Advanced and Nano Manufacturing Research @ NSF

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Civil, Mechanical and Manufacturing Innovation Division

Engineering Directorate

National Science Foundation

Alexandria, VA

RAMP Workshop, ASME MSEC, TAMU, College Station, TX, June 21, 2018

'New' Advanced Manufacturing (AM) Program

https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505572

SYNOPSIS

The Advanced Manufacturing (AM) program supports the fundamental research needed to revitalize American manufacturing to grow the national prosperity and workforce, and to reshape our strategic industries. The AM program accelerates advances in manufacturing technologies with emphasis on multidisciplinary research that fundamentally alters and transforms manufacturing capabilities, methods and practices. Advanced manufacturing research proposals should address issues related to national prosperity and security, and advancing knowledge to sustain global leadership.

Areas of research, for example, include manufacturing systems; materials processing; manufacturing machines; methodologies; and manufacturing across the length scales. ***Researchers working in the areas of cybermanufacturing systems, manufacturing machines and equipment, materials engineering and processing, and nanomanufacturing are encouraged to transcend and cross domain boundaries.*** Interdisciplinary, convergent proposals are welcome that bring manufacturing to new application areas, and that incorporate challenges and approaches outside the customary manufacturing portfolio to broaden the impact of America's advanced manufacturing research.

Proposals of all sizes will therefore be considered as justified by the project description. Investigators are encouraged to discuss their ideas with AM program directors well in advance of submission at AdvancedManufacturing@nsf.gov.

DUE DATES: Full Proposal Accepted Anytime, Effective August 15, 2018

Contacts: Thomas Kuech, Alexis Lewis, Steven Schmid, Brigid Mullany, Khershed Cooper, Bruce Kramer

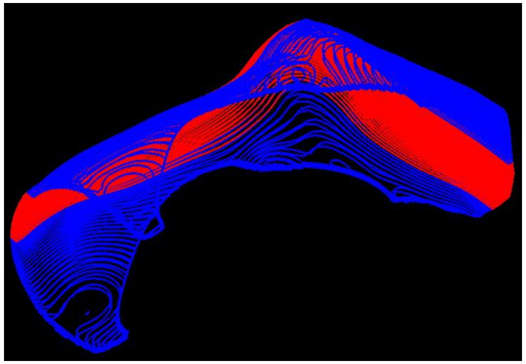
Related: Supporting Fundamental Research to Enable Innovation in Advanced Manufacturing at Manufacturing USA Institutes: *https://www.nsf.gov/pubs/2017/nsf17088/nsf17088.jsp*

Cyber Manufacturing Systems (CM)

- Network-Centric Production
- Create an *interoperable, cross-process manufacturing service layer*, built upon app-based infrastructure for manufacturing processes

Goals:

- Complex, intelligent, precise products
- Interoperable, reliable, secure systems
- Decentralized, but connected systems



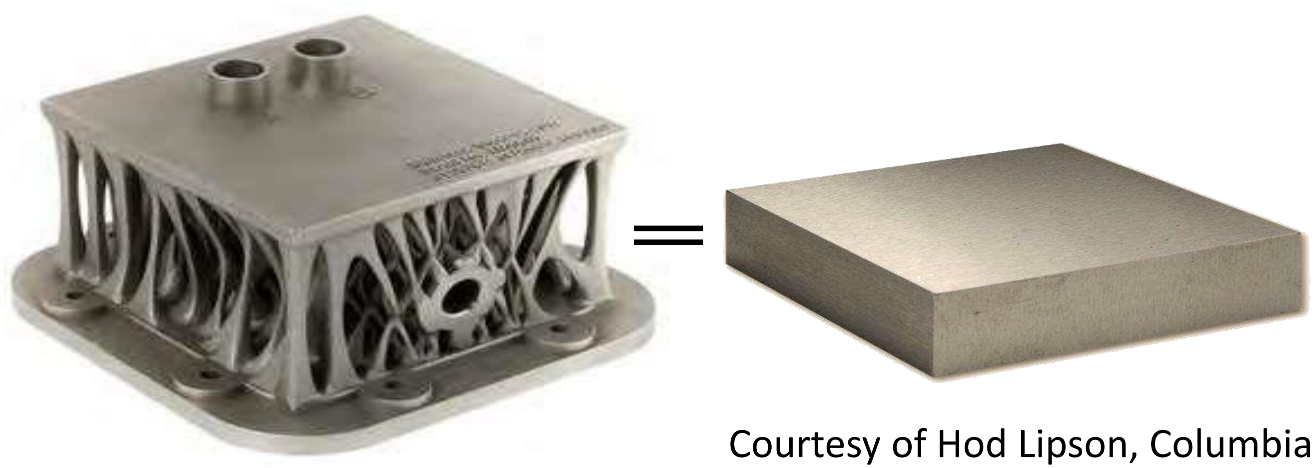
Internet-based design and rapid manufacturing of customized foot orthoses and ankle-foot orthoses with motion sensors (Image shows the path planning for 3-D printing an ankle-foot orthosis) Credit: *Albert Shih, University of Michigan*

Manufacturing Machines and Equipment (MME)

- Mass Customization
- Additive Manufacturing, 3D Printing
  - Fabricate geometrically complex parts and components in small lots, on-demand

<u>Next major challenge</u>:

- Geometric complexity is ‘free’ in AM, but quality control is not
- AM presents a daunting task for quality control due to huge product varieties and extremely small batch size

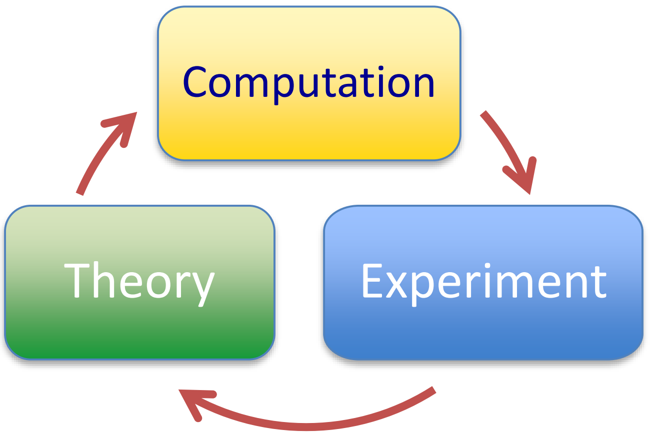


thin Technologies

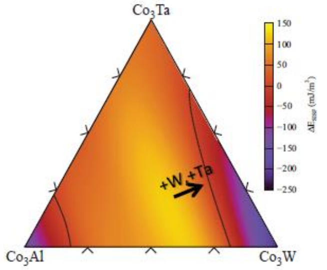
Courtesy of Hod Lipson, Columbia

Designing Materials to Revolutionize and Engineer our Future (DMREF)

- Advanced Materials
- NSF's response to MGI
- *Accelerate materials discovery and development* by building the fundamental knowledge base needed for designing and manufacturing materials with specific functions or properties *from first principles*



Computation



Experiment

Application

New multicomponent, multiphase single crystal materials designed for performance in extreme environments – *UCSB and GE*

Nanomanufacturing (NM)

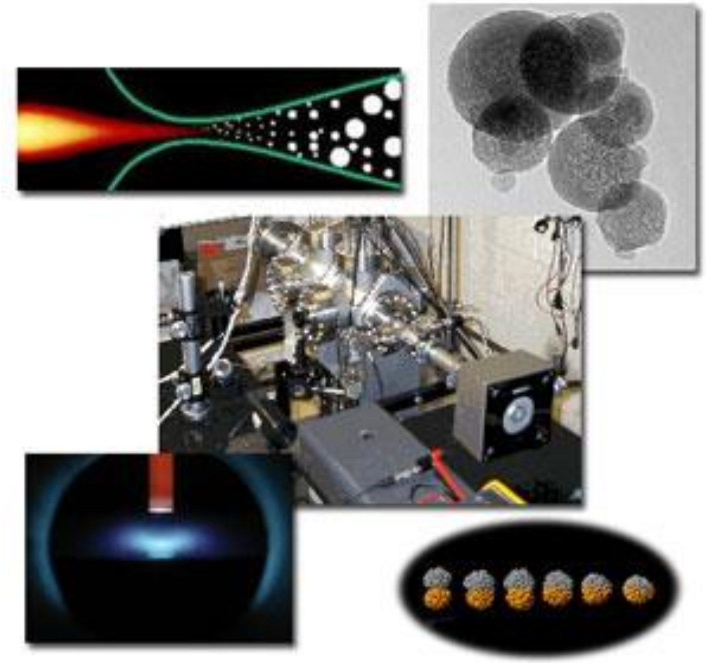
- Tremendous scientific and engineering progress in nanoscience and nanotechnology
- Steady progress along “Moore’s Law”

Goals:

- Establish fundamental principles for *nano-scale manufacturing processes* that enable novel materials, structures, devices and systems
- Achieve scalable pathways from nanomaterials and nanodevices to nanosystems and nano-enabled products

Next major challenge:

How do we go from materials and devices to products and associated scalable nanomanufacturing processes and systems?



What is Nanomanufacturing?

Definition: *Fabrication* of nano-scale building-blocks (nanomaterials, nanostructures), their *assembly* into higher-order structures, and the *integration* of these into larger scale systems with *manipulation and control of matter at the nano-scale, reproducibly*

- **Nanoscale:** Approx. 1-100 nm
- **Processes:** Bottom-up (self- and directed-assembly); top-down (lithography, deposition, removal)
- **Integration:** Hierarchical / heterogeneous; Across: length scales, materials (0D, 1D, 2D), geometries, processes, functions

Nanomanufacturing Challenges

Desired Outcomes

- Process — *manufacturability*, controllability, reproducibility, repeatability, reliability
- Production—scalability, affordability, yield, efficiency, cycle time, *safety*
- Product—quality, durability, performance, functionality

Appropriate Metrics

- Precision of placement
- Feature size and resolution
- Overlay registration
- Nanostructure density, complexity, rate of forming
- ***Compromise***: *feature size and resolution v. processing rate v. volume throughput*

Strategies

- Material choices
- Unit processes (e.g., screen printing)
- Fab integration
- Packaging

QVV – Qualification, Verification, Validation

Nanomanufacturing Research @ NSF

- ***NM:*** *Fundamental research to enable and improve large-scale or customized manufacturing of nanomaterials and nanostructures*
- ***SNM:*** *Research to overcome technical barriers that prevent manufacture of useful nanomaterials, structures at an industrially relevant scale, reliably, at low cost and within EHS guidelines*
- ***SNM-IS:*** *Study and formulate fundamental principles of scalable or customized manufacturing and integration for nanotechnology-based integrated systems towards the eventual manufacture of useful nanotechnology products*
- ***NSEC:*** *Research to understand nanoscale processes, develop tools for measurement and manufacturing at the nanoscale, develop concepts for high-rate synthesis and processing of nanostructures and nanosystems, and scale-up of nanoscale processing methods*
- ***NERC:*** *Integrate engineering research and education with technological innovation*

Research Areas

Materials and Structures

- **C-based:** CNT, Graphene, Bucky-tape, CNT Fibers, Cellulosic
- **0D:** Nanoparticles, QDs, Core-shell, Janus, Hierarchical, Composite
- **1D:** Nanowires, Nanopillars, Nanotubes, Nanofibers
- **2D:** MoS_2, BN, TMDs
- **3D:** Nanoporous, Aerogels, Arrays, Patterns
- **Material Systems:** Metals, Ceramics, Polymers, Organics, Composites

Processes and Methods

- **Chemical/Thermal:** Combustion, Plasma, Hydrothermal, Drawing, Etching
- **Vapor-based:** CVD, PVD, PECVD, Laser CVD, ALD, MLD
- **Fluid/Solution-based:** Coating, Casting, Colloids, Electrospray, Electrophoresis, Electrospinning, Electroetching, Microfluidics, Microreactors, Ink-jet Printing
- **Lithography/Patterning:** BCPs, AFM, DPN, NIL, PLD, Laser Writing, E-beam, Ion-beam
- **Assembly:** Self, Directed (chemical, magnetic, acoustic), Molecular
- **Bio-assisted:** DNA, Virus, Protein, Peptides, Diatoms
- **Mechanical:** Exfoliation, Nanomachining, Ball-milling
- **3D Nanomanufacturing:** 3D Printing, Holographic Lithography, MacEtch

Applications

- **Environmental:** Water/Air Purification, Analytical Separation
- **Chemical:** Catalysis, Gas Storage
- **Energy:** Storage, Conversion, Harvesting, Batteries, Supercapacitors, PVs, Solar Cells, Fuel Cells
- **Electronics:** ICs, Flexible, Storage Memory, 3D Devices, TFTs, EM-Shielding
- **Optoelectronics/Photonics:** Imaging, Waveguides, Displays, Lighting, Metamaterials
- **Sensors:** Biological, Chemical, Multiplexed
- **Structural:** High-Strength, Light-Weighting, Packaging
- **Biomedical:** Implants, Tissue Scaffolds, Diagnostics, Therapeutics, Drugs, Probes
- **Sheets/Wires:** Fibers, Cables, Filters, Membranes, Textiles, Paper, Fabric, Nonwovens

Scale-up Methods

- **Continuous Roll-to-Roll Process, Top-down/Bottom-up Methods**
  - Processes: Printing, Imprinting, Self-assembly, Deposition, Coating, Lamination
  - Examples: Printing of nanoparticles, forming of CNT Bucky paper, and convective deposition of self-assembled nanoparticles

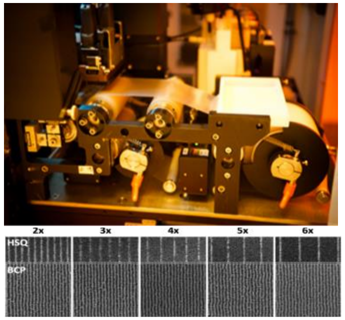
- **Parallel, Large-area Top-down or Bottom-up Processes**
  - Processes: Lithography, Direct-write, Directed-assembly, Self-assembly
  - Example: Optical lithography using parallel nanoantennae arrays

- **Parallel, Large-area 3D Nanofabrication**
  - Processes: 2-Photon Polymerization, Nanoimprinting and Self-assembly, Strain Engineering
  - Example: Projection stereolithography and direct write of 3D heterogeneous biological scaffolds

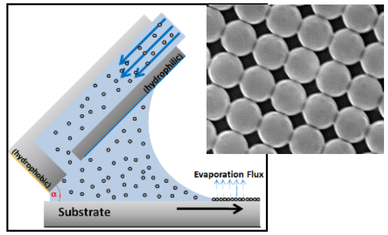
- **Continuous or Parallel Reaction Synthesis/Fluidics Techniques**
  - Processes: Microreactor, Microfluidic, Hydrothermal synthesis, Chemical synthesis, Plasma, Electrospray, Electrospinning, Fiber-drawing
  - Example: Grow quantum dots and core-shell nanoparticles in colloids or solutions

- **Large-area Bio-enabled Nanofabrication**
  - Process: Templating using DNA
  - Example: Molecular self-assembly of atomically-precise, defect-free DNA patterns

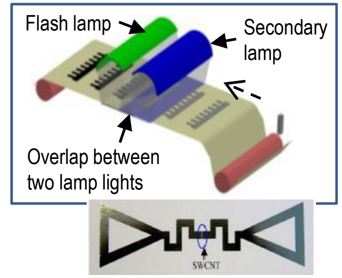
Examples of Scale-up Approaches



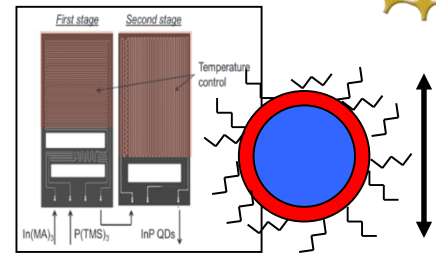
Roll-to-roll Nanopatterning
(SV Sreenivasan, UT-Austin)



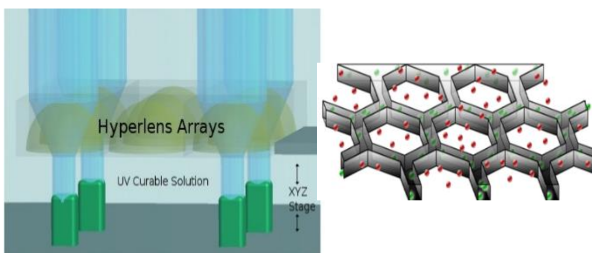
Vibration-assisted Convective Deposition
(James Gilchrist, Lehigh)



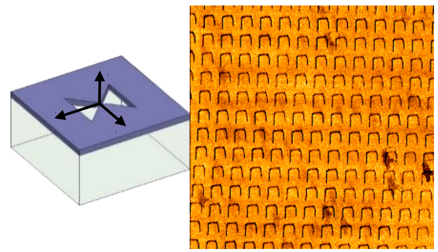
R2R/Flash-Sinter Metal Patterning
(Chih-hung Chang, Oregon State)



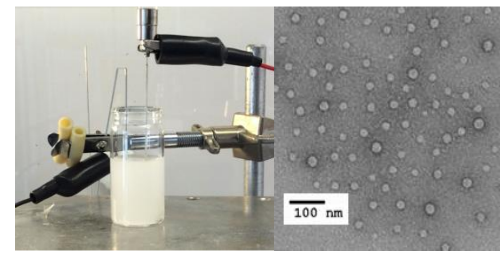
Microfluidic Reactor for QDs
(Klavs Jensen, MIT)



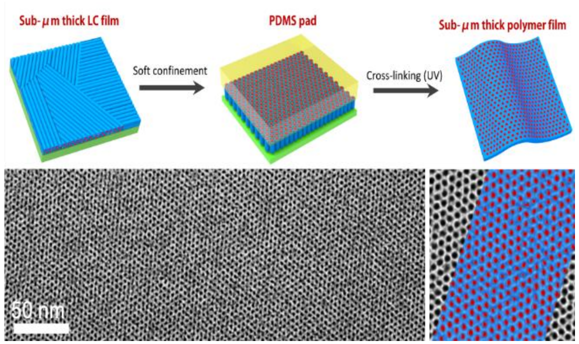
3D Printing of Biomimetic Scaffold
(Shaochen Chen, UC-San Diego)



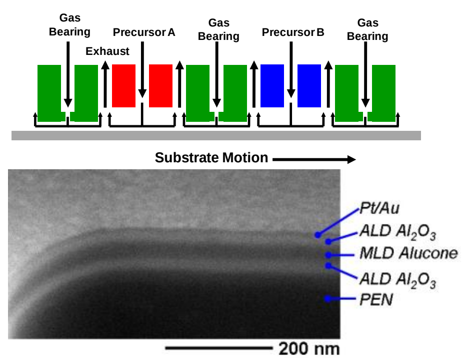
Parallel Bow-tie Antenna Array Patterning
(Xianfan Xu, Purdue)



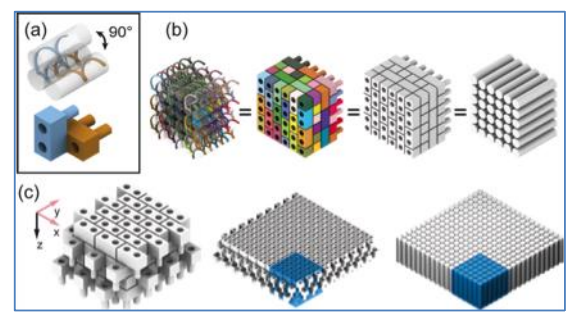
Micellular Electrspray of Nanocomposite
(Jessica Winter, OSU)



Field-directed Aligned Nanoporous Films
(Chinedum Osuji, Yale)

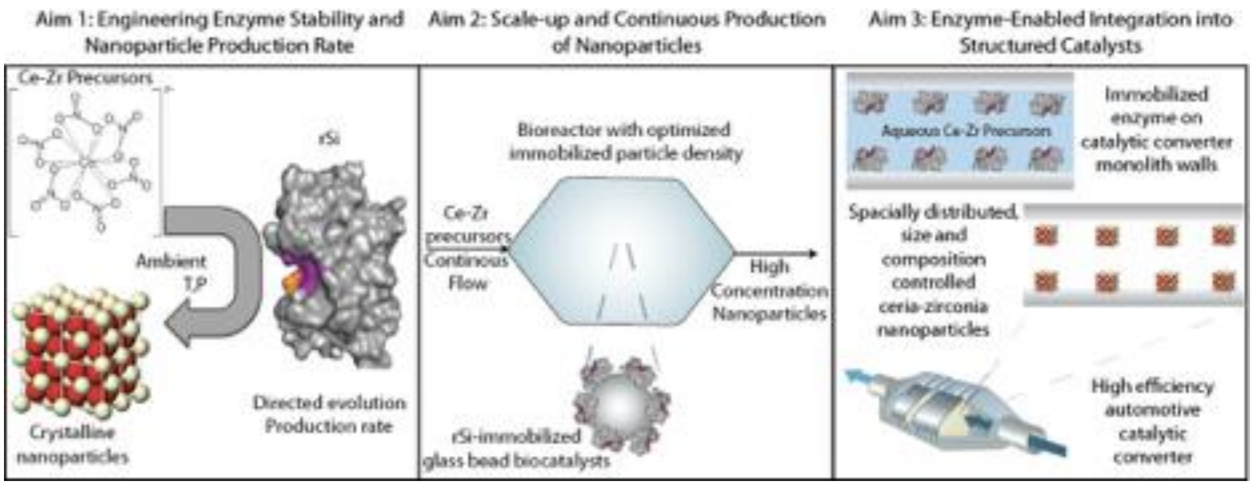


Multi-layer Roll-to-Roll ALD/MLD
(Yung-Cheng Lee, U of Colorado-Boulder)

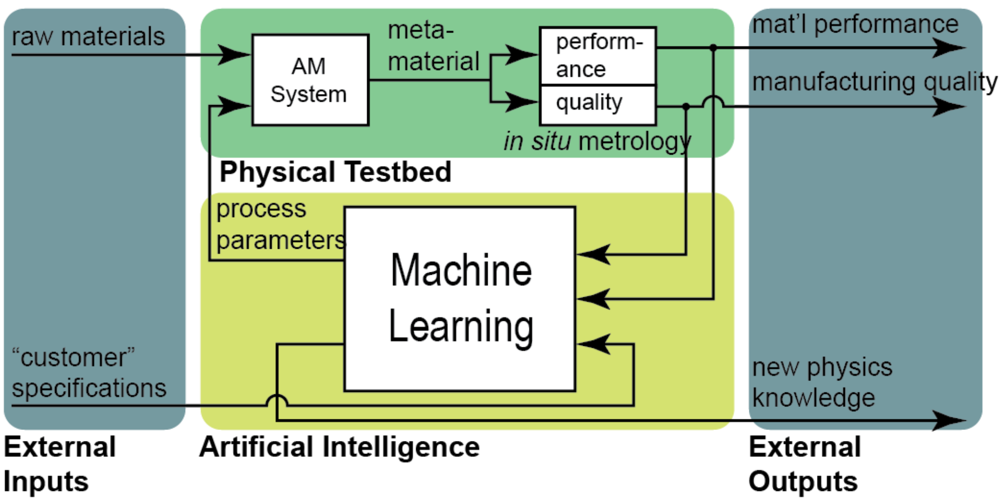


DNA Masks with Embedded Metrology
(William Highes, Boise State)

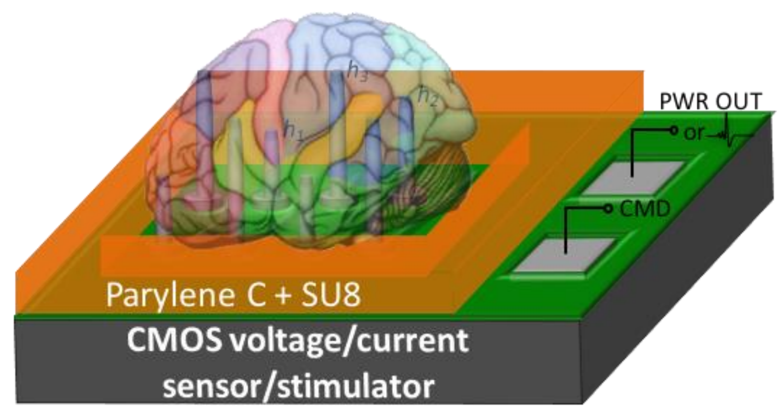
Scalability – Integrated Systems



Scalable Biomineralization of Functional Oxide Nanoparticles and Nanostructures for Environmental and Energy Applications
- Bryan Berger, Lehigh

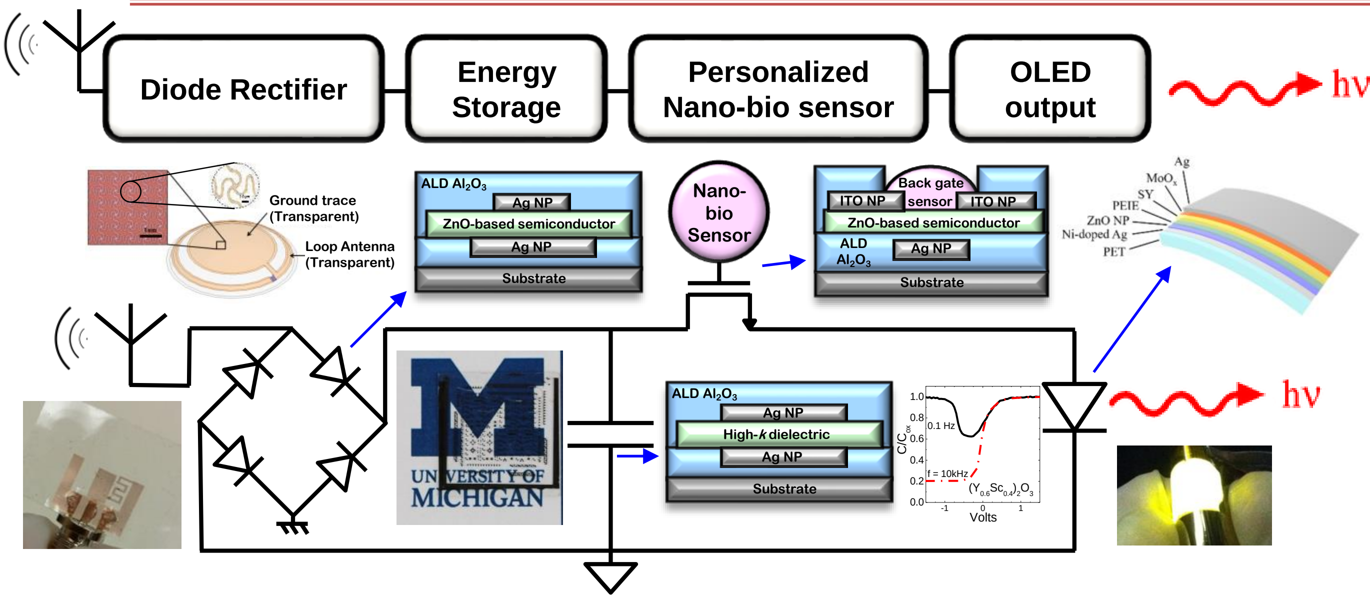


Manufacturing Autonomy for Directed Evolution of Materials (MADE-Materials) for Robust, Scalable Nanomanufacturing - David Hoelzle, Ohio State



Scalable Nanomanufacturing of Fab Compatible High-Density Nanowire Arrays for High Throughput Drug Screening – Shadi Dayeh, UCSD

Customizability – Integrated Systems

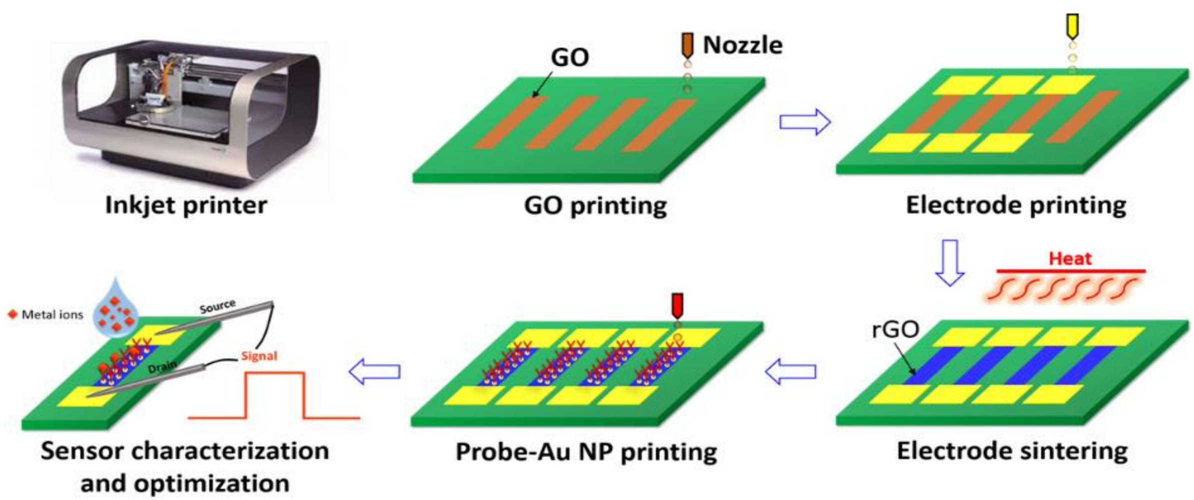


Additive Nanomanufacturing of Integrated Systems for Personalized Health Monitoring

- Neil Dasgupta, U Michigan

Customized Inkjet Printing of Graphene-Based Real-time Water Sensors

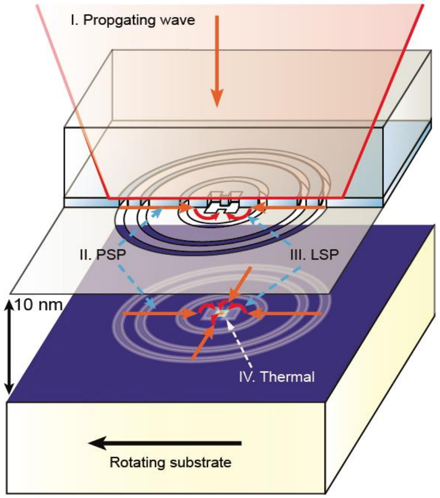
- Deyang Qu, UW-Milwaukee



Tools and Platforms

Scalable and Integrated Nano Manufacturing (SINAM) - Xiang Zhang, UC-Berkeley

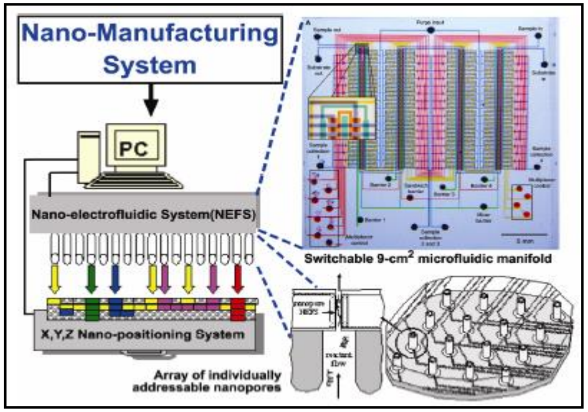
integrate an array of new nanomanufacturing technologies



Plasmonic Nanolithography

Nano Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS) - Placid Ferreira, UIUC

make nanostructures from multiple materials



Nanofluidics, E-jet, S4

Center for High-Rate Nano Manufacturing (CHN) - Ahmed Busnaina, Northeastern

high-rate, high-volume, efficient

https://www.youtube.com/watch?v=2iEjlcog774

Offset-printing

Center for Hierarchical Manufacturing (CHM) - James Watkins, UMass-Amherst

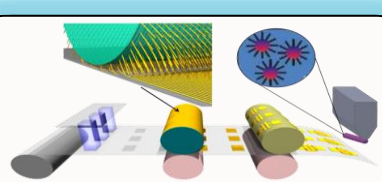
2D/3D integration across multiple length scales

R2R, DSA, NIL

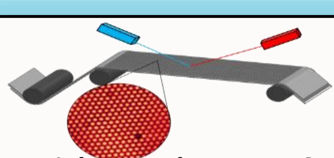
Unit Processes

Nanomanufacturing Systems for Mobile Computing and Energy Technologies (NASCENT) –

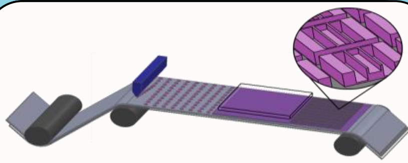
S.V. Sreenivasan and Roger Bonnecaze, UT-Austin



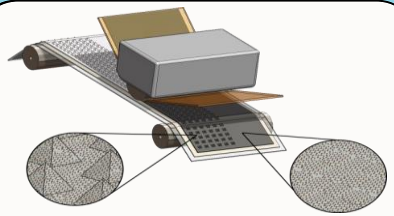
Nanomaterials Deposition



High Speed Process & Functional Metrology

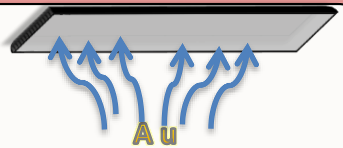


Nanoshape Imprint



Graphene Transfer

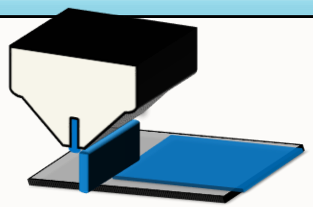
Exemplar Mobile Devices to Validate R2R Manufacturing Capability: THz Graphene Transceivers, Display Polarizers, Plasmonic OLED Cameras , Etc.



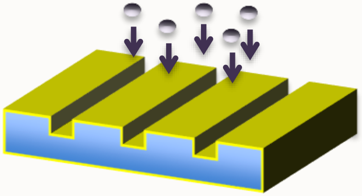
Metal/Dielectric Deposition

NASCENT Technology

Existing Technology



NanoScale Encapsulation



Plasma/Wet Etch

NASCENT nanodevices manufacturability fabrication (NASCENT nm-FAB) facility — R2R and flex WS

R2R *nm*-FAB FACILITY

NSF Network for Computational Nanotechnology - Hierarchical Nanomanufacturing Node


Toussaint

Ferreira

Ertekin

Aluru

Taylor

VISION

To simulate every step of the manufacturing process of a nano-enabled product

MISSION

To be the engine for design, simulation, planning, and optimization of nano-manufacturing processes

GOALS

- *Develop nanoMFG software tools*
- *Experimentally validate all tools*
- *Broadly disseminate*
- *Incorporate diversity at all levels*
- *Train next generation in development and utilization of nanoMFG software tools*
- *Create a sustainable framework*

Layered Computational Tools Infrastructure

Nanoscale transport phenomena

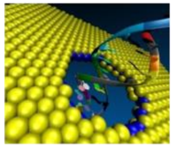
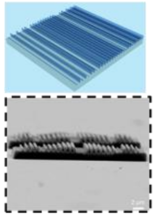
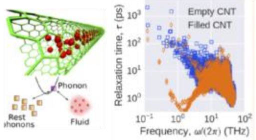


Illustration of a nanopore created in a 2D material by ion bombardment [N. Aluru]

Process Models


A flat optical lens created by TPL

Multiscale Transport Phenomena



Energy Dissipation in Fluid Coupled Nanoresonators [N. Aluru]

Nanoscale self-assembly

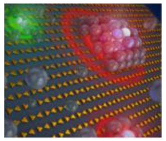


Illustration of plasmon-assisted particle assembly [K. Toussaint]

External Participants

- Fellowships for students, postdocs, and faculty
- White paper submissions for software tool development
- Computational and experimental collaboration required
- Web portal for research matchmaking (computational and experimental)

Education & Industry Outreach

- Industry can submit requests for desired tools
- Tools developed for processes common to nanoMFG and synergistic industries (e.g., CVD, MBE, FIB)
- nanoMFG workshops, online nanoMFG tutorials via nanoHUB, modules for course integration

EXAMPLE

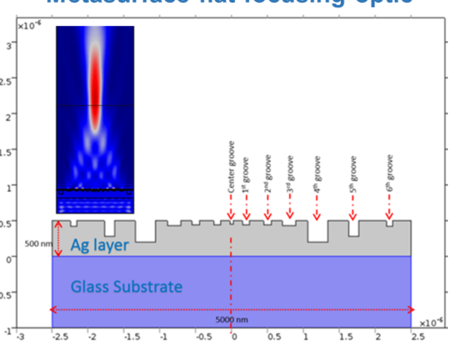
Objective: Fabrication of metasurface (flat optical) lens with nanostructured features that vary in width and height.

Approach: Determine material removal rate for nanopatterning of silver surface using focused ion-beam milling (FIB).

Challenge today: Exploration of FIB parameter space, e.g., beam dwell time and energy, could take several weeks to months.

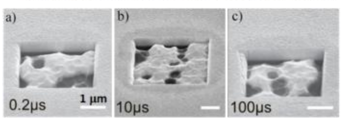
Tomorrow: User-friendly molecular dynamics-based simulation tool of FIB milling of silver significantly reduces lead time to hours.

Metasurface flat focusing optic



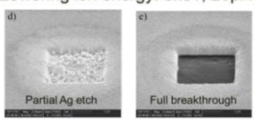
FIB milling: parameter exploration

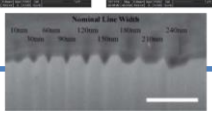
Varying beam dwell time: 30keV, 30pA

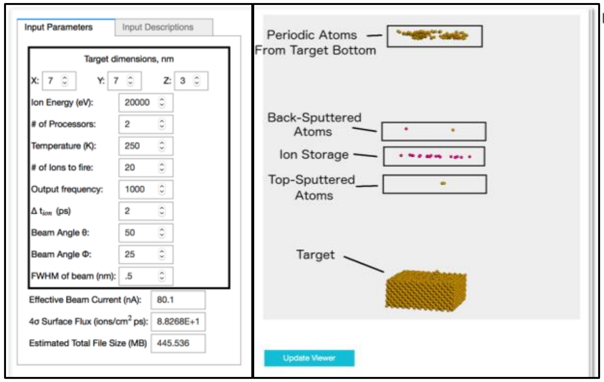


courtesy: K. Jacobs and P. Ferreira

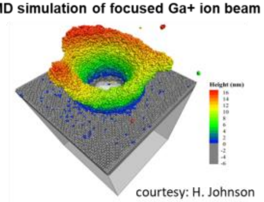
Lowering ion energy: 5keV, 20pA







MD simulation of focused Ga+ ion beam


courtesy: H. Johnson

http://nanomfgnode.illinois.edu/

RAMP

- **Reusable Abstractions of Manufacturing Processes**
- **Need:** Standard representations of manufacturing processes to facilitate the metrics, methods, and tools for the analysis of manufacturing processes and systems to enable smart and sustainable manufacturing
- **Outcomes:** Identify needs for education and research to support characterizing unit manufacturing processes for sustainability assessment, define current limitations in associated education and research practices, and prioritize the challenges to be pursued by the manufacturing research community to best meet industry needs in adopting and applying analytical methods for improving process and system performance
- *Representations for Nanomanufacturing Processes*
- *There are over 150 processes*
- *What basic research is needed?*

Thank you!

khcooper@nsf.gov