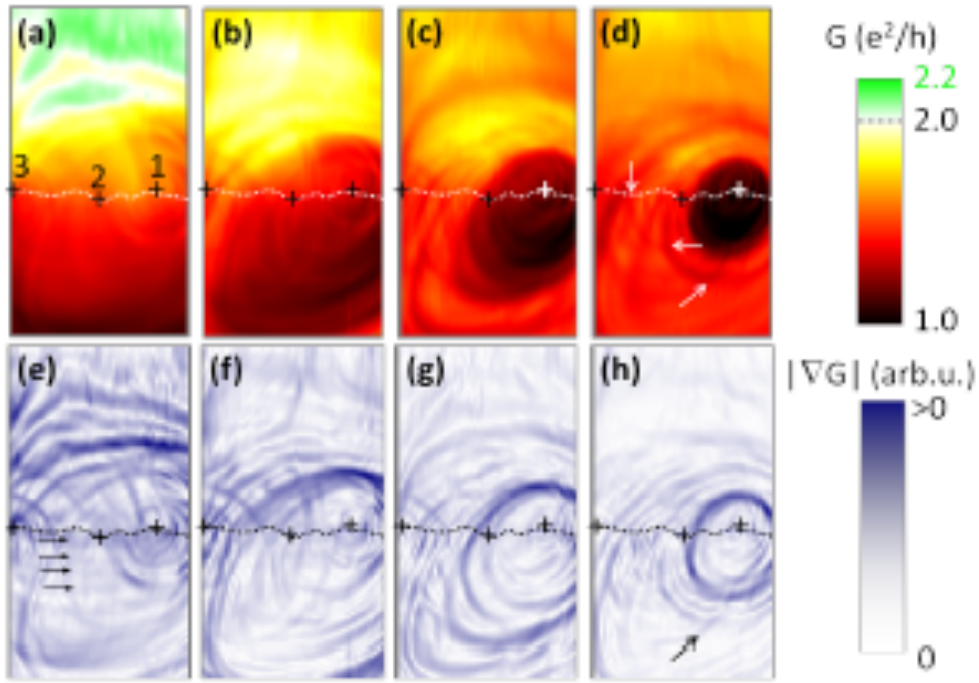


SGM on Quantum Spin Hall States

HgTe quantum wells are
2D topological insulators







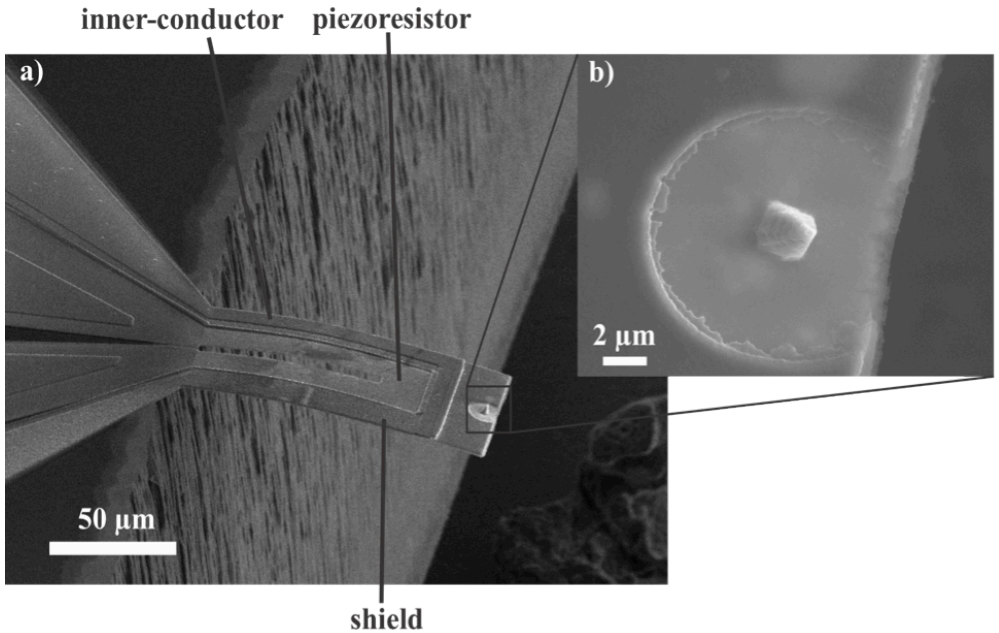
Conductance maps at different applied tip voltages. The dotted lines indicate the edge of the device. The labeled crosses mark the positions of the scattering sites, identified by sets of concentric rings, which likely limit the expected non-dissipative transport in the helical edge channels.

B. Pruitt and D. Goldhaber-Gordon Groups

Markus Koenig, et al, *Physical Review X* 3, 021003 (2013)

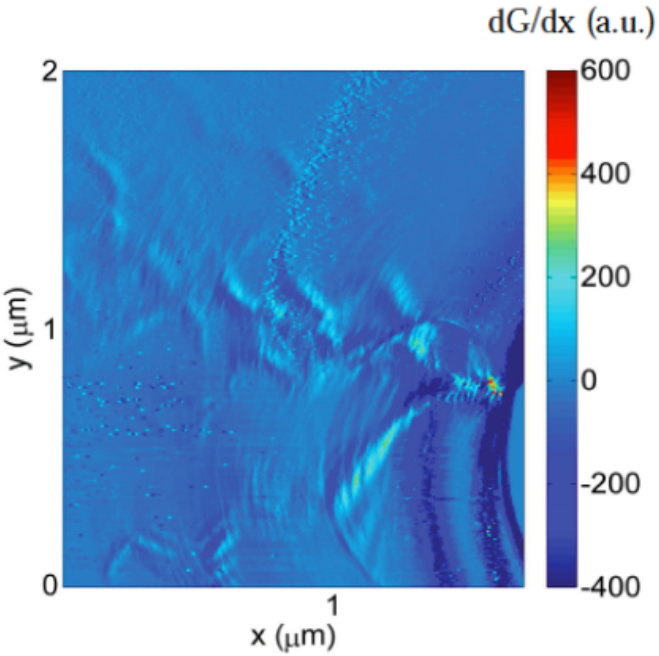
Shielded Tip & Piezoresistive Probes for SGM/MIM

Novel probes integrate a coaxial tip to produce a highly-localized electric field and a piezoresistor for self-sensing tip deflection. These probes have been batch-fabricated and can be used for both SGM and MIM.



(a) SEM image of a device at 45°. (b) Close-up of the shielded tip.

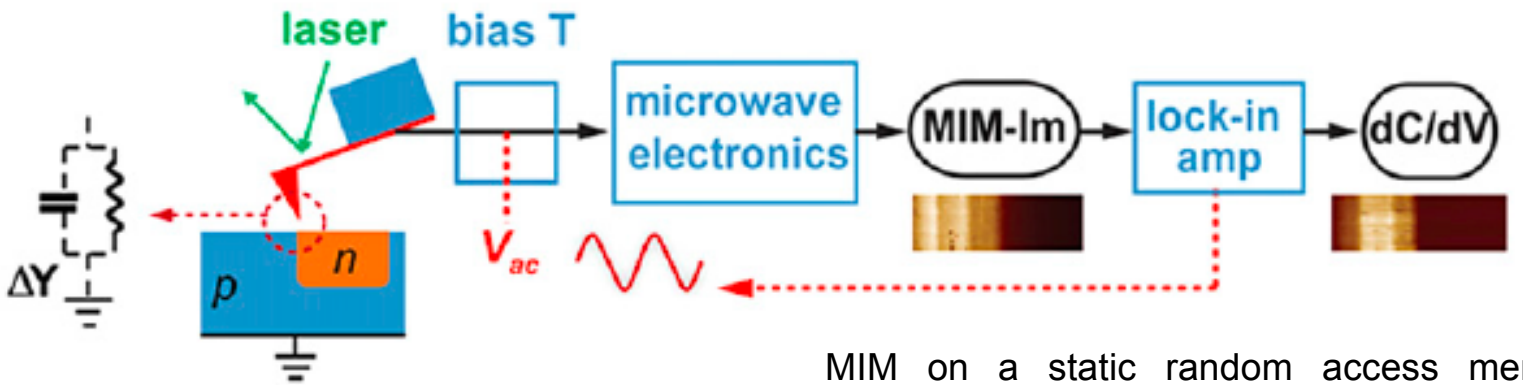
A.J. Haemmerli, et al, *Micro & Nano Letters* **2012,** *7* (4).



Electron backscattering through a QPC imaged using coaxial tips. Ensslin Group at ETH Zurich.

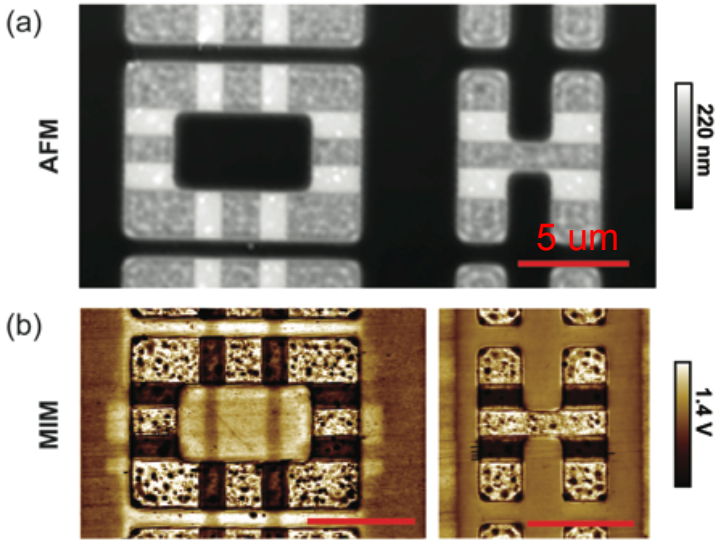
B. Pruitt, Z-X. Shen, D. Goldhaber-Gordon Groups

MIM Instrument Development and Application



MIM on a static random access memory (SRAM) sample reveals a thin layer of the dopant ions penetrating through the protective layers during the heavy-ion implantation steps.

Room-temperature and custom low-temperature (0.3-300K, +/- 12T) systems implemented

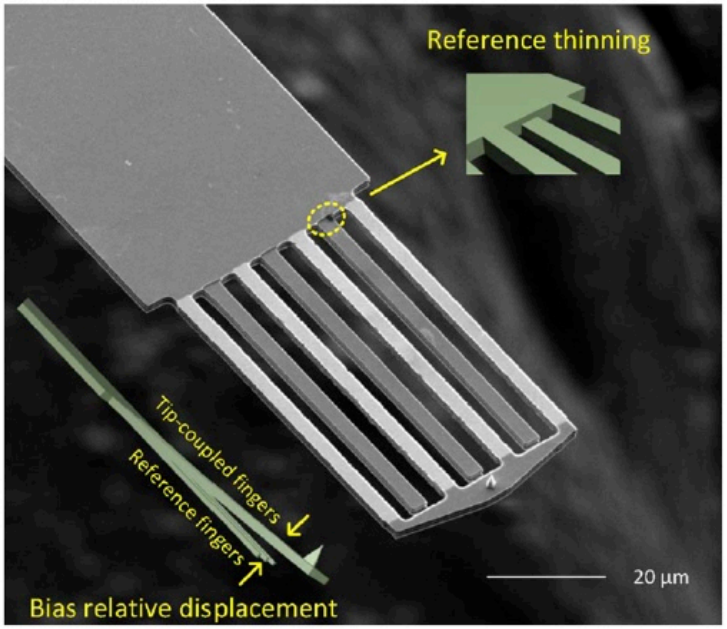


W. Kundhikanjana et al., *Rev. Sci. Instrum.* 82, 033705 (2011)

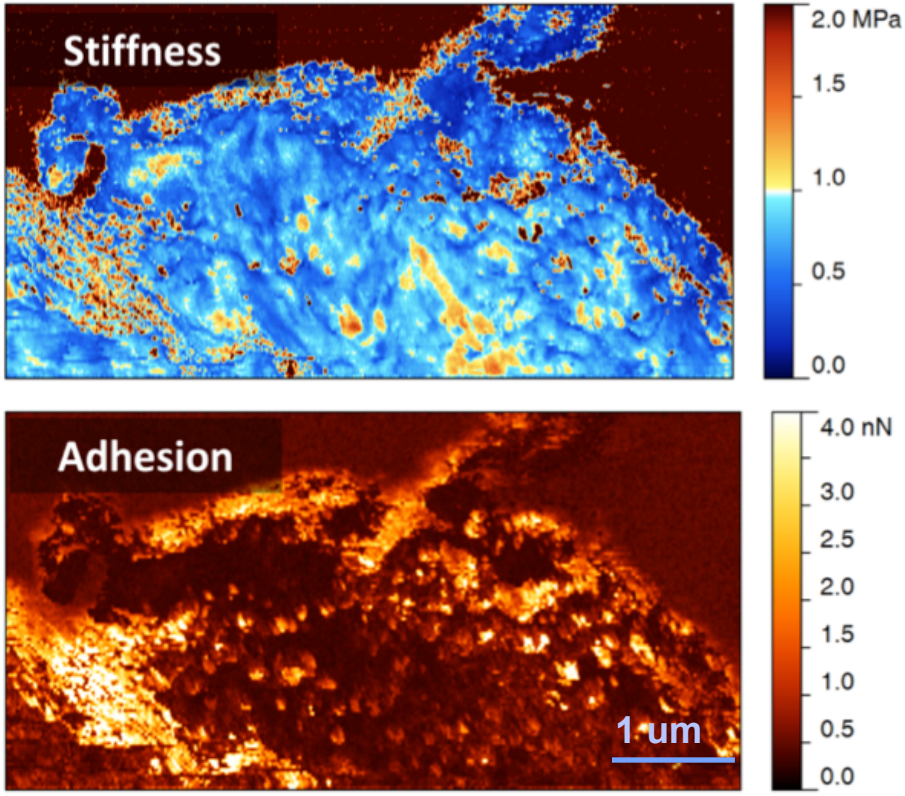
W. Kundhikanjana, et al., *Semiconductor Science and Technology* 28, 025010 (2013)

Cantilevers for High-Bandwidth Force Sensing

- High-bandwidth, diffraction-grating-based force sensor enables measurement of fast varying tip–sample interaction forces
- Physical measurements of material properties of biological cells are acquired in minutes vs. days



SEM image of an interdigitated AFM probe

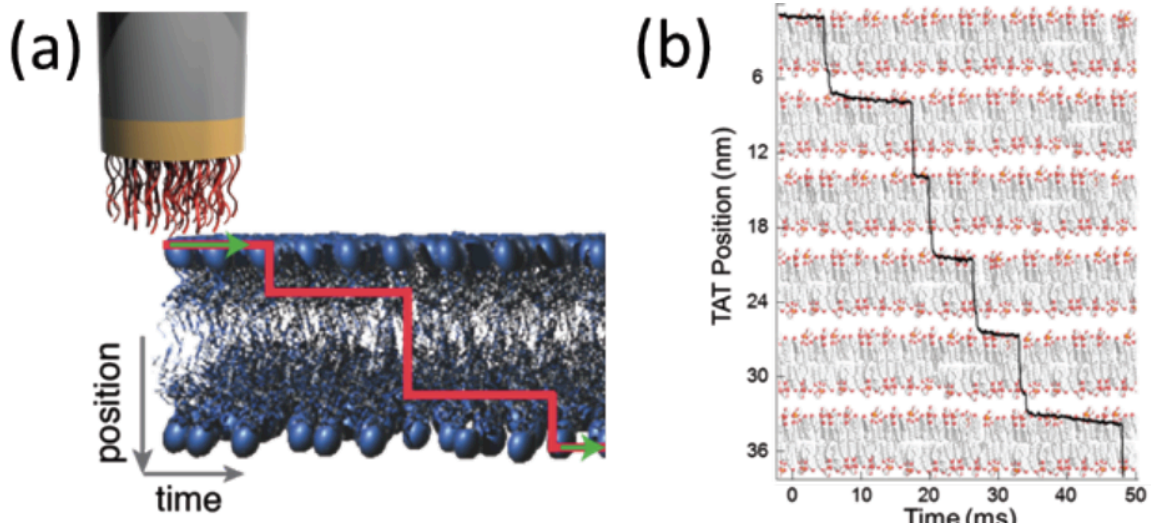


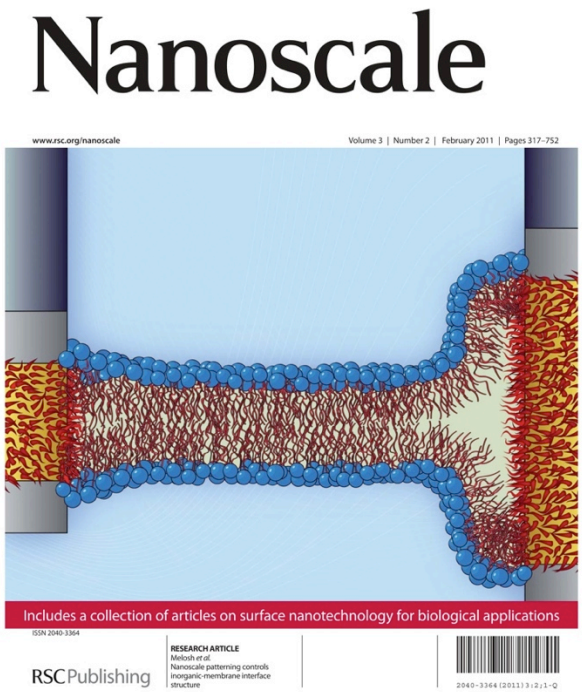
AFM images of fixed T-cells in fluid

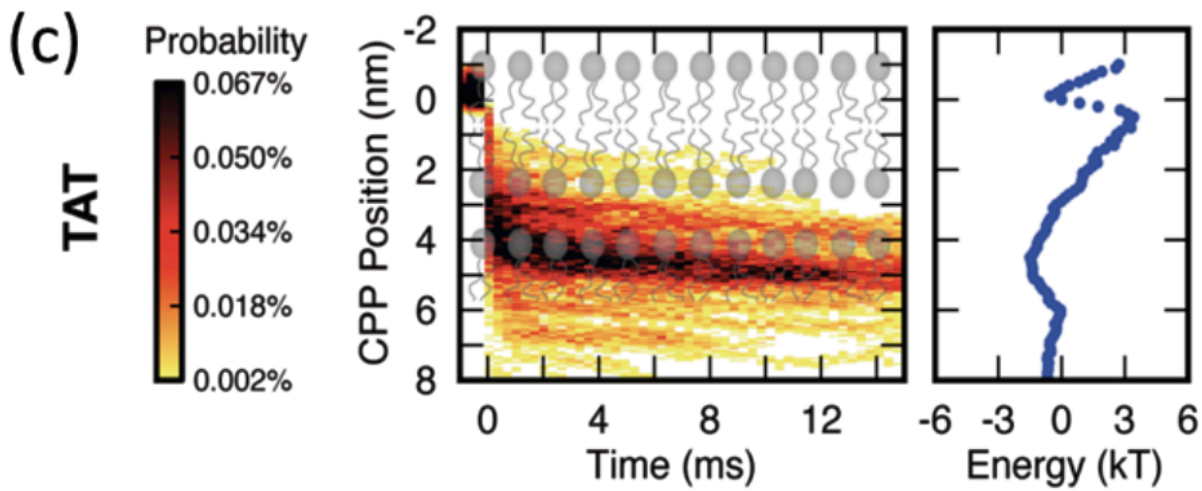
CPN BioProbes Theme Group: Solgaard, Butte and Melosh labs

Biomimetic Stealth Probes

- Bio-functionalized probe mimics membrane proteins and inserts into the lipid bilayer
- Creates an access port to study cell activity and transport mechanisms through cell membranes







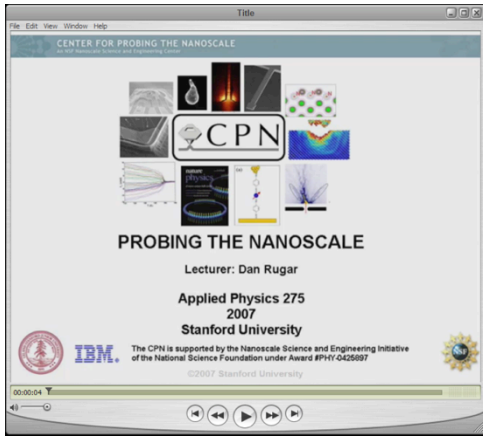
Almquist, Melosh, *PNAS* **107** (2010) and *Nanoscale* **3** (2011)

Education, Outreach, Diversity (Accomplishments and Plans)

Maria Wang
CPN Associate Director

Internal Programs

- Two Stanford courses
  - Undergraduate: *Tools of Nanotechnology* (AP78Q)
  - Graduate: *Probing the Nanoscale* (AP275), videos of lectures available online
- Industry field-trips and speaker series
- CPN research seminars and theme meetings
- Ethics Workshop
- Family and Career Workshop
- Science Communication Workshops

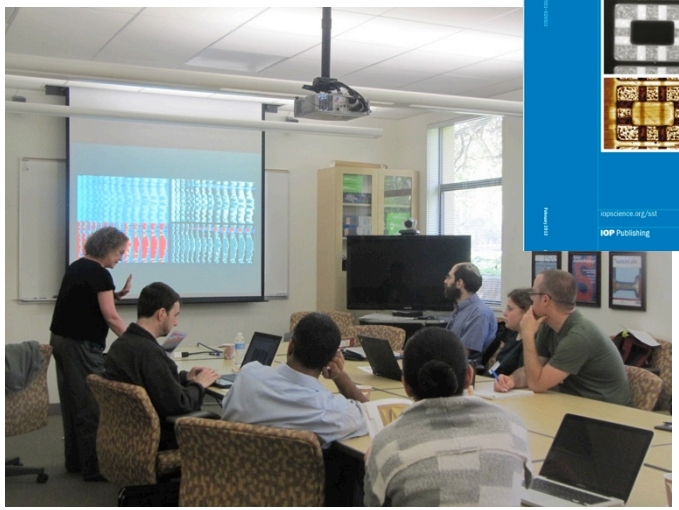


Science Communication Workshops

Motivation: Help students, postdocs and faculty effectively communicate their work to technical and lay audiences

Visual Strategies Workshop

- Resulted in revised posters for the Annual Nanoprobes Workshop
- Figure made the cover of *Semiconductor Science and Technology*



Oral Communication Workshop

- Feedback indicated participants valued:

"*Things to think about when giving a talk which I didn't think of...making ideas 'sticky', firing up someone's dopamine*"

"*Pointers on how to capture audience attention, e.g., tell a story, joke and engage audience*"

External Programs

- Summer Institute for Middle School Teachers
- Partnerships with formal and informal science education centers: K-12 schools, science museums, Nanoscale Informal Science Education Network
- Development of low-cost classroom activities with Bay Area distribution through Resource Area for Teachers (RAFT)
- Public outreach events: Girl Scouts Bridging, Bay Area Science Festival, NanoDays, etc.
- Annual Nanoprobes Workshop

Summer Institute for Middle School Teachers

Goals

- Deepen teachers' knowledge of physical science
- Increase scientific literacy and students in STEM

Week-long program
15 teachers

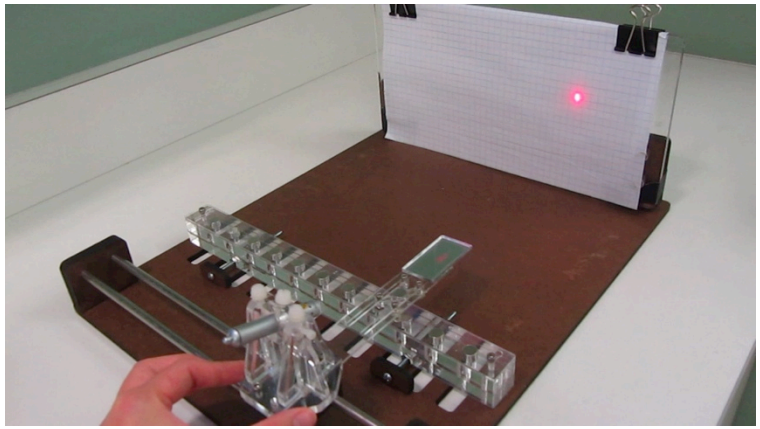
http://simst.stanford.edu

Translating Research from Lab to Classroom

"Seeing" the nanoscale

Lab tours and demos

Activity

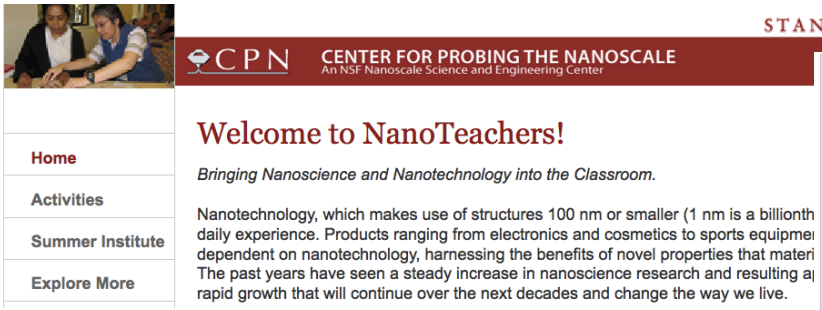


- Hands-on activities linked to CA State Science Content Standards
- Lesson planning and assembling kits for classroom implementation
- Pre- and post-concept maps indicate deepening of teacher knowledge
- Classroom implementation reports indicate our teachers reach over 1,100 students per year
- Lessons learned from 7 years of SIMST disseminated at 2012 MRS Fall Meeting

W. Maria Wang, et al, *Symposium ZZ: Communicating Social Relevancy in Materials Science and Engineering Education,* **2012 MRS Fall Meeting**, Boston, MA, Nov. 28, 2012.

Online Education and Outreach Resources

- CPN website for teachers: **http://teachers.stanford.edu**
  - Activity sheets, reference guides, links, and videos
  - Over 140 downloads of activity sheets since Sept. 2012
- *Close-up on Science* video series – hundreds of views on YouTube



Activity	California Science Standards
How Big Is It? *Investigating size and scale using the metric system.*	Grade 2, Standard 4b – express measurements in metric system units Grade 4, Standard 6b – estimate the length of objects
Pour It Out *Investigating the effects of forces at different scales.*	Grade 5, Standard 1g – properties of water Grade 8, Standard 2b – net force Grade 8, Standard 2c – mechanical equilibrium Grade 8, Standard 2d – identify forces Grades 9-12, Physics Standard 5e – electrostatic force
Bubbling Tablets *Investigating the effects of surface area on reaction rates. NEW! Teacher lesson guide and student worksheet*	Grade 6, Standard 7b – data collection and display Grade 6, Standard 7c – construct graphs and analyze variables (qualitative) Grade 7, Standard 7a – data collection and display Grade 8, Standard 5a – reactants form products Grade 8, Standard 9a – test hypothesis Grade 8, Standard 9b – data accuracy and reproducibility Grade 8, Standard 9c – identify variables and controls Grade 8, Standard 9f – calculate terms in mathematical formula Grade 8, Standard 9g – linear vs. nonlinear graphs Grades 9-12, Chemistry Standard 5 – acids and bases Grades 9-12, Chemistry Standard 6 – solutions Grades 9-12, Chemistry Standard 8 – reaction rates Next Generation Science Standards: MS-PS1 Matter and Its Interactions
Invisible Rays *Investigating the electromagnetic spectrum using ultraviolet beads.*	Grade 7, Standard 6a – electromagnetic spectrum Grade 7, Standard 6e – how color is perceived Grade 7, Standard 6f – light can be reflected, refracted, transmitted or absorbed by matter
Probing What You Can't See *Investigating magnetic forces and poles using a refrigerator magnet.*	Grade 4, Standard 1f – magnetic poles Grade 4, Standard 6a – differentiate observation from inference Grade 5, Standard 1e – scanning probe microscopes

Diversity Plan and Progress

Stanford University programs

- Many programs in place to enhance diversity at all levels
- Center participants are actively engaged in these programs
  - Diversifying Academia, Recruiting Excellence Doctoral Fellowship Program
  - Office of Science Outreach: Research Experience for Undergraduates and Research Experience for Teachers

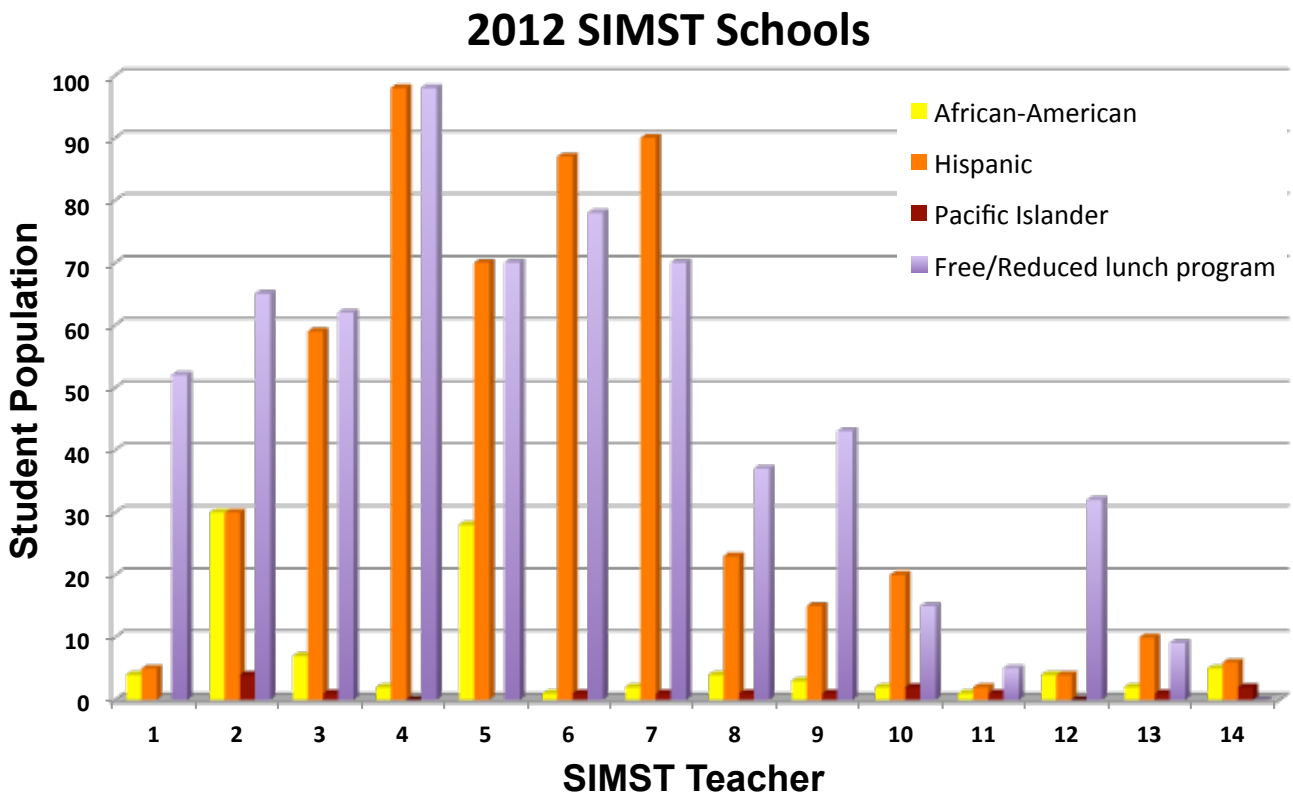
CPN's programs aimed at supporting and adding to Stanford's mission

- Increase participation of underrepresented groups
  - SIMST teachers from schools with diverse population
  - Retain women in science: Family & Career Workshop
  - Partnership with National Hispanic University and Latino College Preparatory Academy
  - Partnership with museums in México
  - Partnership with Techbridge Program for girls

Over 2,750 visitors interacted with the CPN nanoprobe activity station

SIMST Selection Process

- Target economically and academically high-need schools
- Focus on school diversity for acceptance of teachers



- Half of the teachers serve schools with majority of students on free/ reduced lunch programs or who are underrepresented in the sciences

Partnership with Techbridge Program

- **Motivation**: broaden the impact of Stanford's NanoDays to underserved groups
- Techbridge: local organization that promotes girls' skills and interests in STEM fields
- CPN hosted 36 girls from middle schools > 90% socioeconomically disadvantaged and > 90% Latino or African American
- Partnered with Stanford Nanocharacterization Lab, Stanford Nano Center, and the Stanford Nanofabrication Facility
- Girls highlighted the hands-on NISE Network activities as being very *engaging* and discussions with Stanford role models as *inspiring*

Plans for Education, Outreach and Diversity

- SIMST
  - Continue collecting data on teacher learning and the progress of bringing hands-on activities into the classroom
  - Align SIMST content on crosscutting concepts and science practice with the Next Generation Science Standards
  - Alumni Workshop next summer
- Expand teacher website for broad distribution of materials
- Continue offering professional development workshops and seminars for students and postdocs
- Continue partnering with NISE Network, Techbridge, and Stanford Nano Facilities for NanoDays and other outreach events

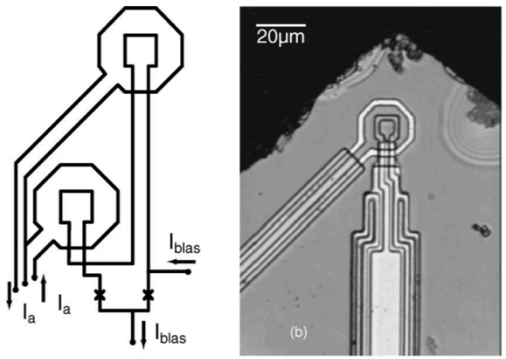
What was the state of Nano research pursued by your NSEC when the center started? What were the challenges? What has been the progress? Looking forward, what does the future look like? What are the opportunities and challenges?

Kam Moler

CPN Director, 2004-2011

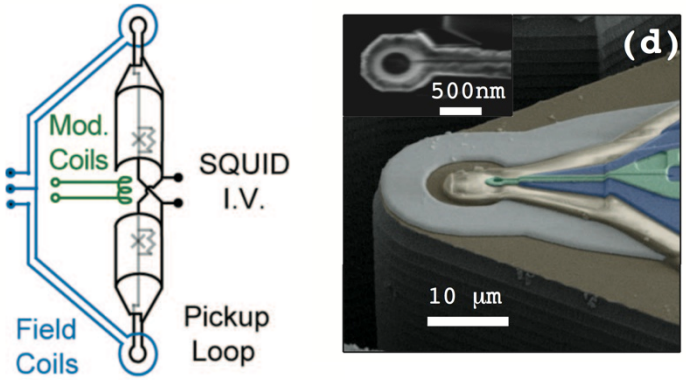
Scanning SQUID Microscopy

Past



Spatial resolution 4 μm
Spin sensitivity 1500 $\mu_B/Hz^{1/2}$

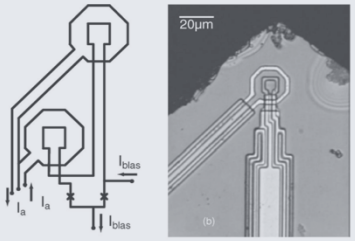
Present



Spatial resolution <1 μm
Spin sensitivity 100 $\mu_B/Hz^{1/2}$

Scanning SQUID Microscopy

Past

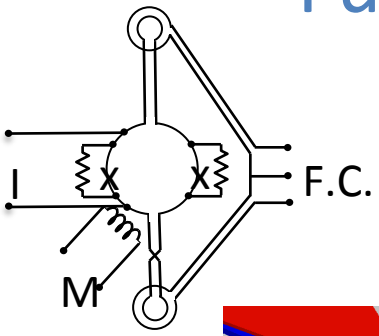


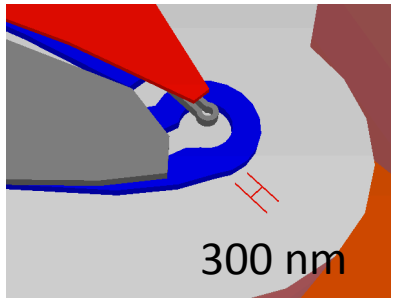
Spatial resolution 4 μm
Spin sensitivity 1500 $\mu_B/Hz^{1/2}$

Present

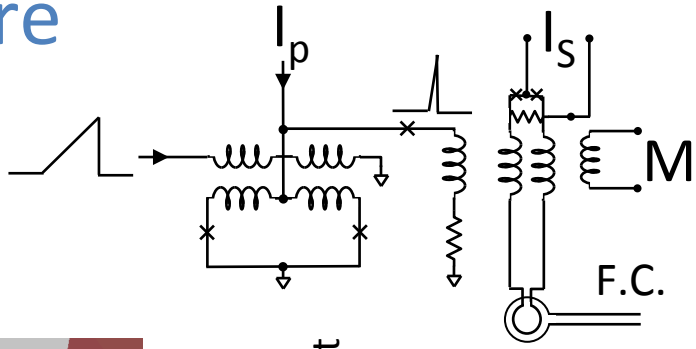
Spatial resolution <1 μm
Spin sensitivity 100 $\mu_B/Hz^{1/2}$

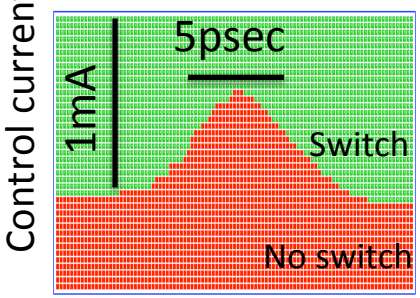
Future



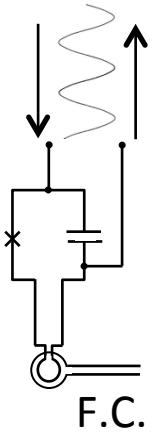


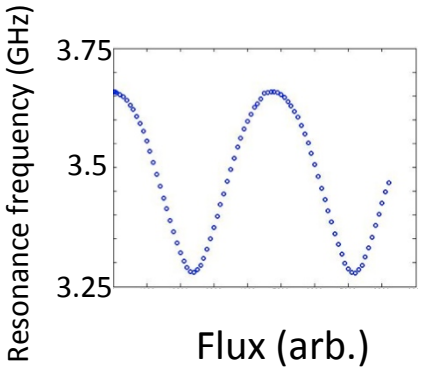
Spatial resolution <0.5 μm





Time resolution <10 psec

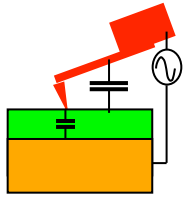




Spin sensitivity ≈ 1 $\mu_B/Hz^{1/2}$

Scanning Microwave Impedance Microscopy

Past

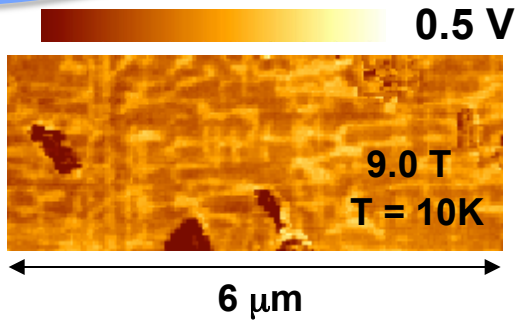


- Scanning capacitance microscopy: widely used but non-quantitative
- Microwave STM: high resolution but shares stringent STM surface and tip requirements
- 1st Gen Microwave impedance (MIM): non-robust, slow

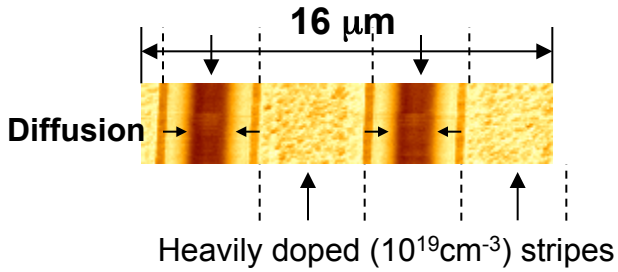
Present

- Microwave electronics improved
  - Automated
  - Miniaturized
  - Multi-frequency 0.8-3.5 GHz
  - Works with standard commercial AFMs
  - Inspired Agilent to commercialize related tool
- Probe tip improved
  - Batch MEMS processing replaces FIB
  - Coaxial shield, insulating cantilever: reduced stray capacitance
  - Sharper and more robust tip
- Modeling makes measurement quantitative
- Cryogenic MIM (0.3K to 200K), magnetic field up to 12T
- Applied to semiconductors, correlated electrons

Refined electronics

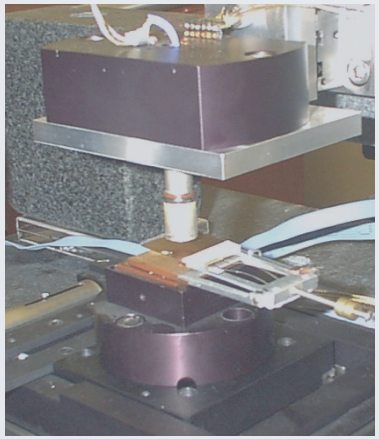


Inhomogeneous metal-insulator transition



Scanning Microwave Impedance Microscopy

Past



Present

He4 (4K) / 9T

He3 (0.3K) / 12T

Future

Expand range of applicability

- Expand conductivity sensitivity: now 100x range, aim for 10,000x, using broadband
- Integrate NSOM spectroscopy to probe
- Enable non-contact scanning to avoid perturbing samples
- Enable operation in liquid for biology: proof of principle demonstrated, sensitivity to dielectric properties allows “seeing” protein without staining, but making it practical will be a challenge

nanoMRI

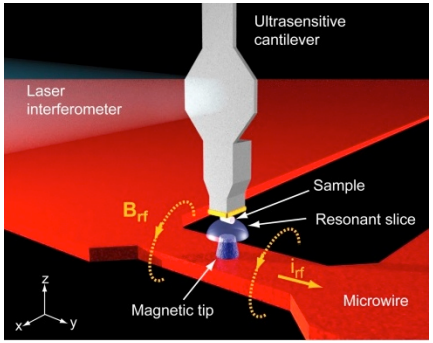
Past

- MRI requires voxels > $(3\ \mu m)^3$
  - At least 10^{12} protons needed per voxel
- Scanning probes (AFM, STM) limited to 2D surface imaging
  - Little or no elemental contrast

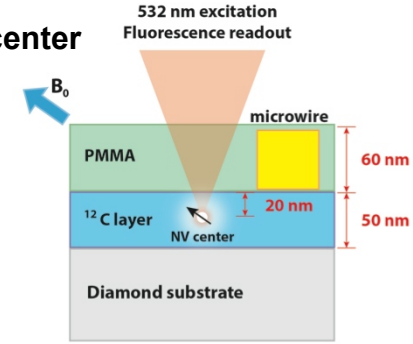
Present

- Magnetic resonance force microscopy (MRFM)
  - Ultrasensitive force detection techniques for NMR imaging
  - First demonstration of nanoscale MRI
  - True 3D sub-surface imaging
  - Elemental selectivity (^{1}H, ^{13}C, ^{19}F, ^{31}P)
  - 100 million times improvement in detection sensitivity over conventional MRI
  - Detection volumes on the order of $(5\ nm)^3$
  - 3D NMR imaging of virus particles

MRFM



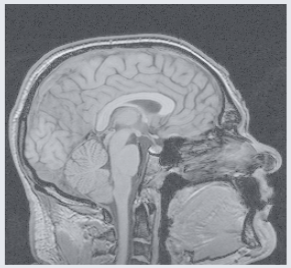
NV center



- NV center in diamond for nanoscale NMR detection
  - NV center acts as atomic-size magnetometer
  - First demonstration of NV-based NMR detection
  - Double resonance allows NMR spectroscopy
  - Detection volume of $(20\ nm)^3$

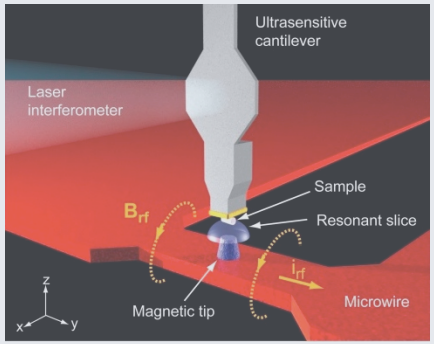
nanoMRI

Past

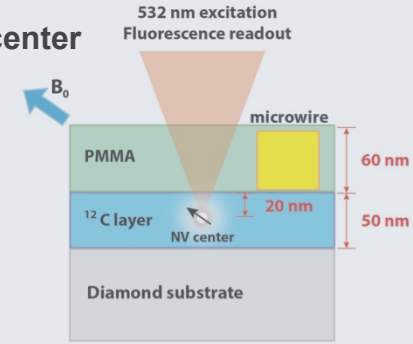


Present

MRFM



NV center



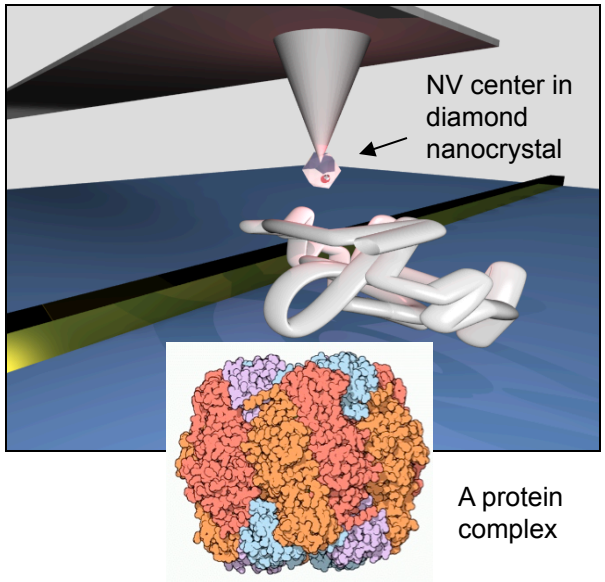
Future

The key to improved resolution and functionality is SNR

- MRFM: Non-contact friction is dominant noise source near surface
- Progress seen with high frequency silicon nanowire cantilevers

- NV centers: SNR depends on quantum coherence of spin near diamond surface
- Studies on-going to understand decoherence mechanisms (dangling bonds, charge fluctuations, etc.)

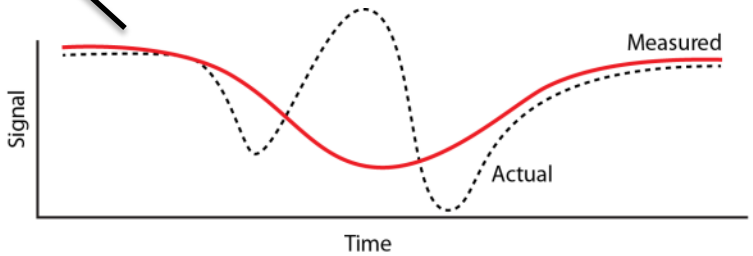
Future NV probe for 3D molecular structure imaging

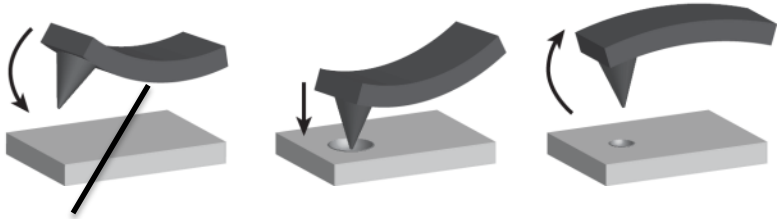


Tapping Mode AFM for Soft Materials

Insensitive output signal

Past





Ponderous tapping mode cantilevers

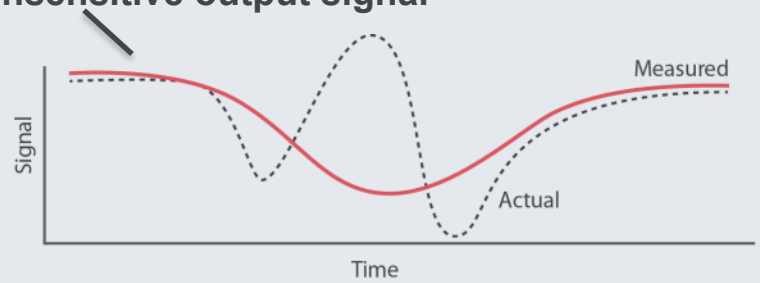
Circa 2003 tapping mode cantilevers

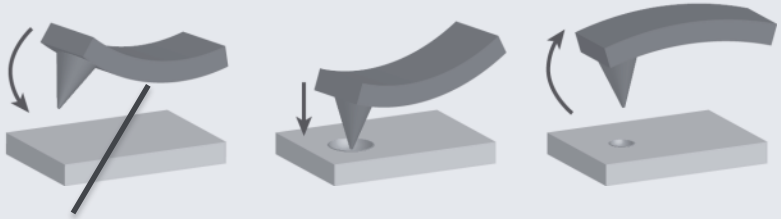
- Low response frequency
- Damaged soft materials
- Washed out actual interactions
- No sample mechanical properties information

Tapping Mode AFM for Soft Materials

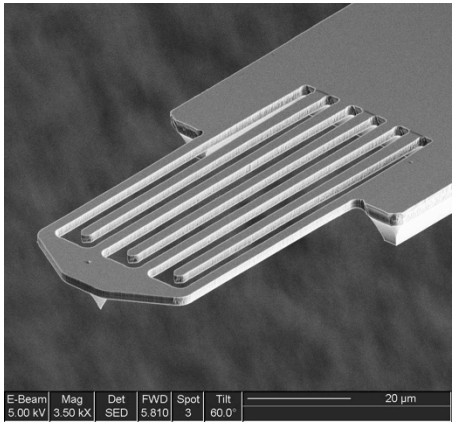
Present

Insensitive output signal

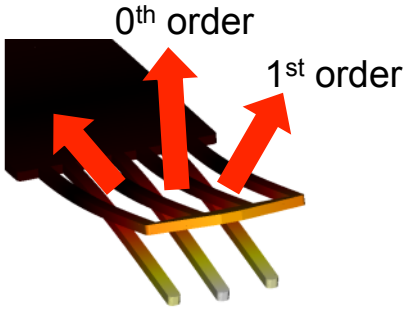




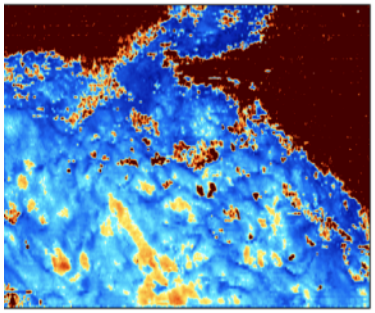
Ponderous tapping mode cantilevers



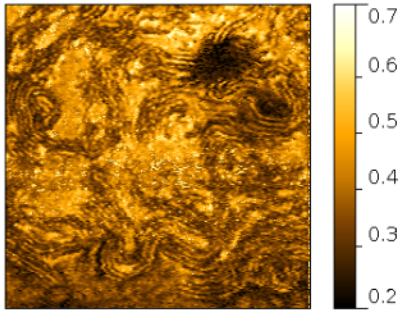
Dual Cantilevers



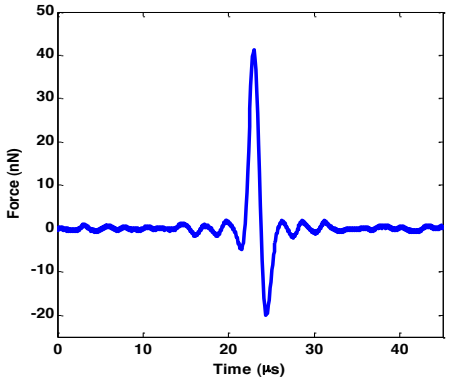
Grating Sensor



Live cell imaging



Elastic Modulus Map

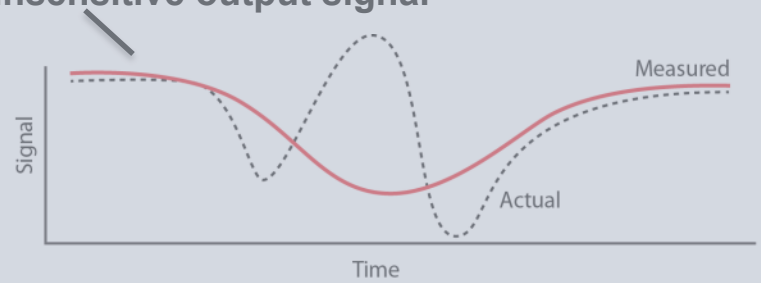


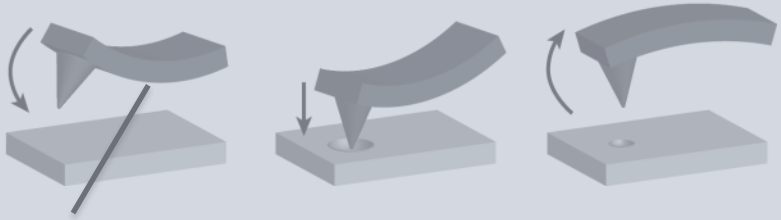
Actual Force Measured

Tapping Mode AFM for Soft Materials

CPN
An NSF Nanoscale Science and Engineering Center

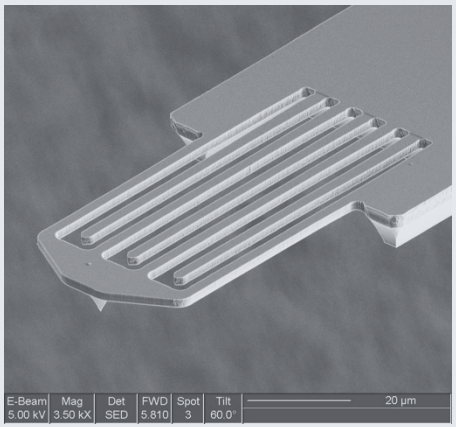
Insensitive output signal





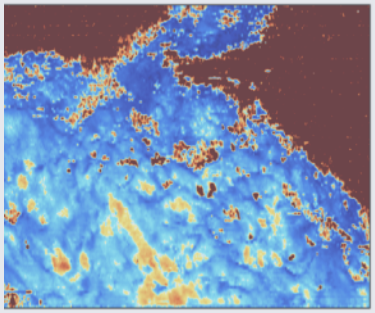
Ponderous tapping mode cantilevers

Future

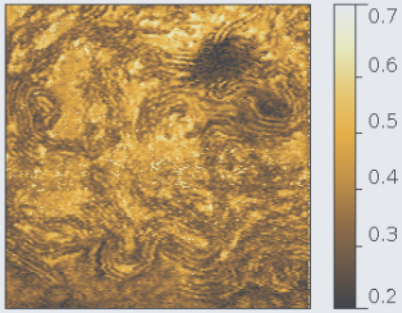


Dual Cantilevers

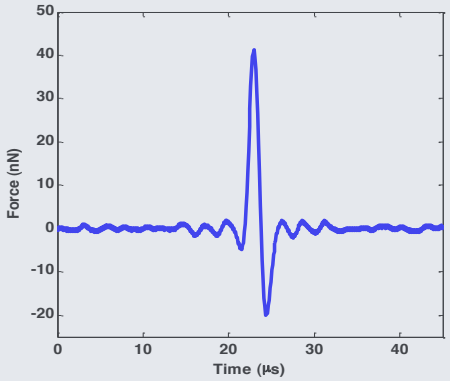
Ultra-fast video rate imaging



Live cell imaging



Elastic Modulus Map



Actual Force Measured

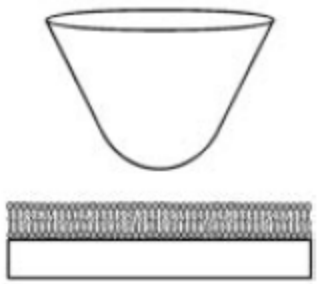
Tip-sample adhesion, receptor ligand studies

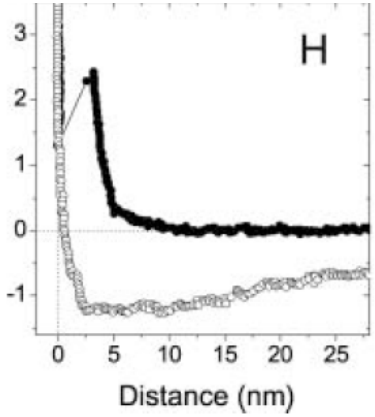
Real-time cell reorganization

Measure nanoscale materials heterogeneity

Probing Lipid Properties

Past





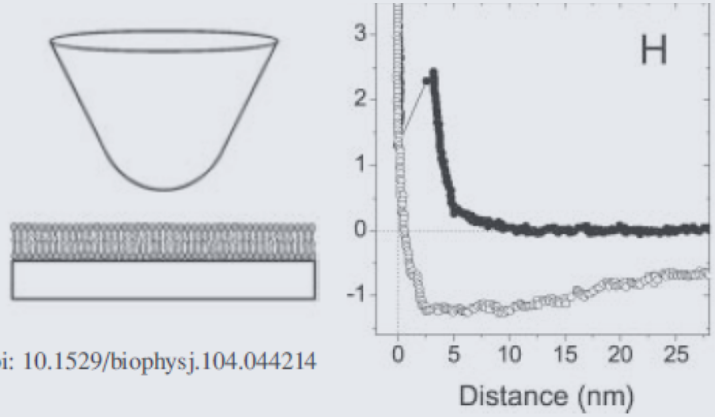
doi: 10.1529/biophysj.104.044214

Circa 2003 Force Measurements on Lipids

- **Probing mechanics of model bilayer failure**
- **Important lipid-based phenomena of peptide penetration for drug delivery and lateral lipid interactions not accessible**
- **AFM on bilayers a small niche**

Probing Lipid Properties

Present



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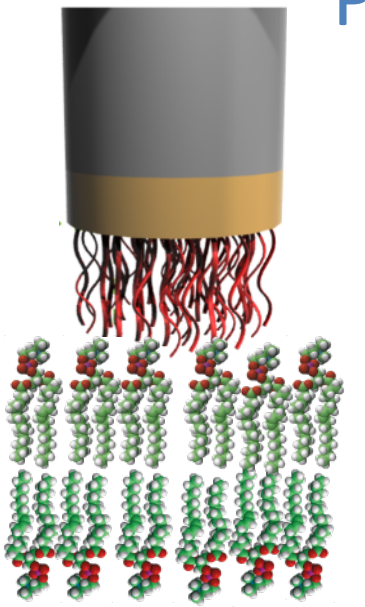
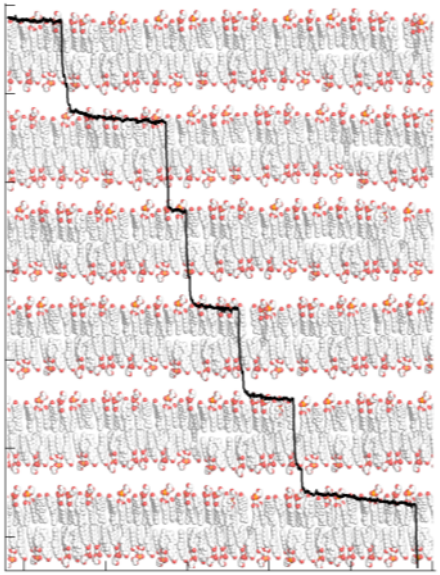
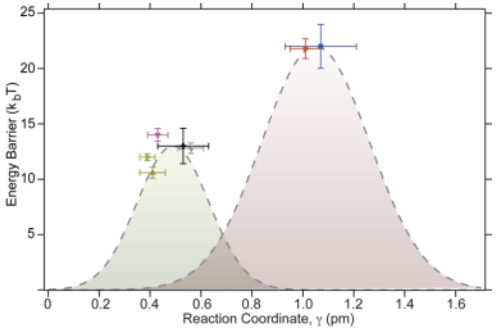
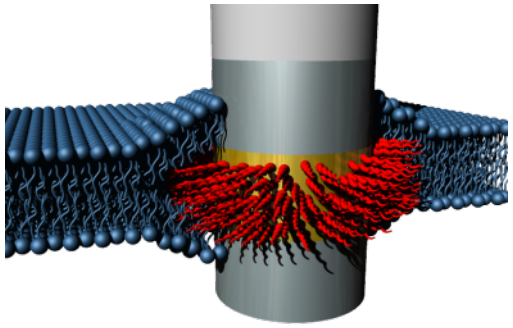




Peptide-Membrane dynamics and energetics

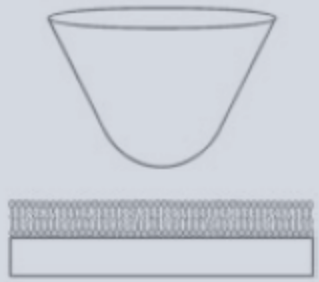


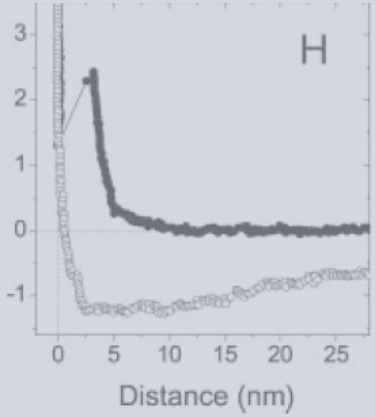
Understanding Inorganic-bilayer interactions



Artificial 'Membrane proteins'

Probing Lipid Properties





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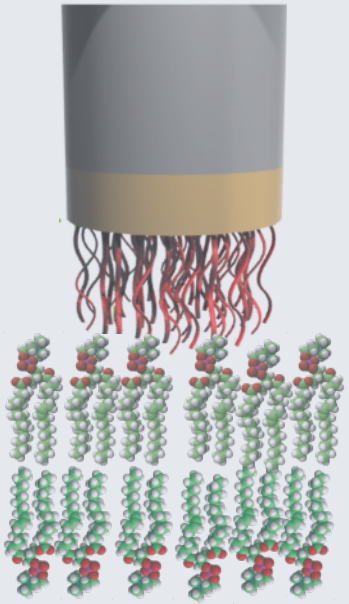

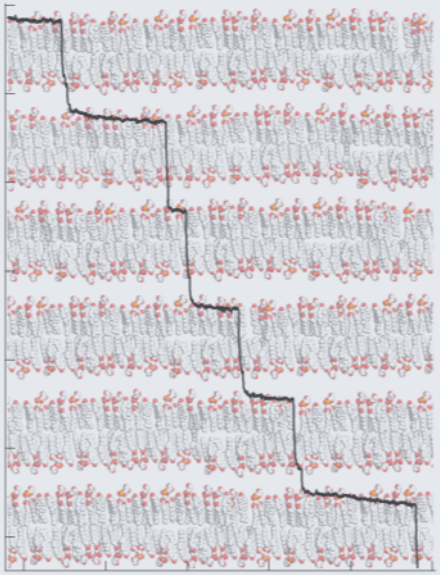

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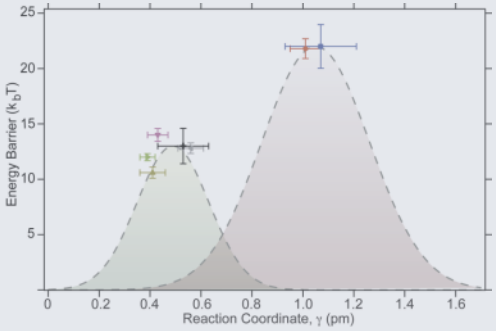
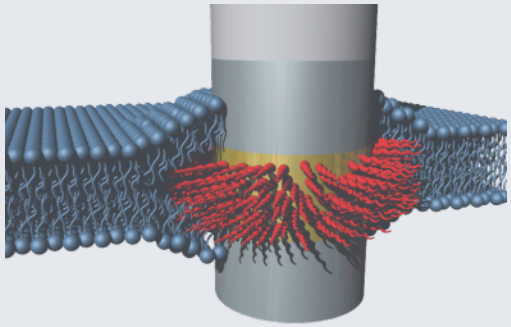




Future

Neural Prostheses

Single cell electrical interfaces

New drug delivery agents

Research Plans for the next year and how you see the NSEC moving forward after the end of the award

Nick Melosh
CPN Deputy Director
Bio-Probes Theme Leader

Nanoelectric Theme Group Plans

Probe fabrication

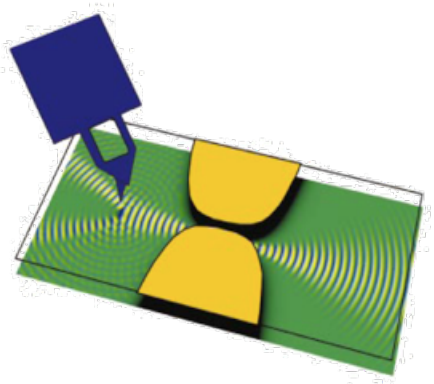
- Next-generation SGM/MIM probes with improved lateral resolution and repeatability.
- Continue collaboration with Prof. Ensslin at ETH Zurich to characterize coaxial probes for high-resolution SGM.
- Exploration of other applications, including the study of biological specimens, dopant profiling in integrated circuits, and sources of noise in semiconductor devices.

Scanning Gate Microscopy:

- Improved devices that can be fully tuned in and out of the QSH regime with a back-gate.
- Continue preparation and characterization of coaxially shielded tips suitable for SGM experiments.
- First SGM experiments on other material systems, e.g., graphene or thin films of three-dimensional topological insulators.

Microwave Impedance Microscopy:

- Continue collaborative research on manganite samples, 2DEG systems, topological insulators, and ferroelectrics.
- *Probe development* – New functions, such as on-chip transistors or a second electrode for transmission measurement, will be gradually added to the basic design. Fabrication of probes shielded up to the tip apex will also be explored on a wafer-scale, which is well aligned with the efforts in the Pruitt and Goldhaber-Gordon groups.
- *Electronics development* – Develop IC-based and fully automated electronics covering an increasing frequency range from 50 MHz to 20 GHz. Explore the feasibility of covering a wider electromagnetic spectrum for probing – down to kHz range (with a capacitance bridge) and up to IR (scattering-NSOM) – to obtain spectroscopic information.



Nanomagnetic Theme Group Plans

SQUID microscopy

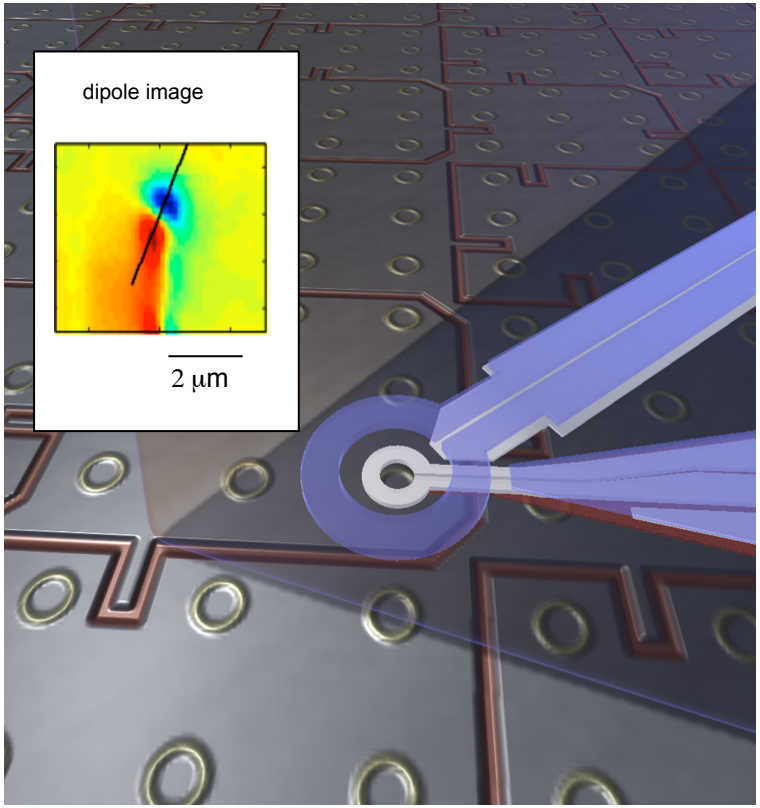
- More accurately determine the magnetic moment by developing standards for calibrating the dependence of sensor height on piezo-voltage at low temperatures.
- Higher spatial resolution will be achieved using the next-generation SQUIDs, with 0.1 micron linewidths and spacings for the pickup loops.
- The dispersive SQUIDs are predicted to have improved sensitivity and 100 MHz bandwidths. These sensors have been designed and are being fabricated at IBM Yorktown Heights, and will be incorporated into the scanning SQUID microscope user facility.

NanoMRI

- Improve signal-to-noise ratio and acquisition time using NV centers formed closer to the diamond surface. Evaluate effect of surface proximity on NV coherence time.
- Initiate work on scanned magnetic resonance imaging using NV center detection.

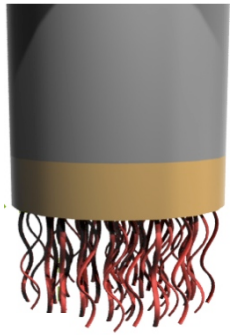
Near-field Sagnac Microscopy

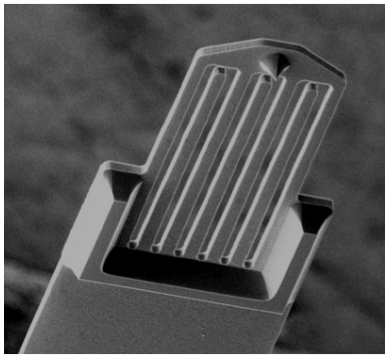
- Improve the spatial resolution by increasing the numerical aperture of the lens used. Presently we have ~0.9 μm resolution, but can go down to ~0.5 μm.
- Explore coupling of the beam to a tapered-fiber tip for near-field demonstration.

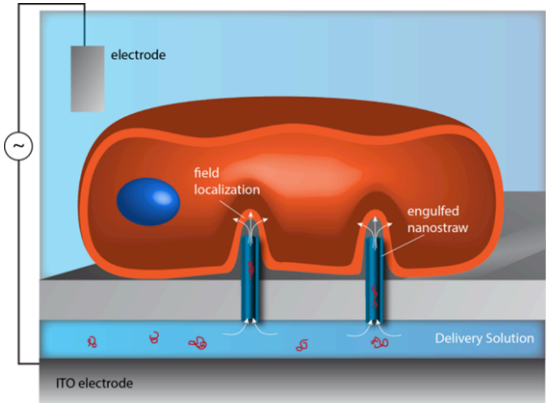


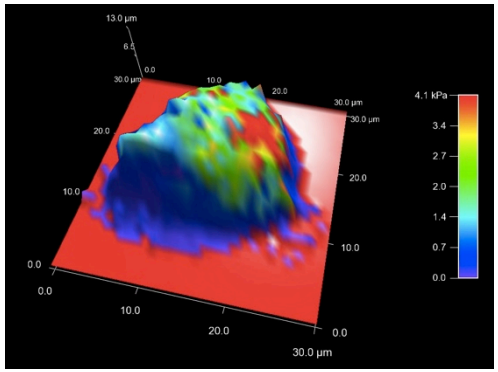
Bio-Probes Theme Group Plans

- Image T-cell receptors in real time on live cell surfaces with <10 nm resolution.
- Enable dynamic, live-cell imaging in real time of functioning biological cells.
- Observe active reorganization of mechanical structures within cells.
- Develop AFM measurement systems that can be employed in more biological settings. Remove current limitations imposed by the large cantilever fixtures and optical routing.
- Develop the theory and practice of penetration pathway analysis to differentiate different classes of cell-penetrating peptides.
- Investigate penetration of different nanostructures into cells to determine if the insights derived thus far for model lipids also work in cell membranes. Examine and fabricate membrane-penetrating structures.
- Demonstrate cell transformations based on nanostructure delivery and directed behavior.









Outlook After NSEC

- Continuation of research projects via other funding sources (NSF, DOE, DARPA, NIH, ERC: Center for Reprogramming & Therapeutics)
- Shared Nano Facilities at Stanford provide home for continuation of this work
- Technology transfer of developed probes to industry, through spin-offs, licensing, and international laboratories
- Application of probes to investigate scientific questions (novel materials, biological processes, etc)
- Lessons learned, coursework and outreach materials from the Summer Institute for Middle School Teachers can be adapted for another Center, e.g., MRSEC.

Summary

- Developed array of new instruments based on scanning probe interface
- High impact science using these probes
- Trained cohort of skilled scientists
- Outreach activities targeted at diverse groups
- Industrial impact and spin-off companies
- Legacy of nano integration and tools at Stanford