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 effective 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 (R2R) 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 bridge to high-volume process technology is accomplished through collaborations with leading industry partners and with academic centers of excellence in process technology, and is demonstrated through system-level test beds. CHM partnerships with commercial fabrication tool and process suppliers provide a mechanism by which these techniques may be widely distributed for use by the broader nanomanufacturing community. Technology transfer is aided by proactive opportunity and application identification, facilitated engagement with potential partners and establishment of unique facilities for the R2R production of functional nanostructured hybrid materials and devices. These facilities include new process tools developed in cooperation with our industry partners. The Center's educational programs reach K-12, community college, undergraduate, graduate students and the general public, while the Center champions diverse participation at all levels of education and NSEC operations.

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 bed 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 nearly three 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. These efforts are directed towards both complex microfluidic systems and readily manufactured low-cost systems for widespread application. A second effort includes new strategies for tracking nanomaterials in the environment and assessing their stability, 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 and industry consortium 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 are roll-to-roll process facilities for self-assembled materials and devices, including micro-gravure, slot-die and roll-to-roll nanoimprint lithographic (NIL) and hybrid coating tools for preparing 30-to-1000 nm thick, ordered polymer and hybrid films. These efforts include 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 recent developments within the CHM include:

- Investigators in TRG 1 developed new pathways for using self-assembly to create ordered hybrid materials with large periods suitable for manipulating light and for the incorporation of relatively large nanoparticles to enable applications involving quantum dots and plasmonics.
- TRG 1 efforts included the fabrication and testing of transparent light-emitting electrochemical cells, supercapacitors, 3-D photonic band gap structures, Bragg and anti-reflection coatings, and other optical media using strategies developed in the CHM for the preparation of highly-ordered and/or highly-filled polymer/nanoparticle hybrid device layers that can be scaled for R2R manufacturing.
- Research in TRG 1 includes theory development, simulations, and experimental validation of models for hybrid materials coating. New tools for in-line assessment of coating processes have been developed.
- TRG 2 research led to the proof-of-concept demonstration of nanoscale magnetic structures with enhanced energy product using a roll-to-roll nanoimprint lithography process. This development suggests a route to scalable manufacturing of ferromagnetic materials useful for electrical power applications, such as motors and generators.
- Developments in TRG 2 initiated a new 3-D computing fabric concept known as “Skybridge”. In this architecture, nanoscale device, circuit, connectivity, thermal management and manufacturing issues are addressed in unison to achieve true 3-D integration and to overcome the types of difficulties encountered in previous attempts to achieve 3D CMOS.
- Researchers in TRG 3 have developed a new mass spectrometric imaging technique for tracking nanoparticles in tissue. This method tracks nanoparticles using the 'mass barcodes' of their ligands, allowing multiplexed imaging of particle distribution in tissues and organs. In addition, self-assembling amphiphilic polymers have been used by TRG 3 researchers to selectively label biomarkers for mass spectrometric detection
- TRG 3 researchers have created a rapid quantum dot-based sensor for detection and phenotyping of cancer cells. These sensors detect changes in cell surface properties, providing rapid and accurate differentiation of cells.
- The test bed completed installation of a slot die coating head for the new R2R Thin Film Coater (R2RTFC). The R2RTFC has been used in multiple CHM and leveraged projects including a Li+ ion battery development project that led to a license to a partner company.

- The test bed has produced IR sensors and terahertz (THz) polarizers and sensors. Fabrication of continuous sheets of superhydrophobic material replicated from original hard template molds has been demonstrated. Continuous photo-roll lithography (PRL) for continuous and scalable patterning with application in flexible electronics photolithography has been developed and used to fabricate wire grid transparent conductors.
- Seed researchers have developed sensitive paper-based detection systems for bacteria in drinking water. These test strips use iron oxide nanoparticles to generate a visual output, facilitating use of these strips in the field.
- Effective strategies for printing enzymes using inkjet printing have been developed by Seed researchers. The resulting paper-based systems are being applied to low-cost cancer diagnostics for the developing world.
- CHM Research led to $46 million investment to establish the Center for Personalized Health Monitoring at UMass Amherst.

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 about thirty science teachers/session for integration into their teaching curriculum during a series of eight annual week-long "Nanotechnology Institute" summer workshops held at UMass Amherst to date. 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 as many as 100 students each year, the educational 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 *Science Quest* days for more than 200 high school students at sessions held in October in over the past three years. An additional spring session was added this year.

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, 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 and 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. 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 (http://www.internano.org/). 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 among 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, the NIST Center for Nanoscale Science and Technology (CNST), the NanoBusiness and Commercialization Association (NanoBCA) 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 External 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 major workshops annually since 2011 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 implementation, and new informatics tools such as middleware for automated database-centered laboratory data information management.

References

[1] For further information about the center link to: www.umass.edu/chm, www.R2Rnano.org and www.internano.org

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