Historic Commitment of the NIST Manufacturing Engineering Laboratory to Nanomanufacturing and Nanometrology

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ABSTRACT

Advanced research of nanomanufacturing technologies and processes has continued at an accelerating rate over the past decade. Profitable niche applications, and the anticipation of the overall impact that nanotechnologies will provide for society, have continued to fuel interest and funding for nanomanufacturing. The National Institute of Standards and Technology (NIST) Manufacturing Engineering Laboratory (MEL), early on, recognized the importance of nanotechnologies for U.S. industries and led a number of nanomanufacturing-relevant activities as early as 1999. This included numerous leadership roles regarding nanotechnologies, nanomanufacturing and nanometrology. Work at NIST in collaboration with other agencies influenced the direction of US nanomanufacturing research and development. In October 2000, NIST MEL created the first Nanomanufacturing Program in order to draw interest in this growing field. Since 2000, the NIST MEL work in nanomanufacturing has included measurement projects that spanned nano- to micro-scale dimensions with key functionality resulting from features at the nanoscale. This paper provides an overview of activities that have lead NIST MEL to its current leadership position. The final section completes the overview with a description of the work currently being conducted within the MEL.

Keywords: Nanomanufacturing, Nanometrology, Standards, NIST, NNI, Interagency Working Group, IWG

1.0 INTRODUCTION

At an ever increasing rate, scientific discoveries in nanoscience are being transformed into potential nano-enabled products. Yet, the marketplace impact has been delayed while the industry defines, develops, and implements nanomanufacturing and nanometrology processes that transform these nanotech discoveries into products. This emphasizes that innovations in nanomanufacturing must occur concurrently so that revolutionary new processes and systems are available in a timely manner, ensuring maximum benefit to society. NIST's existing research strengths in nanometrology, available nanometer scale metrology instrumentation, and staff expertise has supported the development of measurement technology to help speed the transition of products from discovery to production thus facilitating nanomanufacturing. The National Institute of Standards and Technology (NIST) became one of the lead agencies advocating for nanometrology and nanomanufacturing within the National Nanotechnology Initiative (NNI). This led to the creation of the "Nanomanufacturing" and "Instrumentation Research, Metrology, and Standards for Nanotechnology" program component areas (PCA's) which provides an

organizational framework for categorizing the activities of the NNI [1]. NIST MEL was also pleased to have Dr. Clayton Teague, then Chief of the Manufacturing Metrology Division of MEL, chosen as the Director of the National Nanotechnology Coordination Office (NNCO). By retracing the many activities undertaken by the NIST Manufacturing Engineering Laboratory (MEL) through out the past decade, one can view the evolution of nanomanufacturing research and understand the future research goals being pursued today.

2.0 NANOMANUFACTURING

Nanomanufacturing research and development (R&D) provides the means to produce reliable tools and processes for precisely manipulating and assembling the basic building blocks of nanotechnology products, cost-effectively producing these products in large quantities, and integrating them into systems spanning nanoscale to large-scale dimensions [2,3]. Thus nanomanufacturing R&D provides the foundation for nanotechnology-enabled products to be manufactured in market-appropriate quantities by reliable, repeatable, economical, and commercially viable methods. Nanomanufacturing is an essential bridge between the discoveries of nanoscience and real-world nanotechnology-enabled products. A report of the Interagency Working Group on Manufacturing Research and Development (IWG-MRD) [2] defines nanomanufacturing as “all manufacturing activities that collectively support practical approaches to designing, producing, controlling, modifying, manipulating, and assembling nanoscale elements or features for the purpose of realizing products or systems that exploit properties seen at the nanoscale.”

3.0 NANOMETROLOGY

Instrumentation and metrology are essential elements of any manufacturing process, and processes that incorporate nanotechnologies require advanced instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems. Nanometrology supports our understanding of desired behavior and performance of nanomaterials, processes and products. It also supports the development of accurate models for analysis and simulation activities. Although there has been steady progress in the development of new tools, equipment, and instruments for nanomanufacturing, more are needed. Industry requirements highlight the need for new metrology tools that can be brought onto the production floor where measurements, critical for product and process conformance, can be made and issues such as product throughput, process control, health and safety are critical. Standards and industry best practices are essential aspects of addressing nanoscale production challenges and identifying key standards for early introduction and entry into the marketplace will determine the pace of product’s acceptance in the U.S. and internationally.

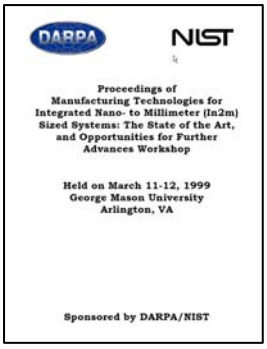
4.0 HIGH IMPACT CONFERENCES AND WORKSHOPS

NIST MEL is a leader in nanometer scale metrology and a pioneer in pursuit of nanomanufacturing research. To define, develop, and execute research and development requires a thorough understanding of the field. An effective method to solicit knowledge about a research area is by organizing and attending workshops, focused meetings, and conferences. These forums can be useful in defining early phases of research or in guiding current efforts by validating the research directions or proposing new focus areas. NIST MEL attended, participated and contributed to most of the NNI Workshops from 2003-2008 and are listed in the participant lists. All of the NNI documents can be downloaded from www.nano.gov. [1]

Workshop reports and web-links provide for increased awareness of research opportunities in the area. For funding agencies, results can be used to define new research areas and identify joint research and collaborative opportunities.

- **March 1999 - Workshop: Manufacturing Technologies for Integrated Nano-to-Millimeter Sized Systems: The State of the Art, and Opportunities for Further Advances - NIST MEL Role: Lead Sponsor and Organizer**

  Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office (DSO) and NIST MEL held a focused workshop entitled “Manufacturing Technologies for Integrated Nano-to-Millimeter Sized Systems: The State of the Art, and Opportunities for Further Advances” The workshop was held at George Mason University, Arlington, VA. This workshop brought together experts in competing yet potentially complementary technologies looking to accelerate the deployment of systems that are comprised of nano- micro- meso- and milli-sized technologies. The objective of the workshop was to identify key requirements for realizing integrated nano-to-millimeter sized systems. To make small-scale systems a reality, a comprehensive, well orchestrated research thrust must address a variety of issues that will serve to "integrate" these technologies from a systems level perspective. The workshop provided a forum for the interaction of different research communities in identifying innovative research aimed at overcoming the barriers in integrating components that are fabricated by multiple processes and span in size scale (nano through millimeter dimensions). NIST interests were in nano-, micro- and meso-scale technology in research, technology, measurements, standards and data. The results of this study contributed toward the development of a plan used to guide research funding by DARPA and NIST. [4]



- **September 1999 - Workshop: Manufacturing 3-Dimensional Components and Devices at the Meso and Micro Scales - NIST MEL Role: Lead sponsor and organizer**

  NIST MEL and the National Science Foundation (NSF) Engineering Directorate organized a workshop entitled "Manufacturing Three-Dimensional Components and Devices at the Meso and Micro Scales." The purpose of the workshop was to bring experts in the field of micro- and mesoscale manufacturing together and, through synergistic interaction, identify processes, measurement methods, targets of opportunity, application areas, and existing barriers to progress in the field. Consequently, research and development priorities for the immediate future were identified. The results of this workshop contributed toward the development of a plan used to guide future research funding by NSF and NIST. [5]

- **September 2001 – Conference: SPIE Nanostructure Science, Metrology and Technology - NIST MEL Role: Sponsor and Organizer**

  This workshop brought together leading scientists and engineers from government, industry and universities, to identify outstanding problems and issues in their respective fields. Questions and challenges raised by key speakers were addressed by panels of specialists in

micromanipulation and metrology of materials and by the audience at large. The goal was to answer questions such as: 1) What major issues in science and technology are addressable by nanostructure fabrication and micromanipulation of materials? 2) What the respective roles of industry, government, and universities are in advancing and nurturing these technologies? 3) What constitutes a successful application? 4) What is the role of basic scientific research in nanotechnology development? Full papers associated with this conference were published as a SPIE Proceedings volume. [6]

- **January 2002 – Workshop: Nanomanufacturing and Processing - NIST MEL Role: Session Chair – Manufacturing Processes and Instrumentation**

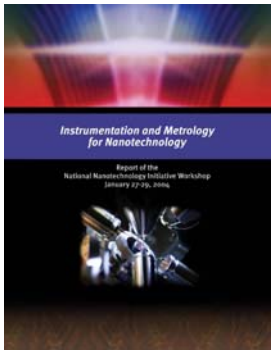
  The National Science Foundation (NSF) - European Community (EC) Workshop on Nanomanufacturing and Processing was held in San Juan, Puerto Rico. The goal of the workshop was to join forces of the NSF with the EC program agencies to catalyze progress in research and education in the emerging field of nanomanufacturing and processing. At that time a comprehensive Memorandum of Understanding (MOU) was signed by these two organizations. This collaboration provides a critical thrust for new scientific developments and engineering applications that were envisioned to have a mutually beneficial impact for both the U.S. and European research partners. The objectives of the workshop were to develop (1) Research milestones in (a) nanomaterials and nanomanufacturing; (b) prototyping, scale-up, and integration issues in nanomanufacturing, (c) measurement and metrology, and (d) theory, modeling, and simulation; (2) Security issues; (3) Resources - equipment, human and funding; (4) NSF-EC Collaboration - cooperative research programs and educational exchanges, sharing of nanomanufacturing research facilities and (5) Interactions in general with the community at-large. [7]

- **January 2003 - Mid-Atlantic Nanometrology and Nanomanufacturing Alliance (MANNA)® Meeting - MEL Role: Organizer**

  Dr. Michael Postek, then in the NIST Program Office, organized and hosted the first regional nanomanufacturing meeting between Virginia, Maryland, Pennsylvania and the District of Columbia. A broad range of organizations were invited to participate in the meeting representing the regional business, economic-development, federal laboratory, and university communities. Attendees at the meeting included: Maryland Technology Development Corporation (TEDCO), Northern Virginia Technology Council, Montgomery County Department of Business and Economic Development, Tech Council of Maryland, University of Maryland, Ben Franklin Technology Partners (Pennsylvania), Greater Washington Nanotech Alliance and Virginia's Center for Innovative Technology. The overall purpose of MANNA from the NIST vantage point was to: 1) lead in bringing the business, technical and governmental organizations together within the region (and country) to maximize the impact of the nanotechnology research funding, effectively leverage resources, and to avoid duplication, 2) enable through strong industrial partnerships, the acceleration of our Nation's ability to bring fundamental nanotechnology discoveries and advances into the commercial market ahead of our international competitors, 3) develop and ensure coordination among the research efforts of the various organizations in the region, 4) use the World-class capabilities of the NIST Advanced Measurements Laboratory and other regional resources to full

advantage, 5) maximize the impact of NIST's unique programs in nanometrology and nanomanufacturing, 6) identify and exploit other unique programs and resources, and 7) increase awareness of resources for NIST's work in nanotechnology. This meeting led to the development of the Chesapeake Bay Initiative driven by the state of Maryland and including Virginia and the District of Columbia. It also led to MOUs signed between NIST and the Northern Virginia Technology Council.

- **January 2004 – NNI Grand Challenge Workshop: Instrumentation and Metrology for Nanotechnology - NIST MEL Role: Sponsor and Organizer**



NIST MEL co-sponsored and organized the workshop under the auspices of the NSET sub-committee seeking input from the research community on one of the original "Grand Challenge" topics - Nanoscale Instrumentation and Metrology. The findings of this workshop were used in formulating the Program Component Area (PCA) on Instrumentation Research, Metrology, and Standards for Nanotechnology. The workshop was structured around five priority areas: (1) nanocharacterization, (2) nanomechanics, (3) nanoelectronics, (4) nanofabrication, and (5) nanomanufacturing. [8]

- **March 2004 to present – Nanotechnology in Microelectronics Workshop Series - NIST MEL Role: Sponsor and Organizer**

The Advanced Lithography community views CMOS as nanotechnology and semiconductor manufacturing as nanomanufacturing. State-of-the-art production lines are routinely producing microprocessors having sub-50 nm structures. The size, dimensions and the quantum confinement and other characteristics exhibited within these devices qualify these as being manufactured using nanotechnology. In 2004, NIST MEL was asked by SPIE to begin a workshop series entitled "Nanotechnology in Microelectronics." The 2009 topic of discussion was: "Is the end of CMOS near? Nanotechnology alternatives to CMOS scaling."

- **November 2005 – Workshop: NIST Carbon Nanotube Manufacturer's Workshop – NIST MEL Role: Sponsor and Organizer**

This meeting offered carbon nanotubes (CNT) manufacturers the chance to talk directly in a small setting. The goal was to identify overlapping measurement problems related to CNT manufacture. For example, many producers need low-cost, real-time measurement methods for process control. Others are concerned with product certification. Still others must find ways to classify materials for specific applications. This meeting was designed to help facilitate the development of a list of common needs, with as many specifics as possible, for which we can then collectively seek solutions. This strategy is not unlike the initial goals of SEMATECH in the mid 1980's, which developed into an industrial consortium for semiconductor manufacturing. While a consortium may not be the right goal for carbon nanotube manufacturing, it was thought that much could be gained by simply initiating a dialogue among suppliers so that they can see that there are commonalities of need on generic measurement issues, leaving proprietary issues to the individual companies. [9]

- **December 2004-2005-2006 – Conference: Nanoscale Science and Technology Grantees Conference - NIST MEL Role: Moderator - Nanomanufacturing Session and presenter**

  The National Science Foundation sponsors annual Grantees Conference on Nanoscale Science and Engineering (NSE) to review programs and research networking focused on the outcomes of the previous year's awards. The conference highlights the ongoing research of grantee projects and includes roundtable discussions designed to promote new partnerships for research and education among the NSE community. The conference is structured to initiate timely dissemination of innovative research progress, facilitation of partnerships, and identification of future research directions; all to advance the goals of the NNI. [10]

- **August 2006 to 2009 - Conference: Instrumentation, Standards and Metrology for Nanomanufacturing - NIST MEL Role: Conference Chair and organizer**

  In early 2006, NIST MEL created a new SPIE – Optics and Photonics – Science and Engineering conference entitled "Instrumentation, Standards and Metrology for Nanomanufacturing". This conference is evolving into a leading forum for the exchange of foundational information and discussion of instrumentation, metrology and standards which are needed components of nanomanufacturing. Advanced instrumentation, metrology and standards are needed to 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. Integration of these instruments, environment, health and safety, interoperability, and information management are all critical topics covered by this conference each of these elements must be considered for viable nanomanufacturing. [11]

- **October 2006 – Workshop: Instrumentation Metrology and Standards for Nanomanufacturing -NIST MEL Role: Lead sponsor and organizer**

  NIST MEL in collaboration with NSF, NRL/ONR and the National Science and Technology Council (NSTC), Interagency Working Group on Manufacturing Research and Development (IWG–MR&D) brought together experts in instrumentation, metrology, computational methods, and manufacturing processes, as well as those who depend on accurate measurements, to discuss and document progress made to date in these various areas, especially focusing on advancements since the January 2004 NNI Grand Challenge Workshop on Instrumentation and Metrology (see workshop description above). Facilitated breakout sessions on four focused areas of application were held to discuss visionary goals for each area, prioritize future needs, and identify the key technical barriers and challenges. The areas were (1) Chemicals, (2) Electronics, (3) Pharmaceuticals Pharma/Biomedical), and (4) Composites. Workshop discussions yielded recommendations for future research to enable the manufacture of real-world nanotechnology products that will help guide the IWG-MR&D in its efforts to assist U.S. manufacturers in leveraging these efforts into a competitive technological advantage. [12]

- **October 2007 - Predictive Modeling of Nanomaterial Properties - Modeling Needs – NIST MEL Role: Invited Participant.**

  The IWG workshop developed a good deal of interest in materials and process modeling. A conclusion was that predictive modeling is a needed tool for nanomanufacturing. Employing predictive modeling will save many millions of dollars if models are sufficiently accurate for a nanomanufacturing process. A workshop on this topic was sponsored by the National Science Foundation and was hosted by the Network for Computational Nanotechnology (NCN). NIST MEL was invited to participate in the workshop to provide a real-world experimental balance to the theoretical aspects being presented. The goal of the workshop was to identify critical needs, common themes, challenges, and opportunities for predictive modeling of nanomaterials and to define a research program to address these challenges and engage the National Science Foundation, U.S. manufacturing industry, and the federal laboratories. [13]

- **April 2008 – Conference: NanoMaterials for Defense Symposium - NIST MEL Role: Session chair/organizer of Nanoscale Production Challenges**

  The Symposium provided a forum to educate the defense community and explore the potential of nanotechnology in the realization of future DoD programs. The Nanoscale Production Challenges Session was focused on production challenges confronted by companies earlier in the design cycle that, if solved, would ensure smoother transition of products from the concept stage to a production level product. This includes all aspects of the production process such as design, metrology, modeling, information technology (IT), and key standards processes. The symposium was sponsored by the Air Force Research Laboratory (AFRL), Materials and Manufacturing Directorate (AFRL/ML) in conjunction with the Defense Advanced Research Projects Agency (DARPA), Army Research Laboratory (ARL), the Office of Naval Research (ONR), and Defense Threat Reduction Agency (DTRA). [14]

- **April 2008 - Workshop: National Science Foundation: Bio-Nano Manufacturing Challenges for 2020 -NIST MEL Role: Organizer and session chair – Measurement and Standards**

  The workshop brought together leaders in the emerging fields of biomanufacturing and nanomanufacturing to explore synergies and opportunities at the interface of bio and nano integrated manufacturing. Topics covered bio-nano manufacturing subjects areas such as cell-based biomanufacturing, freeform fabrication based biomanufacturing, bio-printing and patterning, organ and cell printing, biomaterials designing and coating as well as nanodesigning and multi-scale modeling, active and passive nanostructures by designing, functionally graded hierarchical nanointegrated systems, cellular sensory and actuator systems, multifunctional nano- and micro-scale metrology tools, and targeted drug delivery. The presentation and group discussion forums supported excellent interaction by the attendees resulting in identification of collaborative areas for bio-nano integrated manufacturing. [15]

- **May 2008 - Workshop: Cross Industry Issues in Nanomanufacturing -NIST MEL Role: Organizer and Sponsor**

  This conference identified common problems and common solutions specific to nanotechnology, manufacturing processes, and performance of nanomaterials in commercial products within widely different industries, including aerospace, automotive, chemical, food, forest products, medical technology, pharmaceutical, and semiconductor. The technical focus was on the three highest cross-industry priorities identified in previous workshops and meetings as they apply to the design, synthesis, and production of nanotechnology-enabled products: (1) characterizing nanomaterials and enhancing their separation and fractionation to address challenges in commercial production of uniform, high quality, stable, and consistent (reproducible) nanomaterials in high volume, (2) understanding and controlling the surface-dependent properties of nanomaterials such as dispersion, aggregation, and adhesion at their interface with a matrix, with an emphasis on non-covalent bonding interactions, and (3) understanding and controlling multiple properties of nanocomposites. [16]

5.0 KEY ASSIGNMENTS

The direction of nanomanufacturing research and development within the NIST MEL has been influenced significantly by; 1) research efforts, and 2) events and administrative positions by NIST MEL staff. Under the Nanomanufacturing PCA, there were opportunities for NIST personnel to take on additional assignments working with the NNI, positions within NIST, and positions at other agencies, when it was deemed beneficial to NIST and the collaborating agency. These assignments were critical in establishing NNI directions and in helping to shape MEL Nanomanufacturing and Nanometrology Programs and Projects.

- **June 2000 to September 2004 – Nanomanufacturing Program Manager**
  Mark Luce was selected as the first Program Manager for the Nanomanufacturing Program, succeeded by Kevin Lyons in late 2000. The Program was charged with the initiation, definition and execution of new lab level research efforts in nanomanufacturing. This involved the conceptualization, development, and execution of advanced research and development efforts that support manufacturing measurement sciences and standards. The initial thrust areas focused on atomic scale manufacturing, molecular scale manipulation and assembly, and micro/millimeter scale positioning and assembly. This multi-disciplinary program was cross-divisional within the MEL and supported joint research with other NIST labs, other federal labs, universities, and industry.

- **October 2002 to present – National Nanotechnology Coordination Office (NNCO) Director**

  Dr. E. Clayton Teague, then Chief of the Manufacturing Metrology Division, was assigned as the Director of the National Nanotechnology Coordination Office (NNCO). The NNCO was established in 2001 and serves as the secretariat to the Nanoscale Science, Engineering and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC). The NNCO provides day-to-day technical and administrative support to the NSET Subcommittee and has developed strong nanotechnology coordination between the 24 agencies interested in nanotechnology research activities.

- **March 2003 – National Science Foundation Committee of Visitors Board Member**

  NIST MEL provided a representative on the National Science Foundation (NSF) Committee of Visitors (CoV) responsible for reviewing the academic programs of the Engineering Directorate's Division of Design, Manufacture, and Industrial Innovation (DMII). The review covered the fiscal years 2000, 2001, and 2002. The academic programs in the Division fell into three main clusters, the engineering decision systems cluster, the manufacturing processes and equipment systems cluster, and the bridge programs across NSF. The Manufacturing and Equipment Systems Cluster was comprised of the Manufacturing Machines and Equipment (MME), Material Processing and Manufacture (MPM), and Nanomanufacturing (NM) programs. [17]

- **May 2004 to March 2009 - Interagency Working Group on Manufacturing Research and Development**

  The Interagency Working Group (IWG) on Manufacturing Research and Development (MR&D) was chartered as part of the National Science and Technology Council (NSTC), Committee on Technology in May 2004. This followed the January 2004 release of the Department of Commerce (DoC) report, Manufacturing in America report and the announcement of President Bush's Manufacturing Initiative. The objective of the IWG-MRD was to identify and integrate R&D requirements and to develop strategies for the Federal Government's manufacturing R&D programs [18]. The IWG-MRD selected three technology priority areas to form the basis for a coordinated, multi-agency focus on manufacturing R&D. These topics; 1) Nanomanufacturing, 2) Intelligent & Integrated Manufacturing, and 3) Manufacturing R&D for the Hydrogen Technologies, were presented at a public forum in March 2005 and each are aligned with an existing National Initiative.

  Phil Bond, Undersecretary of Commerce for Technology, was the first IWG Chair and Dr. Dale Hall, Director of the Manufacturing Engineering Laboratory at the National Institute for Standards and Technology (NIST) was the Vice Chair. In June 2005, Dr. Hall assumed responsibility as Acting Chair of the IWG and later that year was officially appointed IWG Chair. Dr. Hall remained in that position until he retired from Federal service in August 2007. From its chartering in May 2004 until May 2006, 2 separate ASME Fellows to OSTP served as IWG Executive Secretary - Michael Molnar first, then Susan Skemp. Following Susan Skemp's departure from OSTP in May 2006, Dave Stieren assumed the Executive Secretary functions for the IWG. The IWGMRD membership includes representatives from 15 federal agencies and the existing Charter ran through March 31, 2009.

  May 2004 – National Science Foundation - Nanoscale Science and Engineering (NS&E) Committee of Visitors Board Member

  NIST MEL provided a representative on the NSF Committee of Visitors (CoV) responsible for reviewing the NSF cross-directorate program in Nanoscale Science and Engineering (NS&E). The review covered the fiscal years 2001, 2002, and 2003. The NS&E program is

complex, highly distributed, involves program managers from seven NSF Directorates, and requires coordination with other Federal agencies. The NS&E solicitations included four modes of support: the Nanoscale Science and Engineering Centers (NSEC), the Nanoscale Interdisciplinary Research Teams (NIRT), Nanoscale Exploratory Research (NER), and Nanotechnology Undergraduate Education (NUE). The solicitations addressed seven themes, including biosystems at the nanoscale; nanoscale structures, novel phenomena, and quantum control; nanoscale devices and architectures; nanoscale processes in the environment; multi-scale, multi-phenomena theory, modeling, and simulation; manufacturing processes at the nanoscale; and societal and educational implications of scientific and technological advances on the nanoscale. [19]

- **October 2004 to October 2006 – NSF Program Director**

  Kevin Lyons was selected as NSF Nanomanufacturing (NM) Program Director. The NSF NM Program supports research and education on manufacturing at the nanoscale, and the transfer of research results in nanoscience and nanotechnology to industrial applications. The program emphasized a systems approach to scale-up of nanotechnology for high rate production, reliability, robustness, yield and cost, and promotes integration of nanostructures to functional micro devices and meso / macroscale systems. Special emphases were on environmental, health, and societal aspects of nanotechnology and nanomanufacturing.

- **October 2003 to May 2008–National Science, Engineering and Technology (NSET) Subcommittee member**

  Dr. Michael Postek was assigned as one of the NIST representatives on the multi-agency National Science, Engineering and Technology (NSET) Subcommittee of the U.S. National Science and Technology Council. The purpose of the NSET Subcommittee is to coordinate multi-agency NSET R&D to (1) assure continued U.S. leadership in nanotechnology; (2) satisfy the needs of the Federal government for advanced nanotechnology; and (3) accelerate development and deployment of advanced nanotechnology to maintain world leadership in science and engineering; enhance national security; improve U.S. productivity and competitiveness and promote long-term economic growth; improve the health of the U.S. citizenry; protect the environment; improve education, training, and life long learning, and improve the quality of life. [20]

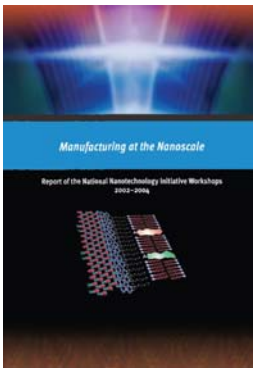
- **January 2004 to June 2007 - Assistant to the NIST Director for Nanotechnology.** NIST developed a Strategic Working Group for Nanotechnology and Dr, Michael Postek was assigned the position of Chair and the Assistant to the NIST Director for Nanotechnology. The Strategic Working Group was responsible for the development of the NIST Accomplishments in Nanotechnology Document (see below), a CRADA with NASA and the planning and execution of several other nanotechnology related workshops (as described above).

- **October 2006 - Sponsor and Organizer of World Technology Evaluation Center (WTEC) study titled "International Assessment of Research and Development on Carbon Nanotubes (CNT's): Manufacturing and Applications"**

The study focused on the manufacturing and emerging applications of carbon nanotubes (CNTs) and supported the free exchange of ideas and research approaches for addressing the challenges of manufacturing CNTs. Four goals were identified: (1) Identify good ideas overseas worth exploring in U.S. R&D programs, (2) Clarify research opportunities and needs for promoting progress in the field generally, (3) Identify opportunities for international collaboration, and (4) Evaluate the position of foreign research programs relative to those in the U.S. [21]

6.0 PUBLICATIONS

- **January 2005 – Manufacturing at the Nanoscale- NIST MEL Role: Principal author and contributor**



The report is based on a series of workshops held from 2002 through 2004 led to this report on the vision, advances, future directions, and strategic priorities for advancing manufacturing at the nanoscale. "Manufacturing at the Nanoscale" published by the National Nanotechnology Initiative (NNI). The report was prepared by NSF Program Directors for Nanomanufacturing Julie Chen, UM-Lowell, Kevin Lyons, NIST MEL, and Haris Doumanidis, University of Cyprus. [22]

- **August 2006 – Accomplishments in Nanotechnology - NIST MEL Role: Editor and contributor**

Michael Postek, Joseph Kopanski and David Wollman compiled and published NIST "Accomplishments in Nanotechnology" that included NIST/MEL nanomanufacturing metrology activities. Special Publication (NIST SP) – 1052 [23]

- **January 2004 - Instrumentation and Metrology for Nanotechnology - NIST MEL Role: Editor and contributor**

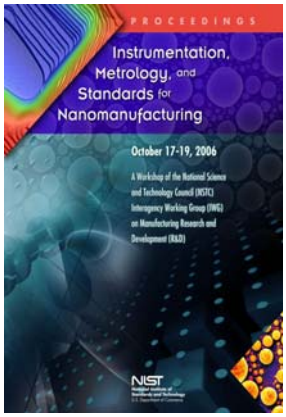
The NNI Workshop report identifies and highlights research needs in five priority areas for nanotechnology-related instrumentation and metrology; (1) nanocharacterization; (2) nanomechanics; (3) nanoelectronics; (4) nanomagnetics and nanophotonics; (4) nanofabrication; and (5) nanomanufacturing. [8]

- **October 2006 - World Technology Evaluation Center (WTEC) study titled "International Assessment of Research and Development on Carbon Nanotubes (CNT's): Manufacturing and Applications" - NIST MEL Role: Sponsor and Organizer**

The study focused on the manufacturing and emerging applications of CNTs and supported the free exchange of ideas and research approaches for addressing the challenges of manufacturing CNTs. Four goals were identified: (1) Identify good ideas overseas worth exploring in U.S. R&D programs, (2) Clarify research opportunities and needs for promoting

progress in the field generally, (3) Identify opportunities for international collaboration, and (4) Evaluate the position of foreign research programs relative to those in the U.S. [24]

- **October 2006 – Instrumentation, Metrology and Standards for Nanomanufacturing - NIST MEL Role: Editor and contributor**



  The National Science and Technology Council (NSTC), Interagency Working Group on Manufacturing Research and Development (IWG-MRD) The report identifies and highlights research needs from the October 2004 workshop. The workshop identified technical challenges for instrumentation, metrology, and standards for manufacturing at the nanometer-scale, and appropriate roles for academia, industry, and government. [12]

7.0 RESEARCH EFFORTS -- PROGRAMS IN MEL

Interest in nanometrology did not just arise within MEL with the surge of interest in nanotechnology. MEL was working on nanoscale measurements for a long time prior to the inception of the NNI. One of the most aggressive projects within MEL was the development of the Molecular Measuring Machine (M^3) which began in 1987. [25] In addition, a good deal of dimensional metrology work in collaboration with the NIST Office of Microelectronics Programs (OMP) and SEMATECH set the stage for the nanometrology needs for nanomanufacturing. Much of this work is infrastructural in that it is capable of being used for many applications other than exclusively for nanoelectronics. For example, dimensional metrology of sub-100 nm transistor gates is directly applicable to particle metrology for environment, health and safety. Therefore, research by MEL in nanotechnology is a logical continuation of the interest of NIST to perform better and more accurate measurements in length, mass and force with the lowest uncertainties possible. [26]

- **June 2000 – Nanomanufacturing Program:** Recognizing the need for the development of needed measurements for nanotechnology, the Manufacturing Engineering Laboratory initiated a new multiyear Nanomanufacturing Program. The Program elements included the conceptualization, development, and execution of advanced research and development efforts that support manufacturing measurement sciences and standards. This multi-disciplinary program was cross-divisional within the MEL and supported joint research with other NIST labs, other federal labs, universities, and industry. The Program identified the following five projects to launch R&D efforts:

    - **Atom-scale Measurement and Manipulation**: The project developed expertise to measure and modify the local atomic structure using scanning probe measurement (SPM) techniques. Work included developing the expertise to fabricate standards that have atomically precise, but pre-determined positions and atomic structure. This type of manufacturing process results in standard reference materials (SRM's) with features written directly in atomically ordered surfaces.

- **Nanolithography of Test Structures and Devices:** This project made test nanostructures and devices, from arrays of features to fluidic devices and three dimensional structures. Fabrication of these test structures and devices supported work in MEL to identify measurement obstacles to efficient nanomanufacturing, and determine the measurement and standards needs of this nascent industry. The proposed lithography techniques, integrated with electronic devices, such as polymer-based integrated circuits and luminescent polymers, opened the possibility of rapid and economical development and manufacturing of components ranging from simple structures to complex 3D components integrating mechanical, electronic, optical, and bio/molecular functions.

- **Optical Manipulation and Assembly of Nanoscale Devices**: This work identified and addressed the fundamental measurement and standards issues related to manipulation and assembly of nanoscale devices. The work entailed building the manipulation technology and using it to understand the measurement issues that arise when assembling devices at the nano level. The measurement and standards issues range from the role of forces (e.g. capillary, Van der Waals) that dominate the interaction of parts at this level, to the interoperability of high level (heuristic) interfaces with tools to allow for efficient assembly at the nanoscale.

- **Performance Evaluation of Nanomanufacturing Tools:** The objective of this work was to define a comprehensive set of parameters and associated testing procedures providing the foundation for standards to specify, describe, and verify the performance of key nanomanufacturing tools. The initial focus was on the development of practical standards that address the key error sources of various scanning probe microscopes for nanoscale measurement and modification. Typical examples of error sources for the scanner module of an SPM are: (uncompensated) piezo non-linearity, axis cross-coupling, hysteresis, creep, effectiveness of the compensation for bowing errors, and ringing. Both the magnitude and effect of these error sources depends on many variables such as scan direction, scan speed, workspace position, scan area, and previous operations (zooming).

- **Virtual Reality for Nanoscale Manipulation, Measurement, and Assembly:** The objective of the work was to develop new methods to support the user in exploring nanoscale manipulation, measurement, and assembly options and in identifying critical problems confounded by working in a non-intuitive environment. Through the use of VR techniques and physics-based models, one is able to present the user with key feedback regarding the nanoscale manipulation, measurement, and assembly process in a meaningful and more intuitive way.

- **High Precision Meso Micro Nano Devices:** The project developed expertise with the design, fabrication, control and performance testing of high precision nanopositioners. A new family of two degree of freedom planar nanopositioners, called “Dual Parallel Lever Nanopositioners,” was invented. Macro scale and meso scale prototypes of this device were built and tested. The device was found to have the lowest angular deviation error than any commercial nanopositioner of comparable

size and range of motion. Based on the design of the planar device a six degree of freedom nanopositioner was invented. A prototype device and controller were built and tested.

- **October 2005 – Cross-laboratory Nanomanufacturing Program:** MEL evolved the previous nanomanufacturing program into an expanded cross-laboratory Nanomanufacturing Program with the goal of developing and delivering timely measurements, standards, and infrastructural technologies that address identified critical U.S. industry and other government agency needs for innovation and traceable metrology, process-control and quality in manufacturing at the nanoscale. The three main programmatic themes included: 1) imaging and metrology (scanning electron microscopy, atomic force metrology, optical metrology, nano-force metrology); 2) nano-fabrication (e-beam lithography, scanned probe microscope lithography, atom-based standards, imprint lithography, nano-machining); and 3) control and assembly (high precision stages, optical tweezers).

- **October 2008** – **Division centric Nanomanufacturing Program:** MEL evolved into a more division centric program model with each division contributing appropriate programs in nanomanufacturing (see below). This new program supports nanomanufacturing [5] by developing a measurement infrastructure that reduces the barriers for technological innovation and successful commercialization of nanoscale products. This is accomplished through fundamental scientific research, theory, and experiments in precision metrology at the nanoscale in the manufacturing sector. The following focus areas are emphasized: 1) reliable, scaled-up, cost effective manufacturing of nanoscale materials, devices and systems; 2) robust manufacturing practices coupled with the necessary standards and measurement infrastructure; 3) development of the instrumentation, tools and processes needed to bridge the gap between discovery and commercialization; 4) development of a measurement infrastructure and a set of standards for nanomanufacturing to reduce the barriers for technological innovation and successful commercialization of nanoscale products.

- **2009 Precision Engineering Division Nanomanufacturing Metrology Program** - The increasing pace of technological change in nanomanufacturing makes accurate dimensional nanometrology critical to innovation and realization of quality products. Industries currently manufacturing at the nanoscale are challenged by the need for new innovative infrastructural metrology and standards to monitor process control and product quality. The goal is to advance U.S. leadership in nanomanufacturing through the development of physics-based models, calibration techniques, and physical standards which enable accurate determination of dimensional information.

- **2009 Precision Engineering Division Next-Generation Nanometrology Program** - The next generation of nanotechnology industries will face dimensional measurement and characterization challenges that far exceed the capabilities of current measurement science. The manufacturing paradigm at this scale is rapidly being transformed by major advances in self-assembly, bio-manufacturing, and massively-parallel atomically-precise manufacturing. These revolutionary manufacturing methods will require a complete rethinking of the methods and application of measurement science to manufacturing; incremental improvements of existing methods will be inadequate. Nanometer-scale objects and features

in complex three-dimensional matrices must be measured with unprecedented precision and uncertainty, and with extremely high throughput.

- **2009 Manufacturing Metrology Division, Mechanical Metrology Program** - Advances the science of SI mechanical metrology to anticipate the future needs – and address unmet present needs – of U.S. industry and government in the areas of acoustics, force, mass, and vibration. New and innovative approaches that push the limits of the current state-of-the-art are required in order to establish the future measurements and standards needed for continued advancement and competitiveness of critical U.S. industries in the global market. In the Small Force Metrology project support for U.S. instrumentation vendors, academic researchers, government scientists, and a broad spectrum of industrial physicists, physical chemists, biophysicists, and materials scientists who seek accuracy in verifying the forces measured by instrumented indentation equipment and atomic force microscopes (AFM). The forces measured by these instruments range from tens of piconewtons in single-molecule biophysical studies of disease therapies, to tens of millinewtons in studies of new dielectric coatings for metals and semiconductors. The need for quantitative force measurement among this wide-ranging constituency is fueled by a variety of factors. In direct response to these customer needs, this project focuses on creating the means to achieve SI traceability for small force measurement and instrumentation, and includes the development and testing of internationally-accepted primary and secondary standards of force in the regime below $^{10-3}$ N, exploration of atomic and single-molecule forces as potential intrinsic standards and references, and the development of new instrument platforms at NIST that are capable of realizing ever smaller values of force in terms of traceably realized SI base units and quantum invariants.

- **2009 Intelligent Systems Division, Measurement Science for Intelligent Manufacturing Robotics and Automation Program**, Control Systems and Positioning for Nanoscale Measurements and Standards Project - The goal of this project is to develop control and positioning systems for nanoscale measurements, manipulation, and standards, and enable scale-up interfaces and standards between the micro/nano manufacturing tools and the macro scale world. A challenge of micro/nano manufacturing is the development of methods to build complex three-dimensional (3-D) micro/nano scale structures and devices using techniques that allow them to interface with the macro scale world (scale-up), at economic production rates. New capabilities at the micro-nano scale must be combined to meet these challenges, such as, dexterous manipulation and assembly, precision motion control, and real-time metrology and sensing. The metrology of micro/nano structures, such as nanowires, nanoparticles, proteins, cells, etc., is a key enabling technology for advances in micro/nano technology and manufacturing, presenting many opportunities for novel micro/nano electromechanical and biomedical systems. High precision macro/meso scale nanopositioners, invented under another MEL program, have been reduced to MEMS micro scale dimensions, fitted with embedded sensors and mounted with nanoprobes. The original nanopositioners have now become arrays of high precision micro/nano robotic manipulators capable of performing sophisticated testing and micro/nano metrology work. We call this "Dynamic and Intelligent Micro/Nano Metrology," because of the ability of these devices to adjust to changing testing conditions and three dimensional (3-D) space manipulation. This is

an enabling technology, which can affect the development of markets in many new classes of products that require accurate nano component 3-D position and orientation.

8.0 SUMMARY AND CONCLUSION

The Government has a key role in the development of tools that can be broadly applied, and infrastructural efforts such as the development of standardized methods, reference data, and calibrated standards are a key role for NIST. [2] U.S. manufacturer's success in nanomanufacturing is reliant on their ability to measure product and process performance. For production, measurement is critical for controlling the processes to maintain needed quality and output levels. For products, measurements ensure product conformance to engineering specifications and customer requirements. One measure of success will be the number of products on the market that exploit nanotechnologies during their production or to achieve end use properties and functionality. Nanomanufacturing innovations will benefit society in various industry sectors such as advanced materials, electronics, aerospace, automotive, appliances, pharmaceutical, biochemical, agriculture/food, energy, environmental monitoring, environmental remediation, health and safety, information technologies, and a variety of yet-to-be-defined service industries. Current product areas that are nano-enabled include antibacterial (washers to food storage containers), battery (cathode, electrode), protective films/surfaces (car wax to sunscreen), conductive films (displays), health (vitamins to nanoparticle syrups), and structural nanocomposite applications (sporting equipment to boat hulls). [27] Promising advances in pre-competitive research indicate accelerating results will likely occur in information technologies, alternative energy and medical applications. Future products may include IT nanodevices such as molecular electronics and spintronics; nanobiotechnology-based diagnostics, implants, and drug-delivery systems; measuring devices and tools for manufacturing; and nano-electromechanical systems.

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