# 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 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 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.

Figure 1. NIL Roll-to-Roll process facility

**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 recently formed 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 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 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:

- *Patterned media from block copolymers:* CHM researchers have shown that long-range ordering of hexagonal arrays of nanostructures of a triblock copolymer was achieved by solvent annealing in vapors of a toluene/hexane mixture. It was also shown that nanoporous templates containing gold nanoparticles within each nanopore could be produced by sequential UV-ozone and oxygen plasma treatments. These nanoporous templates have potential applications for surface enhanced plasmons, immobilization of DNA or organic dyes, catalysis or epitaxial growth of crystal.
- *Additive driven assembly for R2R preparation of ordered hybrid device layers:* CHM researchers have demonstrated that the addition of nanoparticles that selectively hydrogen bond with one of the segments of a block copolymer can induce order in otherwise disordered systems. This enables the fabrication of well-ordered hybrid materials with spherical, cylindrical, or lamellar domains at particle loadings of more than 40%, as evidenced by TEM and SAXS. The approach is simple and applicable to a wide range of nanoparticles and block copolymers, and it lays the groundwork for the design of cooperatively assembled functional devices.
- *Mesoporous nanostructures:* Hierarchically structured silica nanochannels were fabricated through the combination of supercritical carbon dioxide mediated silica deposition and nanoimprint lithography of a sacrificial polymer template. Highly-ordered mesoporous silica was prepared with either spherical or cylindrical domain level features, ~5–6 nm in diameter, to complement the device level structure of the embedded nanochannels. The hierarchical structure was used as a test device for low-k dielectric materials with a dielectric constant of 2.0 observed.
- *Nanoelectronics:* Key elements of a nanowire based computational fabric were designed. Experimental efforts are ongoing in the CHM cleanroom, focused on developing the necessary process sequence for experimental validation. Initial prototypes demonstrating functional devices are expected in 2012. In addition, a spin wave based computational fabric was initiated based on a new type of computational model fundamentally departing from traditional CMOS circuit models. Recent work demonstrated the reversal of vortex magnetization in nanoscopic ferromagnetic rings and the discovery of metallic-like organic nanowires in sedimentary bacteria.
- *Stability of quantum dots in live cells:* CHM scientists developed a new technique based on laser desorption/ionization mass spectrometry (LDI-MS) coupled with inductively-coupled plasma mass spectrometry (ICP-MS) to determine the stability of quantum dots (QDs) in

living cells. These studies demonstrated an unexpected trend of increasing stability with decreasing size. These results are important for understanding the toxicology of QDs as well as providing guidelines for the design of QDs for *in vitro* and *in vivo* imaging.

- *Test strip sensors for bacteria:* Bacterial contamination is a significant threat in terms of drinking water, food safety, and bioterrorism. CHM researchers have developed a test strip sensor for bacteria based on nanoparticle-enzyme complexes. These strips provide a visual colorimetric readout that allows rapid (minutes) quantification of bacteria down to $10^4$ cells/mL
- *Roll-to-Roll NIL tool development*: The Center has developed a roll-to-roll (R2R) nanoimprint lithography tool to enable surface texturing to direct the orientation of self-assembled domains and continuous patterning at the device level. Together with a custom designed coating platform, these tools enable the coating of nanostructured hybrid materials that can serve as functional device layers, transferring imprinted patterns with nanometer-scale features to thin film with high fidelity and depositing multi-functional planarization layers. To date, line widths as narrow as 230 nm have been achieved on a moving web (1 ft/minute).
- *Metrology and modeling for R2R patterned polymer manufacturing:* Collaborators at MIT have demonstrated an innovative rotation-sampling-based SR imaging technology that has the capability to achieve high frequency and wide field of view. This technology is being used to design an inspection system to overcome the vibration in translation scanning in order to facilitate the implementation of the rotational sampling in the R2R manufacturing process.

**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 five 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 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 April and October 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, 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 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 already established 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 a major workshop in December, 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 and www.r2rnano.org.