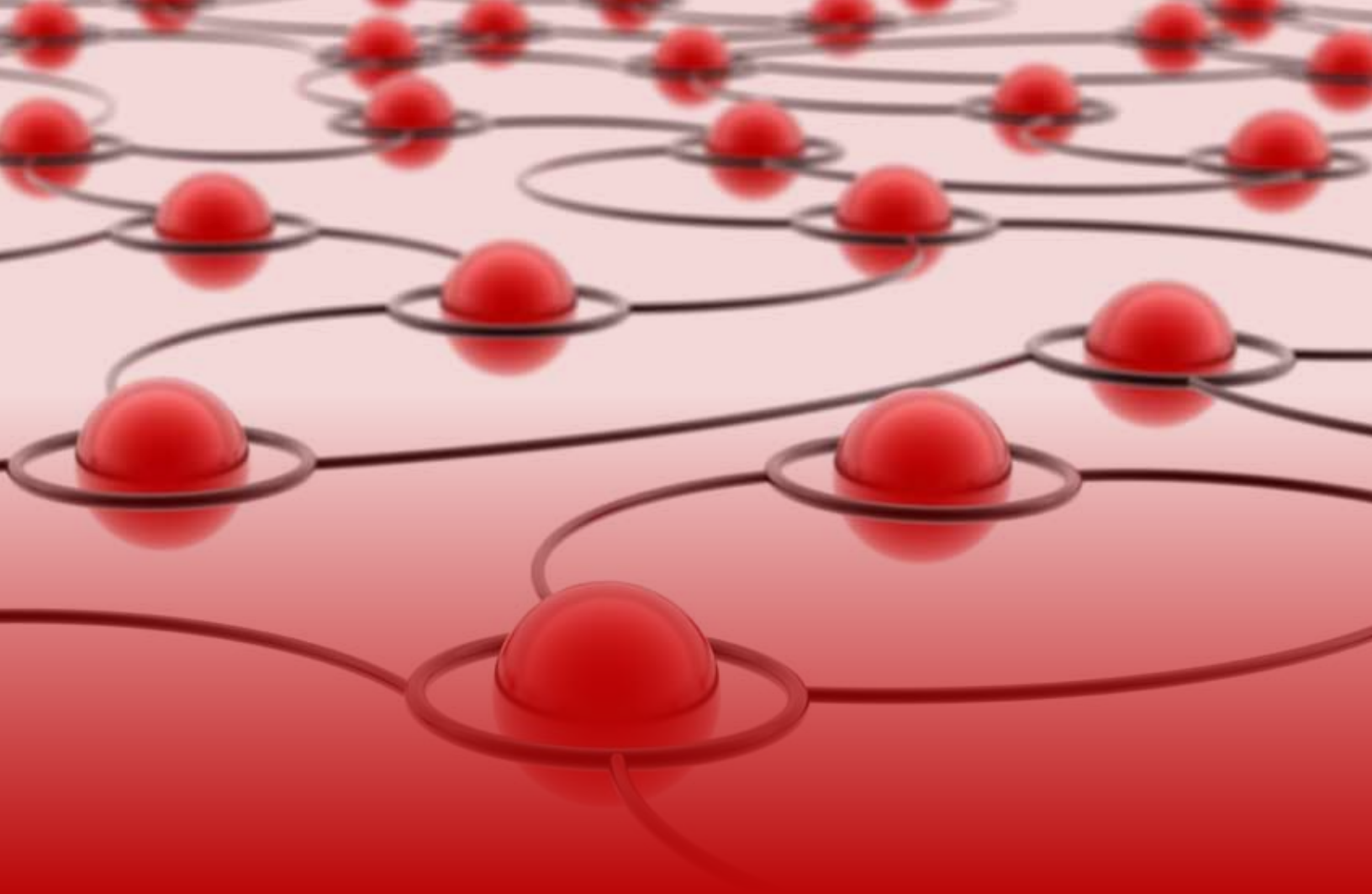

National Nanomanufacturing Network

Nanomanufacturing Summit 2009

May 27-29, 2009

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Summit Overview

Nanomanufacturing Summit 2009
Sheraton Boston Hotel
May 27-29, Boston MA

The Nanomanufacturing Summit 2009 brings together experts in the field of nanomanufacturing, highlighting innovative academic, government and industry research, successful commercialization strategies, and challenges and approaches for bridging the gap between laboratory innovation and shopfloor production. During this event attendees will hear about those areas of practice that stand out from the general nanotechnology and nanoscience themes as being near-term and having the potential to facilitate the commercial development and/or marketable application of nanoscale systems and devices. In addition, attendees will learn about emerging processes, tools, and characterization techniques that will facilitate the next generations of nanomanufacturing practices.

Nanomanufacturing is the controllable manipulation of materials structures, components, devices, and systems at the nanoscale (1 to 100 nanometers) in one, two, and three dimensions for large-scale reproducibility of value-added components and devices. Nanomanufacturing remains the essential bridge between the discoveries of the nanosciences and real-world nanotechnology products.

The challenges facing nanomanufacturing methods, processes, and systems represent an inherently multi-disciplinary set of problems addressing issues that must combine the range of top-down and bottom-up processes available in order to provide multi-scale systems integration. To achieve the necessary economy of scale for large-scale production, new concepts and principles must be envisioned to achieve revolutionary transformation of the existing manufacturing infrastructure. The critical challenges for nanomanufacturing are the need to control assembly of three-dimensional heterogeneous systems; to process nanoscale structures in high-rate/high-volume applications without compromising their inherent properties; and to ensure the long-term reliability of nanostructures through testing and metrics.

Organizing Committee

Ahmed Busnaina, Northeastern University

Placid Ferreira, University of Illinois Urbana-Champaign

Michael Garner, Intel

Robert Hwang, Sandia National Laboratory

Mohan Manoharan, General Electric

Jeff Morse, National Nanomanufacturing Network

Michael Postek, NIST

Skip Rung, ONAMI

Mark Tuominen, National Nanomanufacturing Network

James Watkins, University of Massachusetts Amherst

Theodore Wegner, U.S. Forestry Service

Xiang Zhang, University of California Berkeley

Program Overview

Wednesday 27 May		**Room**
8:30am – 10:00am	Plenary Session	*Fairfax*
10:20am – 12:00pm	Parallel Sessions	
	• Advanced Processes and Tools for Nanoscale Control	*Gardner*
	• Field and Fluidic Assisted Assembly	*Hampton*
1:20pm – 3:00pm	Parallel Sessions	
	• Directed Assembly	*Gardner*
	• Nano ES&H, Risk Assessment	*Hampton*
3:20pm – 5:00pm	Parallel Sessions	
	• Nanomanufacturing Applications: Advanced Materials	*Gardner*
	• Green Nanomanufacturing, ES&H, Risk	*Hampton*
5:00pm – 7:00pm	Reception and Poster Session	*Commonwealth*

Thursday 28 May		**Room**
8:30am – 10:00am	Plenary Session	*Fairfax*
10:20am – 11:35am	Parallel Sessions	
	• Emerging Processes and Tools	*Gardner*
	• Integrated Nanoelectronics	*Hampton*
1:20pm – 3:00pm	Parallel Sessions	
	• Nanomanufacturing Applications: Energy and Environment	*Gardner*
	• Nanotechnology Business and Commercialization I	*Hampton*
3:20pm – 5:00pm	Parallel Sessions	
	• Advanced Tools and Processes for Nanomanufacturing I	*Gardner*
	• Nanotechnology Business and Commercialization II	*Hampton*
5:00pm – 7:00pm	Reception and Poster Session	*Commonwealth*

Friday 29 May		**Room**
8:20am – 10:00am	Parallel Sessions	
	• Advanced Tools and Processes for Nanomanufacturing II	*Gardner*
	• Fundamental and Enabling Science	*Hampton*
10:20am – 12:00am	Parallel Sessions	
	• Advanced Tools and Processes for Nanomanufacturing III	*Gardner*
	• Nanomanufacturing Applications: General	*Hampton*

Full Program

WEDNESDAY 27 MAY		
8:15am	***Plenary Session***	
8:30am	**Long View in Nanomanufacturing** *Mihail C. Roco*, National Science Foundation and National Nanotechnology Initiative (*see page 8)*	
9:00am	**Some Recent Progress in Soft and Fluidic Based Techniques for Nanomanfuacturing** *John Rogers*, Univeristy of Illinois Urbana-Champaign (*see page 8)*	
9:30am	**Nanomanufacturing Technology for Energy Applications** *Omkaram Nalamasu*, Applied Materials (*see page 9)*	
10:00am	**Networking Break**	
	Session IA: Advanced Processes and Tools for Nanoscale Control *(see pages 11-12)*	***Session IIA: Field and Fluidic Assisted Assembly*** *(see pages 12-14)*
10:20am	**The Characterization and Metrology of Graphene** *Alain Diebold,* College of Nanoscale Science and Engineering	**Heterogeneous Functional Integration and Manufacturing at the Nanoscale** *Placid Ferreira*, NSF Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems
10:45am	**Nano Stamp: Single Molecular Stamping of Sub-10nm Colloidal Quantum Dot Array** *Xiaojing (John) Zhang*, Kazunori Hoshino and Ashwini Gopal, The University of Texas at Austin	**Dielectrophoretic Directed Assembly of Nanowires Over Large Areas** *Erik M. Freer*, Oleg Grachev and David P. Stumbo, Nanosys, Inc.
11:10am	**Self-assembled Contacts to Nanoparticles Using Metallic Ga Droplets** *K. Du*, E. Glogowski, M. T. Tuominen, T. Emrick, T. P. Russell and A. D. Dinsmore, University of Massachusetts Amherst	**Precise Large-Scale Control of Electrophoretic Directed Assembly of Nanoparticles** *Cihan Yilmaz*, Sivasubramanian Somu, Ahmed Busnaina and Sanjeev Mukerjee, NSF Center for High-rate Nanomanufacturing and Northeastern University
11:35am	**Measurements, Instrumentation and Standards for Nanomanufacturing** *Michael T. Postek*, National Institute of Standards and Technology	**Nanoscale Deposition and Etching of Silicon Quantum Dots Using Field-Assisted AFM-Based CVD** *Mohammad Reza Dodge* and Massood Tabib-Azar, University of Utah
12:00pm	**Lunch**	
	Session IB: Directed Self-Assembly *(see pages 14-15)*	***Session IIB: Nano ES&H, Risk Assessment*** *(see pages 16-17)*
1:20pm	**Templated Self-assembly of Block Copolymers for Nanoscale Device Fabrication** *C.A. Ross*, Y.S. Jung, V.P. Chuang, Joel W.K. Yang and K.K. Berggren, Massachusetts Institute of Technology	**Challenges for Environmental Health and Safety of Nanomaterials** *Jacqueline A. Isaacs,* NSF Center for High-rate Nanomanufacturing
1:45pm	**Directed Assembly of Polymer Structures for High-rate Nanomanufacturing** *Ming Wei*, Liang Fang, Arun Kumar, Jia Shen, Jun Lee, Sivasubramanian Somu, Xugang Xiong, Carol Barry, Ahmed Busnaina and Joey Mead, NSF Center for High-rate Nanomanufacturing	**Study of Nanoparticle Emission from Production of Multi Walled Carbon Nanotubes** *Su-Jung (Candace) Tsai*, Mario Hofmann, Marilyn Hallock, Earl Ada, Jing Kong and Michael Ellenbecker, NSF Center for High-rate Nanomanufacturing, University of Massachusetts Lowell, and Massachusetts Institute of Technology
2:10pm	**Patterned Media: Processing Technology** *Neil Robertson,* Hitachi Global Storage Technologies	**Controlling Risks and Controlling Costs: Retooling for Codes of Conduct** *Nina Horne,* University of California, Berkeley
2:35pm	**Macroscopic Arrays of Block Copolymers With Areal Densities of 10 Terabit/inch^2 and Beyond** *Thomas P. Russell*, University of Massachusetts Amherst	**Preclinical Characterization Resources for Cancer Nanomedicines** *Anil K. Patri,* Nanotechnology Characterization Laboratory

Full Program

WEDNESDAY 27 MAY		
3:00pm	**Break**	
	Session IC: Nanomanufacturing Applications: Advanced Materials *(see pages 18-19)*	***Session IIC: Green Manufacturing, Nano ES&H, Risk*** *(see pages 20-21)*
3:20pm	**Scaling Up Production of Long Carbon Nanotubes and Multi-function Products** *David Lashmore*, Nanocomp Technologies, Inc.	**Greener Nanomanufacturing: Opportunities to Optimize Performance, Efficiency and Safety in the Production of Nanoscale Materials** *James Hutchison*, University of Oregon
3:45pm	**Emerging Research Materials and Nanofabrication Methods: Challenges and Opportunities** *Daniel Herr*, Semiconductor Research Corporation	**Study of Airborne Nanoparticle Exposure Associated with the Hood Design and the Development of a Standardized Testing Protocol** *Su-Jung (Candace) Tsai* and Michael Ellenbecker, NSF Center for High-rate Nanomanufacturing and University of Massachusetts Lowell
4:10pm	**Nanotechnology Research and Development in the Forest Products Industry—the Green Connection** *Ted Wegner*, World L. S. Neih, John G. Cowie, J. Philip E. Jones, Mike Postek and Andras Vladar, U.S. Forest Service, AF&PA Agenda 2020, Imerys, National Institute of Standards and Technology	**Modeling Approaches for Nanomanufacturing Risk Assessment** *Zeynep D. Ok*, Jacqueline A. Isaacs and James C. Benneyan, NSF Center for High-rate Nanomanufacturing and Northeastern University
4:35pm	**Self-Collimation in Quasi Zero-Average-Refractive-Index Photonic Crystal Metamaterial** *S. Cabrini*, V. Mocella, A.S.P. Chang, P. Dardano, L. Moretti, I. Rendina, D. Olynick, B. Harteneck and S. Dhuey, Lawrence Berkeley National Laboratory and CNR-IMM – Unità di Napoli	**Screening for Potential Toxicity of Engineered Nanomaterials: Its Utility in Developing Responsible Nanomanufacturing** *Dhimiter Bello*, Shu-Feng Hsieh, Anoop K. Pal, Daniel Schmidt and Eugene J. Rogers, NSF Center for High-rate Nanomanufacturing and University of Massachusetts Lowell
5:00pm	***Reception and Poster Session***	
7:00pm	**Close Day 1**	

THURSDAY 28 MAY		
8:15am	***Plenary Session***	
8:30am	**Commercializing Nanotechnology: Setting Expectations After the Hype Has Gone** *Chris Hartshorn*, Lux Research, Inc. *(see page 9)*	
9:00am	**Electron & Ion Beam Microscopies: From Lab to Fab** *David H. Narum*, FEI Company *(see page 10)*	
9:30am	**Nanomanufacturing: Challenges and Opportunities** *Shaochen Chen*, National Science Foundation *(see page 10)*	
10:00am	**Networking Break**	
	Session 1A: Emerging Processes and Tools *(see pages 22-23)*	***Session IIA: Integrated Nanoelectronics*** *(see pages 23-24)*
10:20am	**Nanoprocessing and Device Fabrication** *Costas P. Grigoropoulos*, David J. Hwang, and Seunghwan Ko, University of California, Berkeley	**The SRC-NIST Nanoelectronics Research Initiative: Partnership for Innovation** Jeffrey Welser, *Daniel Herr*, and Ralph K. Cavin, III, Semiconductor Research Corporation

Full Program

THURSDAY 28 MAY		
10:45am	**Advances in Soft-Nanoimprint Lithography** *Isaac W. Moran* and Kenneth R. Carter, University of Massachusetts Amherst	**Heterogeneous Integration of Single-Walled Carbon Nanotubes with CMOS Circuitry** *Chia-Ling Chen*, Vinay Agarwal, Chih-Feng Yang, Chenfu Guo, Sameer Sonkusale, and Mehmet R. Dokmeci, Northeastern University and Tufts University
11:10am	**Layered Nanotubes from Electrostatic Assembly** *Jodie Lutkenhaus*, Yale University	**SWNT-based Thin Film Transistors on a Flexible Substrate** Selvapraba Selvarasah and *Mehmet R. Dokmeci*, Northeastern University
11:35am	**Luncheon Panel Discussion:** ***Economic Development of Nanomanufacturing: Challenges, Approaches, and Opportunites***	**Luncheon Panel Discussion:** ***Information Needs for Nanomanufacturing***
	Session IB: Nanomanufacturing Applications: Energy and Environmental *(see pages 25-27)*	***Session IIB: Nanotechnology Business and Commercialization I*** *(see pages 27-28)*
1:20pm	**Nanotechnology at GE: Path to Commercialization** *Margaret L. Blohm*, GE Global Research	**Involvement of Industry in Nanotechnology Partnerships** *Sean Murdock*, Nano Business Alliance
1:45pm	**Polymer Nanotube Ensembles for Separation and Sensing** *K. Krishnamoorthy*, E. N. Savariar and S. Thayumanavan, University of Massachusetts Amherst	**Nanotechnology for Defense Applications** *Sharon Smith*, Lockheed Martin
2:10pm	**Silicon and Germanium Nanocrystal Electronic Devices** *Zachary Holman*, Chin-Yi Liu and Uwe Kortshagen, University of Minnesota	**Nano Terra: Creating Function at Surfaces Through the Application of Chemistry and Structure. A New Business Model for Platform Technology** *Emanuele Ostuni*, Nano Terra Inc.
2:35pm	**Nanomanufacturing Fuel Cell MEAs Using Layer-By-Layer Assembly** Ryan C. Sekol, Marcelo Carmo and *André D. Taylor*, Yale University	**Roll-to-Roll Nanomanufacturing Opportunities** *Diane Martin*, MicroContinuum, Inc., and Lightwave Power, Inc.
3:00pm	**Break**	
	Session IC: Advanced Tools and Processes for Nanomanufacturing I *(see pages 28-29)*	***Session IIC: Nanotechnology Business and Commercialization II*** *(see pages 30-31)*
3:20pm	**Zone-Plate-Array Approach to Maskless Lithography** *Michael Walsh*, LumArray, Inc.	**The Business of Nanomanufacturing: State/Regional Partnerships, Commercialized Research and Entrepreneurial Startups** *Skip Rung*, ONAMI
3:45pm	**Plasmonic Lithography for Nanomanufacturing** *David B. Bogy* and Liang Pan, University of California, Berkeley	**Organic Photovoltaics – A High Speed, High Volume Manufacturing Technology** *Russell Gaudiana*, Konarka Inc.
4:10pm	**Advanced Solutions in Surface Engineering Technology ASSET™** *Arjan Giaya*, Triton Systems, Inc.	**NanoGram Silicon Ink: Unlocking the Printed Electronics Opportunity** *Sean Stewart*, NanoGram Corporation
4:35pm	**Nanoimprinting with Amorphous Metals** *Jan Schroers* and Golden Kumar, Yale University	**State-Corporate Partnership of Nanoeconomic Development** *Ed Cupoli*, CNSE at University of Albany
5:00pm	***Reception and Poster Session***	
7:00pm	**Close Day 2**	

Full Program

FRIDAY 29 MAY		
	Session IA: Advanced Tools and Processes for Nanomanufacturing II *(see pages 32-33)*	***Session IIA: Fundamental and Enabling Science*** *(see pages 33-35)*
8:20am	**Nanomanufacturing Using Heated Probe Tips** *William King,* University of Illinois Urbana-Champagne	**Sandia's CAE Approach Towards Bottom-up and Top-Down Nanomanufacturing** *Michael Chandross,* Sandia National Laboratory
8:45am	**Dip-Pen Nanolithography®: From the Lab to the Factory Floor** *Mike Nelson,* NanoInk, Inc.	**Investigation of Quality and Repeatability of Nanomanufacturing Processes: Design of Experiments of Magnesium Oxide Growth Process** Ghulam Moeen Uddin, *Abe Zeid*, Sagar Kamarthi, and Katey Ziemer, Northeastern University
9:10am	**Directed Assembly of Nanoelements for High-rate Nanomanufacturing** *Ahmed Busnaina,* NSF Center for High-rate Nanomanufacturing	**Introduction to the Center for Scalable and Integrated NAno-Manufacturing (SINAM)** *Li Zeng,* NSF Center for Scalable and Integrated Nanomanufacturing
9:35am	**Center for Integrated Nanotechnologies** *Robert Hwang,* Center for Integrated NanoTechnologies (CINT)	
10:00am	**Break**	
	Session IB: Advanced Tools and Processes for Nanomanufacturing III *(see pages 35-37)*	***Session IIB: Nanomanufacturing Applications: General*** *(see pages 37-38)*
10:20am	**Self-Assembled Templates for Device Fabrication on Si Wafer and Roll-to-Roll Process Platforms** *James J. Watkins,* NSF Center for Hierarchical Manufacturing	**Functionalized Carbon Nanotube Sensors for Chemical and Biological Detection** *Michelle Chen,* Simmons College
10:45am	**Multifinger Coordinated Manipulation Methodology for Nanomanufacturing** *Laxman Saggere*, Sandeep Krishnan and Christopher Pelzmann, University of Illinois at Chicago	**Controlled Drug Release from Large Area Nanoplatforms** *Evin Gultepe*, Dattatri Nagesha and Srinivas Sridhar, Northeastern University
11:10am	**High Resolution Projection Microstereolithography for 3-D Fabrication** *Chris Spadaccini* and Nick Fang, Lawrence Livermore National Laboratory and University of Illinois	**New Quantum Dot Based Materials** *Y.K. Gun'ko*, M. M. Moloney, S. Gallagher and S. Byrne, Trinity College, University of Dublin
11:35am	**Template for Straight Forward Fabrication of Single Nanowire Devices** *B.J. Hansen*, X. Zhang and J. Chen, Boston University and University of Wisconsin Milwaukee	
12:00pm	***Conference Adjourn***	

Plenary Speakers

PLENARY **Wednesday 27 May, 8:30am**

Mihail C. Roco
Senior Advisor for Nanotechnology, National Science Foundation

Long View in Nanomanufacturing

Nanomanufacturing has been defined as an approach to design, produce, control, modify, manipulate, and assemble nanometer-scale elements or features for the purpose of realizing a product or system that exploits properties seen at the nanoscale. Nanomanufacturing R&D has as its goal enabling the mass production of reliable and economical nanoscale materials, structures, devices, and systems. Nanomanufacturing combines assembling of molecular systems with top-down miniaturization and precise hierarchical integration. Specific instrumentation and standards for nanoscale measurements need to be developed upstream in conjunction with simulations and design of productive processes. The current rudimentary capabilities for systematic control and manufacture at the nanoscale are envisioned to evolve faster after 2010 as we develop new models and instrumentation and enter production of nanosystems for revolutionary new products and processes. We have estimated the global market of final products that incorporate nanotechnology increases by about 25 percent per year reaching US $1 trillion by 2015. This estimation made in 2000 holds in 2009, after passing half of the interval. The research trends and application opportunities in nanomanufacturing will be presented by considering four generations of products by 2020. Each generation of new products is expected to include, at least partially as components, products from previous generation. Convergence with modern biology, digital revolution, cognitive sciences and other areas is expected to accelerate nanotechnology manufacturing.

Dr. Roco is the founding chair of the National Science and Technology Council's subcommittee on Nanoscale Science, Engineering and Technology (NSET), and is the Senior Advisor for Nanotechnology at the National Science Foundation. He also coordinated the programs on academic liaison with industry (GOALI). Prior to joining National Science Foundation, he was Professor of Mechanical Engineering at the University of Kentucky (1981-1995), and held visiting professorships at the California Institute of Technology (1988-89), Johns Hopkins University (1993-1995), Tohoku University (1989), and Delft University of Technology (1997-98).

PLENARY **Wednesday 27 May, 9:00am**

John Rogers
Department of Materials Science and Engineering, University of Illinois Urbana-Champaign

Some Recent Progress in Soft and Fluidic Based Techniques for Nanomanufacturing

Progress in nanoscience and technology relies critically on the ability to build structures with nanometer dimensions. Established tools have their origins in the microelectronics industry and are spectacularly well suited to the applications for which they were principally designed. These methods have drawbacks, however, that limit their use in new fields of study: they require expensive facilities; they have difficulty forming features smaller than ~100 nm; they can pattern directly only narrow classes of specialized polymers; and they can only be applied, in a single step, over relatively small areas on ultraflat substrates. These limitations create opportunities for new methods, ranging from adaptations of conceptually old techniques based on printing, molding and writing, to strategies that rely on bottom-up growth, self-assembly, phase separation and others. This talk describes unconventional approaches to nanomanufacturing, including (1) fluid jet printing techniques, (2) molecular and three dimensional soft lithographic methods and (3) soft transfer printing schemes for heterogeneous materials integration. The underlying scientific principles of these procedures will be discussed, along with representative engineering aspects of application in solid state lighting, flexible electronics and unusual photovoltaic systems.

Professor John A. Rogers obtained B.A. and B.S. degrees in chemistry and in physics from the University of Texas, Austin, in 1989. From MIT, he received S.M. degrees in physics and in chemistry in 1992 and the Ph.D. degree in physical chemistry in 1995. From 1995 to 1997, Rogers was a Junior Fellow in the Harvard University Society of Fellows. He joined Bell Laboratories as a Member of Technical Staff in the Condensed Matter Physics Research Department in 1997, and served as Director of this department from 2000-2002. He currently holds the Flory-Founder Chair in Engineering at University of Illinois at Urbana-Champaign with a primary appointment in the Department of Materials Science and Engineering and affiliate appointments with the Beckman Institute, the Materials Research Laboratory as well as the Departments of Electrical and Computer Engineering, Mechanical Science and Engineering and Chemistry. Rogers' research includes fundamental and applied aspects of nano and molecular scale fabrication as well as materials and patterning techniques for unusual format electronics and photonic systems.

Plenary Speakers

PLENARY **Wednesday 27 May, 9:30am**

Omkaram Nalamasu
Deputy Corporate CTO, Vice President, Advanced Technologies Group, Applied Materials

Nanomanufacturing Technology for Energy Applications

Over 40 years of thin film process innovations have helped enable the IC industry today to produce well over 10^{18} transistors per year at costs of nanodollars per transistor thereby empowering the information age. Likewise large area thin film manufacturing has dramatically improved the performance and cost of low cost displays over the past 15 years, enabling high definition video from the handheld to the wall mounted HDTV. The overwhelming societal and market pull today for new solutions in the field of clean energy offers an exciting opportunity to build on a similar base of technology. Through a combination of materials innovation and highly productive processing platforms we have the potential to enable new solutions for conservation, conversion and storage and thus profoundly change the economics of clean energy.

Dr. Nalamasu leads Applied Material's research and innovation efforts through the funding/incubation of long term R&D/product development activities, spearheads investments into global academia and consortia, and guides Applied Ventures' investments into start-ups. Prior to this, he was the Vice President of Research and NYSTAR Distinguished Professor of Materials Science and Engineering as well as Professor of Chemistry at Rensselaer Polytechnic Institute. Professor Nalamasu was also the founding director of $20MM Center for Future Energy Systems and conceived and founded CCNI (Center for Computational Nanotechnology Innovations), with NY state and IBM in creating world's fastest university based supercomputing center at RPI. Prior to RPI, Dr. Nalamasu was the chief technical officer of the New Jersey Nanotechnology Consortium, a public/private nonprofit enterprise he co-founded to foster nanotechnology partnerships across academia, industry, and government using Bell Labs' $400M device fabrication facilities in Murray Hill, NJ. Prior to joining Rensselaer in 2002, Dr. Nalamasu held several key research and development leadership positions in AT&T Bell Laboratories, Bell Laboratories/Lucent Technologies, and Agere Systems in Murray Hill, N.J. He previously served as Director of Bell Laboratories' Nanofabrication Research Laboratory, MEMS and Waveguides Research, Condensed Matter Physics organizations.

PLENARY **Thursday 28 May, 8:30am**

Chris Hartshorn
Research Director, Lux Research, Inc.

Commercializing Nanotechnology: Setting Expectations After the Hype Has Gone

The luster of nanotechnology as a "can't-lose" theme has been and gone, with some winners but a growing selection of losers. Start-ups are going under, corporations now see nanotech as a tool rather than a goal, and private investment is consolidating rather than broadening. Meanwhile, centralized nanotechnology efforts at the country level are growing, fueled by cross-border collaboration, and the opportunistic vision that a final push towards commercialization will set a global hierarchy for innovation and economic prosperity. Given the diverse range of participants and outcomes, the nanotechnology landscape remains dynamic and complicated. To make rational decisions with respect to nanotechnology commercialization and the requisite manufacturing capability that entails, it is critical to understand how nanotechnology has penetrated some applications and stalled in others, who is prospering and why, and what the future will look like. In attacking this, key questions will be addressed including:

- What is the underlying structure of the nanotechnology value chain?
- What are the themes that have influenced successful nanotechnology commercialization, and how will they change?
- Does the value that nanotechnology brings to the energy and environment sector justify the attention?
- How will the impact of nanotechnology grow in the coming years?

Dr. Hartshorn leads the research team for the consulting practice of Lux Research. Since joining the company, he has advised a broad range of entities—multinationals, start-ups, government organizations, investment banks and venture capitalists—on a range of emerging technology projects. These projects have covered a variety of clean technology areas including green buildings, water recycling, alternative fuels, wireless energy systems and photovoltaics, providing guidance on the specific technologies of relevance today to the technologies and adoption landscapes that will shape the future. He was also lead author on Lux's most recent report addressing environmental health and safety issues relating to nanotechnology and has advised multiple clients in the field of nanotechnology adoption and the applications it will impact. Prior to joining Lux Research, Chris worked for General Electric as a global technology manager in its Advanced Materials business, as well as a product developer within the Plastics business. Originally from New Zealand, where he obtained a Ph.D. in chemistry from the University of Canterbury, Chris then undertook post-doctoral research at the University of North Carolina. This was followed by a position as Senior Scientist contracted to the U.S. Naval Research Laboratory's Center for Biomolecular Science and Engineering, after which he joined GE.

Plenary Speakers

PLENARY **Thursday 28 May, 9:00am**

David H. Narum
CTO, FEI Company

Electron & Ion Beam Microscopies: From Lab to Fab

FEI Company is a world-leading supplier of instrumentation for nanoscale imaging, measurement, analysis and modification of materials and devices. FEI Company's products based on electron and focused ion beam microscopy have enabled R&D in nanoscience and nanotechnology for decades, but more recently these instrumentation technologies have begun to migrate into production ramp-up, production and production support applications. While this might seem inevitable as nano-enabled products are commercialized, successful deployment of these instrumentation technologies into the manufacturing environment hinges on meeting radically different requirements than traditional laboratory applications. Key among these changes are: 1) A shift in product specification and design from a focus on technical performance to a solution orientation, 2) Radical improvements in instrument reliability, automation, time-to-data and throughput, and 3) A shift in the customer's value model from scientific contribution to pure econometrics. Examples of FEI Company's success in supporting this migration of instrumentation technology into nano-scale manufacturing environments in the semiconductor, data storage and mining industries will be used to illustrate these points. Similar migrations anticipated in other industries or application areas will also be discussed.

Dr. Narum joined FEI Co. (Hillsboro, Ore.) in August of 2001 as vice president of R&D for the beam technology division, and was promoted to general manager in July 2002. In May 2003, he was appointed CTO. Prior to FEI, he worked as executive director of advanced technology at Applied Epi, a molecular beam epitaxy equipment supplier. From 1990-2000, Narum was with Physical Electronics Inc. (PHI) as R&D director. Previously, he held research positions at Honeywell and Control Data Corporation. Narum has a B.A. in physics from St. Olaf College (Northfield, Minn.), an MSEE from the University of Minnesota, and a Ph.D. (EE) from Stanford University. FEI Company manufactures focused ion- and e-beam technologies for three-dimensional (3-D) characterization, analysis and modification in the nanoscale arena.

PLENARY **Thursday 28 May, 9:30am**

Shaochen Chen
Program Director of NanoManufacturing, Civil, Mechanical, and Manufacturing Innovation Division, National Science Foundation

NanoManufacturing: Challenges and Opportunities

The National Science Foundation (NSF) provided approximately $27 million in Fiscal Year 2008 for fundamental research and education in nanomanufacturing in the United States, mostly to colleges and universities, with some support provided to small businesses. The core Nanomanufacturing Program emphasizes scale-up of nanotechnology to increase the production rate, reliability, robustness, yield, and efficiency of manufacturing processes and reduce the cost of nanotechnology products and services. Nanomanufacturing capitalizes on the special material properties and processing capabilities at the nanoscale, promotes integration of nanostructures to functional micro devices and meso/macroscale architectures and systems, and addresses interfacing issues across dimensional scales. The program promotes multi-functionality across all energetic domains, including mechanical, thermal, fluidic, chemical, biochemical, electromagnetic, optical etc. The focus incorporates a systems approach, encompassing nanoscale materials and structures, fabrication and integration processes, production equipment and characterization instrumentation, theory/modeling/simulation and control tools, biomimetic design and integration of multiscale functional systems, and industrial application. In this talk, I will overview research projects recently funded in the Nanomanufacturing Program at NSF. I will also talk about tips for NSF proposal writing.

Dr. Chen is the Program Director of NanoManufacturing at NSF. He is on leave from the University of Texas at Austin where he is a Henderson Centennial Endowed Faculty Fellow and Professor in the Mechanical Engineering Department. Dr. Chen received a Ph.D. from the University of California at Berkeley in 1999. His current research interest includes nanophotonics, nanomanufacturing, biomaterials and nanomedicine, ultrafast science and engineering, thermal/fluid transport in micro and nano-systems.

Session Abstracts

SESSION IA: Advanced Processes and Tools for Nanoscale Control — Wednesday 27 May, 10:20am

The Characterization and Metrology of Graphene

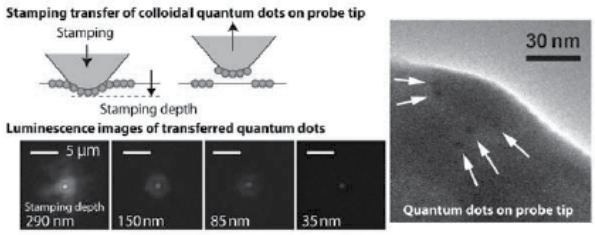
Alain Diebold
College of Nanoscale Science and Engineering, University at Albany, State University of New York

The semiconductor industry is searching for new switches to replace the transistor. Potential devices based on carrier spin, excitons, and other properties are all being investigated. Graphene is considered a strong candidate for many of these applications. In addition to new materials properties, new phenomena abound at nanoscale dimensions, and graphene is no exception. For example, quantum confinement impacts materials properties and measurement itself. New electrical properties such as the Berry Phase correction to carrier transport measurements are also becoming widely recognized. However, new materials such as graphene are difficult to find, manipulate, and measure. One key question is the number of graphene layers in a sample and the stacking of multilayer samples and the relative mis-orientation between layers. Multiple characterization methods are necessary including transmission electron microscopy (TEM), Low Energy Electron Microscopy (LEEM), nano-Raman, and several scanned probe methods. Amazingly, HR-TEM can image single and multilayers of graphene even determining layer mis-orientation. Modeling of metrology is often overlooked in development of new measurement methods. Multislice simulations are a useful guide in determining TEM capability and imaging conditions. We will show simulation work points to the ability to distinguish stacking patterns. Recent work indicates that LEEM can determine the number of layers and the morphology of a graphene sample. Raman provides an excellent means of determining the number of layers in a stack of graphene. Single electron transistors have mapped electron-hole puddles across a sample area. Optical and electrical properties must be understood before they are measured. This paper will cover the research and development of metrology for new Beyond CMOS materials using graphene as an example.

SESSION IA: Advanced Processes and Tools for Nanoscale Control — Wednesday 27 May, 10:45am

Nano Stamp: Single Molecular Stamping of Sub-10nm Colloidal Quantum Dot Array

Xiaojing (John) Zhang, Kazunori Hoshino, Ashwini Gopal
Department of Biomedical Engineering and Microelectronics Research Center, The University of Texas at Austin



We introduce a nano-scale stamping technique of sub-10nm colloidal quantum dot (QD) arrays to highly localized areas of three dimensional nanostructures, using a quartz tuning fork employed as the stamp pad (the "Nano Stamp"). CdSe/ZnS core-shell nanoparticles with diameters of 9.8 nm were deposited on microfabricated silicon probe tips. The number of transferred QDs, which ranged from several thousands down to single molecular order (less than 10), was precisely controlled by adjusting the stamping depths and angles. The stamping areas were varied from 1.2 µm x 1.2 µm down to 30 nm x 30 nm, respectively. Using the Nano Stamp, QDs can be transferred to varieties of protruding nanostructure. The amount of particles transferred to the tip was assessed by fluorescence intensity measurements, and the number of particles was estimated by direct Transmission Electron Microscope (TEM) observation. Correlation between the fluorescence intensity and the observed stamping depth and the approaching angle of the tip was found, demonstrating the efficacy of our Nano-Stamp technique. Considering the sub-nm control capability of the tuning fork based positioning system, we did not see major technical difficulties which may impede the realization of single molecule deposition at the probe apex in the near future.

Manipulation of colloidal QDs in a very small number is becoming an important issue in fabricating colloidal QD-based devices such as light emitting diodes (LEDs), transistors and bio-chemical sensors. Creation of a nanometer-scale LED at the scanning probe tip is one of our promising applications of Nano Stamp. The Nano Stamp can be further applicable to several kinds of particles and surfaces as have been tested in previous studies of micro contact printing. Our test stamping on the tip of drawn optical fibers, which are commonly used in standard NSOM, showed promising results. A vast variety of particles, including polymer, metal, semiconductor or diamond nanoparticles, can be deposited using the similar procedure. Attachment of fluorescent nanodiamonds at the probe tip is a topic of current interest in magnetometry at the nanoscale. Successful single molecular order transfer of nanoparticles on three dimensional nanostructures leads to creation of future scanning probes, sensors and quantum logic devices.

ACKNOWLEDGMENT: This research was performed in part at the Microelectronics Research Center (MRC) at the UT Austin, and the National Nanofabrication Infrastructure Network (NNIN) supported by National Science Foundation (NSF NNIN-0335765). We also thank NSF CAREER Program (ECCS-0846313), NSF EPDT Program (ECS-0725886), NSF IMR Program (DMR-0817541), NSF CMMI Program(CMMI-0826366), UT Research Grant, the Welch Foundation, and The Strategic Partnership for Research in Nanotechnology (SPRING) for partial support of this work.

Session Abstracts

SESSION IA: Advanced Processes and Tools for Nanoscale Control — Wednesday 27 May, 11:10am

Self-Assembled Contacts to Nanoparticles Using Metallic Ga Droplets

K. Du, E. Glogowski, M. T. Tuominen, T. Emrick, T. P. Russell, A. D. Dinsmore
Department of Physics, Department of Polymer Science and Engineering, University of Massachusetts Amherst

We demonstrate a pragmatic approach to forming electronic materials and devices, in which metal droplets serve as electrodes and their spacing is controlled spontaneously, via self-assembly, to allow tunneling contact with nanoparticles. We have fashioned devices consisting of droplets of molten metal (Ga). Ga is suspended in acidic solution. Ligand-stabilized Au nanoparticles in solution assemble on the metal surface, as shown by electro microscopy. Coated droplets which are then placed on a substrate and the solvent removed. Electron-transport measurements reveal the Coulomb blockade, in which current is suppressed below a tunable threshold voltage by the energy of charging individual nanoparticles. The threshold voltage for two different sizes of nanoparticles agrees with theory. Our approach provides a straightforward approach to creating nanoscale-precision contacts to nanoparticles and might lead to formation of a large number of microscopic devices from suspension.

SESSION IA: Advanced Processes and Tools for Nanoscale Control — Wednesday 27 May, 11:35am

Measurements, Instrumentation and Standards for Nanomanufacturing

Michael T. Postek
National Institute of Standards and Technology

Advanced manufacturing is one of the essential bridges between the discoveries of nanoscience and real world nanotech products. Advanced manufacturing is the vehicle by which the Nation and the World will realize the promise of major technological innovation across a spectrum of products that will affect virtually every industrial sector. For nanotech products to achieve the broad impacts envisioned, they must be manufactured in market-appropriate quantities in a reliable, repeatable, economical and commercially viable manner. Economy of scale is imperative. In addition, products must be manufactured so that environmental and human health concerns are met, worker safety issues are appropriately assessed and handled, and liability issues are addressed. Critical to this realization of robust manufacturing is the development of the necessary instrumentation, metrology, and accurate standards. Integration of the instruments, their interoperability, and appropriate information management are also critical elements that must be considered for viable nanomanufacturing. Advanced instrumentation, metrology and standards will allow the physical dimensions, properties, functionality, and purity of the materials, processes, tools, systems, products, and emissions that will constitute nanomanufacturing to be accurately measured and characterized. This will in turn enable production to be scaleable, controllable, predictable, and repeatable to meet market needs. If a product cannot be measured it cannot be manufactured.

SESSION IIA: Field and Fluidic Assisted Assembly — Wednesday 27 May, 10:20am

Heterogeneous Functional Integration and Manufacturing at the Nanoscale

Placid M. Ferreira
NSF Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems

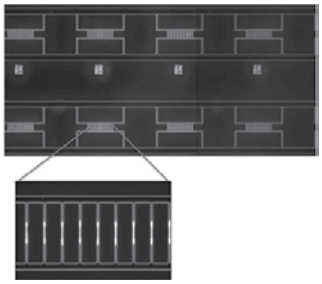
Nanoscience—the 'science of the small'—produces stunning revelations that, almost daily, redefine the realm of the possible. Yet, the manufacturing processes and systems to transform this new knowledge into technologies and products that benefit us in our daily life is a crucial missing element. At Illinois, the Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS) Center, a NSF-sponsored Nanoscale Science and Engineering Center (NSEC), is exploring and developing new methodologies and tools that exploit chemical, mechanical, and electronic phenomena and processes for manufacturing at the nanoscale.This talk is a broad overview of the research within the Center. Specifically, it will describe heterogeneous integration in product design as a motivation for a repertoire of micro and nanoscale manufacturing processes. Processes such as electrohydrodynamic printing, electrochemical patterning, micro transfer printing, etc. will be described. The possibilities for patterning and integrating mechanical, optical and mechanical functions into materials will be discussed.

SESSION IIA: Field and Fluidic Assisted Assembly — Wednesday 27 May, 10:45am

Dielectrophoretic Directed Assembly of Nanowires Over Large Areas

Erik M. Freer, Oleg Grachev, David P. Stumbo
Nanosys, Inc.

In recent years, transistors that outperform traditional thin-film devices, and sensors with the ability to detect single molecules have been made using nanowires. Directed assembly offers the ability to place nanowires on unique substrate materials (plastics, composites) and at length scales not accessible with traditional semiconductor fabrication. For example, the ability to deposit millions of single-crystal silicon transistors on a flexible substrate at reasonable cost promises to be an enabling technology for large area, flexible OLED displays. In addition, directed assembly offers the potential to transform other nanowire-based devices into a multitude of products. However, a robust methodology to assemble nanowires suitable for manufacturing has not been demonstrated. In this work, we report a method to assemble high densities of single or multiple nanowires per site with submicron precision over large areas (Figures 1 and 2). This is accomplished using dielectrophoresis in a well-controlled flow field. In our method, nanowires are captured at electrodes in a self-limiting process in which a large process window exists for single nanowire deposition. After loading all electrodes with single nanowires, removal of excess nanowires yields a substrate with >95% single nanowire deposition over thousands of sites.



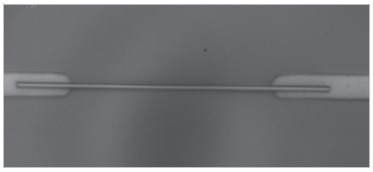


Figure 1: Example of low-defectivity deposition typical on 4-inch quartz wafers. Larger optical image is 490mm x 220mm.

Figure 2: Deep ultraviolet (DUV) images of nanowire deposition. Nanowires center on electrodes with submicron precision. Image is 21.6mm x 9.3mm.

SESSION IIA: Field and Fluidic Assisted Assembly — Wednesday 27 May, 11:10am

Precise Large-Scale Control of Electrophoretic Directed Assembly of Nanoparticles

Cihan Yilmaz[1], Sivasubramanian Somu[1], Ahmed Busnaina[1] and Sanjeev Mukerjee[2]
[1]NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN), Northeastern University
[2]Department of Chemistry and Chemical Biology, Northeastern University

The nanoscale directed assembly of nanoparticles has many potential applications in the fields such as biotechnology, energy storage, nanoelectronics and nanomaterials. The directed assembly of nanoparticles in aqueous solution using an external electric field has attracted great interest because of its speed and control which makes the assembly process suitable for manufacturing. However, precise assembly, positioning of particles and control of the process is challenging. In order to obtain an effective and could be controlled by controlling the applied voltage and the time of assembly. However, the effect of electrochemical parameters such as pH and ionic conductivity of the solution on assembly have not been investigated in great detail. In this study, we have systematically studied the effect of the applied voltage, time of assembly, pH and conductance of the solution on the directed assembly of nanoparticles and have demonstrated how sensitive the process is to some of these parameters. The results show that the assembly could be precisely controlled by the governing parameters to enable precise and repeatable assembly of 50 nm PSL (Polystyrene Latex) nanoparticles over large scale and at high rates. We have observed that at a constant applied voltage and time, it is possible to increase the assembly rate up to some degree by increasing ionic conductivity of the solution. However, great enhancement in the rate of assembly is observed at very small increments of the solution's pH. For example, at a constant potential of 4 V/cm, although a small number of nanoparticles starts to assemble in the trenches at pH 10, full assembly of nanoparticles in the trenches is only achieved at pH 10.7. Higher pH results in particle deposition everywhere and the loss of control of the directed assembly process. The results indicate that electrochemical parameters in the solution should be precisely controlled with the other main parameters for reliable assembly of nanoparticles. As an instance to this, the sensitivity of assembly process to pH of the solution down to 0.1 resolutions is shown. The experimental observations are further discussed with zeta potential measurement and mobility calculations.

SESSION IIA: Field and Fluidic Assisted Assembly — Wednesday 27 May, 11:35am

Nanoscale Deposition and Etching of Silicon Quantum Dots Using Field-Assisted AFM-Based CVD

Mohammad Reza Dodge, Massood Tabib-Azar
ECE Department, University of Utah

Electric-field assisted decomposition of gas molecules near a conducting AFM tip can be used to directly deposit, etch and pattern nanometer-scale silicon structures. We used SiCl4 to deposit silicon on a poorly conducting silicon substrate and SF6 to etch silicon at room temperature and one atmosphere. Deposition and etching can be done under square wave voltage, in the frequency range of 10-50MHz. The deposition and etching rates varies with gas flow rate, and voltage and the type of tip. Deposition and etching from gas phase is relatively a clean process since the byproducts are in gas phase. It is also potentially very fast since gas molecules at 1 atmosphere have around 60 nm mean-free-path and are readily available on demand. Owing to relatively large curvature of our current AFM tip apex ~ 40 nm, the smallest feature size we could pattern was around 100 nm. We discuss kinetics of formation of these dots and propose a reaction mechanism that is being evaluated to improve the spatial resolution of this unique technique. We also discuss the role of thermal decomposition that can deteriorate the spatial resolution of tip-based CVD processing. To avoid thermal contribution and spreading, the tip voltage should be pulsed. We are also in the process of adding microwave excitation to the tip to reduce I^2R heating.

The AFM-based CVD technique is being extended to include electrodes directly on the probe to eliminate any need for conducting substrate. With excitation completely contained in the tip, the AFM-based nanofabrication will become versatile and can be used as a 3-D mask-less nanofabrication on any material from polymers to diamond to clays. To demonstrate the feasibility of this approach, we have developed micro-plasma sources that are being scaled down to nano-scale for direct write and etching.

Acknowledgement: This work is supported by DARPA's Tip-Based Nanomanufacturing program under Dr. Thomas Kenny. We acknowledge useful discussions with Profs. Mortom Litt, Carlos Mastrangelo, Mohan Sankaran and Steve Garverick. Mr. Andrew Barnes, Dr. O. Lucian Vatamano, Mr. M. Abdlatif, Mr. Mousa Souare, and Mr. Joseph Zarycki have contributed at different stages of this work.

SESSION IB: Directed Self Assembly — Wednesday 27 May, 1:20pm

Templated Self-Assembly of Block Copolymers for Nanoscale Device Fabrication

C.A. Ross[1], Y.S. Jung[1], V.P. Chuang[1], Joel W.K. Yang[2] and K.K. Berggren[2]
Massachusetts Institute of Technology, [1]Dept. Materials Science and Engineering; [2]Dept. Electrical Engineering and Computer Science

Thin films of microphase separated block copolymers, which can form patterns consisting of dense arrays of lines, dots, rings and other geometries, are attractive materials for self-assembled nanoscale lithography. The long range order of the block copolymer microdomains can be controlled by the use of chemical or topographical patterns. In this work, we discuss how Si-containing block copolymers, polystyrene-b-polyferrocenyldimethylsilane (PS-PFS), polystyrene-b-polydimethylsiloxane (PS-PDMS), and PS-b-PFS-b-poly-2-vinylpyridine (PS-PFS-P2VP) can be self-assembled as thin films and templated on substrates patterned with posts or steps, and how the resulting patterns can be used to form nanoscale structures.

Si-containing block copolymers are advantageous for nanolithography because of their high etch selectivity and etch resistance and the high chi parameter, which allows small period features to be achieved. Long-range order in PS-PDMS and PS-PFS was achieved using topographical features on the substrate. The locations of 40 nm period spherical PDMS microdomains were controlled by a sparse array of posts, allowing templating of e.g. 20 microdomains per post to form large area dot arrays with excellent order. Linear patterns were formed from 20 - 32 nm period cylindrical morphology PS-PDMS templated using topographical features, to form arrays of straight parallel cylinders with controllable period and orientation, or sharply curved, concentric toroidal structures. The overall morphology and period of the block copolymer microdomain arrays can be varied by solvent annealing in mixed solvent vapors. Triblock copolymers such as PS-PFS-P2VP can create additional morphologies such as ring-shaped structures of period 50 nm. These results will be discussed in the context of nanomanufacturing, including examples of pattern transfer to form metal, oxide and polymer functional nanostructures. In particular, we will discuss the fabrication of patterned magnetic media and nanowire arrays for sensors and interconnects.

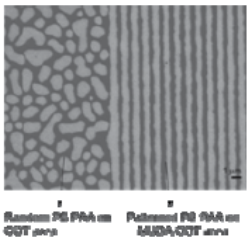
Bita et al, *Science* 321 939 (2008); Jung et al, *Nano Letts.* 7 2046 (2007); 8 2975 (2008)

Session Abstracts

SESSION IB: Directed Self Assembly — Wednesday 27 May, 1:45pm

Directed Assembly of Polymer Structures for High-rate Nanomanufacturing

Ming Wei, Liang Fang, Arun Kumar, Jia Shen, Jun Lee, Sivasubramanian Somu, Xugang Xiong, Carol Barry, Ahmed Busnaina and Joey Mead
NSF Nanoscale Science and Engineering Center for High-Rate Nanomanufacturing



CHN has developed a suite of templates and assembly processes for directing the assembly of a variety of nanoelements. These assembly processes utilize both electric fields and/or chemical functionalization. Chemically functionalized templates have been used to direct the assembly of polymer blends into uniform and nonuniform patterns. The selective assembly process can be finished in 30 seconds directly from a solution of the two polymers. The approach can be used to generate a variety of complex geometries including 90° bends, T-junctions, square and circle arrays, which have potential applications in fabrication of integrated circuits in nanoelectronics. Electrophoretic assembly processes have been used to assemble conducting polymers followed by transfer to a secondary substrate to produce patterned polymer structures. The transfer of both conducting polymers and carbon nanotubes to a polymer substrate in the melt state using both compression molding and the thermoforming process will be discussed. Patterns have been successfully transferred in times under a minute. The entire process of patterning and transfer takes less than five minutes, which is commercially relevant and can be utilized for real time processing.

SESSION IB: Directed Self Assembly — Wednesday 27 May, 2:10pm

Patterned Media: Processing Technology

Neil Robertson
Hitachi Global Storage Technologies

In the field of magnetic recording, patterned media continues to gather momentum as a follow-on technology to continuous perpendicular recording. Patterned media is one of the more challenging examples of nano-technology given the size scale, precision, and throughput requirements. We will examine the requirements for this technology in both the short and long term. The implications of these requirements on process technology and tools for patterning will be discussed in light of some of the unique requirements for disks. The results point to major changes in making disks. Key new technologies will need to be introduced with elements from mask technology to patterning to metrology all in the nanometer scale.

SESSION IB: Directed Self Assembly — Wednesday 27 May, 2:35pm

Macroscopic Arrays of Block Copolymers with Areal Densities of 10 Terabit/inch^2 and Beyond

Soojin Park[1], Dong Hyun Lee[1], Bokyung Kim[1], Sung Woo Hong[1], Ji Xu[1], Unyong Jeong[2], Ting Xu[3] and Thomas P. Russell[1]
[1]University of Massachusetts Amherst
[2]Yonsei University
[3]University of California, Berkeley

By combining confinement effects with the highly directional field inherent in solvent evaporation and the mobility imparted to the BCP by the solvent, perfectly registered arrays of hexagonally packed block copolymer microdomains were produced on surfaces at least 3x3 cm^2 in area with areal densities in excess of 10 terabit/inch2. Registry of the arrays and the perfection of the ordering over macroscopic distances were demonstrated by grazing incidence small angle x-ray scattering and scanning force microscopy. This approach circumvents registry constraints and excessive writing times inherent in e-beam lithographic processes over macroscopic length scales and presents a simple route to addressable patterned media.

SESSION IIB: Nano ES&H, Risk Assessment — Wednesday 27 May, 120pm

Challenges for Environmental Health and Safety of Nanomaterials

Jacqueline A. Isaacs
Associate Director, Center for High-rate Nanomanufacturing Professor, Mechanical & Industrial Engineering, Northeastern University

Investment in nanotech research and products continues to dwarf the funding dedicated to the environmental health and safety (EHS) implications of nanotechnology, though recently federal funding has begun to increase. With more than 800 nano-products listed on the market according to the consumer product inventory created by the Wilson Center's Project for Emerging Nanotechnologies, there are concerns regarding potential unintended consequences that might be caused by nanoparticles in food, air, water and soil. Although research findings over the past several years are not definitive, there are indications that a range of engineered nanomaterials are likely to present potential risks to human health and the environment. In response to appeals for more guidance on understanding the EHS implications of nanomaterials, the U.S. Environmental Protection Agency (EPA), the National Institute for Occupational Safety and Health (NIOSH), the National Science and Technology Council (NSTC) of the U.S. National Nanotechnology Initiative as well as state, local and international governments have begun to develop research strategy documents for nanomaterials and their safe handling in light of uncertain risks.

At the NSF-funded Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN), the objectives of our interdisciplinary work in responsible nanomanufacturing remain to probe and assess the issues that will have direct implications for the nanomanufacturing technologies that are under development at CHN. Results contribute to the global research strategy and will help to guide the development of a sustainable production system for nanomanufactured products. Six complementary research areas are under investigation with goals to: 1) perform fundamental research on methods to measure and control nanoparticles exposures; 2) develop robust, low cost, high-throughput screening methods for nanoparticle exposure; 3) determine the economic feasibility of manufacturing in light of EHS uncertainty and risk for scale-up of technologies; 4) investigate life cycle issues related to manufacture through end-of-life products; 5) create case studies on regulatory scenarios that affect nanomanufacturing for appropriate and effective state environmental, health, and safety approaches; 6) evaluate applications of nanotechnology on their likelihood to promote or compromise environmental and/or ethical values.

An overview of CHN research activities will be presented as an introduction to some of the subsequent talks, but more detail will be provided on the development and implementation of modeling tools to assess the economic and environmental tradeoffs in product life cycles. Results from application of process-base cost modeling techniques and life cycle assessment for a carbon nanotube electromechanical switch will be described.

SESSION IIB: Nano ES&H, Risk Assessment — Wednesday 27 May, 1:45pm

Study of Nanoparticle Emission from Production of Multi Walled Carbon Nanotubes

Su-Jung (Candace) Tsai[1], Mario Hofmann[2], Marilyn Hallock[3], Earl Ada[4], Jing Kong[2] and Michael Ellenbecker[1]
[1]NSF Center for High-rate Nanomanufacturing (CHN), University of Massachusetts Lowell
[2]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology
[3]Department of Environment, Health and Safety, Massachusetts Institute of Technology
[4]Campus Materials Characterization Laboratory, University of Massachusetts Lowell

In January 2009 the state of California asked all manufacturers of CNTs to submit information on CNT operations and release from their facilities, including fate and transport in the environment. Emissions from CNT furnaces have not been extensively characterized. The laboratory production of multi-walled carbon nanotubes by chemical vapor deposition was studied to evaluate and characterize the nanoparticle emission. Particle number concentrations for diameters from 5 nm to 20 μm were measured using the Fast Mobility Particle Sizer and the Aerodynamic Particle Sizer; the particles released from the furnace were found to be less than 500 nm in diameter. The morphology and elemental composition of the released nanoparticles were characterized by scanning and transmission electron microscopy and energy dispersive spectroscopy. Different operating conditions were studied to evaluate their effects on the number and morphology of aerosol particles, and the number of particles released. High concentration of nanoparticle aerosols were measured in the exhaust and CNT filaments and carbon particles in clusters were found. The increase in concentration compared to the background exceeded 106 particle/cm3 and mostly the particle diameters were generally less than 100 nm. Different operating conditions changed the morphology of aerosol particles formed during production of multi-walled carbon nanotubes. The operating condition of using a lower injector temperature during production results in the mutual benefits of enhanced production yield and reduced filament formation during production.

This study demonstrated that large quantities of spherical carbon nanoparticles can be found in the exhaust from carbon nanotube furnaces. That results in the potential for significant exposure to production personnel and the general public. It is essential that steps be taken to control these exposures.

SESSION IIB: Nano ES&H, Risk Assessment **Wednesday 27 May, 2:10pm**

Controlling Risks and Controlling Costs: Retooling for Codes of Conduct

Nina Horne
University of California, Berkeley

Nanoscale science has emerged as a key frontier for technological development, enabling a broad range of applications and promising fundamental improvements to some of the globe's biggest challenges. Yet this industry experiences a wide set of risks, ranging from potential inherent toxicology and environmental fate risks, regulatory shifts, and uncertain business environment factors, such as early insurance failure. By harnessing new risk reduction strategies in the form of codes of conduct and emerging occupational health practices, businesses can more effectively protect investments, with significant spillover effects.Leading companies have implemented significant risk reducing codes, and are paving the way for other companies to reduce risk while ensuring effective cost control. Effective codes share a number of traits: R&D with extensive characterization and toxicology assessment, continual integration of new research, active monitoring of workers, and broad and immediate communication of risk information. Early research indicates sustainable implementation costs.

I. Can Codes of Conduct Reduce Risks Efficiently? The recognition that nanomaterials present potential new risks is driving an increased scrutiny to current regulatory frameworks, and assessment as to whether these current frameworks adequately manage risk for industry, consumers, workers, and the environment. By adopting a code of conduct, a business can essentially create its own regulatory environment, ultimately providing a more predictable and therefore less costly business environment;[1] well-implemented codes can provide greater regulatory certainty during the lag between the availability of commercialized products and development of a scientific consensus regarding product safety. The implementation of industry codes of conduct can vary significantly, from general ethics codes to precise and specific manufacturing practices.[2] Effective implementation, therefore, is critical to improving outcomes.

II. Methodology. This assessment flows from a comprehensive analysis of the existing regulatory frameworks in the U.S. and the EU, including 29 U.S and 57 EU consumer, worker, environmental, intellectual property, and standards and measurements laws cited as potentially applicable to regulating nanotechnology, as well as all U.S. and EU nanomanufacturing codes of conduct, risk management tools. Additional sources include the body of literature on industry codes of conduct and nanotechnology legal analysis.

III. Field of impact and Results. Nanomanufacturers motivated to reduce firm risks in an evolving regulatory environment and to capture "green" market segments can implement these findings within strategic and operational planning processes. Additionally, regulators can respond to these finding by shaping policy implementation within existing regulatory frameworks to better capitalize on public-private partnering opportunities. The systematic comparison of corollary U.S. and EU regulations and codes produces a set of common features and significant variations. The resulting work creates a clear picture of the current challenges and the need for an integrated public-private regulatory framework in order to manage risk efficiently in the face of insufficient scientific data to properly develop new regulation. While firms are implementing occupational health practices common in chemical manufacturing, robust and effective nano-specific codes require full planning, integration, and management to provide risk-reducing benefits and competitive advantages. Resources for implementing codes and better occupational health practices are emerging, and are highly responsive to the most current understanding of true nanotoxicological risks.

[1] Bassett, Carolyn, "Taking Care of Business: Corporate Codes of Conduct as Global Regulation" International Studies Association, Le Centre Sheraton Hotel, Montreal, Quebec, Canada, Mar 17, 2004.
[2] Treviño, L., Weaver, G., Gibson, D. and Toffler, B. (1999). 'Managing ethics and legal compliance," *California Management Review*, 41, 131- 51.

SESSION IIB: Nano ES&H, Risk Assessment **Wednesday 27 May, 2:35pm**

Cancer Nanotechnology: Resources for Clinical Translation

Anil K. Patri
Nanotechnology Characterization Laboratory

Advances in nanotechnology research are bringing about radical changes in early detection, diagnosis and treatment of cancer. Biocompatible nanomaterial can be used to selectively localize and deliver therapies to cancer by Enhanced Permeability and Retention (EPR) phenomenon. Many potential nanomedicines are beyond the discovery phase of research for targeted drug delivery which minimizes dosage, reduces systemic toxicity and side effects of chemotherapy while increasing the therapeutic efficacy. There is an urgent need to quickly transition these novel nanomedicines to clinic. This presentation will highlight the resources available for researchers in academia, industry and government agencies for clinical translation of nanomedicines through the National Cancer Institute's (NCI) Nanotechnology Characterization Laboratory (NCL). The NCL supports the Alliance for Nanotechnology in Cancer and is a formal collaboration between the NCI, the National Institute of Standards in Technology (NIST), and the U.S. Food and Drug Administration (FDA) with a mission to help accelerate the translation of nanotechnology

concepts to clinic. NCL's pre-clinical testing includes physio-chemical characterization, in vitro and in vivo pharmacology, safety and efficacy assessment with standardized tests to facilitate speedy clinical translation of therapeutic, imaging and diagnostic agents.

ACKNOWLEDGMENT: Funded by NCI Contracts N01-CO-12400 and HHSN261200800001E.

SESSION IC: Nanomanufacturing Applications: Advanced Materials — Wednesday 27 May, 3:20pm

Scaling Up Production of Long Carbon Nanotubes and Multi-function Products

David Lashmore
Nanocomp Technologies, Inc.

For years, carbon nanotubes (CNTs) have been hailed as the next great advance in materials technology based on their unique properties of very high tensile strength, highly efficient electrical conductivity, effective thermal transport, and extremely light weight. No commercial or academic developer or manufacturer has had the capacity to produce macro-scale CNT products that demonstrate these attractive nano-scale properties or a scalable manufacturing process—until now. Nanocomp Technologies is focused on fabricating its uniquely long CNTs into basic building-block products—spun conductive yarns and textile-like sheets. Nanocomp further processes these building blocks to enhance their properties, and then has the ability to manufacture them into value-added component products such as conductive cables, thermal straps, shields, and composites with numerous potential applications in security, aerospace, and defense. Nanocomp has, according to experts from industry, academia, and defense who have evaluated the company's functional CNT component products, the highest performing CNT materials with the best path to scale. The company is differentiated from all others players in that that it is currently the only one that:

- has a commercial scale, continuous nanotube growth process, that can selectively grow extraordinarily long carbon nanotubes of any type, including single, dual, or multi-walls,
- has integrated nanotube growth with the production of pure nanotube sheets or yarns,utilizing automated manufacturing equipment,
- is focused on fabricating industrially useful nanotube component products, such as "connectorized" conductive cables or shields,
- has a credible scale-up plan currently being executed to achieve both volume manufacturing and competitive product costs.

In 2008, *The Wall Street Journal* recognized Nanocomp's accomplishments by naming it a recipient of a prestigious Technology Innovation Award for the company's "Process to create large sheets of fabric and lengths of yarn using carbon nanotubes. The technology can be used to make lightweight yarns for wiring and cables." Only 16 companies received such recognition out of 700 entries from around the world. At the Nanomanufacturing Summit, David Lashmore, co-founder, vice-president and CTO of Nanocomp Technologies, will describe the company's vision for scale and progress in scaling up manufacturing to meet the needs of customers who require products with multi-functionality (e.g., electrical conductivity and strength). He will describe cross-service interest in Nanocomp's technology and products and describe how Nanocomp is working to meet demand in a cost-effective manner.

SESSION IC: Nanomanufacturing Applications: Advanced Materials — Wednesday 27 May, 3:45pm

Emerging Research Materials and Nanofabrication Methods: Challenges and Opportunities

Daniel Herr
Director, Nanomanufacturing Sciences Research, Semiconductor Research Corporation; Co-Chair, Emerging Research Materials International Technology Working Group, International Technology Roadmap for Semiconductors

Today's perception that manufacturing costs and percent device variability will increase exponentially with scaling and functional diversification is pervasive. Projected requirements, such as line edge roughness, long range dimensional and positional control, resolution, throughput, dopant variability, pattern matching, and functional density, increasingly challenge our ability to achieve reliable system performance. Extensible fabrication options are needed that enable: Sustainable, centered, low-variability fabrication technologies; new cost curves for nanoelectronics fabrication; and enhanced system value through integrated functional diversification. An optimal manufacturing strategy will reflect the convergence between application and design specific requirements and a synergistic set of material and assembly options. This talk will consider emerging research material and nano-fabrication opportunities that exhibit potential for satisfying projected International Technology Roadmap for Semiconductor (ITRS) requirements and enable extensible nanofabrication. It will include an update on the need for and status of ITRS Emerging Research Materials, such as smart resists, self assembling systems, and environmentally benign, high performance materials and processes. This talk also will explore emerging opportunities in functional diversification, which exhibits potential for enabling enhanced functional density on a CMOS platform, and provide a brief overview of Semiconductor Research Corporation.

Session Abstracts

SESSION IC: Nanomanufacturing Applications: Advanced Materials — Wednesday 27 May, 4:10pm

Nanotechnology Research and Development in the Forest Products Industry—the Green Connection

Theodore H. Wegner[1], World L.-S. Nieh[1], John G. Cowie[2], J. Philip E. Jones[3], Mike Postek[4] and Andras Vladar[4]
[1]USDA Forest Service, Forest Products Laboratory
[2] AF&PA Agenda 2020
[3] Imerys
[4] National Institute of Standards and Technology

The U.S. forest products industry is working with the USDA Forest Service and the National Institute of Standards and Technology (NIST) while partnering with universities to research, develop, and deploy green nanotechnologies in a sustainable way. The forest products industry is a $260 billion per year industry that accounts for 6.2% of U.S. manufacturing GDP. The American Forest & Paper Association Agenda 2020 Technology Alliance (AF&PA Agenda 2020) has adopted nanotechnology as one of its technology platforms to help to revitalize the industry. Partnering with the USDA Forest Service, NIST, and other federal agencies and Departments that are part of the National Nanotechnology Initiative (NNI) and members of the Nanoscale Science, Engineering and Technology (NSET) subcommittee, the Chief Technology Officers (CTO) Committee of AF&PA Agenda 2020 has identified three pre-competitive nanotechnology research areas that will be the foundation of the next generation of high performance forest-based products. The three areas are: 1) using nanotechnology to improve the strength to weight ratio of paper and wood-based structural materials, 2) developing new value-added photonic and electronic features for paper and forest products and 3) creating new revenue streams based on the production of innovative forest-derived nanomaterials. Research and development of specific nanotechnology and nanotechnology-enabled forest-based products in the preceding three pre-competitive areas will be conducted collaboratively. To formalize the public-private partnership, AF&PA Agenda 2020 signed a Consultative Board for Advancing Nanotechnology (CBAN) agreement with the NSET subcommittee through the National Nanotechnology Coordination Office (NNCO). Forest-fiber based nano-dimensional materials originate from cellulose photosynthesized by nature using carbon dioxide, water, and solar energy. Products produced from these cellulosic materials are sustainable, have the ability to store carbon throughout their service life, and can play an important roll in alleviating the negative impacts of climate change.

SESSION IC: Nanomanufacturing Applications: Advanced Materials — Wednesday 27 May, 4:35pm

Self-Collimation in Quasi Zero-Average-Refractive-Index Photonic Crystal Metamaterial

S. Cabrini[1], V. Molcella[1], A.S.P. Chan[1], P. Dardano[2], L. Moretti[2], I. Rendina[2], D. Olynick[1], B. Harteneck[1] and S. Dhuey[1]
[1] Molecular Foundry, Lawrence Berkeley National Laboratory
[2] CNR-IMM, Unita di Napoli

The Molecular Foundry is one of the five DOE Nanoscale Science Research Centers (NSRCs), premier national user facilities for interdisciplinary research at the nanoscale. Together the NSRCs comprise a suite of complementary facilities that provide researchers with state-of-the-art capabilities to fabricate, process, characterize and model nanoscale materials, and constitute the largest infrastructure investment of the National Nanotechnology Initiative. In this framework we will present a user project that will show the potentiality of this DOE initative. The control of light-matter interactions in complex dielectrics offers the ultimate potential for the creation and manipulation of light states. Unlike periodically arranged dielectrics (photonic crystals), periodic and aperiodic dielectric arrays with zero average refractive index (ZARI) show unique light localization and transport properties, which are intrinsically robust to fabrication imperfections, which arise from unavoidable imperfections at small (nanometer) scale, providing a global large scale high-quality of the manufactured devices. This represents an essentially great advantage respect to photonic structure based on the management of defect states inside a bandgap that are intrinsically sensitive to small-scale defects. Negative refracting dielectric photonic crystals (PhCs) represents a viable way to realize Negative Index Materials (NIMs), and are ideal components for ZARI structures for controlling long-range light propagation due to their low absorption loss. We give the first demonstration of a carefully designed and fabricated large-area metamaterials incorporating both negative and positive index media in a synergistic fashion, proving that can be extremely useful for the control of light propagation and light emission. In particular we show that a quasi-zero-average-index metamaterial, leads to strong supercollimation of an near-infrared beam over a large distance of 4 mm. This distance represents more than two thousand times the input wavelength λ=1.55 μm while the beam spot size is fully preserved throughout the entire sample. The negatively refracting PhC layer and the air layer in each pair can be conceptually regarded as each other's complementary media, which are spatial regions that optically cancel out each other completely so that to the incident light it is as if they are removed in space.

Portions of this work were supported by the Office of Science, Office of Basic Energy Sciences of the DOE under Contract No. DE-AC0205CH11231.

SESSION IIC: Green Manufacturing, Nano ES&H, Risk **Wednesday 27 May, 3:20pm**

Greener Nanomanufacturing: Opportunities to Optimize Performance, Efficiency and Safety in the Production of Nanoscale Materials

James Hutchinson
University of Oregon

As nanotechnology emerges from its "discovery" phase, a wide range of promising applications have been uncovered that could provide considerable benefit to society and the environment. These applications have been developed with small amounts of painstakingly prepared nanomaterials. To advance these applications, we must develop new methods of production that address the limitations of discovery scale approaches. These new methods need to scale to higher throughput, provide well-defined material in a reproducible fashion, reduce waste and enhance safety. In this presentation, I will discuss some of the challenges faced in greening the nanomanufacturing process, describe how the principles of green chemistry can guide the development of greener processes, offer examples of initial successes in greener syntheses, purification and continuous flow production and highlight some areas that provide on-going challenges.

SESSION IIC: Green Manufacturing, Nano ES&H, Risk **Wednesday 27 May, 3:45pm**

Study of Airborne Nanoparticle Exposure Associated with the Hood Design and the Development of a Standardized Testing Protocol

Su-Jung (Candace) Tsai and Michael Ellenbecker
NSF Center for High-rate Nanomanufacturing (CHN), Toxics Use Reduction Institute, University of Massachusetts

Tsai et al.[1] found that the handling of dry nano-powders inside laboratory fume hoods can cause significant airborne nanoparticle release. Hood design affects the magnitude of release. Four types of hoods, i.e. conventional, constant velocity, by pass, and air-curtain hoods were evaluated. With traditionally-designed fume hoods, airflow into the hood causes turbulence to be formed in the worker wake region, which interacts with the hood vortex and can cause nanoparticles to be carried out with the circulating airflow. This turbulence pattern has been seen for conventional, constant velocity and by pass hoods.

Airborne particle concentrations were measured for 4 hoods during the manual handling of nanoalumina particles, using the method developed by Dr. Tsai. In order to develop a standard test protocol for evaluating hood performance, it would be desirable to eliminate the manual handling process. The development of an automated testing protocol to compare the manual handling protocol was studied by using a dust generator to release airborne nanoalumina particles. The TSI Fast Mobility and Aerodynamic Particle Sizers were used to measure airborne particle concentrations for diameters from 5-20,000 nm. Air samples were also collected and characterized by TEM. The highest breathing zone concentration was detected while using the conventional hood; the increased concentration above background was as high as 10,000 particles/cm^3 using the dust generator. Smoke tests showed more intense turbulent airflow in the conventional hood than the constant velocity hood, and that the downward airflow from the double-layered sash to the suction slot located on the floor of the air-curtain hood caused no turbulence. The increase in breathing zone concentration for the air-curtain hood was barely detectable using the dust generator, with stable and very low exposure during manual handling. The results when using the constant velocity hood and by-pass hood varied by operating conditions; typically, the release was found to be very low. The performance of the air-curtain hood was consistent under all operating conditions. The hood performance when using the dust generator correlated well with the performance during manual handling for most hoods.

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SESSION IIC: Green Manufacturing, Nano ES&H, Risk **Wednesday 27 May, 4:10pm**

Modeling Approaches for Nanomanufacturing Risk Assessment

Zeynep D. Ok, Jacqueline A. Isaacs and James C. Benneyan
Center for High-rate Nanomanufacturing, Department of Mechanical & Industrial Engineering,
Northeastern University

Although nanotechnology holds enormous promise in energy, technology, medicine, electronics, consumer products, and other applications, significant uncertainty exists regarding associated occupational, consumer, and environmental health and safety (EHS) risks. Of the few toxicity studies to date, several suggest engineered nanomaterials may pose potential risks to human health, due to their small size and large surface area, allowing them to penetrate dermal barriers, cross cell membranes, breach

gas exchange regions in lungs, travel throughout the body, and interact at the molecular level[1]. For example, critical reviews of single wall carbon nanotubes (SWNTs) toxicity found damage to mice lung tissue[2], although further research is necessary to understand risks to humans. In response, several authors and regulatory bodies have advocated more research on nanotechnology EHS[3], including the U.S Environmental Protection Agency and National Institute for Occupational Safety and Health[4,5].

Until proposed studies develop a sufficient risk understanding to inform safe handling of engineered nanomaterials, nanomaterial researchers, policy makers, and businesses have little guidance for safe operating practices. Several risk assessment methods, however, exist in a variety of other industries that also should be useful in nanomanufacturing, including Monte Carlo, multi-criteria, stochastic programming, and desirability function models. These methods differ in the manner by which they handle uncertainty, multiple criteria, and risk-benefits trade-offs. Each approach is illustrated, using occupational health risks associated with carbon nanotube manufacturing processes as an example. As more becomes known about nanomaterial exposure risks, these models can be updated to reflect the current knowledge base, suggesting optimal decisions likely will change over time.

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SESSION IIC: Green Manufacturing, Nano ES&H, Risk **Wednesday 27 May, 4:35pm**

Screening for Potential Toxicity of Engineered Nanomaterials: Its Utility in Developing Responsible Nanomanufacturing

Dhimiter Bello[1], Shu-Feng Hsieh[2], Anoop K. Pal[2], Daniel Schmidt[3] and Eugene J. Rogers[2]
[1]Department of Work Environment
[2]Department of Clinical Laboratory and Nutritional Sciences, School of Health and Environment
[3]Department of Plastics Engineering, Center for High Rate Nanomanufacturing, University of Massachusetts Lowell

Rapid developments and commercialization of nanotechnologies has resulted in a rapid increase in the production rates and variety of novel engineered nanomaterials (ENMs). The potential adverse effects of these materials on human health and the environment are largely unknown. Great concerns have been raised for some classes of ENMs, most notably carbon nanotubes, which have fueled a recent flurry of regulatory initiatives as well perceived high risk among several stakeholders and the public. It is important that the recognition of potential toxicity of certain ENMs should precede commercialization of nanotechnologies. Simple yet reliable and predictive approaches to screen ENMs for potential toxicity are urgently needed. Biological oxidative damage (BOD) has been recognized as a key mechanism of toxicity of particulate matter and has been proposed as a global metric for rapid toxicity screening. A 'Ferric Reducing Ability of Serum (FRAS)' assay was recently optimized by our group as a screening tool to quantitate the degree of biological oxidative damage imparted by ENMs in human blood serum. This approach was used to screen several classes of ENMs (several carbon nanotubes, fullerenes, carbon blacks, titanium dioxide, alumina, and nanosilver) for their ability to cause BOD. Further relationships between FRAS-determined BOD and several measured physico-chemical parameters of ENMs were explored in an effort to explain the observed BOD results, to identify candidate exposure metrics for ENMs, as well as targets for material redesign. The free radical generation capacity of this same group of ENMs was also measured with the commonly used dichlorofluorescin (DCFH) assay. The concordance between the FRAS-measured BOD and toxicity was evaluated for this set of ENMs. We present these results here and discuss the potential utility of these findings for toxicity screening and the greening of nanomanufacturing processes. Biological oxidative damage potential of ENMs as measure by FRAS in human serum appears to be a valid approach for screening purposes.

Session Abstracts

SESSION IA: Emerging Processes and Tools — Thursday 28 May, 10:20am

Nanoprocessing and Device Fabrication

Costas P. Grigoropoulos, David J. Hwang, and Seunghwan Ko

Laser Thermal Laboratory, Department of Mechanical Engineering, University of California, Berkeley

This talk presents recent work at the Laser Thermal Laboratory. Pulsed lasers were coupled to near-field-scanning optical microscopes (NSOMs) for nanoprocessing, nanomachining, nanolithography and nanodeposition. Experiments have been conducted on the surface modification of metals, polymers and semiconductor materials, including the localized activation of electrical and ferromagnetic domains. Ablation nanolithography and patterning has been demonstrated. NSOM-based ablation is also applied to nanoscale chemical analysis. Interactions of pulsed laser radiation with nanostructures are investigated and shown to substantially improve contact resistance and device performance compared to furnace annealing. Probing of the electronic transport in semiconductor nanowires and nanoparticles has been done with scanning probe photoelectron emission spectroscopy. Nano-bio-electronic devices have been fabricated on silicon nanowire platform.

In-situ SEM monitoring of the samples under laser processing was achieved, fully integrated into the dual beam system composed of the focused ion beam (FIB) and the electron beam (SEM). To understand the microstructural evolution of a sample under laser processing we have carried out in-situ nanoscale laser materials processing inside a TEM where the evolving microstructure could be monitored in real time. New concepts are being explored for the high throughput, directed growth and assembly of nanostructures.

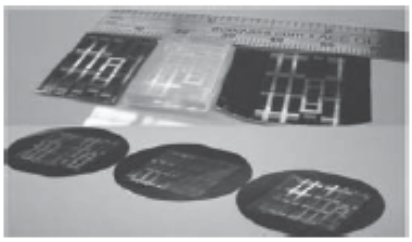
Maskless fabrication of passive and active functional devices on flexible substrates is conducted by utilizing nanoparticles in conjunction with laser processing and nanoimprinting. Low power, short-pulsed laser ablative material removal enabled finer electrical components to overcome the resolution limitation of inkjet deposition. Temporally modulated laser irradiation was utilized to locally evaporate the carrier solvent as well as sinter gold nano-particles, yielding low resistivity conductors. Selective multi-layered nanoparticle film processing was demonstrated. High-performance electronics, including OFETs (organic field effect transistors) and dye-sensitized solar cells have been demonstrated on flexible substrates.

SESSION IA: Emerging Processes and Tools — Thursday 28 May, 10:45am

Advances in Soft-Nanoimprint Lithography

Isaac W. Moran, Kenneth R. Carter

Polymer Science and Engineering Department, University of Massachusetts Amherst



The advent of soft-lithography techniques has generated a number of variant approaches to patterning substrates using elastomeric templates. In general, as an alternative to photo or e-beam lithography, the use of inexpensive nanostructured polydimethylsiloxane (PDMS) molds to impart surface patterns to substrates has been considered highly effective based on the ability of PDMS to achieve conformal contact over large areas due to its low modulus (~2-3 MPa) and low surface energy (20 mJ/m2). These attributes are exploited in many forms of soft lithography including nanotransfer (nTP)[1] and microcontact printing (μCP)[2]. However, such processes, in which material is transferred from the PDMS stamp to the substrate, tend to be restricted by material specific chemistries (i.e. thiols for nobel metals) and hampered by the need to continuously load material onto the stamp in order to produce pattern transfer. Furthermore, interaction between the stamp and transfer material can yield contaminated features, especially in regards to patterning copper.[3] Soft-nanoimprint lithography (S-NIL) provides access to PDMS generated surface patterning in a more generalized fashion. As a subset of nanoimprint lithography (NIL), S-NIL applies the concept of patterning a UV curable photopolymer based resist through filling of features on a mold's surface while exploiting the unique mechanical properties of PDMS to promote conformal contact between mold and substrate which is difficult to achieve with two rigid surfaces as typically done in traditional NIL.

S-NIL has seen extensive use in the patterning of surface features on thick resist films (>1 um) yet virtually no reports exist demonstrating equivalent patterning in submicron films to produce straightforward lift-off masks for conversion of imprinted features to active materials or transfer the underlying substrate. The factor limiting S-NIL in thin films of UV-curable resists is the propensity for PDMS to absorb organic compounds. Accordingly, thin films of resist permeate into the PDMS mold upon contact during imprinting; negating pattern formation. We have developed two approaches[4,5] to overcoming the this limitation ion S-NIL, the first being modification of the PDMS mold to construct a thin, resist impermeable fluorinated oxide (F-ox) barrier layer through surface oxidation and assembly of a fluorinated alkyl silane. These new PDMSF-ox molds effectively imprinted into thin films (70 nm – 630 nm) of UV curable resins consisting of either polyurethanes or acrylates, replicating high fidelity features over the surface of wafer substrates. The second development encompasses the tuning of molecular-weight in a thiol-ene based resist by

a simple pre-cure procedure prior to imprinting resulting in sufficient buildup of resin molecular weight to prevent its absorption into PDMS molds yet maintain a low enough viscosity to allow for rapid molding of nanoscale features during the subsequent imprint-and-cure stage of the process. Both methods allowed direct transfer of the imprinted features to either active materials such as gold, nickel, and aluminum as well as to the underlying substrate by traditional reactive ion etch and lift-off processes.

The later technique, involving the pre-cure step, obviated the need for mold modification and was used to fabricate organic field effect transistors, representing the seminal use of a soft imprint lithographic process to make such devices.

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SESSION IA: Emerging Processes and Tools — Thursday 28 May, 11:10am

Layered Nanotubes from Electrostatic Assembly

Jodie Lutkenhaus
Yale University

As the size of devices and systems becomes increasingly smaller, the need for high-performance, smallgeometry materials increases. Scaling a material down to the nanoscale imparts new, and often synergistic, properties that excel relative to the bulk. This enables the creation of nanotechnologies such as micro- or nanobatteries and nano-fuel cells. For truly micro- to nanoscale devices to be realized, fine spatial control of materials placement and functionality is required. Using directed electrostatic assembly and nanotemplating, we demonstrate the hierarchical design of multifunctional layered nanotubes containing both inorganic and organic components. Layer-by-layer (LbL) assembly is the aqueous-based alternate adsorption of oppositely charged species to a substrate.[1] LbL assembly is performed on an anodic aluminum oxide (AAO) template, where the layers coat the template's pore wall under carefully selected processing conditions.[2] Templates created in-house using a two-step anodization process[3] produce nanotubes having diameters ranging from 15 to 100 nm and lengths from 200 nanometers to 100 micrometers. The combination of these two techniques represents two levels of spatial control. The layer-by-layer assembly technique allows for tuning of layer thickness (Angstroms to nanometers) and spatial placement via sequential deposition, and nanotemplating allows for control of geometric complexity via nanotube diameter and length. Future work will investigate the electrochemical activity of the LbL-nanotubes relative to bulk LbL films. We hypothesize that the reaction-diffusion properties of the nanostructured tubes will surpass those of the bulk film. We envision this breakthrough to emulate structures required for the creation of nanotechnologies such as nanobatteries and nano-fuel cells. References

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SESSION IIA: Integrated Nanoelectronics — Thursday 28 May, 10:20am

The SRC-NIST Nanoelectronics Research Initiative: Partnership for Innovation

Jeffrey Welser, Daniel Herr and Ralph K. Cavin, III
Semiconductor Research Corporation

One of the formidable challenges of the 21st century is to sustain the exponential rate of improvement in performance-per-unit-cost that has been offered by Moore's law for integrated circuits. More than three decades of unparalleled progress in information technologies has been achieved principally by scaling the feature sizes of transistors relentlessly. Indeed, minimum feature sizes of leading-edge transistors are now far into the nanometer regime. There are, however, studies suggesting that the physical limits for scaling of electron devices may be reached in one to two decades. Even before then, the increased energy consumed by aggressively-scaled chips may force expensive cooling solutions and slow progress. In view of these foreseeable challenges, the semiconductor industry, the federal government, and several states have launched the Nanoelectronics Research Initiative (NRI). NRI is a university-based discovery research program whose goal is to seek new physical principles to continue the benefits that have been provided by Moore's law for semiconductor integrated circuits. In this talk, the origin, the goals, and the current implementation of the NRI program is described. The economic significance of the NRI quest is that those who discover new information processing technologies will be positioned to enjoy a competitive advantage in an important market sector.

SESSION IIA: Integrated Nanoelectronics — Thursday 28 May, 10:45am

Heterogeneous Integration of Single-Walled Carbon Nanotubes with CMOS Circuitry

Chia-Ling Chen[1], Vinay Agarwal[2], Chih-Feng Yang[1], Chenfu Guo[1], Sameer Sonkusale[2] and Mehmet R. Dokmeci[1]
[1]Department of Electrical and Computer Engineering, Northeastern University
[2]Department of Electrical and Computer Engineering, Tufts University

Despite the advances in nanowire and nanotube based sensors, system level approaches to nanotechnology is at its infancy. Carbon nanotubes, one of the prominent building blocks of nanotechnology, hold great promise as nanosensors due to their miniscule size, large surface area to volume ratio and extraordinary electrical and mechanical properties. Furthermore, due to their high sensitivity, their discrete implementation as sensors pose numerous challenges such as signal interference from the environment and/or noise along the signal paths demanding integration with on-chip CMOS circuitry. Depending on the application, integration with CMOS circuitry can provide high performance due to lower parasitic and reduced interconnect lines as well as the ability to provide signal conditioning and storage on the same chip[1].

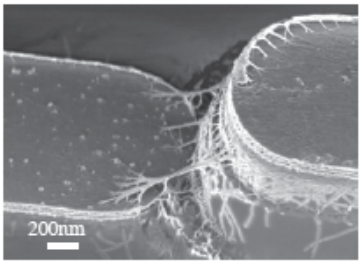

Fig.1 SWNTs integrated on CMOS circuitry

The CMOS chip comprising of the microelectrodes for the SWNT assembly and the interface circuitry was designed and fabricated using the AMI 0.5 μm CMOS process, provided by MOSIS. After receiving the fabricated chips, we first etched the oxide layer (Al2O3) on top of the Al metal electrodes and then coated them with a Zn layer using an electroless plating process[2]. Next, we deposit a 2-3 μl droplet of an aqueous solution containing the nanotubes on to the microelectrodes. An AC voltage of 5Vpp with a frequency of 10 MHz was utilized during the DEP assembly.

The SEM micrograph (Figure 1) shows the SWNTs assembled on to the microelectrodes. The I-V measurements from the assembled SWNTs displayed a resistance of ~22K ohms. The op-amp circuitry in the inverting configuration is utilized to demonstrate the integration of CNTs with CMOS electronics. A high gain op-amp circuitry was designed to demonstrate the integration of nanotubes with CMOS electronics. The SWNTs are into the feedback resistor of the op-amp. The small signal gain of the op-amp with CNT feedback resistors was measured as ~-1.95. The thermal response of SWNTs have been measured and has a negative temperature coefficient of resistance (TCR) ~ -0.4%. In summary, we have successfully integrated SWNTs on to functional CMOS circuitry utilizing a low temperature wafer scale process. The technique is simple, versatile and high yield with potential applications for the realization of nanotube and nanowire based bio and chemical sensors.

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SESSION IIA: Integrated Nanoelectronics — Thursday 28 May, 11:10am

SWNT-based Thin Film Transistors on a Flexible Substrate

Selvapraba Selvarasah and Mehmet R. Dokmeci
Department of Electrical and Computer Engineering, Northeastern University

Carbon nanotubes are promising candidates for use in flexible electronics due to their high carrier mobility, large current carrying capability, and extreme mechanical flexibility.[1-4] Compared to organic molecules such as pentacene, they have much higher mobility and are more stable. The present flexible devices that utilize polymeric substrates either go through complicated processes, but are bulky and lack flexibility. In this paper, we report an ultra thin, extremely flexible and biocompatible Single-Walled Carbon Nanotube based thin film transistor utilizing parylene-C as the substrate and the encapsulation layer for wearable and implantable device applications.

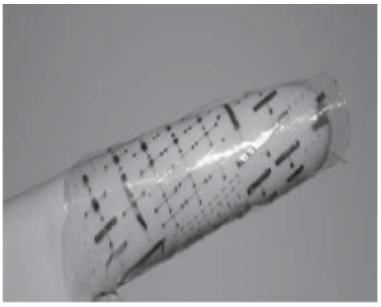
Figure 1: Flexible CNT FET.

To fabricate the flexible SWNT TFT (as shown in Fig.1) we first deposit a 10 μm thick parylene-C at room temperature on a silicon wafer. After deposition of the parylene-C, Al gate electrodes were deposited and patterned. A 1μm thick conformal parylene-C gate dielectric layer was next deposited. Cr/Au source and drain electrodes 200Å/1500Å were deposited and patterned. Dielectrophoretic (DEP) assembly was utilized to assemble the SWNTs between the source and drain electrodes.

After assembly, the drain current (I_{ds}) of the CNTFET was measured as a function of the drain voltage (V_{ds}) as the gate voltage (V_{gs}) was varied from -40V to 40V using a semiconductor parameter analyzer) in air at room temperature. The electrical breakdown

process for destroying metallic nanotubes was conducted at a bias voltage of V_{gs}=20V. Next, I_{ds}-V_{ds} curves were remeasured for Vgs values ranging from -40V to 40V with 10V increments, and corresponding to an increase in V_{gs}, a decrease in conductance was observed. Moreover, I_{ds}-V_{gs} characteristic confirm a p-type behavior with mobility of 2 cm^2/Vs, ON/OFF ratio of about 10^3, and transconductance of 0.5653 µS at V_{ds}=500mV. After I-V measurements, a thin (1.0µm) parylene-C layer was deposited as the encapsulating layer, and contacts to the electrodes were opened. Finally, the parylene C substrate containing the TFT was peeled off from the silicon wafer. Next, electromechanical tests were performed on the SWNT TFT. The change in the ON current (I/I_0) with respect to strain was next recorded for 6 cycles of experiments, and it was found that the ON current varied within the range of ±3.6 and ±8.9%. Measurements after multiple bending experiments indicate that these devices remained operational and showed no significant change in their performance. This is the first flexible SWNTs based TFT that display the highest flexibility at the smallest bending radius as small as 1.5mm.

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SESSION IB: Nanomanufacturing Applications: Energy and Environmental — Thursday 28 May, 1:20pm

Commercializing Nano at GE

Margaret Blohm
Nanotechnology AT Leader, GE Global Research

There is a growing awareness of the need to invest time and effort to commercially realize the potentially disruptive benefits of nanotechnology. Converting any disruptive science into a meaningful disruptive technology takes significant time and money, and nanotechnology is no exception. At GE Global Research, we have been developing a strategy to manufacture and commercialize innovative new nanotechnology-based products across GE's broad technology spaces, from Energy to Healthcare products. Highlights of these learning's will be discussed.

SESSION IB: Nanomanufacturing Applications: Energy and Environmental — Thursday 28 May, 1:45pm

Polymer Nanotube Ensembles for Separation and Sensing

K. Krishnamoorthy, E. N. Savariar and S. Thayumanavan
Department of Chemistry, University of Massachusetts Amherst

We have developed a method to rapidly manufacture nanoporous membranes that are capable of separating small and large biomolecules. In this method, nanoporous membranes are modified with amphiphilic homopolymers that are developed in our lab, to impart selectivity to these membranes. The uniqueness of our polymers is that it comprises hydrophilic and hydrophobic functionalities in each repeat unit of the polymer. These polymers form micelle type assemblies in polar solvents and inverse micelle type assemblies in apolar solvents. We have also synthesized polymers having two hydrophilic functionalities in each repeat unit of the polymer. These polymers have been found to form vesicle type assemblies in water. The possibility of utilizing these micelle and vesicle type assemblies in separation of small molecules and large biomolecules are explored. We hypothesized that high throughput separation is feasible, if we convert the micelles and vesicles into nanotubes. Towards this objective, the nanopores of polycarbonate membranes are decorated with amphiphilic polymer micelles and vesicles. We anticipated that the vesicle type assemblies will functionalize the nanopores and concurrently reduce the pore diameter of the polycarbonate membranes. Such functionalization preferably results in the formation of polymer nanotubes upon its adherence on the pore walls. The functionalization was carried out by treating the commercially available polycarbonate membrane with $SnCl_2$, which imparted positive charge on the membrane surface. Then, a solution containing vesicle type assemblies was filtered through the membrane. To find out whether the filtration process modified the nanopores, the polycarbonate template was dissolved to liberate the nanostructures. TEM images of the liberated nanostructures were found to be polymer nanotubes. The inner diameter of the polymer nanotubes were measured by diffusion of water through the polymer nanotubes embedded in the polycarbonate membranes. By carrying out ion transport experiments using the functionalized polycarbonate membranes, we could ascertain the charge of the polymer nanotubes' interior. Further, by filtering a polymer with complementary charge through the polymer nanotubes, we could modulate the pore size as well as the interior charge of the polymer nanotubes. Such modified membranes were used to separate small molecules based on size, charge and hydrophobicity. We also demonstrated that the amphiphilic polymer functionalized membranes can separate biomolecules such as proteins, based on size and pI.

SESSION IB: Nanomanufacturing Applications: Energy and Environmental — Thursday 28 May, 2:10pm

Silicon and Germanium Nanocrystal Electronic Devices

Zachary Holman, Chin-Yi Liu and Uwe Kortshagen
Mechanical Engineering Department, University of Minnesota

Semiconductor nanocrystals have received significant attention for their potential as low-cost materials in electronic devices. Nanocrystals may be processed with many of the inexpensive techniques that make organic materials attractive, yet they are expected to have superior mobilities and resistance to degradation. In addition, new opportunities arise at the nanoscale—such as tunable absorption and emission via quantum confinement, and multiple exciton generation—that may allow for entirely new device architectures. However, in order to be integrated into devices, *films* of nanocrystals must be developed and the films would ideally have the same properties as their constituent crystals. Significant headway has been made with II-VI and VI-IV solution-synthesized nanocrystals such as CdSe and PbSe, but progress with the popular group IV materials Si and Ge has lagged behind because of a lack of a satisfactory synthesis route. We present on plasma-synthesized Si and Ge nanocrystals, thin films of these crystals, and electronic devices based on the films.

Nanocrystals are synthesized using a nonthermal plasma approach in which precursor gases are dissociated in a radiofrequency discharge and atomic clustering leads to nanoparticle nucleation[1]. The plasma environment is uniquely suited to synthesizing nanocrystals since a unipolar negative charge is dispensed on the particles, suppressing agglomeration, and the particles are selectively heated, allowing for crystallization of high-melting point materials. Silicon and Ge nanocrystals are produced with respectable mass yields, yet retain a narrow size distribution as is necessary to avoid diluting the tunability of their optical properties. Additionally, the nanocrystals are synthesized as a powder with hydrogen-terminated surfaces, which makes this process particularly clean and allows for flexibility in subsequent processing.

Several methods have been developed for depositing thin films of nanocrystals. In one technique, Si or Ge nanocrystalline powder is transferred into solution and films are spun onto substrates. The nanocrystals are not solubilized by most solvents, leading to flocculation and poor film morphology. However, solvents with similar dielectric constants as Si and Ge suppress the van der Waals attraction between nanocrystals, resulting in a stable colloid. Films cast from these solutions are particularly smooth and have been used for thin-film field-effect transistors. Germanium nanocrystal transistors exhibit *n*-type behavior with electron mobilities as large as 7×10^{-3} cm^2/Vs and on-off ratios of 10^4.

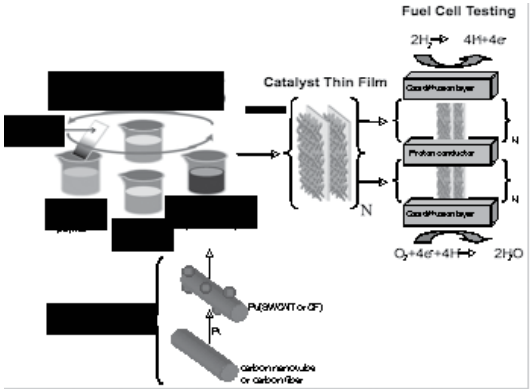
We have also investigated inorganic-organic hybrid devices based on Si nanocrystals and poly-3(hexylthiophene) (P3HT). P3HT was added to Si nanocrystal solutions and blend films were spun as the active layer in photovoltaic devices. These devices, in which the Si nanocrystals act as the electron conductor and the P3HT acts as the hole conductor, have achieved open-circuit voltages of 0.8 V, short-circuit currents of 3.9 mA/cm^2, and power conversion efficiencies of 1.5% under solar irradiation[2].

[1] L. Mangolini, E. Thimsen, and U. Kortshagen, *Nano Lett.* 5, 655 (2005).
[2] C.Y. Liu, Z.C. Holman, and U.R. Kortshagen, *Nano Lett.* 9, 449 (2009).

SESSION IB: Nanomanufacturing Applications: Energy and Environmental — Thursday 28 May, 2:35pm

Nanomanufacturing Fuel Cell MEAs Using Layer-By-Layer Assembly

Ryan C. Sekol, Marcelo Carmo and André D. Taylor
Department of Chemical Engineering, Yale University



The multifunctional requirement for thin-film fuel cell electrodes remains a significant challenge. Although nanofabrication techniques including chemical vapor deposition, colloidal assembly, atomic layer deposition and molecular beam epitaxy are currently being developed, the cost for these methods remains high. In this work, we report a new kind of fuel cell MEA constructed by using layer-by-layer (LBL) assembly. This method, developed by Decher et al., allows the build-up of polyelectrolyte multilayered films on almost any kind of surface, whatever its shape, and with a wide choice of possible polyelectrolytes[1]. Here we show that freestanding films of single-walled carbon nanotubes, Nafion, and polyaniline (PANI) can be constructed using this method[2].

As an electrocatalyst support, single walled carbon nanotubes (SWCNTs) have been shown to give a higher performance than standard carbon black (CB) based catalysts and we will describe a method of decorating these materials with Pt using supercritical fluids[3]. The average particle size was

7.8 nm with a range of 2.3 to 15 nm. The figure illustrates the synthesis and LBL nanomanufacturing assembly of these materials. The LBL catalyst layer consisted of 400 bi-layers of functionalized SWCNTs, Nafion®, and PANI (Polyaniline). The Pt loading for this LBL thin film was 0.05 mg/cm^2. The films were evaluated as both catalysts with conventional gas diffusion layers and as catalyzed gas diffusion layers. One example MEA demonstrated a peak power density of 127 mW/cm^2. Although this value was less than our standard Pt/CB MEA (400 mW/ cm2) with an anode loading 0.5 mg/cm^2, the Pt utilization of the LBL catalyst layer was 2,540 mW/mg compared to 800 mW/mg[4].

[1] For further information about this project link to <http://seas.yale.edu/taylor> or email <Andre.Taylor@yale.edu>
[2] Reilkoff, T. (2009) Construction of Fuel Cell Catalyst Layers with Nanometer Precision, <www.seas.yale.edu/news-news-detail.php?id=62>
[3] Taylor, A.D., R.C. Sekol, J.M. Kizuka, S. D'Cunha, and C.M. Comisar, Fuel cell performance and characterization of 1-D carbon-supported platinum nanocomposites synthesized in supercritical fluids, *Journal of Catalysis*, 2008. 259(1): p. 5-16.
[4] Taylor, A.D., M. Michel, R. Sekol, J.M. Kizuka, N.A. Kotov, and L.T. Thompson, Fuel Cell MEAs (Membrane Electrode Assemblies) Created by Layer-By-Layer Electrostatic Self Assembly Techniques, *Advanced Functional Materials*, 2008. 18: p. 1-7.

SESSION IIB: Nanotechnology Business and Commercialization I — Thursday 28 May, 1:20pm

Involvement of Industry in Nanotechnology Partnerships

Sean Murdock
Nano Business Alliance

SESSION IIB: Nanotechnology Business and Commercialization I — Thursday 28 May, 1:45pm

Nanotechnology in the Defense Industry

Sharon Smith
Lockheed Martin Corporation

This talk will give an overview of some of the major interests and needs in the broad area of nanomanufacturing that are important to the aerospace and defense industries. Areas to be covered will include some of our major challenges, from a business and technical perspective, as well as the impact of some of the emerging efforts going on in the U.S. government and DoD.

SESSION IIB: Nanotechnology Business and Commercialization I — Thursday 28 May, 2:10pm

Nano Terra: Creating Function at Surfaces Through the Application of Chemistry and Structure. A New Business Model for a Platform Technology.

Emanuele Ostuni
Nano Terra Inc.

Nano-Terra's technology platform is centered on the precise and localized application of chemistry and structure at the nano- and micro-scales to improve or enable function at surfaces; Professor George Whitesides of Harvard developed this technology. This technology platform is unique over other competing technologies in that it has the potential to deploy over large areas, at low cost, on curved or flexible surfaces, and at high speed. In the transition from the microscale to the nanoscale, as engineering approaches reach certain limits, chemistry and its interplay with structure are critical to achieving higher function. Such a powerful portfolio cannot be commercialized through a conventional vertically integrated business model. We have developed a collaborative model that leverages our core technical strengths to develop new products and processes with partners who manufacture and market the proposed solutions. Incentives are aligned through deal structures and co-investments. We will review our business model and our core science along with examples of how we have created value for our partners.

SESSION IIB: Nanotechnology Business and Commercialization I — Thursday 28 May, 2:35pm

Technology Transfer: Real Life Stories From A Roll-To-Roll Embossing/Nano-Replication Company

B. Diane Martin
MicroContinuum, Inc., and Lightwave Power, Inc.

Technology transfer is the process of transferring scientific and technical knowledge from one organization to another for the purpose of further development and economic advantage. We—scientists and business people—engage in the transfer of

technology to facilitate the commercialization of our ideas.

My company is the direct result of a change that has taken place in technology transfer over the last fifteen years. The traditional model of the large, vertically integrated company (in my case, Polaroid Corporation) has changed to an approach of industrial development that depends on technology transfer between large corporations, small companies, and universities, as well as individual inventors.

Successful commercialization requires the balance of:

- Identifying new technologies and processes
- Protecting your intellectual property through patents and other legal means
- Forming development and commercialization strategies such as marketing and licensing to existing companies, or creating new startup companies or joint ventures based on the technology

This talk will look at the technology transfer experiences of several small nanotechnology companies. The client names have been changed to protect both the guilty and innocent but the SEMs are real.

SESSION IC: Advanced Tools and Processes for Nanomanufacturing I — Thursday 28 May, 3:20pm

Zone-Plate-Array Lithography: Enabling Nanotechnology from Research through Production

Michael E Walsh[1], Feng Zhang[1], Rajesh Menon[1,2] and Henry I. Smith[1,2]

[1] LumArray, Inc.

[2] Research Laboratory of Electronics, MIT

Increasing interest in micro- and nanofabrication technology for applications outside of the traditional semiconductor industry has highlighted the limitations of current lithographic techniques. Mask-based optical projection lithography, exemplified by steppers and scanners, is magnificently adapted to the specific needs of semiconductor manufacturing but high-cost and lack of flexibility limit its utility in other arenas. Electron-beam lithography (EBL) offers high resolution but severely limited throughput. Systems of various architectures employing a multitude of parallel electron-beams are currently under development with the expectation of solving the well-known problem of low throughput in EBL, however this approach often overlooks other problems of EBL, notably pattern-placement accuracy. Between these two alternatives, innovation is hindered as researchers and entrepreneurs struggle to find an affordable patterning solution that combines the simplicity and throughput of optical patterning with the flexibility and resolution of an electron-beam.

We present zone-plate- array lithography (ZPAL)[1] as an alternative approach for high-speed maskless lithography utilizing a massively-parallel array of photon beams rather than electron beams. The ZPAL technique uses an array of high-numerical-aperture diffractive lenses, known as zone-plates, to create an array of focal spots on the substrate. Patterns of arbitrary geometry are created in a dot-matrix fashion as the substrate is scanned across the focal plane. Incident light to each lens is modulated synchronously with the scan using a spatial-light modulator upstream of the zone-plate array.

In this paper we present system-level design and lithographic results from the ZP-150 alpha-tool. The ZP-150 has been designed with emphasis on flexibility for low-volume manufacturing, prototyping and R&D. Tool design for pattern-placement accuracy is discussed in relation to electron beam systems. Proximity-effect correction (PEC) for improving fidelity is demonstrated, and the role of PEC in maskless lithography is discussed. Lithographic results from the ZP-150 alpha tool will be shown demonstrating the viability of ZPAL for direct-write and mask making with resolution down to 150nm. Absorbance-modulation[2] will be introduced as a technique with the potential to achieve ~20 nm resolution, comparable to an electron-beam while retaining all the benefits of optical lithography.

[1] H.I. Smith, R.Menon, A.Patel, D.Chao, M.Walsh, G. Barbasthasis, "Zone-Plate-Array Lithography: A low-cost complement or competitor to scanning-electron-beam lithography." *Microelectronic Engineering*, 83, pp. 956-961 (2006)

[2] R. Menon, H.I. Smith, "Absorbance Modulation Optical Lithography" *J. Opt. Sci. Am. A* ,23, pp. 2290-2294 (2006)

SESSION IC: Advanced Tools and Processes for Nanomanufacturing I — Thursday 28 May, 3:45pm

Plasmonic Lithography for Nanomanufacturing

David B. Bogy and Lian Pan

Computer Mechanics Laboratory, Department of Mechanical Engineering, University of California, Berkeley

The semiconductor industry is beginning to be affected by the increasing cost of photolithography systems. Although the EUV immersion lithography system is expected to deliver 22 nm half pitch resolution, so far, there is still no cost effective solution for achieving smaller half pitch in mass production. In addition, the photo masks are becoming more and more complex and prohibitively expensive as the node size reduces. This trend opens up opportunities for high throughput mask-less approaches to

address IC manufacturing. However, most mask-less lithography solutions are limited by their low throughput capabilities, making them unable to present a credible option for manufacturing purposes.

Here we report a new high-throughput mask-less nanolithography approach using plasmonic lens arrays flying over a disk at close proximity at 10 meter/second. The lens concentrates short wavelength surface plasmons into a sub-100 nm spot. However, the nano-scale focus only exists at the near field of the lens, typically 10-100 nm, making high-speed scanning of such arrays very difficult. We designed and fabricated a unique air-bearing slider that flies the arrays 10 nm above the surface of a spinning disk with speeds of 4-12 meter/second. We experimentally demonstrated the capability of patterning with 20 nm features. This low-cost nano-fabrication scheme has the potential of a few orders of magnitude higher throughput than current mask-less techniques, and it therefore promises a new route towards the next generation of nanomanufacturing.

Besides its application in nanolithography, this technique may also lead optical and magnetic data storage to achieve two orders of magnitude higher capacities in the future.

SESSION IC: Advanced Tools and Processes for Nanomanufacturing I — Thursday 28 May, 4:10pm

Advanced Solutions in Surface Engineering Technology ASSET™

Arjan Giaya
Triton Systems, Inc.

ASSET™ combines chemistry and formulation expertise at Triton Systems with the Atmospheric Pressure Plasma Liquid Deposition (APPLD™) process developed by Dow Corning. This unique approach for surface modification and functional coatings enables new products and applications for a host of end uses. The patented APPLD™ technology allows users to engineer the surface of virtually any substrate, rigid or flexible, smooth or textured, finished or unfinished (for example electronics, various hardware, optical components, devices, films, textiles, fibers) by applying thin (typically 10-250 nanometer) coatings of various materials that bond strongly to the underlying substrate. Coatings have a wide range of characteristics, such as waterproofing, oil proofing, low-friction slickness, adhesion promotion, antireflective, dielectric or antimicrobial properties. The energy-efficient APPLD™ process operates at near room temperature and pressure, uses no water, solvents or surfactants and has negligible waste disposal or recycling needs. It offers broad design flexibility and functionality. Examples that show the advantages of this technology will be shared in this presentation.

SESSION IC: Advanced Tools and Processes for Nanomanufacturing I — Thursday 28 May, 4:35pm

Nanoimprinting with Amorphous Metals

Jan Schroers and Golden Kumar
Yale University

The random structure in amorphous metals (AM) is homogeneous down to the atomic length scale and results in highest strength and hardness, combined with other attractive properties as a structural material. Even more unique is the softening behavior of AM; they can be considered high strength metals that can be processed like plastics. Recently, we showed that some AM can massively replicate features as small as ~10 nm through direct embossing by utilizing favorable wetting conditions between the AM and the mold material[1]. The unique softening behavior in combination with a wider range of softening temperatures, which span a range of 50°C-500°C among AM provides a versatile toolbox for nanoimprinting. This includes the ability to use AM as a hard mold or, alternatively, a soft imprint material. This toolbox can be used for example in nanoimprint lithography where the robust AM would replace the fragile Si mold in the imprinting process. The low softening temperature of AM and the associate low strength permits to directly write onto the AM as in nano probe lithography. Furthermore, the ability to erase multiple times (10^3-10^4 times) features through the action of the surface tension alone before crystallization sets in[2], can be combined with direct writing and used for high density data storage.

[1] G. Kumar, H.X. Tang, and J. Schroers, Nanomoulding with amorphous metals. *Nature*, 2009. 457(7231): p. 868-U128.
[2] G. Kumar and J. Schroers, Write and erase mechanisms for bulk metallic glass. *Applied Physics Letters*, 2008. 92(3): p. -.

SESSION IIC: Nanotechnology Business and Commercialization II **Thursday 28 May, 3:20pm**

The Business of Nanomanufacturing: State/Regionial Partnerships, Commercialized Research and Entrepreneurial Startups

Skip Rung
Oregon Nanoscience and Microtechnologies Institute

Oregon Nanoscience and Microtechnologies Institute grew from the firm conviction that innovation in the form of commercialized micro- and nano-scale technologies was going to be the key to Oregon's high-wage future, enabling or touching many, if not most, of our industrial and manufacturing sectors. The selection of this field was unambiguous, based on an inventory of Oregon's remarkable set of industrial R&D assets, but it remained to develop operating models that would efficiently convert state investment to accelerated growth in research and commercialization. These successful models have proven to be (1) large inter-institutional collaborative projects in carefully chosen categories (e.g. green nanotechnology) and (2) a closely-tied, investor-advised "gap grant" fund intended to assist existing small businesses or newly formed companies through the crucial proof-of-concept stage to the point where they become attractive private investment opportunities. To date, 14 companies, in partnership with ONAMI-affiliated researchers and facilities, have received gap grants, and have collectively leveraged over $14M to date in additional grants and private investment. Several of these companies have significant ties to projects associated with our Safer Nanomaterials and Nanomanufacturing Initiative.

SESSION IIC: Nanotechnology Business and Commercialization II **Thursday 28 May, 3:45pm**

Organic Photovoltaics–A High Speed, High Volume Manufacturing Technology

Russell Gaudiana
Konarka

Organic Photovoltaics are being produced in a roll-to-roll manufacturing process based on standard coating/printing/laminating processes. The various layers may be coated from a wide variety of solvents at high speed to produce flexible, light weight solar modules. The current manufacturing facility is capable of producing modules that will generate 1 GW/year of power at low cost.

SESSION IIC: Nanotechnology Business and Commercialization II **Thursday 28 May, 4:10pm**

NanoGram Silicon Ink: Unlocking the Printed Electronics Opportunity

Sean Stewart
NanoGram Corporation

NanoGram is a world leader in manufacturing complex nanomaterials and high-rate thick film deposition. The company has over 12 years of experience in applying its core technologies to product applications in the fields of batteries, solid state lighting, telecommunications, display films and photovoltaics. The core, enabling technology is NanoGram's proprietary Laser Pyrolysis process for the production of precision inorganic nanomaterials. NanoGram's Laser Pyrolysis process employs an optically flattened laser beam to enable fabrication of crystalline silicon nanoparticles and films. Laser Pyrolysis produces nanoparticles with precise control over particle size and size distribution, crystallinity and dopant element distribution. This process was first invented in 1996 and used to create nanoscale battery electrode materials (NanoGram Devices spin-out, now Greatbatch Technologies) and further adapted in 1999 for the manufacturing of thick films of precision glass for optical telecommunications (NeoPhotonics spin-out). NanoGram has adapted this technology over the past four years to develop silicon inks and deposited films for FPD and PV applications. The use of NanoGram Silicon inks dramatically reduces the number of manufacturing steps needed to produce FPD Thin Film Transistors (TFT) and PV panels. As a result, the total amount of both capital expense and energy required to manufacture electronics by NanoGram's process is much lower than the conventional subtractive process. NanoGram inventors have filed over 100 utility patent applications with the USPTO and have 56 issued US Patents. NanoGram employs more than 60 people at its Milpitas, California facility. Over half of the employees hold advanced technical degrees.

SESSION IIC: Nanotechnology Business and Commercialization II **Thursday 28 May, 4:35pm**

CNSE: State-Corporate Partnership of Nanoeconomic Development

Edward M. Cupoli
Professor and Head, NanoEconomics Constellation, College of Nanoscale Science and Engineering, University at Albany SUNY

The College of Nanoscale Science and Engineering (CNSE) at the University at Albany SUNY is the first college in the world dedicated to research, development, education, and deployment in the emerging disciplines of nanoscience, nanoengineering, nanobioscience, and nanoeconomics. New York State laid the foundations for the CNSE in 2000, with the creation of the Centers of Excellence Program. Five centers were created to stimulate regional-industrial growth and competitiveness, using public funds to leverage private sector know-how and investments. One such center was the Albany Center of Excellence in Nanoelectronics and Nanotechnology. It was envisioned as a new educational model, one that would teach in an interdisciplinary fashion, integrating nanoscale science, engineering, biotechnology and economics. At the CNSE, the study of science is not only for science sake, but also to advance the commercialization of technology, and to prepare the students (i.e. the future workforce) to meet future needs and create a positive societal impact in New York State and the nation as a whole.

The CNSE model focuses on the exploration of synergistic effects within emerging nanoelectronics clusters. It started as an attractor for skilled labor, thus producing high-technology job insourcing. It did this by partnering with internationally-respected corporations from the nanoelectronics industry, including IBM, Applied Materials, Tokyo Electron, Intel, SEMATECH and ASML. The nanoelectronics industry has immense complexity, and combining this complexity in tandem with the growing cost of research and development, it is nearly impossible for any one company to thrive independently.

The College provides an environment for students, faculty, industry, and the surrounding community to learn, innovate and transform such knowledge and ideas into new products and greater wealth. The CNSE-model mirrors the behavior of the knowledge-intensive economy, in which all actors of a society work in capital intensive, R&D intensive, high-wage industries which continuously require the input of added value that allows industries to systematically reinvent themselves.

To accelerate technological development, the CNSE has established key Technology Focus Centers in critical areas of Nanomaterials, Nanolithography, Nanoscale Characterization, and Sustainable Ecosystems Nanotechnologies and among others. Currently 16 Technology Focus Centers bring together academics from the best educational institutions all over the U.S. and corporate researchers from some of the most technologically advanced companies in the world. Each center is created as a unique entity, one that is able to explore the partnerships that will generate the faster advancement of technologies, whether they are corporate, academic or combined. There is no established monolithic structure as CNSE's Technology Focus Centers are encouraged to evolve, innovate and adapt accommodating to the requirements and challenges of generating knew and useful knowledge.

In only five years of operation the CNSE-model has become a globally recognized entity. CNSE's Albany NanoTech complex is today the most advanced research enterprise of its kind at any university in the world: a $4.5 billion, 450,000-square-foot complex that continuously attracts corporate partners from around the world, offers students a one-of-a-kind academic experience, and educates society on the implications of advances in nanotechnology. The CNSE houses the only academic fully-integrated, 300mm wafer, computer chip pilot prototyping and demonstration line within 65,000 square feet of Class 1 capable cleanrooms. More than 2,500 scientists, researchers, engineers, students, and faculty work on site at CNSE's Albany NanoTech complex. The CNSE currently has a network of industrial partners of more than 250 companies, including IBM, AMD, SEMATECH, Toshiba, ASML, Applied Materials, Tokyo Electron, Vistec Lithography and Freescale among others. Currently CNSE's Albany NanoTech complex covers over 800,000 square feet, including over 80,000 square feet of Class 1 capable cleanroom space. For the CNSE, the future holds a continuous acceleration of technologies, where the only constant is change.

These next-generation actors must manage change quickly and efficiently. Our stakeholders collaborate not only because it mitigates costs and reduces risk, but because they see the vision and foresight of our institution. CNSE subsequently creates leverage for its industrial partners by helping them maintain and increase their competitive advantages in rapidly-changing-markets. For academics, collaboration implies greater opportunities for creating knowledge, a unique setting to explore great intellectual challenges, and the potential of becoming the entrepreneurial actors that might transform our world. And perhaps most importantly, for our surrounding society this collaboration model ensures the creation of a strong economic base in which jobs are created both by corporate growth, and successful high-tech entrepreneurial ventures.

Session Abstracts

SESSION IA: Advanced Tools and Processes for Nanomanufacturing II — Friday 29 May, 8:20am

Nanomanufacturing using Heated Probe Tips

William P. King
Department of Mechanical Science and Engineering, University of Illinois Urbana-Champaign

When the tip of a heated atomic force microscope (AFM) cantilever is in contact with a solid surface, the tip-surface contact is as small as a few nm. Resistive heating in the cantilever can heat this small contact area up to 1200°C. This paper describes how this ultrasmall hotspot can be used for thermal nanomanufacturing.

Heated AFM cantilevers were developed for data storage[1], but have since been used for measurements of materials properties [2], studies of nanometer-scale heat transfer[3], and nano-manufacturing[4,5]. A key requirement for these applications of heated AFM cantilevers is their thermal, mechanical, and electrical design and calibration[6].

In thermal dip pen nanolithography (tDPN)[4], a heated cantilever tip is coated with an ink that is solid at room temperature but can be melted from the tip when the cantilever is hot. When the tip scans over a surface, deposition from the tip can be controlled through the cantilever temperature. It is possible to deposit both organic materials and low melting temperature metal solders with nm-scale features. In thermochemical nanolithography (TCNL), a heated tip is in contact with and scans over an organic film having a thermally-reactive chemistry[5]. TCNL offers the ability control chemical reactions with nm-scale features.

[1] Vettiger, P., G. Cross, et al. (2002). "The "Millipede"-Nanotechnology Entering Data Storage." *IEEE Transactions on Nanotechnology* 1(1): 39-55.
[2] King, W. P., S. Saxena, et al. (2006). "Nanoscale Thermal Analysis of an Energetic Material." *Nano Letters* 6(9): 2145-2149.
[3] Park, K., G. L. W. Cross, et al. (2008). "Experimental Investigation on the Heat Transfer Between a Heated Microcantilever and a Substrate." *Journal of Heat Transfer-Transactions of the Asme* 130: 1002401-1-1002401-9.
[4] Nelson, B. A., W. P. King, et al. (2006). "Direct deposition of continuous metal nanostructures by thermal dip-pen nanolithography." *Applied Physics Letters* 88(3).
[5] Szoszkiewicz, R., T. Okada, et al. (2007). "High-speed, sub-15 nm feature size thermochemical nanolithography." *Nano Letters* 7(4): 1064-1069.
[6] Lee, J., T. Beechem, et al. (2006). "Electrical, thermal, and mechanical characterization of silicon microcantilever heaters." *Journal of Microelectromechanical Systems* 15(6): 1644-1655.

SESSION IA: Advanced Tools and Processes for Nanomanufacturing II — Friday 29 May, 8:45am

Dip-Pen Nanolithography®: From the Lab to the Factory Floor

Mike Nelson
NanoInk, Inc.

A limited number of tools are available for direct manipulation and fabrication of structures from diverse materials at the sub-100nm length scale. The Dip-Pen Nanolithography (DPN®) process is one such method that employs a scanning-probe based system which can be used for a variety of bottom-up assembly techniques including direct-write fabrication, templating, resist patterning and etching, and surface functionalization. Since its invention in the late 1990's, there has been considerable development of DPN applications, processes and instrumentation. DPN is now poised to transition from a tool used primarily in research to a powerful, nanomanufacturing platform. This talk will review the history of the technology in terms of those elements that are critical for DPN to function as a nanomanufacturing process. Recent developments in instrumentation, MEMS and DPN methods will be presented. A specific nanomanufacturing application for large area, nanopatterned surfaces will be described.

SESSION IA: Advanced Tools and Processes for Nanomanufacturing II — Friday 29 May, 9:10am

Directed Assembly of Nanoelements for High-rate Nanomanufacturing

Ahmed Busnaina
W.L. Smith Professor and Director, The NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN)

The transfer of nano-science accomplishments into technology is severely hindered by a lack of understanding of barriers to nanoscale manufacturing. The NSF Center for High-rate Nanomanufacturing (CHN) is developing tools and processes to conduct fast massive directed assembly of nanoscale elements by controlling the forces required to assemble, detach, and transfer nanoelements at high rates and over large areas. The center has developed templates with nanofeatures to direct the assembly of carbon nanotubes and nanoparticles (down to 10 nm) into nanoscale trenches in a short time (in seconds) and over a large area (measured in inches). The center has demonstrated that nanotemplates can be used to pattern conducting polymers and that the patterned polymer can be transferred onto a second polymer substrate. The center has many applications where the technology has been demonstrated. For example, the nonvolatile nanotube memory device switches, the actuating elements (SWNTs) are assembled down to a size that will enable a one SWNT per switch on a wafer level. A new biosensor chip (0.1 mm x0.1 mm)

attached to a catheter could detect multiple biomarkers simultaneously and can be in vitro and in vivo (as part of an intravenous catheter). The center has developed the fundamental science and engineering platform necessary to manufacture a wide array of applications ranging from electronics, energy, and materials to biotechnology.

SESSION IA: Advanced Tools and Processes for Nanomanufacturing II — Friday 29 May, 9:35am

The Center for Integrated Nanotechnologies

Robert Hwang
Center for Integrated Nanotechnologies

The Center for Integrated Nanotechnologies (CINT) is one of five Nanoscale Science Research Centers supported by the U.S. Department of Energy's Nanoscale to promote and accelerate interdisciplinary research in nanoscale phenomena. These facilities are located at national laboratories distributed across the U.S. The distinguishing characteristic of CINT is its emphasis on exploring the path from scientific discovery to the integration of nanostructures into the micro and macro worlds. This pathway involves the experimental and theoretical exploration of behavior, the development of a wide variety of synthesis and processing approaches, and an understanding of new performance regimes, testing design, and integration of nanoscale materials and structures. Integration itself is key to the exploitation of nanomaterials, and the scientific challenges that it poses are at the heart of CINT's mission.

CINT is also unique in that it is operated as a partnership between two national laboratories, Sandia National Labs and Los Alamos National Lab. In this way CINT builds on the strength of both labs. The scientific activities within CINT are organized into four thrust areas: Nanoscale Electronics and Mechanics; Nanophotonics and Optical Nanomaterials; Soft, Biological and Composite Nanomaterials; and Theory and Simulation of Nanoscale Phenomena.

In this talk, I will describe the science and technology activities in CINT and highlight areas that may be of interest to the nanomanufacturing.

ACKNOWLEDGMENT: This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility operated jointly by Los Alamos and Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

SESSION IIA: Fundamental and Enabling Science — Friday 29 May, 8:20am

Sandia's CAE Approach Towards Bottom-up and Top-Down Nanomanufacturing

M. Chandross, P. R. Schunk, J. B. Lechman, G. S. Grest and E. D. Reedy
Sandia National Laboratories

Practically, two options exist for production of materials and surfaces with controllable/tunable nanostructure: bottom-up processing with small, nanometer-scale building blocks (e.g. nanoparticle self- and directed-assembly) or top-down processing with nano-pattering from a prefabricated template (e.g. imprint lithography, mechanical embossing, contact printing, etc.). Although successful applications resulting in useful devices or materials using either approach are now common-place, new scientific breakthroughs in nanostructure control are still frequent and managing these processes over large areas and at throughputs practical for commercial or government applications can be very difficult. Empirical approaches (managed with careful experimental design methods) are currently the norm for industrial scale-up but are often prohibitively time-consuming and expensive. Modeling and simulation can decrease manufacturing process design cycle time enormously, as has been proved in many industry segments. Investment casting, high speed thin-film coating, specialty metals processing are but a few manufacturing processes in which Sandia has provided modeling support and accelerated process design. Nanomanufacturing processes are ripe for this type of support.

This presentation covers key elements of an ongoing research program at Sandia that seeks to develop and apply modeling and simulation tools to solve some of the outstanding challenges of nanopatterning by top-down and bottom up methods and to aid in the scale-up to large-area and/or high throughput. The nanopatterning processes using nanoparticle assembly or top-down methods can be broken down into simpler, underpinning physical rate processes and material phenomena. From a thermo-mechanical standpoint, material deformation, fluid-solid interactions (wetting, spreading, etc.), material rheology are but a few phenomena difficult to manage at high-speeds and over large areas. We will provide an overview of our ongoing modeling and simulation efforts across these areas. We also detail our activities specifically with regard to nanopatterning by detailed large-scale simulations of nanolithographical processes in which rigid molds are imprinted into polymer liquid that is subsequently hardened. We use a generic bead-spring polymer model that can be applied to both step-flash imprint lithography (SFIL), in which the polymer is either cross-linked by exposure to UV irradiationor nanoimprint lithography (NIL), in which the polymer liquid is

hardened by lowering the temperature below its glass transition. Stamps are then either removed at constant velocity to study the effects of stress and adhesion on resulting features, or simply deleted to study the zero stress limit. We vary the size and pitch of the stamps in order to study the resolution limits of both methods.

SESSION IIA: Fundamental and Enabling Science — Friday 29 May, 8:45am

Investigation of Quality and Repeatability of Nanomanufacturing Processes: Design of Experiments of Magnesium Oxide Growth Process

Ghulam Moeen Uddin, Abe Zeid, Sagar Kamarthi and Kate Ziemer
Northeastern University

Establishing reliable, reproducible, and economically viable nano processes is one of the challenges in integrated systems nanomanufacturing research[1]

There is a growing interest in the integration of functional oxides, such as ferroelectric barium titanate (BTO) and ferromagnetic barium ferrite (BaM) on wide-band-gap semiconductors, like hexagonal silicon carbide (*6H*-SiC). The idea of integrating oxides with semiconductors by molecular beam epitaxy (MBE) is recently gaining much attention. By addressing quality issues at the nano process and nano product design stage, we can reap bigger gains than if we paid attention to them at the commercial production stage. Keeping this in mind this research investigates quality and repeatability issues in MgO growth process.[2]

First we identify inputs, outputs, and state variables of MBE process by creating input-process-output diagrams and fishbone diagrams for MBE based MgO growth process. Next we conduct experiments on the MBE setup in the Interface Engineering Lab to generate the process performance data. Using this data we conduct design of experiments (DOE) based analysis to identify the cause and effect relationships among process inputs and outputs. We investigate the effect of growth time, substrate temperature, Mg source temperatures, plasma pressure, plasma power, plasma intensity, and other important process parameters on the key process performance indicators such chemical composition and the material structure. We use Taguchi's robustness strategies to identify a combination of process input parameters that can produce MgO thin films with desirable characteristics with high repeatability. Some of the process parameters such as Mg source-substrate distance, vacuum level, Mg and O_2 quality are considered either constants or noise. We us X-ray photoelectron spectroscopy, reflection high energy electron diffraction, and atomic microscope to characterize the process performance parameters. The growth of high quality thin films of functional oxides on a silicon substrate requires an interface layer to accommodate their mismatch in lattice and thermal characteristics and band offset. MgO, because of its structural match with both the functional oxides and the substrate, serves as an appropriate interface material. We are investigating the use of MBE process, which offers the ability to control the stoichiometry and structure at the atomic level, to grow MgO films. Looking forward from a systems engineering perspective, this research addresses the issue of quality and repeatability of the MBE process to grow MgO thin films on a 6H-SiC substrate with controlled structural, stoichiometric and functional properties.

This research lays a found for developing process models that could relate process inputs and outputs accurately and to develop process-model-based methods for detecting and predicting process faults and averting defects in MgO films.

[1] J. D. Morse (editor), report from the NSF workshop on "Research challenges for integrated nanomanufacturing."
[2] W. A. Doolittle, A. G. Carver, and W. Henderson, "Molecular beam epitaxy of complex metal-oxides: Where have we come, where are we going, and how are we going to get there." *J. of Vacuum Sci. Tech.* B, v 23, pp. 1272-1276, 2005.

SESSION IIA: Fundamental and Enabling Science — Friday 29 May, 9:10am

Introduction to Center for Scalable and Integrated Nano-Manufacturing (SINAM)

Li Zeng
NSF Center for Scalable and Integrated Nanomanufacturing

The Center for Scalable and Integrated NAno-Manufacturing (SINAM) was established through the National Science Foundation's (NSF) Nano-scale Science and Engineering Centers (NSEC) program. Under the vision of a new nanotechnology manufacturing paradigm combining fundamental scientific research with industrial outlook, SINAM is developing high-throughput, large scale nano-manufacturing tools through the collective effort of its exceptional interdisciplinary team. One of the major challenges in capitalization on nanotechnology is the development of a high-throughput nano-fabrication technology that allows frequent and easy design changes for a wide material selection. Maskless nanolithography, such as electron-beam and scanning-probe-lithography, offers the desired flexibility but suffers from low throughput. SINAM has proposed and developed a new low-cost high-throughput approach of mask-less nanolithography that uses an array of plasmonic lenses which can "fly" at high speed above the surface to be patterned, concentrating short wavelength surface plasmons into sub-100 nm spots for photolithography. A self-spacing air-bearing was designed, which can fly the array just 20 nm above a disk substrate that is spinning at speeds of 4-12 meter/second to utilize the near field focusing effect. A linewidth as small as 80 nm and a patterning resolution of 145 nm

are experimentally demonstrated. This low-cost nano-fabrication scheme has the potential to achieve throughputs that are two to five orders of magnitude higher than other maskless techniques. SINAM is also exploring other disruptive nanomanufacturing methods for niche applications in healthcare and energy that will impact the whole society.

SESSION IB: Advanced Tools and Processes for Nanomanufacturing III — Friday 29 May, 10:20am

Self-Assembled Templates for Device Fabrication on Si Wafer and Roll-to-Roll Process Platforms

James J. Watkins
Polymer Science and Engineering Department and Center for Hierarchical Manufacturing, University of Massachusetts Amherst

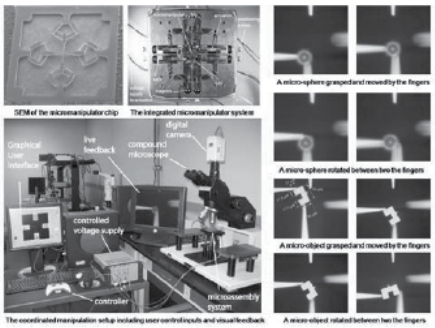
The fabrication of nanotechnology enabled devices requires not only the creation and functionalization of well defined nanostructures, but also practical routes for the two and three dimensional integration of these structures with components and systems across multiple length scales. Approaches for the use of self-assembled block copolymer templates to achieve these goals for sub-10 nm elements using either Si wafer or roll to roll processing platforms will be discussed. While the potential for these materials for patterning precision electronics, including high density data storage is an area of active study and great promise, less work has been carried out to adapt these strategies for lower cost per function devices, including solar energy applications and flexible electronics. For example, use of self assembly in roll to roll processes to achieve these goals requires the development of versatile, low cost templates.

Recently we reported that nanostructured templates with sub-10 nm domains can be easily obtained through the blending of disordered polymer surfactants containing poly(ethylene oxide) (PEO) as the hydrophilic block with homopolymers including poly (acrylic acid), poly (4-vinyl phenol) and poly (styrene sulfonate) that selectively associate with the PEO block through hydrogen bonding. These inexpensive blends are strongly segregated, yielding well ordered domains. Moreover, the functionalities imparted by the homopolymers provide convenient handles for binding active materials such as nanoparticles and for promoting in situ, phase selective reactions to produce hierarchical metal oxide polymer composites. We have now extended our approach to demonstrate that ordering can likewise be induced by small molecule additives that can undergo multi-point hydrogen bonding with the surfactants. The use of small molecule additives offers additional structural, chemical and functional diversity. The behavior of the template systems and their use for the fabrication of well ordered polymer/nanoparticle, metal oxide/polymer, and metal oxide/polymer/nanoparticle composites will be discussed.

SESSION IB: Advanced Tools and Processes for Nanomanufacturing III — Friday 29 May, 10:45am

Multifinger Coordinated Manipulation Methodology for Nanomanufacturing

Laxman Saggere, Sandeep Krishnan and Christopher Pelzmann
University of Illinois at Chicago



Fabrication of new functional and useful micro/nano-scale machines potentially involve complex asymmetric 3D arrangements of the nano-scale entities that are beyond the current capabilities of the "bottom-up" and "top-down" approaches for nanomanufacturing. To fill the void between these approaches and enable assembly of building blocks in future NEMS, the capability of mechanically manipulating micro- and nano-scale objects is highly essential. Although significant progress through a variety of strategies and tools for manipulation (pushing, pulling, bending, twisting, and even, grasping) of nano-scale objects have been reported over the last decades, currently available tools and techniques still lack sufficient of dexterity for assembling nano-scale objects. For the ultimate success of assembly-based nanomanufacturing, a manipulator tool with high-degree of dexterity beyond those provided by current simple cantilevers and parallel jaw grippers and tweezers is required.

Motivated by the need for dexterous manipulation and assembly at nano-scales, this project aims to investigate the principles and fundamental issues in a novel manipulation methodology based on the coordinated action of multiple agile fingers at a chipscale to accomplish a controlled manipulation tasks such as grasp, rotate, regrasp, move point-to-point and position micro- and nano-scale objects in a defined 2D workspace[1,2]. The multiple fingers are capable of not only manipulating multiple objects simultaneously but also coordinating with each other to bring the grasped parts into desired alignment just as a pair of human fingers in each hand articulates to assemble small parts.

This presentation will discuss the development of a novel micromanipulator system comprising a multifingered manipulator chip (5 mm × 5 mm) and piezoelectric actuators and a specially designed compact housing (5 cm × 5 cm). The topology and shape of

the miltifingered micromanipulator chip were obtained through a systematic design optimization process maximizing the operating workspace of the micromanipulator. The specially designed, precision machined housing encloses the micromanipulator chip, facilitates the integration of meso-scale piezoelectric actuators with the micromanipulator fingers and isolates the workspace area of the manipulator to minimize external disturbances. This micromanipulator system enables a highly dexterous manipulation of micro-scale objects within a defined workspace area (> 4600 μm^2) at the center of the chip by the coordinated action between the fingers, which can be controlled in a close-loop through external user inputs with visual feedback. Preliminary experiments have confirmed the predicted behavior of the micromanipulator fingers as well as the feasibility of controlling multiple fingers to achieve a coordinated action to grasp, rotate and move a micro-scale object as commanded by the user. The ultimate goal of this work is to enable coordinated nanomanipulation and assembly of nano-scale objects.

Acknowledgements: This work is supported by the National Science Foundation Grant Number 0800741.

[1] Krishnan, S., and Saggere, L., Proc. of the Intl. Mech. Eng. Congress and Exposition, Orlando, FL, Nov. 5-11, 2005.
[2] Krishnan, S., and Saggere, L., *Journal of Micromechanics and Microengineering*, Vol. 17, No. 3, 2007, pp. 576-585.

SESSION IB: Advanced Tools and Processes for Nanomanufacturing III — Friday 29 May, 11:10am

High Resolution Projection Microstereolithography for 3-D Fabrication

Christopher M. Spadaccini[1], George Farquar[1], Todd Weisgraber[1], Steve Gemberling[1], Nicholas Fang[2], Jun Xu[2] and Matthew Alonso[2]
[1]Center for Micro and NanoTechnology, Lawrence Livermore National Laboratory (LLNL)
[2]Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), University of Illinois, Urbana-Champaign (UIUC)

There is a growing need to develop fabrication and manufacturing technologies which can rapidly generate 3-D components at the meso-scale with micro- and nano-scale features as well as graded density structures with multiple material constituents. Applications of interest for LLNL include laser fusion targets for the Nation Ignition Campaign (NIC) and Laser Inertial Confinement Fusion-Fission Energy (LIFE), high energy density physics targets, and complex micro and nanostructures for national security such as sensing technologies.

Projection Microstereolithography (PμSL) is a potentially low cost, high throughput, micro-scale, stereolithography technique which uses a spatial light modulator (Liquid Crystal on Silicon - LCoS) chip as a dynamically reconfigurable digital photomask. PμSL is capable of fabricating complex 3-D microstructures in a bottom-up, layer-by-layer fashion. A 3-D model is first sliced into a series of closely spaced horizontal planes. These 2-D images are transmitted to the LCoS and illuminated with an ultra-violet source. The LCoS acts as a dynamically reconfigurable photomask and transmits the image through a reduction lens into a bath of photosensitive resin. The resin that is exposed to the UV light is cured and anchored to a substrate and z-axis motion stage. The stage is lowered a small increment and the next two-dimensional slice is projected into the resin and cured on top of the previously exposed structure.

We are currently working on refining this capability in order to produce nano-scale features and to use multiple materials. This is being accomplished by:

1. Incorporation of a far-field superlens (FSL) to enhance resolution to the tens of nanometer-scale (well below the diffraction limit of UV light).
2. Use of laminar flow microfluidic systems to more optimally deliver and distribute photosensitive resins enabling fabrication with multiple materials.
3. A coupled optical-chemical-fluidic model to elucidate the governing physics.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. (Document release number LLNL-ABS-413095.)

SESSION IB: Advanced Tools and Processes for Nanomanufacturing III — Friday 29 May, 11:35am

A Template for Straight Forward Fabrication of Single Nanowire Devices

B. J. Hansen, X. Zhang[1] and J. Chen[2]
[1]Department of Mechanical Engineering Boston University
[2]Department of Mechanical Engineering, University of Wisconsin Milwaukee

There is high demand for easy and effective ways of manufacturing single NW devices both for fundamental research and for technology development of advanced electronic, electro-mechanical, optoelectronic and chemical devices. While useful information and devices can be obtained by studying NW *arrays*, some of the physics and performance associated with a *single*

NW is lost due to averaging effects. We present a simple method of fabricating single NW devices. The devices were then directly

used to make white light sensing, gas sensing and electrical measurements or the single nanowire device. To fabricate single NW FETs, we begin with a p-type Si oxide substrate with a 500 nm SiO2 top layer. Next, standard photolithographic techniques are used to pattern multiple 1 cm × 1 cm arrays of 100 μm x 100 μm squares with 5 μm spacing between each square. Using an e-beam evaporator, 200 nm thick Ag islands are formed with a 10 nm intermediate Cr layer for adhesion. Next, CuO NWs are grown by direct oxidation of copper (Figure 1). To remove the NWs cleanly from the surface without removing the intermediate amorphous oxide layer a 5 mm x 5 mm piece of PDMS is gently used to shear off the NWs (Figure 2.). The PDMS with high density NWs on the surface is placed in ethanol and ultrasonicated for 5min. Next, the NWs now dispersed in ethanol are deposited onto the electrode grids. Alternatively, the PDMS with a high density of NWs on the surface can directly be used to perform optical

measurements of the NW array. A high resolution optical microscope (500x to 1000x) is then used to locate a NW that bridges two of the Ag islands, and their location is recorded (electrode column and row number). Fig. 3(b) is an optical image of a single NW, bridging two small Ag electrodes. The two electrodes in contact with a single NW then operate as the source and the drain with the underlying silicon substrate as the back gate (Figure 4). To improve the ohmic contact a top electrode layer is deposited using standard photolithography techniques. The devices are then conveniently packaged into a proto-chip by wire bonding for subsequent gas and light sensing measurement.

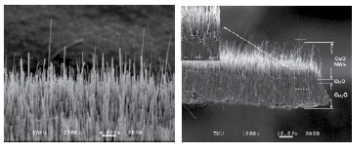


Figure 1: CuO nanowires grown by direct oxidation of copper at 500C for 150min in 100% O_2.

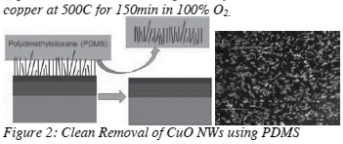


Figure 2: Clean Removal of CuO NWs using PDMS

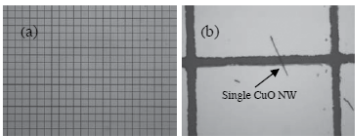


Figure 2. (a) Ag electrode grids (b) and single NW bridging two electrodes.

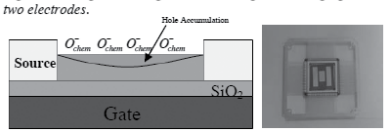


Figure 3. Schematic of Single NW device configuration and Device packaged into a functional proto-chip.

SESSION IIB: Nanomanufacturing Applications: General — Friday 29 May, 10:20am

Functionalized Carbon Nanotube Sensors for Chemical and Biological Detection

Michelle Chen
Physics Department, Simmons College

We developed nanoscaled chemical and biological sensors based on functionalized single-walled carbon nanotube field transistors (SWNT-FETs). SWNTs were synthesized via catalytic chemical vapor deposition method. SWNTs were fabricated into field effect transistors (FETs) via electron beam lithography followed by chrome and gold deposition. Only the devices consisted of individual semiconducting SWNT with on/off ratio greater than 1000 were selected for sensing experiments. The SWNT-FET functionalized with short oligonucleotide such as single-stranded DNA was found to be sensitive and selective for a variety of chemical vapors. The SWNT-FET functionalized with human receptor proteins was found to specifically detect the complimentary adenovirus. Our results demonstrated that functionalized SWNT-FETs serve as promising building blocks for manufacturing large arrays of sensitive and specific nanoscaled sensors for chemical analysis and biomedical diagnostics. Key words: Carbon Nanotubes, Sensors, Field Effect Transistors, Functionalization, DNA, Adenovirus Abstract: Specific, sensitive, reproducible, and rapid detection of chemical and biological species is crucial for the environment, disease diagnosis, and even homeland security. Owing to the miniature size, large surface to volume ratio, high electrical conductivity, and compatibility with dense array fabrication, carbon nanotubes are excellent candidates for sensing application. In this paper we present nanoscaled chemical and biological sensors based on functionalized single-walled carbon nanotube field effect transistors (SWNT-FETs). The chemical sensor work was done at Prof. A.T. Charlie Johnson's lab at University of Pennsylvania. The biological sensor work was done in collaboration with Dr. J.A. Misewich at Brookhaven National Laboratory, and with Prof. S.S. Wong at Brookhaven State University of New York at Stony Brook. For chemical sensors, single stranded DNA serve as the chemical recognition sites and SWNT-FETs as the electronic readout components. Non-covalent functionalization of SWNTFETs with DNA resulted in current changes when exposed to gaseous analytes, whereas the bare nanotube devices show no detectable change[1]. The sensor responses differ in sign and magnitude depending both on the type of gaseous analyte and the sequence of DNA being used. DNA functionalized SWNT-FET gas sensors possess rapid recovery and self-regenerating ability, which could lead to realization of large arrays for sensitive electronic olfaction and disease diagnosis[2]. For biological sensors, we present proof-of-concept experiments for developing highly sensitive and fast-response miniaturized SWNT-FET biosensors for electrically detecting adenovirus using ligand-receptor-protein specificity[3]. SWNTs are mildly oxidized to form carboxylic groups on the surfaces without compromising the electronic integrity of the nanotubes. Then the human coxsackievirus and adenovirus receptor (CAR) is covalently functionalized onto the nanotube surface via diimide-activated amidation process. Upon exposure of the device to adenovirus protein, Ad12 Knob (Knob), specific binding of Knob to CAR decreases the current that flows through the SWNT-FET device. For control experiment, the CAR-SWNT device is exposed to YieF, which is a virus protein that does not bind specifically to CAR, and no current change is observed. Our results show that the CAR does immobilize on SWNT surface while

fully retains its biological activity. Moreover, the specific binding of CAR to its complementary Knob can be electrically detected using individual SWNT-FET devices. These findings suggest that CAR-functionalized SWNT-FETs can ably serve as biosensors for detection of environmental adenoviruses.

[1] C. Staii, M. Chen, A. Gelperin, and A. T. Johnson, *Nano Letters* 5, 1774 (2005).
[2] M. Chen et al., *Materials Research Society Symposium Proceedings*, 963E, 0963-Q21-04 (2007).
[3] Y.-B. Zhang et al., *Nano Letters* 7, 3086 (2007).

SESSION IIB: Nanomanufacturing Applications: General — Friday 29 May, 10:45am

Controlled Drug Release from Large Area Nanoplatforms

Evin Gultepe[1,2], Dattatri Nagesha[1,2], Srinivas Sridhar[1,2]
[1] Electronics Materials Research Institute Northeastern University
[2] Department of Physics, Northeastern University

A model drug, doxorubicin, was assembled into large area nanoporous platforms and PCL plugs, and the subsequent release profile was observed by in-situ fluorometry. After an initial burst release phase during the first 100 minutes, a long time sustained release followed for several weeks. The long-time sustained release behavior can be tuned by varying nanotube pore length and diameter. While the sustained release was dominated by non-Fickian diffusion for polymeric platforms, an activated surface density dependent desorption was in effect for nanoporous templates. It has been showed that non-eroding nanoporous coatings of titania or alumina can be used as an alternative to polymeric drug release systems for sustained release over several weeks, see Figure 1.

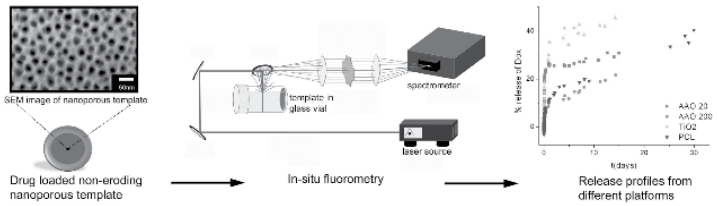


Figure 1: Drug release from nanoporous coatings.

ACKNOWLEDGMENT: This work is supported by IGERT Nanomedicine Science and Technology Program (NSF-0504331).

SESSION IIB: Nanomanufacturing Applications: General — Friday 29 May, 11:10am

New Quantum Dot Based Materials

Y. K. Gun'ko, M. M. Moloney, S. Gallagher and S. Byrne
The School of Chemistry and CRANN Institute, Trinity College, University of Dublin

Quantum dots (QDs) are fluorescent semiconductor (e.g. II-VI) nanocrystals, which have a strong characteristic spectral emission. This emission is tunable to a desired energy by selecting variable particle size, size distribution and composition of the nanocrystals. QDs have recently attracted enormous interest due to their unique photophysical properties and range of potential applications in photonics and biochemistry.The main aim of our work is develop new materials based chiral quantum dots (QDs) and establish fundamental principles influencing the structure and properties of chiral QDs.

Here we present the synthesis and characterisation of various chiral II-VI (CdS, CdSe and CdTe) semiconductor nanoparticles. The most interesting are penicillamine stabilised CdS and CdSe nanoparticles, which have shown both very strong and very broad luminescence spectra. Circular dichroism (CD) spectroscopy studies have revealed that the D- and L- penicillamine stabilised CdS and CdSe QDs demonstrate circular dichroism and possess almost identical mirror images of CD signals.[1,2] Studies of photoluminescence and CD spectra have shown that there is a clear relationship between defect emission and CD activity. We believe that these new QDs could find important applications as fluorescent assays and sensors (or probes) in asymmetric synthesis, catalysis, enantioseparation, biochemical analysis and medical diagnostics. Also chiral QDs with an appropriate functionality could potentially serve as materials for the fabrication of circularly polarised light emitting devices. These devices are necessary components of chiroptical detectors used in polarimetry and CD spectrometers. Finally, circular polarized light emitters might have a potential application in colour displays.

1. M. M. Moloney, Y. K. Gun'ko, J. M. Kelly, *Chem.Comm.* 2007, 3900 – 3902.
2. S. D. Elliott, M. P. Moloney and Y. K. Gun'ko, *Nano Lett.*, 2008, 8(8), 2452-2457.

Invited Speaker Biographies

Dhimiter Bello
Dept of Work Health and Safety, University of Massachusetts Lowell

Dr. Bello is an Assistant Professor of occupational and environmental hygiene in the Department of Work Environment at the University of Massachusetts Lowell. He completed a post-doctoral fellowship at the Harvard School of Public Health in the Exposure, Epidemiology and Risk program where he specialized in environmental epidemiology. He received his doctorate (Sc.D.) in occupational hygiene from the University of Massachusetts Lowell. Dr. Bello holds a M.Sc. in Environmental Sciences and Policy, (University of Manchester, U.K.), and a B.S. in Industrial Chemistry (University of Tirana, Albania).

Margaret L. Blohm
GE Global Research

Dr. Blohm was born in Schenectady, New York. She attended Russell Sage College and graduated with a B.S. Degree in Chemistry in 1981. She then received her Ph.D. in Inorganic Chemistry from the University of Minnesota in 1985. After a Post-Doctoral fellowship at the Colorado State University, she joined GE Global Research in Niskayuna in 1987. She worked on several projects in support of GE Plastics, from 1987 to 1997, when she was named Lab Manager of Weatherables & Special Effects Laboratory. Her team invented, developed and supported the commercialization of LEXAN SLX. In 2001 she was appointed Leader of the Nanotechnology Advanced Technology Program at Global Research, where she has been leading a multi-disciplinary team of scientists and engineers to develop high impact nanotechnology platforms for GE's businesses.

David Bogy
University of California Berkeley

Dr. Bogy is the William S. Floyd, Jr. Distinguished Professor in Engineering. He was Chairman of the Department of Mechanical Engineering at UC Berkeley from 1991-1999, and he is the founding Director of the Computer Mechanics Laboratory. He is a member of the National Academy of Engineers, and he served on the U.S. National Committee on Theoretical and Applied Mechanics. He has served as Chair of the Executive Committees of the Applied Mechanics and the Tribology Divisions of the American Society of Mechanical Engineers. He received his B.S. Degrees in Geology and Mechanical Engineering in 1959, and his M.S. degree in Mechanical Engineering from Rice University in 1961. He received a Ph.D. degree in Applied Mathematics from Brown University in 1966 and spent a year as Postdoctoral Fellow in Applied Mechanics at the California Institute of Technology before joining the faculty of the Department of Mechanical Engineering at the University of California Berkeley in 1967. Professor Bogy's industrial experience includes work for Shell Development Company and IBM San Jose Research Laboratory. Professor Bogy's research interests are in solid and fluid mechanics as well as dynamics and tribology, especially as applied to computer technology, in particular data storage systems.

Ahmed Busnaina
Center for High-rate Nanomanufacturing (CHN), Northeastern University

Dr. Busnaina is the William Lincoln Smith Chair Professor and Director of National Science Foundation's Nanoscale Science and Engineering Center (NSEC) for High-rate Nanomanufacturing and the NSF Center for Nano and Microcontamination Control at Northeastern University, Boston, MA. He is internationally recognized for his work on nano and micro scale defects (particulate and chemical) mitigation and removal in semiconductor fabrication. He also involved in the fabrication of nanoscale wires, structures and interconnects. He specializes in directed assembly of nanoelements and in the fabrication of micro and nanoscale structures. He served as a consultant on micro contamination and particle adhesion issues to the semiconductor industry. He authored more than 350 papers in journals, proceedings and conferences. He is on the editorial advisory board of Semiconductor International, the Journal of Particulate Science and Technology. He is a fellow of the American Society of Mechanical Engineers, and the Adhesion Society, a Fulbright Senior Scholar and listed in Who's Who in the World, in America, in science and engineering.

Stefano Cabrini
Molecular Foundry, Lawrence Berkeley National Laboratory

Dr. Cabrini has been the Director of the Nanofabrication Facility at Molecular Foundry (Lawrence Berkeley National laboratory) since 2006, and head of the interfacility nanophotonic group. Molecular Foundry is one of the five DOE NanoScale Research Centers; it is a user-oriented facility, where 50% of time is dedicated to user projects and 50% to internal research. Dr. Cabrini has over 60 publications in the field of nanofabrication, 18 years of experience in experimental physics, ten years of experience in micro-nano-faberication, electron-beam lithography, focued ion beam lithography, wet chemical, thin-film deposition and plasma etch processing, and experience in nanophotonic and metamaterials, semiconductor device fabrication, optical device fabrication, MEMS fabrication, and the development of new lithographic tools.

Invited Speaker Biographies

Michael Chandross
Sandia National Laboratories

Dr. Chandross has been on the technical staff at Sandia National Laboratories for over 10 years, using large-scale computations to study the aging and reliability of nanomaterials. Prior to joining Sandia he was a National Research Council postdoctoral fellow at SPAWAR San Diego. He holds an M.S. and Ph.D. in physics from the University of Arizona (1996) and a B.S. in physics with electrical engineering from the Massachusetts Institute of Technology (1990).

Edward M. Cupoli
NanoEcomonics Consteallation, College of Nanoscale Sciene and Engineering, University at Albany SUNY

Dr. Cupoli is Professor of NanoEconomics and Head of the NanoEconomics Constellation at the College of Nanoscale Science and Engineering. His research concentrates on the economic implications of nanotechnology and economic forecasting for nanotechnology, as well as the competitive position of New York State and the U.S. in the world economy. Dr. Cupoli earned doctoral and masters degrees in economics from the Maxwell School of Citizenship and Public Affairs at Syracuse University, and received a bachelor's degree in mathematics from LeMoyne College. His extensive experience in government and academia, as well as his close ties with the business community throughout New York State, has provided Dr. Cupoli with a deep understanding of the interrelationship between academia, business, and government. Prior to joining CNSE, Dr. Cupoli was Chief Economist and Director of Research for the New York State Assembly Ways and Means Committee, where he played a leading role in gauging and directing state and federal economic initiatives throughout New York State.

Placid Ferreira
Nano CEMMS, University of Illinois Urbana-Champaign

Dr. Ferreira is the Grayce Wicall Gauthier Professor of Mechanical Science and Engineering at Illinois. He is also the director of the Center for Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), an NSF-sponsored Nanoscale Science and Engineering Center. He graduated with a Ph.D in Industrial Engineering from Purdue University in 1987, M.Tech (Mechanical) from IIT Bombay, 1982 and B.E. (Mechanical) for University of Bombay in 1980. He has been on the mechanical engineering faculty at Illinois since 1987, serving as the associate head for graduate programs and research from 1999 to 2002.

Russell Gaudiana
Konarka

Dr. Gaudiana is Vice President of Research at Konarka, where he oversees early stage research programs and shares responsibility for developing Konarka's extensive IP portfolio of over 300 patents and patent applications. He led the research and development efforts needed to establish Konarka's viability as a company when it was founded in 2001, which resulted in many patent applications, early prototypes, and a multi-million dollar round of venture capital funding. He joined Konarka after 27 years at Polaroid, where he managed the Chemical Research Division of R&D. Dr. Gaudiana holds over 50 U.S. patents and has authored or co-authored more than 60 publications. He is also the executive editor of the Journal of Macromolecular Science - Pure and Applied Chemistry and an Adjunct Professor in the Chemistry Department at The University of Massachusetts (Lowell). Dr. Gaudiana has a Ph.D. in Photochemistry from the University of Massachusetts at Amherst where he also had a post-doctoral fellowship in the Department of Polymer Science and Engineering before joining Polaroid.

Costas Grigoropoulos
University of California Berkeley

Dr. Grigoropoulos received his Diploma Degrees in Naval Architecture and Marine Engineering (1978), and in Mechanical Engineering (1980) from the National Technical University of Athens, Greece. He holds a M.Sc. degree (1983), and a Ph.D. (1986), both in Mechanical Engineering from Columbia University. He joined the faculty of the Department of Mechanical Engineering at the University of California at Berkeley as an Assistant Professor in 1990, after serving as an Assistant Professor of Mechanical Engineering at the University of Washington from 1986-1990. He was promoted to Associate Professor in July 1993 and to Professor in Mechanical Engineering in July 1997. He also holds an appointment as a Faculty Staff Scientist with the Environmental Energy Technologies Division of LBNL. He has conducted research at the Xerox Mechanical Engineering Sciences Laboratory, the IBM Almaden Research Center and the Institute of Electronic Structure and Laser, FORTH, Greece.

Invited Speaker Biographies

Dan Herr
Semiconductor Research Corporation

Dr. Herr is Semiconductor Research Corporation's Director of Nanomanufacturing Sciences Research. He leads an international team that provides vision, guidance, and leveraged support for a number of the world class collaborative interdisciplinary university research programs on emerging nanoelectronics related materials and assembly methods, environmentally benign high performance manufacturing, and enabling nano-characterization technology options. He held senior engineering positions at Honeywell Corporation and Shipley Company and founded Avatar R&D Corporation. Dr. Herr serves as Adjunct Associate Professor in the Department of Materials Science and Engineering at North Carolina State University. He provides ongoing technical leadership for the Semiconductor Industry Association's Lithography, Metrology, and ESH International Technology Working Groups. He co-founded and co-chairs the International Technology Roadmap for Semiconductors [ITRS] International Technology Working Group on Emerging Research Materials. Dr. Herr holds 12 foundational patents and 14 pending patent applications and has authored over 45 publications.

Zachary Holman
University of Minnesota

Holman is a final-year Ph.D. student under Prof. Uwe Kortshagen in the Mechanical Engineering Department at the University of Minnesota. His research focuses on the synthesis of group IV nanocrystals and their use in thin film electronic devices.

Jim Hutchison
University of Oregon

Dr. Hutchison joined the faculty at the University of Oregon (UO) in the fall of 1994 where he is currently the Lokey-Harrington Professor of Chemistry and Associate Vice President for Research and Strategic Initiatives. His research interests are in green chemistry, materials chemistry and nanoscience. He led the development of the UO's nation-leading program in "green" (environmentally-benign) organic chemistry, launched the university's pioneering Center in Green Nanoscience and is a member of the Governing Board of the ACS Green Chemistry Institute. He is a member of the leadership team for the Oregon Nanoscience and Microtechnologies Institute (ONAMI) and founded, and now directs, the ONAMI's Safer Nanomaterials and Nanomanufacturing Initiative.

Robert Hwang
Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories

Dr. Hwang received his undergraduate degree from UCLA in physics and his Ph.D. from the University of Maryland. He then went on to a postdoc position at the University of California, Berkeley and Lawrence Berkeley National Lab. Dr. Hwang was then awarded an Alexander von Humboldt award and spent one year at the University of Munich. In 1991, he took a position at Sandia National Labs in Livermore, CA where he conducted research in the area of surface physics. In 2003 he moved to Brookhaven National Lab as director of the Center for Functional Nanomaterials where he stayed until 2006. He is presently at Sandia National Labs in New Mexico where he serves as the director of the Center for Integrated Nanotechnologies (CINT), which is a DOE supported Nanoscale Science Research Center.

Jackie Isaacs
Northeastern University

Dr. Isaacs is an Associate Director of the NSF-funded Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (CHN) and a Professor of Mechanical and Industrial Engineering at Northeastern University. Dr. Isaacs has a B.S. in Metallurgical Engineering and Materials Science from Carnegie Mellon University and M.S and Ph.D. Degrees in Materials Science and Engineering from the Massachusetts Institute of Technology. Since joining Northeastern University, she has worked on assessing the economic, environmental and technological tradeoffs for existing and emerging technologies, and was awarded a National Science Foundation Career Award for her work. Her role in the CHN involves leading the responsible nanomanufacturing research thrust team, whose research includes screening and monitoring of nanomaterials, applying life cycle assessment methods to manufacturing processes, assessing economic viability as well as the regulatory and social implications of emerging technologies. She is a Co-PI on an NSF Nanoscale Interdisciplinary Research Team award entitled: "Nanotechnology in the Public Interest: Regulatory Challenges, Capacity, and Policy Recommendations."

Invited Speaker Biographies

William King
Department of Mechanical Science and Engineering, University of Illinois Urbana-Champagne

Dr. King is Associate Professor and Kritzer Faculty Scholar in the Department of Mechanical Science and Engineering at University of Illinois Urbana-Champaign. He received the Ph.D. (2002) degree in mechanical engineering from Stanford University. During 1999-2001, he spent 16 months in the Micro/NanoMechanics Group of the IBM Zurich Research Laboratory. During the years 2002-2006 he was on the faculty at Georgia Tech. Dr. King is the winner of the CAREER award from the National Science Foundation (2003), the PECASE award from the Department of Energy (2005), and the Young Investigator Award from the Office of Naval Research (2007). In 2006, Technology Review Magazine named him to the TR35—one of the people under the age of 35 whose innovations are likely to change the world. He won R&D 100 Awards in 2007 and 2008, and a Micro/Nano 25 Award in 2007. He is co-founder of two companies and is a Fellow of the Defense Sciences Research Council.

K. Krishnamoorthy
Department of Chemistry, University of Massachusetts Amherst

Dr. Krishnamoorthy is a Research Assistant Professor in the Chemistry Department at the University of Massachusetts Amherst. He recieved his Ph. D from the Indian Institute of Technology - Bombay, India. He has held post-doc positions with Professor Zoski, Georgia State University-Atlanta, and with Professor Thayumanavan, University of Massachusetts-Amherst.

David S. Lashmore
Nanocomp Technologies Inc.

Dr. Lashmore is Co-founder, Vice-president and CTO of Nanocomp Technologies. Dr.Lashmore recieved a B.S. in Engineering Science from the University of Florida in 1969, an M.S. in Physics from the Michigan Technological University in 1970, and a Ph.D. in Materials Science from the University of Virginia in 1977. Dr. Lashmore served as the Electrodeposition Group Leader in the Metallurgy Division of the National Institute for Standards and Technology from 1978 - 1994 before moving into the industrial sector. He was Director of Research and Development at Materials Innovation from 1994 - 2002 and Senior Scientist at Synergy Innovation, Inc., from 2002 - 2004 before co-founding Nanocomp Technologies. Dr. Lashmore holds 33 patents.

B. Diane Martin
MicroContinuum, Inc., and Lightwave Power, Inc.

Martin is an entrepreneur with a law degree. She is a founding member of her current companies: MicroContinuum, Inc., Lightwave Power, Inc., and StereoJet, Inc. She has experience in developing intellectual property strategies for new technologies as well as developing and operating strategic partnerships. Prior to her move into new technology development, Martin was a Connecticut Assistant Attorney General and a Director of Polaroid's Holographic Division.

Mike Nelson
NanoInk, Inc.

As the Senior Vice President, Engineering at NanoInk, Nelson directs the science and engineering teams that develop hardware and software systems used for nanofabrication. In addition to new product design and development, he also manages several of the operational aspects of NanoInk's business including manufacturing and information technology. Prior to joining NanoInk, Nelson served as the Senior Vice President, Engineering at Molecular Diagnostics, Inc. At Molecular Diagnostics, Nelson directed the design and development of in-vitro diagnostic screening systems to assist in the early detection of cancer. Other previous assignments include Vice President, Systems Development for AccuMed International, Inc., Director of Technology for Caremark, Director of Systems Engineering for Baxter International and Director of Engineering for the Perkin-Elmer Corporation. He earned his M.S. in Computer Science and M.B.A. degrees from DePaul University in Chicago.

Emanuele Ostuni
NanoTerra, Inc.

Dr. Ostuni sources and structures collaborative programs and value sharing deals with partners across multiple industrial sectors. He is also currently on the Advisory Board of iValue's nanotechnology practice. Prior to Nano Terra, Emanuele was a Manager at McKinsey & Co. in the Boston and Philadelphia offices where he worked with healthcare and high-tech clients on issues of strategy, growth, licensing and M&A. Before McKinsey Emanuele was a Senior Research

Investigator at Surface Logix, a company founded by George Whitesides and Carmichael Roberts. There he helped to establish the company's Pharmacomer platform for discovering new drugs. Emanuele was a Glaxo Wellcome fellow at Harvard University where he completed his Ph.D. in Physical Chemistry under the supervision of George Whitesides. He was the recipient of an NSF summer fellowship at NIST to study small angle neutron scattering, and holds BS (cum laude) and MS (distinction) degrees in chemistry from Georgetown University. Emanuele has co-authored over 30 publications and is co-inventor on over 30 patents.

Anil K. Patri
Nanotechnology Characterization Laboratory

Dr. Patri leads a multi-disciplinary research team at NCL to conduct pre-clinical characterization of nanomaterial intended for cancer therapy and diagnosis. He interfaces with many collaborators from federal agencies, academia and small business on projects related to nanotechnology. He serves as NCL's liaison with NIST and FDA staff for characterization and standards development activities at ASTM and ISO.

Mike Postek
National Institute for Standards and Technology

Dr. Postek is the Chief of the Precision Engineering Division and Program Manager of the Nanomanufacturing Program in the Manufacturing Engineering Laboratory at the National Institute of Standards and Technology (NIST). Dr. Postek also functioned as the Assistant to the NIST Director for Nanotechnology and he is both a nationally and internationally recognized expert in nanometrology particularly scanning electron microscope (SEM) particle and semiconductor critical dimension (CD) metrology. Dr. Postek received his B.A. from the University of South Florida (1973); M.S. from Texas A&M University (1974); Ph.D. from Louisiana State University (1980) and an Executive M.S. in Technology Management from the University of Maryland (1997).

Neil Robertson
Hitachi Global Storage Technologies

Dr. Robertson is a Manager at Hitachi Global Storage Technologies. He presently manages the Advanced Head Development and Nanotechnology Department at the San Jose Research Division. He received his B.S. degree Chemical Engineering from Cornell University and his Ph.D. in Chemical Engineering from UC Berkeley where he worked on problems in high temperature electrochemical engineering. He worked on advanced technology for magnetic recording heads for the 14 years at the IBM Almaden Research Center and the IBM Storage Division. He managed projects on head design, magnetic materials and process integration for advanced heads. Major projects included: advanced recording density demonstrations, the first integration of GMR spin-valve materials in to a recording head, advanced tape heads, and the development of advanced electroplated write head materials. Recently he has been using his experience in process technology to advance patterned media. A major thrust of his work has been the use of new materials, processes and designs to improve magnetic recording performance. He has 65 patents filed or pending as well as 30 external publications. He has been given several internal IBM awards for his work. He is a member for the Electrochemical Society and the IEEE Magnetics Society.

Caroline A. Ross
Massachusetts Institute of Technology

Dr. Ross is Professor of Materials Science and Engineering at Massachusetts Institute of Technology. She joined MIT in 1997, after spending six years in research and development at Komag, a hard disk manufacturer in San Jose, California. Her background includes a B.A. and Ph.D. (1988) in materials science from Cambridge University, UK, and a postdoctoral fellowship at Harvard University. Her areas of research are focussed on magnetic materials, especially for data storage applications in hard disks, patterned media, magnetic random access memories and magnetic logic; materials for magnetooptical applications; and templated self-assembly processes such as the formation of ordered structures in block copolymers for nanolithography applications.

Skip Rung
Oregon Nanoscience and Microtechnologies Institute

Mr. Rung is a senior high technology R&D executive with over 25 years of R&D management experience in CMOS process technology, application-specific integrated circuit (ASIC) design and electronic design automation (EDA), IC packaging, MEMS, microfluidics, and inkjet printing.

Invited Speaker Biographies

Thomas P. Russell
Department of Polymer Science and Engineering, University of Massachusetts, Amherst

Dr. Russell, the Silvio O. Conte Distinguished Professor of Polymer Science and Engineering, received his Ph.D. in 1979 in Polymer Science and Engineering from the University of Massachusetts Amherst. He was a Research Staff Member at the IBM Almaden Research Center in San Jose, CA (1981-96) and became a Professor of Polymer Science and Engineering at the University of Massachusetts Amherst (1997). His research interests include the surface and interfacial properties of polymers, phase transitions in polymers, directed self-assembly processes, the use of polymers as scaffolds and templates for the generation of nanoscopic structures, the interfacial assembly of nanoparticles, and the influence of supercritical fluids on phase transitions and dynamics in polymer thin films. He is the Director of the Materials Research Science and Engineering Center on Polymers, and an Associate Editor of Macromolecules. He is a fellow of the American Physical Society, the American Association for the Advancement of Science and the Neutron Scattering Society of America, and a member of the National Academy of Engineering.

Sharon Smith
Lockheed Martin, Inc.

Dr. Smith is the Director, Advanced Technology, for Lockheed Martin. She is the prior chair of the Lockheed Martin Steering Group on Microsystems/MEMS (Micro Electro Mechanical Systems) and is currently the co-chair of the Corporation's Steering Group on Nanotechnology/Biosystems Technology. She has over 28 years of experience in management, program management, engineering, and research and development at Eli Lilly and Company, IBM Corporation, Loral, and Lockheed Martin Corporation. She has more than thirty technical publications and has given numerous technical presentations in the US and Europe. Sharon has a Ph.D. in Analytical Chemistry from Indiana University and Bachelor's and Master's degrees in Chemistry from Indiana and Purdue Universities.

Michael Walsh
LumArray, Inc.

Dr. Walsh received his Ph.D. (2004) and M.S. (2000) degrees in Electrical Engineering from the Massachusetts Institute of Technology. While at MIT he studied interference lithography and process development for nanostructures fabrication, including applications in distributed feedback lasers, magnetic random-access memory, quantum dots, and diffractive optics. He is currently the Vice President of LumArray Inc. where he has been employed since 2004. At LumArray he is responsible for the development and commercialization of zone-plate array lithography. An author of more than 14 technical articles and 2 U.S. patents, his research interests include diffractive optics, nanofabrication and precision engineering and microscopy.

Jim Watkins
Polymer Science and Engineering Department and Center for Hierarchical Manufacturing, University of Massachusetts Amherst

Dr. Watkins is the Co-Director of the MassNanoTech Institute and the Director of the NSF Center for Hierarchical Manufacturing at the University of Massachusetts Amherst. He is a professor in the University's Polymer Science Department and the recipient of numerous awards, including the NSF CAREER Award, the Camille Dreyfus Teacher-Scholar Award, and the David and Lucille Packard Foundation Fellowship for Science and Engineering. His research interests include macromolecular templates for functional device structures, materials synthesis and processing in supercritical fluids, phase behavior and transport in multi-component polymer systems, and scalable fabrication of nanostructure materials.

Li Zeng
Center for Scalable and Integrated Nanomanfuacturing (SINAM), University of California, Berkeley

Dr. Zeng received his Ph.D. in Materials Science and Engineering from UC San Diego in 2007. He obtained his B.S. from Tsinghua University and his M.S. from the College of William and Mary. He is currently the Center Manager for the Center for Scalable and Integrated NAnoManufacturing (SINAM) at UC Berkeley. Dr. Zeng has been working on transport and magnetic properties of magnetically doped group-IV semiconductors like germanium, silicon and carbon, both for fundamental studies and practical device applications in spintronics. After joint SINAM in Jan. 2008 as the Center manager, Dr. Zeng oversees all center projects such as the plasmonic nanolithography tool development, large scale nanomanufacturing for plasmonic sensors and nanomanufacturing for energy applications. Dr. Zeng's research interests include material physics, metamaterials, solid state nano-devices and nanomanufacturing.

Exhibiting Sponsors

The National Nanomanufacturing Network (NNN) is an alliance of academic, government and industry partners that cooperate to advance nanomanufacturing strength in the U.S. The goal of the NNN is to build a network of experts and organizations that facilitate and expedite the transition of nanotechnologies from core research and breakthroughs in the laboratory to production manufacturing. Partners and affiliates will find value added through a range of services including training and education, industrial vision and roadmap development, thematic conferences and workshops, and a comprehensive information clearinghouse on the latest in nanomanufacturing and promotion of best practices. Additional services will provide user forums for ES&H discussions, description of evolving processes, trends, and technologies in the area of nanomanufacturing.

The NNN links the four NSF nanomanufacturing NSECs: The Center for Hierarchical Manufacturing at the University of Massachusetts Amherst, the Center for High-Rate Nanomanufacturing at Northeastern/UMass Lowell/UNH, the Center for Scalable and Integrated Nanomanufacturing at Berkeley/UCLA, and the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems at the University of Illinois. The NNN also highlights the activities of other affiliated research centers with a nanomanufacturing emphasis, including the Center for Integrated Nanotechnologies at Sandia National Labs, other government labs at NIST, DOD, DOE, NIH, NIOSH, and other academic centers. Perhaps most importantly, the NNN engages industry to help identify and communicate manufacturing needs and challenges to academic and government research centers to develop effective strategies to build a robust platform of U.S. nanomanufacturing. The NNN collaborates with industrial consortia, professional societies and individual companies on focused issues and roadmapping to aid the advance of nanomanufacturing.

The NNN's information clearinghouse, InterNano (www.internano.org), is a community knowledgebase that is designed to provide information on nanomanufacturing centers, experts and current events, nanomanufacturing processes and nanostructured materials, and best practices. It hosts a range of nanomanufacturing resources, including Expert Reviews of recently-published research, Topics in Nanomanufacturing feature pages, Nano Health Reviews, and a newly-integrated e-print repository for research publications, reports, conference items, and more.

Learn more: www.nanomanufacturing.org

InterNano is the on-line information clearinghouse of the National Nanomanufacturing Network. Collecting, organizing, and providing access to nanomanufacturing information is our mission.

InterNano supports the information needs of the nanomanufacturing community by bringing together resources about the advances in applications, devices, metrology, and materials that will facilitate the commercial development and/or marketable application of nanotechnology. InterNano aggregates existing resources related to nanomanufacturing and creates original commentary on those resources, including news highlights, review and feature articles, and topical assessments of the current state of practice in nanomanufacturing.

Learn more: www.internano.org

The Center for Hierarchical Manufacturing (CHM) is a National Science Foundation Nanoscale Science and Engineering Center (NSEC) established in 2006. It is focused on the discovery, development and platforming of methodologies and processes that yield well-defined nanostructured materials and elements essential for the manufacturing of next generation devices to enhance computing and information processing, energy conversion and human health. The emphasis is on versatile tools and high-rate processes for well-defined nanostructures that can be systematically integrated into existing manufacturing flows, an objective that requires the bridging of bottom-up techniques to yield sub-30 nm structures with top-down techniques to yield device elements at larger length scales. The approach integrates nanofabrication processes based on directed self-assembly, nanoimprint lithography, high-fidelity 3-D polymer template replication, and conformal deposition at the nanoscale with Si wafer

platforms and high-rate roll-to-roll based production tools. The nanofabrication processes are based on recognized CHM research strengths that comprise core technologies within the center.

The essential research structure of the CHM consists of three Technical Research Groups (TRGs) and system level test beds in which the key scientific barriers to the manufacturing of device nanostructures using the CHM platform tools are identified, systematically addressed and resolved. The TRGs provide multi-disciplinary collaborative structure to enable high-impact fundamental research and new discoveries.

Learn more: chm.pse.umass.edu

Center for High-rate Nanomanufacturing

The NSF Nanoscale Science and Engineering Center for High-rate Nanomanufacturing (Northeastern, UMass-Lowell, University of New Hampshire, Michigan State) is developing tools and processes to enable high-rate/high-volume bottom-up, precise, assembly of nanoelements (such as carbon nanotubes, nanoparticles, etc.) and polymer nanostructures. The center's nanotemplates are utilized to conduct fast massive directed assembly of nanoelements by controlling the forces required to assemble, detach, and transfer nanoelements over large areas. The developed technology will accelerate the creation of highly anticipated commercial products and will enable the creation of an entirely new generation of applications in electronics, energy, material, bio/medical areas.

Learn more: www.nano.neu.edu

Harvard University
Center for Nanoscale Systems

The Center for Nanoscale Systems, operating in the newly opened LISE science building on the Harvard campus, operates state-of-art instrumentation in support of nanofabrication, materials characterization, imaging, and nano-computation. The Center excels in the areas of advanced materials processing and analysis, small feature formation (running three electron beam lithography systems), and high resolution imaging (aberration-corrected STEM and TEM). In the most recent 12 months over 1000 experimentalists have used the facilities, and the user population of the Center has been growing at 30% for several years. The Center is open to non-Harvard users on a dollar-per-hour basis, and is situated in a dense environment of academic institutions and technology enterprises.

Learn more: www.cns.fas.harvard.edu

InterNano

National Nanomanufacturing Network

CHM Center for Hierarchical Manufacturing University of Massachusetts Amherst

Center for Integrated Nanotechnologies CINT Sandia Los Alamos

CNST Center for Nanoscale Science & Technology

Harvard University Center for Nanoscale Systems

MASSNANOTECH

Center for High-rate Nanomanufacturing

MASSACHUSETTS TECHNOLOGY COLLABORATIVE
John Adams Innovation Institute

nanoterra

MEL innovation & productivity

SINAM

LUMARRAY

Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems

luxresearch

NanoGram corporation

SNNI

NANOINK INC. NanoFabrication Systems