Center for Hierarchical Manufacturing

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The Center for Hierarchical Manufacturing (CHM) is a leading research and education center for the development of precision and cost efficient process platforms and tools for the manufacturing of next generation, nanotechnology-enabled devices for electronics, energy conversion, resource conservation and human health. The Center's approach involves the integration of components and systems across multiple length scales and integrates nanofabrication processes for sub-30 nm elements based on directed self-assembly, additive-driven assembly, nanoimprint lithography, and conformal deposition at the nanoscale with Si wafer technologies or high-rate roll-to-roll based production tools. The CHM effort is made comprehensive by research on device design, modeling and prototype testing in functional architectures that take advantage of the specific hierarchical nanomanufacturing capabilities developed by the Center.

The implementation of efficient nanomanufacturing strategies that are compatible with Si wafer processing or high-volume roll-to-roll processing will enable the production of high performance computing, memory, sensing and photonic/optically active media and devices as well as nano-enabled products in energy conversion, organic electronics and displays at acceptable cost. Such advances will help to transform the nation's substantial investment in basic research into products that provide substantial societal and economic benefits.

1. Fundamental and Translational Research: The CHM research structure consists of three Technical Research Groups (TRGs), *(1) Nanoscale Materials and Processes, (2) Nanoscale Devices, Systems, and Metrology* and *(3) Sensors and Environmental Monitoring*, in which fundamental research is performed. Translational research is conducted in the system-level test beds in which the key science, engineering and process barriers to the manufacturing of device nanostructures using the CHM platform tools are identified, systematically addressed and resolved.

The CHM's fundamental science and translational test bed efforts incorporate faculty and research professionals at UMass Amherst, Binghamton University, MIT, The University of Michigan, Mount Holyoke College, NIST, The University of Puerto Rico, and Rice University and benefit from collaborations with leading groups in Europe and Asia.

2. Technical Research Groups: The three Technical Research Groups, which involve more than two dozen investigators at UMass Amherst and our collaborating institutions, are described in more detail below:

TRG 1, *Nanoscale Materials and Processes*, addresses the materials systems and processes necessary for high reliability nanofabrication and supports fundamental research on the CHM's core technologies. Essential elements include the massively parallel generation of nanostructures, their functionalization to achieve desired physical or chemical properties, and the development of models and simulations to understand and, ultimately, predict the assembly process, system dynamics, transport and materials properties. The TRG also develops functional materials sets for applications in energy conversion and storage (batteries, photovoltaics, fuel cells), separations and computing. The approaches employed reflect the unique expertise and achievements of the CHM, including directed self-assembly, additive driven assembly of hybrid nanocomposites, self-assembly of low cost templates from commodity components for high volume applications, 3-D replication techniques in which the hierarchical morphologies achieved in soft materials are replicated in inorganic materials without loss of fidelity, nanoimprint lithography and novel conformal and spray-on deposition techniques for nanostructured films.

TRG 2, *Nanoscale Devices, Systems, and Metrology*, supports fundamental studies in magnetics, photonics and device design to generate proof-of-concept prototypes that can be assembled using advances from TRG 1 and the CHM's process platforms. It provides a balanced complement of theoretical and experimental components to guide a system-level design-for-manufacturing approach and the development of metrology methods for property characterization and nanomanufacturing control. Specific efforts include the development of high magnetic permeability ("high-μ") effective medium materials for high frequency wireless device applications, nanoscale device fabrics for computation, and plasmonic arrays for optical sensors based on the CHM's self-assembly and additive driven assembly platforms. The TRG also develops new metrology techniques based on thermoreflectance microscopy.

The efforts in TRG 3, *Sensors and Environmental Monitoring*, recognize that engineered nanomaterials provide both opportunities and challenges in environmental and health sciences. In one effort, the TRG is creating new systems for on-chip separations, diagnostics and environmental monitoring that incorporate unique and enabling technology developed in TRG 1 and the test beds. A second effort includes new strategies for tracking nanomaterials in the environment and assessing their toxicity and biodistribution in plant and animal species. This effort is relevant not only to the use of nanoparticles in CHM projects, but also to their use throughout the nanomanufacturing and nanoscience communities.

3. Test Beds: The test beds are the heart of process and platform development where promising concepts transition from laboratory results into reliable, rapid, high-yield and transferable methodologies for nanostructure fabrication. CHM partnerships as well as a targeted Industry Advisory Board for the effort provide mechanisms by which these techniques may be widely distributed for use by the broader nanomanufacturing community. The center piece of the CHM test beds is a roll-to-roll process facility for self-assembled materials and devices, including micro-gravure and roll-to-roll nanoimprint lithographic (NIL) tools for preparing 30-to-1000 nm thick, ordered polymer and hybrid films (Figure 1). These efforts include

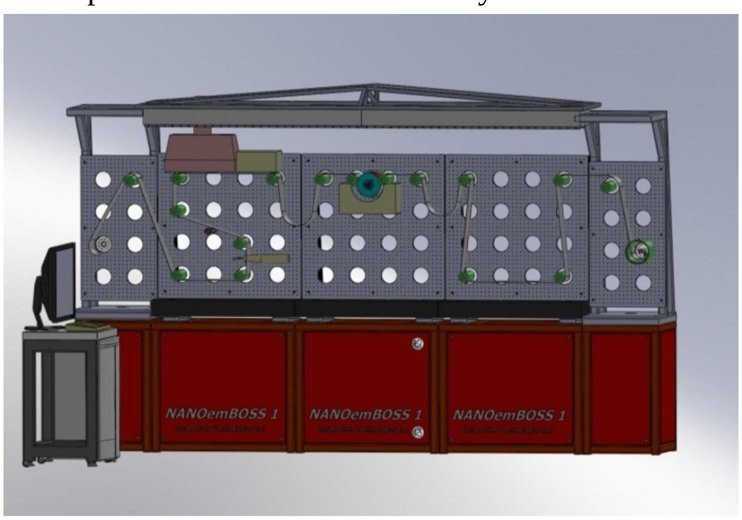

Figure 1. Schematic of Roll-to-Roll process facility

demonstration projects in polymer batteries, aligned carbon nanotube composites for separations and electronics, flexible media for data storage and flexible photovoltaics. The projects are arrayed in order of increasing complexity and drive development, illustrate capability and foster commercialization of the platform. Success will be a driver for the introduction of nanotechnology enabled devices to the market by aligning manufacturing costs with market tolerance. Test beds for cost effective nanomanufacturing of next generation devices based on other technologies, including on-chip, modular arrays of functional nanochannels for biomolecule separation and detection, will be promptly introduced as prototypes emerge from TRG research.

4. Research Highlights: Significant developments within the CHM to date include:

- *Additive driven assembly for R2R preparation of ordered hybrid device layers:* CHM researchers demonstrated through strong specific interactions, highly-ordered periodic templates could be obtained from blends of commercially-available commodity materials. Further, specifically functionalized metal and semiconductor nanoparticles can be used to drive strong order, enabling high loadings in hybrid materials. Together these enable low cost, roll-to-roll assembly of nanostructured media using self-assembly strategies.
- *Patterned magnetic media from block copolymers:* In the area of directed self-assembly, CHM research demonstrated reductions in feature size and attainment of long-range order necessary to generate templates for 10 terabyte/in^2 media, an order of magnitude greater than previously possible.
- *Nanoelectronics:* The Center demonstrated a prototype of a multistate data storage element using a cluster of 3 interacting nanomagnets and a feasible route to manufacturing using guided self-assembly of block copolymers. In addition, plasmonic arrays were developed to demonstrate significantly enhanced fluorescence for sensor applications.
- *Chemical nose sensors for rapid cancer diagnosis:* The CHM developed a sensor array containing non-covalent gold nanoparticle-fluorescent polymer conjugates that is capable of detecting, identifying, and quantifying protein targets. CHM researchers also developed unique “chemical nose” sensors for cells and serum. These sensors target the rapid and efficient identification of healthy, cancerous, and metastatic cells for cancer diagnosis. CHM research further demonstrated that simple chemical functionalization of polycarbonate membranes generates effective tools for protein separations.
- *Formation of hierarchical ULK device structures:* The CHM demonstrated the direct patterning of mesoporous films for use as ultra-low dielectric constant thin films in microelectronics using a process in which selective area exposure of block copolymer templates, doped with photoacid generators. simultaneously dictate structure at the nanoscale and device scales, achieving process efficiencies by eliminating the need for etching. The Center further developed techniques for producing nanochannel arrays that will enable modular design of on-chip devices for bio-molecule separations, sensors and diagnostics and a novel low cost spray-on approach of nanostructured metal oxide films for use in alternative energy generation.
- *Easy Soft Imprint Nano-Lithography (ESINL) Process:* The CHM demonstrated a new nanoimprint molding technique to rapidly prototype device structures and created nanowires of cadmium selenide (CdSe) using a simple electrochemical deposition process and polymer templates created by NIL. CHM researchers have developed an ESINL process to use polydimethylsiloxane rubber to replicate device patterns. It was used to fabricate organic

field effect transistors. This represents the first use of soft imprint lithography to fabricate such devices.

- *Biodistribution of nanoparticles:* CHM scientists developed a new technique based on laser desorption/ionization mass spectrometry (LDI-MS) to track the distribution and fate of nanoparticles (NPs) in the environment. NPs with positively charged surfaces were found to be 3 to 10 times more likely to accumulate in fish than negative or neutral NPs. These results may inform the development of more environmentally sustainable nanomaterials for inclusion into commercial products, a result that is important to the CHM and to the broader nanomanufacturing community.
- *Spin-offs:* Alenas Imaging, Inc. was co-founded by CHM Participant Professor Janice Hudgings of Mount Holyoke College to commercialize the applications of stochastic resonance enhanced thermoreflectance (SRETR). This inspection method offers high spatial resolution and low cost for a wide range of nanomanufacturing applications. Alenas received a Phase I STTR grant from NSF to explore applications in the green energy industry.

5. Educational Impact and Societal Implications: The educational activities of the CHM serve to impact a broad audience of learners including those in K-12, community college, undergraduate, graduate, professional and the public. At the K-12 level, educational lesson plans, hands-on activities and digital video tutorial modules were developed and delivered to more than thirty science teachers/session for integration into their teaching curriculum during a series of four annual week-long "Nanotechnology Institute" summer workshops at UMass Amherst. The learning materials integrated nanoscale science and engineering concepts into the existing science curriculum in a format compatible with state and national curriculum standards. Since each teacher contacts many students each year, the education impact is widespread. The curriculum materials are open access and made available to other teachers via the web. Shorter K-12 educational interactions take place in the form of one-day teacher training events, student lab tours and a Science Day for high schoolers.

The CHM also has a comprehensive Nanotechnology Educational Development Group that creates digital video-based teaching modules on nanoscience and nanomanufacturing. This group includes UMass Amherst faculty, Springfield Technical Community College faculty, science teachers, and university students who design, plan, produce and test web-based modules conveying science topics through appropriate use of video, 3D animation, graphics, text and voice. Module creation and development follows an open source philosophy such that, after one module is created for a specific educational audience, it can be easily re-purposed for other audiences. Each module receives alpha and beta testing from target audiences, which provide formative evaluation for improvements. To date, these modules have had high impact since they have been customized for several educational levels (informal science, K-12, community college, university, professional) and disseminated at national events and over the web.

The CHM fostered the creation of several new university courses that include nanoscience and nanomanufacturing curriculum, including one undergraduate class, "Introduction to Nanotechnology and Nanomanufacturing", and several graduate courses have been created or modified to cover these topics. Students and faculty associated with the CHM also benefit from the "Nanotechnology and Innovation" graduate seminar series, which covers scientific, technical, business, legal, environmental health and safety, and societal issues of nanotechnology through the broad expertise of the invited speakers. The CHM leverages methods on innovation education developed during a previous IGERT by providing graduate students training at the interface of research, business and entrepreneurship.

6. Networking, Collaboration and Information Dissemination: The CHM is the administrative hub of the National Nanomanufacturing Network (NNN) - a catalyst for U.S. nanomanufacturing-based economic development and research collaboration, a network of manufacturing facilities and expertise, a dynamic web-based information resource, and a pathway for university-industry-government partnerships. The NNN efforts include InterNano, a freely accessible digital library and information resource on nanomanufacturing. The NNN has coordinated, hosted and distributed the outcome of workshops on emerging areas in nanotechnology research, implementation and societal implications.

Providing value-added services to industry, stakeholders, and practitioners engaged in nanomanufacturing, the NNN has established a leadership role in such important activities as standards and terminology, nanoinformatics, education and workforce training, materials database federation, R&D collaborations, and archiving of nanomanufacturing relevant information. The network presently consists of centers, leaders, experts, and stakeholders from the nanomanufacturing research, development and education community representing a partnership between academia, industry and government. The core foundation of the NNN consists of the four NSF nanomanufacturing NSECs, the Center for Hierarchical Manufacturing (CHM), the Center for High-Rate Nanomanufacturing (CHN), the Center for Scalable and Integrated NanoManufacturing (SINAM), and the Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), as well as the DOE Center for Integrated Nanotechnologies (CINT) at Sandia National Laboratories, and the NIST Center for Nanoscale Science and Technology (CNST) and other affiliations.

With the goal of transitioning of the NNN into an independent network having a sustainable business plan and secure long-term support, activities have created a functioning, action-oriented network populated by leaders of U.S. R&D programs, centers and enterprises related to nanomanufacturing, including an already established Industrial Advisory Board. These activities also firmly establish InterNano as the premier information site and resource of the nanomanufacturing community, and clearly demonstrate singular NNN contributions to transformational progress in U.S. nanomanufacturing. To accomplish this, the NNN has established a portfolio and database of enabling nanomanufacturing processes, capabilities, and organizations; expanded the NNN base through increased affiliations with government, industry, and academic organizations; and continued to sponsor and organize thematic workshops and conferences targeting priority challenges in nanomanufacturing. New or expanded network activities include education and training, promotion of best practices, facilitating collaborations, and promoting emerging tools supporting design for nanomanufacturing. InterNano has expanded its leadership role in nanoinformatics by organizing a major workshop in November, 2010, as well as database federation activities. It has also continued to increase its editorial authority through expanded nanomanufacturing content, networking and community building with expanded outreach via monthly newsletters, increased functionality on the website with new interface dashboard implementation, and new informatics tools such as middleware for automated database-centered laboratory data information management.

References

[1] For further information about this project link to **http://chm.pse.umass.edu/**