

Research Challenges for Integrated Systems Nanomanufacturing

**Report from the National Science Foundation Workshop
February 10-11, 2008**

Edited by Jeffrey D. Morse

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Executive Summary

The emerging capabilities of nanotechnology today for systematic control and manufacturing across multiple length scales are evolving into the next generations of nanotechnology products. These products can be categorized as passive nanostructures, active nanostructures, multi-dimensional nanosystems, heterogeneous molecular nanosystems, and multiscale, integrated nanosystems. The improved understanding of interactive forces among nanostructures and materials, combined with the resulting collective behavior within integrated systems has enabled new methodologies for the controlled manipulation of nanocomponents and structures comprising a broader hierarchy. As such, this new understanding will become a central research topic for discoveries and innovations toward new commercial applications, along with new paradigms in manufacturing sciences to address the necessary economy of scale requirements for these new products. Integrated systems nanomanufacturing must combine the understanding that has evolved to achieve this controlled manipulation of materials and structures with emerging capabilities and methodologies to realize new collective functionality for next generation systems.

Integrated systems nanomanufacturing research focus and challenges include the following topical areas,

- Establishing reliable, reproducible and economically viable means of assembling arrays of nanoscale components, effectuating their deterministic placement and integrating the nanostructures with device architectures that span multiple length scales. This must be accomplished for application appropriate manufacturing platforms ranging from batch processing to high speed, low cost continuous manufacturing platforms.
- The investigation of new nanotechnology system architectures for various functionalities and applications including nanoelectronics, hybrid nanobiosystems, sensors and structures for use in medicine, agriculture and basic biological research, energy conversion and storage systems, water filtration, information technologies, textiles, and intelligent materials.
- Understanding of system behavior at the nanoscale, including the emerging behavior of integrated systems with large number of nanocomponents, understanding the underlying mechanistic, chemical, and materials properties and phenomena, exploiting self-assembly and evolutionary methodologies in nanosystems, and extending the functionality demonstrated by individual nanocomponent to the collective behavior of the integrated system.
- The development and implementation of tools for measuring, simulating and restructuring matter with nanometer scale precision. Further combining new tools for characterization of thermal, time resolved reaction kinetics, and chemical properties at the nanoscale. Further implementation of these tools in scaled manufacturing environments for *in situ* or embedded process control.
- Information exchange relative to systems nanomanufacturing including definition of terms, federation of materials and process databases, implementation of intelligent informatics tools, and establishing best practices for scalable systems integration.

Integrated systems nanomanufacturing will address these issues and challenges thereby providing unprecedented control and understanding of the collective functionality that networks of interdependent nanocomponents may enable. Further integration of micro, nano, and molecular scale designs, will bring nanoscience and engineering to new levels in which nanoscale building blocks make up the integrated system designed to perform specific tasks or provide specific properties enabling a range of new applications and products.

Examples of integrated systems nanomanufacturing are illustrated in the figures below. In both examples, multiscale processes must be incorporated through top-down and bottom-up processes to integrate the various materials, structures, and devices thereby providing the ultimate system functionality.

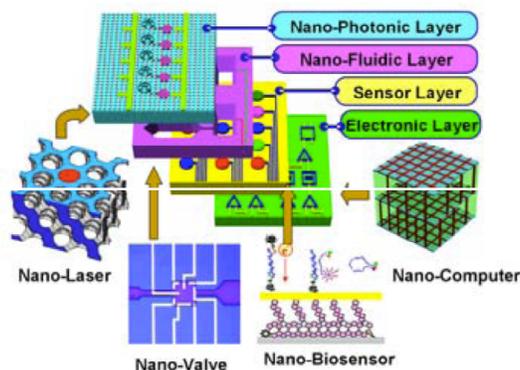


Figure 1: Conceptual schematic of a manufactured nanosystem. The hope for this device is its use to identify the molecular signature of breast tumors. NSF Funding: X Zhang, 0725886, for Center for Scalable Integrated Nanomanufacturing.

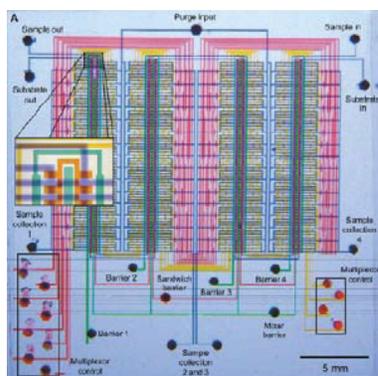


Figure 2: Integrated circuits that are smaller and faster are possible with microfluidics systems built from or incorporating nanocomponents. Above is a microfluidic chip incorporating 2056 integrated valves in an area of one square inch (image courtesy of Thorsen et al.). NSF funding: Ferreira, 0328162, for the Center for Nano-Chemical-Electrical-Mechanical Manufacturing Systems.

Integrated Systems Nanomanufacturing

Nanomanufacturing remains the essential bridge between the discoveries of the nanosciences and real-world nanotechnology products. Advancing nanotechnology from the laboratory into high-volume production ultimately requires careful study of manufacturing system issues including product design, reliability and quality, process design and control, shop floor operations and supply chain management. Nanomanufacturing is the controllable manipulation of materials structures, components, devices/machines, 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 encompasses bottom-up directed assembly, top-down high resolution processing, molecular systems engineering, and hierarchical integration with larger scale systems. As dimensional scales of materials and molecular systems approach the nanoscale, the conventional rules governing the behavior and properties of these components, devices, and systems change significantly. As such, the behavior of the final product is enabled by the collective performance of the nanoscale building blocks.

Research Challenges

The challenges facing integrated systems nanomanufacturing represent an inherently multi-disciplinary set of problems addressing issues for working with structures in the 1-100 nm regime 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 providing revolutionary approaches, thereby extending the capabilities of existing manufacturing and infrastructure. A cross-section of scientific disciplines is contributing to the greater understanding and control of nanoscale phenomena—physics, chemistry, biology, material and information sciences, engineering, and polymer science. The collective knowledge of these disciplines will redefine the relationships between materials, processes and property phenomena, allowing for the creation of novel nanomanufacturing techniques. Those techniques will help to bridge the manufacturing gap between the innovations of the research laboratory and the economic viability of nanotechnology.

The critical challenges for systems 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. These challenges reflect the need for research in the characterization of nanomaterials and nanoparticles as the building-blocks of nanostructures and in the fabrication and synthesis of both top-down and bottom-up processes. Further, they require advanced instrumentation to characterize and measure nanostructures in order to provide predictive simulation of nanostructure behavior, and to contribute to the design and integration of nanodevices and systems. Finally, knowledge sharing and outreach is a challenge to be overcome to enable technology transfer and to contribute to public awareness of nanotechnologies.

Nanotechnology Infrastructure

Nanomanufacturing includes processes, tools, and phenomena occurring at the nanoscale that enable the assembly of components and devices making up the overall system. Some of the momentum for nanomanufacturing has emanated from the semiconductor industry, where the

push to create smaller, faster, and more efficient microprocessors has heralded the creation of circuitry critical features less than 100 nanometers. On the federal level, the National Nanotechnology Initiative (NNI) is a cross-agency program that has been in place since 2001 to support and advance the development of nanotechnologies in the United States. The NNI has identified nanomanufacturing as one of seven Program Component Areas and, in 2006, earmarked \$47 million for research in this area. At present, the National Science Foundation (NSF) funds four Nanoscale Science and Engineering Centers explicitly focused on nanomanufacturing.

With nearly 60 federally funded research centers under NNI governance and over 1200 nanotech companies based in the United States as of 2006, the drive to move nanotechnology from laboratory to marketplace is strong.

Areas of application for nanomanufacturing include:

- Electronics and Semiconductor
- IT and Telecommunications
- Aerospace and Automotive Industries
- Energy and Utilities
- Pharmaceuticals, Biomedical and Biotechnology
- Environmental Remediation and Green Technologies
- National Security

Workshop Goal

The goal of this workshop was to elucidate the key research challenges facing Integrated Systems Nanomanufacturing, thereby providing a roadmap of the near term and long term focus areas that must be addressed. In prioritizing these challenges, needs for systems nanomanufacturing were emphasized, including

1. Understanding the mechanisms and patterns of integrated system behavior as a function of components, interaction forces, and networks at the nanoscale;
2. Considering the scalability of systems having large numbers of nanocomponents and non-linear interactions;
3. Establishing reliable, reproducible and economically viable means of assembling arrays of nanoscale components, effectuating their deterministic placement and integrating the nanostructures with device architectures that span multiple length scales. This must be achieved on application appropriate manufacturing platforms ranging from wafer based batch processing to high speed, low cost roll-roll manufacturing platforms.
4. Determining the tools required for measuring, simulating, and manufacturing of engineered nanosystems;
5. Establishing the framework for product lifecycle and environmental health and safety controls addressing emerging functions of integrated nanosystems with potential use in consumer products, energy, medical treatments, the food industry, and other areas that will be most impacted by nanomanufacturing systems.

Workshop Organization and Format

This two-day workshop brought together approximately 25 leading experts to identify key issues for manufacturing of nanotechnology-enabled products and to begin the process of categorizing specific concerns for individual product technologies and segments. The workshop also addressed the theory of systems-level behavior of integrated nanosystems, including how nanoscale phenomena ultimately affect the characteristics and operability of macroscale systems.

Topical areas for the workshop included:

- Design for Nanomanufacturing
- Design of Experiments/Reliability/Quality
- Metrology
- Process/Feedback Control
- Shop Floor/Manufacturing Systems
- Enterprise/Supply Chain/Reverse Logistics
- Theory of Large-Scale Integrated Nanosystems
- New Services Enabled by Nanoproducts

The specific objectives of this workshop were to:

- Identify needs, challenges and priorities for research and development related to nanomanufacturing systems.
- Discuss nanomanufacturing systems projects currently underway that address needs in various R&D sectors.
- Identify and prioritize strategies best suited for catalyzing nanomanufacturing systems research.
- Produce a report for dissemination to the relevant stakeholders that can serve as guidance for future initiatives in nanomanufacturing systems.

Experts in the areas of the key focus topics were invited to attend the workshop and present a twenty-minute talk on their view of the state of nanomanufacturing in their research area and on their vision of priorities for future work. The participants' expertise were categorized in the areas of:

- Design for Nanomanufacturing
- Engineering Considerations for Nanotechnology Enabled Products
- Manufacturing Processes
- Metrology for Nanomanufacturing

The Workshop was organized into six sessions, each session having focused topics and subject matter. The agenda and presentations for the workshop can be found at:

<http://chm.pse.umass.edu/NMSworkshop/protected/index.htm>

Integrated Nanomanufacturing Processes

Integrated nanomanufacturing processes must achieve targeted product quality via regulation of events at molecular and nano length scales while controlling process variables at macroscopic length scales. In order to achieve sustainable levels of quality and reliability in manufacturing environments, the target properties and performance must be defined, experimental measurements conducted, relevant models established, and data analyzed, with subsequent iterations for optimization, and ultimately end-to-end process control. Presently, the predominant approach to nanomanufacturing process control incorporates experimental design in order to establish viable models for process control. With sufficient factorial design, and appropriate definition of the process objectives, statistical models and nonlinear feedback can be effective in optimizing nanomanufacturing processes. Careful selection of process variables, anticipated response factorials, and sufficient sophistication of sensors for experimental data collection and analysis can result in highly effective process control. The shortcomings of the experimental design approach to nanomanufacturing process design include adaptability to new processes and equipment, limited knowledge of the physical mechanisms applied to the process development, and the time necessary to conduct sufficient experiments to achieve the desired process performance. These limitations are further complicated at the nanoscale where novel physics and materials properties are exploited to achieve new products, requiring new sensors and diagnostics to validate both the mechanistic models and the results of experimental design.

Incorporation of mechanistic modeling of the underlying physics, chemistry, or biology in combination with the statistical models established through experimental design leads to enhanced process control wherein improved understanding of the products and processes is developed. Such a model-based approach to process and controller design uses first principles and system specifications for model construction, thereby naturally accounting for inherent process characteristics, including nonlinearities, spatial variations, and multiscale behavior. For many processes, large disparities exist in time and length scales of phenomena occurring within the processes thereby requiring the establishment of multiscale models coupled through appropriate boundary conditions. Control of nonlinear distributed systems is possible by combining nonlinear models describing macroscale process control with localized physical kinetic models. Combining this with practical control and process feedback, facilitated by optimal placement of sensors for real time analytical data, an integrated nanomanufacturing capability can be realized that is robust, scalable, and adaptable to a range of processes and products. Ultimately, more advanced models will require more advanced sensors and placements to predict process performance at the microscale, as well as to provide the level of control necessary to sustain the processes.

Integrated nanomanufacturing processes require systematic integration of product design, process design and control. Challenges to resolve in achieving this goal are methodologies for experimental design, execution, and translation to control of process variables, development of combined statistical and physical models, and ultimately control system structure, design, and implementation. These challenges include data acquisition, analysis and information processing of multiscale variables with different frequencies and categories. This information is further combined with physical models providing *a priori* knowledge of process performance, and relevant controls that update the process design with operating data, statistical analysis and estimations. While the end product design criteria can be implemented at the initial stage of process design through improved statistical and physical models, reliable and robust processes still need rigorous statistical and probabilistic models for accurate decision making. An optimal

number of experiments are necessary to improve the models with the tradeoff of more cost and time, which are usually not feasible in production environments.

To address these key challenges, appropriate on-line analytical techniques for characterizing nanostructures must be developed. The availability of process and product performance data enables the model to further infer unavailable process parameters from measurement data, thereby achieving more accuracy for predicting the response of active control. With this level of process control, new nanosystems processes will be enabled incorporating a natural design evolution via self-assembly, or directed assembly, for example. Thus, experimental control of nanostructures must first identify the best synthesis approach for the targeted result, then determine the process control variables. Reliability models and performance must further be implemented into product and process designs. Ultimately, a robust process design must combine experimental and physical knowledge of the specific nanosystem in understanding product and process properties and for designing further experiments. To achieve this goal, future improvements in models, on-line sensors and diagnostics, and system knowledge are necessary.

Manufacturing of Nanoscale Materials

Materials aspects in nanomanufacturing encompass both the materials synthesis to achieve a specific product and performance, along with the properties of the materials that enable the nanosystems synthesis. Research priorities in materials synthesis include materials by design, deterministic fabrication, and low temperature materials and processes. Example of enabling aspects of nanoscale materials include directed self-assembly for patterning, and functional diversification wherein materials are added to an integrated nanosystem providing new functionality to the system. To maximize potential commercial impact, low cost, rapid assembly and compatibility with multiple process platforms including roll-roll processing is required. Nanoengineered materials now entail a range of macromolecular scale components including low dimensional nanostructures, macromolecules, complex metal oxides, heterostructures and interfaces, and electronic spin devices. While nanomaterials synthesis has produced compelling examples of nanoengineering, broad issues remain in the ability to reliably synthesize specified properties. Since many materials and nanocomponent properties depend on the specific structures, the challenge remains in developing a predictive materials-by-design capability. While the key research focus has been on the synthesis and properties of resulting nanostructured materials, less research has been devoted to understanding the relationship among process conditions, control, resulting materials structures, and aggregate materials properties. By developing a better understanding of these relationships, deterministic fabrication and synthesis may offer reduced variability, higher throughput, lower cost and improved performance for a given nanosystem design.

Invariably, the challenges associated with materials properties and synthesis are directly linked to process design and control. Further challenges relate to the fabrication process when processes such as directed assembly or nano-templating are utilized to produce the material structure. Additional development of physics and chemistry-based models would predict nanosystem or component properties and performance. Directed assembly and deterministic positioning/patterning further provide scalable approaches to design of nanomaterials structures, as well as integration within the specific nanosystem design.

Metrology for Nanomanufacturing

Micro- and nano-metrology provides the means to measure and characterize process and product performance and covers an expanse of topics including instrumentation, measurement methods off-line and in-process production applications, and standards. To meet the needs of this emerging integrated nanomanufacturing community, it is important that research on scale-up of nanotechnology for high rate production, reliability, robustness, yield, efficiency and cost issues for manufacturing products and services be pursued. To achieve this objective, new research directions must include a systems approach that encompasses the qualification of new instrumentation and techniques, three dimensional metrology, and production hardened metrology.

Critical to the realization of robust nanomanufacturing is the development of the necessary instrumentation, metrology, and 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 measured and characterized. This will in turn enable production to be scaleable, controllable, predictable, and repeatable to meet market needs. Central challenges in the areas of metrology, diagnostics, sensors, and analytical instrumentation supporting nanomanufacturing include on-line techniques that do not require processes to be taken off-line while critical measurements and diagnostics are conducted, *in-situ* sensors that provide macroscale analysis of nanoscale properties, standards that are adaptable to a range of processes, and new analytical techniques that monitor aggregate properties of the nanosystem to determine nanocomponent performance.

Breakout Session I: Integration for Nanosystems Manufacturing

Target Applications

The breakout session discussions first identified target applications and products where the integration for nanosystems manufacturing would have the highest impact. Identified targets included medical applications, electronics, energy, consumer care products, materials, transportation, and separations and purifications. In the case of medical applications, the highest impact is in the areas of targeted drug delivery, tissue engineering, custom drugs, chip-based screening, sensors and diagnostics, and chip-based drug manufacturing. High impact areas for electronics include alternative switch technologies to CMOS, integrated optoelectronics, memory, ultra large displays, and high power, high voltage control. Energy generation, harvesting, and storage would be most impacted by advances in ultracapacitors, micro fuel cells, solar cells, and energy transmission by new low loss conductors. Consumer care products include cosmetics, age care, hair loss, and weight control. While not considered high value, consumer care does represent large market segments resulting from the direct impact on targeted demographics within the general population. The highest impact on materials are anticipated for composites wherein the dispersion and distribution of nanocomponents within the composite are controlled through some form of artificial assembly, thereby controlling the range of properties for the materials. Additionally, metamaterials and asymmetric quantum dots are expected to hold significant long term potential. Separations are expected to be another high impact area for applications in water purification, along with removal of greenhouse gases from energy and

chemical production environments. Finally, transportation will be impacted through the introduction of lighter weight cheaper systems, high performance materials and components, and increased energy efficiency.

Challenges to Achieving Targets

From the set of high impact technologies identified, discussions focused on the key challenges in achieving these targets. For aspects related to integration of nanomanufacturing systems, many requirements overlap standard manufacturing challenges, including yield, high volume, economic and reliable raw materials, scale-up, and compatibility with surrounding manufacturing processes. Additional challenges unique to nanomanufacturing include heterogeneous components, interface management, processing economics, materials specifications and properties enabling design, modeling and planning tools. Three dimensional processes and integration were cited as critical long term needs, essentially an analog to 3-D rapid prototyping at the nanoscale. Ultimately, integrated nanomanufacturing systems must be materials flexible with the ability to customize processes for small volume production.

Process Innovation and Needs

In order to address these challenges, a range of process innovations and needs must be developed. In general, there exists a need for disruptive processes that revolutionize nanomanufacturing, as opposed to evolutionary changes. The range of processes include roll-to-roll and liquid processing for containment, dispersion, and means for delivery. Deterministic placement and mechanisms assembly with alignment were discussed. Various forms of self assembly must be studied to enable these processes, including programmable, directed, and selective processes that can ultimately provide 3D assembly at low cost and high precision. Such an effort requires development in both process and materials. Tip based process for custom high vacuum applications were cited as a key challenge. Additional process needs included encapsulation and stabilization for nanopackaging, nanoparticle solids manipulations, process repeatability, and better, cheaper metrology. Consideration of nanoproduct life-cycle, disposal, and occupational safety were also considered high value needs for future process innovations.

Tool Challenges

Manufacturing tools must be further developed to meet the challenges for future nanosystems integration and production. These challenges include registration and alignment, multiscale interfacing between micro and nanosystems, new sensing mechanisms, and embedded metrology. As such, tools must have rigid prequalification specifications, with some form of self calibration being highly desirable. Eventually, nanosystems manufacturing will exploit an analog to pick and place methodologies for assembly at the nanoscale. In essence, tools and systems that interface to the nanoscale will be needed.

Training and Education Needs

Training, education, and outreach to high schools, community colleges, and junior colleges are essential ingredients in order to train the workforce of the future for integrated nanosystems manufacturing. In order to facilitate this, novel methods to socialize and introduce nanotechnology and, specifically, nanomanufacturing technologies to young people will be needed. This informal education is necessary to provide the educated decision making as career

choices are considered. Additional needs include low cost, user friendly educational tools and instruments for instructional purposes, short courses for direct outreach through community provided education, or possibly associated with specified topical conferences on a regional basis. Online training and education can be further facilitated through web sites such as the NNN/InterNano. Organizational activities including establishing user networks for access to tools for both manufacturing and education will be essential. This type of information clearinghouse can facilitate donations of low cost transitions of equipment and tools for companies that are upgrading. Further clearinghouse information on equipment availability may be facilitated through InterNano, and may further exploit national laboratory and network resources, thereby providing a key resource for organizations working in nanosystems manufacturing without sufficient resources to develop their own processes, or without trained personnel to operate the equipment.

Infrastructure and Fundamental Studies

The breakout session concluded that several fundamental studies were needed to facilitate integrated systems nanomanufacturing in the future. The studies include;

- 1.) Model systems to study nanoscale interactions and systems mechanisms.
- 2.) Understanding and exploitation of surface interactions.
- 3.) New nanoscale architectures – better performance, new functionality, integrated functionality.
- 4.) Robust integration and interfacing (good properties ruined by integration processes).
- 5.) Low cost, high rate systems for self-assembly including 3-D structures and deterministic placement of nanostructures.
- 6.) Design, model and simulation – affected more by the environment as it gets smaller.

Additionally, it was suggested that an organized network to distribute information regarding tools, equipment and process availability to the end users would provide an invaluable resource to further the development of integrated nanomanufacturing systems and nanoscale technologies. Information provided would range from evolving processes and techniques to equipment for sale as it is replaced by new equipment. These resources could be further supported through existing infrastructure established at the National Laboratories, the NNIN, and the NNN.

Breakout Session II: Control, Design, and Metrology for Nanosystems

The second breakout session addressed the topics of control, design and metrology for nanosystems. The discussions of these topics were broken into segments focusing on specific subsets of these topics as follows.

Interaction of Control, Functionality, and Design of Nanosystems

The critical interactions between control and functionality of the processes, and the design of specific nanosystems will be facilitated through key improvements in physics based models of both the processes and the integrated nanosystems thereby enabling predictive designs for the nanomanufactured processes and products. Combining statistical and physics based models and further implementing advanced process control via nonlinear control and feedback, the mathematical models can incorporate additional knowledge within the statistical control

approaches. Ultimately, these approaches must validate the process designs and models through rigorous experimental methodologies.

To better understand the interactions between process control and design of nanosystems, architectural aspects for both device and systems must be considered, and understood to the point where device and component level physics and processes can be scaled to system level functionality. This requires an intimate knowledge and understanding of the functional interaction at both device and system levels. Depending on the specific processes, and device technologies, the integrated nanosystems must address layouts, components, topology, connections, layering, and integrated process steps that differentiate the necessary process control and device design rules to provide 2-D and 3-D nanosystems. Examples of where immediate impact could be made are in the area of real-time process analysis and control, where results from each process step could be used as feedback for subsequent steps. This would enable appropriate adjustment of process parameters to compensate for defects resulting from the previous process step in order to address downstream design issues. While real time process analysis and decision making requires intermediate measurements and discrete time interval availability between process steps, the processes most impacted by this capability include growth, deposition, etch, self-assembly, and directed assembly processes. While the control of process parameters is specific to individual processes, it was felt that a wider view of process design and control issues across multiple steps in the integrated nanoscale system would lend itself towards process and yield improvements for integrated designs.

In order to enable real-time process analysis and feedback control, fundamental approaches to interpreting the embedded properties of integrated nanomanufacturing processes must be explored and developed. This approach seeks to create a new paradigm for process analysis and control feedback by measuring the macroscale, or collective properties of the integrated nanosystem *in situ*, thereby determining the nanoscale properties of the system, which could provide critical feedback for control optimization during manufacturing. Such multiscale analysis would provide key connectivity during nanomanufacturing process steps to retain nanoscale device and materials properties for a broadly scaled or replicated system. Example of processes where this capability would have a high impact include nanoparticle dispersion requiring precise, deterministic positioning, or process sequences where compensation for critical process steps is necessary. Some examples of methods for interpreting embedded properties of integrated nanosystems include electrical or optical techniques wherein measurements can be made via macroscale electrodes that are easy to access, yet provide information on nanoscale attributes of the system. The ability to design the nanoscale properties, processes and analysis measurements as part of integrated nanomanufacturing process development is critical to achieving high performance, economical nanotechnology products.

Reliable Systems from Unreliable Components

Nanoscale systems manufacturing combine devices, materials, and processes where classic physics end and quantum mechanics begin. In order to make definitive, high impact advances for the nanomanufacturing of these systems, new physical paradigms in processing technologies must be realized providing *in situ* device, process, and materials analysis. While the specific issues remain process dependent, core methodologies can be established that address the necessary approaches to be explored to improve the manufacturability of a given nanoscale system. The first is design for reliability, which would consider the critical path device and

process design requirements to optimize the nanomanufacturing of the product. Tradeoff in cost and complexity of the processes must be considered, striving for fault tolerant, redundant designs where defects are not necessarily catastrophic. This approaches may have a high impact on inherently redundant product designs such as displays or electronics, and can further be implemented through an overdesign approach. Combining this with critical inspection procedures between each process step provides the compensation necessary to improve process yields in subsequent steps.

Inherent to the manufacturing of future integrated nanosystems will be the need for a specific design phase associated with the variability of the nanosystem. In other words, as new materials, devices, or nanocomponents are designed into the system, inevitably the new component or process leads to problems downstream. While the notion of design for reliability would loosen tolerances on individual parameters in order to improve process yield, the design for variability would seek to improve processes and yields by focusing on manufacturing designs, introducing new nanomanufacturing practices, and establishing revolutionary process methodologies. This approach must embrace broad based aspects of manufacturing, including redundant designs, critical process controls, incorporation of new nanomaterials in the system design to improve reliability, and functional tailoring of materials properties to meet the unique requirements of the nanosystem integration. Ultimately, the ability to incorporate unlike materials and uncommon building blocks to enable unique functionality will be necessary.

Embedded Metrology for *in situ* Quality Control

Metrology for nanoscale systems remains one of the critical aspects of verifying the features and properties of materials, components and devices. From a process and manufacturing viewpoint, metrology remains inherently disruptive and complex (especially for vacuum-based tools), therefore are either relatively low cycle time and throughput, or are expensive for both equipment costs, as well as cost to the overall manufacturing process. Furthermore, present metrology and analysis tools having sufficient resolution for nanoscale processes, materials and devices, have difficulty imaging or analyzing large areas, an issue that makes these tools less attractive for production scale nanomanufacturing. The concept of embedded or *in situ* metrology is highly desirable since it does not require the process to stop while measurements and analysis are conducted. The challenges for embedded metrology are to first determine approaches that provide sufficient accuracy, calibration, and repeatability, and identify areas where sensor technology requires further development. Present examples are in dry etch or thin film coatings where real-time control and monitoring of the processes are available with high precision. Additionally, the embedded metrology needs to be extended for wafer scale analysis providing the same accuracy as well as more efficiency on the overall process flow.

Similar to the need for interpreting the nanoscale properties of materials, devices, components, and nanosystems by analyzing some macroscale property, advanced models that will translate macroscale measurements to nanoscale features and properties are needed. In this manner, broader area design of experiments may be conducted on large area substrates and processes, yet make use of localized metrology to determine device, material, and system performance for the nanoscale product. Combining statistical and physical models will further improve this approach such that interpretation of both materials and device properties and metrology properties will be indicative of the nanosystem performance and manufacturing yield.

Sensors and Actuation

Sensors and actuators for process control, design, and metrology of nanoscale systems require new sensors having nanoscale availability that can perform in harsh environments. Embedded sensors enabling on-chip analysis, along with detection of defects, patterns and features are key challenges. Inexpensive displacement sensors for automated mask positioning would have an immediate impact. As discussed previously, multiscale sensors providing some averaging of aggregate properties of the system are needed. Investigations of approaches to predict nanoscale properties through interpretation of macroscale measurements would have the highest impact for nanomanufacturing process control and scaleup.

Feedback from Pre-Workshop Questionnaire

Participants were requested to complete a pre-workshop survey to obtain their candid response to the selected questions. The following incorporates a cross section of relevant excerpts and quotations from those responses.

What is the current context/definition/status of nanomanufacturing in your area of expertise?

Nanomanufacturing addresses the control (e.g., size, positioning, orientation) of materials and components at the nanoscale, over large areas and at high rates. Nanomanufacturing is defined as the low cost, volume production of nano scale devices (multiple assembled nano scale components) integrated with the macro world. The components and devices should conform to designed specifications to meet the quality requirement. Specifically, we are looking primarily at high rate nanomanufacturing of polymers (dispersion in nanocomposites, electrospinning of nanofibers, extrusion of multi-layer films, molding of nanofeatures). Definition includes manufacturing of nanomaterials and nano-enabled products and manufacturing processes that are enabled or enhanced by nanotechnology. Status is that significant effort, time, and money is being put into product development of commercial nanotechnology but that commercial realization is making only slow progress. Scaling requires novel ideas to overcome the perception of cost and variability as potential showstoppers. Functional diversification is ushering new families of materials and applications, which must be integrated with known technologies.

How do you see your field of expertise impacting nanomanufacturing in the future?

Nanomanufacturing offers the opportunity to truly achieve multi-functionality -- for example, transparent materials with increased toughness, sensing elements that benefit structural properties, and biosensors with high sensitivity over a broad spectrum. Manufacturing processes and systems include the need in nanomanufacturing for more flexible process technology and my field of expertise allows me to develop process platforms. I also work in tooling and equipment and here we contribute to ultraprecision engineering (nanopositioning and manipulation). Polymers are very versatile materials and composites are by definition meant to be engineered.

Nanoscale metrology and characterization is critical for successful R&D and scale-up of nanomanufactured products. Scientists and engineers need to be able to "see" the products they are building to succeed with high yield manufacturing. Metrology is a key enabler for fulfilling the promise of micro and nanotechnologies. In order to control processes at the nanoscale and predictably achieve expected product performance, manufacturers must be able to measure

critical product and process parameters accurately and at production determined rates.

The advanced control of material microstructure will significantly improve the operation and performance of semiconductor manufacturing processes, increase process yield and reliability, and minimize the negative economic impact of failures on overall process operation. This research addresses the design of feedback control and estimation systems accounting explicitly for multi-scale process behavior and the occurrence of actuator/sensor faults and uniquely integrates fault-tolerant control, fault-detection and isolation, and decision support technologies and provides the potential for significant insight on the balance that can exist between these in practical implementation.

Process modeling abilities can be used to develop and understand relationships between process parameters and manufacturing throughput, yield and quality to aid development of optimized processes. Develop process and system level simulations to aid product design and manufacturing. Integration of design with nanomanufacturing.

The impact of this field will be in (1) better understanding of existing technology in terms of developing models and understanding fundamental limitations on design performances, (2) coming up with new modes of operation that give significant improvement in device performance (3) in integration of fabrication and control design to evolve superior devices. All these components will be a must in realizing the important goals of nanomanufacturing: repeatable and reliable control, manipulation and interrogation at atomic scales.

Engineering is the bridge between scientific possibility and consumer demand. There is considerable disagreement among chemical engineers—who understand the physical limits of atomically-precise nanostructures (but have been constrained by thermodynamically-driven assembly processes), and electrical engineers—who understand the mathematical limits of machines (but don't understand chemistry). Neither group has any experience with exponential manufacturing, which depends on replicated closure. The field of machine replication has examined many of the issues involved, and may be able to help link the two approaches.

In your field of expertise, what differentiates nanoscale manufacturing from conventional manufacturing?

Conventional manufacturing and nanomanufacturing will run hand-in hand. Scale of the initial components defines the two. Conventional manufacturing of automobiles use components made of carbon nanotubes to make cars lighter and hence more fuel efficient. Nanomanufacturing of the carbon nanotubes may require conventionally manufactured precursors such as carbon rods.

Nanoscale manufacturing currently is geared more towards prototyping, utilizing capital intensive equipment and rather long process chains. Integrated manufacturing systems for nano manufacturing similar to those used for conventional manufacturing do not exist. Conventional manufacturing on the other hand has focused on cost and volume production. Design modeling and simulation tools are available for conventional manufacturing to help reduce the product development and manufacturing cycle time.

There are two kinds of nanoscale manufacturing: (1) The bottom-up stochastic manufacturing of nanoparticles and nanocoatings going on since the Lycurgus cup; and (2) The top-down

deterministic manufacturing of sub-100nm lithography, SPM, and related processes, started with the microphotolithographically-made integrated circuit, and continued with the development of the STM and AFM. These two approaches require very different mindsets, so people who work in these two fields rarely talk to each other, and even rarely do they understand each other. Ordinary manufacturing doesn't have the problem of turning well-understood stochastic processes into deterministic procedures.

What are the most significant research challenges related to progress in nanomanufacturing in your area?

Current product development of nano-enabled products is very time, money, and energy intensive. Because predictive models (and manufacturing/product development expertise) are lacking in terms of guiding product development, commercial progress is being made experimentally, i.e., change filler size, make nanocomposite, measure properties, repeat with new filler size, repeat with new filler vendor source, repeat with new surface treatment process, etc. New predictive models to enable product development would enhance rate of commercialization and reduce costs. Applied research in developing tools and collecting knowledge in areas relevant to assessing occupational safety and health concerns would address the current knowledge gap in workplace safety in the area of nanotechnology. Developing methods and tools to enable scale-up productions of commercial scale quantities of nanomaterials with sufficient control over properties and with reduced lot-to-lot variability would aid in product development and in identification of nanotechnology parameters that influence/improve product performance. Nanometrology for many nanomaterials has not yet been developed. Many critical process measurements have yet to be defined (what needs to be measured in the process). Automated production tools do not exist. Deep pockets manufacturers do not exist for many products.

The ability to measure: Precisely across large (500 mm, full device) areas with sub-nanometer accuracies, in times consistent with production and associated process controls. Ability to transmit large amounts of data to/from a variety of sensors/tools/instruments in a suitable format. Ability to measure dense collections of nano-elements (including in fluids) through deconvoluting the signals and obtaining signals from complex environments.

Many issues still abound and most lie in the transition of nano production from the lab to the production environment. For instance, do you need an expensive AFM or SEM to locate a product so that it can be processed? Is a high vacuum required for fabrication? Can many features be populated using automation processes?

Can you envision particular milestones to be set ahead for meeting those research challenges?

We need better interaction between experimental materials scientists in nanoscience and researchers in systems engineering and manufacturing. Researchers in computational materials science can help to provide a bridge, but the goals of their models may be different and not appropriate for all nanomanufacturing tasks. One way to tackle this problem is to define specific grand challenges in nanomanufacturing. Prizes could be awarded to achieving certain goals, perhaps by a certain date, and funding opportunities could be created for these challenges, specifically for truly interdisciplinary teams, including systems engineers, to catalyze efforts the

manufacturing part of nanomanufacturing.

The first step would be to integrate device and control design to enable simple primitive manufacturing tasks such as gripping, holding, moving and other manipulation. This would be followed by determination of the limits of performance of these combined designs, achieve and demonstrate the performance, then iterate on the above steps for better designs and achieving better performance and understanding.

Specific milestones may include; Automated sensing and control of nanomanufacturing processes; New tip based nanomanufacturing methods; Modeling of nanomanufacturing processes; Human-machine interfacing of manufacturing systems; Developing high yield and volume manufacturing processes; Combining directed self-assembly with precision assembly; Design and assembly of heterogeneous building blocks; Layer-by-layer assembly in high speeds.

Summary

The workshop concluded with several key discussions and recommendations for focus research areas that could benefit from further exploration and possible support. It was suggested that many times the applications become the driving force behind specified manufacturing developments, and several were identified as being critical to emerging markets, including energy and power, environmental and clean technologies, separations and purifications, nanoelectronics and information technologies, medical, therapeutics and drug delivery, sensors, actuators and diagnostics, consumer care products, and transportation. The key barriers to processes and manufacturing methodologies for emerging nanotechnology enabled products include aspects related to integration of nanosystems, with many requirements overlapping standard manufacturing challenges, such as yield, high volume, economic and reliable raw materials, scale-up, and compatibility with surrounding manufacturing processes. Additional challenges unique to nanomanufacturing include heterogeneous components, interface management, processing economics, materials specifications and properties enabling design, modeling and planning tools. Three-dimensional processes and integration were cited as critical long term needs. Approaches to meeting these challenges include focus on deterministic assembly and integration, with further exploitation of directed or coordinated self-assembly of multi-variate nanostructures and components.

Manufacturing tools and metrology were specified as key areas to process scaling and further integration of nanosystems. New tools incorporating the multi-scale nature and requirements for integrated systems nanomanufacturing were seen as crucial to meeting the economy of scale and cost drivers for emerging products. Embedded metrology, sensors and diagnostics would provide continuous process flow while accumulating key yield analysis and statistics for each process step and product cycle. Further combination of statistical process control and feedback with mechanistic process models would improve the yields and production cycle duration and costs. Ultimately, these approaches must validate the process designs and models through rigorous experimental methodologies coupled to the statistical and mechanistic methods.

Another consensus of the workshop included reliable and robust design approaches for manufacturing scale-up. This area of research may include advanced defect characterization in situ combined with process tolerant designs that are not catastrophic to achieving reasonable yields. Self-healing materials and processes were another suggestion that could further facilitate

this concept. In order to make definitive, high impact advances for the nanomanufacturing of emerging technologies and systems, new physical paradigms in processing technologies must be realized providing *in situ* device, process, and materials analysis. In general, there exists a need for disruptive processes that revolutionize nanomanufacturing, as opposed to evolutionary changes. The range of processes include roll-to-roll and liquid processing for containment, dispersion, and means for delivery. The challenge here is having the present industrial manufacturing base adopt the emerging processes, particularly if completely new tooling is required, translating to significant capital investment.

Education, training and information exchange were further discussed relative to integrated systems nanomanufacturing. While workforce training has been undertaken with increasing availability of programs at the high school, junior and community college levels, the social aspects of nanotechnology still remain a barrier to begin to educate adults and children alike of the social benefits and general terminologies associated with nanotechnology, and more specifically, nanomanufacturing. Information exchange was cited as a key factor to proliferation and sharing the details of process scaling, best practices, safety and health, applications, and general physics and chemistry behind many nanomanufacturing approaches. While the challenges exist to balance this with the need to maintain proprietary information for commercial entities, the economic and societal benefits may far outweigh the commercialization benefits in many areas. Central to this concept were the formation of materials and process databases, standards and terminology databases, and a unified information exchange platform or clearinghouse to facilitate this.

The workshop concluded that several fundamental studies were needed to facilitate integrated systems nanomanufacturing in the future. The studies include,

- Model systems to study nanoscale interactions and systems mechanisms.
- Understanding and exploitation of surface interactions.
- New nanoscale architectures enabling improved performance, new functionality, and integrated functionality.
- Robust integration and interfacing in order to maintain the properties of individual nanocomponents ruined by integration of scaled processes.
- Low cost, high rate systems for self-assembly including 3-D structures and deterministic placement of nanostructures, particularly on roll-roll platforms
- Design, model and simulation incorporating mechanistic, multi-scale methods supported by experimental validations.
- Embedded metrology, sensors and analysis techniques to better understand process performance at each step, provide details of the individual nanocomponent performance by observing macroscale properties of the system.