COINS Overview, Accomplishments, and Plans

Alex Zettl: Director

Willi Mickelson: Executive Director

Ali Javey: Integration Co-Leader

Meltem Erol: Education and Outreach Director

UC Berkeley, Stanford, CalTech, and UC Merced

NSF Site Visit, June 10-11, 2013

COINS Center of Integrated Nanomechanical Systems

National Science Foundation WHERE DISCOVERIES BEGIN

Outline

Center Overview:	Alex Zettl
Research Accomplishments:	Alex Zettl
Research Plans:	Willi Mickelson
Education and Outreach:	Meltem Erol
Progress, Challenges, and Future:	Alex Zettl

COINS Vision and Goals

COINS mission is to inspire and realize applications directed towards sensing of environmental conditions using nanotechnology.

Three environmental sensing applications guide the research:

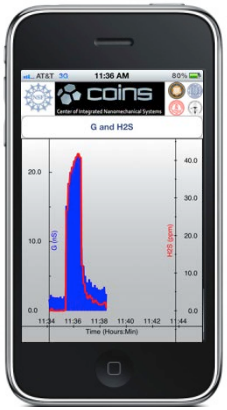
- Personal Environmental Monitoring
- Community-based Environmental Monitoring
- Mobile Environmental Monitoring

COINS Application Drivers

Personal Environmental Monitoring

Pollution

State-of-the-Art Personal Monitor



Smart Phone

- Current personal environmental monitors are still expensive ($5k), power hungry, run only for hours at a time, and can measure limited gases.
- COINS goal: Interface nano-enabled sensors with smart phone technology
  - Should be small, sensitive, low-cost, low-power, and detect multiple analytes
  - Interface with smart phones, eventually becoming embedded in the device

COINS Application Drivers

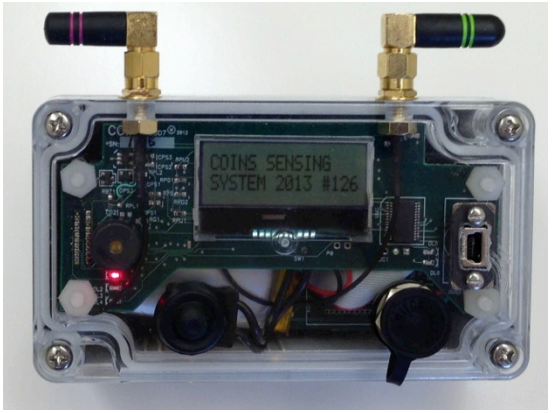
Community-based Environment Monitoring

Chevron Refinery Fire
Richmond, CA August 2012

Radioactive Waste Leaking from
Fukushima Nuclear Power Plant, 2011

- Low-power, low-cost chemical sensors will enable fixed broad area coverage or semi-portable field monitors to provide real-time feedback of environmental conditions to:
  - Detect and locate leaks of explosive gas, radiation, and harmful pollutants
  - Monitor pesticide drift in air and chemical build-up in ground and drinking water

- COINS goal: Develop novel low-power, low-cost, selective nanomaterials-enabled sensing systems for real-time detection of explosives, toxicants, and radiation.



Third-Generation COINS Sensing System

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COINS Application Drivers

Mobile Environmental Monitoring

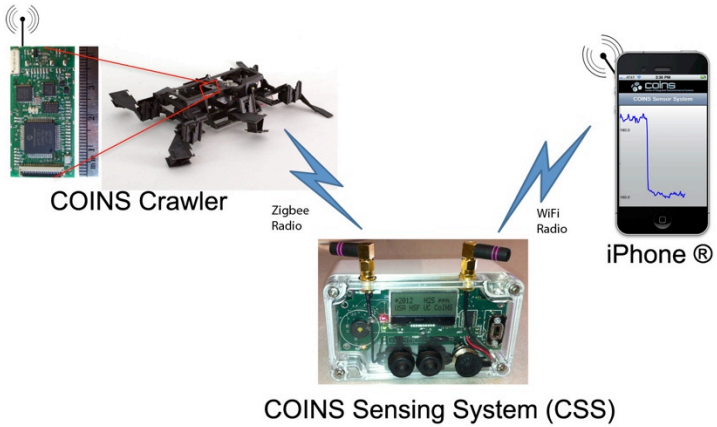
Rescuers search for survivors after building collapse, Bangladesh, 2013

Deployable Chemical Detection System

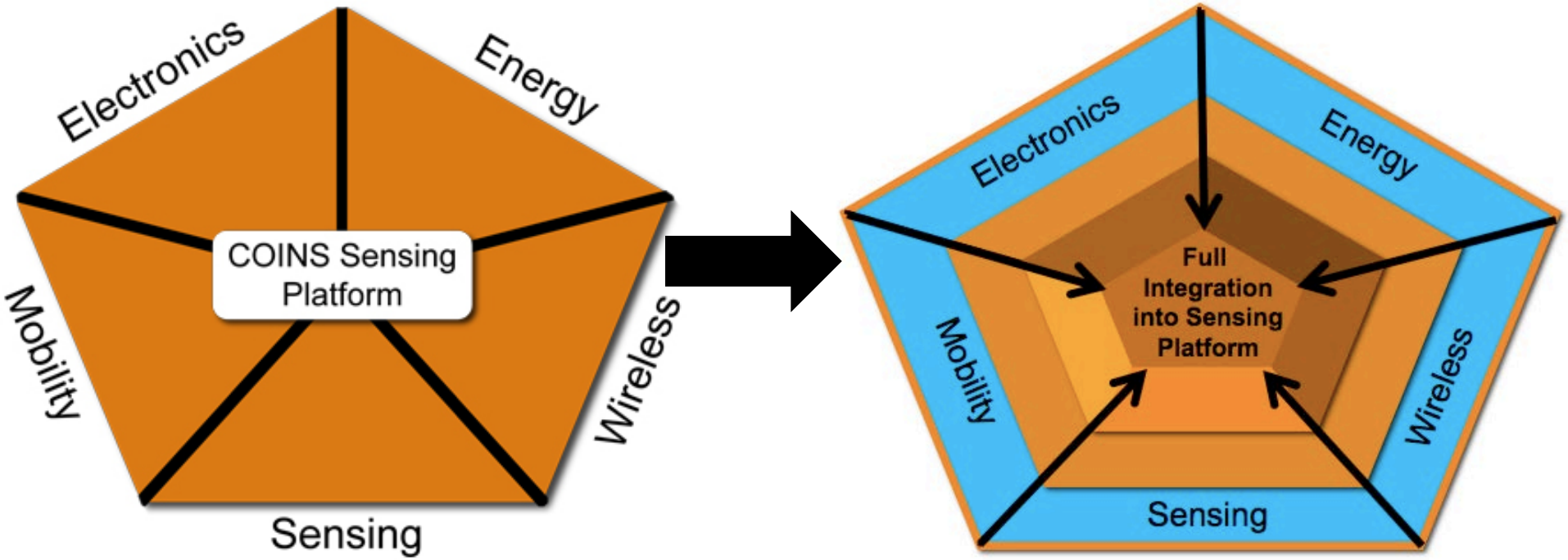
Nuclear Crisis at the Fukushima Daiichi Plant, Japan, 2011

- Expensive and power hungry, most current mobile monitoring systems require either gas-powered vehicles or humans for mobility.
- After disasters, collapsed buildings, mine shafts, or damaged plants are dangerous for response teams making it difficult to monitor and control situations.
- COINS goal: Create mobile robots with application-appropriate detection capabilities, such as survivor or hazard location.

  - Should be self propelled, communicate wirelessly, and able to reach confined spaces

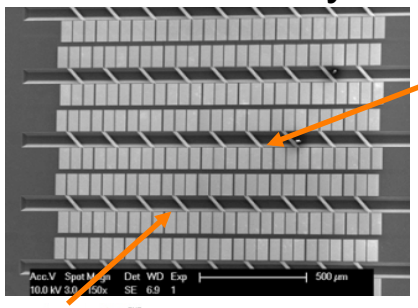


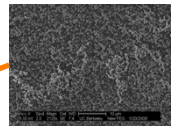
COINS Technical Thrusts



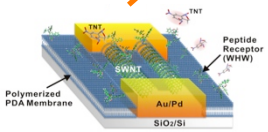
Systems Integration

Sensor Arrays

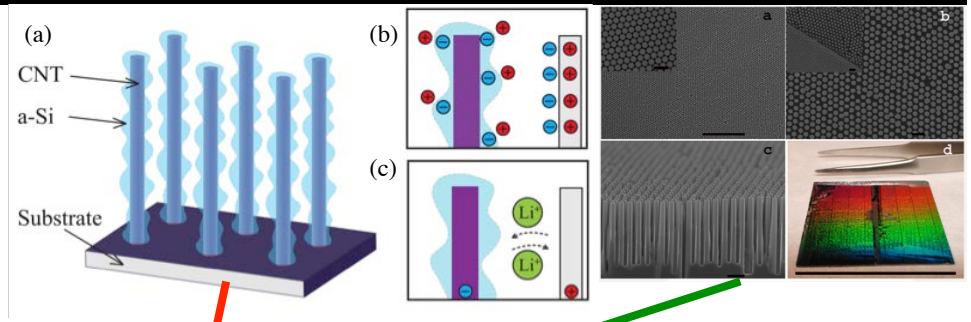


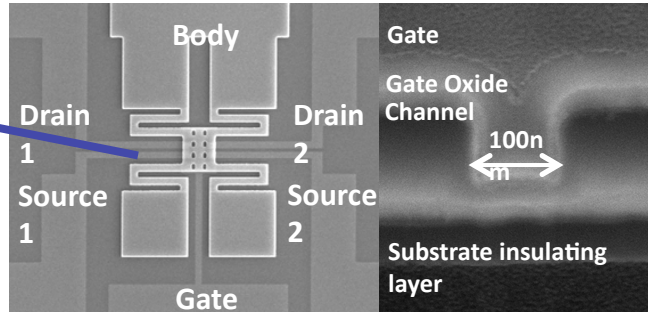


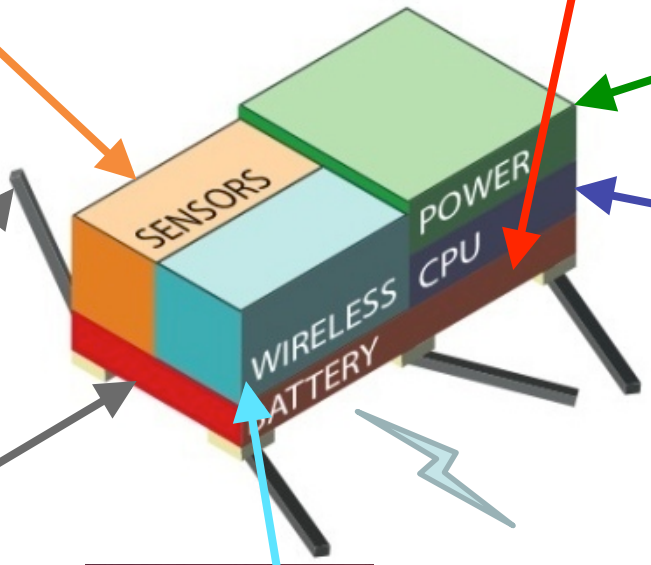
Nanoparticle Sensors

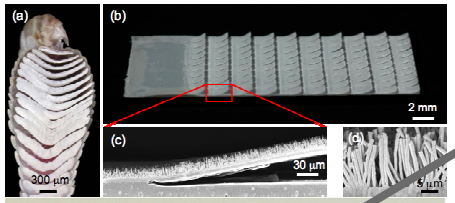


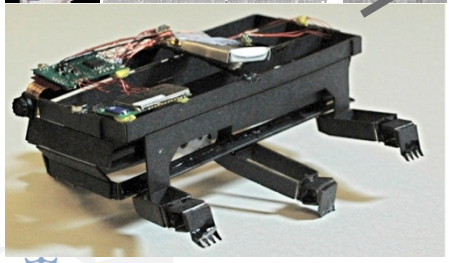
Recognition Peptide Sensors

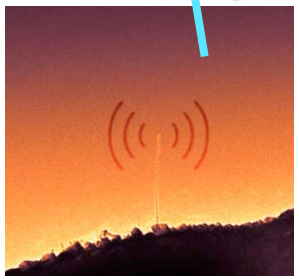




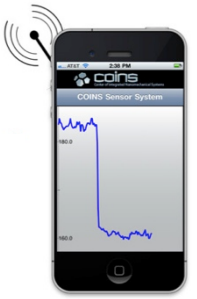








COINS Sensing System (CSS)



iPhone ®

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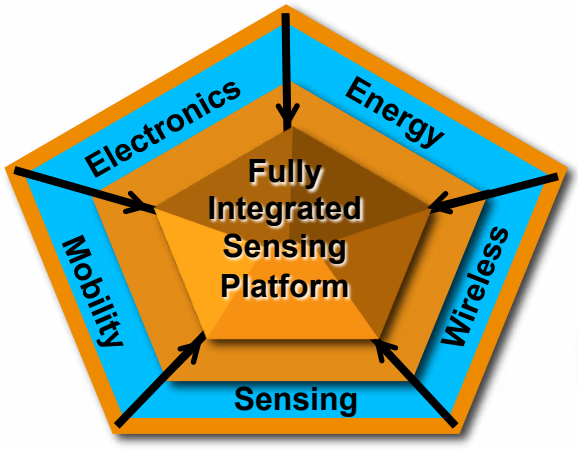
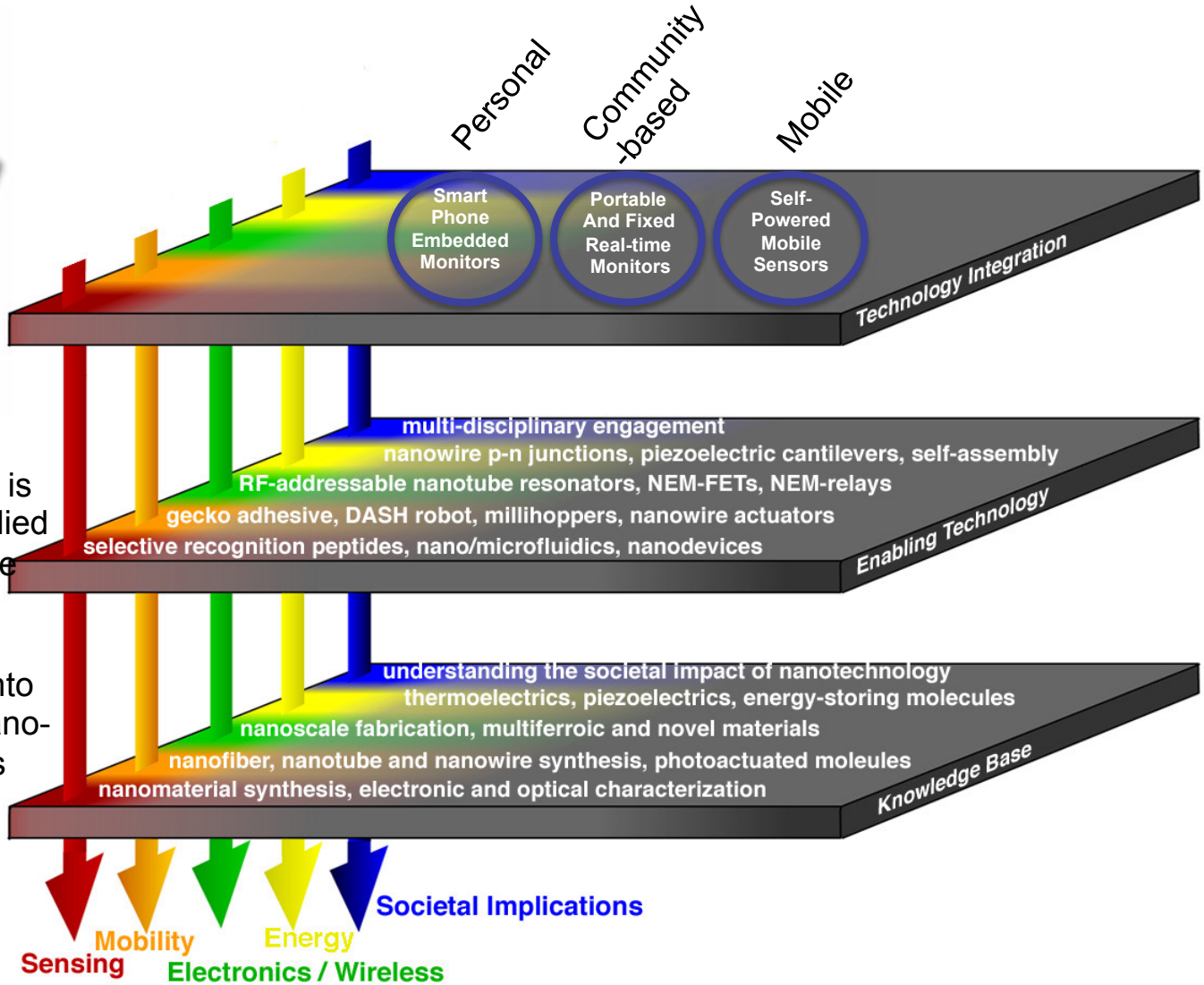
Systems Integration Plan



- To achieve its mission, COINS is carrying out the basic and applied research necessary to integrate nanoscale sensing, power, electronics, wireless communication, and mobility into the Platforms for Advanced Nano-enabled Detection Applications (PANDA)



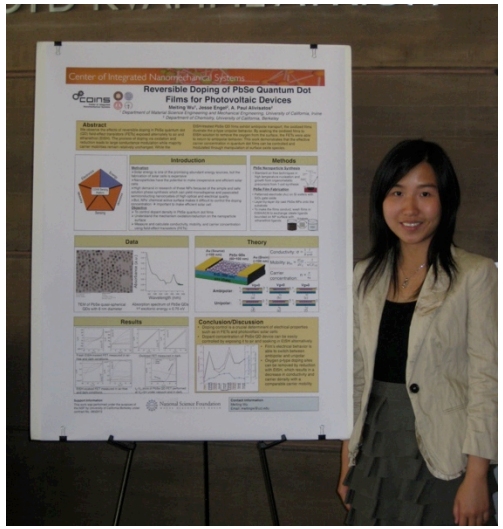
Education and Outreach

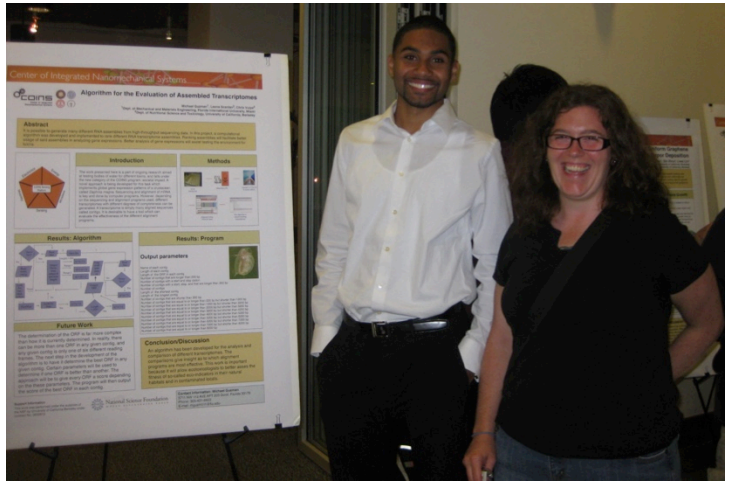
Current Programs:

- Research Experience for Undergraduates (REU)
- Research Experience for Teachers (RET)
- Nano Experience of Students (NES)

Future:

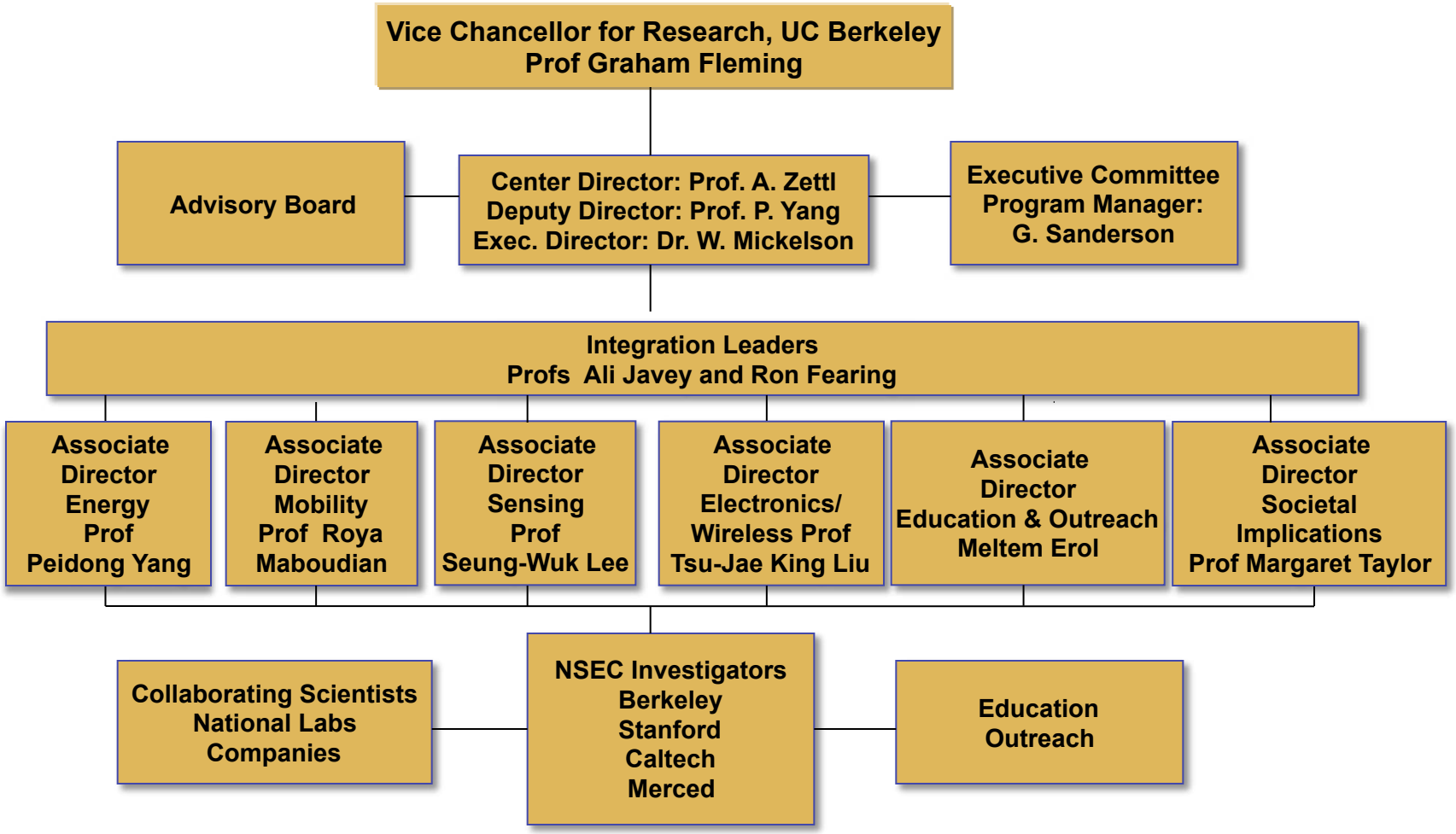
- Expanding REU program to entire College of Engineering





Graduate Pipeline Success: 3 URM & 1 female REU participants admitted to UCB PhD Programs & *attended* FA'12; 3 REU alumni, including two URM, admitted and will *attend* in Fall '13

COINS Management



COINS Investigators

University of California, Berkeley (Lead Institution)

Paul Alivisatos (Chem, MSE)

Daryl Chrzan (MSE)

Marvin Cohen (Physics)

Michael Crommie (Physics)

Ronald Fearing (EECS)

Ben Gilbert (LBNL)

Amy Herr (BioE)

Ali Javey (EECS)

Tsu-Jae King Liu (EECS)

Luke Lee (BioE)

Liwei Lin (ME)

Seung-Wuk Lee (BioE)

Roya Maboudian (ChemE)

Kris Pister (EECS)

Ramamoorthy Ramesh (MSE, Physics)

Sayeef Salahuddin (EECS)

Rachel Segalman (ChemE)

Ting Xu (MSE)

Margaret Taylor (Public Policy)

Chris Vulpe (Nutritional Science & Toxicology)

Feng Wang (Physics)

Junqiao Wu (MSE)

Peidong Yang (Chem)

Alex Zettl (Physics)

California Institute of Technology

Keith Schwab (Applied Physics)

Michael Roukes (Physics, Applied Physics, Bioengineering)

Stanford University

Beth Pruitt (Mechanical Engineering)

Tom Kenny (Mechanical Engineering)

Roger Howe (Electrical Engineering)

University of California, Merced

Lilian Davila (School of Engineering)

Valerie Leppert (School of Engineering)

Jennifer Lu (School of Engineering)

Erik Menke (School of Natural Sciences)

Michael Scheibner (School of Natural Sciences)

Lin Tian (School of Natural Sciences)

10 Represented Departments: Applied Physics, Bioengineering, Chemical Engineering, Chemistry, Environmental Science, Policy & Management, Electrical Engineering and Computer Science, Materials Science and Engineering, Mechanical Engineering, Nutritional Science & Toxicology, Physics

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WHERE DISCOVERIES BEGIN

Outline

Center Overview:	Alex Zettl
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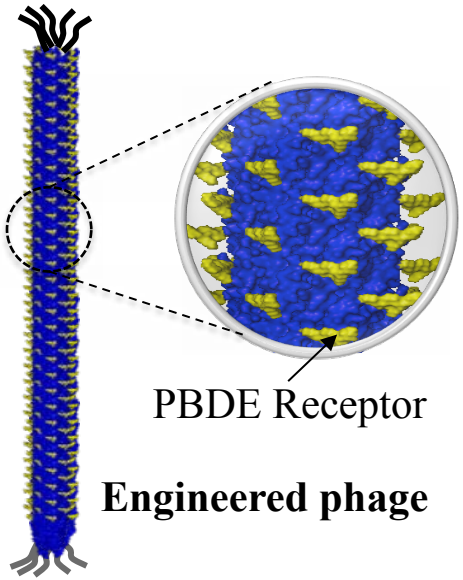
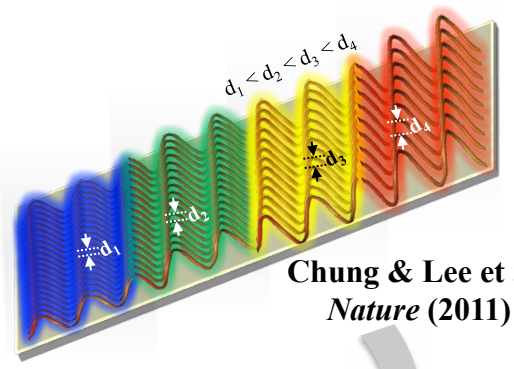
Sensing – Peptide-based Colorimetric Sensor



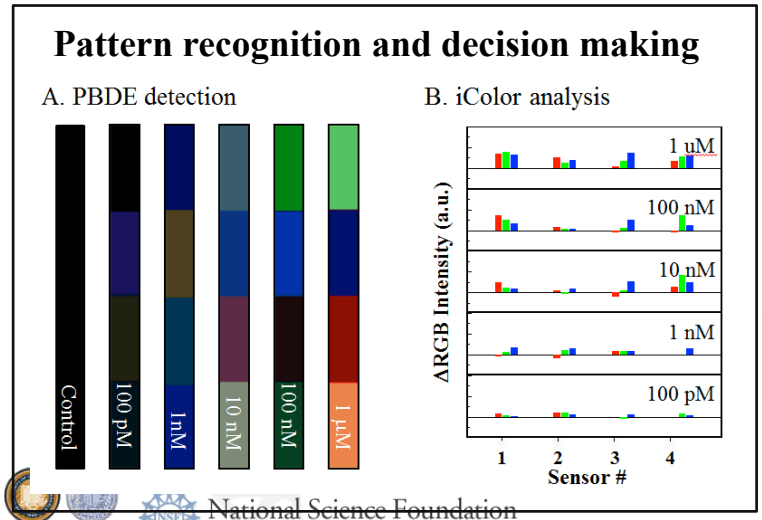
Self-assembly



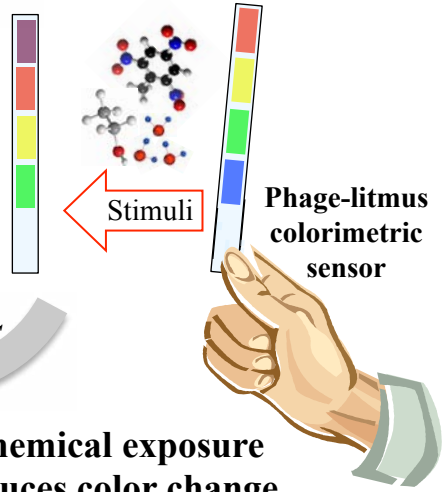
Chung & Lee et al, *Nature* (2011)

Sensing

Bio-inspired colorimetric sensor system



iColor reader



Decision

Analysis

Chemical exposure induces color change

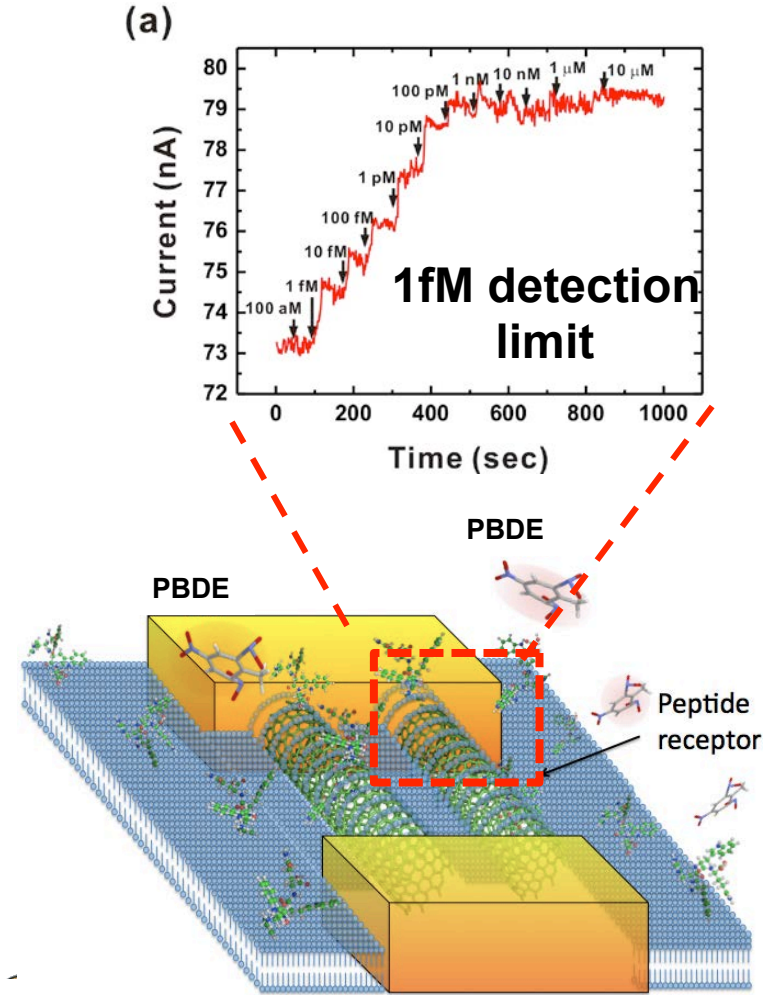
Reverse Site Visit
June10, 2013

Lee Lab

National Science Foundation
WHERE DISCOVERIES BEGIN

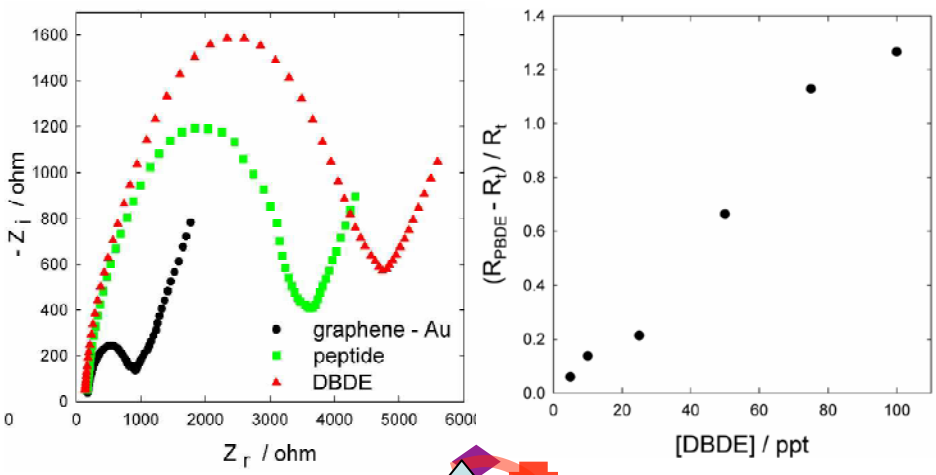
Sensing – Peptide/Nanodevice Integration

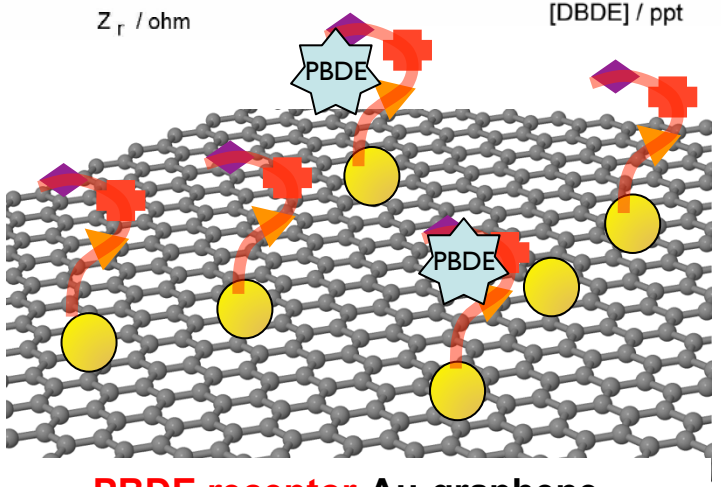
CNT-FET based PBDE sensor



***ACS Nano* (2011)**

Graphene-Au Impedimetric Sensor





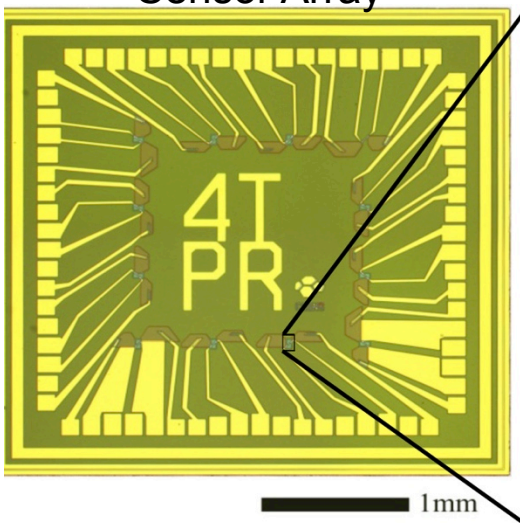
PBDE receptor-Au-graphene

***Nanoscale* (2013)**

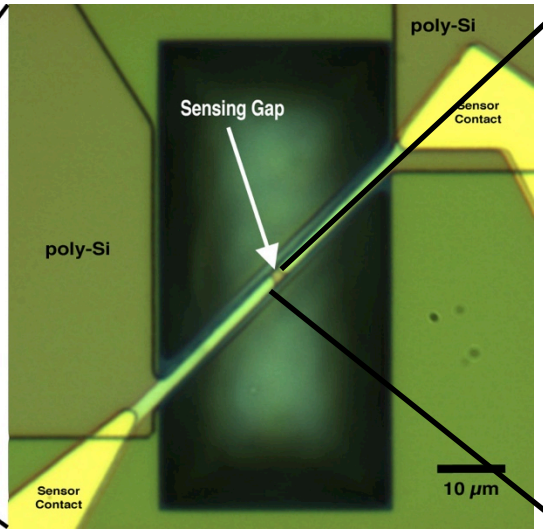
Reverse Site Visit
June10, 2013

Sensing - Microheater Gas Sensor Arrays

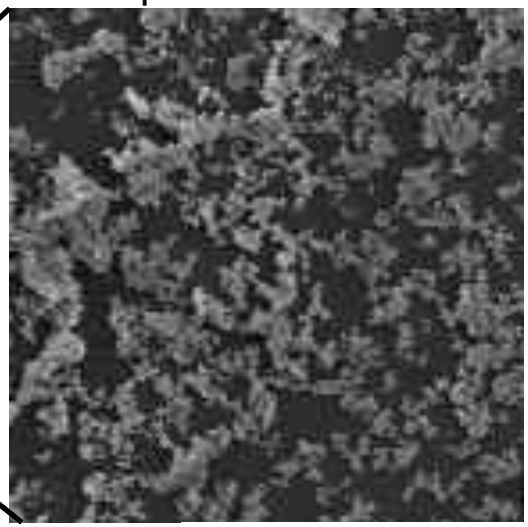
Sensor Array



Microheater Sensor

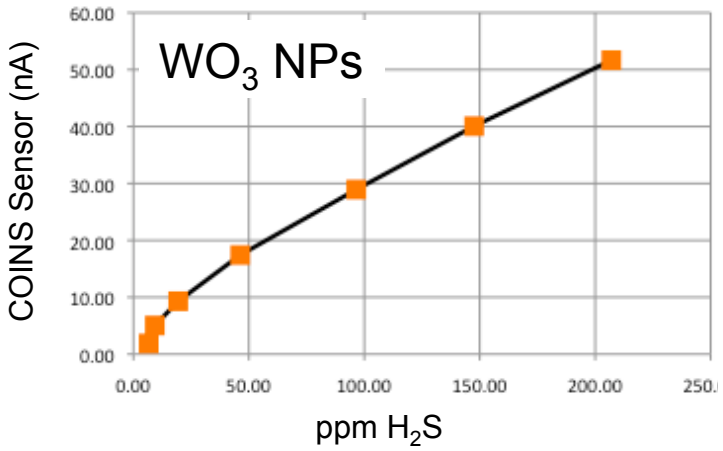


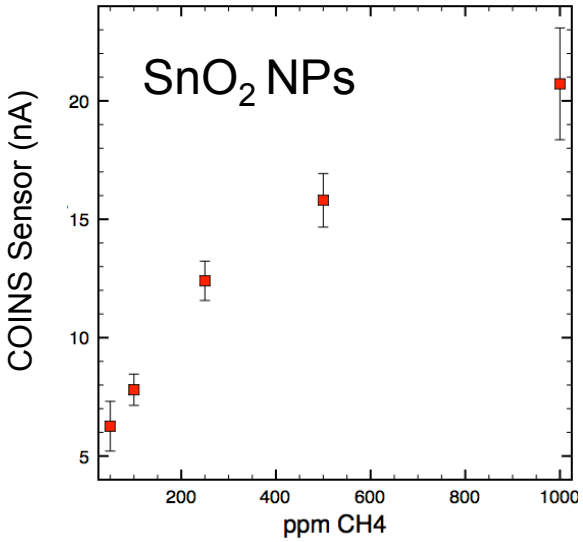
Nanoparticle Network



- 12 heaters per chip
  Peak power: ~4 mW @ 300°C
  Average power: 4 μW for 1ms pulses per second

- Multiplexing capabilities compatible with COINS Sensing System prototype for multi-analyte detection





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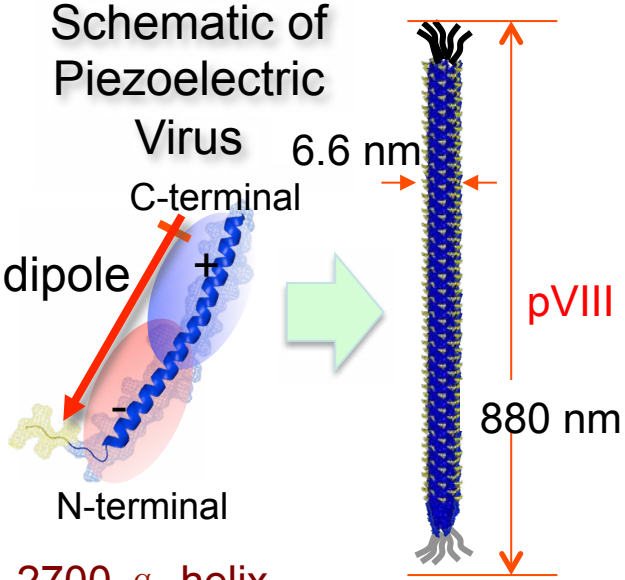
WHERE DISCOVERIES BEGIN

Reverse Site Visit
June10, 2013

Mickelson, Maboudian, & Zettl

Energy - Biopiezoelectric Energy Generator

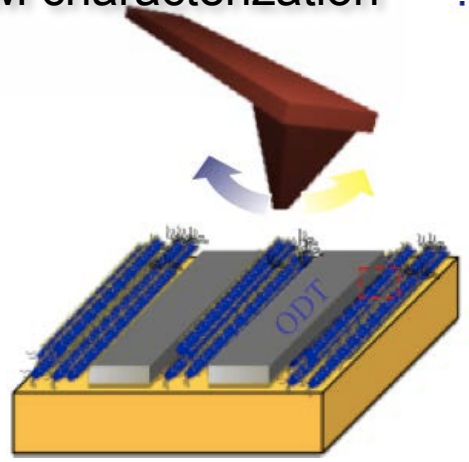
Schematic of Piezoelectric Virus



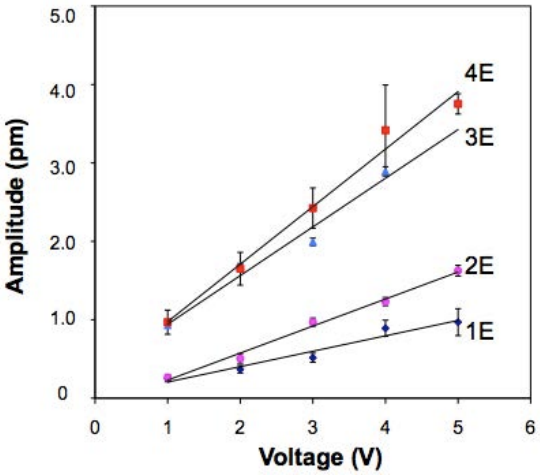
2700 α -helix pVIII subunits

Piezoelectric nanofiber

PFM characterization

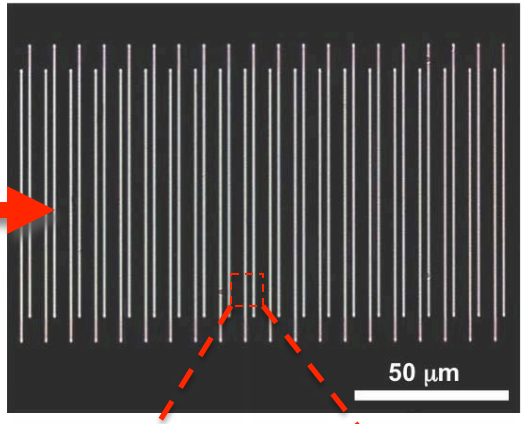


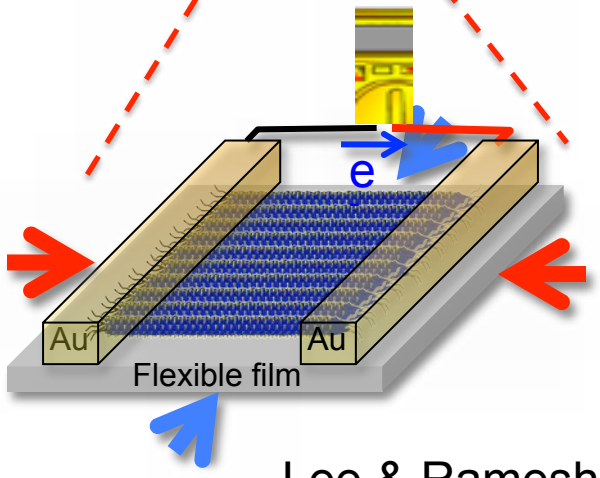
Performance Test

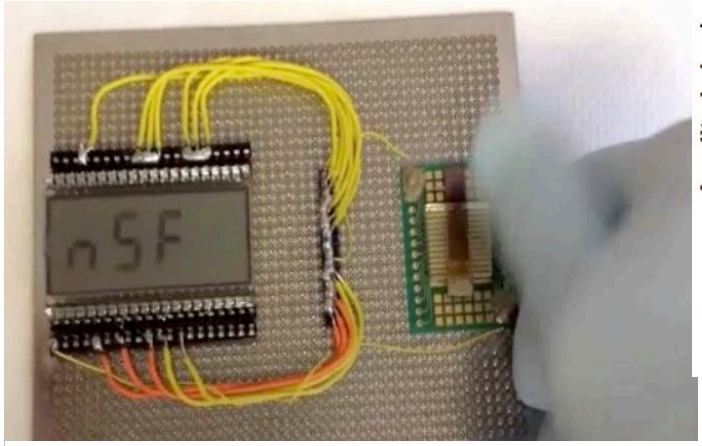


Device fabrication

Gold electrodes in Flexible PDMS





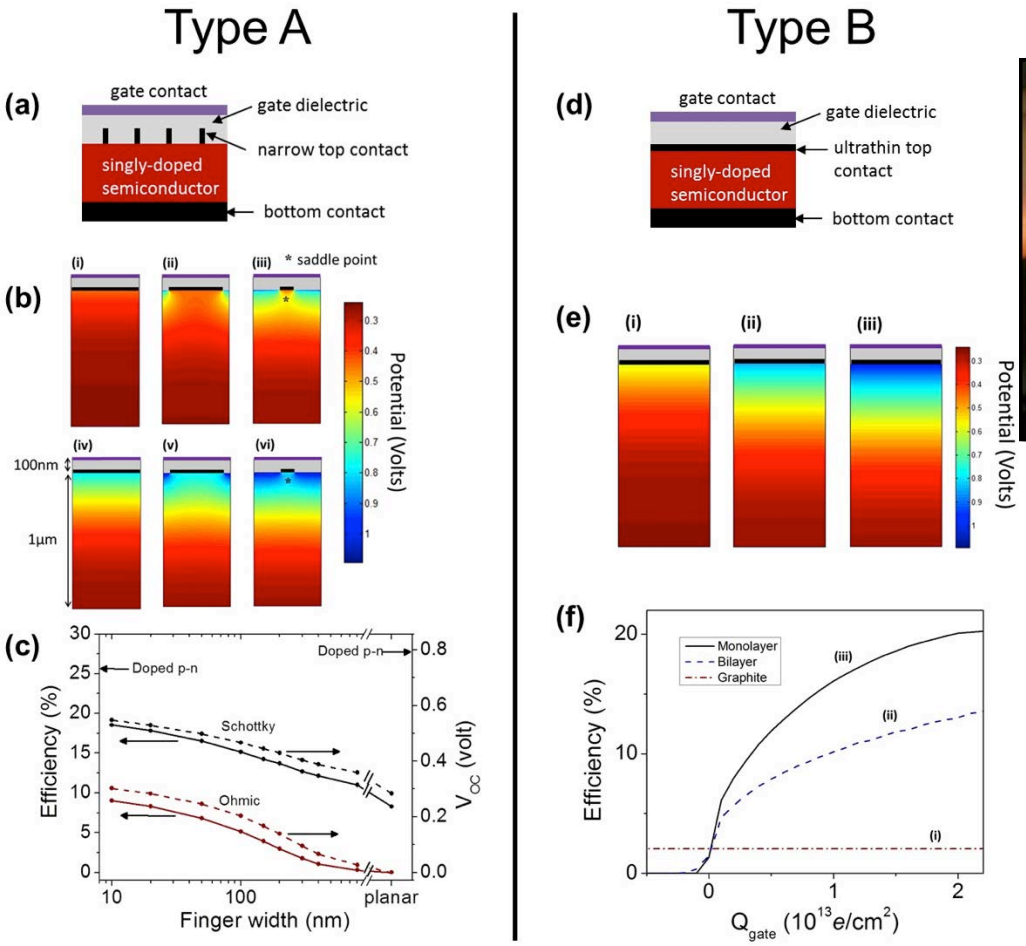


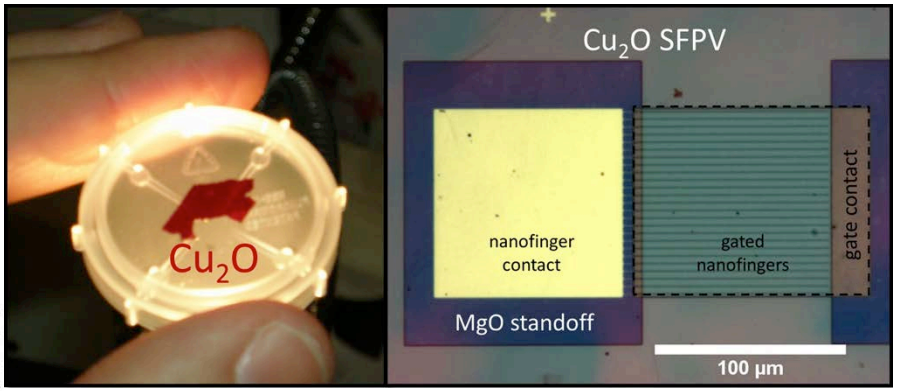
Biopiezoelectric Energy Generator

Reverse Site Visit
June10, 2013

Lee & Ramesh

Energy – Screen-Engineered Field-Effect Photovoltaics



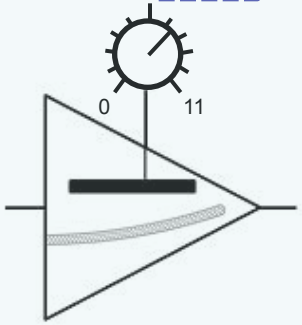


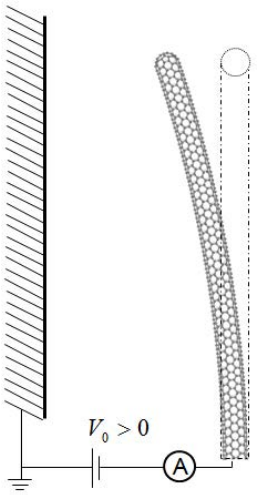
Screening-engineered field-effect photovoltaics (SFPV) – enables fabrication of low-cost, high efficiency PV from virtually any class of semiconductor

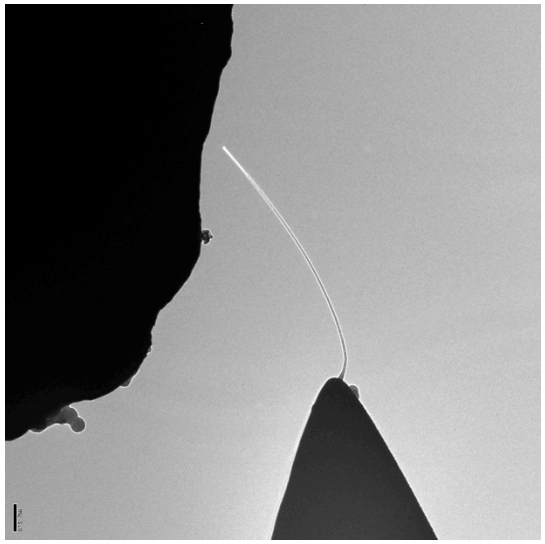
Electronics and Wireless – CNT Self-Oscillations and Parametric Amplification

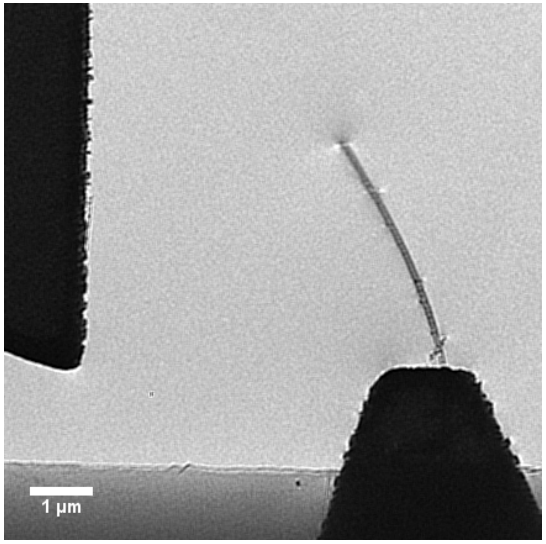
No External Control

$G(V_0, V_p, \phi)$

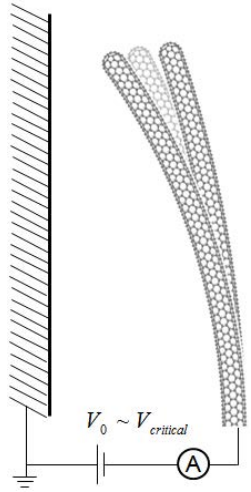


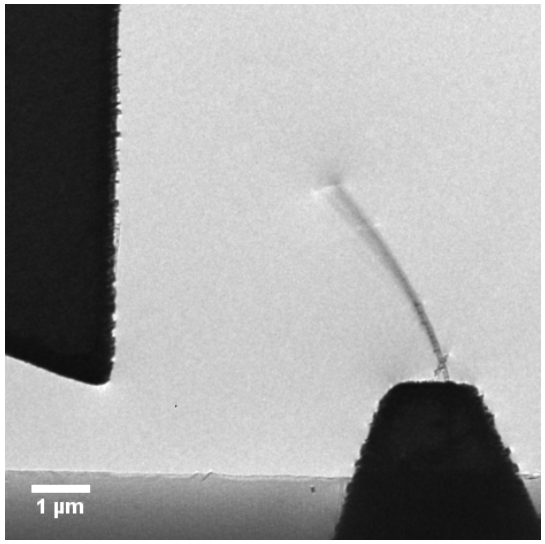






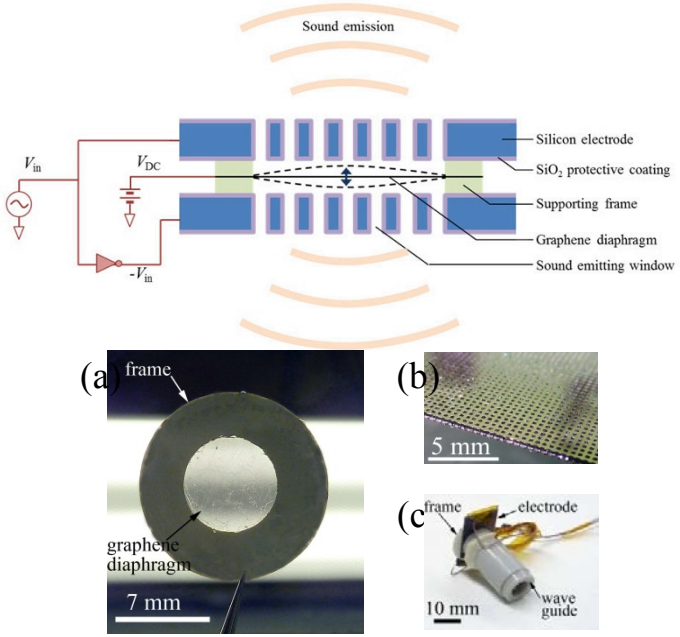
Sustained self-oscillations occur with a fixed DC bias!

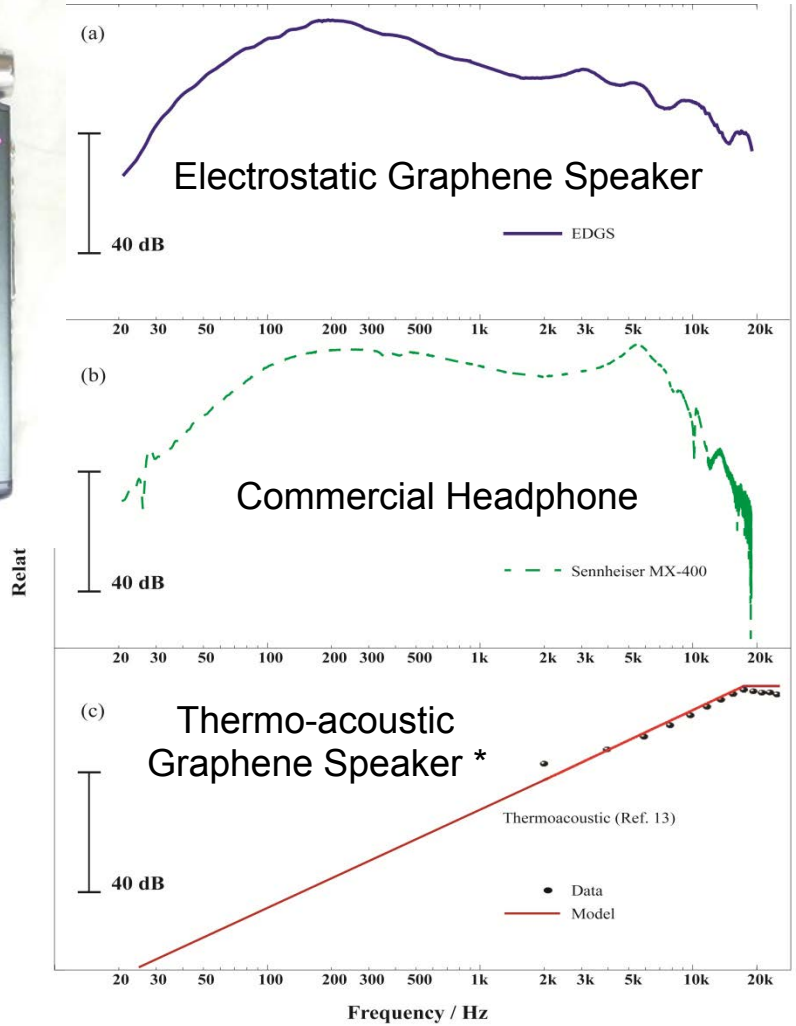




Alemán, B., Zettl. A., *et al*.

Electronics and Wireless - Graphene Electrostatic Loudspeaker



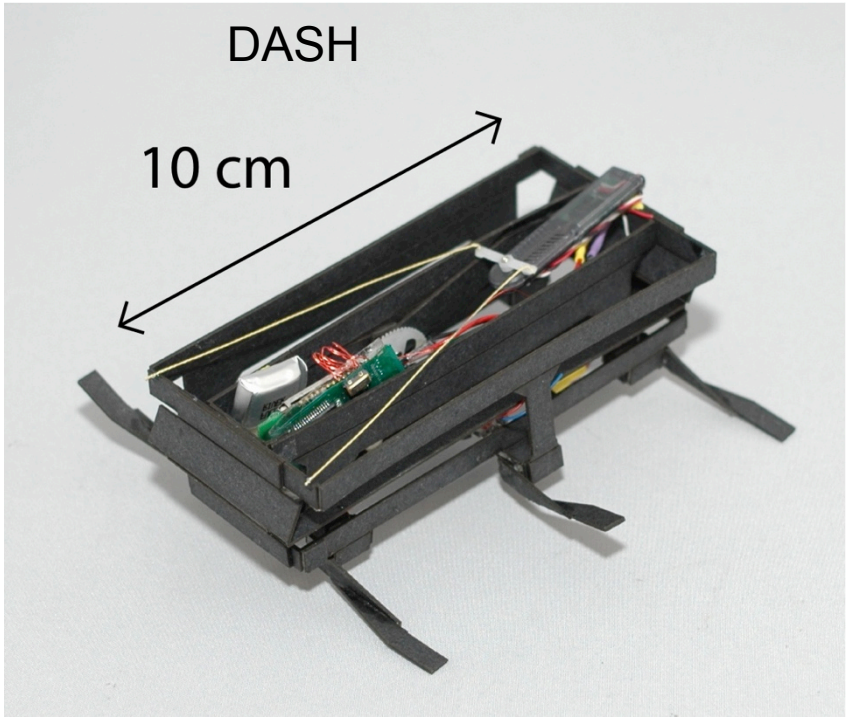


- Superior sound quality
- Flat response
- Low power consumption (<1 μW)
- High efficiency

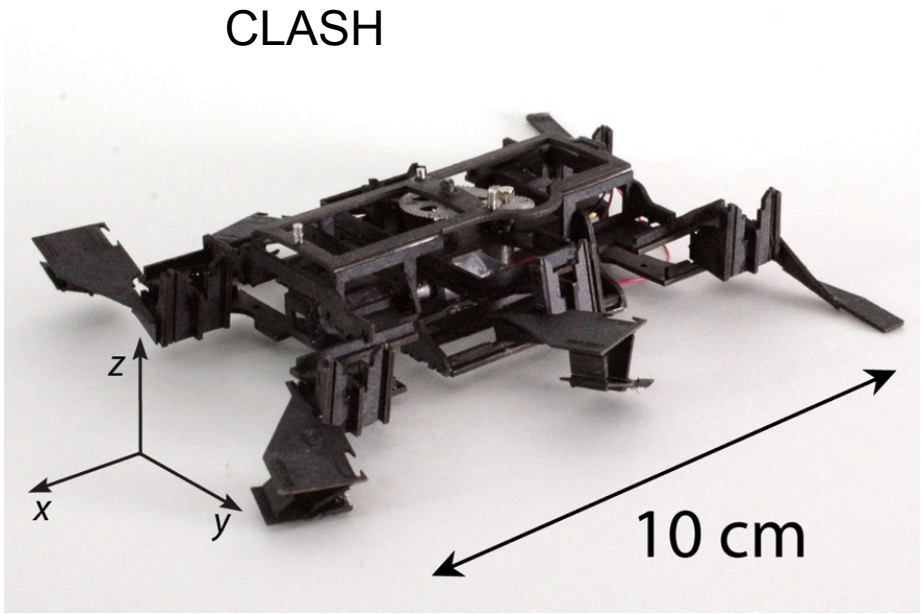
* H. Tian et al, ACS Nano **5** (6), 4878 (2011).

Mobility Platform

COINS CRAWLERS

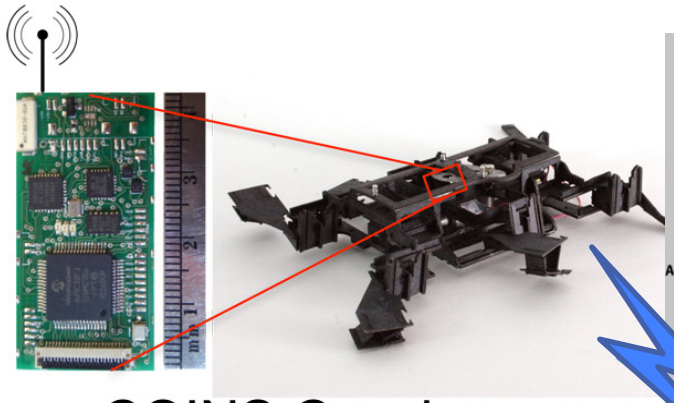


16 gram, 15 bl/sec



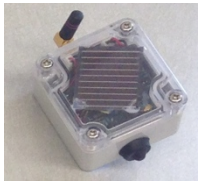
15 grams, 1.5 bl/sec (climbing)

Systems Integration – COINS Sensing System

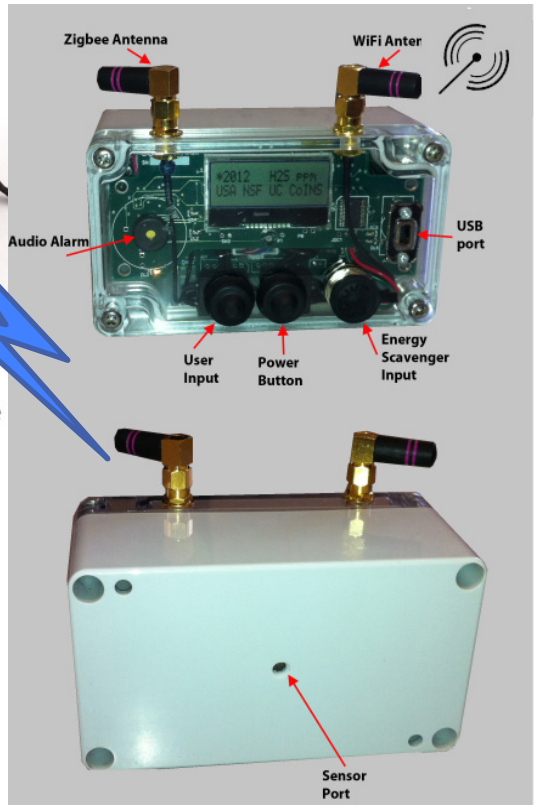


COINS Crawler

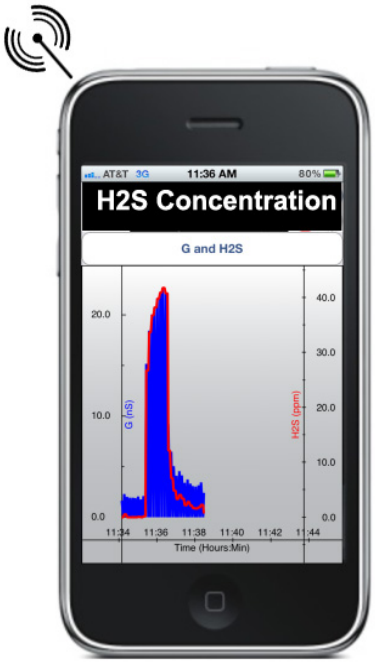
Zigbee Radio



COINS Sensor Tag



COINS Sensing System (CSS)



Outline

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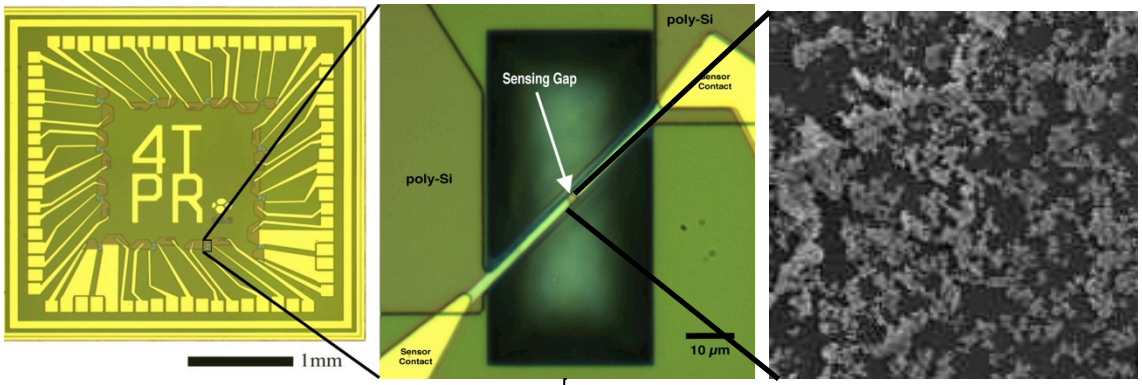
Research Plans:	Willi Mickelson
Education and Outreach:	Meltem Erol
Progress, Challenges, and Future:	Alex Zettl

Sensing Plans – Scalable Nanomanufacturing of Microheater Sensor Arrays



Current Status:

H_2S and CH_4 sensing capabilities with ultra low power. Low cost microheater fabrication on wafer scale. Nanomaterials sensing layer deposited manually.

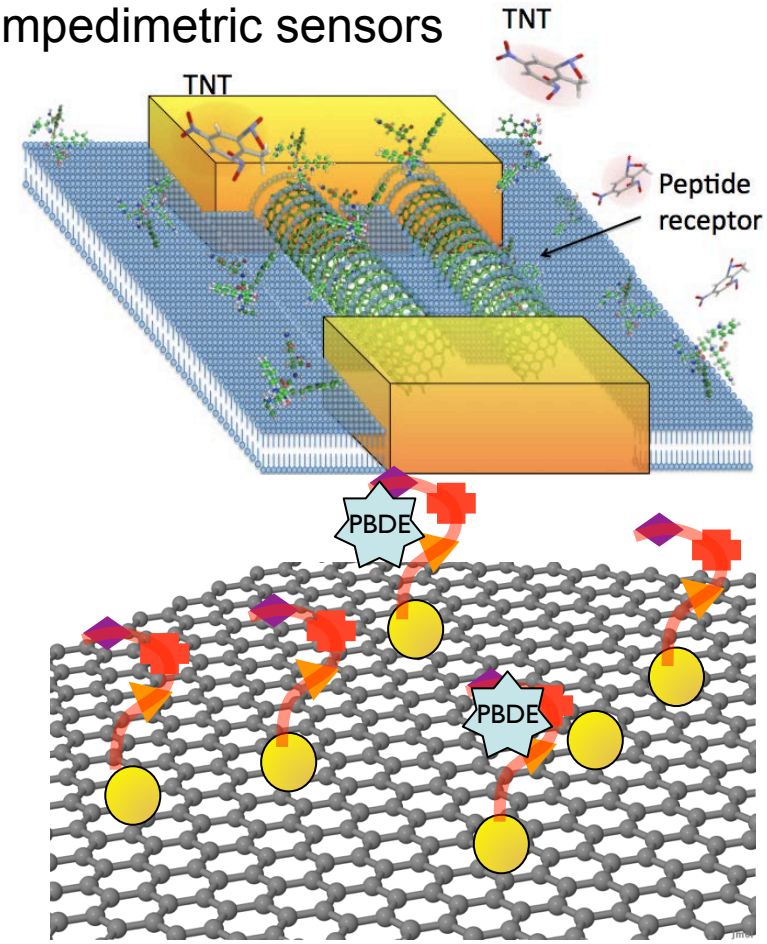
Future:

Use nanomaterials printing as a scalable method to manufacture multi-gas sensor arrays on a single chip.

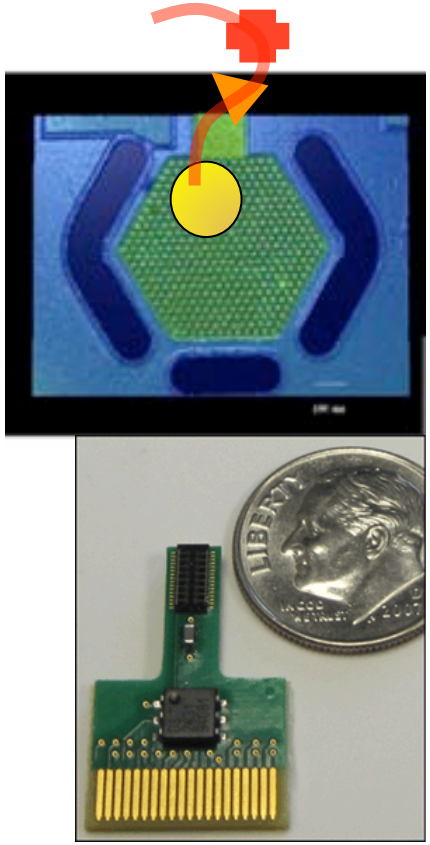
Target Gas	Candidate Nanomaterials	Why ?
Ozone (O_3)	CeO_2 and Fe_2O_3 with In_2O_3	EPA air quality index (AQI) gas, lung irritant, smog constituent
Carbon Monoxide (CO)	TiO_2; Pt, Pd, Au with WO_3; Pt with SnO_2	EPA AQI gas, toxic
Sulfur Dioxide (SO_2)	Pt with WO_3; Ni with SnO_2; ZnO	EPA AQI gas, causes acid rain
Nitrogen Dioxide (NO_2)	Pd with TiO_2; Au with WO_3; WO_3 with TiO_2	EPA AQI gas, smog constituent
Ammonia (NH_3)	Au, Pt with WO_3; SnO_2 with ZnO	Toxic, byproduct of livestock
Carbon Dioxide (CO_2)	Co, La with SnO_2; WO_3 with TiO_2	Personal comfort, air circulation management
Hydrogen Sulfide (H_2S)	WO_3; CuO with SnO_2; Ag with SnO_2; In_2O_3	Highly toxic, exhaust from petroleum refineries
Explosive gases (H_2 ,CH_4, C_3H_8, etc.)	Ag, Cu, Mo, Pd, and Pt with SnO_2 and ZnO	Home and personal safety, e.g., leak detection

Sensing Plans – Recognition Peptide-based Sensors

Current Status:
Peptide-based FET and impedimetric sensors



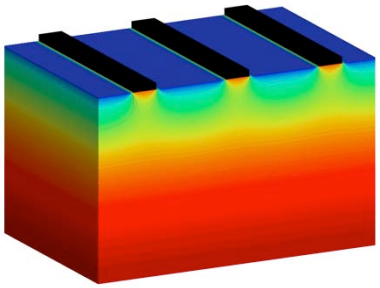
Future:
Peptide-based ultra sensitive mass sensors



Partnering with
Matrix Sensors, Inc.

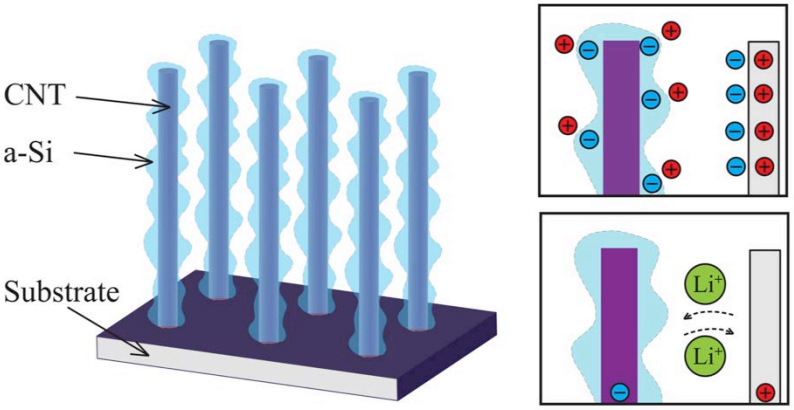
Energy Plans

- **Current Status:**
- SFPV devices made for Si, Cu_2O



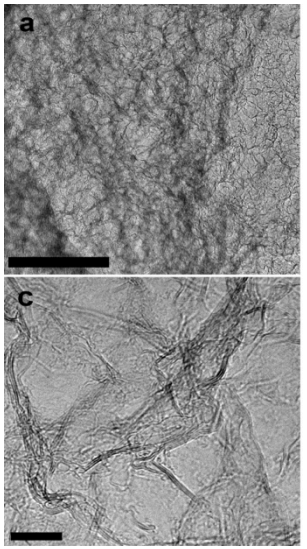
- **Future:**
- Explore new materials, such as sulfides and phosphides for SFPV

-Carbon nanotube and SiC nanowire-based supercapacitors



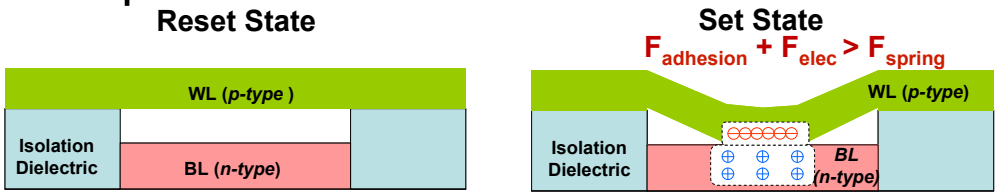
-High porosity monoliths graphene aerogels for supercapacitors and battery electrode

5 mm

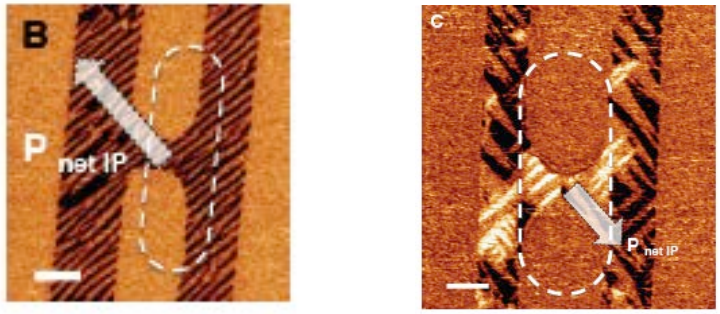


Electronics and Wireless Plans

- **Current Status:**
- Nanoelectromechanical Memory (NEMory) with 4 μm x 4μm cross point size

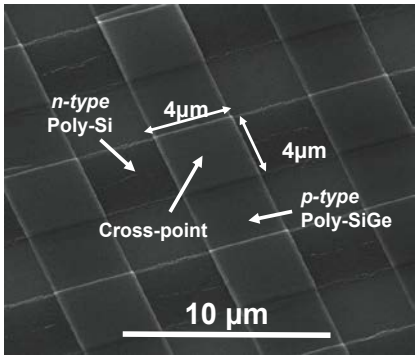


- Magnetic Domain Switching with Electric Fields

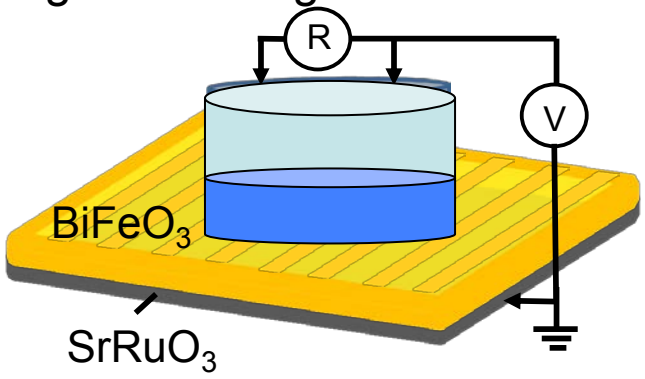


Experimental domain pattern before and after applying and electric field

- **Future:**
- NEMory with sub-micron cross point size

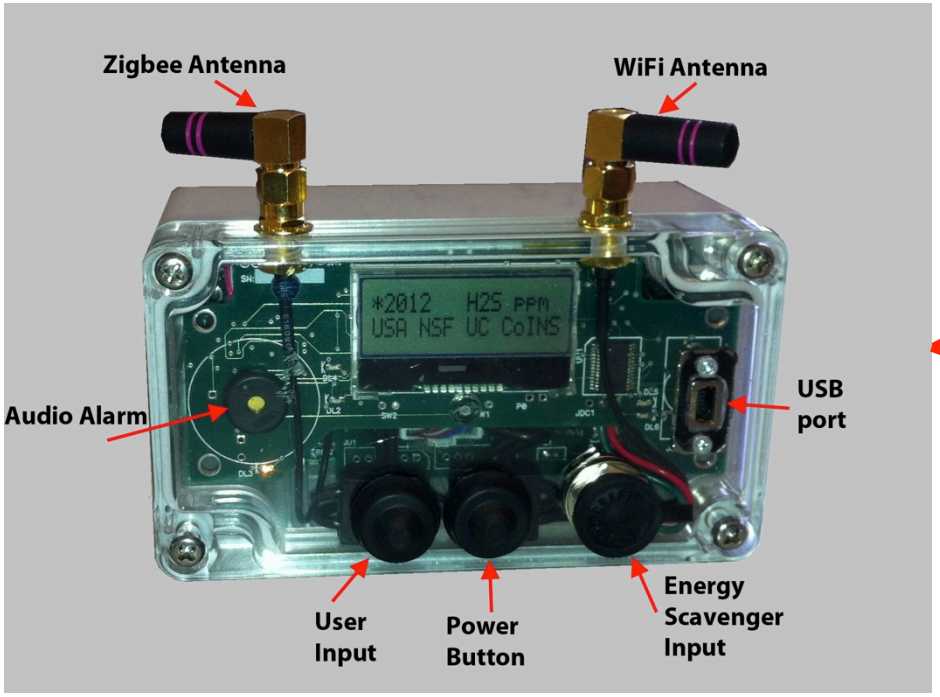


- Electric field-switchable magnetic storage

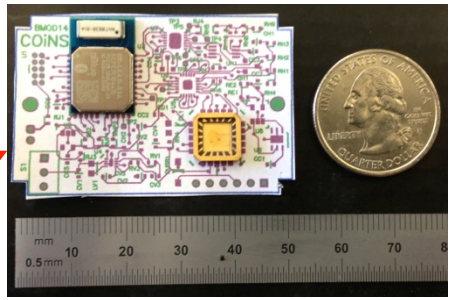


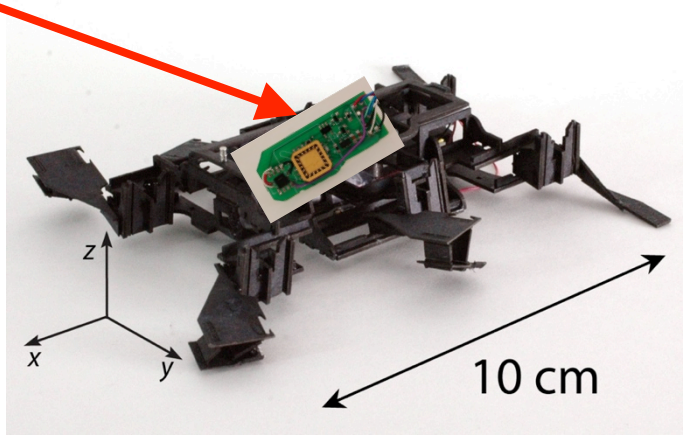
Mobility and Systems Integration

Current Status:
Full Featured Prototype



Future:
Bluetooth Low Energy (BLE) Module
Optimized for Microheater Platform





Gas Sensing Robots

Post NSEC COINS

Research

Education and Outreach

Current

Fundamental: Basic research critical to understanding nanomaterials, nanodevices, and nanosystems

Next Generation: Applied research that is 5-10 years away from commercialization

Applied: Applied research that could feasibly be commercialized within 5 years

Future Legacy

Academic

Continue the multidisciplinary research partnerships forged within COINS to pursue long-term nano-enabling sensing technologies though both industrial and government funded projects

Commercial

Commercialize COINS applied research technologies via spin-off company formation and incubation within the continually-developing UC Berkeley innovation centers

Educational

Expand the education and outreach infrastructure built by COINS to the entire campus. Leverage the great REU programs to bring a campus-wide program open to all STEM faculty

COINS Beyond 2014

- **Academic**
  - Multidisciplinary connections made within COINS will remain and teams will pursue nano-enabled sensing and energy related research
  - Funding will be through federal grants, such as ERCs, MURIs, and MRSECs, and leveraged through industrially sponsored research
- **Commercial**
  - COINS has and continues to spin-off companies based on its technologies.
  - COINS is working with UC Berkeley administration to formulate an innovation infrastructure to nurture and incubate technologies in collaboration with the business school and law school to assess technologies, formulate business plans, and IP strategies at a very early stage
- **Education**
  - COINS successful E&O program is being transformed into a larger program encompassing the entire College of Engineering
  - All STEM related faculty will be able to participate in the summer REU program and increase the impact of their E&O effort

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Education and Outreach

Overview

Education and Outreach Goals:

- Recruit and retain the NSE/STEM workforce
- Prepare the NSE workforce
- Increase the public's awareness and understanding of NSE

A common thread: Focus on increasing diversity

NSE Courses Offered

NSE Courses at UC Merced:

Primarily NSE

MSE 118: Intro to Nanotechnology and Nanoscience (undergraduate)

MSE 126: Nanodevice Fabrication (undergraduate)

BEST 226: Nanodevice Fabrication (graduate)

Nanocontent is incorporated into several other courses

The Biological Engineering and Small-Scale Technologies Graduate Emphasis Program continues to grow: 19 students are currently in the program with an additional 4 in the pipeline.

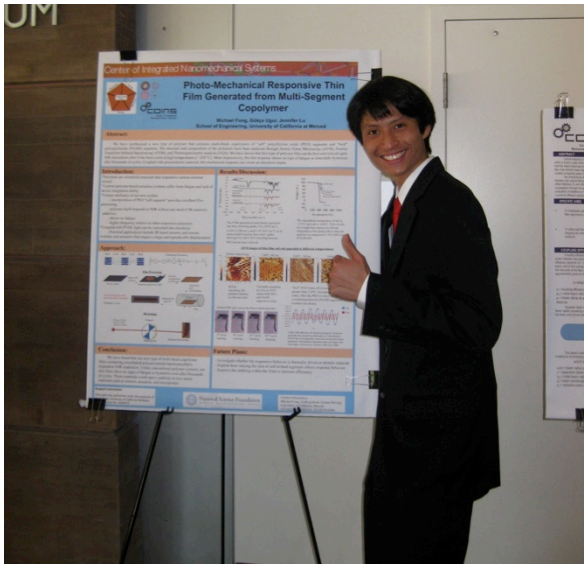
The Nanotechnology Emphasis for Materials and Biological Engineering continues to be a popular option for undergraduate students and the associated courses are being added as technical electives for Mechanical Engineering.

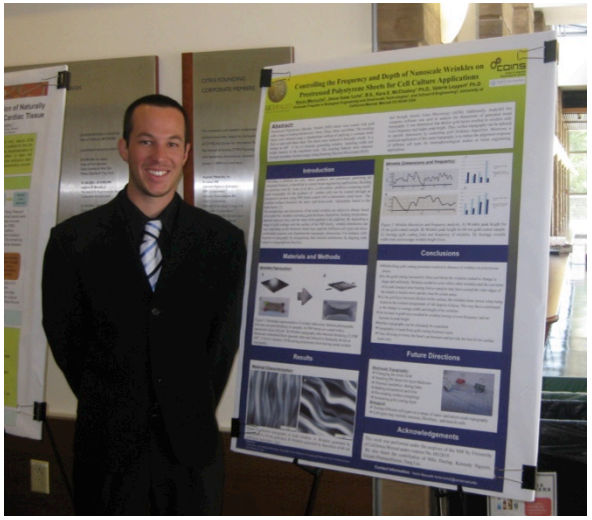
Undergraduate Education

Summer Research Program

UC Merced

- 11-15 students
- 10 week experience
- Joint orientation & poster session with UC Berkeley
- Fall Showcase to interest students in COINS & nanoscience research





Graduate School Success: COINS REU a pipeline to UC Merced Biological Engineering Small Scale Technologies (BEST) MS program. Twenty three current graduate students; 6 are former Merced COINS participants.

Engineering Service Learning

- Program created by COINS UCM PI
- Pairs Merced undergraduate teams with local non-profit organizations
- Castle Science & Technology Center Team has developed numerous nanoscience exhibits:
  - developed and delivered 6 exhibit panels on nanotechnology, including a working model of a Space Elevator based on carbon nanotubes
  - Students have worked with the museum to provide improved signage (over 100 signs) for the museum in English, Spanish, and Hmong

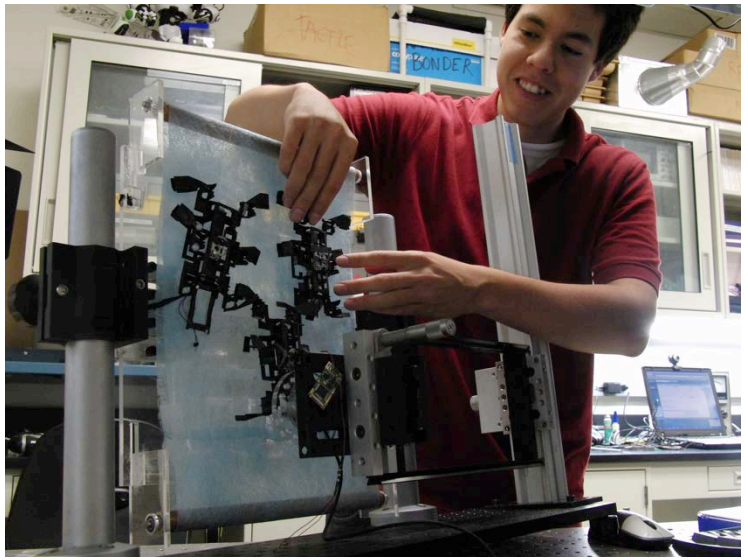
Undergraduate Education/Graduate Recruitment

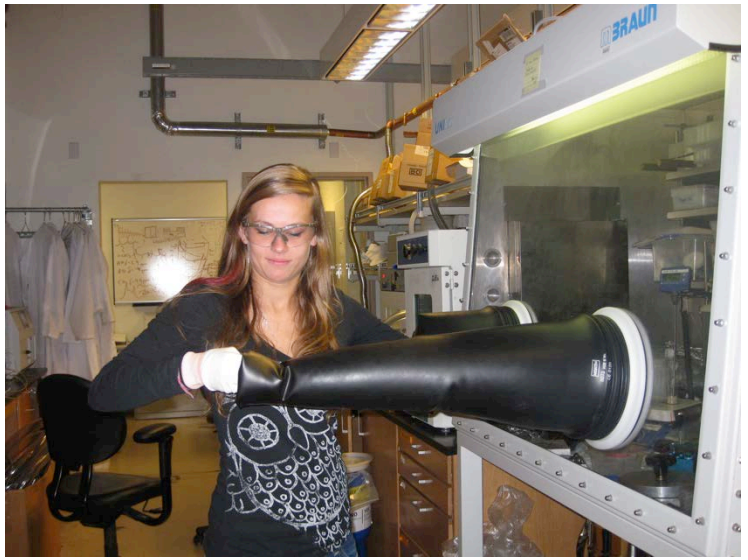
Summer Research Program

UC Berkeley

- 12-14 participants
- Weekly seminars
- GRE Prep Course
- Technical Paper & Presentation
- Individual advising and counseling

Graduate Pipeline Success: Since 2010, 9 URM/female students have enrolled in PhD programs (7 at UCB ; 2 at Stanford)





Looking Ahead

Office of Engineering Graduate Outreach

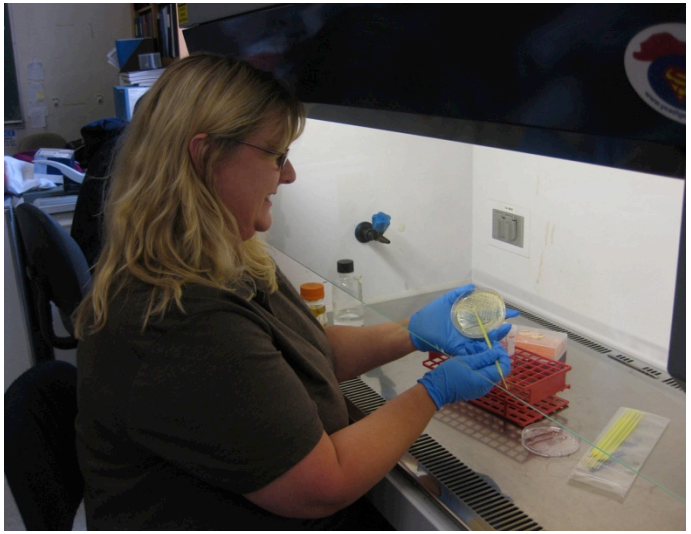
- Umbrella organization for REU programs
- Coordination with NSF centers on using REU's as URM graduate pipeline
- Resource to faculty affiliated with NSF centers on other campuses

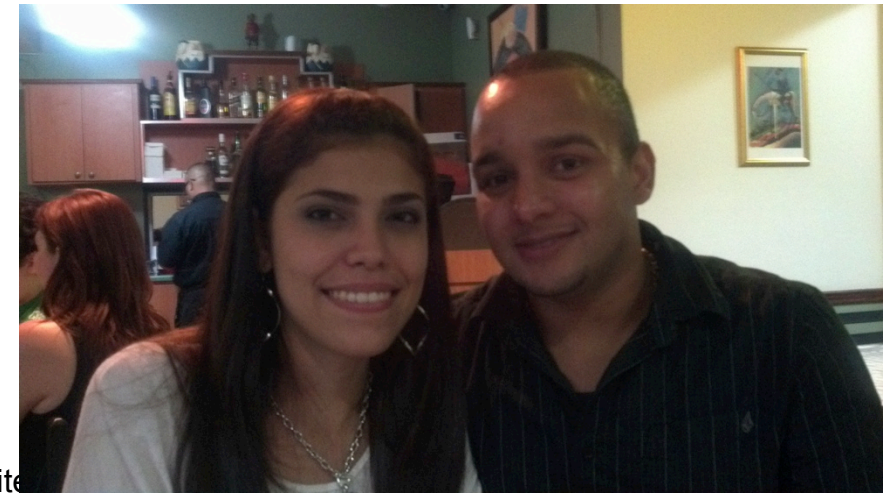
Engineering Preview Day

- Pilot program launched in Spring 2013 bringing 11 academically talented female and URM rising seniors to visit the Berkeley campus (9 URM/5 female)
- 3 days of networking with faculty, students, and research scientists, including individual meetings with faculty
- Workshops related to graduate school, strengthening the application & tour of Molecular Foundry at LBL
- Goal: instill a connection to Berkeley to help recruit for graduate school if admitted
- Co-sponsored by COINS, Sandia National Laboratory and College of Engineering

COINS Making a Difference!

I had a great time, met a bunch of really awesome people, and learned a lot of valuable information. It has definitely been one of the highlights of my undergrad years.I hope to see you again someday, perhaps next fall ;). – Preview Day Participant





It exceeded my expectations. I got so much hands on experience, I gained confidence in the lab. I also discovered how easy it is to explore another discipline if you are willing to put in the effort and are not afraid to ask for guidance. –Deborah Corvaglia, UC Merced

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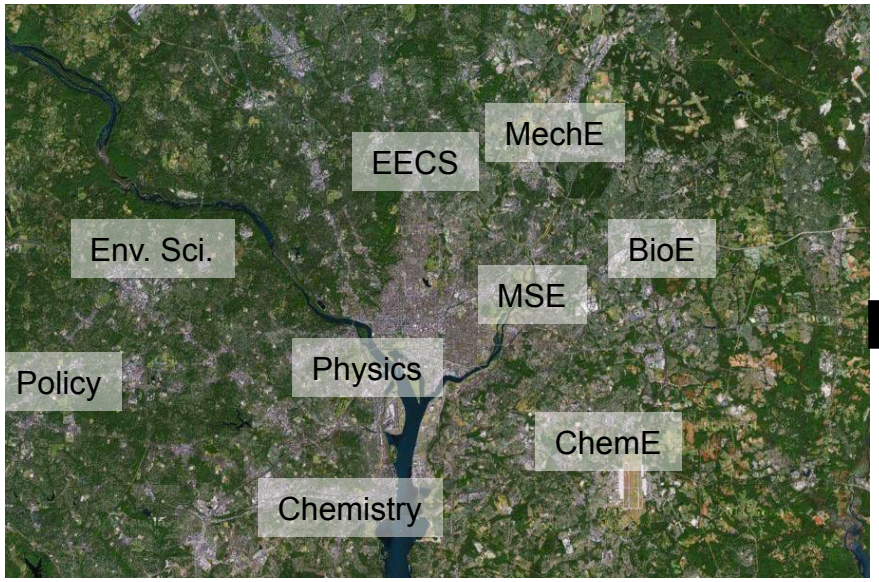
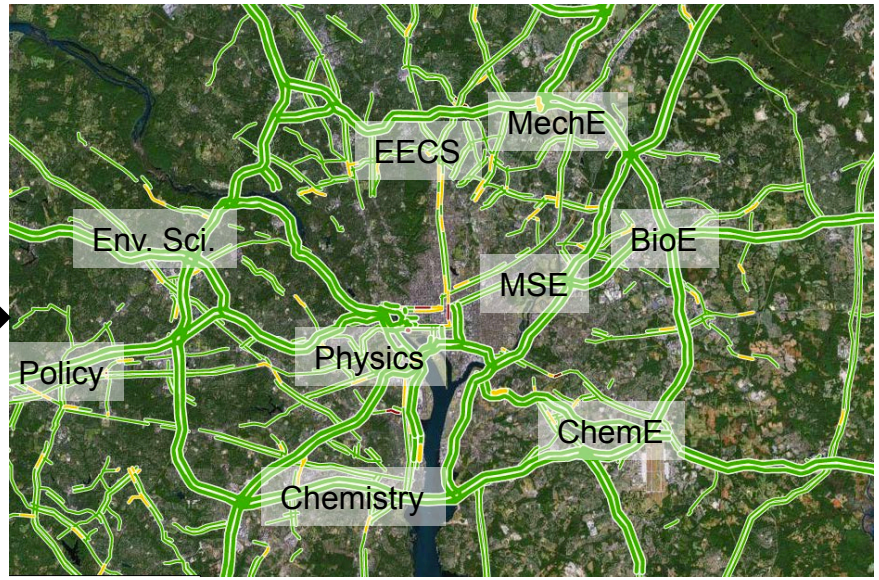
COINS Effect on UC Berkeley

Pre - COINS



Post - COINS

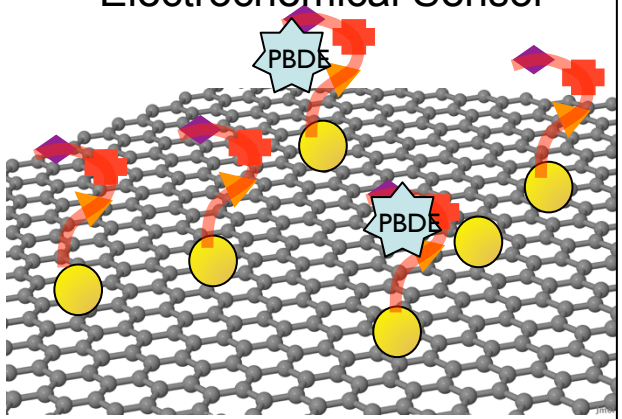


COINS Progress

- Multidisciplinary Research Partnerships
  - Teams from physics, engineering, chemistry, and biosciences have formed resulting in innovative and novel research and technological solutions

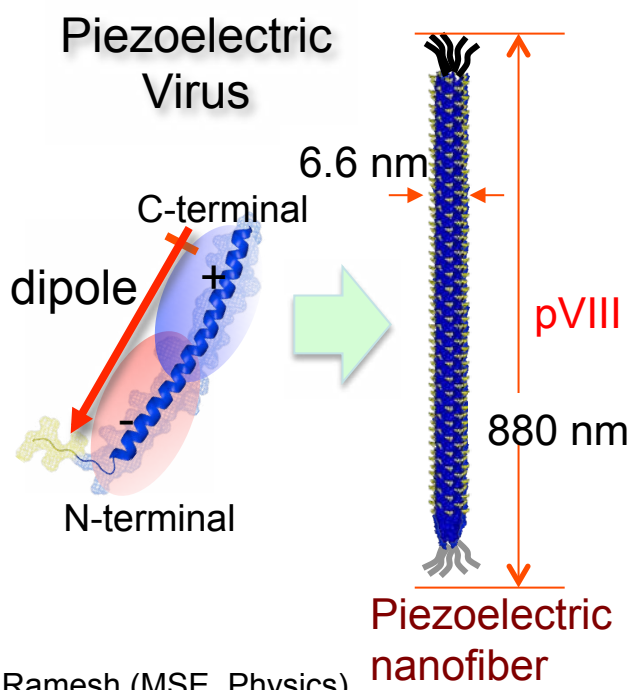
Examples

Graphene/peptide-based Electrochemical Sensor



Mickelson (Physics), Maboudian (ChemE), and Lee (BioE)

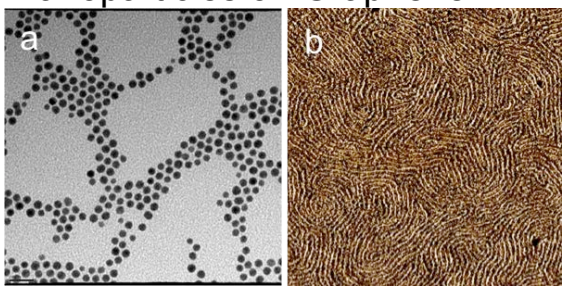
Piezoelectric Virus



Ramesh (MSE, Physics) and Lee (BioE)

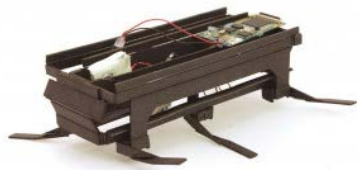
Reverse Site Visit
June10, 2013

Block Copolymer Patterning of Nanoparticles on Graphene



Zettl, Mickelson (Physics), and Xu (MSE, Chemistry)

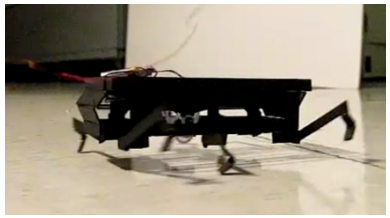
COINS Robotic Platform



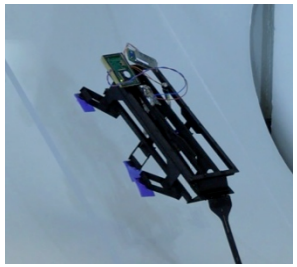
Fearing (EECS), Maboudian (ChemE), Mickelson, Zettl (Physics), Full (Biology), Javey (EECS), Milgrome (BNNI)

National Science Foundation
WHERE DISCOVERIES BEGIN

Mobility - Robotic Crawlers and Gecko Adhesives

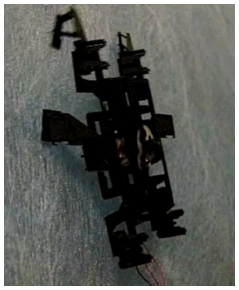


DASH on horizontal surfaces



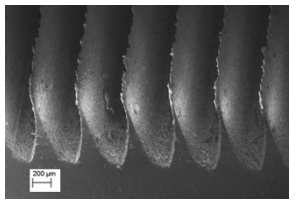
DASH with PDMS ridges climbs statically at 60°

HDPE adhesive foot testing



CLASH climbs vertical cloth

CLASH climbs with magnets

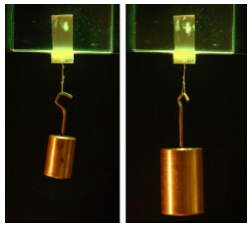


CLASH climbs dynamically at 70°; statically at 75°

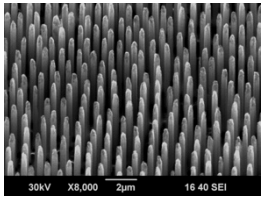
MOBILITY PLATFORM

COINS ADHESIVE

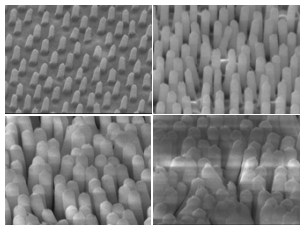
High friction on glass from PP nanofibers from PC mold



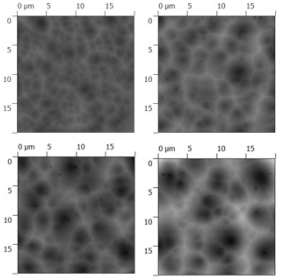
Adhesion on glass from PP nanofibers from PC mold



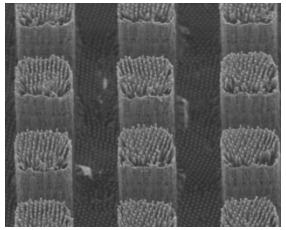
Si template using colloidal process



Varied nanofiber geometries from Si mold yield high friction



Characterization of surface roughness and energy



Hierarchical PE nanofibers from Si mold

COINS Progress

- Technology and Knowledge Transfer
  - Over 30 PhDs awarded (13 to industry), over 200 publications, 28 patents awarded, and over 20 patent applicants and invention disclosures, 7 spin-off companies
- Recent Spin-Off Companies:

Dash Robotics

  - Commercializing the DASH robot that was developed under COINS

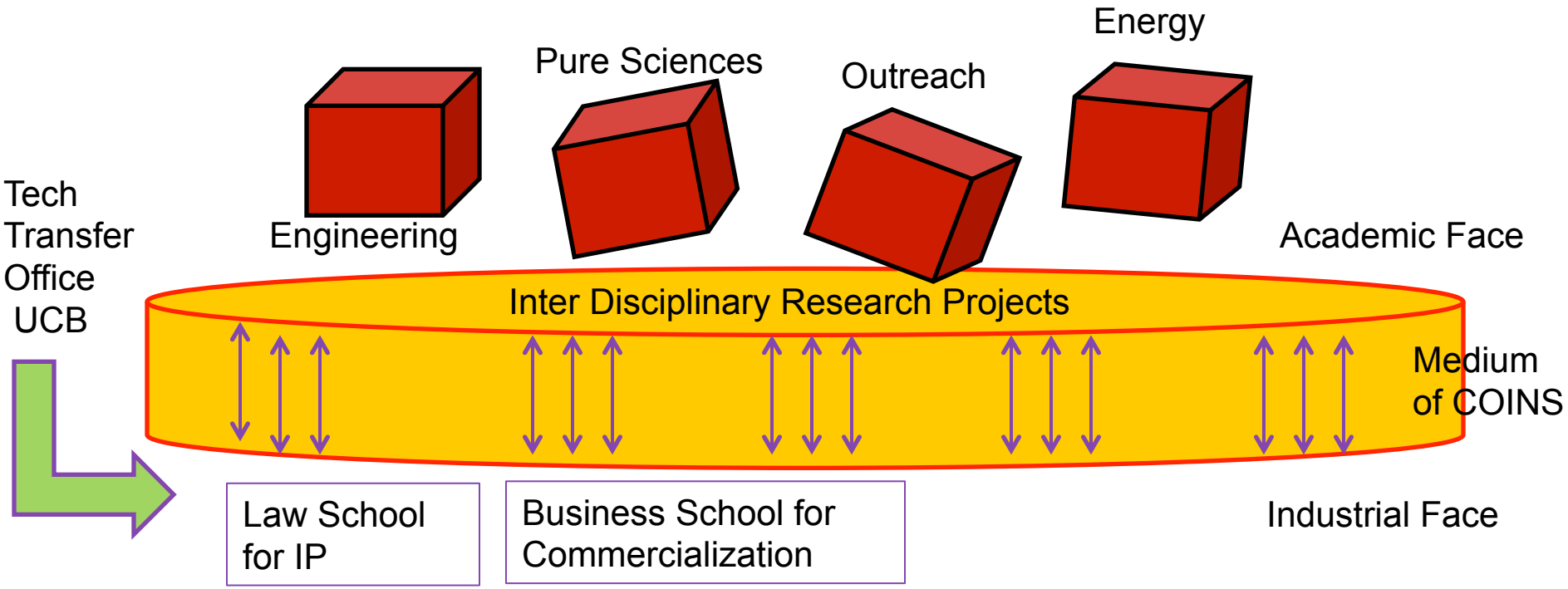
Xite Solar

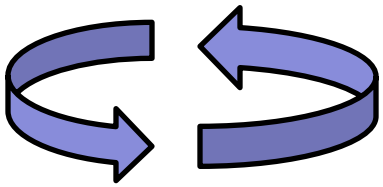
  - Formed around the screen-engineering field-effect photovoltaic technology and IP pursuing low cost solar cells from Earth abundant compounds

Challenges and Solutions

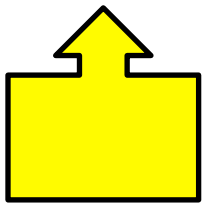
- Challenge: “Language Barrier”
  - Multidisciplinary researchers often don’t speak the same language and comprehension across disciplines was low.
- Solution: Biweekly COINS meetings
  - Graduate students, postdocs, and investigators meet regularly to discuss research results and goals. Over time this forum lower that “language barrier” enabling multidisciplinary collaboration
- Challenge: Working outside of comfort zone
- Solution: Persistence and Highly Desirable Common Goals
  - Emphasis on a multidisciplinary approach to research by the COINS executive committee in their selection of projects created a sea change in collaboration

Future Innovation Infrastructure

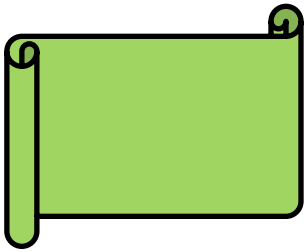




Spin offs



Industry Collaborations (JDA)



Licensing

Future Opportunities and Challenges

- Research Topics
  - Scalable Nanomanufacturing
  - 2D Materials: Beyond Graphene
  - Nano-Neuro (Brain Initiative) and Sensors
  - Nano-Energy (Energy Circuits)

- Funding Mechanisms
  - Federal: MRSEC, ERC, MURI, Nanotechnology Signature Initiatives
  - Industrial Sponsored Research

- Commercialization
  - UCB Incubators: Skydeck, Foundry @ CITRIS
  - Coupling to Haas School of Business and Boalt School of Law

Thank You

Questions?