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## Advanced Nanomanufacturing for Wearable Human Performance Monitoring Sensor Platforms

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## **Advanced Nanomanufacturing for Wearable Human Performance Monitoring Sensor Platforms**

**Jeffrey Morse, Managing Director  
National Nanomanufacturing Network**

**James Watkins, Director  
NSF Center for Hierarchical Manufacturing**

**Center for Personalized Health Monitoring**

# The Concept: Enabling a New Paradigm in Personalized Health Monitoring

## Home Health Monitoring Prevention and Intervention

### Personal Health Monitoring

Vital signs and medical information  
Are measured and reported to local  
wireless hub

Respiration, ECG

Lab-on-a-Chip  
Measures drug levels,  
biomarkers

PPG, blood pressure,  
vascular performance

3-axis accelerometer  
Measures activity, falls



### Real Time Medical Tracking

Medical Information is continuously  
monitored

**Health Care Providers**  
Medical professionals  
can monitor in-home  
patients in real time



### First Responders

Automatic notification  
In event of emergency



## Biometrics, Human Augmentation and Performance Monitoring for Military

Stress/Fatigue  
-Pocket Lab  
-Biomarkers

Biometrics  
-EKG  
-Blood Pressure  
-Body Temp  
-Blood oxygen  
-Pulse/heart rate



### Future Solutions

Advanced Mobile Diagnostics  
Intuitive Information Displays  
Sensor-Incorporated Garments  
Simple Go/No-Go Indicators

### Trauma

-Impact  
-Blast  
-Chem/Bio Exposure

## Point-of-Care Chemical and Microfluidic Sensors



## New Paradigm for Patient Care Diagnostics

## Activity and Fitness Monitoring

### Wireless Body Area Network

Motion, vital signs, activity  
measured by various sensors  
and sent to a mobile device

Respiration, ECG

Skin Temperature,  
Resistance

PPG, blood pressure,  
vascular performance

3-axis accelerometer



### Cellular Data Transfer

Activity and workout  
data transferred in  
real time



### Information Storage

Data is viewed by user  
on mobile device,  
personal computer, or  
stored in database



Personal Computer



Mobile Device



Central Database



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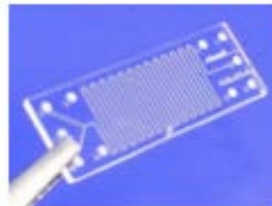
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## Young Athlete Safety



- **Monitor Cumulative Impact and Return Risk Score**
  - alerts for immediate removal from play & assessment
- **Monitor Fatigue, Stress, Hydration ....**
  - establish return to play, rest and recovery guidelines
- **Optional Sport-Specific Performance and Effort Monitoring**

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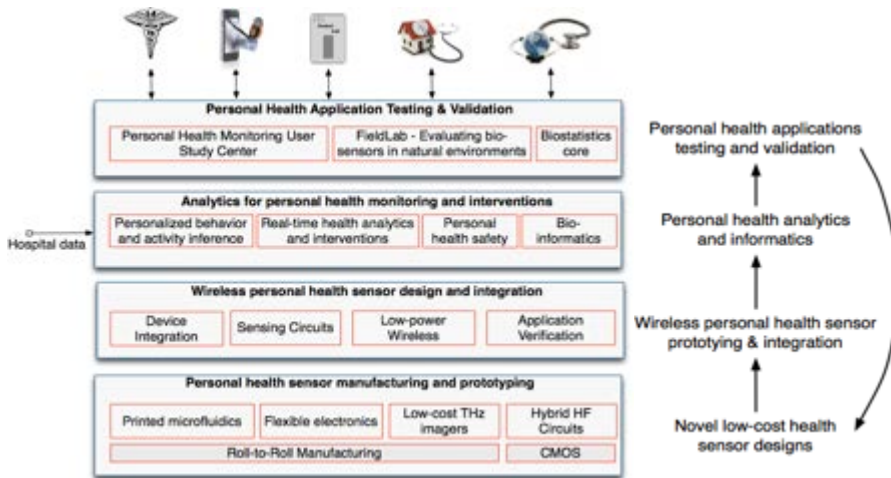
Central Database



# CPHM will Catalyze New Opportunities

UMass Amherst Center for Personalized Health

Monitoring and Biometric Sensors Utilizes CHM Process Platforms



The CPHM will include the \$25,000,000 Center for Advanced Roll-to-Roll Manufacturing for the Life and Nano Sciences, an open access facility that will deploy leading edge technology and pilot tools for sensor systems, packaging and associated flexible electronics platforms and enhance University-Industry partnerships. This Center is built upon and has been enabled by advances in the CHM.

- The Commonwealth of Massachusetts has earmarked \$ 90,000,000 in capital funds for life sciences research in Western Massachusetts
- The University of Massachusetts Amherst was awarded \$46,000,000 in capital funds to establish the Center for Personalized Health Monitoring (CPHM)
- The CPHM uses material and process platforms developed by the CHM

## Home Health Monitoring Prevention and Intervention

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# Mission

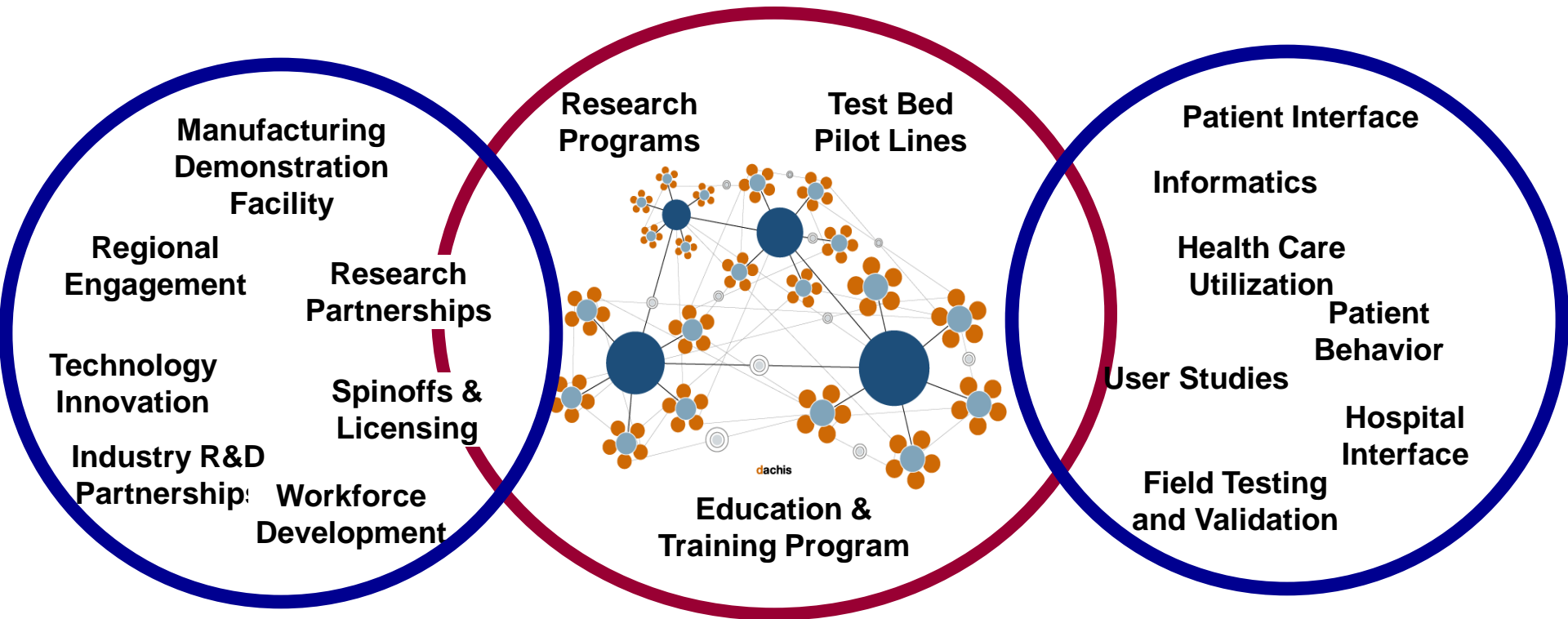
*To be a world-leading research, partnership and demonstration facility for accelerating the commercialization of low-cost, multi-function, wearable, wireless sensor systems for personalized health care and biometric monitoring.*

**Focal point for an interdisciplinary center at UMass Amherst that:**

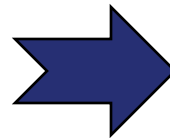
- Innovates and develops sensor systems in partnership with industry through a **vertically integrated process**
- Develops novel bio, chemical, electronic, and nano personal health sensor designs using **low cost manufacturing platforms**
- Designs for low-power, wireless networking, on-board memory and optimum form factor
- Evaluates and test in controlled but highly realistic conditions
- Bridges sensor design, human interaction and informatics to **inform health care trends and utilization**
- **Foster Massachusetts leadership** in health care delivery and an emerging biomedical device field



# Comprehensive, Synergistic Initiative for Maximum Impact to Massachusetts Life Science Industry



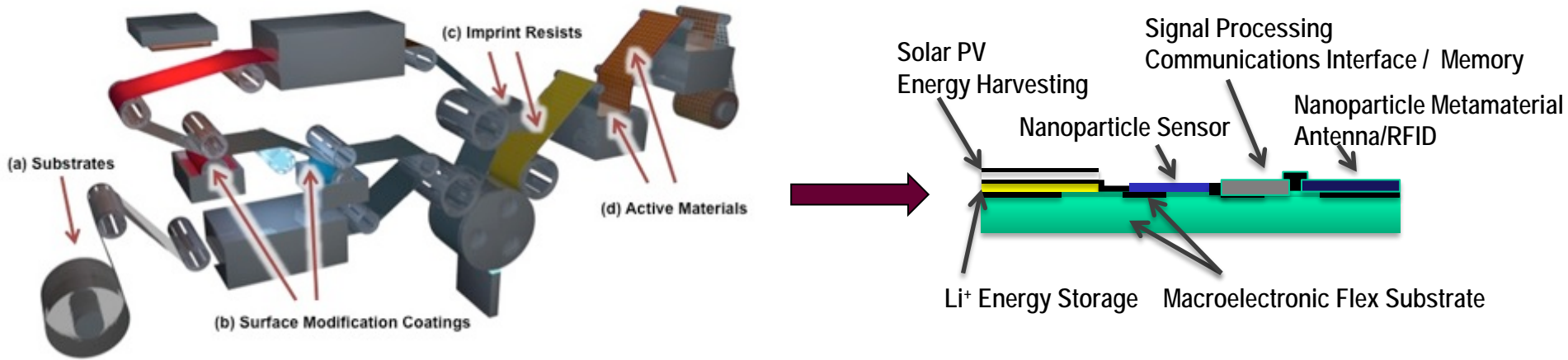
Sensor Technology  
Imaging Technology  
Wireless Technology  
Information Technology  
Manufacturing Technology  
Point-of-Care Testing



Low-Cost, High-tech,  
Wearable Wireless  
Sensor Systems For  
Health Monitoring



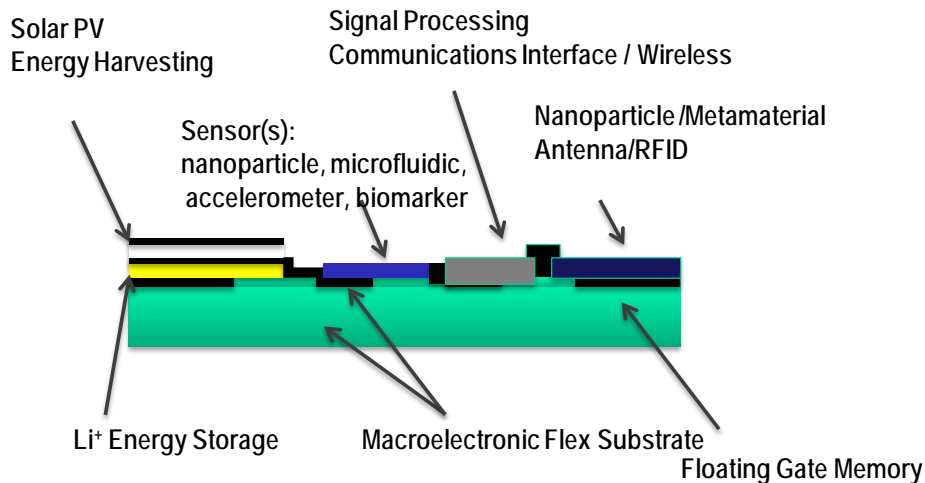
# The CHM is Systematically Resolving Critical Barriers to Cost-Effective, Continuous Manufacturing of Nanotechnology-Enabled Devices



## Focused Research Initiatives to:

1. Enable large area, continuous manufacturing platforms including roll-to-roll
2. Create new materials and process methodology to enhance performance
3. Organize nanostructured active layers by self-assembly of hybrid materials (3-100 nm length scale)
  - nanoparticles, fullerenes, nanorods, nanotubes
4. Develop high speed, continuous patterning processes for devices on a web (50-5000 nm features)
5. Employ solution-based processing, eliminate vacuum and high T
6. Utilize additive approach where possible
7. Integrate devices and systems
8. Build tools for partner access and technology demonstration

# One Goal: Integrated Low-Cost, Flexible Device or Patch

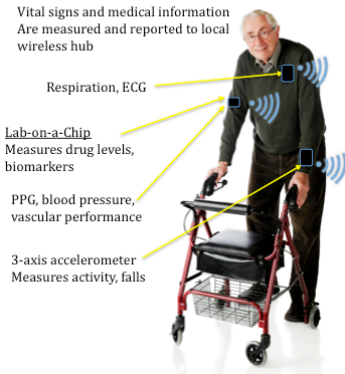


The NSF Center for Hierarchical Manufacturing is developing nanotechnology-enabled and high-performance, hybrid device layers for advanced device fabrication using novel R2R platforms and tools. These advances can be combined with silicon-chip pick-and-place assembly for expanded sensor platform capability

## Personalized Health Monitoring

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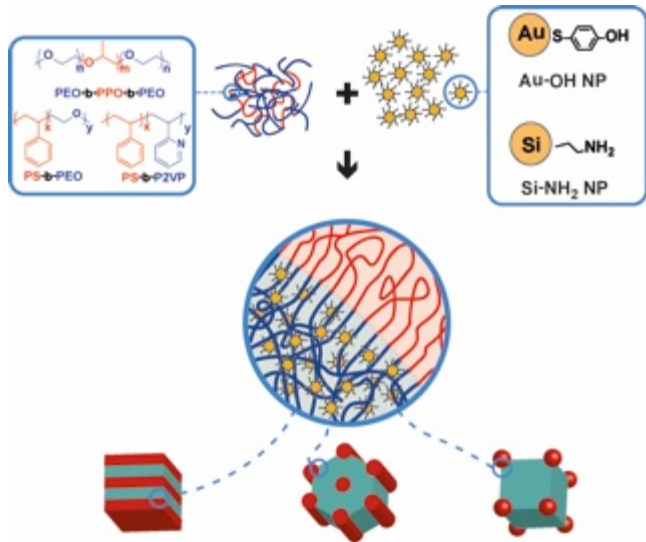
## Distributed Sensing Networks & Security



## Building and Infrastructure Integrated Systems

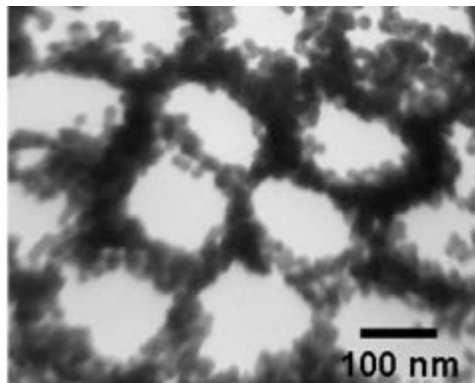


# Additive-Driven Self Assembly Enables Practical Fabrication of Devices

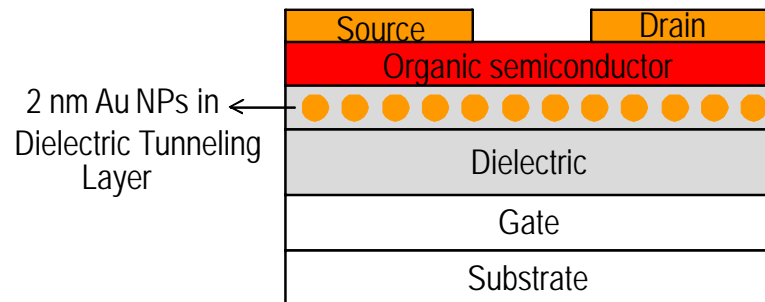


- Incorporation of nanoparticles, nanorods in well ordered materials
- Enabled by strong polymer-particle interactions
- Additive loadings greater than 70 wt.%
- Domain sizes from 3 nm to 125 nm – extends self-assembly for optical and meta materials
- Nanoparticle sizes up to 15 nm - extends self-assembly for quantum dots, plasmonics
- Integration of self-assembled layers in devices
- Large-area coating

High Loadings, Large NPs,  
Large Periods



Self-Assemble Layers in Devices  
ex. Floating Gate Memory



Additive Approach,  
Solution-Processable



Ordered Structures at Length Scales from 3 to 125 nm

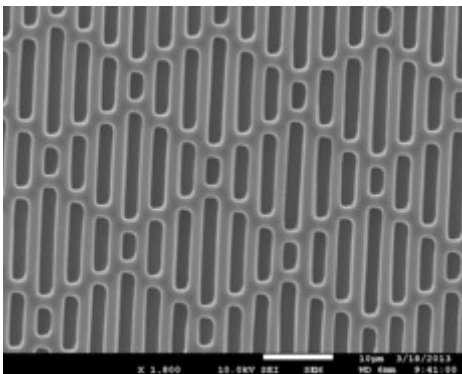
Spontaneous Assembly from Solution, Complete Control of Morphology

# UV-Assisted Nanoimprint Lithography and New Resist Technology for Large-Area Patterning of Functional Devices

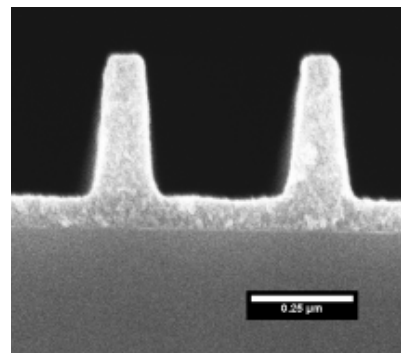


- Developed new roll-to-roll UV-NIL tool with industry partner, 6" web width
- Features as small as 50 nm at feet-per-minute rate
- Development of new nanoparticle based resists for printing of directly patterned crystalline metal oxide films (conductors and dielectrics)
- Creation of anti-microbial and ultrahydrophobic surfaces
- Complete R2R fabrication of sensors and optical materials
- Development of in-line metrology with MIT and NIST

Patterned Surfaces and Devices



Direct Printing of Crystalline Metal Oxides



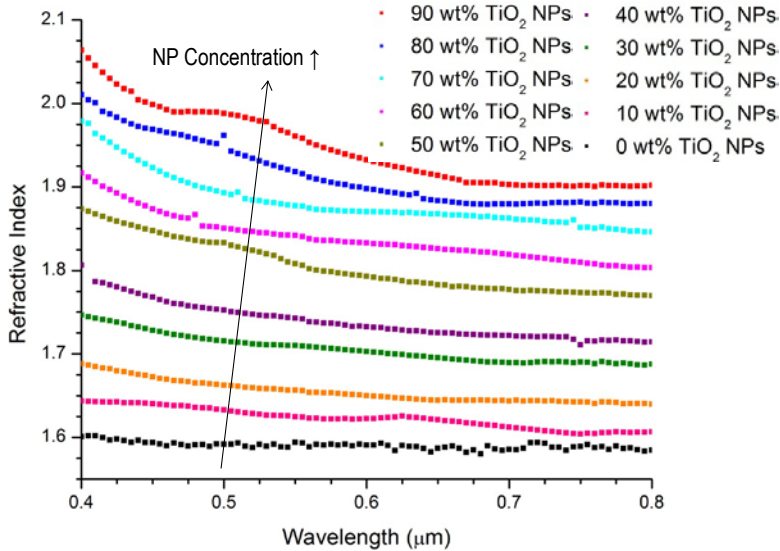
All R2R Fabrication of THZ Sensors



Rapid, Continuous Patterning of Features > 50 nm on Robust, Scalable Platform  
New Resist Materials Enable New Applications

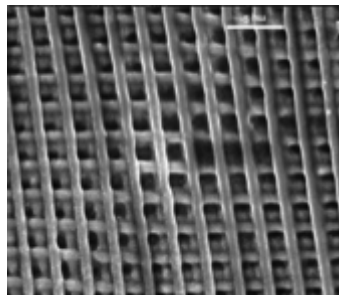
# Polymer Nanoparticle Hybrids for Solution Processing of Optical and Electronic Devices

## RI Control in NP/Polymer Hybrid

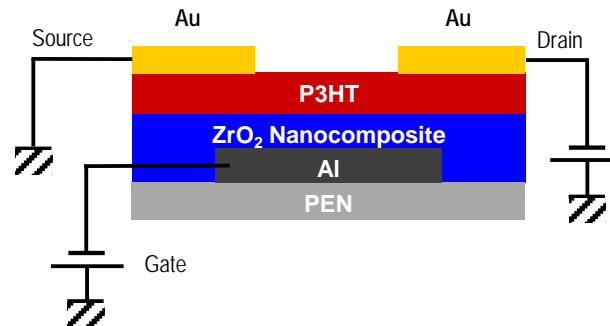


- Tune materials properties by controlling NP loading
- Example at right shows refractive index tuning of a nanoparticle polymer system
- Control of NP-polymer interactions enable particle loadings up to 90 wt. %
- Hybrids can be used as planar device layers (high k dielectrics)
- Hybrids can be used as inks for patterning and printing processes (e.g. ink jet or NIL)
- Solution processable in CHM Nanocoater

## Printing of Optical and 3-D Photonic Structures



## Device Layers for Printed Electronics



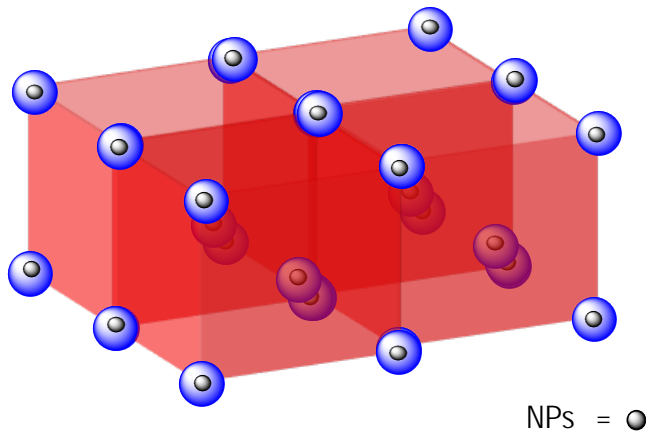
## Additive Approach, Solution-Processable



Provide Alternatives to Batch Processes and High T and Vacuum  
 Enable Large-Area Processing of Devices

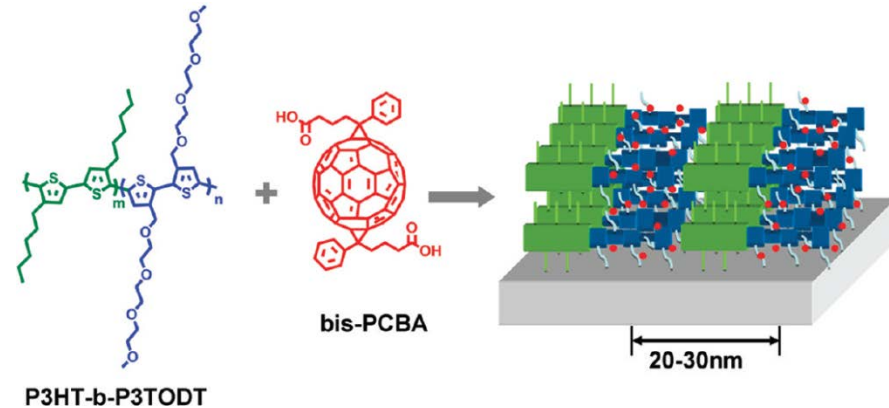
# CHM Examples: Devices and Device Layers

## Ordered Metamaterials

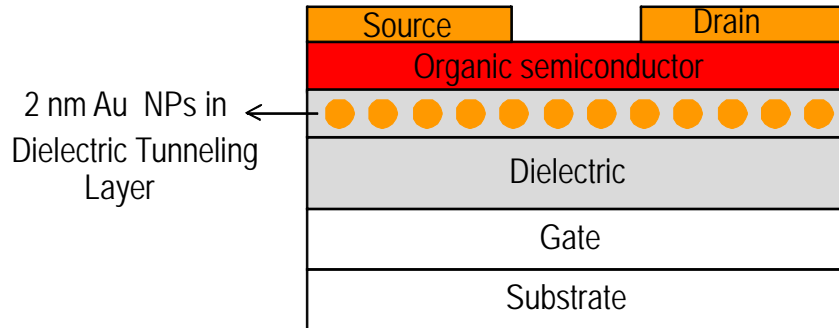


NPs = ●

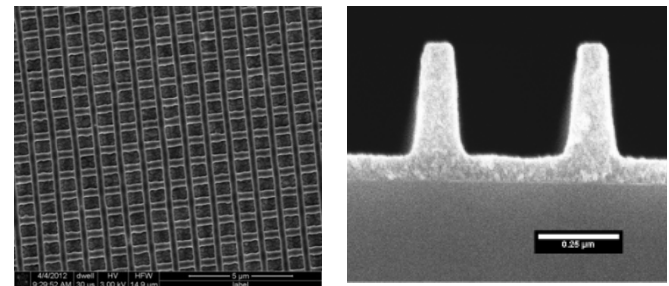
## PV Heterojunctions



## Device Architectures on Flex



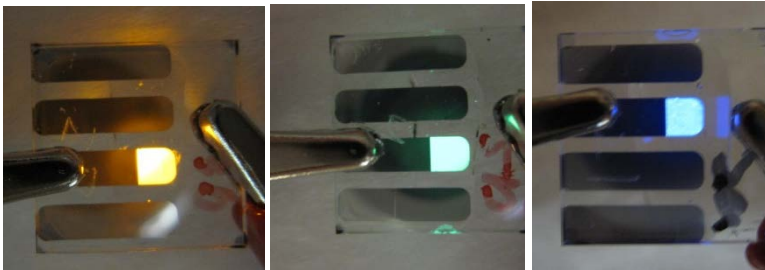
## Printed Hybrid and Inorganic Nanostructures



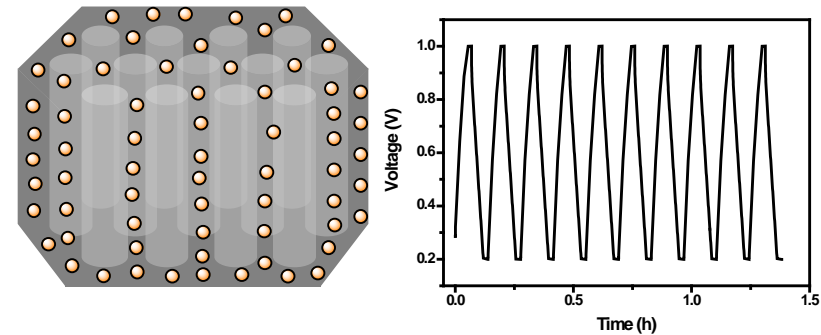
- Many applications require large active areas
- Both morphology control and morphological stability are needed

# CHM Examples: Devices and Device Layers

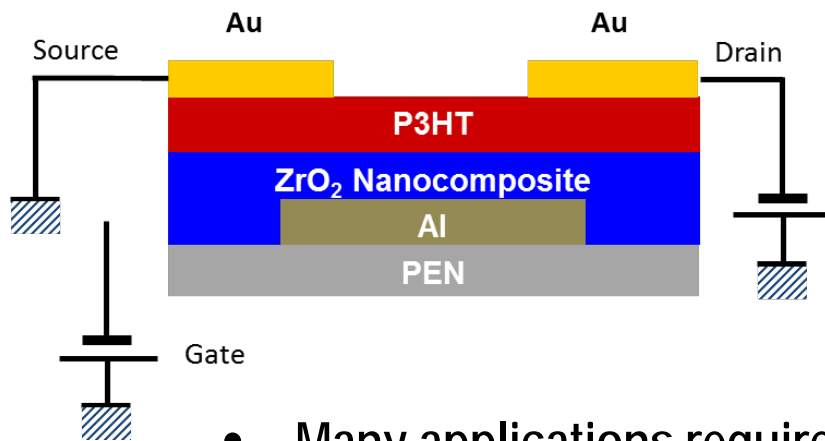
## QD-Based LECs



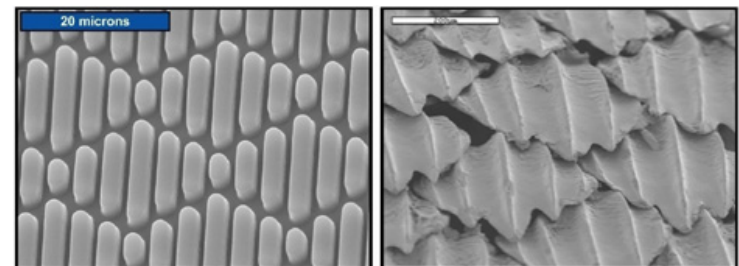
## Nanostructured SuperCaps



## Solution Coat-able High K



## Bio-Mimetic Anti-Microbial Surfaces

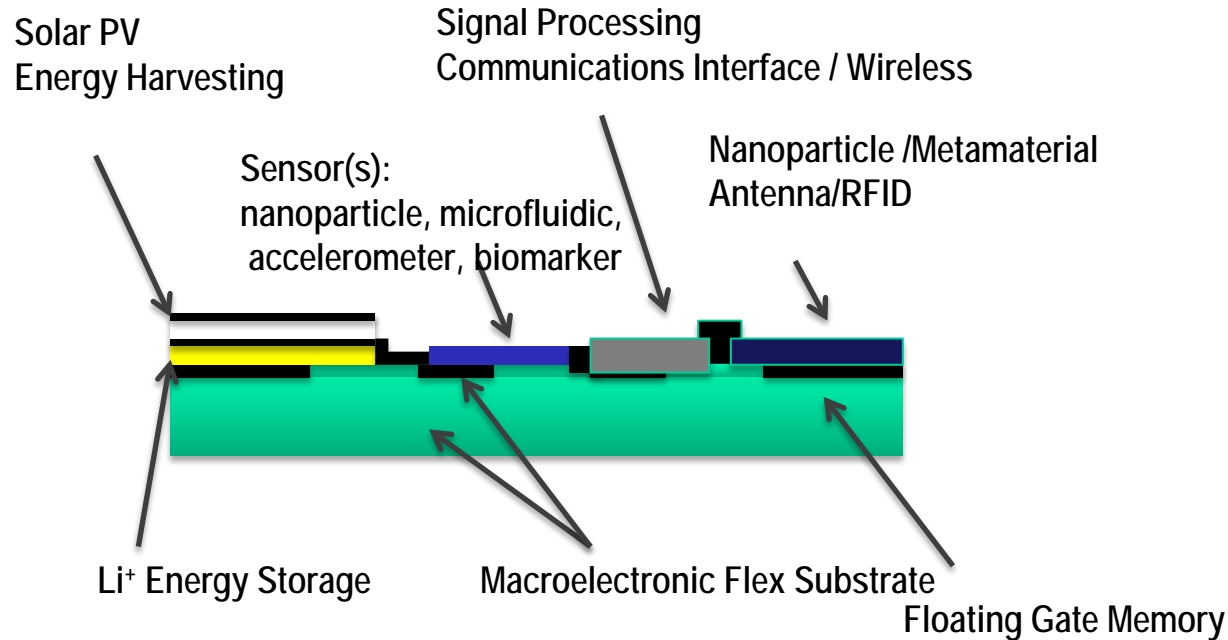


Sharklet™ Surface Technology

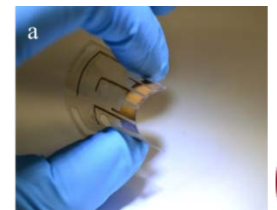
Galapagos Shark Skin

- Many applications require large active areas
- Both morphology control and morphological stability are needed

# Goal: Integrated Low-Cost, Flexible Device or Patch



The NSF Center for Hierarchical Manufacturing is developing nanotechnology-enabled and high-performance, hybrid device layers for advanced device fabrication using novel R2R platforms and tools. These advances can be combined with silicon-chip pick-and-place assembly for expanded sensor platform capability



# DoD Currently Supports UMass Amherst's R2R Biosensor Research

## National BioNano Manufacturing Consortium

*Air Force Research Laboratory*

- UMass Amherst is a founding member
- Project Goals: Demonstrate a micro-fluidic biosensor system implemented in a flexible/conformal platform for the purpose of detecting analytes accessible through intimate contact with skin.



### AF Customers

#### *First Responders*



### Current Monitoring Needs

Hydration / Electrolytes  
Core Temperature  
Skin Temperature  
Vitals



### Future Solutions

#### *Advanced Mobile Diagnostics*



#### *Intuitive Sensor Information Displays*



Hydration / Electrolytes  
Body Temperature  
Awareness / Vigilance



#### *Sensor-Incorporated Garments*

*Flexible, Wearable, Wireless Biosensors*

Pulse Oxygenation  
Blood Pressure  
Blood Gases  
Awareness



#### *Simple Go/ No-Go Indicators*



## Dynamic Multifunctional Materials for a Second Skin

*Defense Threat Reduction Agency*

- \$13 million project; \$1.8 million to UMass Amherst
- Designing materials and manufacturing processes for breathable soldier garments protecting against chemical/biological agents



## Ongoing Program Support:

**DOD/DARPA/DTRA are Significant Drivers and Funders of Printed Intelligence Platforms including Biometric Sensors**



# Wearable Paper-Based Microfluidic Biomarker Sensor Patch

- **UMass Amherst** (J. Watkins, J. Morse, V. Rotello, S. Nugen)
- **GE Global Research** (A. Alizadeh, R. Potyrailo, N. Nagraj, L. Carr, B. Li, J. Ashe)
- **U. Cincinnati** (J. Heikenfeld)
- **AFRL** (J. Hagen)

UMassAmherst



UNIVERSITY OF



# UMass Amherst Team Will develop Microfluidic Subsystem For Measurement of Stress/Fatigue Biomarkers from Sweat

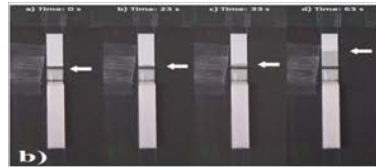
## Detection Platforms

- Bio-recognition Element Attachment
- Zinc Oxide FET
- Resonance Impedance RF
- Performance Screening



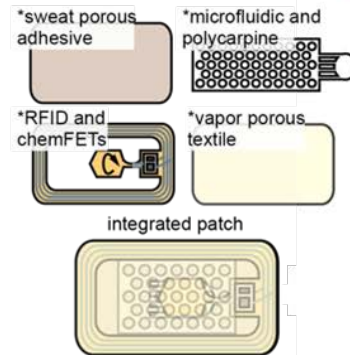
## Paper Microfluidics

- Non-Specific Binding Prevention
- Sweat Flow Control- EW Valves



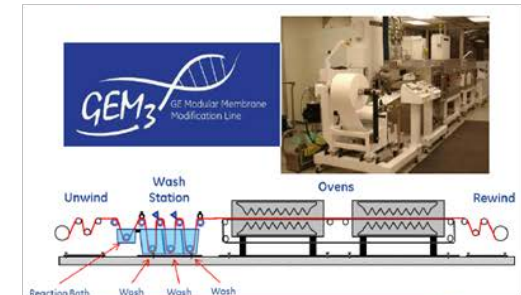
## Sub-System Integration

- Sweat Stimulator
- Paper Microfluidics
- Detection Platform
- Hand-Crafted Integration
- Prototype Demonstration
- Performance Screening



## Manufacturing

- R2R processing
- Inkjet Printing
- Substrate Integration



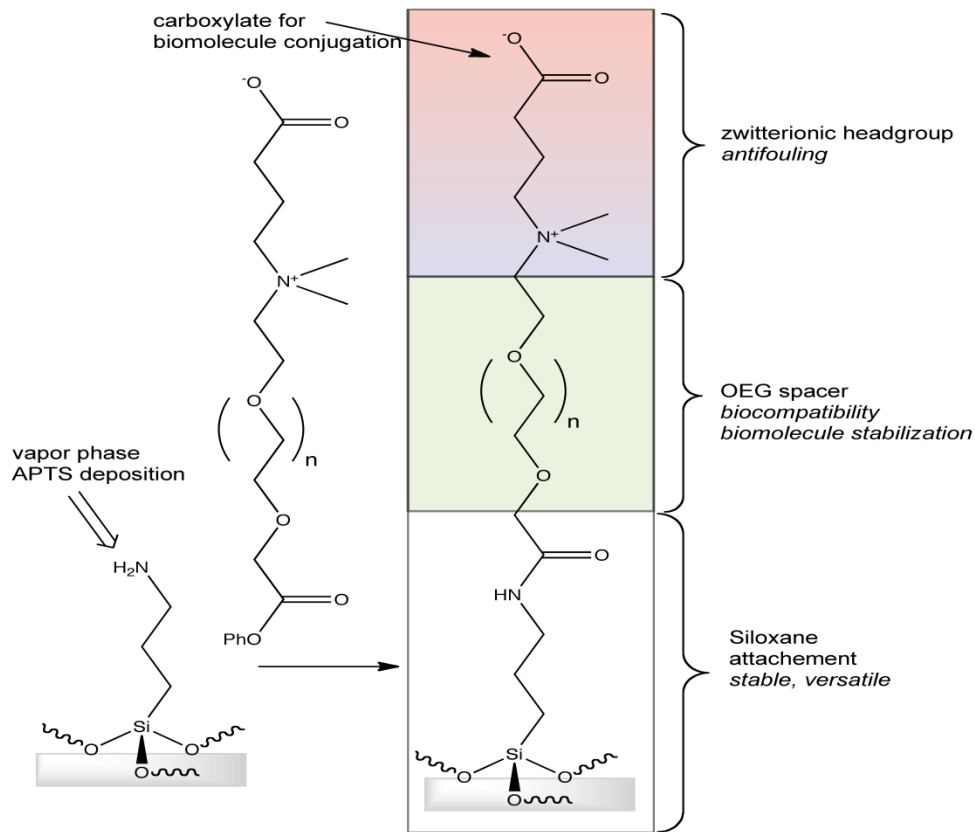
## Roadmaps Towards Full System Development

- TRL / MRL Evaluation
- Dual-use Product Strategy
- Market Analysis
- Biomarker + Biometric Sensor Integration
- Manufacturing Pathway
- Collaborations and Joint Development

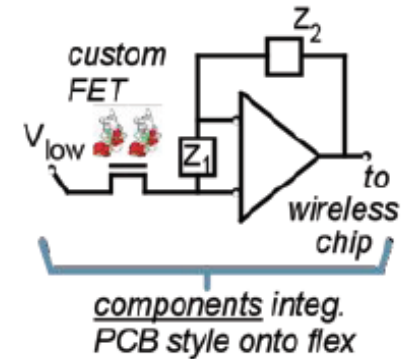
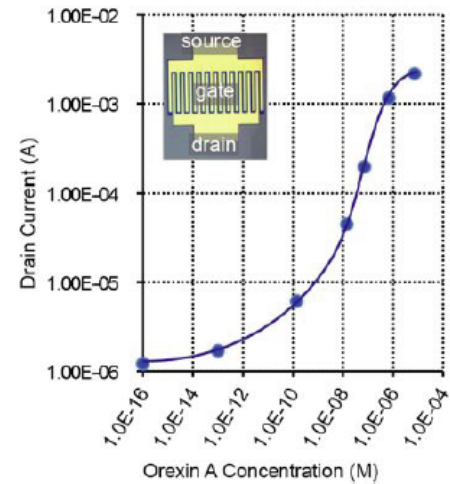
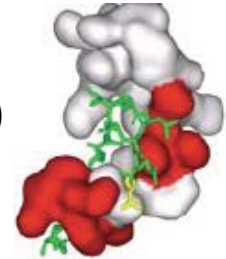
**Development Partners: General Electric Corp.  
University of Cincinnati**

# Sensor Surface Functionalization and Bio-Recognition Elements

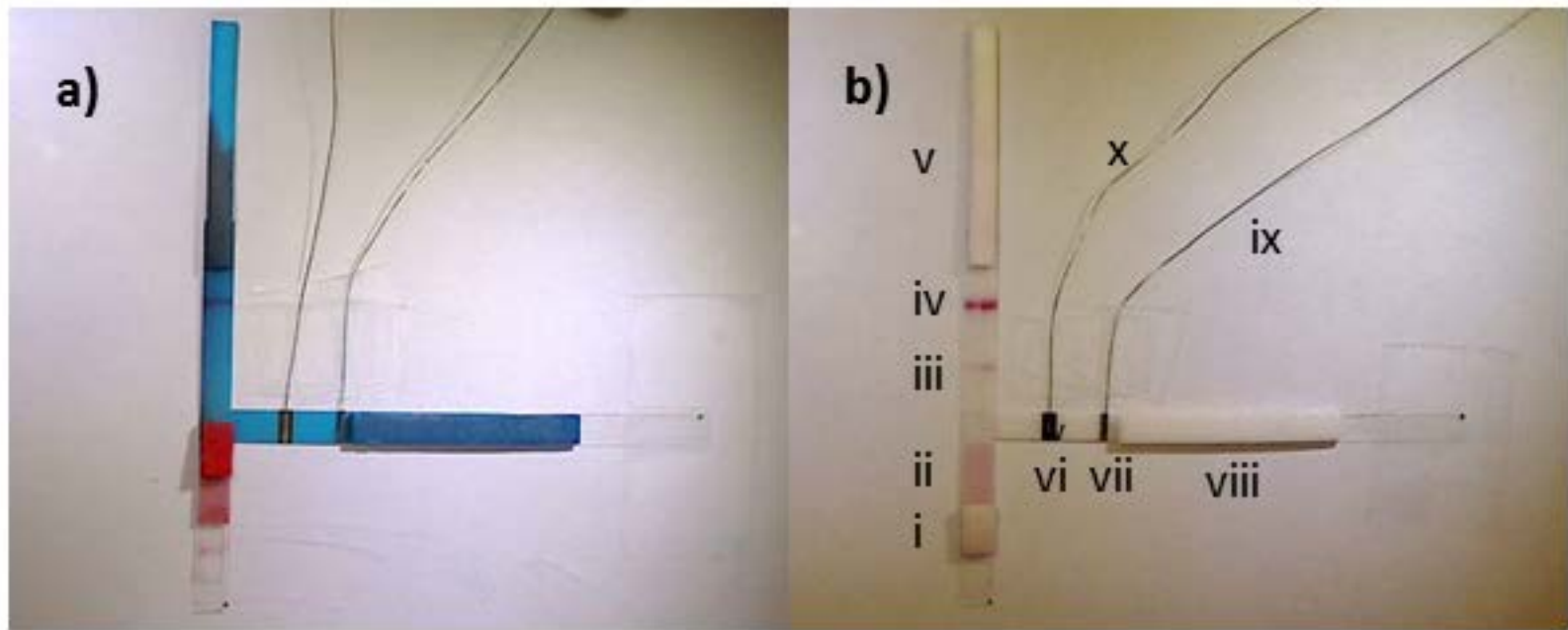
**UMass:** Universal design and synthesis of linker for bio-recognition element attachment to the sensor surface



Bio-recognition element (OABP)



# Electrowetting Valves on Paper Fluidics Enable Accurate Sample Acquisition Over 24-72 Hour Period



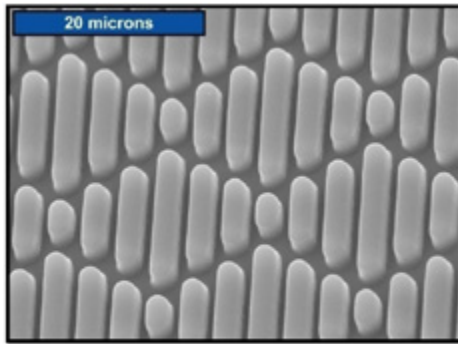
Application of valves in the detection of *nucleic acids* in lateral flow assays.

a) Visualization of the flow of the “sample” (red dye) and “buffer” (blue dye)

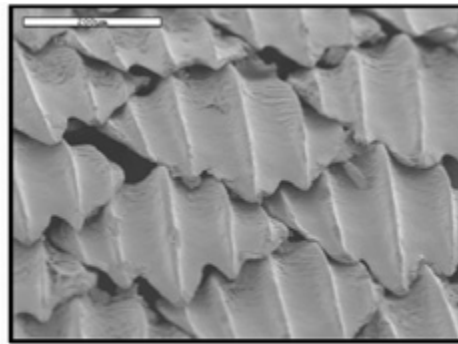
b) Valves incorporated in the lateral flow assay. A positive result is shown.

- |      |                       |       |                             |
|------|-----------------------|-------|-----------------------------|
| i.   | Sample pad            | vi.   | Hydrophobic electrode/valve |
| ii.  | Conjugate pad         | vii.  | Hydrophilic electrode       |
| iii. | Positive test line    | viii. | Buffer pad                  |
| iv.  | Positive control line | ix.   | Wire/Negative terminal      |
| v.   | Absorbent pad         | x.    | Wire/Positive terminal      |

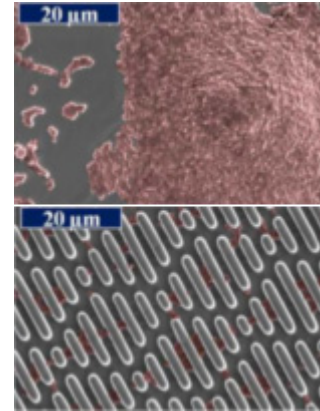
# Large Area Antimicrobial Textured Layers



*Sharklet™ Surface Technology*

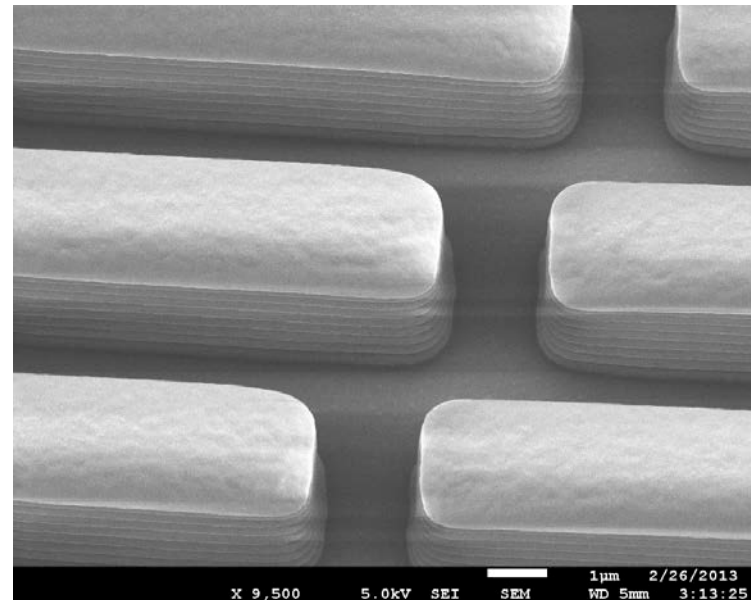
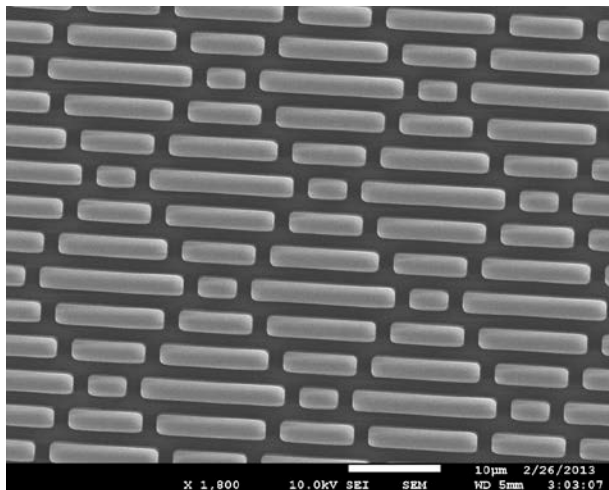


*Galapagos Shark Skin*

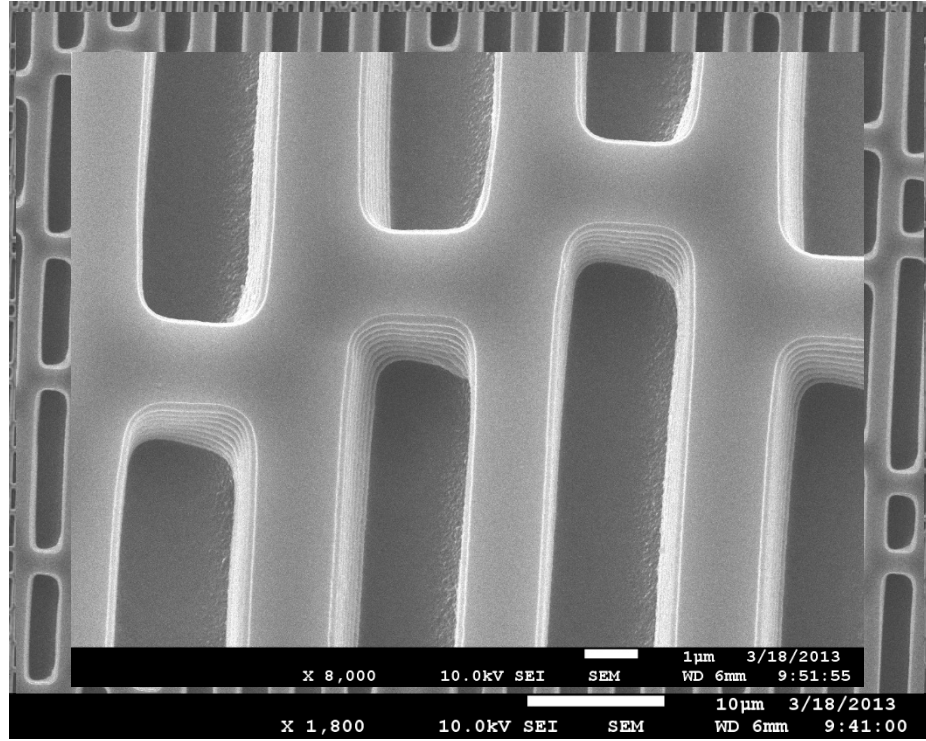
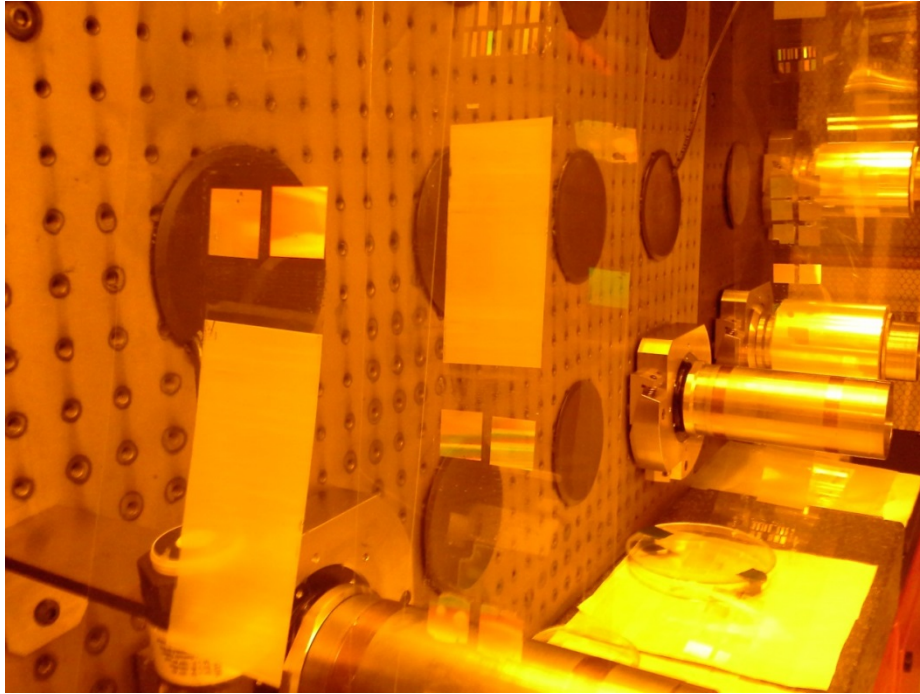


NIL and R2RNIL Challenge: Can we replicate Sharklet pattern?

PFPE daughter mold from 6 inch master



# R2RNIL on CHM Nanoemboss



## Mold Preparation:

- Negative of Sharklet features on 6 inch wafer was replicated on to PFPE on PET hybrid mold

## Substrate Treatment:

- PET web was coated with an adhesion agent then a photoresist layer was applied
- This PET pre-treatment improves the quality of imprinted features in long runs

## R2RNIL Conditions:

- Resist: NOA adhesive - 40 v/v % in PGMEA
- Speed: Imprinter was run at 10 -12 inches / minute
- Exposure at 365 nm

# R2R Research and Demonstration Facilities

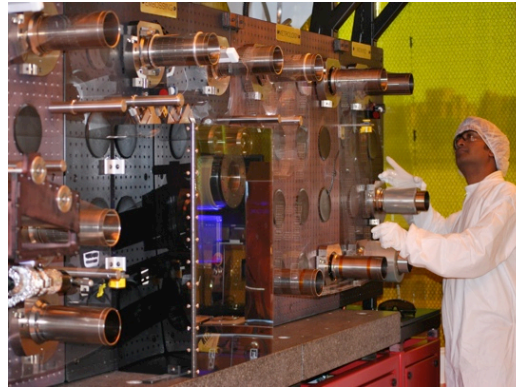
## EXISTING R2R TOOLS

### *R2R Test Frames/Tools*

- One high speed coater, 6"
- One R2R system with coater, 6"
- Coating heads: Gravure, Slot-die

### *Related Processing/Metrology Tools*

- Stand-alone gravure coater
- 3 nanoimprinters
- 1 plasma etcher
- In-line NIL



## **\$25M IN NEW R2R TOOLS AND FACILITIES READY BY 2015-16**

- Five coaters and nanoimprint lithography tools, 6" to 12", featuring gravure, slot-die, flexographic, and inkjet heads
- In-line tools for UV annealing/sintering, CVD/graphene, PEVCD, ALD, layer-by-Layer wet assembly, nanoimprint lithography, and metrology
- Ovens, wet etch, dry etch/RIE, sputter deposition, flow coating, spin coating, inkjet print
- Optical inspection/microscopy, particle counter, ellipsometry, profilometry, atomic force microscopy, electrical testing
- UV/IR/solar permeation/transport
- Dry room, controlled emissions, inert atmosphere
- Secondary processes: slitting/cutting, layer release/transfer, integration/bonding/assembly