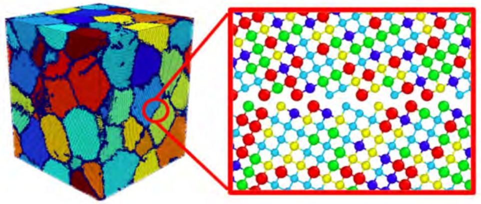
# Materials and Chemical Research

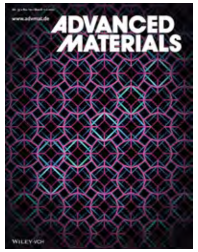
UCI Samueli
School of Engineering

### Manufacturing Science

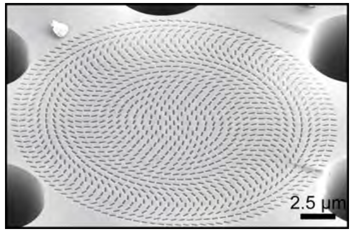
### Structural Nanomaterials



### Mechanical micro/nano-metamaterials

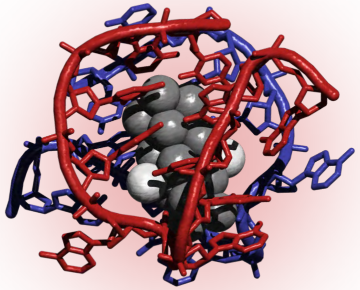




### Nanomaterials for Light-Matter Interaction

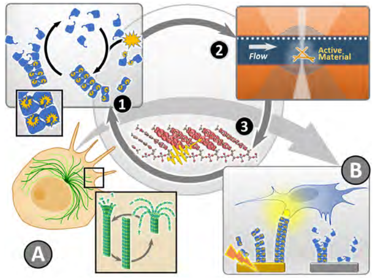



### Nanomaterials for Quantum Science

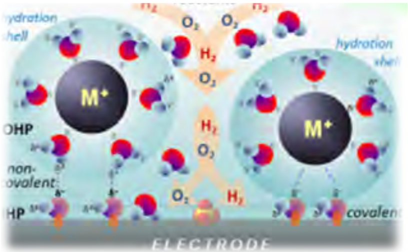
### Materials Informatics



### Bio- and bio-inspired materials




### Electrochemistry Energy Materials



# Materials and Chemical Research



## Manufacturing Science

Diran Apelian

Julie Schoenung

Lorenzo Valdevit

Tim Rupert

Ramin Bostanabad

D. R. Mumm

# Institute for Design and Manufacturing Innovation (IDMI)

UCI Samueli
School of Engineering

SLM® 125HL
(metals)


Stratasys Fortus 450mc
(workhorse FDM)


Stratasys Objet260 Connex3
(1000 digital materials)

(7) Autodesk Embers
(high-res. stereolithography)

Trotec Speedy 360
(laser cutter)


## UCI/Saratech partnership

Big Rep Studio
(large area FDM)


HP 4200
(polymers)

**+**
**HP and Siemens**

- Software donations
- Funding of senior design projects

Markforged X7
(continuous fiber PMC)

Markforged Metal X
(metals)

# IDMI – Advanced Casting Research Center

UCI Samueli School of Engineering

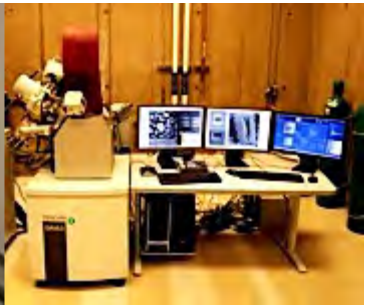


# Irvine Materials Research Institute (IMRI)

UCI Samueli School of Engineering

## Laboratory for Electron & X-ray Instrumentation (LEXI)

Magellan 400 SEM



GAIA-3 GMH FIB-SEM

## Surface Science Facility (SSF)

AXIS Supra by Kratos Analytical

## Center for Transmission Electron Microscopy (CTEM)

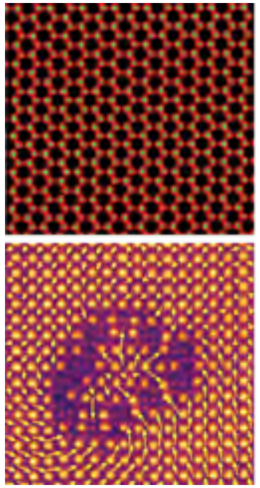
NION HERMES

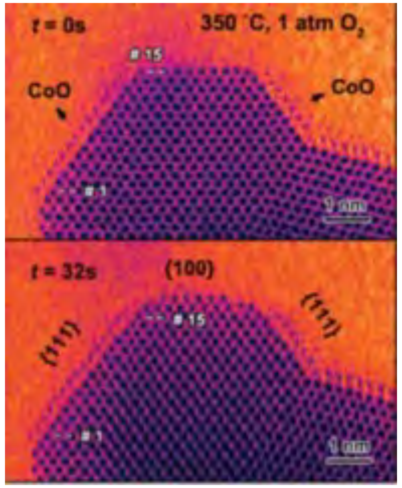
Grand ARM

CryoTEM 2100F

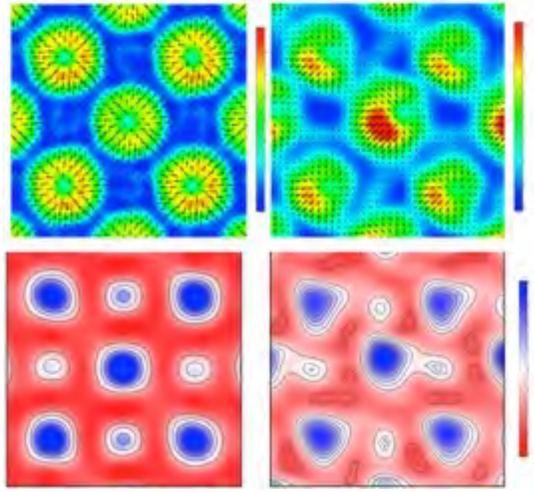
## TEMPR Facility for Soft Materials Characterization

A cross-disciplinary institute offering world-class facilities to researchers engaged in the discovery, development and commercialization of all types of materials.

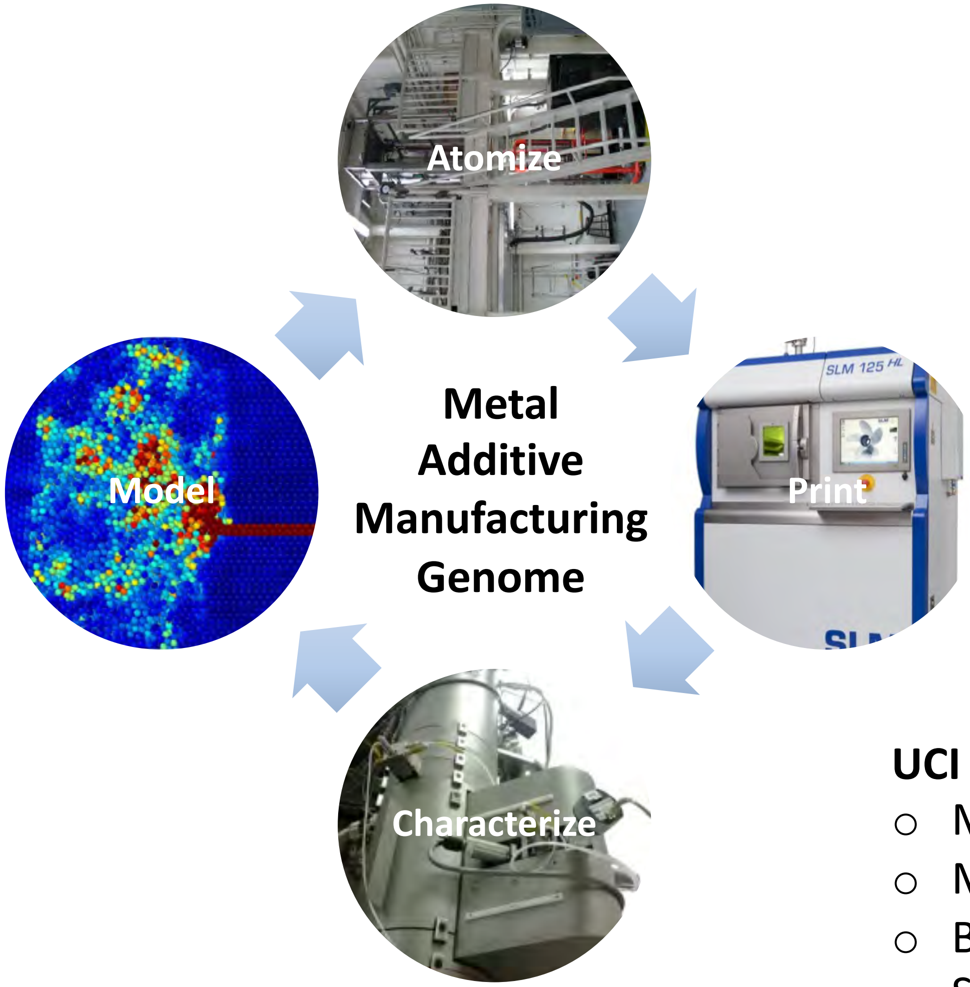


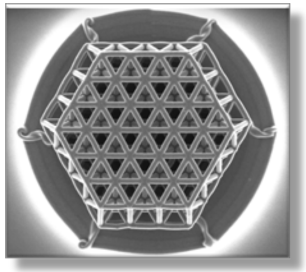


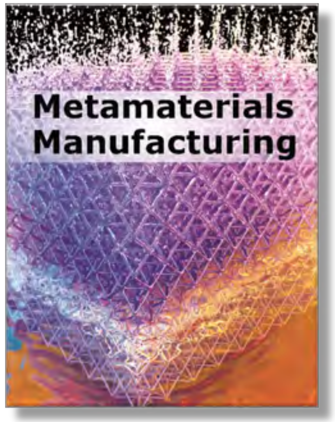

- Direct imaging of single atoms, 3D atomic structure, chemical bonds, and local electronic properties
- *In situ* observation of the phase transition and dynamic behaviors of materials under different conditions and environments with the atomic resolution.
- The unique Nion UltraSTEM HERMES200 is an ideal microscopy for the study of 2D materials.
- The world record energy resolution (4.2 meV) allows one to measure the molecular vibration and phonons in crystal.

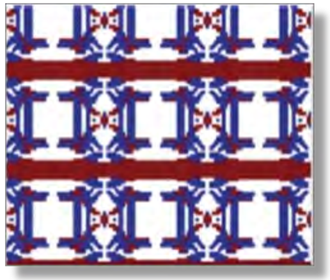


# Why Additive / Metal Manufacturing





**UCI expertise in:**

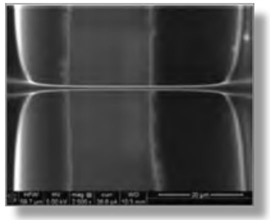
- Metal processing
- Machine learning
- Big data
- Sensors and control

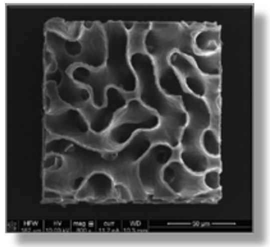
Research Center on:

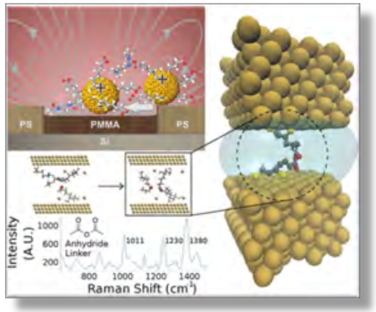
**Novel Materials, Processes and Tools for Additive Manufacturing**

- *Architected materials*
- *Scalable nano-manufacturing*
- *Metal AM*
- *Optimal design for AM*

**Scalable Nanomanufacturing**

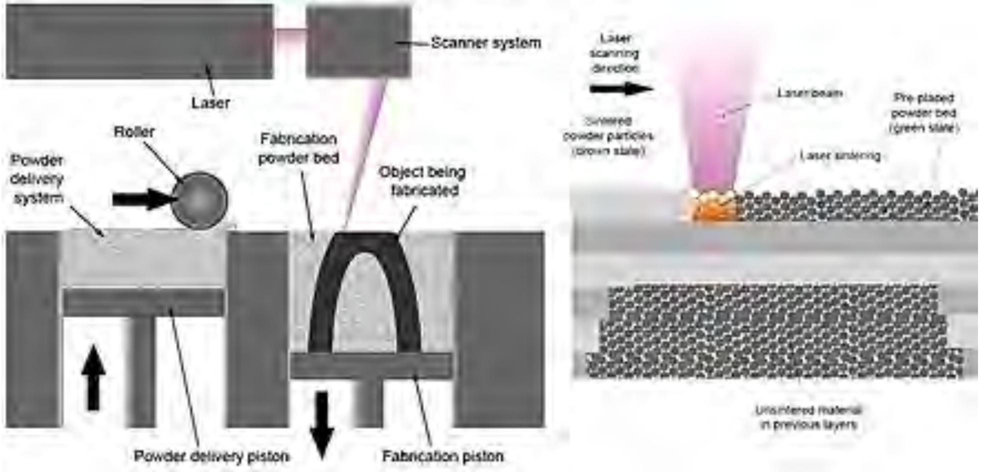


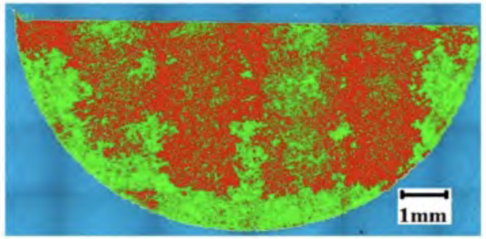


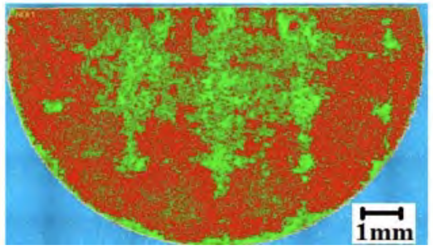


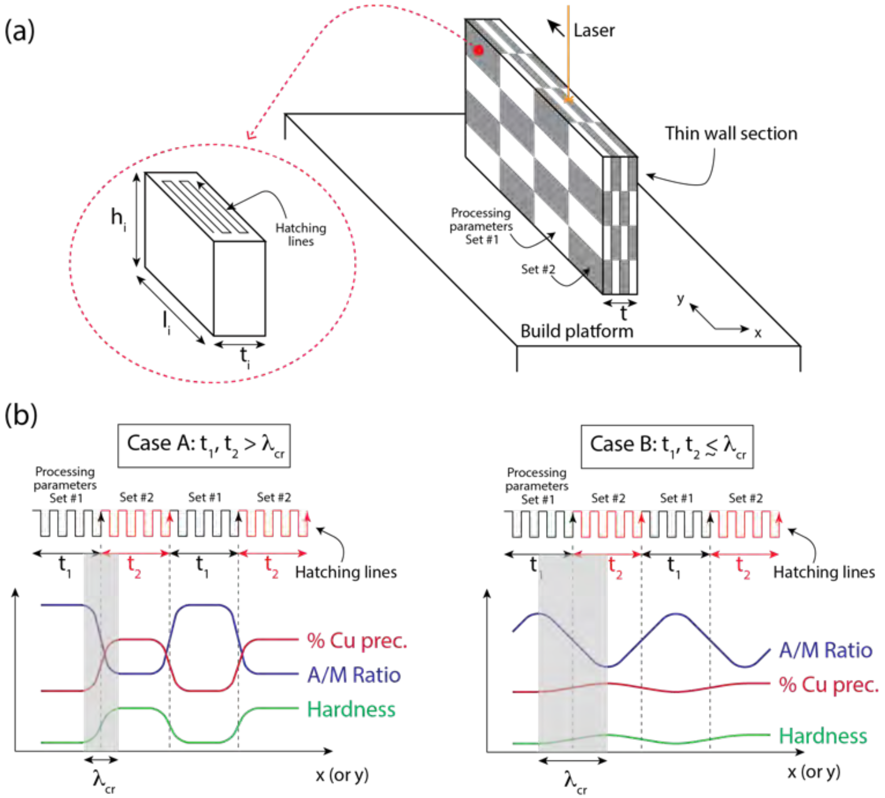
# Laser Powder Bed Fusion: Shell-based PH steel metamaterials

L. Valdevit, D. Apelian (UCI), M. Begley (UCSB), A. Asadpoure, M. Tootkaboni (UMass Dartmouth)




# Direct Energy Deposition - Processing Science of Functionally graded materials

J. Schoenung, L. Valdevit, P. Cao

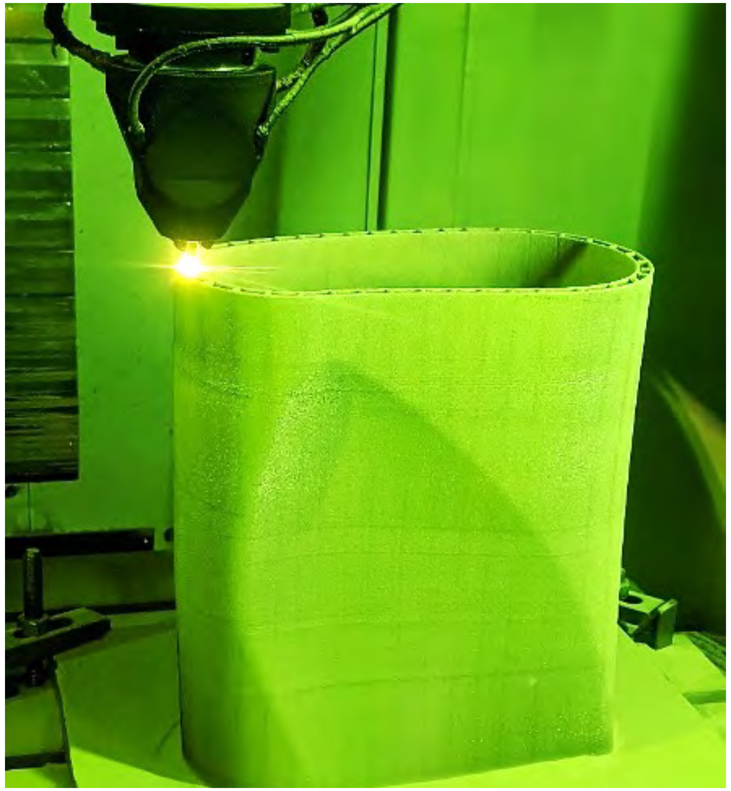
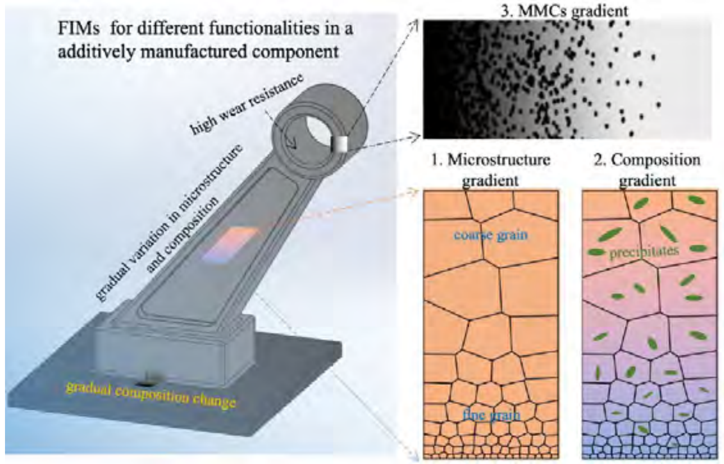
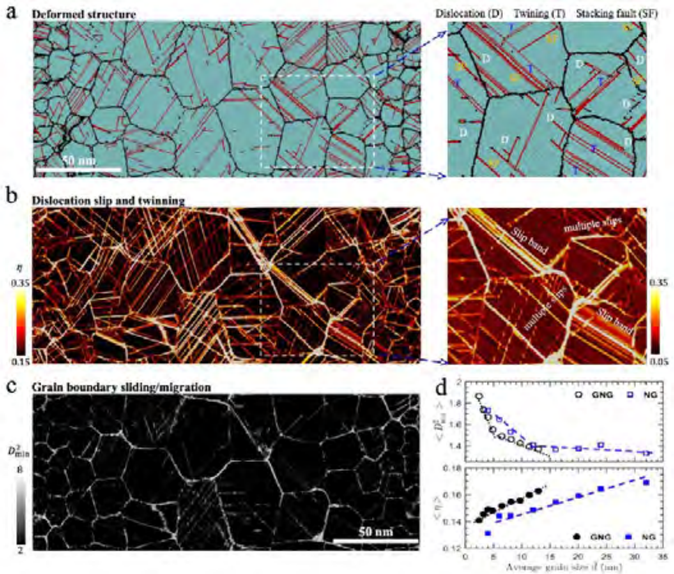


Image courtesy of Optomec

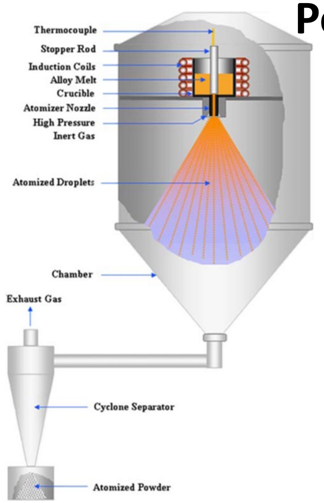


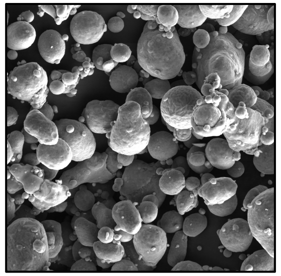

# Cold Spray for Large Area Additive Manufacturing

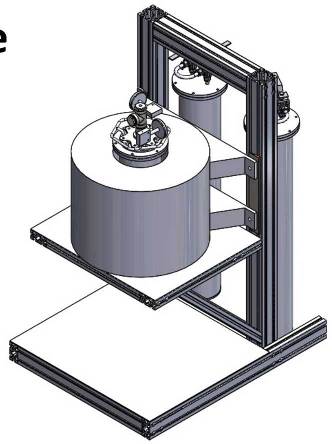
D. Apelian, L. Valdevit, D. R. Mumm

## Gas atomization



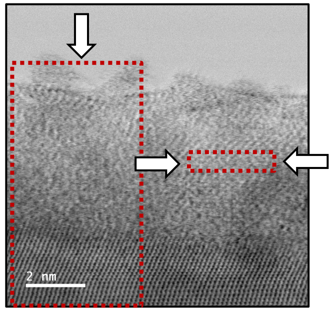

## Powder Exposure

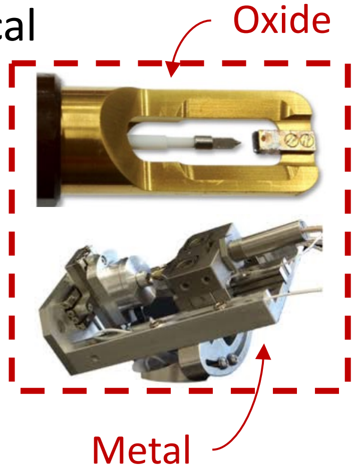




## Powder characterization

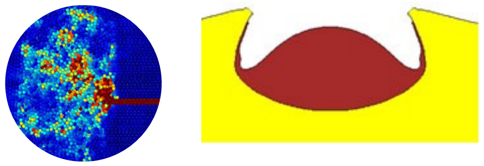
- Microstructural
- Mechanical



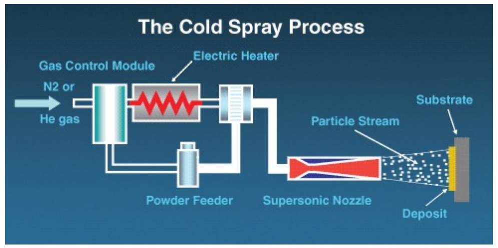




## Modeling

- Microstructural (ICME)
- Mechanical

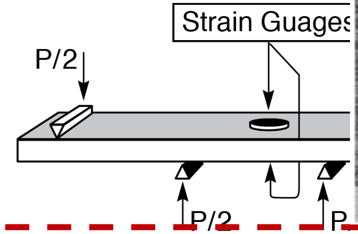


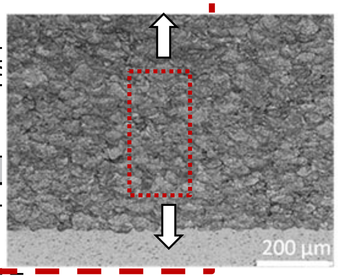
## Spraying




## Coating characterization

- Microstructural
- Mechanical



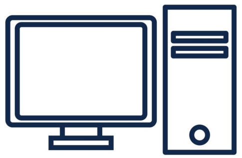
# Metals Processing – Additive Manufacturing

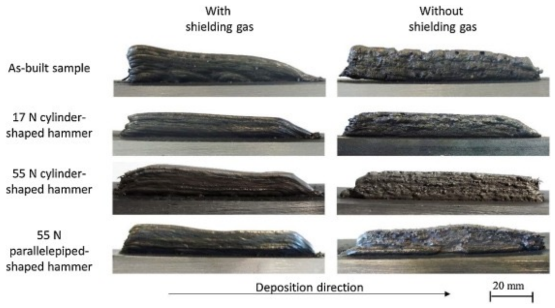
UCI Samueli School of Engineering

## Wire Arc Additive Manufacturing (WAAM)

D. Apelian

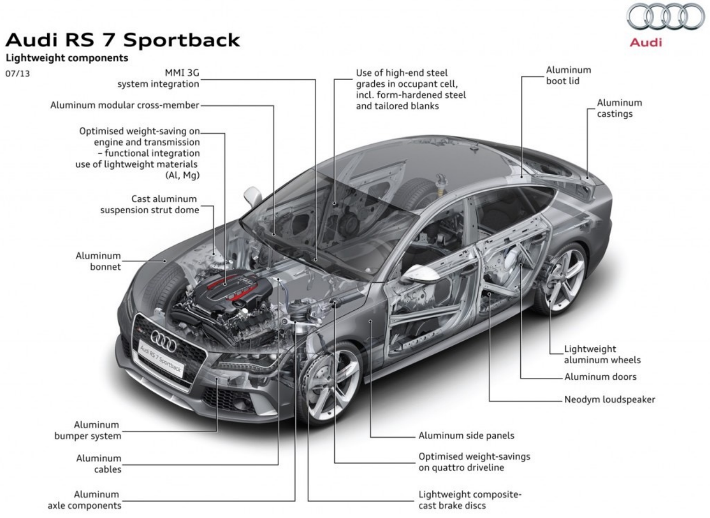
DEVCOM ARMY RESEARCH LABORATORY




## Advanced Casting

D. Apelian

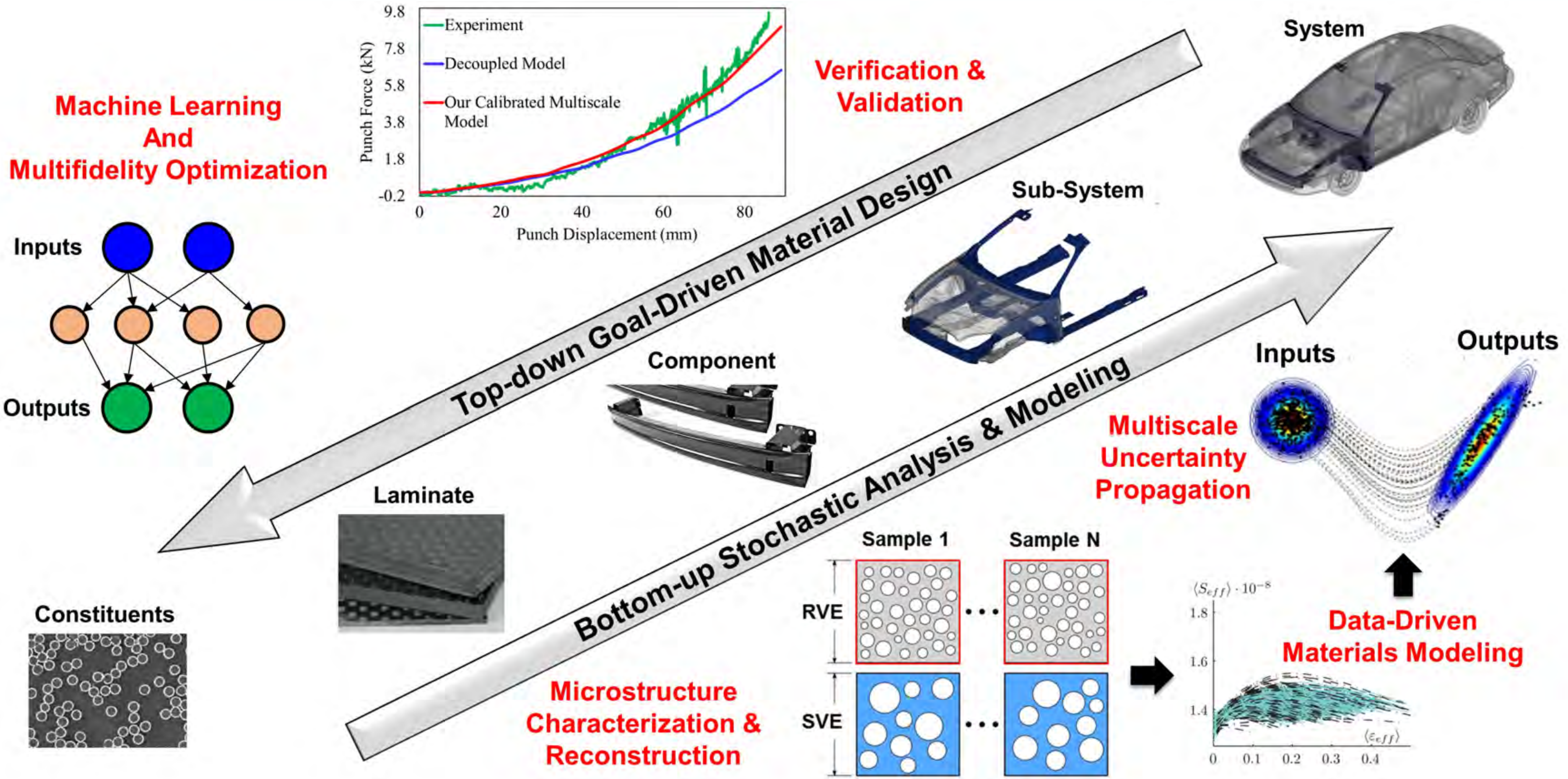



## ACRC Consortium

Aluminum Association, AFS, ATEK Metal Technologies, CAN-ENG, CONMET, Eck Industries, Inc., FCA, FOSECO, General Aluminum, GM, Harley-Davidson, HAZELETT, H.C. Starck, LIJFENG, MAGMA, MAGNA, MERCURY, MONTUPET, NADCA, nemak, NMA, OSHKOSH, PALMER FOUNDRY, QuesTek Innovations LLC, RHEINFELDEN, Rio Tinto, THE SAKTHI GROUP, SHILOH, SPACE X, TERVES, TESLA, VJ TECHNOLOGIES

## Thixotropic Casting

# Metals Processing – Additive Manufacturing



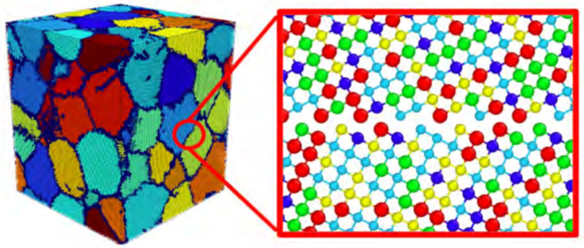


R. Bostanabad

# Materials and Chemical Research

UCI Samueli School of Engineering

**Structural Nanomaterials**



Diran Apelian

Julie Schoenung

Penghui Cao

Tim Rupert

Xiaoqing Pan

D. R. Mumm

Center for Complex and Active Materials

UCI MRSEC

National Science Foundation

MRSEC

MATERIALS RESEARCH SCIENCE AND ENGINEERING CENTERS

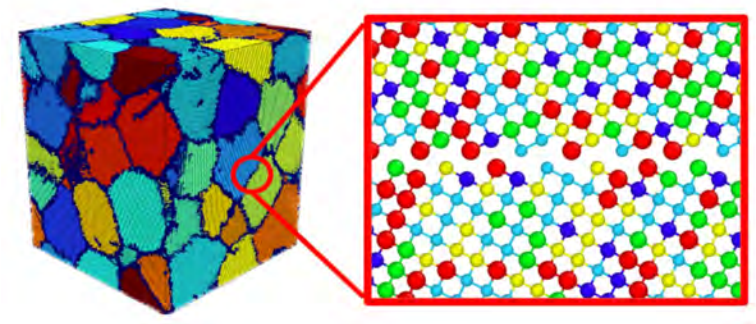
Xiaoqing Pan, PI

Funded by **National Science Foundation**
$18 million over 6 years
*Premier Center Program in MSE*
Total MRSECs Nationwide: 19

Director: Professor Xiaoqing Pan

Participants:
19 Faculty
25 Junior Research Fellows

**IRG 1 – Complex Concentrated Materials**

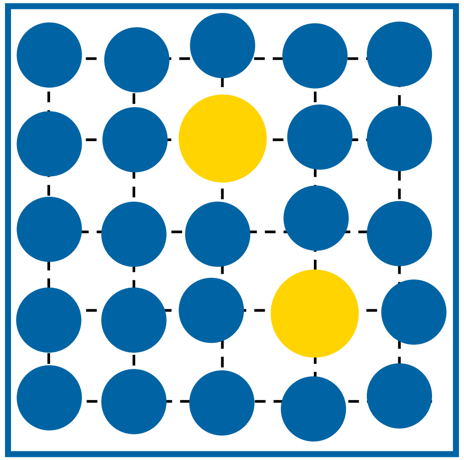


**IRG 2 – Bioinspired Active Materials**

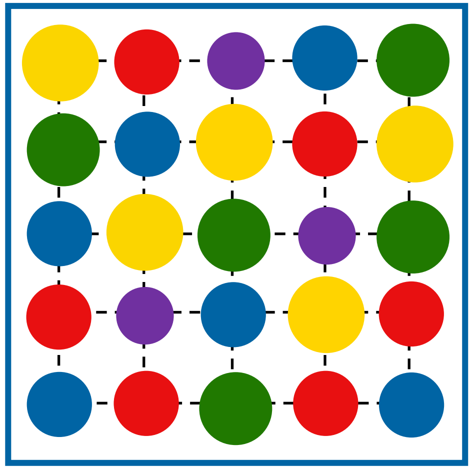

Materials Research Science and Engineering Centers (MRSECs) support interdisciplinary and multidisciplinary materials research and education of the highest quality while addressing fundamental problems in science and engineering that are important to society.

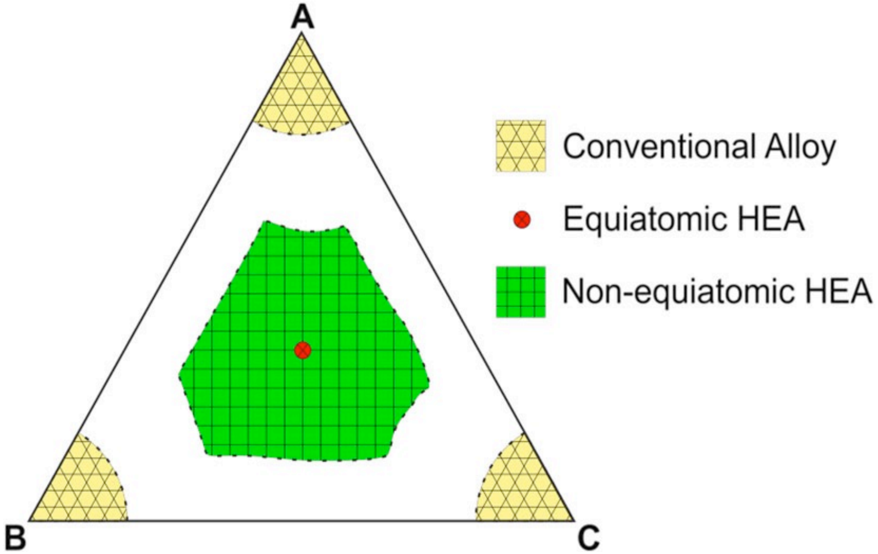
https://ccam.uci.edu/
https://www.mrsec.org/mrsec-program-overview

<u>Conventional Alloy:</u>
**Dilute Solid Solution**

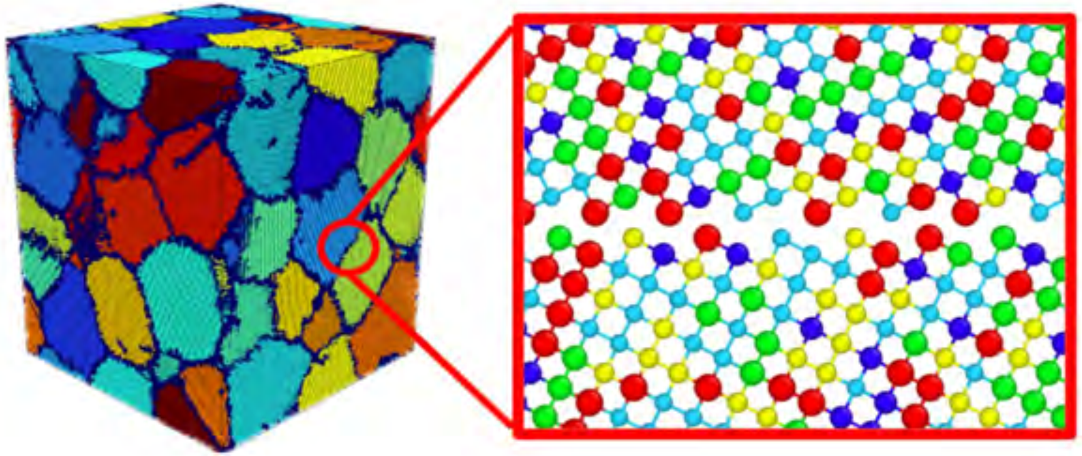


<u>High Entropy Alloys:</u>
**Disordered Solid Solution**






**Specifically investigate the role of interfaces**




Tim Rupert

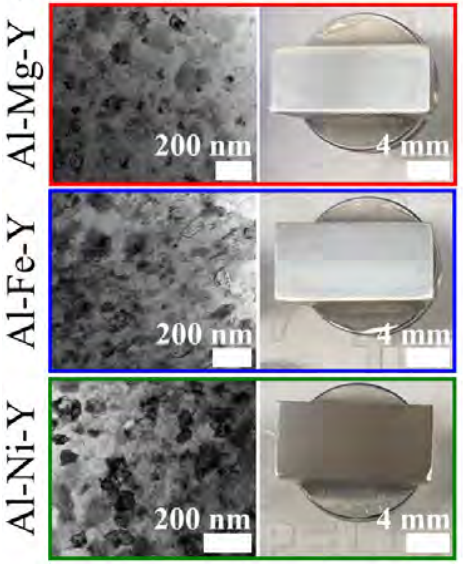

Diran Apelian


Julie Schoenung

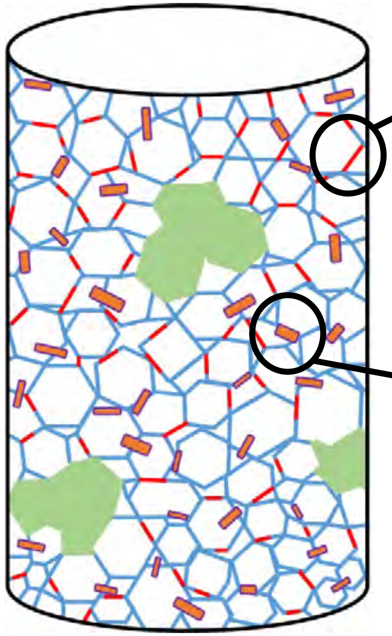

Penghui Cao

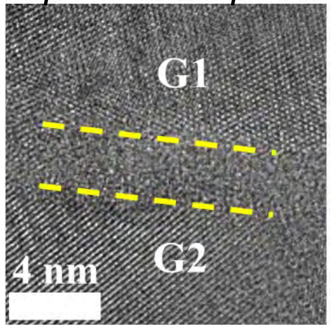
# Bulk Al alloys with hierarchical nanostructures

*T. Rupert*

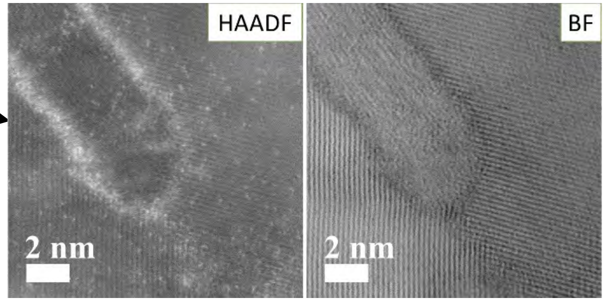



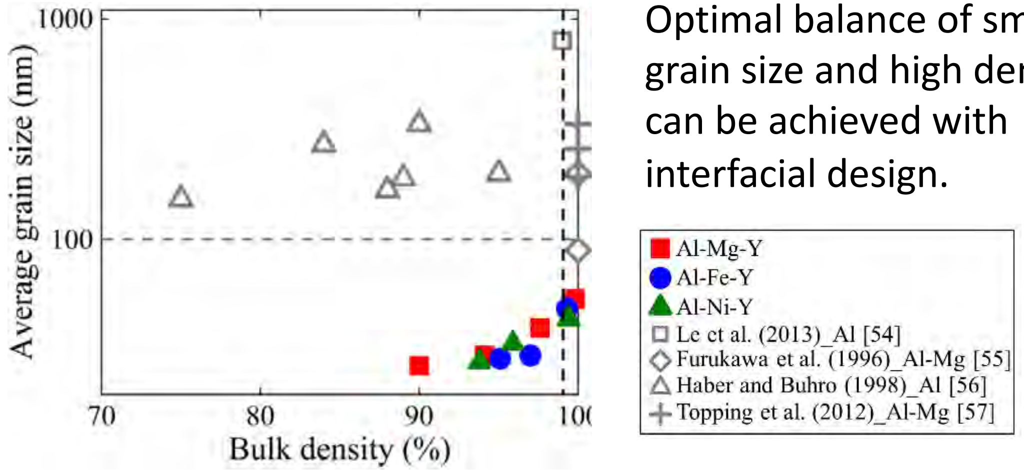

*Amorphous complexions*





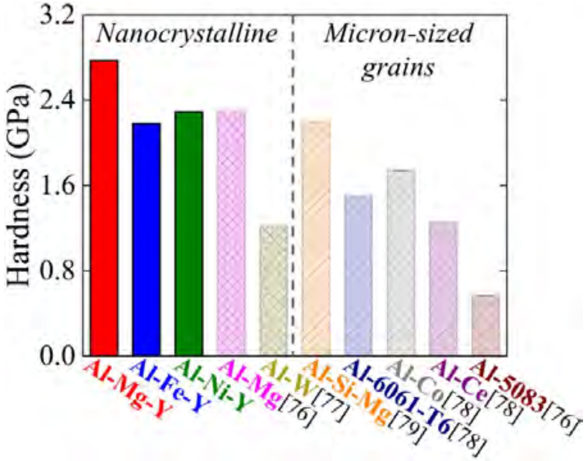

*Nanorod precipitates*




Optimal balance of small grain size and high density can be achieved with interfacial design.

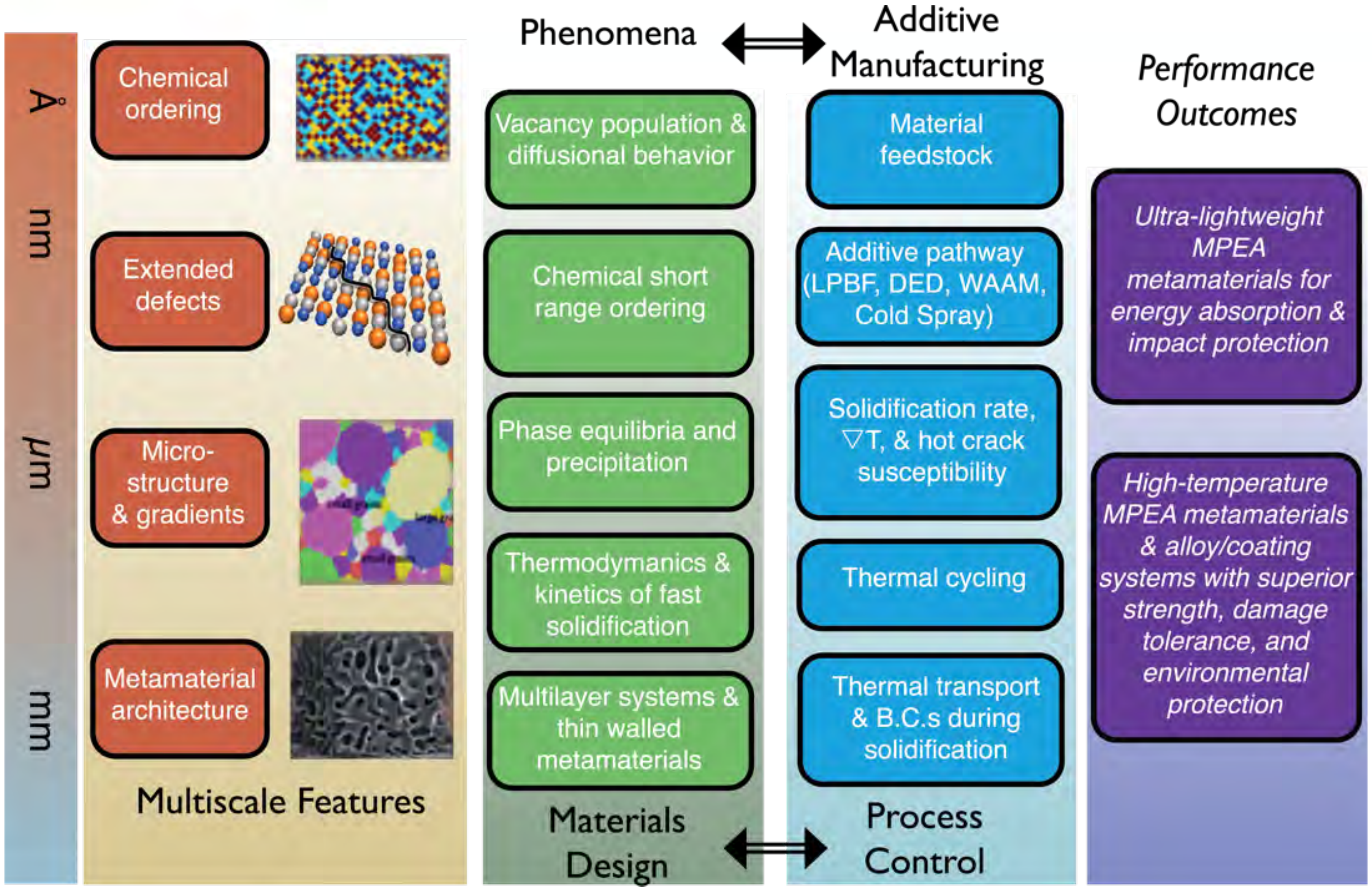
**Alloys are stronger than all previously reported bulk nano- and micro-structured Al alloys**



# Design Philosophy for Advanced Materials

## Refractory MPEAs for Extreme Environments

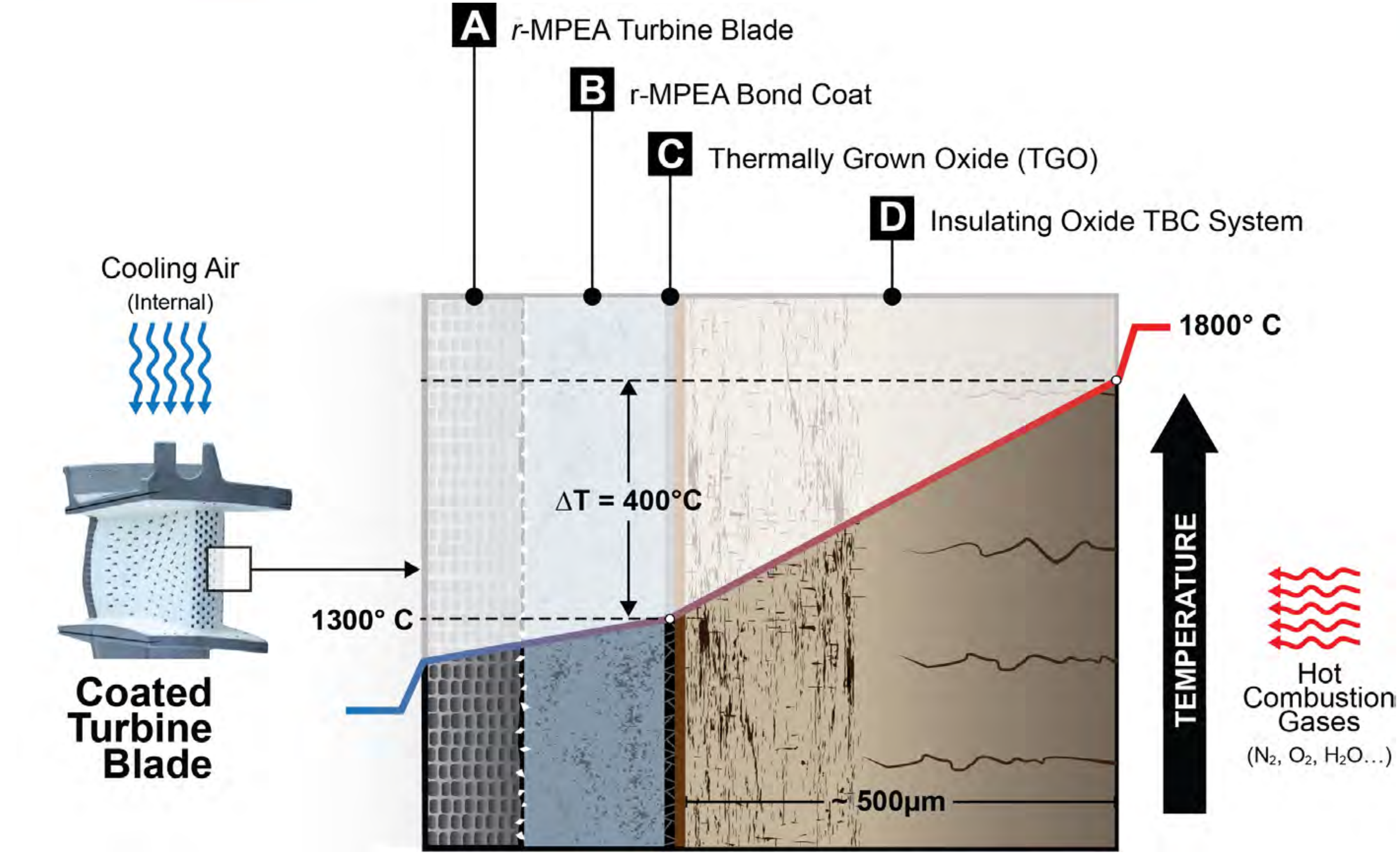
UCI Samueli School of Engineering




# Design Philosophy for Advanced Materials

## Refractory MPEAs for Extreme Environments

UCI Samueli School of Engineering

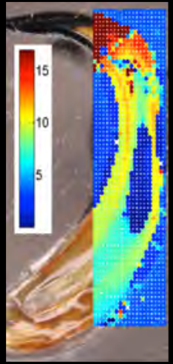


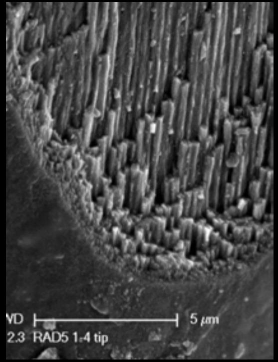

# Biomimetic and Nanostructured Materials

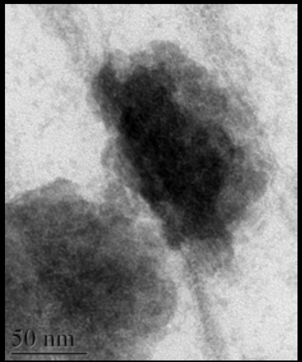
UCI Samueli School of Engineering

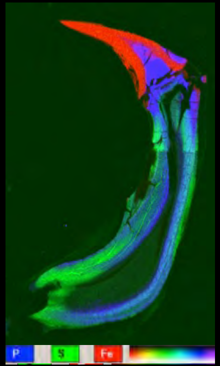
David Kisailus

- Synthesis – Structure - Function (mechanical, optical, thermal) analysis of biological materials

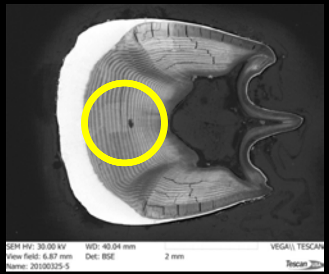



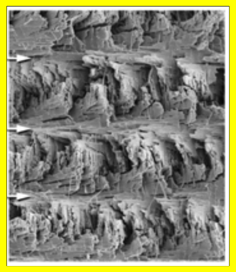



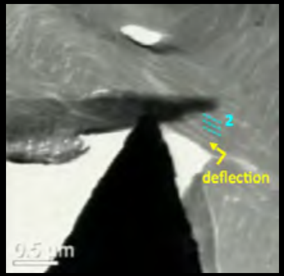



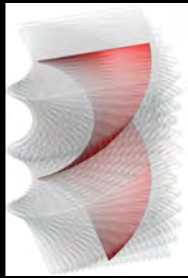



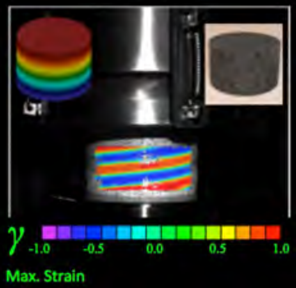

- Biomimetic Synthesis of Impact, Abrasion, Thermal Resistant Multifunctional Materials

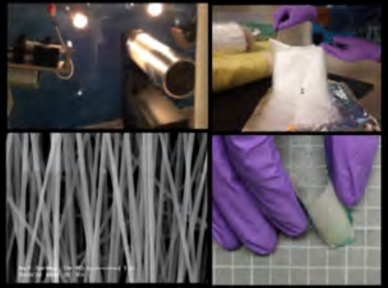




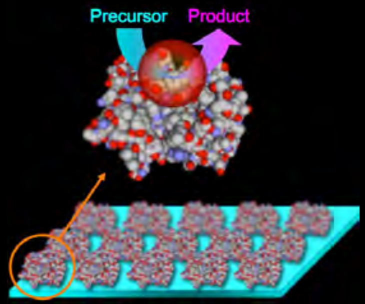


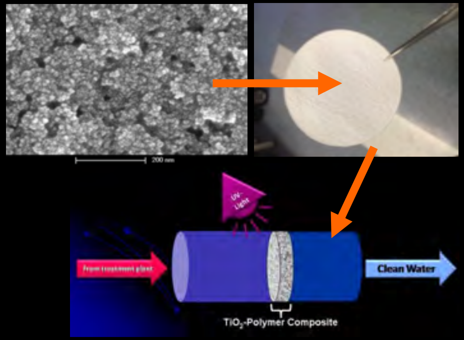


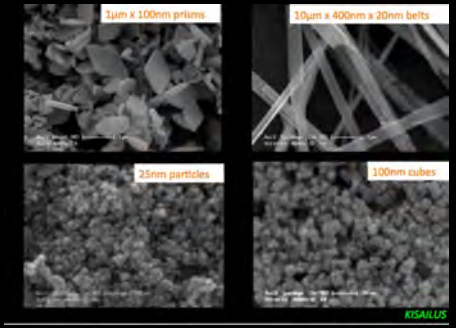
- Low temperature, Bio-mediated / inspired syntheses of nanomaterials for energy and environmental applications



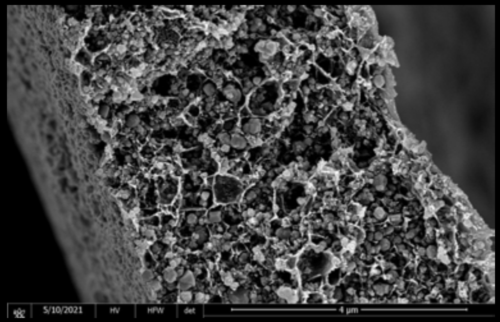

Enzyme driven synthesis



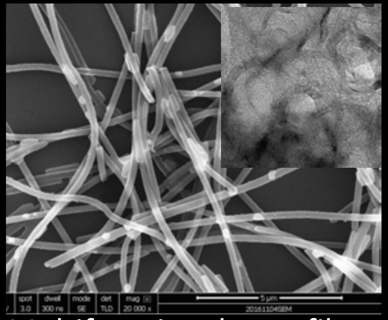

Self-cleaning, adaptive membranes




Fast charging 3D batteries

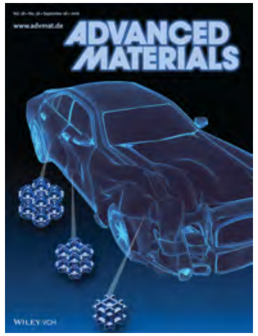


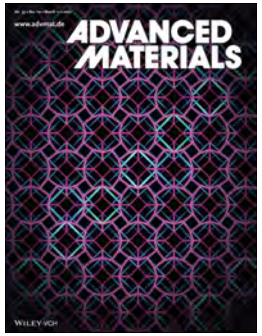
Impact & abrasion resistant coatings



Multifunctional nanofibers: Gas sensing, catalysis

**Mechanical micro/nano-Metamaterials**




Lorenzo Valdevit

P. Cao

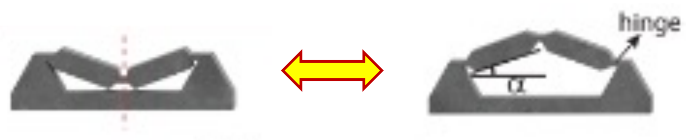
R. Bostanabad

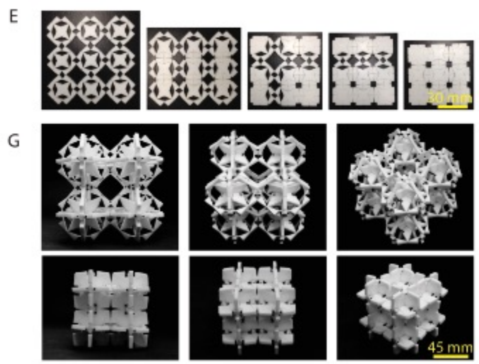
# Architected Materials for Impact Mitigation

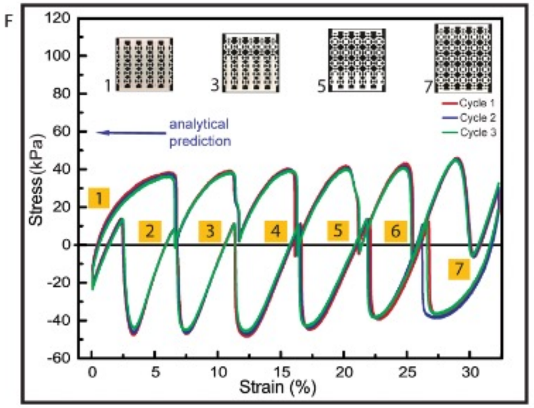
L. Valdevit

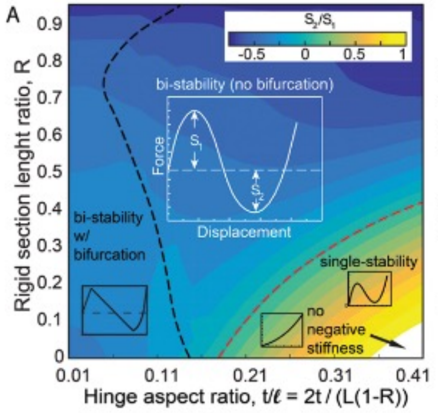
UCI Samueli School of Engineering

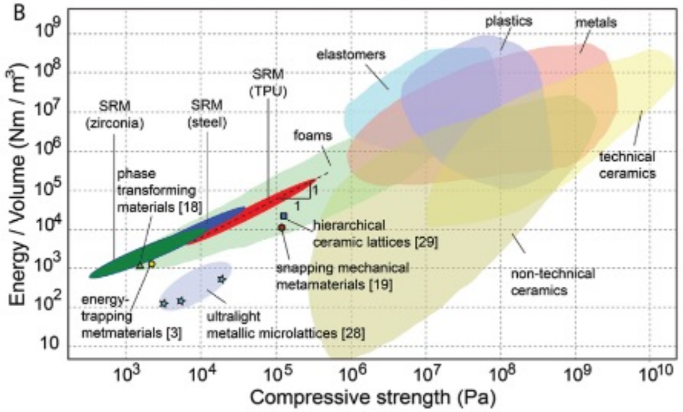
## Multi-stable architected materials



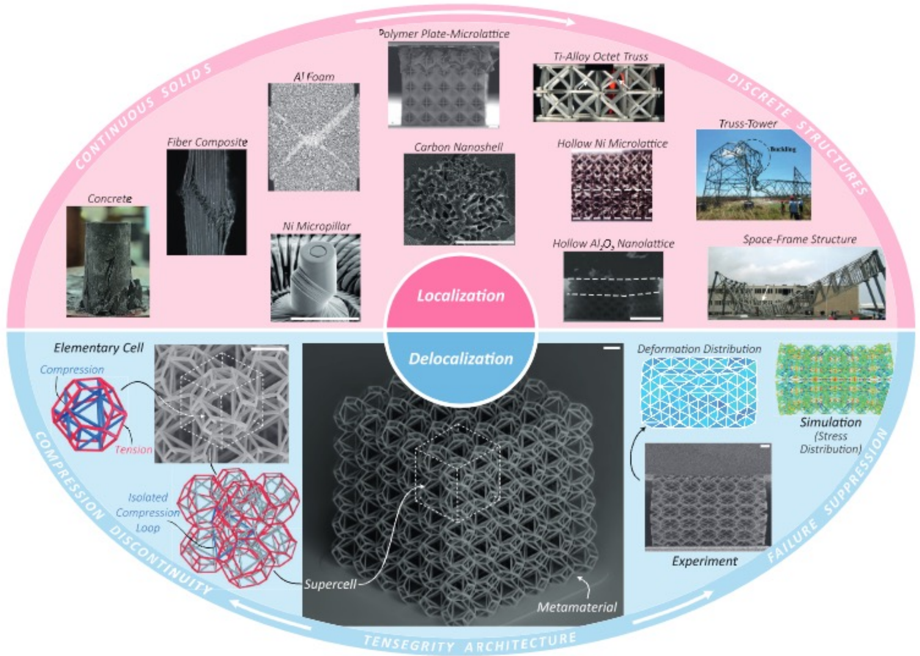



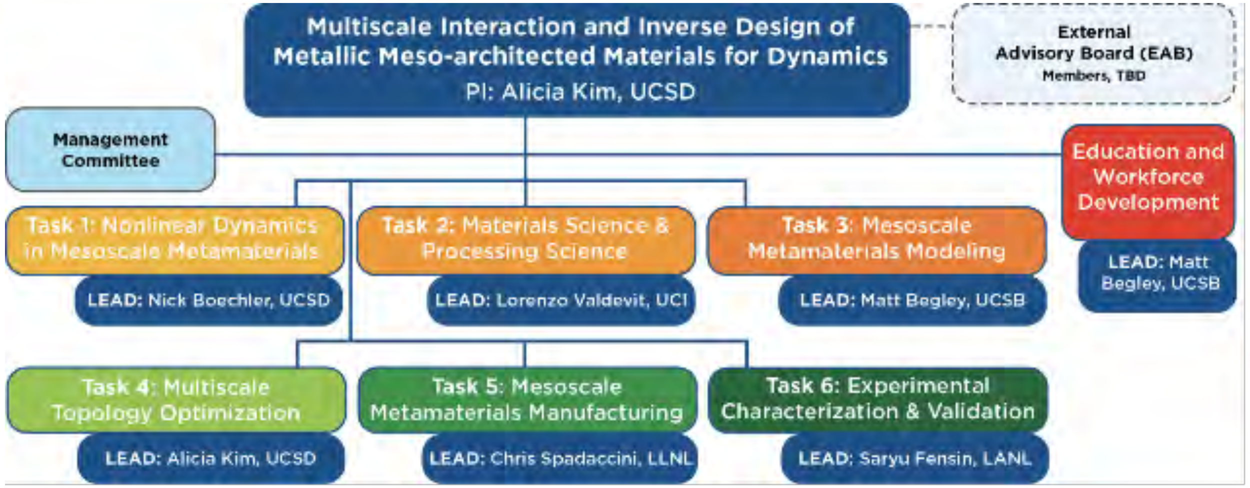

## Novel tensegrity lattice designs for robustness

(in collaboration with J. Rimoli, GaTech)



# Architected Materials as Mesoscale Materials
## (Pending) UC-NL Collaborative Research and Training Award

UCI Samueli School of Engineering



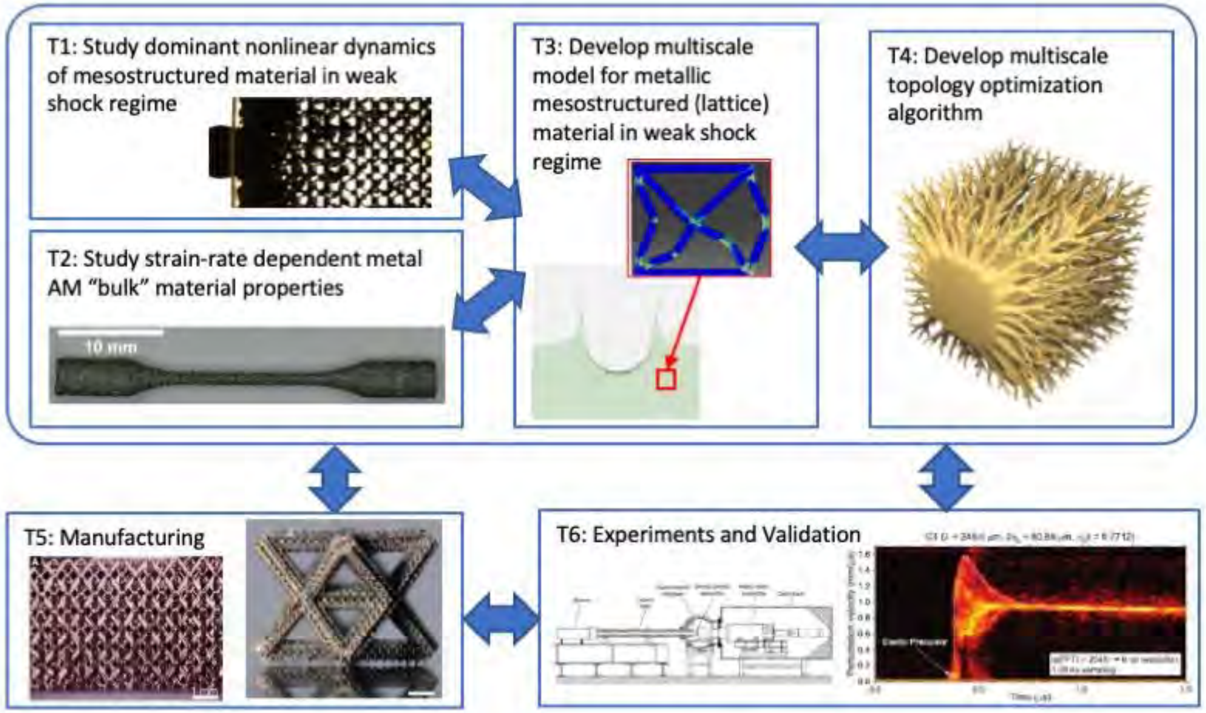


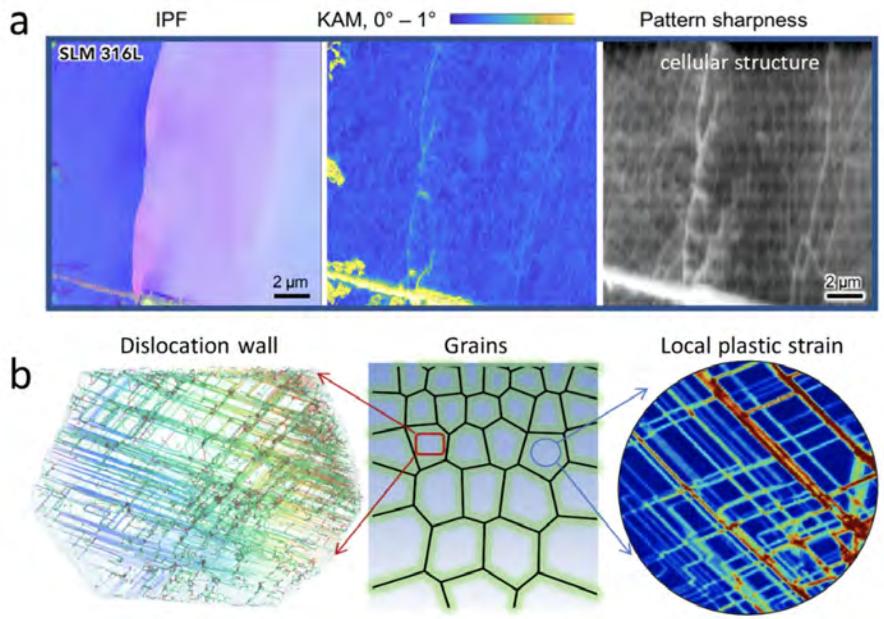
L. Valdevit

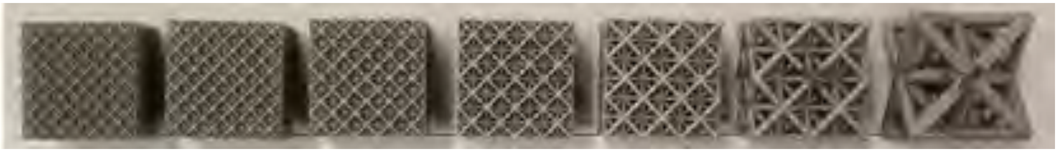

P. Cao


R. Bostanabad

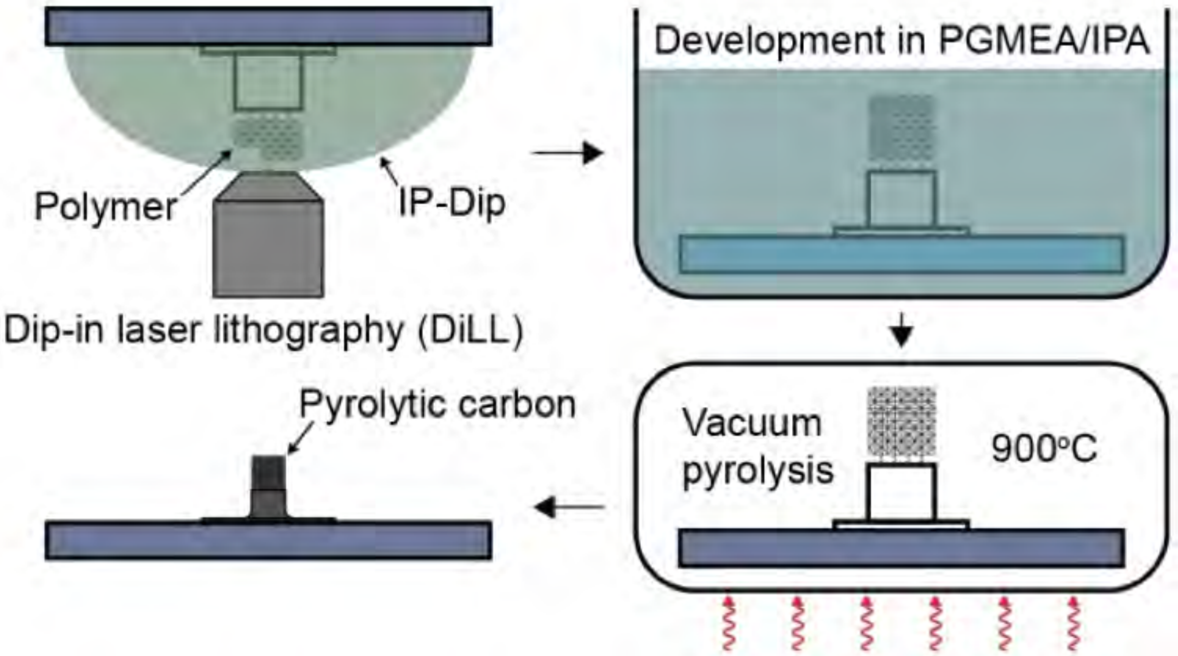
**LANL TEAM**
Saryu Fensin
Abigail Hunter

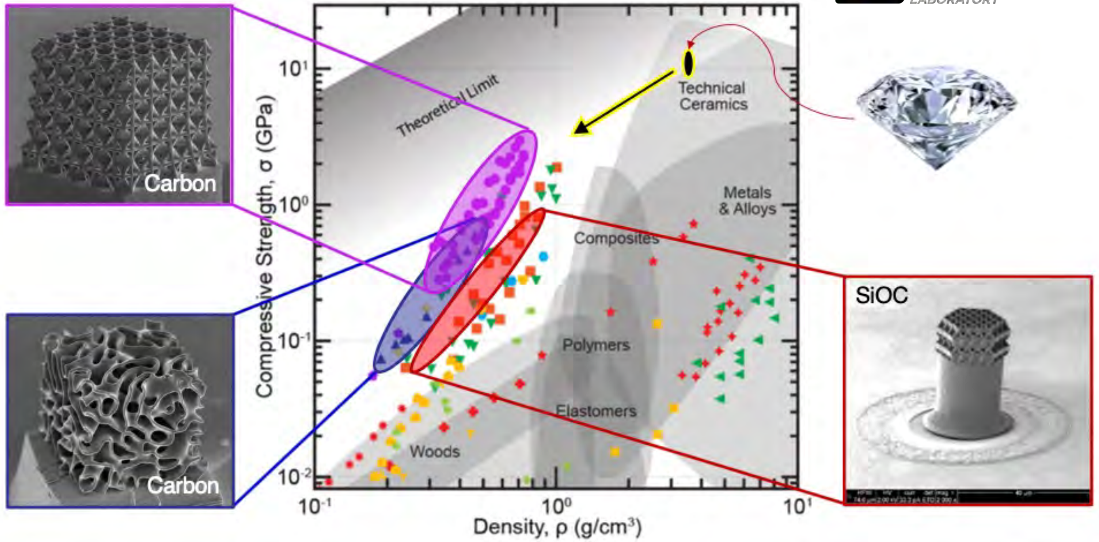


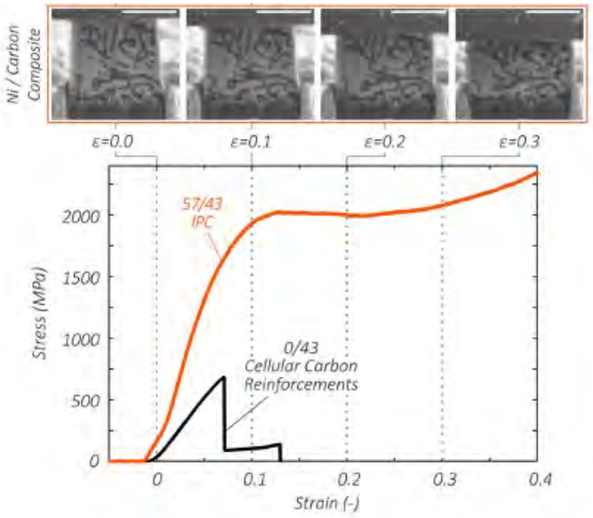



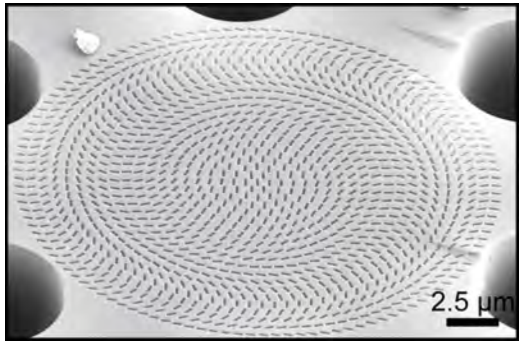
## Nano-architected ceramic materials with superior mechanical properties



**Nanomaterials for Light-Matter Interaction**




Maxim Shcherbakov

Filippo Capolino

Odzal Boyraz

Howard Lee

Daryl Preece

# Nanophotonic devices: Shcherbakov lab

**Maxim Shcherbakov**

**Filippo Capolino**

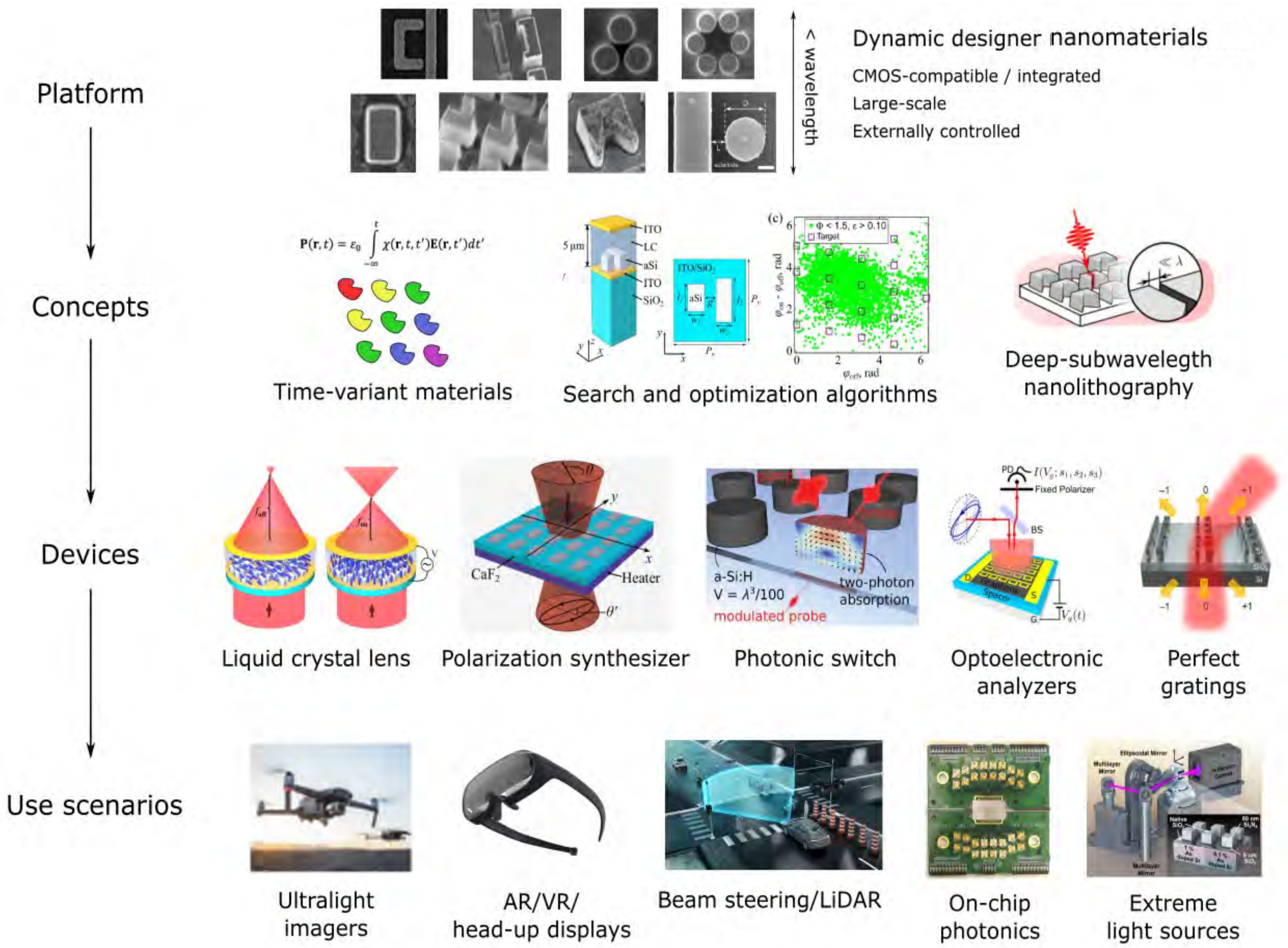
**Howard Lee**

**Odzal Boyraz**

**Daryl Preece**

**Dmitry Fishman**

***And others!***



# Photonic Metasurfaces and Metamaterials

## Lee Nano Optics Lab

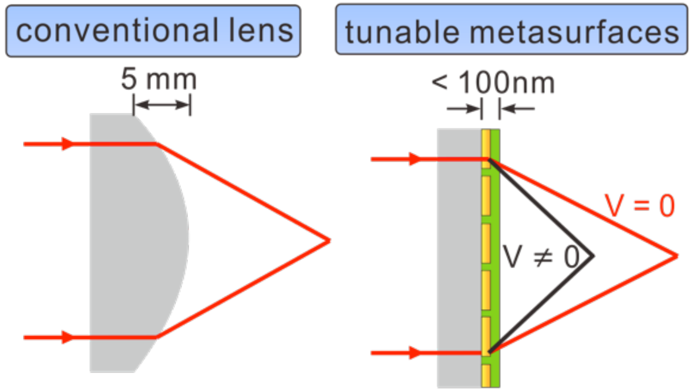
UCI Samueli School of Engineering

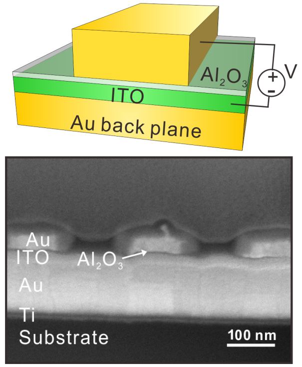
*Extreme light-matter interaction, optical metasurfaces and metamaterials, tunable optical materials, quantum/bio-photonics, and photonic applications at nanometer scale*

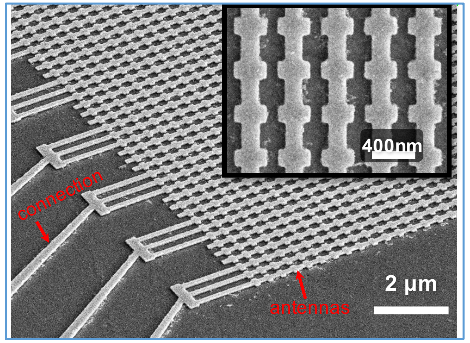
**Howard Lee**

*Member of Beckman Laser Institute*

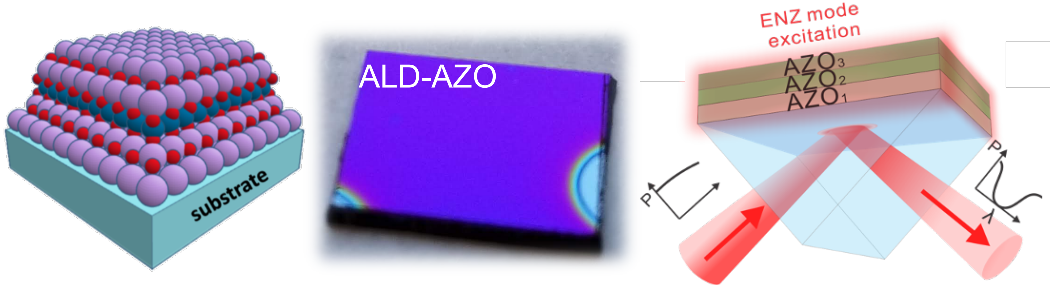
### Active optical metasurfaces



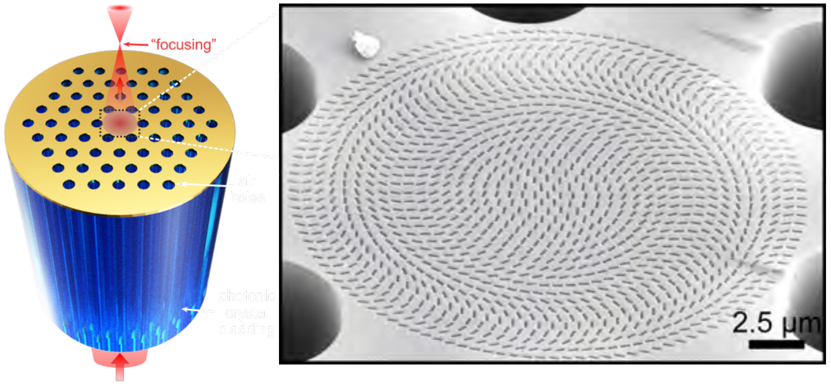




### Novel optical materials




### "Meta"-optical fibers



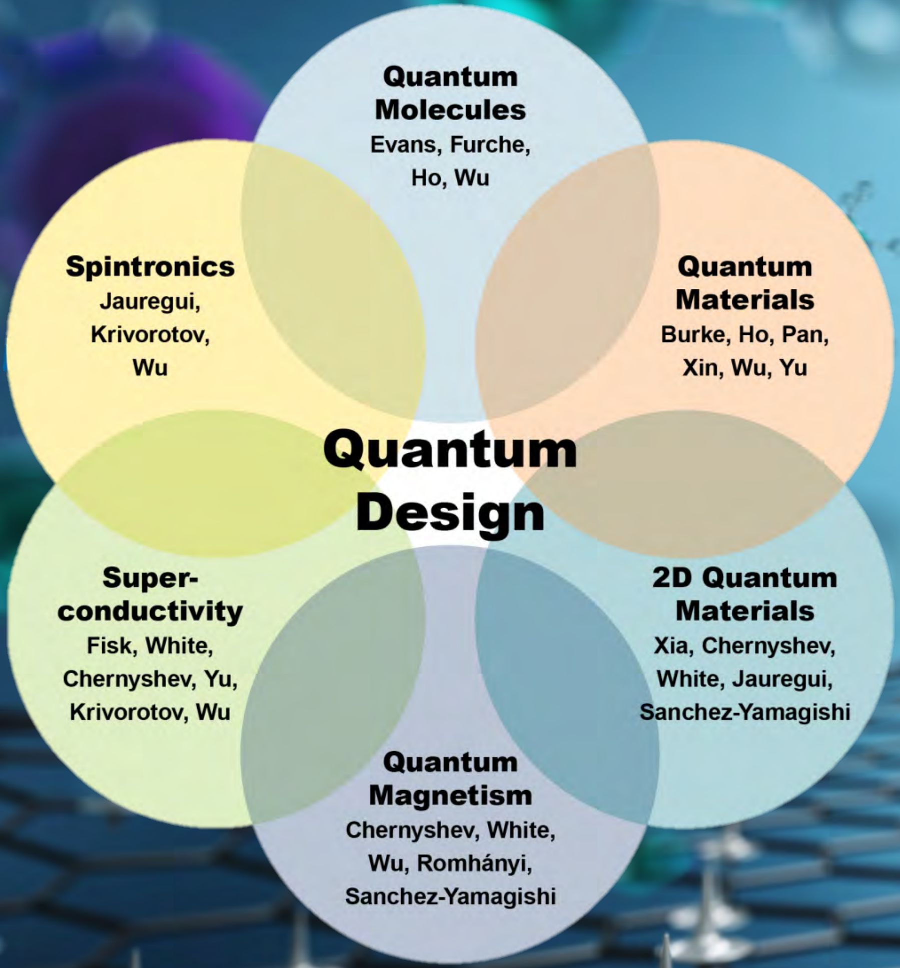
**Nanomaterials for Quantum Science**

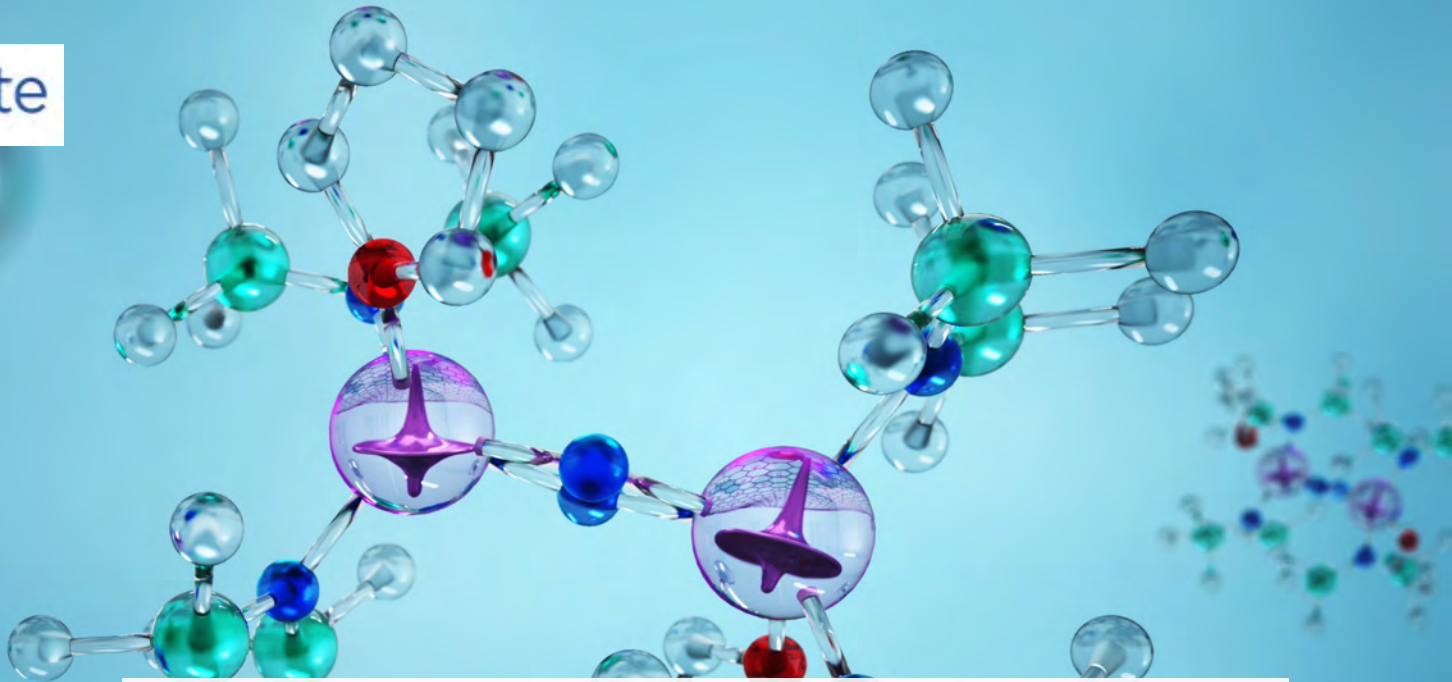
UCI Eddleman Quantum Institute

# Quantum Materials

## Eddleman Quantum Institute

**UCI Eddleman Quantum Institute**



<u>Concentrated efforts in:</u>

- Quantum materials and rare-earth metals
- Theory of quantum systems, especially for correlated systems and rare earth-containing materials

# Quantum Materials
## Eddleman Quantum Institute

UCI Samueli School of Engineering

# Eddleman Quantum Institute Faculty

Faculty from both School of Engineering and School of Physical Sciences

**Maxx Q. Arguilla**

Growth and Chemistry of Low-Dimensional Quantum Materials

**Kieron Burke**

Development of Quantum Simulations

**Sasha Chernyshev**

Quantum Magnetism

**William J. Evans, Director**

Synthesis of Rare-Earth Metal Compounds, Single-Molecule Magnets, Molecular Qubits

**Filipp Ulrich Furche**

Novel Methods in Quantum Chemistry

**Wilson Ho**

Single-Molecule Coherence and Entanglement, SpaceTime Spectromicroscopy of Matter

**Sandy Irani**

Quantum Computational Complexity and Algorithms

**Luis Jauregui**

Properties of Emergent Quantum Materials

**Svetlana Jitomirskaya**

Mathematics of Incommensurable Quantum Structures

**Ilya Krivorotov**

Spintronics and Nanomagnetism

**Howard Lee**

Metamaterials, Quantum Nanophotonics and Biophotonics

**Thorsten Ritz**

Theoretical and Computational Biophysics, Quantum Biology of Photosynthesis

**Judit Romhányi**

Condensed Matter Physics and Quantum Matter

**Javier Sanchez-Yamagishi**

Electronic 2-Dimensional Quantum Materials

**Steven R. White**

Quantum Simulations and Numerical Methods

**Ruqian Wu**

Quantum Simulations of Nano-magnetic Systems

**Jing Xia**

Novel Quantum Materials

**Huolin Xin**

Next Generation Energy Storage

**Clare Yu**

Noise and Decoherence in Superconducting Devices and Qubits

# *Quantum Materials Research*

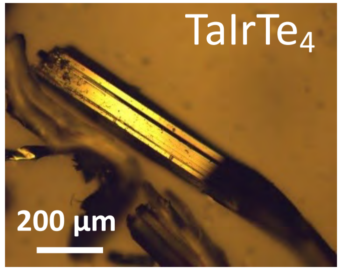
*Jauregui, Sanchez-Yamagishi*

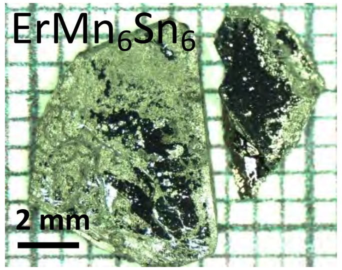
UCI Samueli School of Engineering

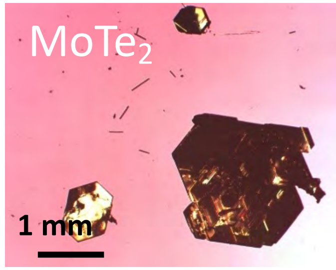
## Luis A. Jauregui

*Electrical and optical properties of van der Waals quantum materials and devices.*

### Growth of high-quality topological quantum materials:

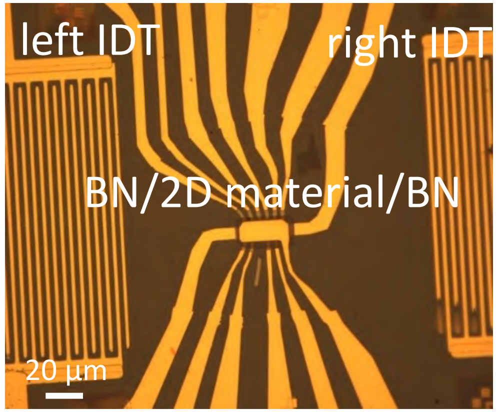


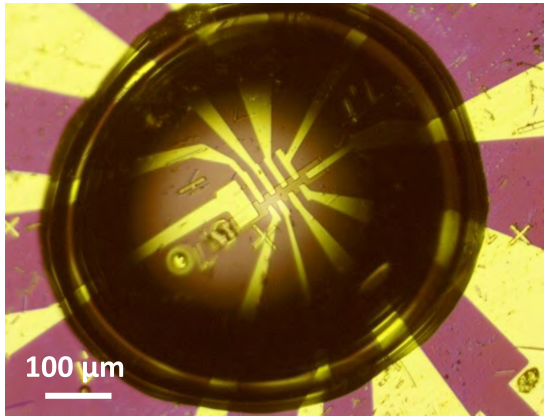




### Quantum optoelectronic devices

Acoustic control of excitons:




Thin topological field effect devices:



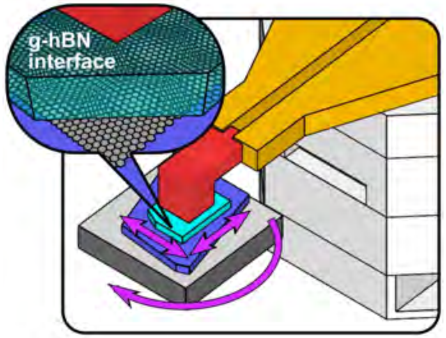

Funded by NSF

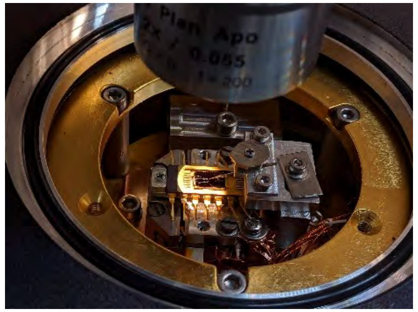
In collaboration with: Michael Pettes from LANL

## Javier Sanchez-Yamagishi

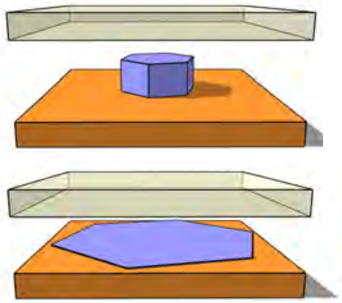
*New measurement and fabrication techniques for quantum materials*

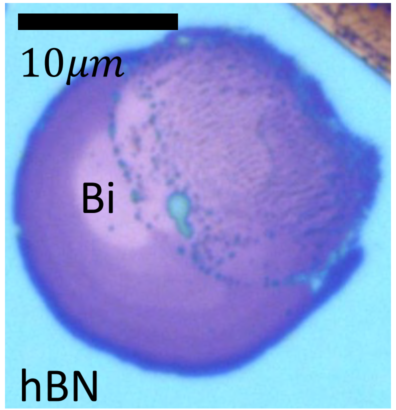
### In-situ nanomanipulation of van der Waals heterostructures

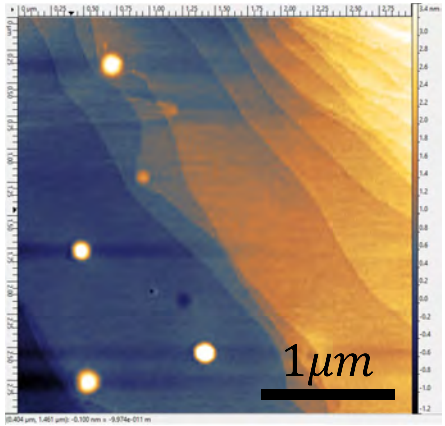


### Squeeze-grown 2D topological materials

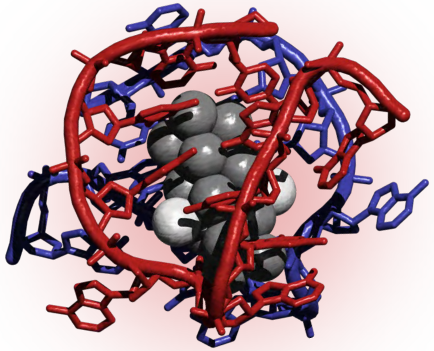





ultrathin and atomically flat bismuth

**Materials Informatics**



Huolin Xin

Stacy Copp

Zuzanna Siwy

Regina Ragan

Allon Hochbaum

# Accelerating Materials Science with Informatics

## Xin Group, Copp Group

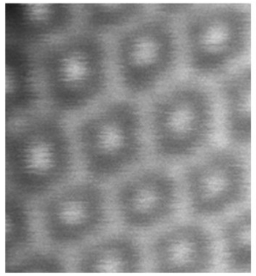
UCI Samueli School of Engineering

## "Artificially Intelligent" Transmission Electron Microscopy (TEM)

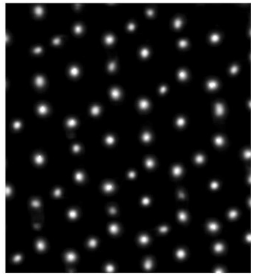
**Huolin Xin**

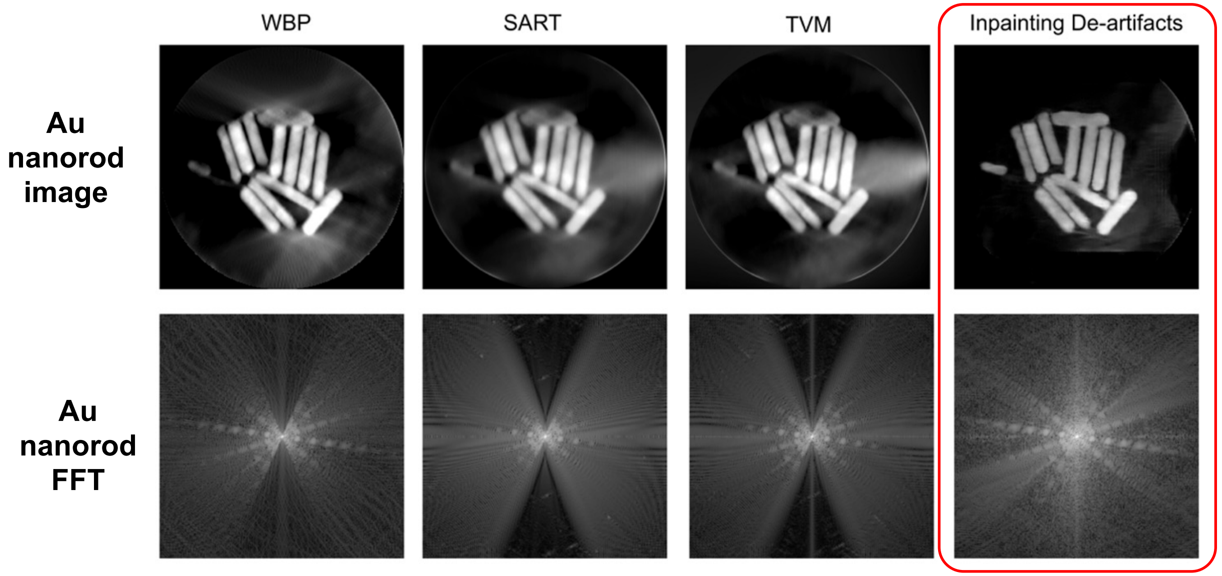
***Overcoming the limitations of conventional TEM and electron tomography through deep learning***

**ADF-STEM micrograph of $Co_3O_4$**



**Deep learning reconstruction of atomic column**

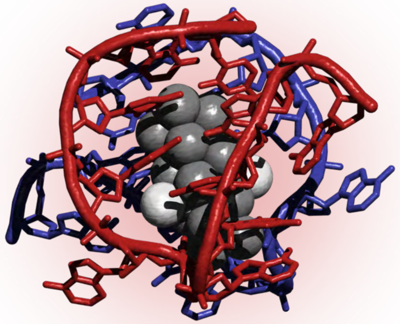


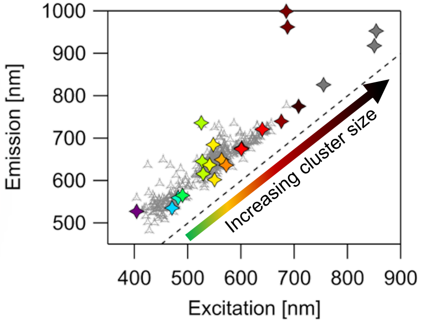



R. Lin, *et al.*, *Sci Rep.* 2021; G. Ding, *et al.*, *Sci Rep.* 2019

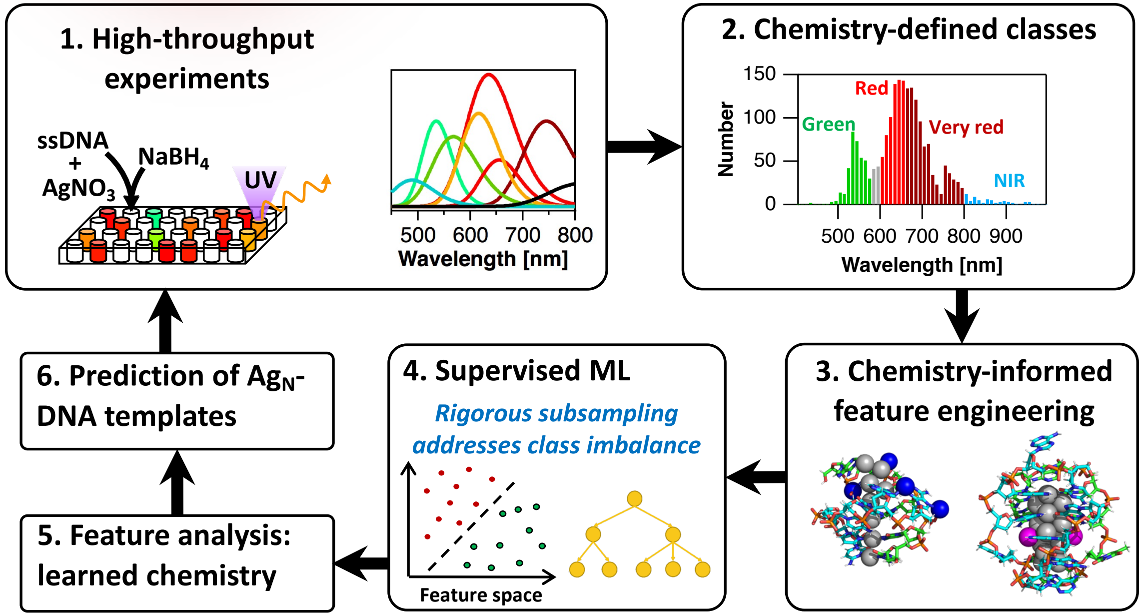
## Chemistry-informed machine learning (ML)

***DNA-stabilized silver nanoclusters as sequence-encoded materials for quantum plasmonics, sensing, and bioimaging***






**Stacy Copp**




S. Copp, *et al.*, *Chem. Mater.* 2020; P. Mastracco, *et al.*, *In prep.*

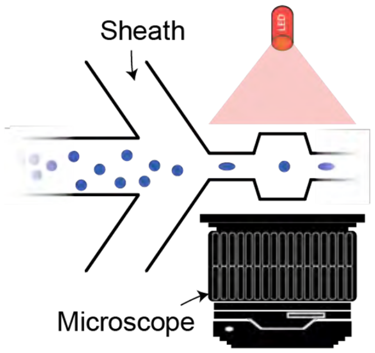
# *Deep Learning-Enabled Nanomaterials Devices*

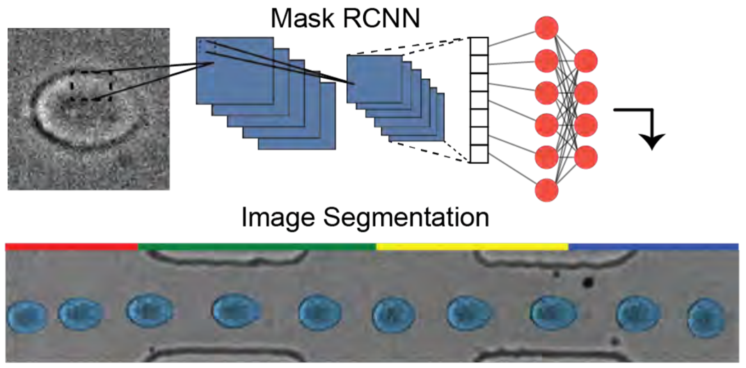
*Siwy; Ragan and Hochbaum*

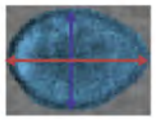
UCI Samueli School of Engineering

## *Deep learning enabled mechanotyping*

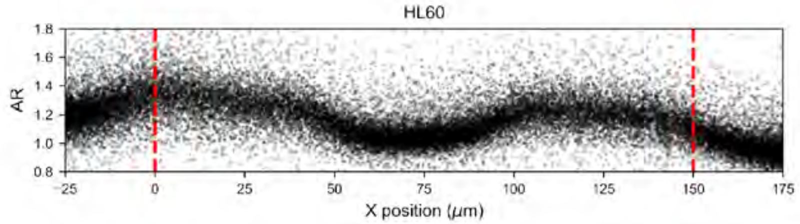
***Harnessing supervised and unsupervised machine learning to identify cell types by mechanical property differences***



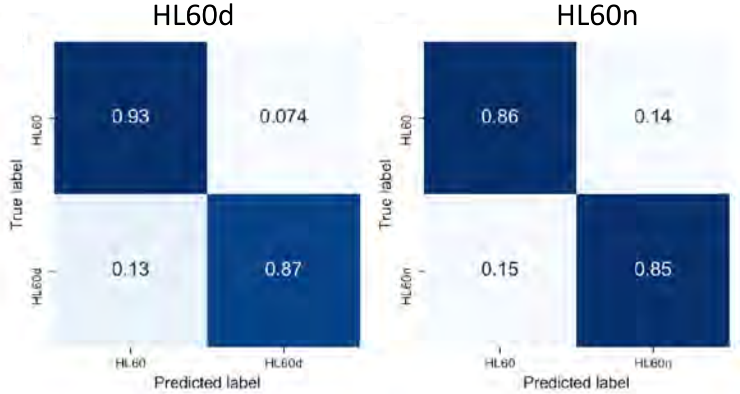



AR = $\frac{a}{b}$

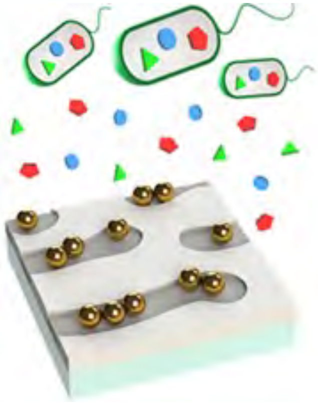


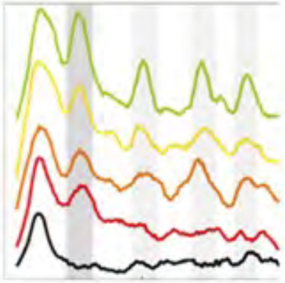

Combs, *et al. Bioarxiv* 2021




**Zuzanna Siwy**

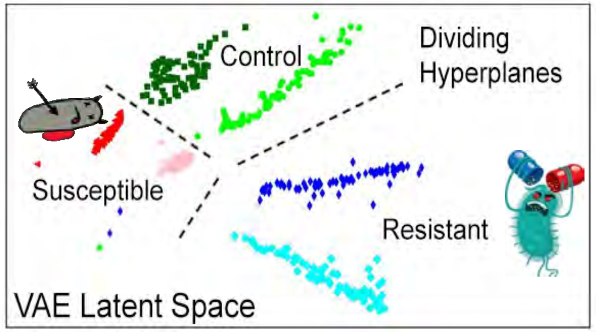
## *Fingerprinting vibrational spectra of bacterial metabolites*

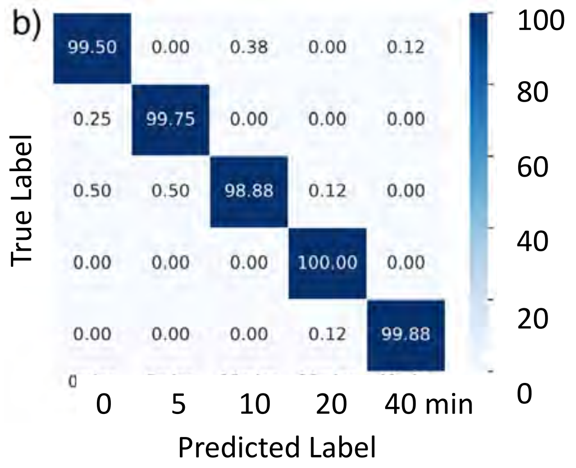




***Surface enhanced Raman scattering sensors with controlled nanogap chemistry produce rapid, sensitive, and reproducible data for ML analysis.***

**Rapid Antimicrobial Susceptibility Tests**
**Latent space representations provide mechanistic insights**




Thrift, *et al. ACS Nano* 2017
Thrift, *et al. ACS Nano* 2020

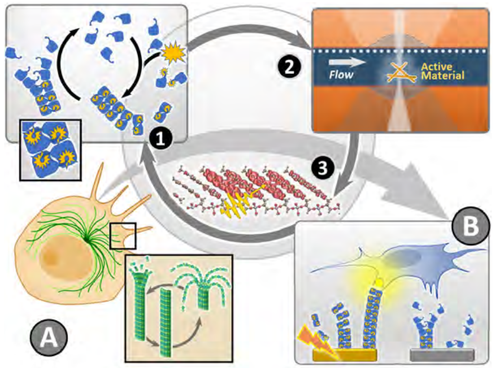
**Regina Ragan**

**Allon Hochbaum**

Center for Complex and Active Materials

UCI MRSEC

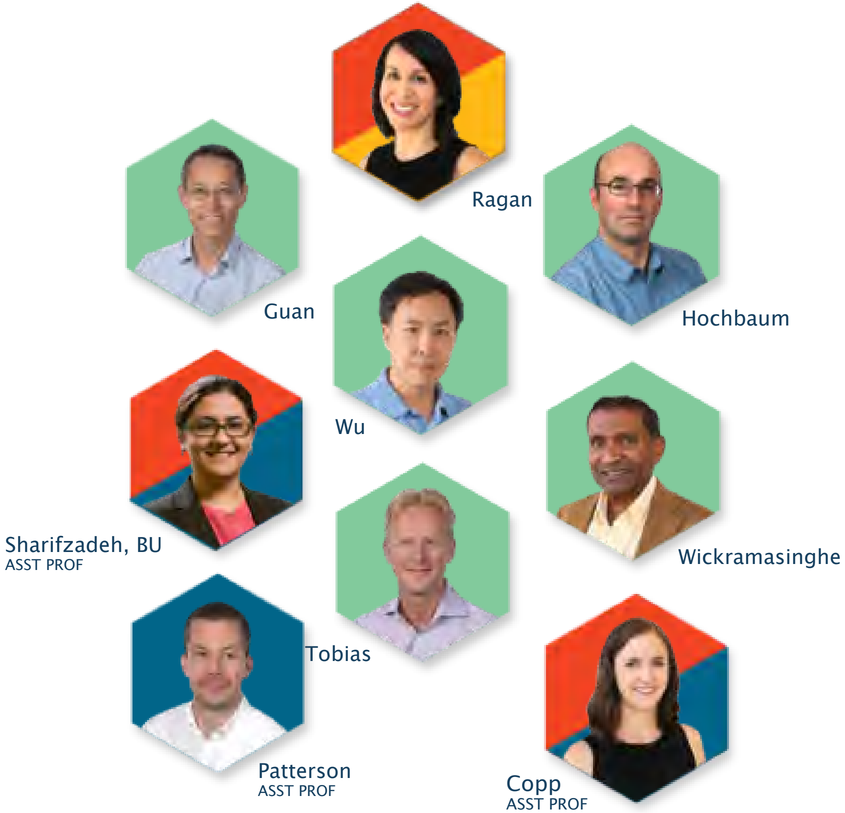
## Bio- and bio-inspired materials




**Herdeline Ardoña**

**Seunghyun Sim**

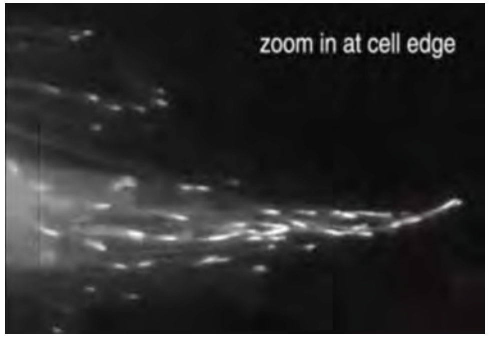
**Ken Shea**



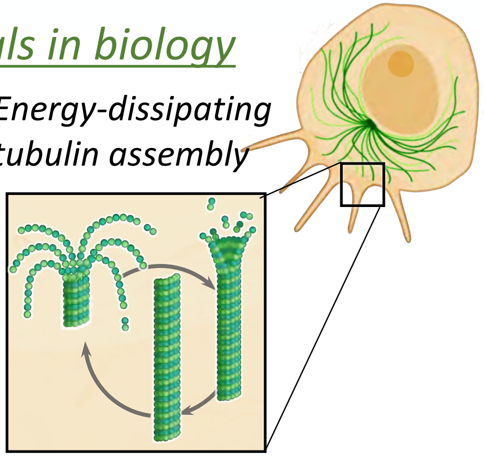
# Life exists far from equilibrium – why not synthetic materials?

Center for Complex and Active Materials
UCI MRSEC

## *Out of equilibrium materials in biology*




*Energy-dissipating tubulin assembly*



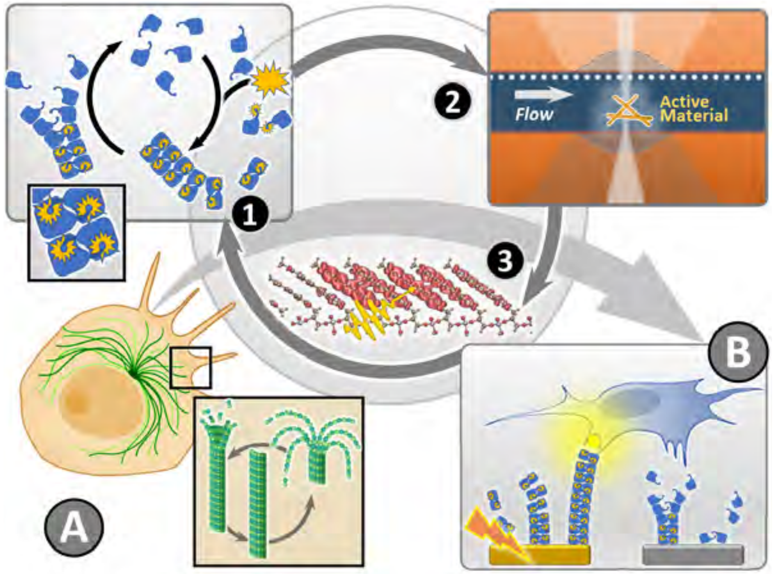
*Essential Cell Biology*, 4th Ed.

**Vision:** Develop ***supramolecular materials*** that mimic biological function and interface with biological systems.

MRSEC Interdisciplinary Research Group 2: Bioinspired Active Materials

**1. Reaction networks for actively assembling conductive materials**

**2. *In situ* TEM and spectroscopy and molecular modeling**



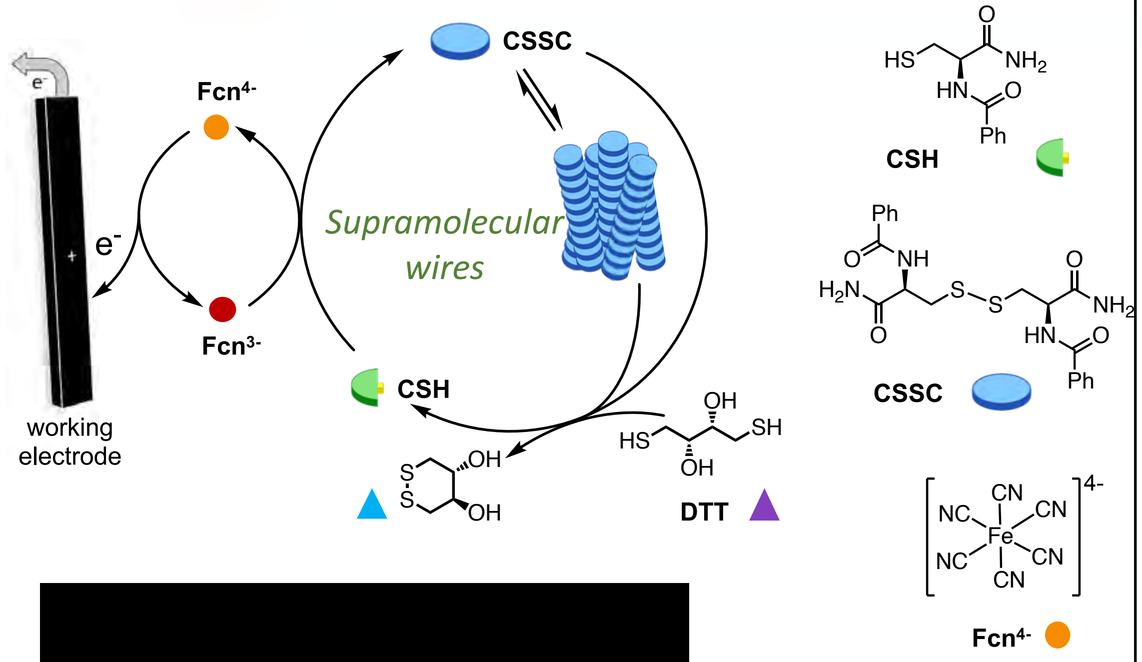

**3. First-principles and ML models for emergent electronic and structural properties**

# Building Blocks of Active Materials

## Guan, Hochbaum, and collaborators

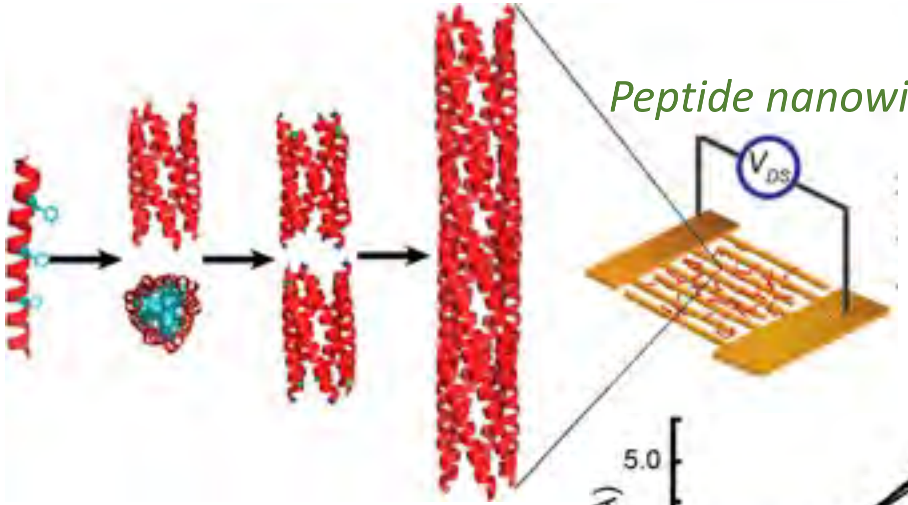
UCI Samueli School of Engineering

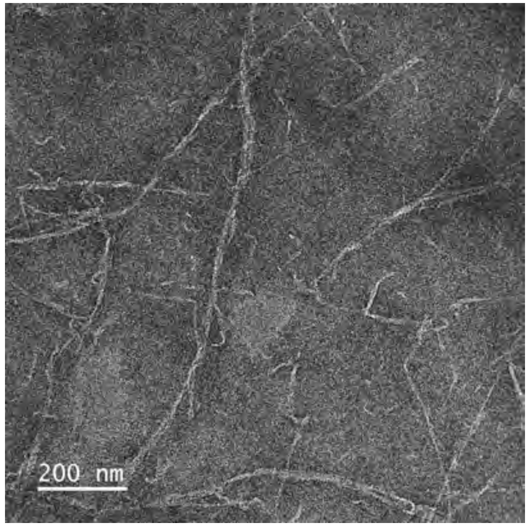
### Electricity Fueled Dissipative Assembly Platform

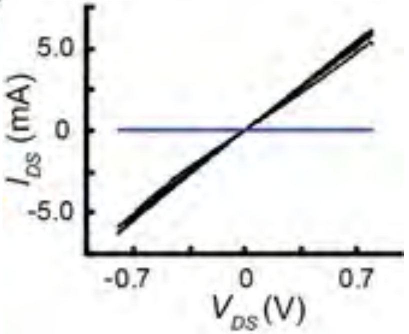



Guan

### Conductive Supramolecular Peptide Fibers




Hochbaum

Guan, Ragan, Patterson, Hochbaum, *et. al. in review*; Ing, *et al.*, *ACS Nano* 2018

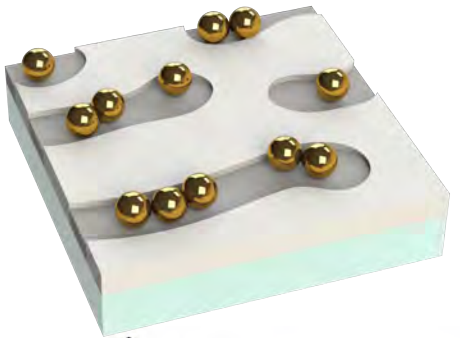
# *Understanding Dissipative Assembly*

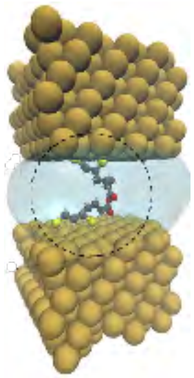
*Ragan, Wickramasinghe, Patterson, Tobias*

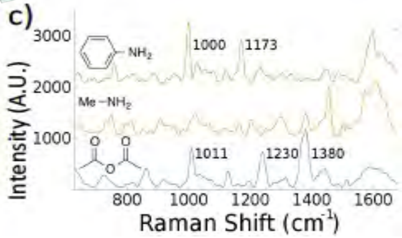
UCI Samueli School of Engineering

## *Characterizing complex, out-of-equilibrium soft matter systems*

### Surface enhanced Raman spectroscopy and photo-induced force microscopy (PiFM)





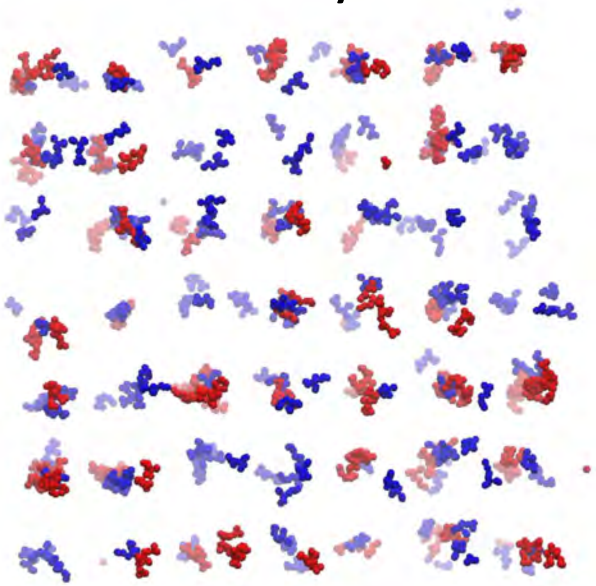



Ragan

Wickramasinghe

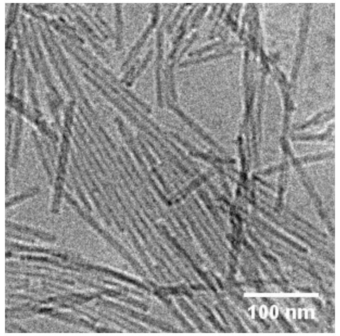
molecular VISTA

### Multi-scale molecular dynamics modeling of supramolecular assembly

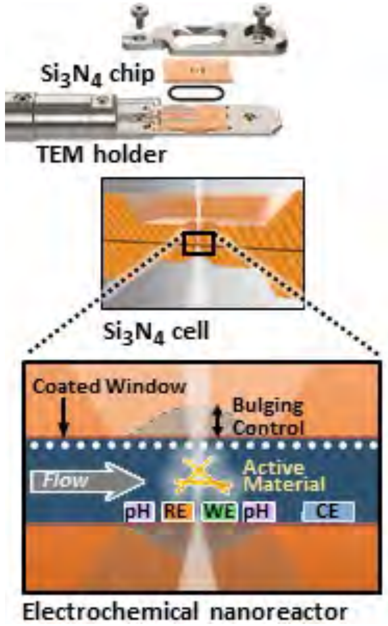


Tobias

### CryoEM and *in situ* TEM




Patterson




DENS solutions

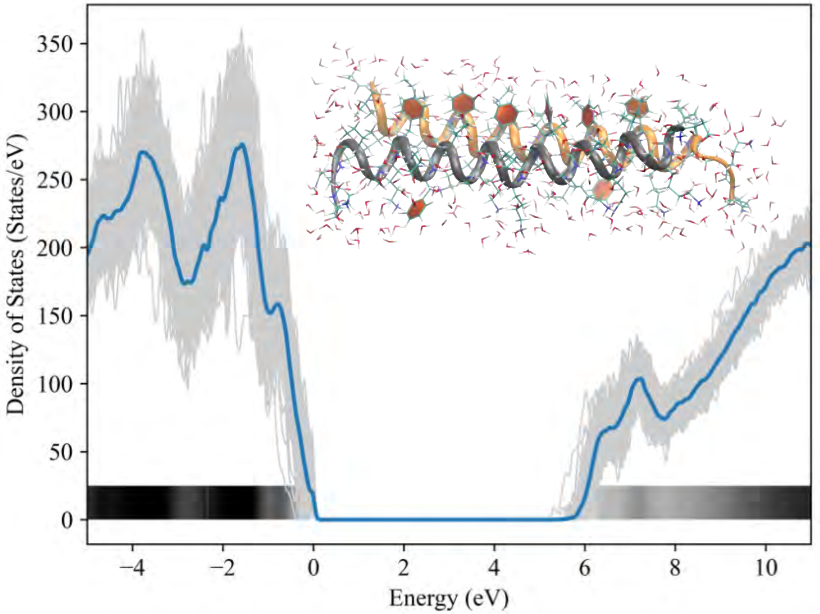

Thirft, Hochbaum, Ragan *et al*, *ACS Nano*, 2017, 11, 11317; Rajaei, Wickramasinghe *et al*, *Opt Expr*, 2018, 26, 26365; Wong, Tobias *et al*, *Biochemistry*, 2019, 58, 3691; Ianiro, Patterson *et al*, *Nature Chem*, 2019, 11, 320.

# *Charge Transport in Biomolecular Materials*

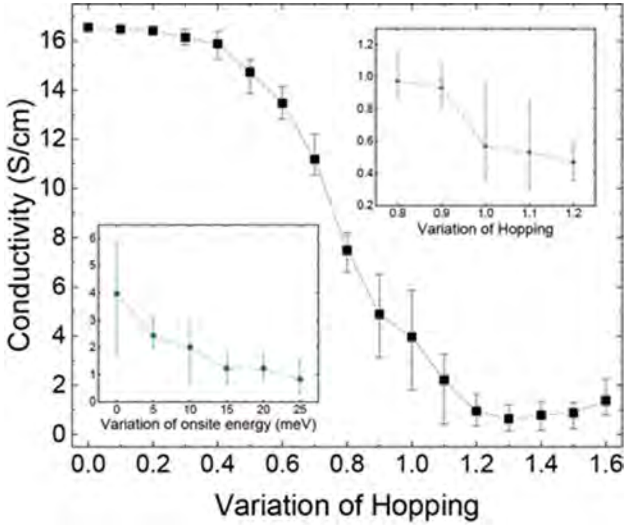
*Sharifzadeh, Wu, Hochbaum, Copp*

UCI Samueli School of Engineering

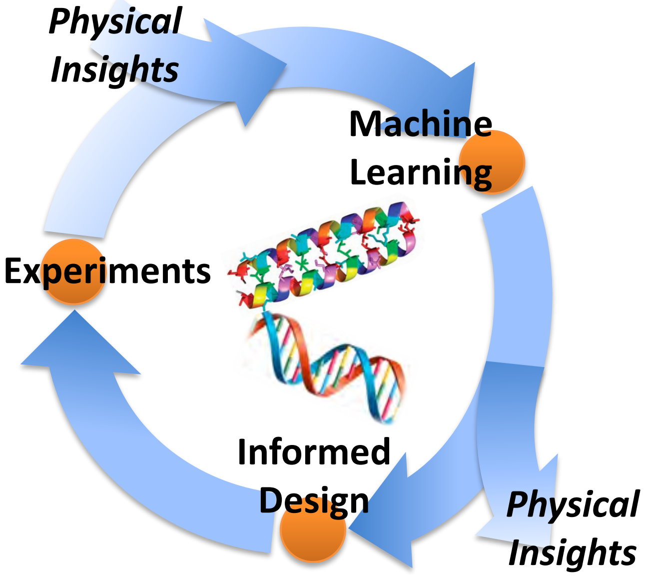
## Electronic structure of supramolecular peptide assemblies through all atom MD-DFT calculations



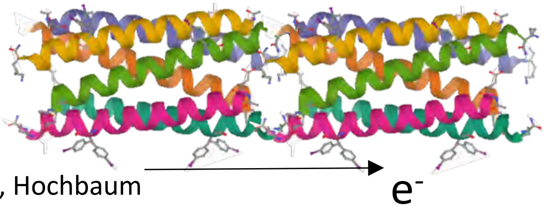

## DFT informs state-coupling in hopping charge transport conduction model




## Machine learning-enabled study and design

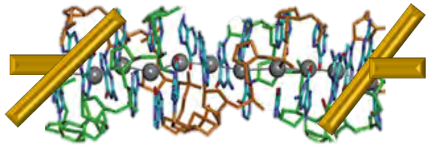



## *Self-assembling conductive peptide fibers*




PDB: 5EOJ, Hochbaum

## *Metal-enhanced DNA nanowires*



Sharifzadeh, BU
ASST PROF

Wu

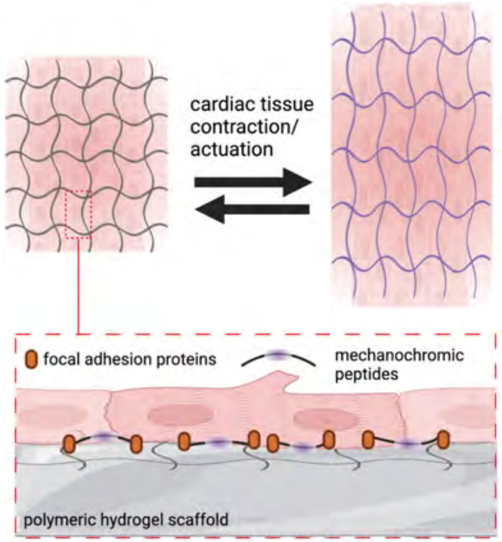
Copp
ASST PROF

# Materials for the Biological Interface

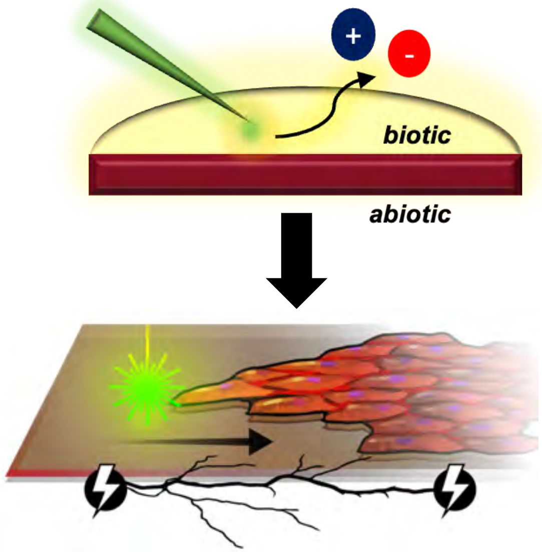
UCI Samueli School of Engineering

*Molecular design of functional soft materials for biointerfacing*

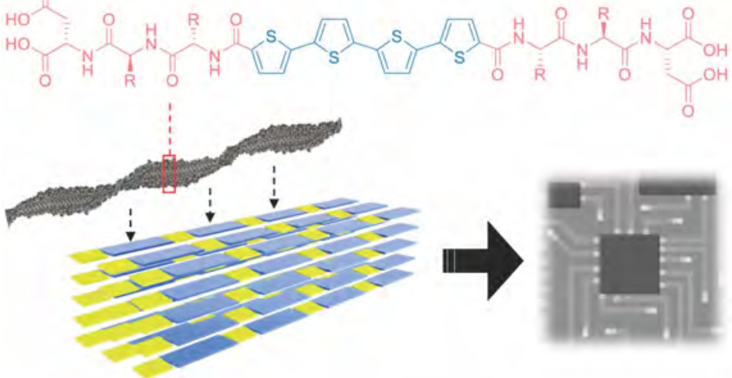
**Probing Biological Processes**




**Driving Biological Processes**



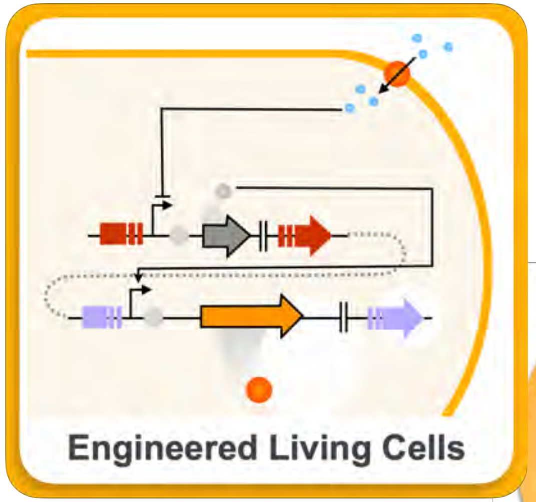

Polymer-Assisted Patterning of Optoelectronic Peptides (*with A. Yee)*

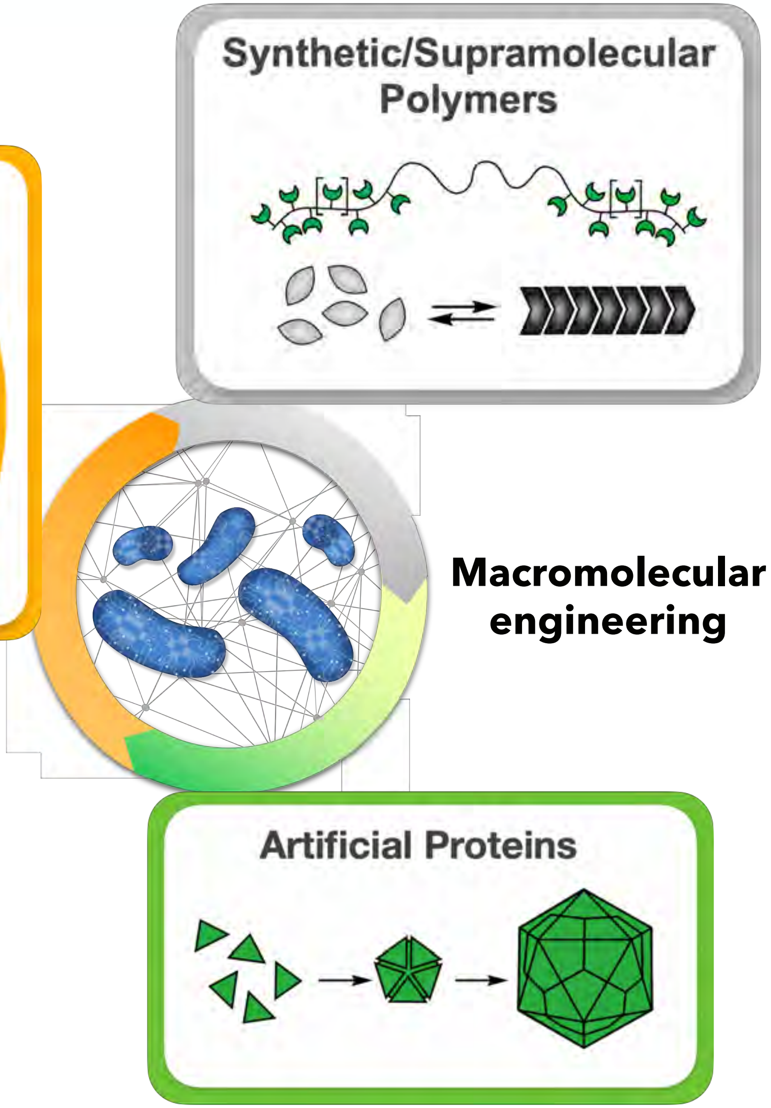


**Herdeline Ardoña**

*Programmable living functionality within soft materials*

**Synthetic Biology**




**Seunghyun Sim**

# Synthetic Antibodies

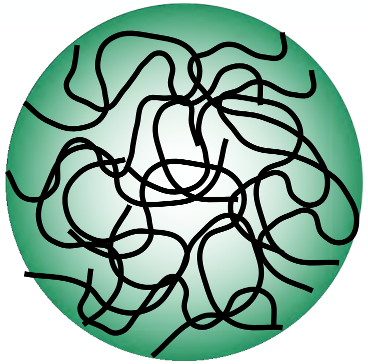
## Ken Shea

UCI Samueli School of Engineering

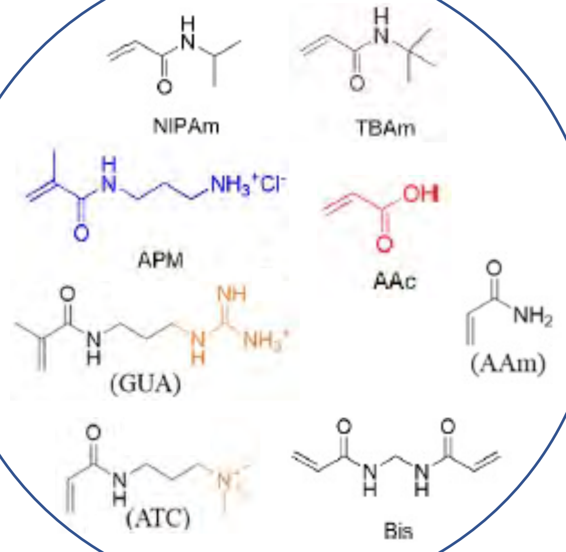
**Synthetic hydrogel copolymers engineered with antibody-like affinity and selectivity for biological macromolecules.**

**Ken Shea**

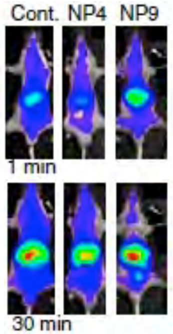
*Biology's antibodies*

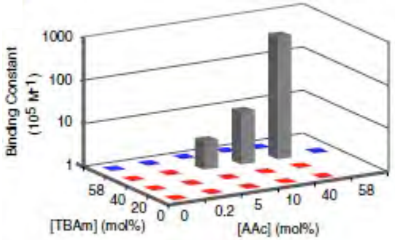


*Synthetic hydrogels*




### Anti-toxin



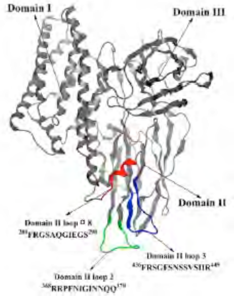



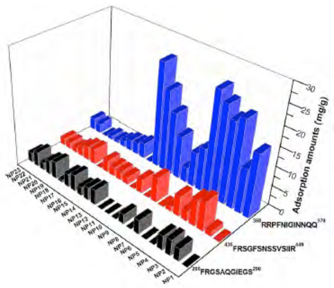

*Cy7-mellitin tracking*

$K_d$ = 15 nM

*J. Am. Chem. Soc.* **2010**, *132*, 13648 - 13650.
*Proc. Nat. Acad. Sci.* **2012,** *109*, 33-38.
*Nature Protocols*, **2015**, *10*, 595–604
*Nature Com*, ***2021***, *12*, *doi.org/10.1038/s41467-021-25847-2*

### Targeting bacterial proteins



*Bacillus thuringiensis Cry1Ab*

$K_d$ = 26 pM

*J. Am. Chem. Soc.* **2018,** *140*, 6853-6864.

# Energy Conversion and Storage



**WHAT**
**HOW**
**WHY**

*Vojislav Stamenkovic*

*Plamen Atanassov*

*Iryna Zenyuk*

*Jack Brouwer*

*Shane Ardo*

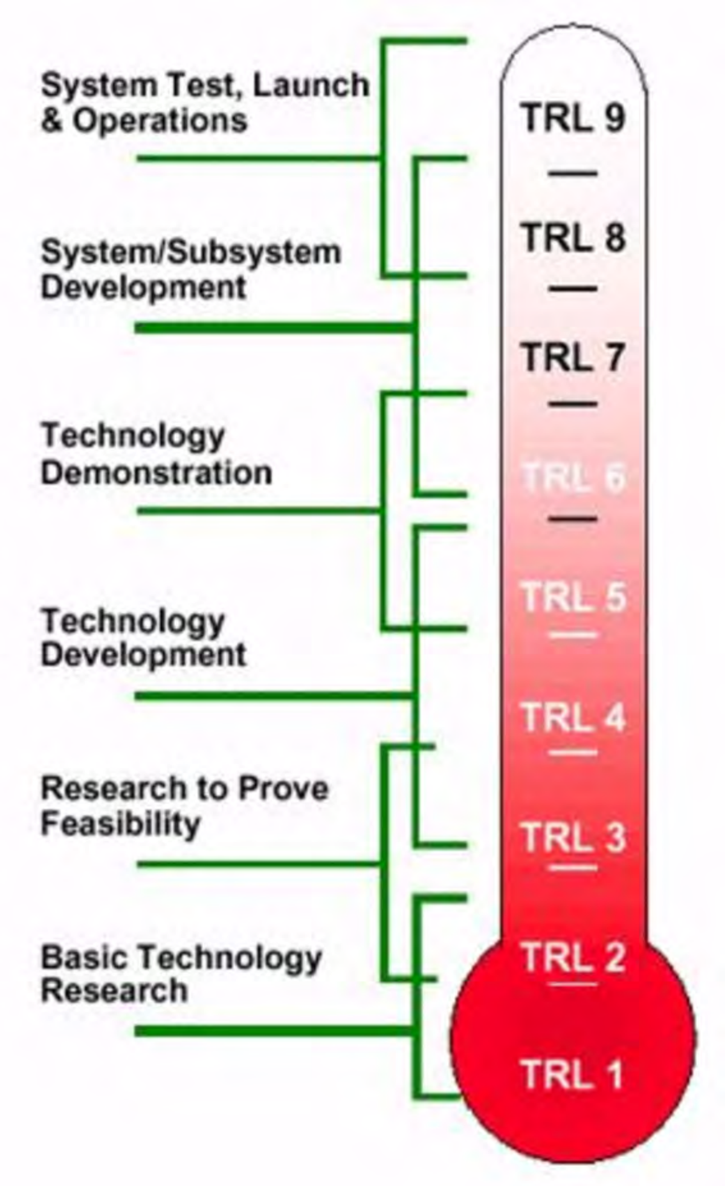
*Jenny Yang*

*Matt Law*

*Reg Penner*

# Electrochemical Technologies Readiness Level

*TRL: Batteries >> Fuel Cells >> Electrolyzers*




***Transportation***

***Li-ion*** **BATTERIES**

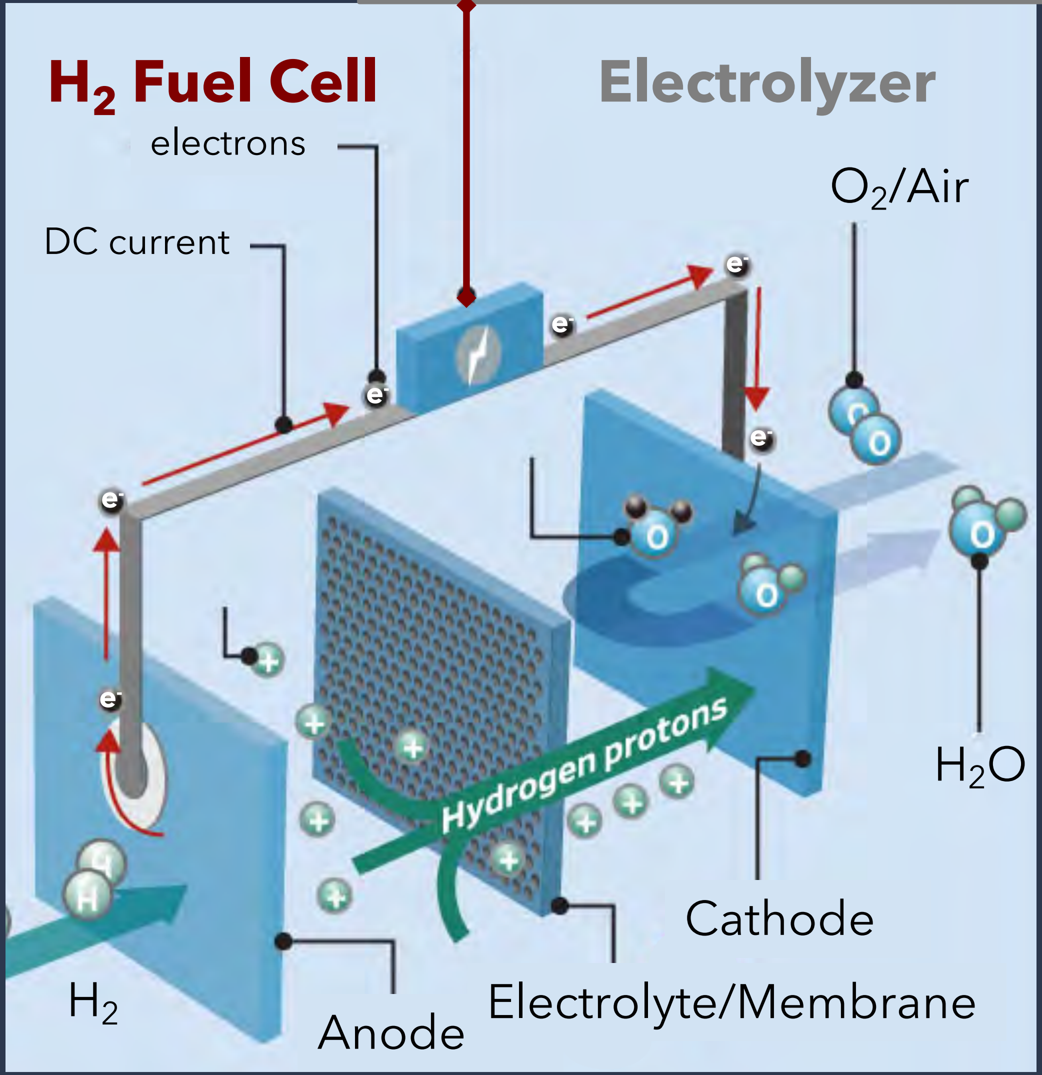
*Now*

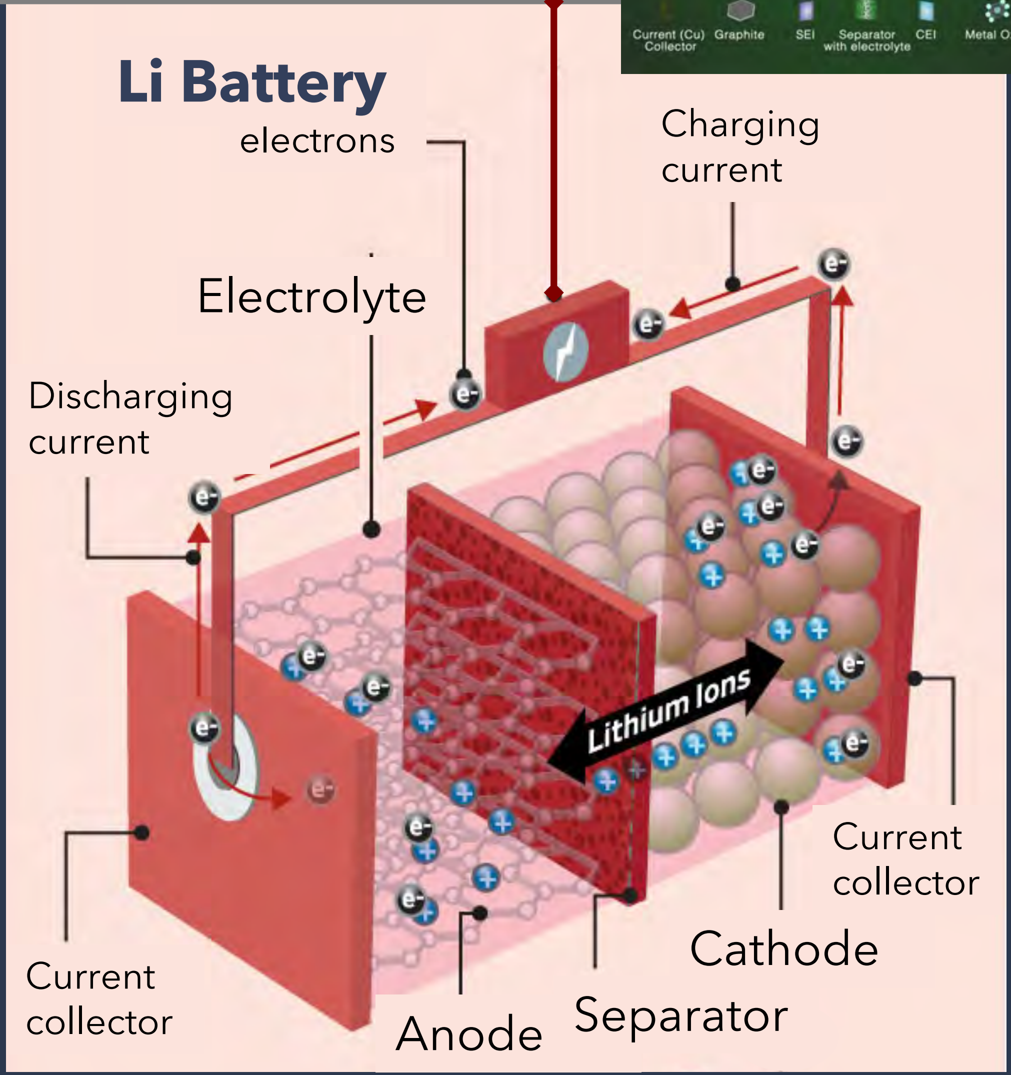
***$H_2$*** **FUEL CELLS**

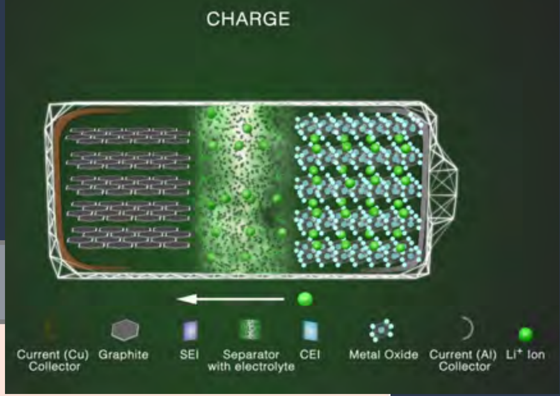
# Electrochemical Technologies

***Fuel Cells* | *Electrolyzers* | *Batteries***

**electrons flow through a circuit generating direct electric current**

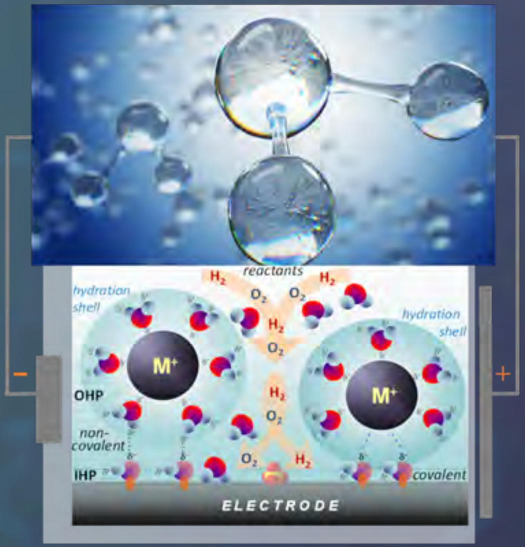


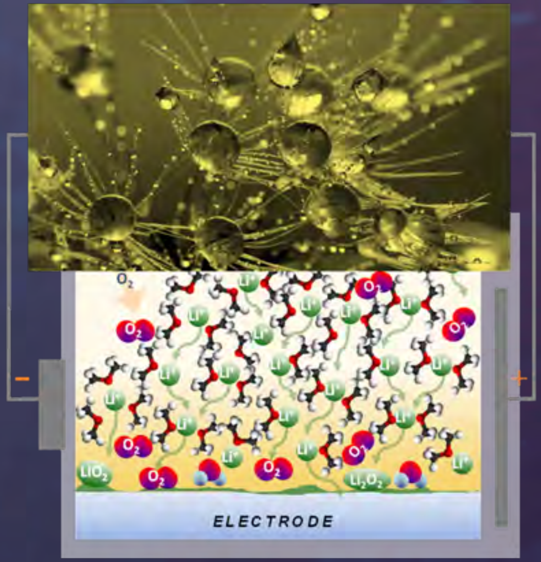



# Electrochemical Technologies: Common Denominator

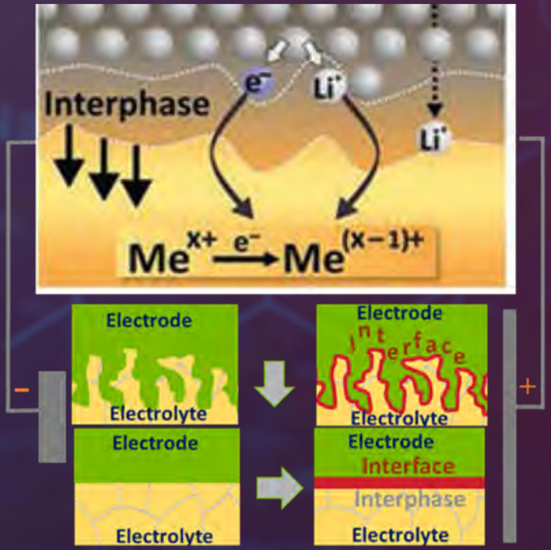
## *ELECTROCHEMICAL INTERFACES*




Solid-Aqueous




Solid-Organic




Solid-Solid

### Topics

- Structure-function properties
- Modification of electrochemical interfaces
- Guided synthesis of functional materials
- Formation of interfaces and role of impurities

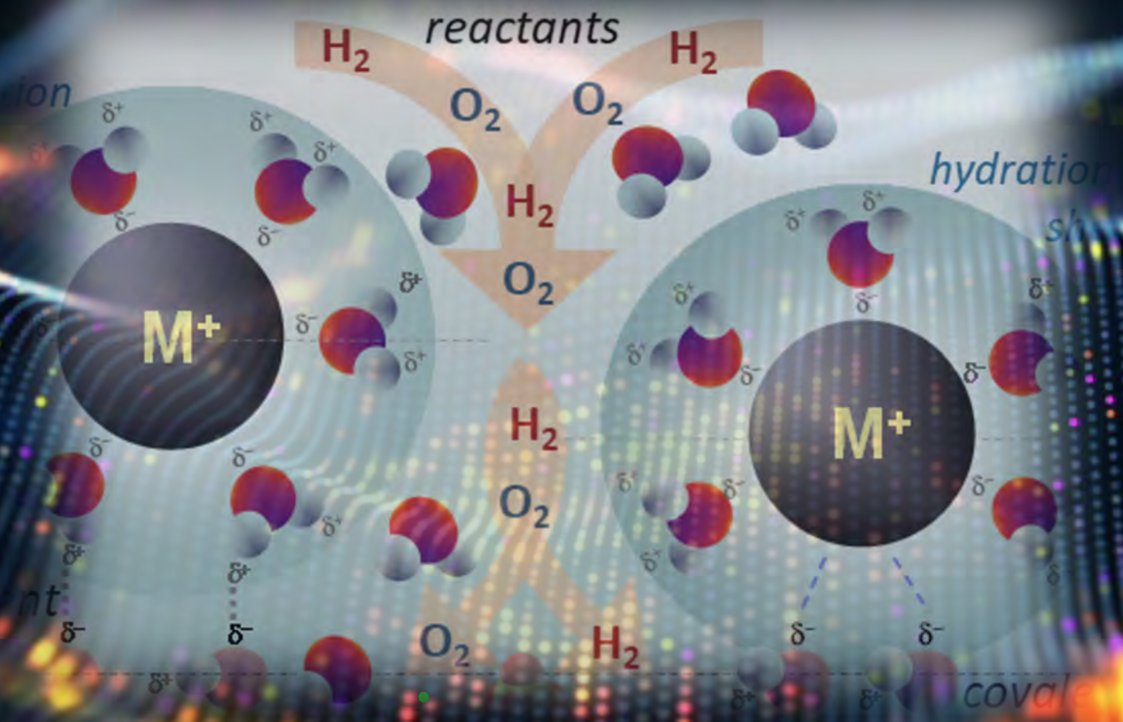
### Challenges

- Performance (reaction rate, capacity)
- Efficiency
- Durability
- Cost

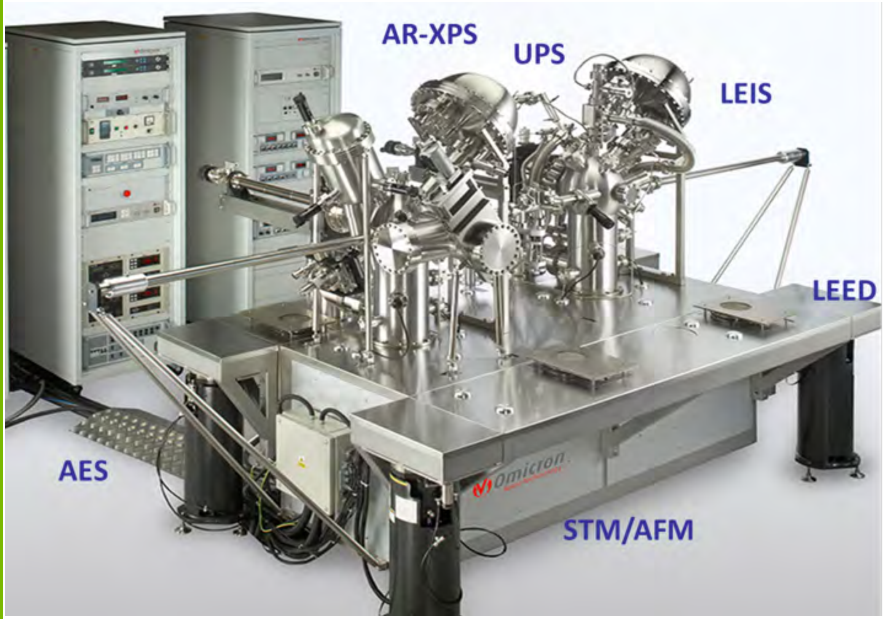
# *ELECTROCHEMICAL INTERFACES:*

# Research Topics

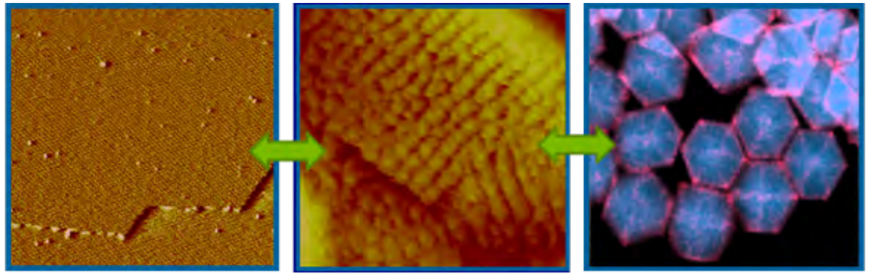
1. **ACTIVITY GAIN FROM SOLID PHASE**
2. **TUNING OF THE DOUBLE LAYER**
3. **STABILITY OF INTERFACES**



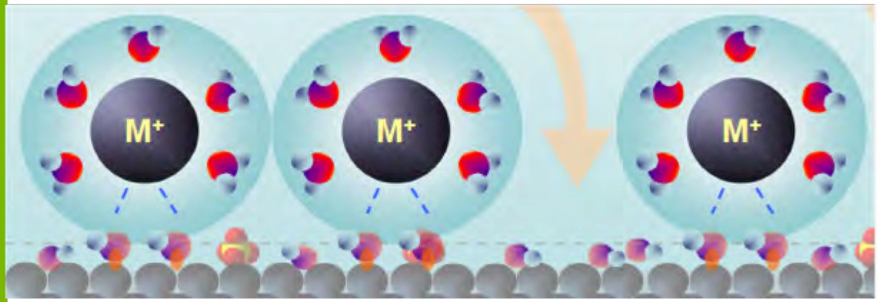
# ELECTROCHEMICAL INTERFACES BY DESIGN

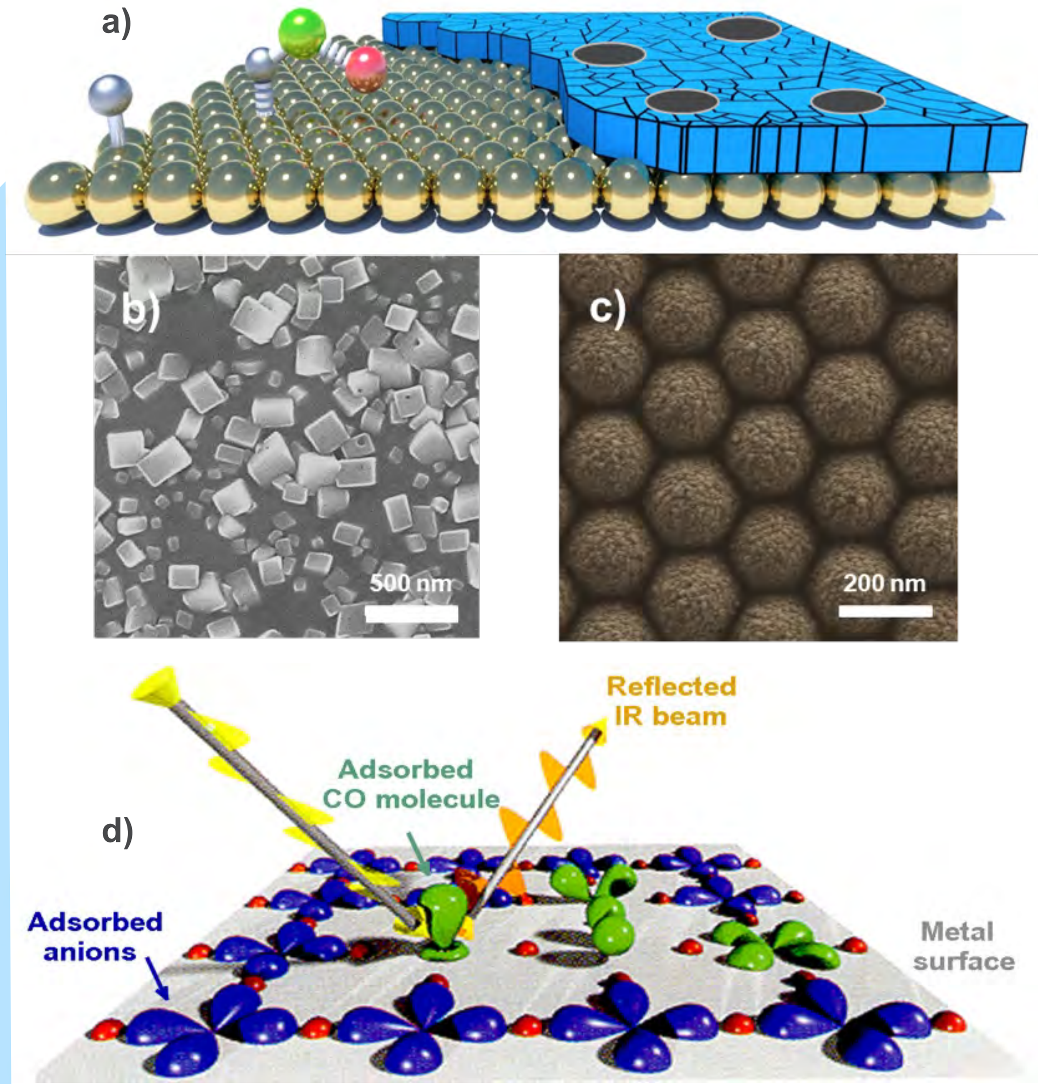



1. *Ultra High Vacuum & Surface Science Approach*

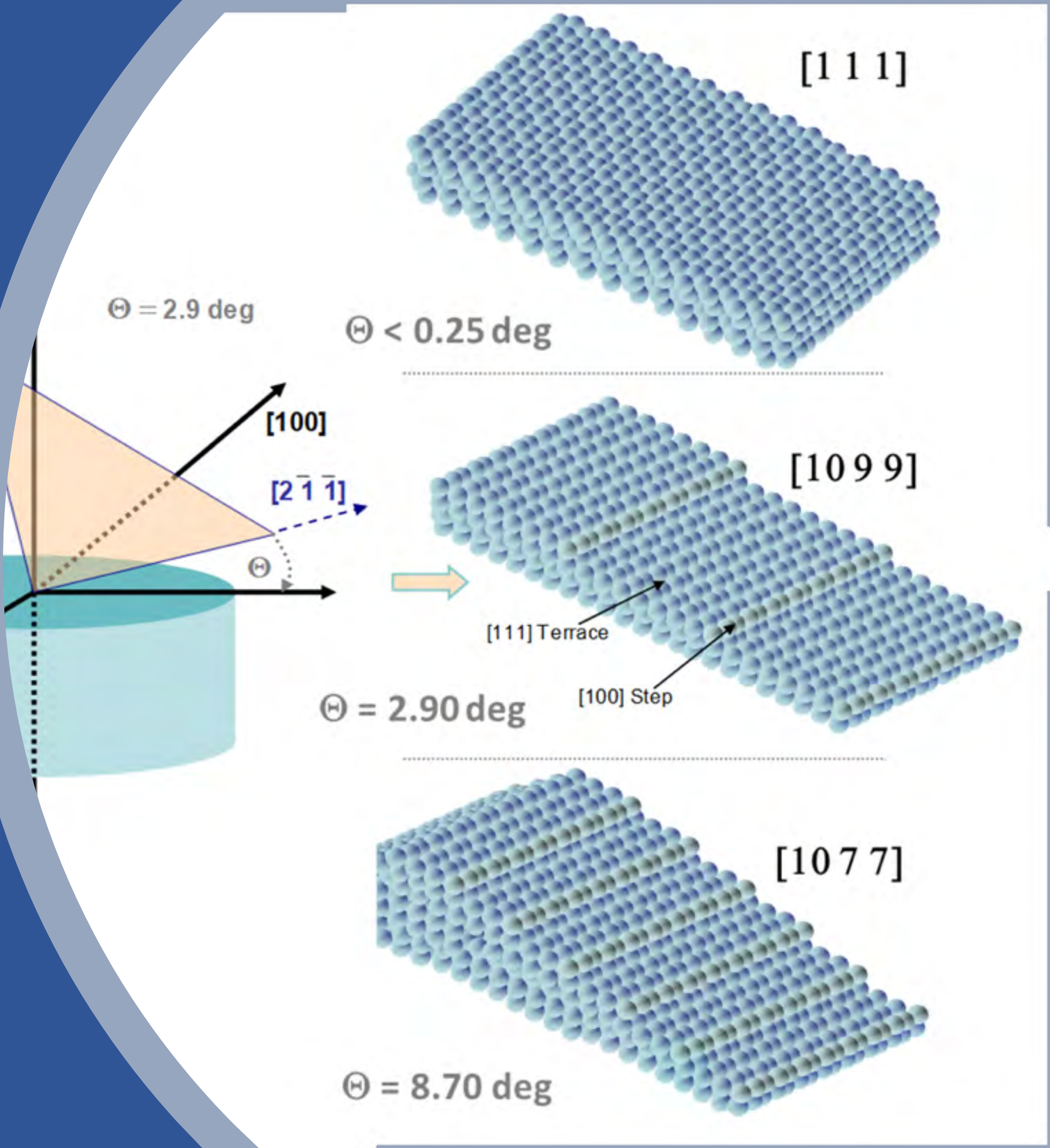


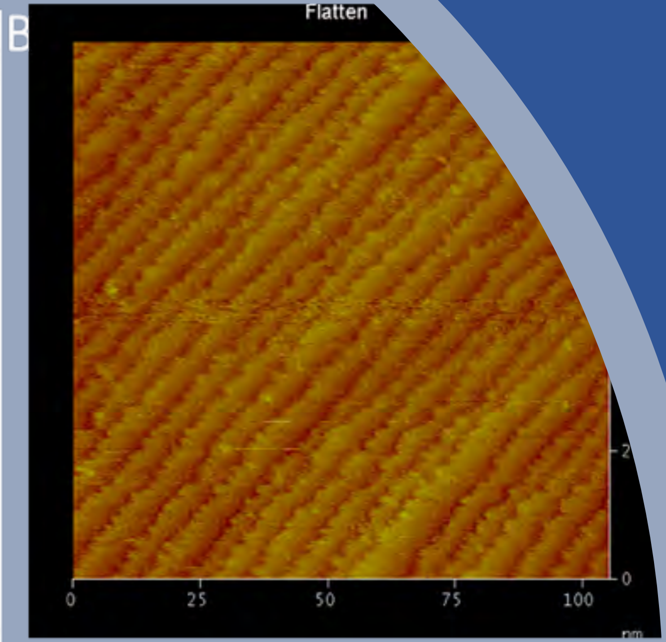
Single Crystals Thin Films Nanomaterials



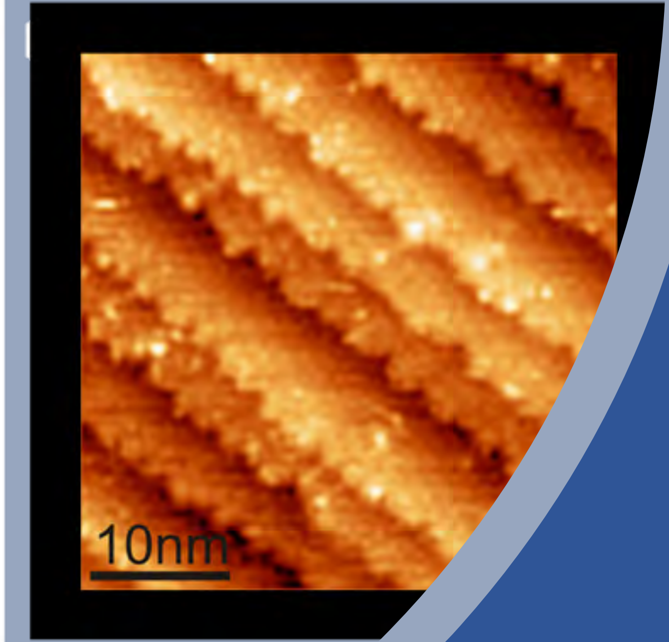




*Electrochemical Interfaces @ Play*

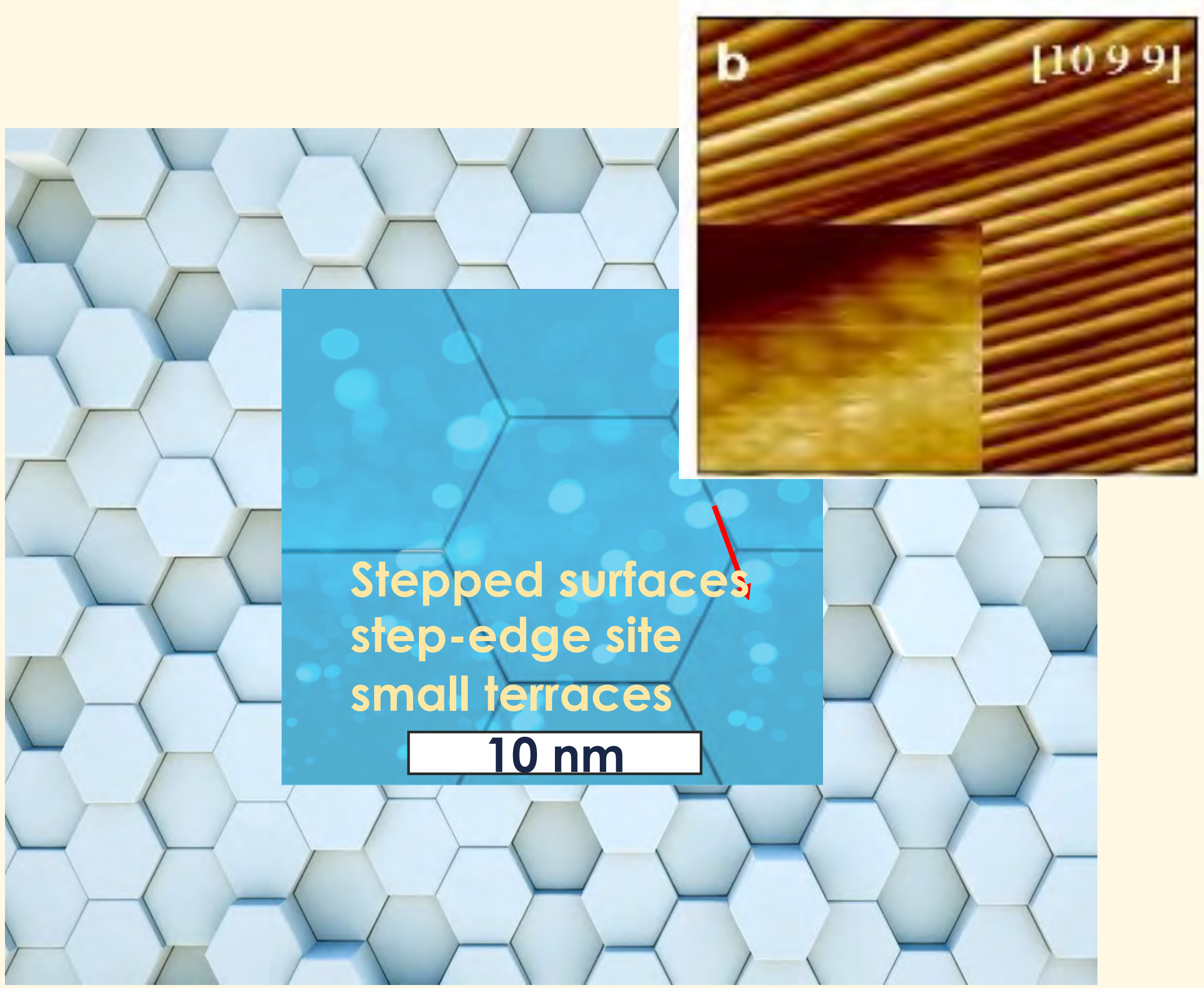


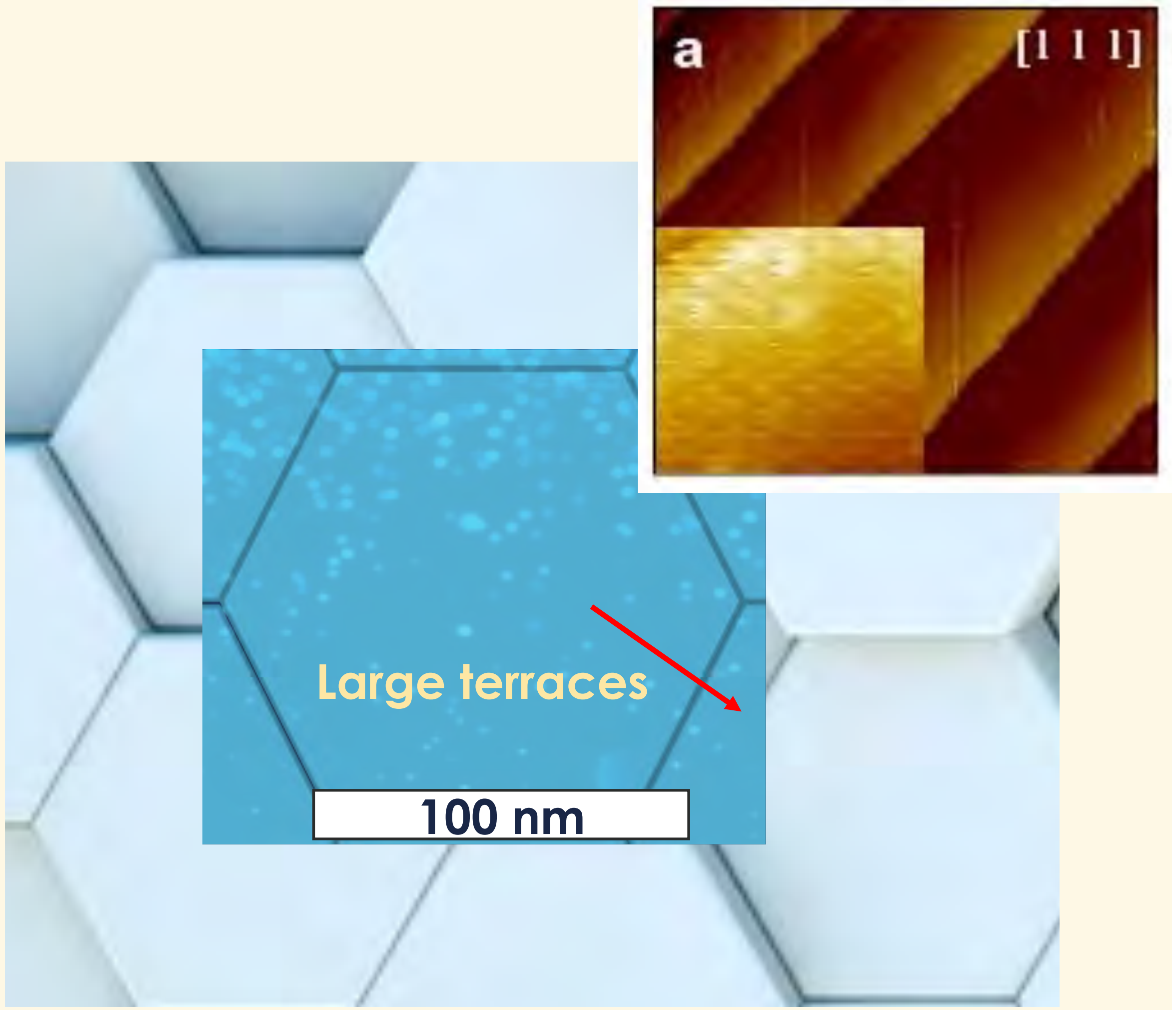




**STM:** Pt[10 9 9] - $CO_{ad}$



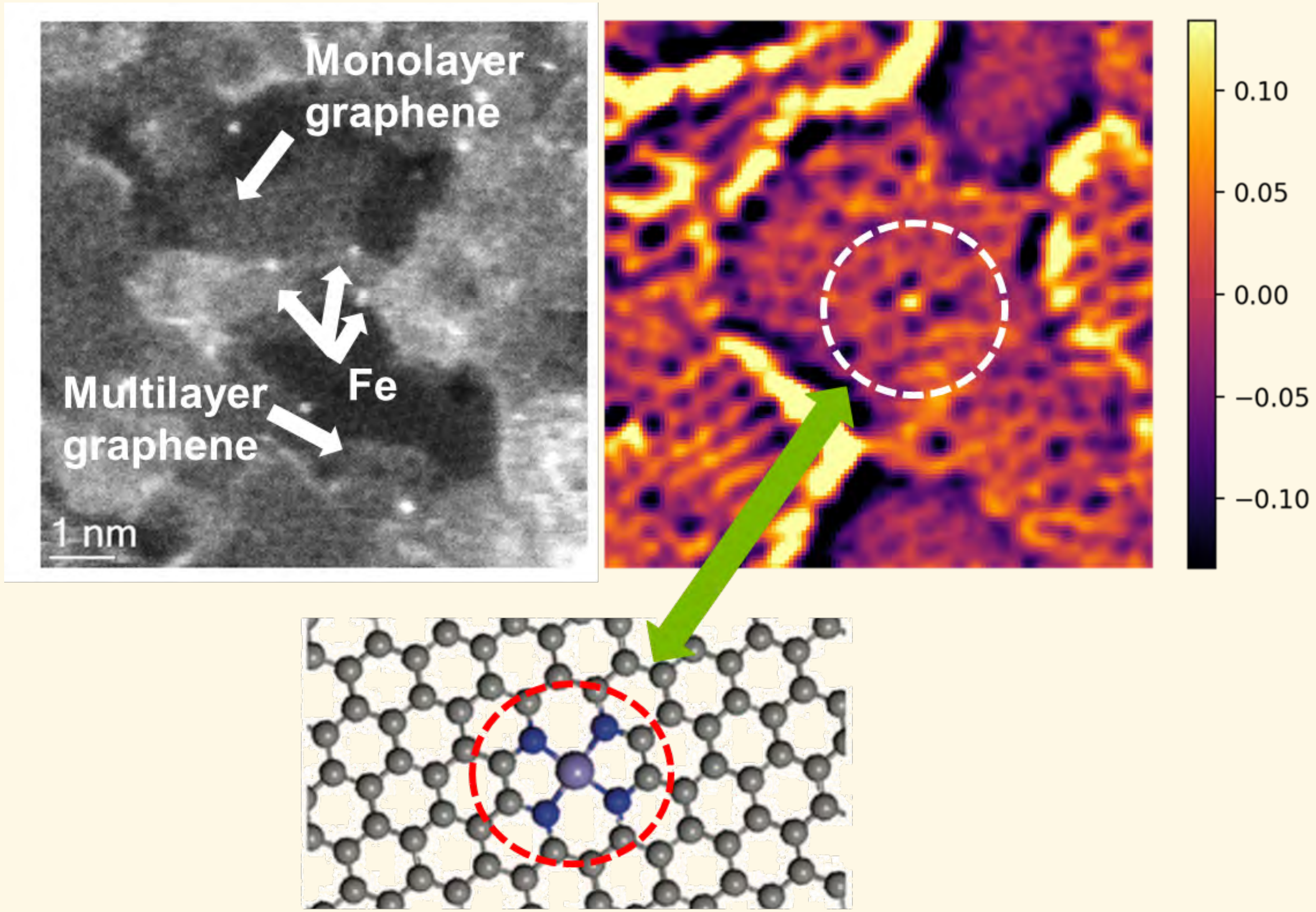
# Design @ Atomic Scale



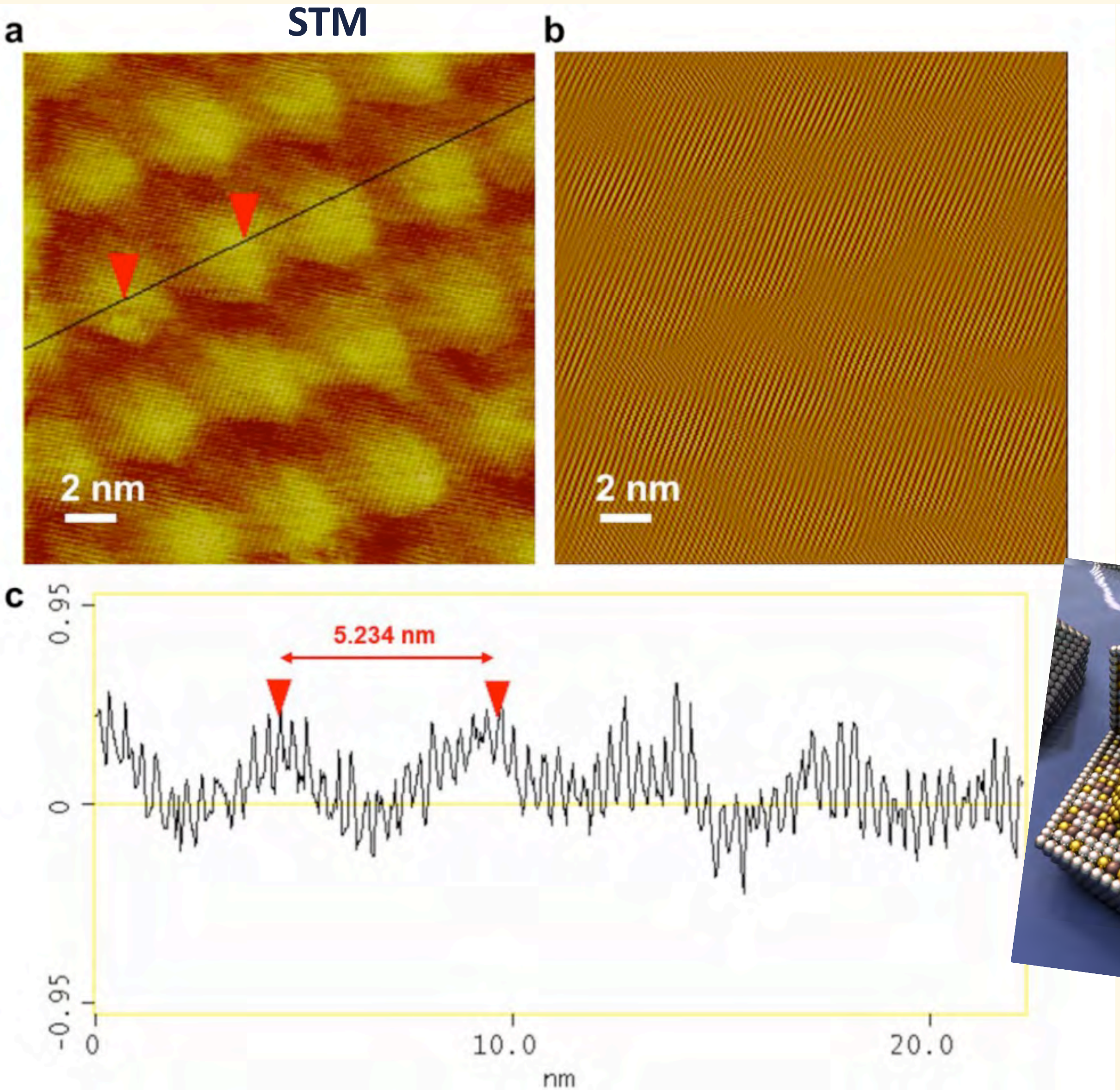

→**Larger terraces** lead to **higher** reaction rate for ORR:  improvement factor 100

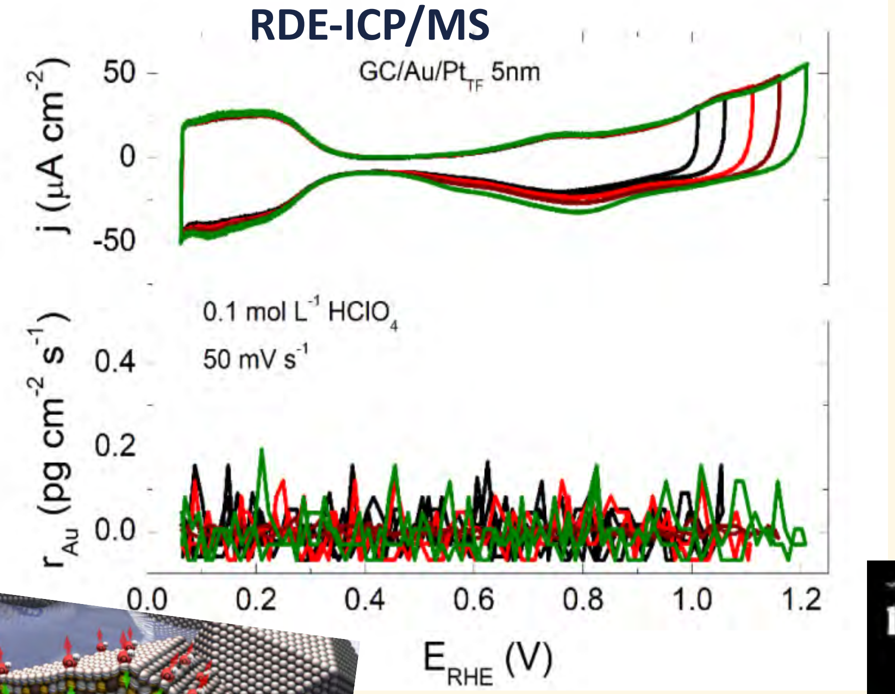
# Design @ Atomic Scale: nature of active sites

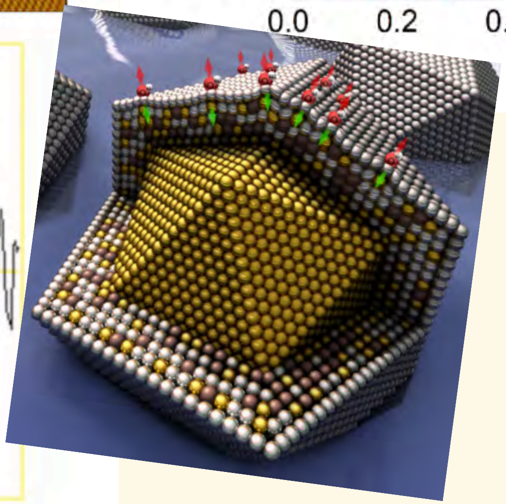



$FeN_4$/Graphene Structure

# Durability @ Atomic Scale



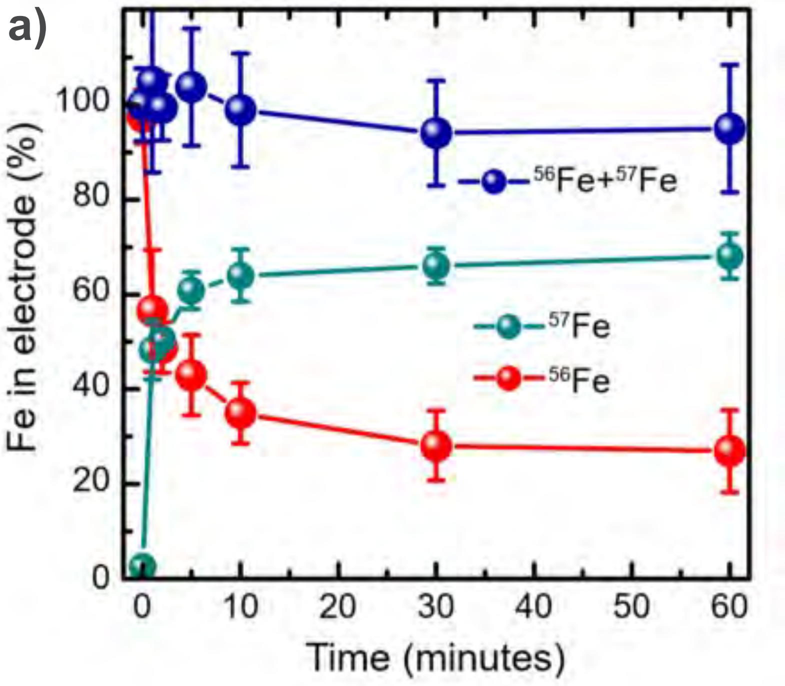



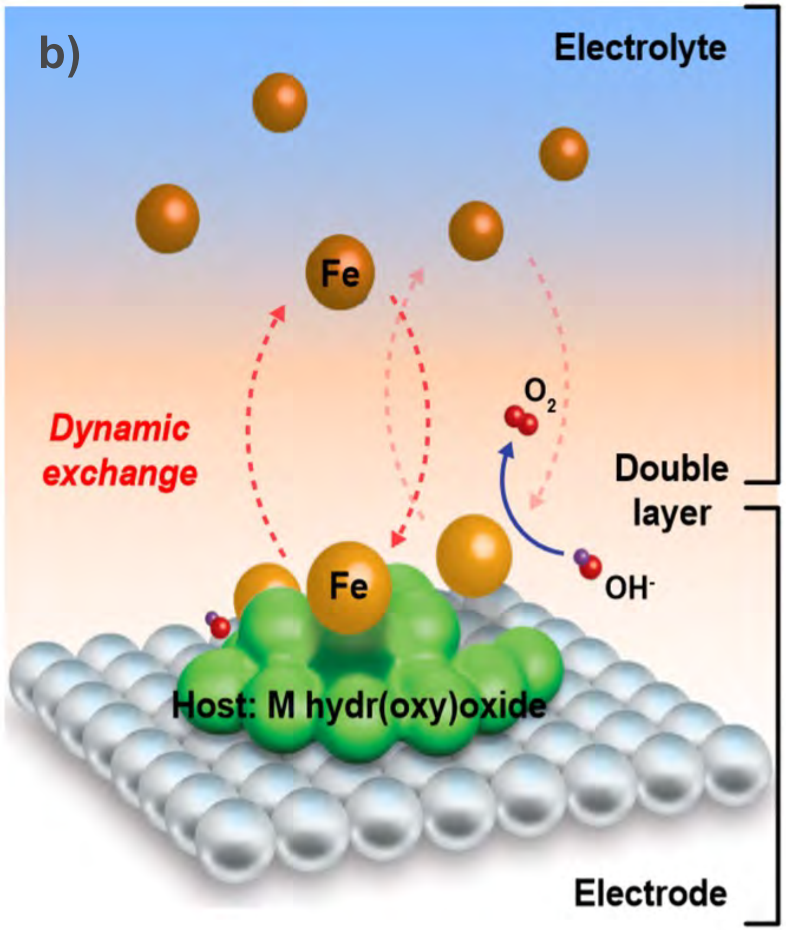

**REFERENCE**

Nature Materials 19 (2020) 1207-1214

# NATURE of active sites: Dynamic stability for OER

*alkaline electrolytes*




- The strong interaction between Fe and $TMO_xH_y$ is the key to control the average number of Fe active sites present at the interface
- The Fe-M adsorption energy is a reaction descriptor that unifies OER on 3d TM hydr(oxy)oxides, and extends the design rules for active and stable electrochemical interfaces

- Resolved the nature of active sites and mechanism for OER through the balanced Fe dissolution and redeposition over TM-oxide

**a)** Isotope exchange between the electrode ($^{56}Fe$) and electrolyte ($^{57}Fe$) by ICP-MS

**b)** Schematic of the dynamic stable Fe active site during OER in alkaline electrolyte

**REFERENCE**

Nature Energy 5 (2020) 222

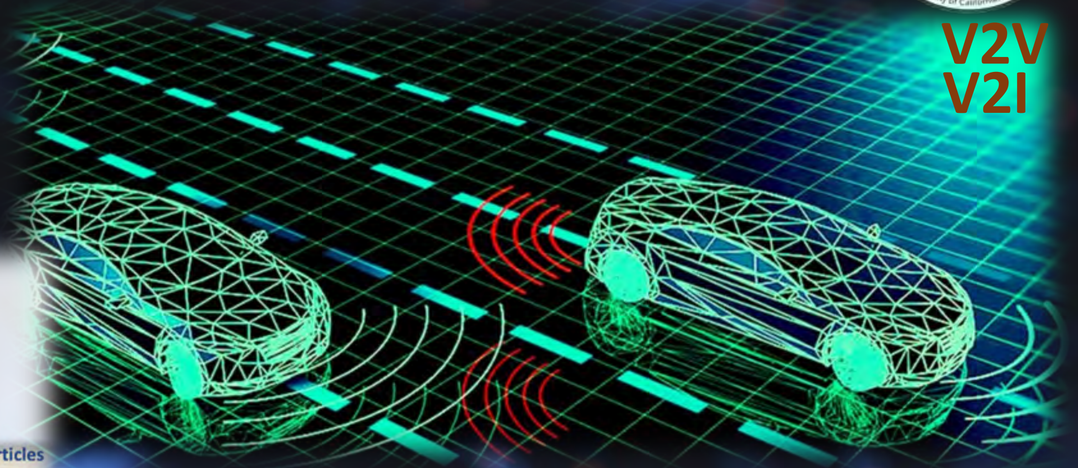
# Electrochemical Technologies are Complementary

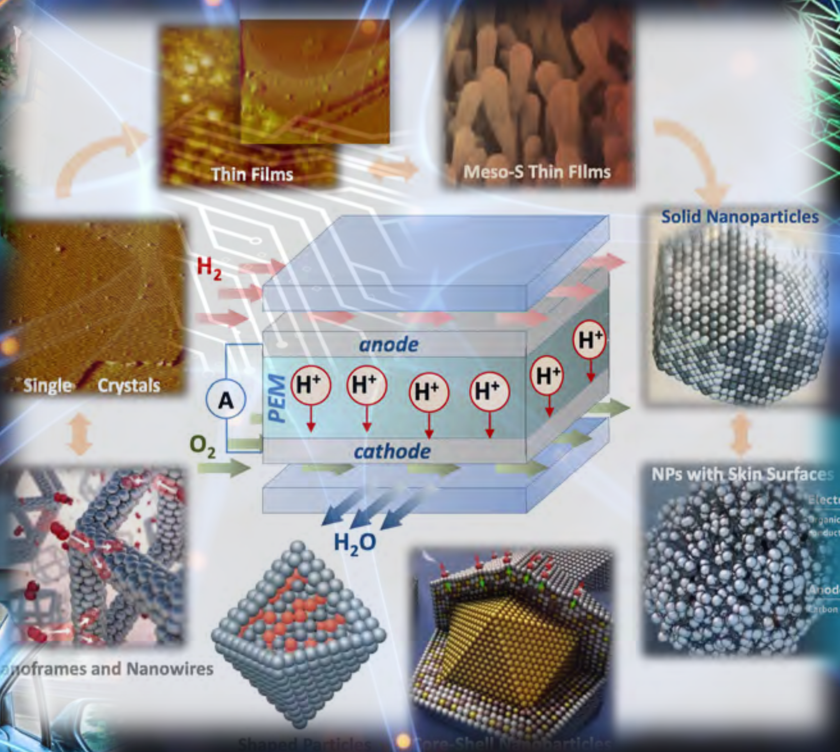
*Batteries -- Fuel Cells -- Electrolyzers*

~~Electrification in Transportation: Batteries and Hydrogen Fuel Cells~~

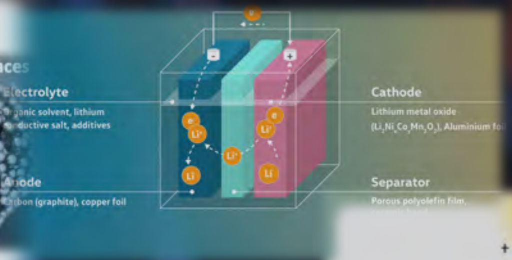
~~The Electric-Truck Battle to Come: Batteries vs. Hydrogen Fuel Cells~~

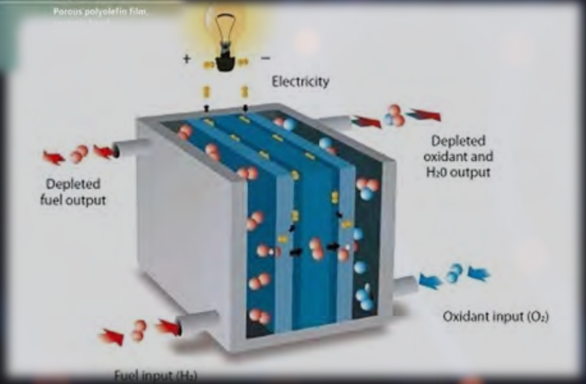
# Horiba Institute for Mobility and Connectivity$^2$





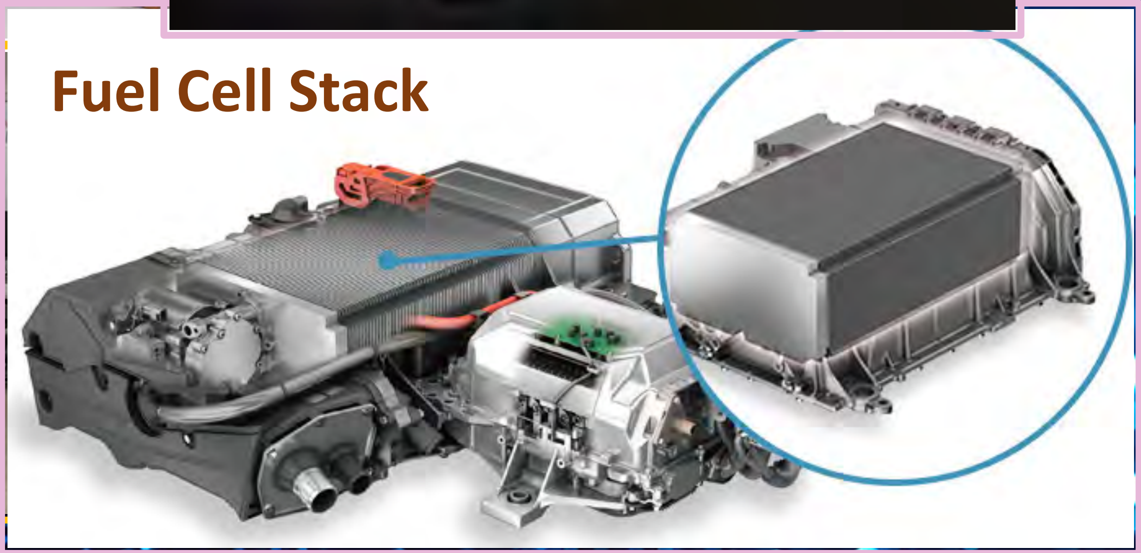


# Horiba Institute for Mobility and Connectivity²






## Levels of Autonomous Driving Network

| Level Definition | L0: Manual Operation & Maintenance | L1: Assisted Operation & Maintenance | L2: Partial Autonomous Network | L3: Conditional Autonomous Network | L4: Highly Autonomous Network | L5: Full Autonomous Network |
|---|---|---|---|---|---|---|
| Execution (Hands) | | | | | | |
| Awareness (Eyes) | | | | | | |
| Decision (Minds) | | | | | | |
| Service Experience | | | | | | |
| System Complexity | Not Applicable | Sub-Task Mode-Specific | Unit Level Mode-Specific | Domain Level Mode-Specific | Service Level Mode-Specific | All Modes |

Icons by: Pixel perfect from www.flaticon.com; Freepik from www.flaticon.com; Smashicons from www.flaticon.com; Kiranshastry from www.flaticon.com