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A Method for Assigning Priorities to United States Measurement System (USMS) Needs: Nano-electrotechnologies[+,*]

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Abstract

In 2006, the National Institute of Standards and Technology conducted an assessment of the U.S. measurement system (USMS), which encompasses all private and public organizations that develop, supply, use, or ensure the validity of measurement results. As part of that assessment, NIST collaborated with Energetics Incorporated to identify and authenticate 723 measurement needs that are barriers to technological innovations. A number of these measurement needs (64) are relevant to accelerating innovation and commercialization of nano-electrotechnologies. In this paper, we apply the taxonomy from a 2008 international survey that established a global consensus of priorities for standards and measurements in nano-electrotechnologies to rank in priority order the relevant 64 USMS-identified measurement needs. This paper presents a method for assigning priorities that is statistically based and represents a global consensus of stakeholders. Such a method is needed because limited resources exist to address the large number of measurement needs in nano-electrotechnologies, and the most critical measurement needs should be addressed first.

Key Words: United States Measurement System, nano-electrotechnologies, median method, Borda count method, standards, rankings, priorities, statistical significance, and measurement needs.

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A Method for Assigning Priorities to United States Measurement System Needs: Nano-electrotechnologies

1. Introduction

Nano-electrotechnologies are expected to be among the key technologies of the 21st century. They have enormous potential for the development of new products with exceptional performance. Nano-electrotechnologies will enable society to take advantage of economic successes, as well as improvements in the quality of life by using nano-enabled products. A strong measurements and standards infrastructure is essential if the investments in nanotechnologies are to be successful for the delivery of useful products and services.[1,2] International commerce in nano-electrotechnologies will require technically valid standards and related measurements that are suitable for use in any nation. These standards must therefore be developed with input from all stakeholders.

According to a recently published report of Semiconductor Equipment and Materials International (SEMI) in cooperation with the Semiconductor Industry Association (SIA) [3] and by the RNCOS Group [4], the materials and equipment market for nanoelectronics was US$ 1.8 Billion in 2005 and is expected to be US$ 4.2 Billion in 2010. The continued rapid growth of this and other nano-electrotechnologies-based industries has required increased international standardization activities to support equitable and efficient business models.

Applications of Nano-electrotechnologies [5]

- Analytical equipment and techniques for measurement of electrotechnical properties
- Fabrication tools for integrated circuits (electronic, photonics, and optoelectronic)
- Nano-structured sensors
- Nano-electronics, materials and devices
- Optoelectronics
- Optical materials and devices
- Organic (opto) electronics
- Magnetic materials and devices
- Radio frequency devices, components, and systems
- Electrodes with nano-structured surfaces
- Electrotechnical properties of nanotubes/nanowires
- Fuel cells
- Energy storage devices (e.g., batteries)
- Bioelectronic applications
- Nano-enabled solar cells

Due to the large number of potential applications for nano-electrotechnologies and to the limited resources for development of standards, there is a need to prioritize future standardization work and make certain that the most important standards are developed first. A recent international effort in this regard is the NIST-Energetics-International Electrotechnical Commission (IEC) Technical Committee (TC) 113 International Survey.[6] The analysis described in this paper builds on this previous effort to prioritize standards and their associated measurement needs (MNs) by applying a method for assigning priorities that is statistically based and represents a global consensus of stakeholders.

1.1 Objectives

The objectives of this paper focus on the results of previous efforts and the analyses conducted on a proof-of-concept approach for prioritization. Section 2 summarizes the background, origin, structure, methodology, demographics, and results of prior efforts to prioritize measurement needs, including a 2006 assessment of the U.S. measurement system [7] and the IEC international Survey. Section 3 contains the procedures by which we assign priorities to the 64 USMS MNs on nano-electrotechnologies identified in the 2006 assessment based on the Survey taxonomy. Section 4 contains a summary of the major results. Finally, Appendix A contains a listing of the 64 case studies of USMS MNs on nano-electrotechnologies.

Definitions

*"**Nanotechnology** is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale. …. Dimensions between approximately 1 and 100 nanometers are known as the nanoscale. Unusual physical, chemical, and biological properties can emerge in materials at the nanoscale. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules."* [8]

Nano-electrotechnologies - include the following areas at the nanoscale: nanostructured sensors; nano-electronics, nano-materials and nano-devices; optoelectronics; optical materials and devices; organic (opto)-electronics; magnetic materials and devices; radio frequency devices, components and systems; electrodes with nanostructured surfaces; electrotechnical properties of nanotubes/nanowires; analytical equipment and techniques for measurement of electrotechnical properties; patterning equipment and techniques; masks and lithography; performance, durability, and reliability assessment for nanoelectronics; batteries; fuel cells; and bioelectronic applications. [9]

2.0 Nanotechnology Measurement and Standards: Assessment and Prioritization

2.1 2006 Assessment of the U.S. Measurement System

As the national measurement institute for the United States, the National Institute of Standards and Technology (NIST) assists all stakeholders in selected fields with measurement and standards needs. The goal of NIST's involvement is to enhance efficiency and productivity and to increase the rate of technological innovation. NIST is not a regulatory agency, but rather serves as a neutral third party often providing technical input in matters related to measurements and standards to a variety of customers such as standards committees, regulatory agencies, other government agencies, universities, and the private sector where appropriate. In 2006, NIST accepted the challenge to evaluate whether the U.S. measurement system (USMS) is meeting the nation's measurement needs and produced an assessment detailing the findings.[7] Nanotechnology was one of the sector areas assessed in terms of measurement needs for accelerating technological innovation and commercialization.

As part of that assessment, NIST collaborated with Energetics Incorporated to identify and authenticate 723 measurement needs that are barriers to technological innovations. These measurement needs were derived from case studies and a review of technology roadmaps and reports in the public literature. Appendix B of the June 2006 USMS Assessment Report [7] contains 342 case studies of measurement needs (MNs), of which 64 cases studies concerned nano-electrotechnologies.

Based on their evaluation of measurement needs, the authors of the June 2006 USMS Assessment Report [7] made the following observations about nanotechnologies:

- Nanotechnology is unique among the sector/technology areas in its high demand for new advanced measurement instrumentation, which is needed to achieve accurate, high-resolution characterization of physical, chemical, and biological properties of materials at nanometer dimensions.

- Industry is limited not only in its ability to measure key parameters but also in its ability to identify which key parameters must be measured to meet anticipated regulations.

- The absence of measurement tools with the capability to measure properties of nanomaterials and nanodevices as they relate to functional performance and to make such measurements at speed are impediments to realization of nanotechnology products.

- Public-sector measurement providers that are linked to applied research sectors, production communities, market drivers, and user issues can help accelerate the innovative process.

- Innovative approaches to the measurement of nanoscale physical and chemical properties are key to technological innovation for Nanotechnology, especially where the fundamental limits of current measurement techniques are being approached.

Industry technology roadmaps are an important source of measurement needs pertinent to nanotechnologies. These include the 2007 International Technology Roadmap for Semiconductors [1] and the 2003 Chemical Industry Roadmap for Nanomaterials by Design.[4] Prepared in conjunction with the USMS 2006 Assessment, the USMS Technology Roadmap Review Summary Report identified a number of measurement needs relevant to nanotechnologies, some of which are shown below.[7]

- Sensing and detection devices operating at the nanoscale are likely to have myriad applications, including: detection of chemical, biological, radiological, and explosive elements; detection and treatment of infection, nutrient deficiency, and other health problems; tracking of food pathogens and agricultural products; nanoseparation and nanobioreactors; ensuring food safety; environmental monitoring; advanced protective clothing and filters and remediation of attacks; and creating anti-fouling nanosurfaces (e.g., packaging).

- A broad range of measurement needs associated with the understanding, characterizing, synthesizing, and manufacturing of new nanomaterials: characterization tools, methods, and instruments for properties measurement; tool development infrastructure; reference standards and protocols for synthesis and analysis protocols; robust measurement tools for manufacturing; characterization, measurement, and simulation probes for use during synthesis; and measurements for environmental, health, and safety impacts of nanomaterials.

- Measurement capabilities to further development and application of nanostructures as energy carriers (optimized energy transport); characterization methods, theory, imaging tools, and simulation and modeling to link nanoscale structure and function for nanomaterial assembly and architecture with the design of new materials for energy applications; and measurements to aid evaluation and development of carbon nanotubes for hydrogen storage.

2.2 NIST-Energetics-IEC TC 113 International Survey

In 2008, the IEC TC 113 on nano-electrotechnologies invited members of the international nanotechnologies community to respond to a Survey to identify those nano-electrotechnologies relevant to electronics and electrical products and systems for which standards are critically needed to accelerate innovation. The resulting Survey paper [6] contains the analyses of 459 Survey responses from 45 countries.

The Survey represents one way to begin building a consensus on a framework leading to nano-electrotechnologies standards development by standards organizations and national measurement institutes. The expectation was that responses to the Survey would enable the IEC TC 113 to:

- set procedures for ranking proposals and associated documents for new work in priority order;
- identify members for work groups on standards and associated documents; and
- make informed responses to proposals from IEC National Committees.

The distributions of priority rankings from all 459 respondents are such that there are perceived distinctions with statistical confidence between the relative international priorities for the several items ranked in each of the following five Survey category types:

1) Nano-electrotechnology Properties,
2) Nano-electrotechnology Taxonomy: Products,
3) Nano-electrotechnology Taxonomy: Cross-Cutting Technologies,
4) IEC General Discipline Areas, and
5) Stages of the Economic Model.

Table 1 illustrates the category types and taxonomy employed in the Survey. One of the primary goals was to determine a consensus prioritization among the items listed for each of the category types. With this goal in mind, the Survey required the respondents to rank all items for each of the five category types, with no ties allowed.

Tables 2 through 4 from the Survey paper [6] show the consensus priorities for each of the first three category types as determined by a traditionally weighted scoring technique called the Borda count.[10] The Survey paper provides complete details of the method and results of the statistical analyses. Applying this procedure to the Survey category types, the following Borda score-weights were assigned: the first-placed items (highest priority or most significant) on every ballot receive scores of n_i, the second-placed items receive scores of n_i - 1, and so forth, until the lowest priority or least significant items on the ballot receive scores of 1. Scores were assigned to each of the 459 ballots from the respondents individually and then summed over all ballots within the category type of interest.

Items were ranked in descending order by the Borda score; *i.e.,* the highest score is the “winner.” In short, the Borda score is a weighted mean with a particular assignment of weights to ballot positions. These Borda count orderings are referred to throughout the paper as the “global consensus” orderings. The global consensus order may not be the same as the order when only

rank 1 votes are considered. For example, *Fabrication Tools* in Table 4 received 109 rank 1 votes, 61 rank 2 votes,…, and 44 rank 8 votes. All of the remaining 7 items in Table 4 received fewer than 109 rank 1 votes. The median rank of the underlying random variable was estimated to be 3 ±0.29. The global consensus is that *Fabrication Tools* is second to *Sensors* as a priority activity. Appendix B of the Survey paper [6] contains the definition for the 95 % confidence interval (CI) and describes the methodology in detail.

Table 1. Category Types and Rank Items Employed in the Survey [denotes abbreviation in data tables]
1. Properties • *Electronic and Electrical* [Electronic] • *Optical* [Optical] • *Biological* [Biological] • *Chemical* [Chemical] • *Radio Frequency* [Radio] • *Magnetic* [Magnetic]
2. Products • *Energy (production, conversion, and storage)* [Energy] • *Medical Products* [Medical] • *Computers (PDA and similar, laptop, desktop, mainframe) and Computer Peripherals (printers, monitors/displays, etc.)* [Computers] • *Telecommunication and Data Communications (wireless and wired-physical connection)* [Telecom] • *Security and Emergency Response Devices and Applications* [Security] • *Multimedia Consumer Electronics* [Multimedia] • *Household and Consumer Applications* [Household] • *Transportation (sea/water, ground, air, space*) [Transportation]
3. Cross-Cutting Technologies • *Sensors (chemical, physical, mechanical, etc.)* [Sensors] • *Fabrication tools for integrated circuits (electronic, photonic, optoelectronic, and mechanical)* [Fab. Tools] • *Nano-electromechanical systems* [NEMS] • *Performance and reliability assessment for nanoelectronics* [Performance] • *Analytical equipment and techniques for measurements of electro-technical properties* [Analytic Eq.] • *Environment, Health, and Safety (EHS) applications and effects* [EHS] • *Instrumentation (test equipment and industrial process control for use in fabrication)* [Instrumentation] • *Optical technologies (optoelectronics and illumination)* [Optical Tech.]
4. General Discipline Areas • *Measurement and Performance* [Measurement] • *Design and Development* [Design] • *Health, Safety, and Environment (HSE)* [HSE] • *Dependability and Reliability* [Dependability] • *Electromagnetic Compatibility* [Compatibility] • *Terminology, Nomenclature, and Symbols* [Terminology]
• **Stages of Economic Model** • *Basic Technical Research* [Research] • *Technology Development (prototype development)* [Development] • *Initial deployment* [Deployment] • *Commercialization (large-scale, high-volume manufacturing)* [Commercialization] • *End of initial use by the Customers-Consumers (End of Initial Usefulness)* [End-of-Usefulness] • *End-of-Life (disposing and recycling)* [End-of-Life]

Table 2. Consensus Priority Rankings for Properties [6]

	Raw Data						Median and 95 % CI	Borda Score	Borda Global Consensus Rank
	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6			
Electronic	292	57	58	26	13	13	1 (+ 0.07)	2,386	1
Optical	17	115	112	105	78	32	3 (± 0.15)	1,628	2
Biological	68	73	68	75	77	98	4 (± 0.22)	1,522	3
Chemical	37	86	70	68	113	85	4 (± 0.22)	1,447	4
Radio	34	83	69	78	63	132	4 (± 0.29)	1,387	5
Magnetic	11	45	82	107	115	99	4 (± 0.15)	1,269	6

Table 3. Consensus Priority Rankings for Products [6]

	Raw Data								Median and 95 % CI	Borda Score	Borda Global Consensus Rank
	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8			
Energy	130	94	69	52	34	37	18	25	3 (± 0.22)	2,680	1
Medical	85	103	85	57	41	45	26	17	3 (± 0.22)	2,564	2
Computers	109	63	60	59	57	52	31	28	3 (± 0.22)	2,442	3
Telecom	57	82	72	89	72	43	29	15	4 (± 0.22)	2,397	4
Security	25	43	62	67	75	77	51	59	5 (± 0.22)	1,900	5
Multimedia	22	39	47	59	72	65	83	72	5 (± 0.22)	1,747	6
Household	20	12	39	30	47	76	119	116	7 (± 0.22)	1,398	7
Transportation	11	23	25	46	61	64	102	127	6 (± 0.22)	1,396	8

Table 4. Consensus Priority Rankings for Cross-Cutting Technologies [6]

	Raw Data								Median and 95 % CI	Borda Score	Borda Global Consensus Rank
	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8			
Sensors	100	94	60	49	51	45	34	26	3 (± 0.22)	2,496	1
Fab. Tools	109	61	66	52	47	40	40	44	3 (± 0.29)	2,387	2
NEMS	59	71	59	58	65	45	46	56	4 (± 0.29)	2,156	3
Performance	55	54	58	57	57	61	60	57	5 (± 0.29)	2,039	4
Analytical Eq.	30	57	54	70	80	74	58	36	5 (± 0.22)	2,007	5
EHS	71	40	45	39	48	54	66	96	5 (± 0.29)	1,895	6
Instrumentation	13	39	58	73	60	71	84	61	5 (± 0.22)	1,772	7
Optical Tech.	22	43	59	61	51	69	71	83	5 (± 0.29)	1,772	7

3. Assigning Priorities to USMS Measurement Needs for Nano-electrotechnologies

As noted earlier, there is a large number of measurement needs for nano-electrotechnologies and limited resources to address them (both domestically and globally). Consequently, there is a need to rank these in priority order so that resources can be applied to addressing those needs that are most important to accelerating innovation.

For this analysis we assumed that the set of 64 MNs identified in the 2006 USMS assessment may serve as a proxy for the universe of nano-electrotechnology measurement needs. We then apply a process to analyze and rank this set in priority order using the taxonomy developed for the 2008 NIST-Energetics- IEC TC 113 Survey on Nano-electrotechnologies.[6] As a proof-of-concept, we use the following method for assigning priorities to the 64 nano-electrotechnology USMS case studies of MNs listed in Appendix A.

3.1 Tagging Methodology for USMS Measurement Needs

A "tagging" process was employed to provide a consistent set of information from each MN. The tags correspond to the first three categories and ranked items given in Table 1, namely Properties, Products, and Cross-Cutting Technologies. Through this process we were able to uniformly gather a set of priority information for each MN that corresponded to the same ranking choices given to the Survey respondents.

A set of "*items-tags*" (i.e., ranked items from the Properties, Products, and Cross-Cutting Technologies category types) was selected for each of the 64 USMS MN case studies. Selection of tags was based on best scientific and engineering judgment, given the information presented in the case studies. Only one ranked item was assigned from each Survey category type to each USMS MN. Examples of the actual tags assigned to case studies for this analysis are shown in Table 5. For this proof-of-concept study, only three respondents participated in the tagging process.

Table 5. Selected Examples of Tagging for USMS MN Case Studies

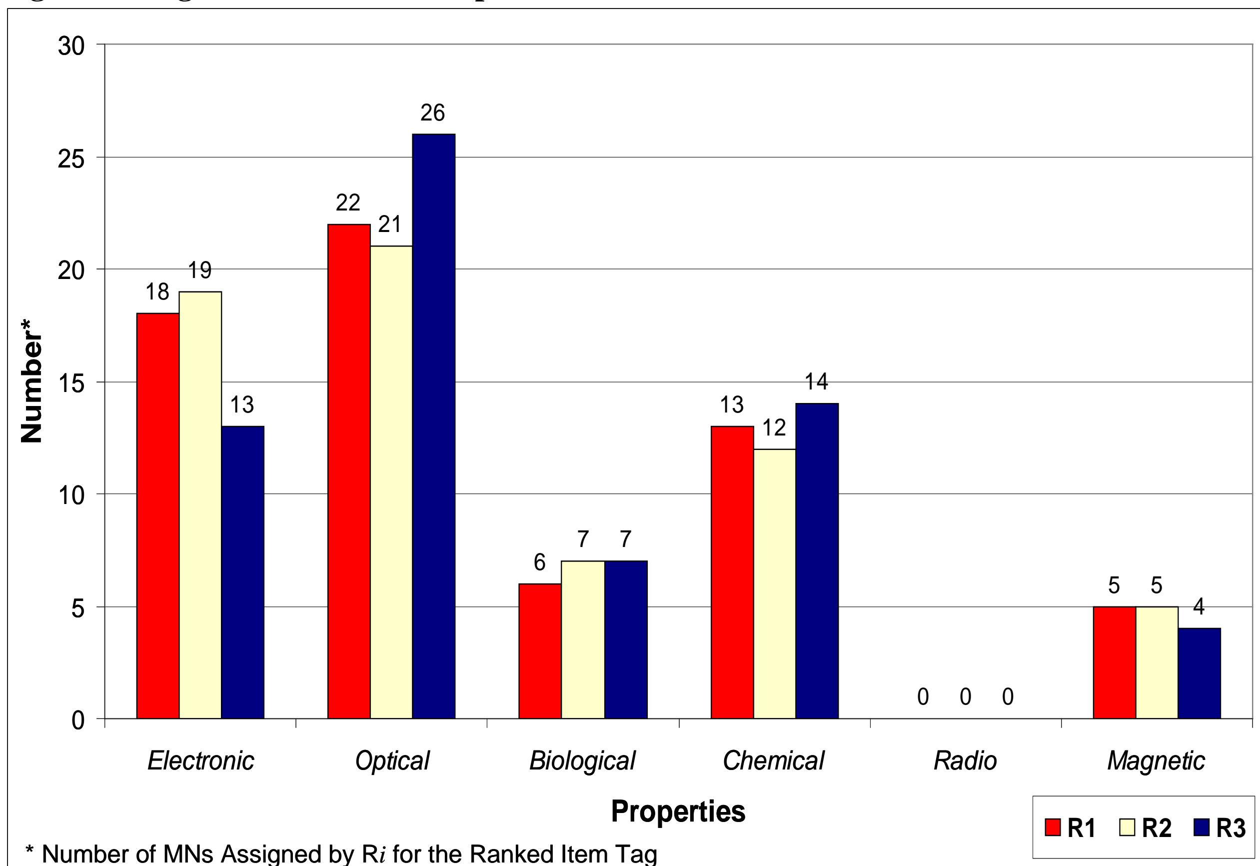
USMS MN Case Study Title	Property Tag	Product Tag	Cross-cutting Technology Tag
Nanomagnetic MRI Contrast Agents (p. A-52)	*Optical*	*Medical*	*EHS Application and Effects*
Cell-Based Analysis Using Lab-on-a-Chip Technologies (p. A-12)	*Electronic and Electrical*	*Medical*	*Fabrication Tools*
Nanoscale Chemical Characterization of Advanced Materials (p. A-63)	*Optical*	*Computers*	*Fabrication Tools*

3.2 Tagging Results

We developed a set of histograms to illustrate the distributions of Properties, Products, and Cross-Cutting Technologies ranked "*items-tags*" that the 3 respondents assigned to each of the 64 USMS MN case studies. These are shown in Figures 1 through 3. These histograms give rise to some general observations and also provide a basis for comparison with the NIST-Energetics-IEC TC 113 Survey, as outlined below.

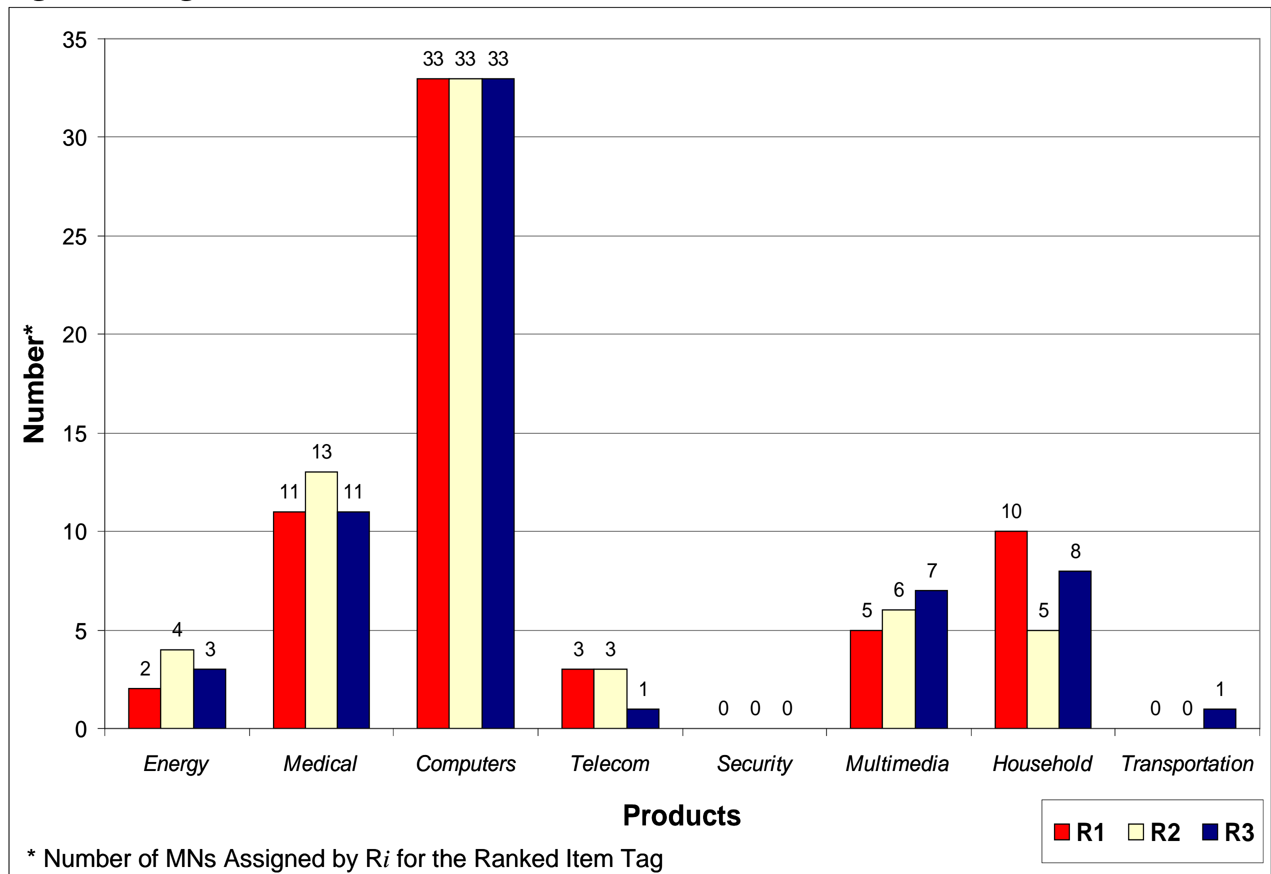
- **Properties** (Figure 1) – The properties most frequently identified in the USMS MN cases studies fall within the areas of *Optical* and *Electronic*. This is somewhat comparable to the priorities identified in the Survey (refer to Figures 4 and 9 in [6]). However, the overwhelming priority from the Survey was *Electronic* properties, compared with the USMS MN case studies, for which *Electronic* and *Optical* properties share large portions in the distribution of tags for properties. In the Survey, *Optical* properties received low priority rankings. *Biological* properties have a moderate but similar share in both the USMS MN tagging and the Survey.

Figure 1. Tag Distribution for Properties



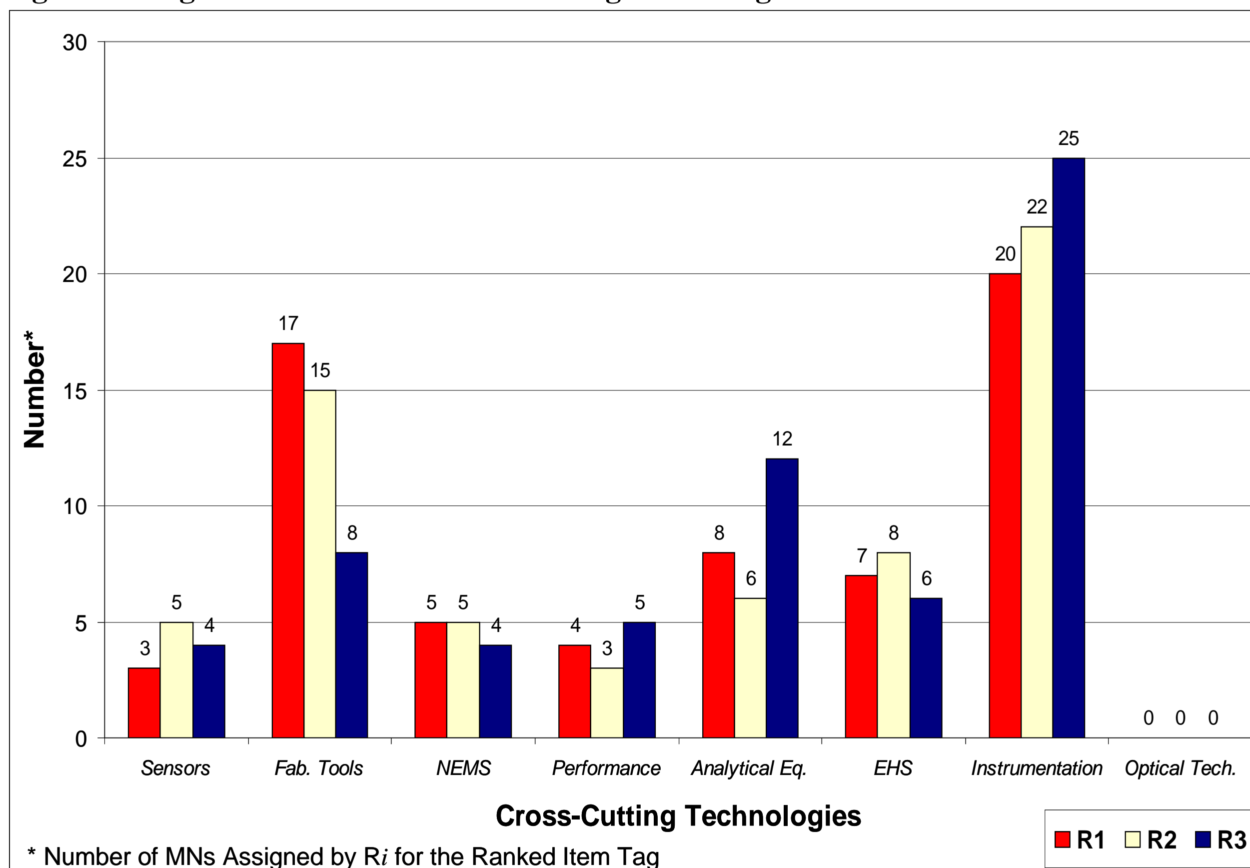
- **Products** (Figure 2) – The Product category most frequently identified in the USMS MN case studies was *Computers*, followed (but not closely) by *Medical* products. However, the product categories of *Computers*, *Medica,l* and *Energy* in the Survey itself (refer to Figures 5 and 10 in [6]) all have relatively high priority rankings. A possible reason for this is the more recent emphasis worldwide on energy as a priority compared to when the 2006 USMS report was conducted. While important, energy was not viewed to be at such a critical juncture in 2006 as it is today. In the medical field, recent rapid advances in innovative fields may be fueling a greater need for standards. *Telecommunications* received a relatively large share of high priority rankings, compared with the USMS MN case studies, where it only appeared in a few cases.

Figure 2. Tag Distribution for Products



- **Cross-Cutting Technologies** (Figure 3) – In this category, *Instrumentation* has the highest number of assignments, followed by *Fabrication Tools* and *Analytical Equipment*. When compared with the Survey (refer to Figures 6 and 11in [6]), only *Fabrication Tools* follows the same pattern. In the Survey, *Instrumentation* actually was ranked at the lowest prioriy. *Sensors* was highest in priority among the eight items for Cross-Cutting Technologies in the Survey, but very seldom assigned as a tag for the USMS MN case studies. In some respects, this may be an artifact of attempting to match the Survey categories to the USMS MN case studies; the latter of which were developed with a different perspective and not for the taxonomy used in the Survey. This is particularly true where overlap may exist between *Instrumentation* for testing and controlling fabrication processes or *Analytical Equipment* for measuring electro-technical properties. It may be difficult to distinguish which category is more appropriate in some cases. This sort of anomaly might be removed if the case studies were written more clearly or with these particular categories in mind. Another anomaly is Cross-Cutting Technology Item *Environmental Health and Safety (EHS)*, which was identified as a relatively high priority in the Survey, but was identified in only a small number of the USMS MN case studies. This is another case of a change in global priorities and interests – with the advent of more nanotechnologies into the marketplace and on the drawing board, interest in their safety and impact on the environment has increased.

Figure 3. Tag Distribution for Cross-Cutting Technologies



We also compared the distributions of assigned USMS MN tags for Properties, Products, and Cross-Cutting Technologies with the high priority rankings from the Survey. Table 6 illustrates the results of this analysis.

The scorings in the column on the right in Table 6 show the total score for each MN based on the Survey Borda global consensus ranks. This total score is the sum of the Borda ranks for each of the three ranked Survey items which the respondents assigned to an MN. That is, each MN has three tags, one each from Properties, Products, and Cross-cutting Technologies. The minimum total score that the three respondents could assign a given MN is 3(1+1+1) = 9 (highest priority). The maximum total score that they could assign is 3(6+8+8) = 66 (lowest priority). Thus, a low score in the far right column indicates that this USMS MN has a very high priority based on the Survey's global consensus. Alternatively, a high score indicates that this USMS MN has a very low priority based on the Survey's global consensus. For example, the lowest score of 15 received for the MN "Carbon Nanotube Materials" indicates that the tagging for Properties, Products, and Cross-Cutting Technologies was highly correlated to high rankings in the original Survey. The high score of 54 received for MN "Self Assembly of Soft Nanomaterials" indicates that tagging results for this MN were the least correlated with high-ranked items in the original Survey.

The standard deviation for the total scores given in Table 6 is ±9. Figure 4 shows the distributions for the number of MNs receiving totals scores in the bands with total score widths of 10. The first bar is the number of MNs with scores between 9 and 19; the second bar is the number of MNs with scores between 20 and 30; and so on, with the fifth bar having scores between 53 and 66. Figure 4 suggests that, using the tagging process, the Survey respondents would assign 4 MNs the highest priority and 1 MN the lowest priority. They would assign 25 MNs high priority and 12 MNs low priority. The middle band has 22 MNs, indicating that those MNs are neither high nor low priority. Because the MNs are distributed among all 5 bands, we conclude that the set of 64 MNs correlates with the priorities of the Survey respondents.

Appendix A: Page No.	Table 6: Priorities for USMS Nano-electrotechnology Measurement Needs by Total Score Based on Borda Global Consensus Rank The lower the total score the higher the priority Measurement Need (MN) Title	TOTAL SCORE Based on Borda Global Consensus Rank
A-1	Carbon Nanotube Materials	**15**
A-2	Quantum Computing	**18**
A-3	Nanoscale Integrated Circuits: Dimensional Control	**18**
A-4	Advanced CMOS Gate Stacks for Next Generation Integrated Circuit Devices	**18**
A-5	Top Down Micro/Nano Manufacturing	**20**
A-6	Nanostructured Materials for Photovoltaic	**21**
A-7	High Accuracy Dimensional Metrology for Manufacturing	**21**
A-8	Integrated Circuit Overlay Metrology	**21**
A-9	Sub-50 nm Lithography	**21**
A-10	Small Particle Monitoring For Advanced Semiconductor Manufacturing	**21**
A-11	Advanced DNA Analyses Using Lab-on-a-Chip Technology	**22**
A-12	Cell-Based Analysis Using Lab-on-a-Chip Technologies	**22**
A-13	Sub-10 nm SEM Metrology Tools	**23**
A-14	Nanoscale Biological Imaging	**24**
A-15	Compound Semiconductor Cluster Tools	**25**
A-16	Molecule-Based Nanoelectronics	**26**
A-17	Nanomanufactured Components	**26**
A-18	Multi-layer Nanostructures for Electronic and Photonic Devices	**26**
A-19	In-line Inspection and Factory Control Equipment	**26**
A-20	Interfacial Characterization Instrumentation	**26**
A-21	Semiconductor Industry Defect Metrology Tools	**26**
A-22	Nanoimprint Lithography (NIL)	**27**
A-23	Nanocrystal Biophotonic Sensors	**27**
A-24	Current Flow in Nanoscale Electronic Devices	**27**
A-25	Next Generation Electrical Instrumentation	**29**

Appendix A: Page No.	Table 6 (continued). Priority Rankings by Total Score Measurement Need (MN) Title	TOTAL SCORE Based on Borda Global Consensus Rank
A-26	Next-Generation Active Nanodevices	**30**
A-27	Single Molecule Optical Measurement	**30**
A-28	Integrated Circuit Optical Linewidth Metrology	**30**
A-29	Single Biomolecule Detection, Classification, and Measurement	**30**
A-30	Integrated Circuit Photomask Metrology	**31**
A-31	Nanomanufacturing	**32**
A-32	Sidewall Characterization Instrumentation	**32**
A-33	Health Care/Nanotechnology - Cancer Diagnosis and Treatment	**33**
A-34	Advanced Force Measurements in Nanotechnology	**33**
A-35	Advancing the Fundamental Science of Nanobiotechnological Systems	**33**
A-36	In-line/Real-time Analytic Tools for Measuring Sub-10 nm Defects	**34**
A-37	Dopant Distribution Instrumentation	**34**
A-38	Atomic Mapping Instrumentation	**34**
A-39	MEMS	**34**
A-40	Dimensionally Critical Nanomanufacturing	**35**
A-41	Airborne Contamination in Semiconductor Wafer Processing	**36**
A-42	Carbon Nanotube Identification	**36**
A-43	Multilayer Film Structures for Electronics and Optics Industries	**36**
A-44	Novel Materials for Nanoscale Diffusion Barriers in Microelectronics	**36**
A-45	Next-Generation Optical Microscopes	**36**
A-46	Nano-Scale Drug Delivery	**38**
A-47	Directed Nanoscale Assembly	**39**
A-48	Strained-layer Engineering for High Performance Electronic and Optoelectronic Devices	**39**
A-49	Instrumentation for Measurement of Electrical Properties at the Nanoscale	**39**
A-50	SEM and AFM Modeling for Semiconductor Electronics and Nanotechnology	**40**

Appendix A: Page No.	Table 6 (continued). Priority Rankings by Total Score Measurement Need (MN) Title	TOTAL SCORE Based on Borda Global Consensus Rank
A-51	Micro/Nano-Technology	**40**
A-52	Nanomagnetic MRI Contrast Agents	**42**
A-53	Atomic-Precision Imaging to Aid Development of New Materials	**42**
A-54	Hard Disk Stack Metrology	**43**
A-55	Carbon Nanotubes (CNTs)	**44**
A-56	Toxicology of Nano-particles in Biological Systems	**44**
A-57	Next Generation Electrotechnical Products, Components, and Raw Materials	**45**
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A-61	Hard Disk Sheet Magnetoresistive	**48**
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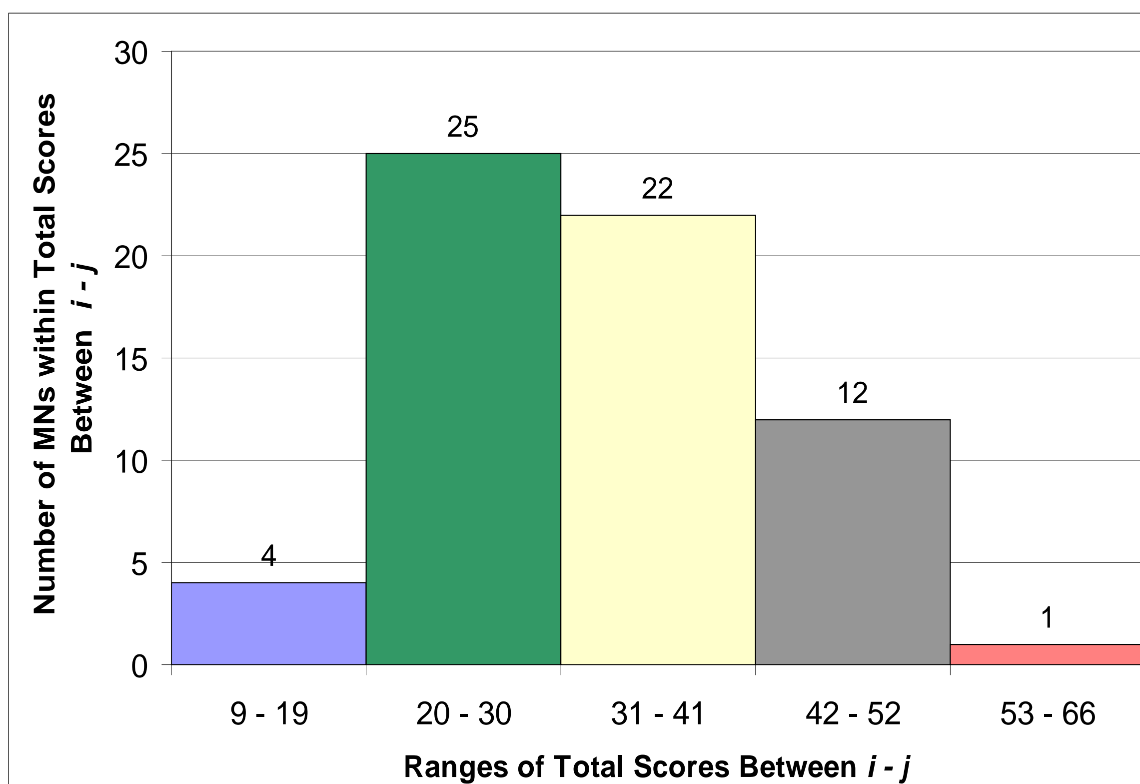
Figure 4. Distribution of Total Scores for 2006 USMS MNs in Nano-electrotechnologies



4. Conclusions

We have successfully demonstrated as a viable proof-of-concept a method for placing in priority order USMS MNs by assigning ranked items from an independent survey to the USMS MNs. Our analyses suggest that from the perspectives of the 459 Survey respondents the priority ranking of the 64 USMS MN case studies for nano-electrotechnologies given in Appendix A is consistent with the Survey's global consensus rankings. That is, by comparing the tagging selections with those of the Borda global consensus rankings in the Survey, we have established that the ranked set of 64 MNs correlates with the priorities of the Survey respondents.

Three additional considerations are in order. First, the case studies used in the 2006 USMS assessment were not written with the Survey tagging concept in mind. As a result, interpretation of the case studies to identify the most appropriate tags may be in some cases relatively subjective. Second, as might be expected, global priorities for business, energy, medicine, environment, and other areas have changed since 2006. This change in global priorities may be reflected in a few cases by differences between the ranked items in Survey taxonomy categories and the content of some USMS MN case studies. Third, the USMS MN case studies were written by a narrow segment of the U.S. measurement community, whereas the Survey was developed and responded to by a much broader international measurement community. Even with these considerations, the process was still able to provide a viable proof-of-concept.

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Figure Captions

Figure 1. Tag Distribution for Properties

Figure 2. Tag Distribution for Products

Figure 3. Tag Distribution for Cross-Cutting Technologies

Figure 4. Distribution of Total Scores for the 2006 USMS MNs in Nano-electrotechnologies

Appendix A: Listing of USMS MNs on Nano-electrotechnologies

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Carbon Nanotube Materials

Submitter(s): Kalman Migler

Technological Innovation at Stake: Nanotube materials possess an extraordinary combination of materials properties: strength, thermal conductivity and electronic properties. Successful incorporation of nanotube materials into a broad-range of critical technologies including fuel cells, semi-conductors, sensors, fibers, displays, and composite materials will yield revolutionary advances in product performance. As one example, in fuel cell applications, the nanometer scale and novel chemical characteristics of Single Wall Nanotubes (SWNTs) give them profound advantages as electro-catalyst supports and enable the fabrication of "free standing" fuel cell electrodes considerably more powerful than those currently in use.

***Economic Significance of Innovation*:** In the automotive arena alone, the DOC Office of Technology Policy (OTP) projects a $70 billion market at stake for vehicles powered by fuel cells. FreedomCAR describes the necessary performance/cost requirements of the fuel cells that include 60 % efficiency at a price of $30/kW. Nanotube based fuel-cells are leading contenders to meet these requirements.

***Technical Barrier to the Innovation*:** The *quality* (e.g. length, diameter, distribution…) and *purity* (e.g. levels of carbonaceous impurities and residual catalyst) of nanotubes is preventing high-tech applications because they require reliable and consistent materials of a given sub-type. All nanotube materials are comprised of dozens of subtypes of nanotubes that differ in length, diameter and electronic properties. There are no accepted methods of characterizing nanotube samples for these parameters, hindering trade and, there is no technique that allows a manufacturer to isolate and identify the appropriate type of nanotube needed for a given product.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** In order to for a manufacturer to provide nanotube materials of specified length, diameter and chirality, they need quantitative measurement techniques to characterize their samples, so that techniques to sort them by these characteristics can be developed.

Potential Solutions to Measurement Problem: Development of solution based chromatography to sort the nanotubes, coupled with quantitative spectroscopic methodology to efficiently determine the nanotube type. Development of precision control of growth of nanotubes.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Quantum Computing

Submitter(s): Ronald F. Boisvert, NIST

Technological Innovation at Stake: Recent advances at the intersection of quantum physics and computer science have opened up the possibility of using the quantum properties of physical systems as the basis for computation. The exploitation of quantum systems themselves for computation is a breakthrough which could sustain future progress in computer technology.

Economic Significance of Innovation: The semiconductor industry is now the largest US manufacturing industry, riding the wave of global sales reaching $213B in 2004. Progress in miniaturization in semi-conductors, which has been the technological engine driving steady increases in computer power for some 40 years, may stagnate in the foreseeable future as domain sizes reach atomic levels and quantum effects begin to dominate. Fundamental new computing technologies must be developed if we are to continue to increase computing power and capacity. Also, since quantum computers theoretically can perform certain tasks (e.g., factoring, searching, and simulation) much faster than classical systems, there is great potential for applications impossible with current technology.

Technical Barrier to the Innovation: The manipulation and control of quantum systems is extremely difficult, and only a few research groups worldwide have been able to demonstrate rudimentary capabilities.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Many physical systems of widely varying capabilities are currently under study as potential bases for quantum computers. Limited funding means that attention must be focused on best prospects. Comparatively little effort has gone in to evaluate and compare such technologies objectively, using measures of their information processing reliability, capacity, and efficiency.

Potential Solutions to Measurement Problem: The so-called DiVincenzo Criteria for determining if a physical system is usable for quantum computing have been very helpful in making gross evaluations of proposed technologies. Further progress requires a more detailed and carefully presented set of benchmarks which can be used to evaluate the information processing capabilities of a physical system.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanoscale Integrated Circuits: Dimensional Control

Submitter(s): Eric K. Lin, Wen-li Wu

Technological Innovation at Stake: The production of integrated circuits with nanoscale device structures is needed for the continued increase in cost to performance of integrated circuits; 20 nm by 2009 and 10 nm by 2013. Continued progress in the semiconductor industry depends upon the ability to manufacture designed patterns with sub-50 nm dimensions with sufficient dimensional control and resolution. To do this on a manufacturing scale, new sophisticated process control methods that include structure and device inspection are needed because current solutions are not sufficient.

***Economic Significance of Innovation*:** The semiconductor industry is a significant driving force in the U.S. economy through the continued price per function that arises from the fabrication of ever smaller structures, which can result in products that are smaller, cheaper, and with more functionality Lithography, including dimensional metrology currently comprises 30 to 40 % of the entire cost of semiconductor manufacturing, a several billion dollar enterprise. The continued economic success of the semiconductor industry depends upon capabilities to control device dimensions at nanometer length scales.

***Technical Barrier to the Innovation*:** Current methods such as scanning electron microscopy (SEM) and optical scatterometry face significant challenges to provide the needed nondestructive, production-worthy wafer and mask-level measurement of nanoscale critical dimensions, line-edge roughness, interfacial structure, and defect levels of complex 3D structures. These challenges become more difficult as new materials such as those with low-dielectric constant (k) that require additional structural information (porosity), or extreme ultraviolet photoresists that degrade when exposed to electron beams are introduced into production.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Rapid, on-line, non-destructive measurements of the structure of densely patterned features such as gates and trenches with their smallest, or "critical", dimensions < 40 nm and a roughness of < 1 nm. This level of inspection is important because variations in feature size of one tenth of the nominal dimension often results in significant changes in device properties.

Potential Solutions to Measurement Problem: A high precision X-ray based measurement method, Critical Dimension Small Angle X-ray Scattering (CD-SAXS) may provide a solution. This technique is capable of non-destructive measurements of test patterns used by microelectronic industries to monitor their fabrication process. CD-SAXS measurements performed at synchrotron facilities have successfully demonstrated the potential capability for sub-nm precision for periodicity and line width measurements and initial characterization of line-edge roughness. Challenges remain to enable this technology at production lines and in-house laboratories including the development of sufficiently bright sources in a compact form.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Advanced CMOS Gate Stacks for Next Generation Integrated Circuit Devices

Submitter(s): Martin Green

Technological Innovation at Stake: Further scaling (dimensional shrinkage of integrated circuit device elements according to Moore's Law) in Si microelectronics is presently limited by a lack of new materials to replace the gate stack layers. A material with a dielectric constant greater than about 20 is needed to replace the SiO_2 (dielectric constant ~3.9) gate dielectric, and a metal is needed to replace the degenerately doped polycrystalline Si gate electrode.

Economic Significance of Innovation: The silicon microelectronics industry, and the consumer electronics and information revolution that it fuels, is, at $750 billion, one of the largest sectors of the global (and US) economy. Continued innovation in Si microelectronics is of immense importance.

Technical Barrier to the Innovation: The gate stack of CMOSFET (complementary-metal-oxide-silicon-field-effect-transistor, the workhorse of advanced chips such as Pentium microprocessors) transistors poses a complex materials science issue. Well over 10,000 papers have been devoted to it since Si integration began in the late 1960's. Now, for the first time, materials native to and compatible with Si (SiO_2 and polycrystalline Si) are being replaced; the introduction of new gate dielectric and gate electrode layer materials requires an entirely new understanding of, for example, interfacial stability, as well as the effect of processing variables on electronic properties such as work function and interface state density. Further, the required research effort is greatly multiplied by the wide choice of candidate materials identified for both applications.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: There are two aspects to the measurement problem—identification of techniques, and the number/speed of measurements that are needed. First, for some measurements, such as work function, identifying the most appropriate measurement is not even clear. Second, even for known measurement techniques, it is imperative to be able to make hundreds or thousands of measurements at once, since there are at least that many combinations of gate dielectric and metal electrode materials compositions that need to be assessed for each material system considered.

Potential Solutions to Measurement Problem: Combinatorial materials science methodologies offer great promise to identify classes of materials, layer compositions, and multilayer (gate stack) combinations that are both thermally stable, and possess the required electronic characteristics. New high-throughput, combinatorial measurement techniques, such as nano-calorimetry to measure thermal stability, and capacitance-voltage to derive the metal-semiconductor work function, must be devised.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Top Down Micro/Nano Manufacturing

Submitter(s): Nicholas G. Dagalakis

Technological Innovation at Stake: A central 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). Top down nano manufacturing refers to human-directed organization of nano scale components into structures, which must then interface with the macro scale world through some kind of scale-up interface. Top down manufacturing of these devices must be explored and standardized in order to allow for the economies of scale needed for successful production.

***Economic Significance of Innovation*:** This is an enabling technology, which can affect the development of markets in many new classes of products, which require accurate nano component 3-D position and orientation. For example this technology can accelerate the production of nano component, electronics, composite materials, sensors, fuel cells, etc. According to a Lux Research report, the nano technology products market could reach $2.6 trillion in approximately 10 years. Assuming this infrastructure gets put in place, an estimated 10 million manufacturing jobs worldwide – or about 11 % of the total manufacturing jobs – may involve nano technology in that time frame. According to a SusChem report the nano technology machinery market is expected to grow by 30 % per annum.

***Technical Barrier to the Innovation*:** Integration of micro and nano systems over multiple length scales ranging over orders of magnitudes is a challenge that must be met. Many factors make up this challenge, including: raw material supply and product transport, precise and inexpensive arrays of fast parallel 3-D human directed manufacturing cells, massive parallel controls, sensors, fast imaging, scale-up interfaces. Manipulation, placement, actuation, and packaging of nano devices such as nano tubes, nano particles, or single molecules is a largely unexplored area.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** Fast and precise positioning and manipulation require accurate mathematical models, force, position and velocity sensing. Due to design required fabrication process variations, it is necessary to know mechanical properties of materials and the shapes of surfaces and features in hard to reach places, at different locations and orientations of a die. Since contact of fast moving objects might be necessary, it will be required to know the tribological, static friction, and wear properties of the materials involved.

Potential Solutions to Measurement Problem: Develop micro/nano sensors that can be embedded into fast moving devices. Develop compact models using controlled physical signals as input and material mechanical properties of dies at different positions and orientations as output. Identify nondestructive measurement methods for the shape of surfaces and buried structures.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue**:** Nanostructured Materials for Photovoltaic

Submitter**:** S. Robey, L. Richter

Technological Innovation at Stake**:** Successful development of nano-structured organic and organic-inorganic hybrid photovoltaic (PV)/solar cell technologies holds great potential for the development of solar energy modules at costs competitive or below current costs of fossil fuel generated electricity. Broad usage of PV technology innovations will reduce dependence on imported natural gas and reduce greenhouse gas and particulate emissions from coal-fired power plants. The architecture of power generation will also change with reduction of large generation sources replaced by a distributed renewable, non-polluting, domestic energy source. Low-cost, reliable, long-lived PV modules will also reduce the strain power distribution grids.

Economic Significance of Innovation**:** Combustion processes, natural gas and petroleum (~20 %) and coal (50 %) are the dominate energy producers of electricity generation and of the dominant greenhouse gas, CO2, emission, ~20 tons yearly per U.S. consumer. U.S. electricity generation with natural gas averaged ~27 % of total imports between 2001 and 2005 at costs ranging from ~$20B (2001) to $44B (2005). Technological innovations that reduce U.S. dependency for electricity produced by combustion process costs, both economic and environmental, improve our economic and societal health. Innovation in PV technologies provides a means to reduce U.S. dependence on combustion-generated electricity with significantly reduced environmental issues (air pollution, mining effects, oil spills, etc.) and U.S. reliance on foreign natural gas. New PV technology development and implementation are costs that reduce the economic impact of their use.

Technical Barrier to the Innovation**:** The principles of operation of revolutionary nano-structured organic and organic-inorganic hybrid PV technologies are fundamentally different from conventional inorganic (Si) solar cells. Processes occurring at interfaces (exiciton dissociation/recombination, charge and energy transport) in nanosstructured material blends (organic-organic, organic-inorganic nanocrystal) dominate operating efficiency. Understanding correlations between interfacial electronic structure and molecular/atomic structure and their interplay charge transport and exciton dissociation processes, and their connection to nanoscale morphology, is crucial to the achieving high efficiency, i.e., cost/Watt, targets that can spur widespread PV use.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Discovery science is needed to better understand physical/chemical mechanisms governing operation of future devices. Measurement methods with spatial and temporal resolution for nanoscale structure, combined with spectroscopic/physical parameter measurement, are needed to gain insight into charge generation and transport processes in nano-structured materials of interest for advanced PV technologies.

Potential Solutions to Measurement Problem**:** Non-destructive measurement methods with nanoscale spatial resolution, combined with high speed spectroscopic/physical parameter measurement, suitable for small organic molecule/polymer systems are needed. Atomic force microscopy methods and its variations are likely to allow measurements under actual illumination, in addition to use of advanced electron microscopies.

Technology at Issue: High Accuracy Dimensional Metrology for Manufacturing

Submitter(s): T. LeBrun

Technological Innovation at Stake: Technological progress in many high-technology manufacturing industries continually pushes the limits of accuracy required in dimensional measurement. Diverse needs ranging from the manufacturing of next generation semiconductor devices to the development of nanotechnology-based products for health care or advanced computing require dimensional measurements with better accuracy than is currently achieved anywhere in the world.

Economic Significance of Innovation**:** Improved dimensional metrology allows manufacturers to maintain higher standards and lower costs, by enhancing repeatability and throughput of manufacturing processes, thus increasing manufacturing yield and profitability. Improved metrology also fosters the creation of new products such as high-density memory, that require ever higher densities of components to be fabricated in small devices. These all contribute to competitiveness, and generate economic benefits for U.S. industry.

Technical Barrier to the Innovation**:** Manufacturers of leading edge products in the semiconductor and nanotechnology areas, among others, need access to better dimensional measurements than are currently available. Many of these manufacturers use NIST standards and measurement services to calibrate their key measurement tools for production and development. In some highly competitive areas where NIST Standard Reference Materials (SRMs) are just keeping up with industry needs, the dominant uncertainty in the SRMs result from the limits in NIST's ability to measure length — even when using a tool that is one of the most accurate in the world.

Stage of Innovation Where Barrier Appears**:** R&D (primary), Production (secondary)

Measurement-Problem Part of Technical Barrier**:** The best dimensional metrology tools in the world are generally limited by two problems: the uncertainty in the index of refraction of air (which changes the wavelength of light and thus the scale of the measurement), and the ability to accurately and reproducibly measure the position of a line to within nanometers.

Potential Solutions to Measurement Problem: Develop a next-generation dimensional measurement instrument to replace the current facility (the NIST linescale interferometer). The new instrument should incorporate vacuum beam paths for refractive index compensation and CCD imaging paired with a traditional slit-scanning photomultiplier for nanometer-scale line position measurement.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Integrated Circuit Overlay Metrology

Submitter(s): Rick Silver

Technological Innovation at Stake: As the critical dimensions of key attributes in advanced semiconductor devices for the worldwide electronic products market get smaller and smaller, measuring the relative alignment of these features is becoming increasingly difficult. New challenges are arising, such as maintaining higher accuracy requirements and even the fundamental ability to resolve such small features. Meeting these challenges will allow the development of more powerful, more reliable, and/or less expensive electronic products.

***Economic Significance of Innovation*:** The U.S. industry has held a preeminent position in the design of advanced and next generation semiconductor devices as well as the instrumentation used to manufacture them. For U.S. industry to maintain a leadership role in the continued exponential shrinkage of semiconductors, as well as in their production with yet lower cost per function, significant investment and R & D in manufacturing metrology is required. The exponential growth of semiconductor production has created very significant market segments with technological leadership from the U.S. Even the smallest improvements in measurement innovation and manufacturing process control can yield millions of dollars in return. This economic sector is so advanced and automated that clever solutions and advances can have very significant and measurable effects.

***Technical Barrier to the Innovation*:** The sizes and placement of features on the mask must be measured accurately in order to obtain acceptable manufacturing yields and profit levels. To accurately provide robust measurement and process control capabilities, accurate optical measurement techniques, tool alignment and electromagnetic scattering models, which simulate the imaging process, are needed.

***Stage of Innovation Where Barrier Appears*:** R&D (primary) and Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** There are several challenges in measuring optical targets composed of features nearly $1/10^{th}$ the size of the measurement wavelength used. These challenges include: aligning the optics, defining algorithms, and developing CCD measurement capabilities with better than 1 nm resolution and accuracy. Doing this in a way to enable high throughput and accuracy requires pushing optical techniques to new levels.

Potential Solutions to Measurement Problem: Implement new high resolution scatterfield microscopy techniques to the overlay wafer measurement domain. Quantify the effect of measurement uncertainty on device yield and process control.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Sub-50 nm Lithography Materials

Submitter(s): Vivek M. Prabhu

Technological Innovation at Stake: The production of smaller device structures for the continued improvement in cost to performance of integrated circuits is at stake: 20 nm by 2009 and 10 nm by 2013. Continued progress in the semiconductor industry depends upon the ability to develop materials capable of manufacturing designed patterns with sub-50 nm dimensions with sufficient dimensional control and resolution.

***Economic Significance of Innovation*:** The semiconductor industry is a significant driving force in the U.S. economy and the lithography process is a major part of the cost of manufacturing integrated circuits. Lithography, including dimensional metrology currently comprises 30 to 40 % of the entire cost of semiconductor manufacturing, a several billion dollar enterprise. The continued rate of the economic success of the semiconductor industry depends upon ability to fabricate ever smaller device dimensions.

***Technical Barrier to the Innovation*:** It is unknown whether apparent limitations in the patterning ability of current materials for industrial nanofabrication, chemically amplified photoresists, are intrinsic material resolution limits (line-edge roughness of 4 nm) or can be improved with better optics and process control. Maintaining the rapid pace of shrinking dimensions requires significant improvements in optical projection lithography technology or the development of alternative, next generation lithography technologies.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** At nanoscale dimensions, the details of local materials properties and physico-chemical processes affect the resolution of the lithographic process. Current measurement methods do not provide the spatial resolution or chemically specific information needed to carefully probe process parameters that limit the patterning resolution and to inform potential solutions. There are too many variables including the specific formulation of a multicomponent material, dose, post-exposure bake conditions, or developer concentration to depend on the success of trial-and-error improvements.

Potential Solutions to Measurement Problem: Integrated measurements that can provide unique information about complex physico–chemical processes used in advanced chemically amplified photoresists. Methods include x-ray and neutron reflectivity, near-edge x-ray absorption fine structure spectroscopy, and quartz crystal microbalance measurements. With this information, better physical/chemical models can be developed to predict three-dimensional resist geometries after development and process windows, including effects such as line-edge roughness.

Technology at Issue: Small Particle Monitoring For Advanced Semiconductor Manufacturing

Submitter(s): Carlo Waldfried, Axcelis Technologies

Technological Innovation at Stake: Control of particle concentration and size distribution is critical in advanced semiconductor manufacturing because it strongly affects yield and device performance. Cost-effective measurement of particle sizes below 90 nm is needed to improve device performance of current and future technologies.

Economic Significance of Innovation*:* Cost-effective device development and manufacturing of integrated circuits with smaller feature size requires high resolution tools. The device performance and yield of advanced IC designs becomes more sensitive to smaller and fewer particles. Therefore it is necessary to control the particle contamination during the IC fabrication process. An innovative detection method is needed to capture smaller-sized particles.

***Technical Barrier to the Innovation*:** Reliable particle measurements for particle sizes below 90 nm will require new techniques based on shorter-wavelength radiation and with the stability and quality of synchrotron sources. Such sources and the corresponding detecting instrumentation of scattered radiation are not available for the manufacturing environment.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** Current particle detection metrology is based on optical methods. Limitations are due to the relatively long wavelength of the optical lasers that are being employed, as well as detector designs and beam optics. Available particle measurement systems can accurately measure particle sizes down to 0.09 microns and work is being pursued in the industry to develop metrology capabilities to detect smaller particle sizes in response to the need of the semiconductor industry. While improved particle metrology capabilities do in principle exist, they are not readily available due to high cost.

Potential Solutions to Measurement Problem: New laser sources and scattering techniques are needed to accurately and reliably measure particles 90 nm and below with cost effective metrology equipment that is capable of operation in the semiconductor manufacturing industry environment. Development and validation of new measurement techniques including those at synchrotron and neutron facilities. Development of standard methods and data for new instrumentation.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Advanced DNA Analysis Using Lab-on-a-Chip Technology

***Submitter(s)*:** B. Jones, NIST

Technological Innovation at Stake: DNA analysis genome analysis for forensic, healthcare, agricultural and environmental applications using ultra-small sample size. Lab-on-a-chip technology promises rapid and inexpensive approaches to DNA analysis for the many applications where genomic information provides insights into the state of biological systems. This new measurement technology has the potential to offer many advantage, low fluid volume consumption reduces waste, lower cost accrue because only small amounts of expensive reagents are needed, and higher analysis and control speed results due to short mixing times, fast heating times coupled with small heat capacity significantly reduced power consumption thereby enabling single use approaches at much reduced cost. Lower fabrication costs of mass production promise a safer platform for chemical, radioactive or biological studies because of large integration of functionality and low stored fluid volumes and energies.

***Economic Significance of Innovation*:** DNA analysis technology has permeated many sectors of the economy including agriculture, industrial processes, environmental biotechnology, and healthcare and forensics. Future applications in healthcare include genetic targeting of pharmaceutical production and diagnostics, and the individualization of drugs and other therapies. The agricultural sector has a great need for a cost effective means of testing exports for genetic modification, while environmental biotechnology employs DNA analysis in the bioremediation of sites contaminated with organic waste. Lab-on-a-chip DNA analysis technology greatly reduces the cost of the analysis device, in many cases from hundreds of dollars to pennies, decreases the time of each analysis from many hours to mere seconds, and considerably reduces the capital expenditure for analytical instruments, and facilitates automation.

***Technical Barrier to the Innovation*:** Lab-on-a-chip DNA analysis requires miniaturization of analytical components such as thermoregulation for polymerase chain reaction (PCR) replication of DNA, separation of DNA fragments, and optical or chemical detection. Multiplexing of these analysis components requires complicated interfacing and device fabrication.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Industry's need to characterize 3-dimensional features of a microdevice as well as materials characterization in a high throughput format is universal. Specific to microfluidic devices is the need to accurately measure flow, viscosity, electrophoretic mobility, temperature, fouling, and fluorescence calibration within a microchannel.

Potential Solutions to Measurement Problem: New technological approaches are needed. Academic, private sector and government laboratories have active R&D efforts. NIST can provide standard methods to accurately measure parameters such as flow, temperature, channel dimensions, and electrophoretic mobility among others is critical to bring micro-analytical processes into control.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Cell Based Analysis using Lab-on-a-Chip Technologies

***Submitter*:** B. Jones, L. Locascio

***Technological Innovation at Stake*:** Robust and reproducible methods are needed to determine the response of biological cells to proposed compounds in pharmaceutical development and approval. The at-cell analysis capability afforded by combination of chemical analysis methods with microfluidic device technologies, Lab-on-a-Chip, may allow multiplexed delivery of toxicological agents/cell insults with immediate diagnostic quantification of metabolic responses, a capability currently unavailable. This cell-based analysis will decrease analysis time, eliminate the need for large samples, and enable toxicological analysis of different cell types (liver, lung, heart) in one assay. Additionally, this format enables ultra-low concentration detection of harmful metabolites dangerous in later animal and human trials.

***Economic Significance of Innovation*:** It is estimated that only one out of 10,000 drug candidates ever reach the consumer. Each drug costs over $897 million to take from conception to FDA post-approval. This R&D cost plays a major role in limiting pharmaceutical development. Current estimates for costs due to poor absorption, distribution, metabolism, elimination or toxicity (ADME/Tox) properties alone are $50-70 million annually. Each year the Pharmaceutical Industry generates $550 billion in revenue worldwide. The potential impact to this industry in improving the ratio of drugs taken from conception to market and reducing ADME/Tox problems early in the screening process could result in billions of dollars in economic gains and potential health with significant associated societal benefits.

***Technical Barrier to the Innovation*:** The maturity of this technology is dependent on cell viability within microchannel devices. In addition, materials and device physical characterization is important as well as standardization of microfluidic processes in order to fully control analysis progression.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Measurement and standardization of cell viability within the micro-environment is essential. Measurements of the microfluidic parameters such as flow temperature, viscosity, fluorescence calibration, and device fouling; and on-chip measurements of complex biology-surface interactions, nutrient delivery, cell manipulation, and electrophoretic mobility are also vital to device development.

***Potential Solutions to Measurement Problem*:** Bottom-up solution development, i.e., proceeding from fundamentals of biology and chemistry, is necessary because modification of existing methods is not a reasonable expectation. Standard methods to accurately measure parameters such as flow, temperature, channel dimensions, and electrophoretic mobility among others is critical to bring micro-analytical processes into control.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Sub-10 nm SEM Metrology Tools

Submitter: C. Michael Garner

Technological Innovation at Stake: In-line/real-time measurement tools for sub-10 nm features (critical dimensions (CD) - scanning electron microscopy (SEM) to support patterning for integrated circuits (ICs). The International Technology Roadmap for Semiconductors (ITRS) anticipates that the broad industry manufacture of the 22 nanometer (nm) IC technology generation will have minimum features of ~ 10 nm in 2016. Early developers will start development on this technology within the next two years; however, tools to measure critical dimensions are not capable of being used as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce the growth in the electronic sector, which has considerable productivity implications for all economic sectors that rely on semiconductors. Furthermore, if the process has a large variation in feature sizes, the yield for circuit designs will be very low and this would dramatically increase the cost of products and make the new technology too costly for production.

Technical Barrier to the Innovation: Metrology tools to measure critical features are incapable of measuring sub-20 nm features precisely and accurately within the manufacturing line. Thus, wafers must be sacrificed to destructive analysis to measure process dimensions outside of the wafer fabrication facility. Only a few samples will be characterized per operation, so significant information will be lost on the variability of the process in development.

Stage of Innovation Where Barrier Appears: R&D and production

Measurement-Problem Part of Technical Barrier: The integrated circuit industry requires processes that produce 100's of billions of features uniformly across each wafer for each mask operation with a tight distribution of sizes. The inability to measure critical sub-20 nm features on a large number of features and wafers per lot will dramatically slow the development of integrated circuit technology.

Potential Solutions to Measurement Problem: R&D to extend conventional e-beam based critical metrology tools. This would include aberration correction, brighter sources, and techniques to reduce dielectric charging on wafers.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Nanoscale biological imaging

Submitter: S. Buntin, NIST

Technological Innovation at Stake: Successful development of complex biological systems at nanometer dimensions will be limited without the capability to make quantitative determination of the composition of the individual atoms and molecules comprising them. A quantitative understanding of the distribution of chemical species in three dimensions including the internal structure, interfaces and surfaces of micro- and nanoscale systems are critical to the development of successful commercial products in nanotechnology. Current nanoscale-chemical 3D measurement tools are in their infancy. The aggressive development of diverse measurement technologies will overcome critical measurement barriers significantly promoting the a wide range of nanoscale technologies.

Economic Significance of Innovation: Biotechnology is a critical sector for the U.S economy, as the source of innovative firms, high-wage jobs, and products with a high value in both financial and human health terms. Potential applications of a nanoscale-chemical 3D measurement tools in bioprocessing and biotechnology include improved drug delivery systems, more effective clinical diagnostics, and increased biomedical knowledge. Even small improvements in research, manufacturing or clinical efficiency would yield substantial economic gains and provide improved diagnosis and treatment of human disease.

Technical Barrier to the Innovation: There have been remarkable advances in the development of bioimaging techniques over the last few decades. Medical diagnostic imaging tools such as Computer Aided Tomography (CAT), Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET) have revolutionized the diagnoses and treatment of disease. New developments in drug discovery, clinical diagnostics and nanotechnology are driving a push for development of novel measurement approaches that will extend bioimaging to the cellular and even molecular level. Current state-of-the-art approaches typically utilize fluorescent optical microscopy but suffer from limited spatial resolution and the inability to provide compositional analysis. New imaging technologies based on electron, ion and photon beam probes must be developed to push biomedical imaging to the nanoscale level. While potentially promising, these techniques are currently of limited use for the nondestructive/noninvasive imaging of processes within living cells and tissue where length scales of interest are commonly a few nanometers.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** The combination of high spatial resolution to provide sufficient 3-D information necessary to develop new nano-molecular technologies. There are no existing measurement techniques that combine high spatial resolution with chemical compositionally specific non-invasive, nondestructive in-vivo real-time imaging. Trade-offs are made whenever ion, photon, or electron methods are selected, leading to extra work, greater expense, higher uncertainties and incomplete specimen characterization.

Potential Solutions to Measurement Problem: Substantial improvement in optics for optical microscopy (thus keeping the real-time living specimen capability but improving resolution), or improvement in electron and ion techniques for atmospheric pressure measurements would create substantially more efficient and informative bioimaging techniques. Development of nanoscale biomarkers useful with current technologies also offers significant potential.

Technology at Issue: Compound Semiconductor Cluster Tools

Submitters: Herbert Bennett, Howard Hung, and James Maslar

Technological Innovation at Stake: Instrumentation with integrated software for cluster tools, which determines non-destructively in real-time and on-line whether III-V compound semiconductor materials meet specifications and are worthy for further processing, is needed to make next generation devices with greater figures of merit such as switching speeds and operating efficiencies.

Economic Significance of Innovation: The global market for compound semiconductors exceeds $25 billion. III-V compound semiconductors enable many technologies that in turn provide large markets for silicon-based semiconductors. Examples include laser printers, cellular telephones and pagers, global positioning, DVD/CD players and recorders, laser fax machines, displays, and solid-state lighting. High-growth applications for devices based on III-V semiconductors continue. The semiconductor and chemical industry roadmaps call for next generation of III-V semiconductor processing cluster tools that quickly measure transport properties. Such tools are needed to reduce the cost per unit area and the cost per function and to increase yield and productivity. According to Intel, continuing Moore's law beyond 2015 will require using III-V semiconductors in mainstream applications to complement scaled silicon.

Technical Barrier to the Innovation: The barriers are the lack of 1) adequate knowledge of III-V semiconductor transport properties needed for the design and manufacture of new-technology devices; 2) analytical tools that can measure these properties quickly for real-time process control during manufacturing; and 3) high-speed computing for extracting semiconductor transport properties from measured parameters and for simulating fabrication processes on-line.

Stage of Innovation Where Barrier Appears: R&D and Production.

Measurement-Problem Part of Technical Barrier: There is no equipment that accurately, non-destructively, cost effectively, and directly measures parameters related to device performance and to process control.

Potential Solutions to Measurement Problem: Combining validated, robust theoretical models that are based upon robust quantum mechanical calculations, advanced computer simulations, and Raman spectra "will allow the semiconductor industry to go from what it can measure to what it needs, but can not measure. Raman spectroscopy requires minimal sample preparation and is particularly useful as a non-destructive technique. This theory and software will enable process engineers to extract in real-time transport properties from Raman spectra of III-V semiconductors.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Molecule-Based Nanoelectronics

Submitters: C.D. Zangmeister/R.D. van Zee; NIST

Technological Innovation at Stake: Component miniaturization and new materials are needed to meet the ever-increasing speed and power requirements of computers. However, the CMOS field-effect transistor, engine of the modern computer, is forecast to reach performance limits some time between 2010 and 2015. Further reduction in component size will require new technologies that complement and enhance CMOS devices. Manufacturers are developing strategies to integrate molecule-based nanoelectronic ("moletronic") components into memory and computing circuits.

***Economic Significance of Innovation*:** Computer processor production is a $200 billion/yr industry and is projected to grow to $500 billion/yr by 2010. This growth depends on innovation that increases processor speed, efficiency, and reduces fabrication costs. The development of molecule-based component technologies will enhance the pace of innovation of new processors, as well as cut production costs by reducing the number of fabrication steps. Moletronic devices have already been demonstrated to make ultrahigh density memory (100 GB cm^{-2}). In 2005 dynamic random-access memory sales were $30 billion, and if scale-up can be achieved, moletronic memory devices are expected to dominate that market.

***Technical Barrier to the Innovation*:** While many promising device prototypes have been demonstrated, yield and reliability remain key barriers to commercialization of moletronic devices. These fabrication difficulties can often be linked to the lack of reproducible and reliable methods for measuring the electrical performance of fabricated devices. New approaches to measurement of molecular-scale electrical behavior are critical to successful realization of such molecule-based components. Such approaches also support the performance evaluation of prototype device structures and materials in device/component development.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Conventional test and measurement devices and approaches are inadequate and, many times, inappropriate to molecule-based components. For example, it is often unclear whether the measured electrical characteristics of a moletronics circuit are linked to the way a particular measurement is made or to actual device performance. Such ambiguity clouds interpretation of basic measurements and slows innovation. It could be eliminated with reference data for performance of prototypical molecular components in a validated test-bed. New tools and methods for measuring electrical properties at the molecular level are required for reliable and reproducible measurements in robust manufacturing.

Potential Solutions to Measurement Problem: New measurement tools capable of characterizing molecular electronic structure, the electrical behavior of small number of organic molecules will serve both production and R&D needs. These tools must be validated against prototypical molecules and devices. Reference data and materials will be required to calibrate and maintain these instruments.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanomanufactured Components

Submitter(s): Ronald Jones

Technological Innovation at Stake: Emerging nanotechnologies for microelectronics, data storage, and bio-agent sensors are based on large area substrates patterned with trillions of nanometer scale components. In the case of data storage, the switch from uniform magnetic films to arrays of nanostructures will increase data density from ≈ 10 Gb/in^2 to > 100 Gb/in^2. Increases in areal density will facilitate a range of high storage applications (i.e. medical records, digital video cameras).

***Economic Significance of Innovation*:** The data storage market alone is projected to increase 35 % in 2006 based on the emergence of high density drives for consumer products, while the multibillion dollar microelectronic industry is moving toward patterning of sub-50 nm features by 2007. In each of these markets, products will feature macroscopic areas patterned with dense arrays of nanostructures.

***Technical Barrier to the Innovation*:** In applications requiring dense arrays of nanostructures, the small dimensions of the structures will require sub-nm tolerances in positional placement. Current methods of manufacturing are not capable of consistent structural placement on this scale. As a result of the low cost of the final product, nanomanufacturing will need to inspect trillions of nanometer scale components at high speeds, identifying defects such as voids at early stages in production to be economically viable.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** The primary measurement challenge is the "needle in a haystack" issue. The problem requires techniques to search macroscopic areas, a single nm at a time to find errors in size and shape of nanostructures. As an example, a single 50 nm void within a 50 nm wide insulating layer in state of the art microelectronic circuits can lead to short circuits and device failure. A typical circuit design can feature a mile of insulating layer length, challenging all existing platforms for defect inspection.

Potential Solutions to Measurement Problem: Development of size- and shape-sensitive nanoprobes may provide a massively parallel optical measure of defect location across large areas. Other possibilities include the use of sub-wavelength optical probes and large area x-ray microscopy to identify "defective zones" that limit the area of searching for higher resolution imaging techniques.

Technology at Issue**:** Multi-layer Nanostructures for Electronic and Photonic Devices

Submitter**:** Grady White, Ed Fuller, George Quinn, Lawrence Robins

Technological Innovation at Stake**:** Systems composed of multiple layers of 1nm – 50 nm thick films with diverse compositions and lattice parameters achieve dielectric, carrier mobility, and recombination properties that are unachievable in bulk or monolithic material devices.

Economic Significance of Innovation**:** Nanoscale structures and material diversity will enable smaller, cheaper, faster, and more powerful electronic and photonic devices that will maintain U.S. competitiveness in critical global arena. The 2005 global semiconductor market was $227 billion. A 2004 NRC report stated, "The US semiconductor industry is, today, the largest value added industry in manufacturing" and in 2005, the U.S. market share for microelectronics was 46 %.

Technical Barrier to the Innovation**:** A major barrier to implementation of devices based on complex multi-material structures is obtaining predictable performance and guaranteeing short- and long-term reliability. Specifically, stresses/strains from mismatch between layers and other sources affect carrier lifetimes and mobilities in electronic devices, emission/absorption energies in photonic devices, and lifetime to failure in both device classes. The barrier can appear during R&D because designers cannot confirm that design models are predicting accurate strain levels, during Production when components begin to fail on the wafer level, or End Use because customers want reliability predictions that are not available.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** To assess local fluctuations in critical electronic and optical properties in sub-micrometer devices, strains need to be measured with spatial resolution of 10 nm -30 nm. Current techniques are limited to about 500 nm.

Potential Solutions to Measurement Problem**:** Development of tools for optical spectroscopic measurements with nanometer scale resolution. Simultaneous development of models or calibration procedures to quantify the strain from the spectroscopic data.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: In-line Inspection and Factory Control Equipment

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of 22 nanometer integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, in-line factory process control equipment for making sub-32 nm circuits is not available.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and other sectors that depend on semiconductor advances.

Technical Barrier to the Innovation: Device features already have nano-sized dimensions and high aspect ratios. Developing and manufacturing devices at these sizes and aspect ratios require advanced in-line and real-time factory control systems that monitor processing steps to make certain that critical processing parameters remain within acceptable tolerances. Such factory control equipment with integrated characterization and metrology tools for measuring interfacial, structural, and materials properties on nano-sized devices does not exist.

Stage of Innovation Where Barrier Appears: R&D and production

Measurement-Problem Part of Technical Barrier: Next generation control and monitoring equipment needs new characterization and metrology tools that measure at the nanoscale interfacial, structural, and materials properties of ultra-thin films and nano-wire sized lines with the required resolution. These tools are either unavailable or in early development. Examples include optical measurements of thin layers and interfaces.

Potential Solutions to Measurement Problem: Develop manufacturing worthy, high throughput methods such as optical metrology from the far IR to VUV, X-ray reflectivity, small angle X-ray scattering, X-ray diffraction, X-ray photoelectron spectroscopy, and Auger electron spectroscopy. In addition, develop electrical metrology for new materials such as high speed atomic force microscopy.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Interfacial Characterization Instrumentation

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: Advanced, beyond next generation, instrumentation to measure electronic properties of sub-22 nm materials and devices**.** The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of integrated circuits, based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, tools to measure precisely and accurately interfacial properties are not capable of being used as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and in many other sectors that depend on semiconductor advances.

Technical Barrier to the Innovation: Incomplete understanding of the physical and chemical processes limits the rate of progress in developing appropriate instrumentation. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes requires characterization and metrology tools that measure interfacial, structural and materials properties on nano-sized devices. Such tools are not available for high-volume and high-quality manufacturing with high yields.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Characterization and metrology tools that measure interfacial, structural and materials properties of ultra-thin films and nano-wire sized lines with the required resolution, precision, and accuracy are either unavailable or in early development and not available to industry. Examples include optical measurements of thin layers and interfaces.

Potential Solutions to Measurement Problem: Develop metrology tools from the far IR to VUV to X-ray. Examples include polarized reflectivity, spectroscopic ellipsometry, non-linear optical methods such as second harmonic generation, X-ray reflectivity, small angle X-ray scattering, X-ray diffraction, X-ray photoelectron spectroscopy, Auger electron spectroscopy such as co-incidence methodologies, and higher energy resolution backscattering methods.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Semiconductor industry defect metrology tools

***Submitter*:** Kent Irwin

***Technological Innovation at Stake*:** The next generation of energy-dispersive spectrometers (EDS). The exponential rate of progress depends on continuously shrinking the minimum feature size. As the minimum feature size on integrated circuits shrinks, the size of "killer" defects and particles shrinks as well. The high yield of semiconductor processes, and thus Moore's Law, can only be maintained if metrology tools that provide non-destructive detection and simultaneous differentiation of the multiple killer defect types at high throughput are available. The standard in-line tool for the chemical analysis of defects and particles is a scanning-electron microscope (SEM) with an EDS X-ray detector. At present, these tools fail to provide fast and unambiguous analysis of nanoparticles and defects less than about 100 nm in diameter due to insufficient energy resolution to distinguish the low-energy X-ray lines. The critical defect particle size is presently 40 nm, and will reduce to 23 nm by 2010. New EDS tools are already needed by the industry today.

***Economic Significance of Innovation*:** Sales of EDS X-ray detector systems are on the order of $100 million per year, but these tools leverage the much larger semiconductor industry, which grossed about $228 billion in sales in 2005. If the semiconductor industry does not have the necessary metrology tools to control defects at smaller feature size, the impact on the industry will be significant, perhaps many billions of dollars.

***Technical Barrier to the Innovation*:** New EDS tools are already needed by the industry. The critical defect particle size is presently 40 nm and will reduce to 22 nm by 2010. As the size of critical defects and particles is reduced, the beam energy of the SEM must also be reduced to control the spot size. Low energy X-ray lines that are excited frequently overlap in a conventional EDS system. Such overlap makes it difficult to analyze the chemical composition of the particle and require the implementation of off-line, destructive, and time consuming analyses such as TEM.

***Stage of Innovation Where Barrier Appears*:** R&D and production

***Measurement-Problem Part of Technical Barrier*:** The energy resolution of conventional EDS systems are approaching the fundamental limit set by the statistics of charge carrier generation. New detector technologies are required that can measure X-ray energies more precisely.

***Potential Solutions to Measurement Problem*:** The 2005 International Technology Roadmap for Semiconductors specifies a potential solution: "Prototype microcalorimeter energy dispersive spectrometers (EDS) and superconducting tunnel junction techniques have X-ray energy resolution capable of separating overlapping peaks and providing chemical information. These advances over traditional EDS and some wavelength dispersive spectrometers can enable particle and defect analysis on SEMs located in the clean room."

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanoimprint Lithography (NIL)

Submitter(s): Christopher L. Soles

Technological Innovation at Stake: To date, all lithography tools capable of patterning with 5 to 10 nm resolution, write serially with a beam spot size that is also 5 to 10 nm. These techniques are extremely slow, very costly, and not suitable for high volume manufacturing. NIL is rapidly emerging as a nanoscale replication technique, capable of producing high resolution copies of nanoscale patterns fabricated over large areas at production speeds that approach multiple wafers per minute. This seminal advancement in mass production lithography has the potential to bring high volume nanotechnology to the commercial marketplace in markets extending from the semiconductor industry and beyond.

***Economic Significance of Innovation*:** NIL tools are relatively inexpensive, ranging from $100K to $1M. This is a fraction of the cost of the current state of the art high volume lithography tools that cost upwards of $25M to $50M. For this reason the semiconductor industry is pushing hard to integrate NIL capabilities into their production infrastructure. At the same time, the low cost of the NIL technique is making high resolution patterning a reality for small, high tech business in the nanotechnology arena. For these reasons *MITs Technology Review* (Feb, 2003) identified NIL as one of the 10 emerging technologies that will change the world by making nanomanufacturing a reality.

***Technical Barrier to the Innovation*:** Our ability to create patterns now exceeds our ability to quantify, evaluate, or measure the quality of the new nanoscale metrologies needed to help evaluate and optimize NIL processes to the level required for commercial applications. Current electron beam inspection tools are being improved in terms of their throughput and resolution. Scanning probe techniques are also being adapted for more accurate measurements. Both of these solutions require significant efforts in calibration and tractability. Optical techniques are also being considered but require extensive model libraries to yield quantitative parameters. All of these techniques have great difficulties in characterizing densely packed or buried nanostructures.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Critical dimension (sample shape) metrologies that are non-destructive and offer sub-nm resolution are critically needed to optimize NIL materials, process, and products. The International Technology Roadmap for Semiconductors clearly states viable solutions to critical dimension metrologies at the patterning length scales achievable by NIL *do not exist*.

Potential Solutions to Measurement Problem: X-ray scattering and reflectivity techniques are generating interest because of their ability to characterize very small patterns non-destructively. NIST has recently developed Critical Dimension Small Angle Scattering (CD-SAXS) as one such alternative. Because of its potential, CD-SAXS will be included in future versions of the ITRS Roadmap as a candidate next generation metrology.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanocrystal Biophotonic Sensors

Submitter(s): Jeeseong Hwang and Kimberly Briggman

Technological Innovation at Stake: The technology at stake is a variety of biocompatible luminescent nanocrystals (NCs) tailored with a number of unique optical and physical properties beyond the limitations of conventional organic probes used in a number of biomedical applications. NCs enhance and/or exhibit stronger optical signals than conventional organic tags and have a much longer shelf life.

Economic Significance of Innovation**:** The NC industry is rapidly growing in the U.S. market: according to a new report, sensors designed and built using nanotechnology will generate global revenues of $2.7 billion in 2008 and reach $17.2 billion in 2012. Needs of NCs are rapidly growing in basic biomedical research (flowcytometry and parallel biodetection assay), diagnostics (*in vivo* imaging, chemical sensors, and biomarkers), and clinical treatment (eradication of cancers and detection/destruction of pathogens).

Technical Barrier to the Innovation**:** Despite the excellent photochemical and physical properties of NCs, the optical (fluorescent, scattering etc.) properties of NCs have been observed to be strongly dependent upon their nano-environment. For quantitative applications, a complete understanding of the physical and optical characteristics of NCs on a variety of biomimetic parameters is essential. The following technical needs are identified: (1) a platform to fabricate NC samples containing many environmental variables for the rapid characterization; (2) a set of new tools to quantitatively correlate optical properties and chemical or physical conditions of NCs in a controlled environment; and (3) measurement strategies and standards to assess NC properties when they are delivered into cells, tissues, and organisms.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** The primary measurement challenge towards quantitative clinical and *in vivo* applications is significantly enhanced knowledge of the dependence of optical characteristics and chemical properties (change in surface functionalities, release of substances that cause toxicity, etc.) of NCs on a set of biomimetic parameters such as buffer pH, ionic concentration, and linkers and surfactants used to cluster or disperse the NCs.

Potential Solutions to Measurement Problem: (1) Reference specimens: A microarrayer to dispense picoliters of nanosensor solution onto a functionalized substrate with high-accuracy positioning capability is an ideal tool to produce arrays of a few hundred to thousand combinatorial nanosensor spots on one sample substrate with biomimetic parameters varied at different sample spots. (2) Simultaneous optical and physical characterization: Chemical sensing microscopy combined with optical spectroscopy will provide nanoscale chemical details of the NC surfaces to be correlated with optical characteristics. (3) Dynamic evaluation of *in vivo* delivery effect: Multi-dimensional chemical and optical imaging (vibrational spectroscopy, fluorescence lifetime measurements, etc) will not only characterize NCs themselves, but allow them be employed as nanosensors to probe local *in vivo* environment.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Current flow in nanoscale electronic devices

Submitter(s): Richard E. Harris (for EEEL)

Technological Innovation at Stake: Full understanding or measurement techniques for electrical current flow in nanoscale electronic devices is critically needed. Progress to date has been made in the absence of this information, but the lack of these data/techniques impedes medium to long-term innovation in these widely used electronic systems. The technical basis of the entire electronics and computing industries is now dominated by electronic integrated circuits having typical critical dimensions well less than 100 nm. All observers expect this trend toward smaller sizes to continue for the foreseeable future, even if it eventually requires moving beyond the present technology based on silicon devices.

***Economic Significance of Innovation*:** The combination of the worldwide electronic and computer industries is hundreds of billions of dollars per year. Should these industries be limited by fundamental understanding or lack of measurement capability, a significant fraction of both industries could be jeopardized.

***Technical Barrier to the Innovation*:** What is needed by design engineers of these complex integrated circuits is the ability to measure and understand their behavior. Ultimately that must be reduced to computer code to permit automatic design at size scales approaching a few atoms. A trial-and-error approach is useless at these levels of complexity.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** For accurate diagnosis and understanding of individual nanoscale electronic devices it is essential that current flow be understood. In both silicon and all other anticipated electronic devices it is not possible to measure electrical performance of devices at their required speeds of operation when combined with spatial resolution. Integrated circuits that must operate at tens of GHz (billions of operations per second) can only be measured at tens of thousands of operations per second, a factor of about a million times too small.

Potential Solutions to Measurement Problem: There may be a wide variety of measurement solutions available from superconducting electronic techniques involving SQUIDs (superconducting quantum interference devices) to high frequency optical approaches. The solutions may well involve significant interdisciplinary approaches.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Next generation electrical instrumentation

***Submitter*:** Yicheng Wang

***Technological Innovation at Stake*:** Emerging technologies such as integrated nano-biosensors and next-generation electrical instrumentation require new and better electrical standards for calibrations. New dissipation factor measurement capabilities for capacitance standards are needed for calibrations of nano capacitive transducers, new capacitance bridges, LCR meters, and network analyzers.

***Economic Significance of Innovation*:** Capacitive transducers are widely used in nano devices and their traceability is needed when the new devices become commercialized. New measurement capabilities of dissipation factor of capacitors will also enable traceability of energy and power instruments needed under the new rules for international trade, and better characterization of dielectric materials, aged underground power cables, and high-temperature superconducting cables. Precision capacitors are also essential in a variety of electrical instruments including capacitance bridges, LCR meters, lock-in amplifiers, and network analyzers. These electrical instruments, in turn, have wide applications in a broad market; for example, maintenance of aircraft for reliability, quality control in integrated circuits production, DNA characterization, and real-time monitoring of wireless communication networks.

***Technical Barrier to the Innovation*:** There are no dissipation factor measurement services available in the U.S., so domestic instrument manufacturers have to turn to overseas which do not completely address their needs. For example, Andeen-Hagerling, Inc. in Ohio, which is the manufacturer of the world's most accurate commercial capacitance bridges, has relied on a foreign national lab for dissipation factor calibrations in the past. However, the solution has become unsatisfactory to Andeen-Hagerling because the calibration uncertainties now significantly exceed the resolution and stability of their new instruments.

***Stage of Innovation Where Barrier Appears*:** R&D, Production, Marketing, End Use.

***Measurement-Problem Part of Technical Barrier*:** Accurate calibrations of dissipation factors require reference capacitance standards whose capacitance and dissipation factor can be calculated from basic electromagnetic theories and a scaling system that allows direct comparison between the reference standards and transportable customer standards from 1 pF to 1 µF in the frequency range from a few Hz to 1 MHz.

***Potential Solutions to Measurement Problem*:** R&D to improve and characterize toroidal cross capacitors whose dissipation factor can be calculated, and to develop automated capacitance and dissipation factor scaling bridges for dissemination. Characterized transportable standards that can be utilized in an industrial environment. An in-depth uncertainty analysis to identify individual measurement contributions to overall uncertainty budget.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Next-Generation Active Nanodevices

Submitter(s): Chad Snyder

Technological Innovation at Stake: Next generation active, i.e., powered, nanodevices will enable greater functionality (e.g., faster computations, larger memory storage, or combinations thereof) in smaller packages, providing the basis for a broad range of high tech products. A broad range of new products will be impacted, e.g., components of integrated circuits, NEMS, and optoelectronic devices.

***Economic Significance of Innovation*:** As an example of the economic significance of this innovation, the U.S. Department of Commerce's Bureau of Economic Analysis estimates the domestic semiconductor and related devices industries' gross output to be $80B in 2004. To keep up with Moore's law and to maintain or grow the output level of this industry, next generation devices must be developed.

***Technical Barrier to the Innovation*:** One of the barriers to this innovation is heat dissipation, i.e., the problem of thermal management. The *2003 ITRS* indicates that the task of dissipating heat from nanodevices will *significantly increase in the future due to increasing power, decreasing junction temperatures, and a continuing need to have cost-effective solutions*. Many MEMS applications demand an inert or vacuum environment inside the package, eliminating the possibility of air cooling and making thermal management even more critical; and optoelectronic devices have temperature sensitivity in their operating parameters, such as wavelength. Additionally, there will be thermal management problems with emerging devices such as NEMS, quantum cellular automata, cellular nonlinear networks, biologically inspired architectures, and coherent quantum computing; predictive capabilities for the behavior of these systems are currently model and input data limited.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** Thermal conductivity/diffusivity in complex geometries and at the nanoscale requires measurement techniques beyond the current state-of-the-art. Further, measurements that can provide insight into the effects of defects, interfaces, and molecular anisotropy on the thermal characteristics of nanodevices are critically needed. Existing characterization techniques are designed to characterize bulk materials or films on substrates and therefore cannot address issues such as spatial confinement of photons at the nanoscale and thermal boundary resistance (which is a function of defects and interfaces) between multiple structures.

Potential Solutions to Measurement Problem: R&D to find practical way to extend the capabilities of current measurement instrumentation, e.g., the widely accepted 3□ technique for direct measurement of thermal conductivity, and to develop appropriate testbeds, with controlled defects, interfaces, molecular anisotropy and 3D geometries, which allow quantification of nanoscale effects, e.g., nanofilled block copolymers.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Single molecule optical measurement

Submitter(s): Lori Goldner

Technological Innovation at Stake: The ultimate limit of all nanobiotechnology is the ability to follow a bioreaction on a single molecule scale which requires optical detection and measurement of single molecules. This ability makes the optical detection and measurement of rare species possible and can revolutionize the basic understanding of biological and biochemical processes, and thereby advancing the understanding of cellular activity and treatment of disease.

Economic Significance of Innovation**:** The ability to make single molecule measurements eliminates the waste of expensive resources and reduces to a minimum the need to deal with harmful or toxic substances. Significant reductions in time and costs can be realized by using single molecule measurement techniques to replace laboratory processes that require amplification such as polymerase chain reaction (PCR). Reduction in costs and damage to the environment can be achieved by minimizing the use of expensive chemical reagents, which may pose significant health hazards when used in greater than trace quantities.

Technical Barrier to the Innovation**:** Isolation, immobilization (when necessary), and chemical labeling of the species under investigation are the primary technical challenges facing industry regarding the use and reliability of single molecule measurements.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Nanoencapsulation and labeling schemes that are minimally perturbative to a single molecule or a single nanobiosystem such as a molecular complex, virus, or organelle are needed. A good nanoencapsulation system will not change the functionality of the molecule or nanobiosystem under test. Determining the magnitude or the degree of perturbation requires research into measurement methods and technologies.

Potential Solutions to Measurement Problem: Nanoencapsulation schemes involving water-in-oil reverse emulsions and liposomes are possible and should be physically investigated. Current labeling schemes involve commercial dyes. New fluorescent species and analogs and optically detectable nanoparticles are alternatives that can increase sensitivity, therefore reducing the concentration of nanoparticles required. In some cases, comparison of single molecule and traditional bulk experiments can be used to investigate degree of perturbation and optimize single molecule technique. In other cases, direct investigation and modeling of single molecule dynamics can be used to validate these techniques.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Integrated Circuit Optical Linewidth Metrology

Submitter(s): Rick Silver

Technological Innovation at Stake: Measuring feature linewidth directly on a wafer at different photolithographic levels in the manufacturing integrated circuits is an enabling technology for the worldwide electronic products economic market. As the critical dimensions of key attributes in semiconductor devices get smaller and smaller, measuring the sizes of these features is becoming increasingly difficult with new challenges in maintaining the accuracy requirements and the basic ability to even resolve the features.

***Economic Significance of Innovation*:** The US semiconductor industry has held a preeminent position in the design of advanced and next generation semiconductor devices as well as the instrumentation used to manufacture them. For US industry to maintain a leadership role in the continued exponential shrinkage and production of semiconductors with yet lower cost per function, significant investment and R & D in manufacturing metrology is required. This exponential growth has created very significant market segments with technological leadership from the US. Even the smallest improvements in measurement innovation and manufacturing process control can yield millions of dollars in return. This economic sector is so advanced and automated that clever solutions and advances can have very significant and measurable effects on profit levels. The techniques suggested for development would enable closed loop, high through-put metrology improving yield which is becoming a requirement at this level. High through-put non-destructive metrology capable of measuring 10 nm sized features with sub-nm accuracy would enable improved manufacturing as required by the ITRS roadmap.

***Technical Barrier to the Innovation*:** Accurate optical measurement techniques, optical hardware alignment and electromagnetic scattering models which simulate the imaging process are needed to accurately and provide robust measurement and process control capabilities. The dimensions of features on the wafer must be measured accurately in order to obtain acceptable manufacturing yields, device performance, and profit levels. An improvement in linewidth process control or measurement of only a single nanometer can result in millions of dollars in increased profits.

Stage of Innovation Where Barrier Appears: R&D and Production

***Measurement-Problem Part of Technical Barrier*:** There are several challenges in measuring optical targets composed of features nearly $1/10^{th}$ the size of the measurement wavelength used. Aligning the optics, defining algorithms and CCD measurement capabilities with better than 1 nm resolution and accuracy is very challenging. Accomplishing this in a way which enables high throughput and accuracy requires pushing optical techniques to new, advanced levels. Current CCD metrology is limited by target sizes to 20 microns for scatterometry and electron microscopes have a host of challenges at this level. Overlay tools cannot measure or image features the sizes coming in manufacturing. The ability to measure 10 nm sized features with placement accuracy of 0.1 nm is not currently attainable.

Potential Solutions to Measurement Problem: Implement new high resolution scatterfield microscopy techniques to the critical dimension wafer measurements. Quantify the effect of measurement uncertainty on device yield and process control.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue*:* Single biomolecule detection, classification, and measurement.

Submitter(s): David Nesbitt, John Kasianowicz & Vincent Stanford (NIST)

Technological Innovation at Stake: Detecting and analyzing biomolecules at low concentrations, such as biowarfare toxins, products of pathogenic organisms, and pollutants.

Economic Significance of Innovation: This technological innovation has potential to thwart acts of bioterrorism, enable a better understanding of fundamental processes in biology, and permit long-term monitoring of pollutants in the environment. Achieving this innovation would provide significant benefits to national health, defense, and security.

Technical Barriers to the Innovation: Fundamental physical measurement and theoretical techniques are still rudimentary. For example, there is a lack of fluorescent probe molecules that do not photobleach or blink. Electrical measurements in this domain encounter fundamental physical limitations on the continuity assumptions of classical physics. New theories of fundamental measurement and statistical signal processing theory must be co-developed to open the domain to bioengineering applications.

Stage of Innovation Where Barrier Appears: R&D.

Measurement-Problem Part of Technical Barrier: Existing methods have fundamental limitations: optical methods are currently limited to fluorescence measurements. Non-fluorescent optical methods are needed. Electrical and electronic methods can be limited by the small current flows and the discrete number of ions available in high bandwidth measurements. Advanced statistical algorithms are needed to address that issue.

Potential Solutions to Measurement Problem: The Government must work with the nanobiotechnology research community to develop new methods and materials. Nanofabrication, a new suite of physical measurement technologies, and better theoretical methods will guide the development of measurement technology.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Integrated Circuit Photomask Metrology

Submitter(s): James Potzick

Technological Innovation at Stake: Integrated circuit photomask technology is an enabler for the worldwide electronic products economic engine. Photomasks face new challenges in maintaining the vigor of this engine, in the form of innovative *resolution enhancement features* like sub-resolution scattering bars, Optical Proximity Correction (OPC) serifs, and phase shifters. Overcoming these challenges will enable the continued progression of Moore's law and the economic benefits that follow.

***Economic Significance of Innovation*:** The functional density of integrated circuits has been growing exponentially for over 25 years (see Moore's Law) with the cost per function in consumer products declining commensurately. This exponential growth has created one of the largest market segments of the world economy and improved the worldwide standard of living. The market, however, has discounted this historical growth, so that any slippage below the Moore's law curve is perceived as a decline. Should the cost per function of consumer electronic products level off or increase within a relatively short time span, the potential for an economic worldwide depression may be realized.

***Technical Barrier to the Innovation*:** Improved accuracy optical imaging models are needed in order to specify mask features that will achieve the desired effect on the wafer during exposure. The sizes and placement of these features on the mask must be measured accurately in order to manufacture a photomask to its specifications. A misplacement of a subresolution scatter bar by a few nanometers can render a $100,000 photomask marginal in its performance, resulting in the loss of perhaps millions of dollars in wafer product. There is no optical limit to the smallest feature size on a wafer; instead the process becomes more dependent on control of process parameters like feature size and placement on the photomask, focus, dose, illumination parameters, etc. Thus, smaller features do not become impossible at some point, they just gradually become more difficult and expensive.

***Stage of Innovation Where Barrier Appears*:** R&D and Production

***Measurement-Problem Part of Technical Barrier*:** The tolerances of photomask resolution enhancement features and the uncertainties of their measurements combine to establish the probability that the mask will perform as intended. As the cost per unit area of making integrated circuit chips rises exponentially with diminishing feature sizes, this probability can be maximized only through research.

Potential Solutions to Measurement Problem: Verify and improve the performance of existing optical imaging models. Improve photomask feature measurement techniques. Quantify the effect of measurement uncertainty on mask performance.

Technology at Issue: Nanomanufacturing

Submitter(s): J. Cline

Technological Innovation at Stake: Nano-materials hold forth the promise of unprecedented potential to design devices with unique properties and capabilities. Requisite to realization of these devices, however, is the ability to quantitatively measure nanoscale features of these structures. These measurement data will permit the understanding of origin of the properties these devices exhibit, and, therefore, their optimization.

***Economic Significance of Innovation*:** Nanomaterials are being pursued as the basis for next-generation developments in a wide range of applications, including high-density electronics, sensors for biochemical applications, actuators in nanomechanical devices, and biomedical diagnostic and delivery mechanisms. The Nanotech Report (2003) projects a $1 trillion nanotechnology industry by 2015.

***Technical Barrier to the Innovation*:** Nanomanufacturing requires an understanding and control of the adhesion and bonding of the surfaces, particles, and nanoelements comprising a nanodevice. Interactions at the nanoscale, however, are highly dependent on the composition of the surface layers, size, and composition of the nanoparticles. Traditional analysis methods and assumptions, such as those based on bulk crystalline structures, are known to be inaccurate and the cause of erroneous models.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** A primary challenge is to achieve a reliable, quantitative measure of the nano-particle surface layer thickness, size, crystalline perfection and interatomic spacing.

Potential Solutions to Measurement Problem: Diffraction methods are predicated on the presence of crystalline structures and are well suited to measurement of features of nanomaterials that are inaccesable by alternative methods. The combination of high resolution x-ray diffraction metrology and standard reference materials certified for crystallite size, amorphous content, and lattice parameter are key to an industry accessible measurement procedure for assessing quantitatively character of nanomaterials.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Sidewall Characterization Instrumentation

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: Advanced instrumentation to characterize nanometer scale sidewall composition and roughness for sub-32 nm technologies. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of 22 nm integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start development of this technology within the next two years; however, existing tools to measure sidewall composition and roughness are not capable of being used as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector.

Technical Barrier to the Innovation: Lack of acceptable instrumentation to determine sidewall composition and aspect ratio. Device features already have nanometer-sized dimensions with high aspect ratios. Developing and manufacturing devices at these sizes and aspect ratios require characterization and metrology tools that characterize sidewall with essentially atomic resolution.

Stage of Innovation Where Barrier Appears: R&D and production

Measurement-Problem Part of Technical Barrier: Present in-line methods measure large horizontal areas and infer sidewall properties. Sidewall roughness can be measured by atomic force microscopy (AFM) and critical dimension scanning electron microscopy (CD-SEM) on today's features but not on the features that will be of the order of 10 nm in size by 2016.

Potential Solutions to Measurement Problem: Invent new methods to measure the sidewall composition and roughness of sub-22 nm features.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Health Care/Nanotechnology - Cancer Diagnosis and Treatment

Submitter(s): Vincent A. Hackley

Technological Innovation at Stake*:* Nanoparticle-based vectors for detection and treatment of cancer. Success would result in precise in situ imaging/localization of tumors, sensitive ex situ detection, and localized application of chemotherapy directly to tumor cells. Innovations will provide for early detection, improved efficacy of anti-cancer drugs, and decreased toxicity of treatments to non-targeted cells.

Economic Significance of Innovation: From the 2005 ASTM Workshop "NCI Alliance for Nanotechnology in Cancer," the cancer mortality rate in 2002 was identical to that in 1950; the healthcare cost associated with cancer treatment was $189 billion in 2002. Due to the potential benefits of nanotechnology in cancer treatments, by 2005, 61 nanotech drugs or delivery systems had been developed and 91 devices or diagnostic tests based upon nanotech had been developed. According to the National Cancer Institute, "nanotechnology will change the very foundations of cancer diagnosis, treatment, and prevention."

Technical Barrier to the Innovation**:** Lack of a standardized, analytical cascade for the physical (physico-chemical) characterization of nanomaterial vectors and lack of knowledge of critical material parameters that influence nanomaterial transport, toxicology and effectiveness in biological systems; undefined clinical pathways for approval of nanomaterial-based drugs. These materials must be evaluated for both efficacy and toxicity before going on to clinical studies and FDA approval. Improved understanding of nanomaterial interactions in biological systems will also impact how new NP platforms are developed, as well as impact future FDA guidance on these materials and their approval.

Stage of Innovation Where Barrier Appears: R&D and Production

Measurement-Problem Part of Technical Barrier**:** Measurement protocols must be developed and standardized for the physical characterization of different nanomaterial classes under physiologic conditions. Properties include hydrodynamic size and size distribution, morphology, aggregation, stability, surface charge, zeta potential, chemical composition and purity. Parameters that impact nanomaterial behavior in biological systems must be identified and systematically interrogated.

Potential Solutions to Measurement Problem**:** Improved methods for physical characterization of nanoparticles under relevant conditions and R&D to relate physical (material) characteristics to biological interactions (e.g., toxicity, reactivity, mobility) and pharmacokinetics. Relevant reference materials, protocols, and internationally recognized consensus standards for measurements.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Advanced Force Measurements in Nanotechnology

Submitter(s): Richard Gates & Robert Cook

Technological Innovation at Stake: Nanoscale Measurement Accuracy: Atomic Force Microscopy (AFM) is widely used for characterizing surfaces at the nanoscale; however, accurate understanding of the forces being applied to surfaces is limited by the lack of SI traceable standards at the force scale applicable to AFM. This affects not only specific force measurements (adhesion, deformation, friction) but imaging as well since excessive forces can lead to structural deformations that alter the image and can lead to erroneous interpretation. Improved nanoscale measurement accuracy will enhance the ability to measure materials microstructures and properties at the nanoscale and increase our abilities to evaluate and enable MEMS structures.

Economic Significance of Innovation**:** Ability to provide accurate nanoscale force measurements will enable better design of nanoscale devices (MEMS, NEMS) and lead to cost savings from improved tolerances. M/NEMs devices are involved in applications as diverse as safety (accelerometer sensors for automotive airbags), communication (optical switches), and entertainment (micromirror arrays for projection televisions) The worldwide MEMS market is currently approximately $30B/yr and forecast to grow very strongly in the foreseeable future.

Technical Barrier to the Innovation**:** SI traceable calibrations are very difficult at the cantilever stiffness range typically observed in AFM (approximately from 100 pN/nm to 10 nN/nm). A single accurate determination requires specialized research equipment (e.g NIST electrostatic force balance – a unique, sensitive instrument capable of measuring nanonewton forces in an SI-traceable fashion) and laboratory facilities (NIST AML) and can take hours or days per determination.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier**:** No readily available SI traceable, accurate, reference calibration cantilever standard is available.

Potential Solutions to Measurement Problem: The solution is to develop reliable standards for the calibration of AFM force measurements. Large batches of very uniform reference cantilevers will need to be made with stiffness values relevant to AFM cantilever spring constants. The cantilevers must be calibrated with measurements traceable to the SI, and a standardized measurement procedure will be essential to enable both precise and accurate calibrations.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue**:** Advancing the Fundamental Science of Nanobiotechnological Systems

Submitter(s): Michael J. Tarlov, John Kasianowicz (NIST)

Technological Innovation at Stake: Nanobiotechnology (NBT) develops and applies tools and processes of molecular nanotechnology for the study of biological systems. It borrows concepts from biological systems to design either materials with novel and improved properties or nano/micro-devices that mimic living biological systems. Nanomedicine, a subset of NBT, will use the tools of molecular nanotechnology to diagnose, treat, and prevent disease; relieve pain; and improve human health. The development of NBT as a mature scientific and technological discipline will enable scientists to build synthetic biological devices, such as tiny sensors to scan for the presence of infectious agents or metabolic imbalances, and engineered nanoscale therapeutics to target and destroy infectious agents or fix "broken" parts in cells. NBT tools will be useful for a wide range of tissues and disease, not just for a single disease or particular type of cell.

Economic Significance of Innovation**:** The potential of NBT are more efficient, cost-effective healthcare that will improve our quality of life. Many diseases such as cancer, diabetes, Alzheimer's and Parkinson's disease, cardiovascular problems, etc., are currently diagnosed at acute or chronic stages where treatments are expensive and not particularly effective. Advances in NBT are expected to lead to early diagnosis, smart treatments, and the triggering of self-healing mechanisms. Total US health expenditures, $1.7 trillion in 2003, are currently rising at 4 times the rate of inflation and represent 15.3 % of the GDP.

Technical Barrier to the Innovation**:** Full realization of NBT's potential requires more fundamental understanding of nanotechnology as it relates to biomedical applications. A central theme of NBT is exploiting novel and improved properties that emerge at the nanoscale. Knowledge of these properties will help scientists predict, develop, characterize, and control nanoscale hybrid structures for biomedical applications.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Progress in NBT requires biophysical and biochemical measurements, development of theoretical models, and experimental validation. One barrier is the ability to obtain pure, monodisperse materials for these measurements. Macroscopic measurements of ensembles of materials are often dominated by substituent's properties. Improved methods for purifying and separating samples are required. The development of non-invasive probes of single-particle NBT properties is also needed. Current computational models for NBT materials can only handle systems consisting of hundreds of atoms. More robust computational methods that can predict properties for thousands of atoms are needed.

Potential Solutions to the Measurement Problem: Improvements in spectroscopic methods and nanoscale probe tools are needed to measure the physical and chemical properties and biological activity of NBT systems. New nanoscale measurement tools will be used to improve the basic scientific understanding of self-assembly and biologically driven self-assembly to enable the design, fabrication, and characterization of novel NBT structures for biomedical applications. Improvements in the accuracy, reliability, and transferability of quantum chemical methods are required for predicting the chemical and physical properties of NBT systems and comparing experiment with theory. An improved understanding of separation mechanisms needs to be established to improve the purity of NBT samples for further probing of fundamental properties.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** In-line/Real-time Analytic Tools for Measuring Sub-10 nm Defects

***Submitters*:** Herbert Bennett, for industry

***Technological Innovation at Stake*:** In-line/real-time detection, review, and analysis of sub-10 nm defects and particles on patterned and un-patterned wafers. The International Technology Roadmap for Semiconductors anticipates that the broad industry manufacture of integrated circuits based on the 22 nanometer technology generation will have minimum features of ~ 10 nm by 2016. Early developers will start on this technology within the next two years; however, tools to measure critical dimensions are not capable of being used as in-line monitors.

***Economic Significance of Innovation*:** The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector. When defect or particles are not detected, the yield of integrated circuits is reduced below that required for economically viable manufacturing.

***Technical Barrier to the Innovation*:** Metrology tools to detect particles and defects are incapable of measuring defects or particles for sub-32 nm technology generations with a high capture rate and with precise and accurate sizing on the manufacturing line.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** The integrated circuit industry requires processes that produce hundreds of billions of features uniformly across each wafer for each mask operation with a tight distribution of sizes. The inability to detect particles or defects on a large number of chips per wafer and wafers per lot will dramatically slow the development of integrated circuit technology.

***Potential Solutions to Measurement Problem*:** Perform R&D to extend conventional e-beam and optical based defect detection tools. Evaluating progress will require standardized and patterned wafers with defects and particles several generations ahead of the leading-edge manufacturing of integrated circuits. The solution must include reference materials to test R&D progress.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Dopant Distribution Instrumentation

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: Instrumentation for determining 3D dopant distributions in wafers and epilayers (dopant distribution mapping) for sub-22 nm processing technologies. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of the 22 nanometer integrated circuits, which will have minimum features of ~ 10 nm by 2016. Early developers will start work on this technology within the next two years; however, current tools to measure 3D dopant distributions at the nanoscale are not capable of being used as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and other sectors that depend on semiconductors.

Technical Barrier to the Innovation: There is a lack of adequate instrumentation to measure in real-time and in-line 3D dopant distributions in wafers and epilayers for sub-22 nm technologies. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes in high volume require characterization and metrology tools that give 3D dopant distributions and structural and material properties with atomic resolution.

Stage of Innovation Where Barrier Appears: R&D and production

Measurement-Problem Part of Technical Barrier: Develop characterization and metrology tools that measure dopant concentration, location, and activation. Such tools are just becoming capable of near atomic resolution. Examples include aberration corrected scanning transmission electron microscopy (STEM) and local electrode atom probes (LEAP). Dopant location in the smallest transistors such as FINFETS is almost impossible to determine.

Potential Solutions to Measurement Problem: The solution includes working to improve resolution of new characterization and metrology tools such as aberration-corrected STEM, LEAP, STEM, scanning capacitance microscopy, spreading resistance measurements at the nanoscale, and secondary ion mass spectroscopy (SIMS) of small structures and thin films for dopant measurements.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Atomic Mapping Instrumentation

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: Advanced atomic mapping instrumentation for structural and compositional analyses at the nanoscale for sub-22 nm generations. The International Technology Roadmap for Semiconductors anticipates broad industry manufacture of integrated circuits based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, tools for structural and compositional analyses are not capable of being used as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector and will have a negative ripple effect on many other economic sectors that depend on advance semiconductors.

Technical Barrier to the Innovation: Device features already have nano-sized dimensions. Adequate characterization and metrology tools that measure structural and materials properties with atomic resolution do not exist. Such tools are needed to develop and manufacture devices at these sizes.

Stage of Innovation Where Barrier Appears: R&D and production

Measurement-Problem Part of Technical Barrier: Improving resolution and precision of atomic mapping instrumentation. True atomic resolution in 3D must become routine for the entire range of materials and structures. Characterization and metrology tools that are just becoming capable of near atomic resolution include aberration corrected transmission electron microscopes, local electrode atom probes, and scanned probe microscopes. In addition to the hardware, simulations of the measurement and the measurement system are required for the considerable amount of new phenomena associated with nano-sized dimensions. Tomography of structural features must be extended beyond the large feature capability presently available.

Potential Solutions to Measurement Problem: Improving resolution and precision from near atomic resolution to true atomic resolution by developing next generation aberration corrected electron microscopes such as scanning electron microscopes and transmission electron microscopes (TEM), and scanning TEM, and scanned probe microscopes such as atomic force microscopes, scanning potential microscopes, scanning near field acoustic microscopes, scanning thermal microscopes, and local electrode atom probes.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: MEMS

Submitters: USMS MEMS/NEMS Group, D. T. Read

Technological Innovation at Stake: Micro-Electro-Mechanical System (MEMS) are a new technology for switching of radio-frequency (RF) signals is wireless telecommunications. These MEMS-RF switches will enable multi-band operation, with higher efficiency and lower cost than transistor switches, in a variety of wireless devices, such as multi-band handsets, that support a variety of wireless services, such as voice and computer communications.

Economic Significance of Innovation: The market for RF MEMS in 2009 has been estimated at $1.1 billion, according to Jérémie Bouchaud and Henning Wicht of Wicht Technology Consulting reported in ***Microwave Engineering*** and elsewhere. This lags an earlier forecast from the same source, which had predicted a market of $1 billion 2007. Technical barriers impeding market acceptance is considered to be one of the causes of this lag.

Technical Barrier to Innovation: MEMS RF switches, which open and close to an RF signal in response to a control voltage, while offering known technical and economic advantages in terms of performance *vs* price compared to alternative switching technologies in compact wireless device, have unknowns regarding reliability. The field reliability of such MEMS components is untested and there are no established methods for assuring field reliability. Devices of suspect reliability cannot be marketed profitably; reliability complaints that arise after a product is introduced can be costly. Unexplained deviations from expected service lifetime have been noted in reliability tests during the product development cycle. This issue threatens the viability of a significant family of products.

Stages of Innovation Where Barrier Appears: Production

Measurement-Problem Part of Technical Barrier There is presently no way to adequately measure the changes in surface chemistry, surface electrical charge, microstructure of the metal region the flexure elements that are suspected to contributors to early failure of MEMS RF switches.

Potential Solutions to Measurement Problem: The solution has multiple parts: developing a practical understanding of the relationships between measurable material properties at the time of manufacture and in-service reliability of MEMS; development and fielding of advanced inspection tools for use in the production lines; and creation of a set of software to generate pass *vs* fail *vs* test further decisions based on inputs of quantitative material properties and quantitative inspection results.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Dimensionally Critical Nanomanufacturing

Submitter(s): John Kramar

Technological Innovation at Stake: Nanotechnology is predicted to have major positive impacts in a broad array of applications, including health care, homeland security, and communications. In order to turn this potential into a viable economic reality, the newly developed technologies must be grounded in accurate metrology to enable efficient process control and quality assurance. This is particularly true in dimensionally critical nanomanufacturing, where the performance of the product depends critically on the precise dimensions of specific features, and on the consistency of these dimensions throughout a manufactured product, or from device to device.

***Economic Significance of Innovation*:** Many reputable studies have predicted significant economic impacts for nanotechnology. For example, a recent National Science Foundation study projected a $1 trillion global market for nano products by 2015; private investment companies have offered similar estimates. This large economic potential is driven by the new properties and performance characteristics that occur at the nano level. The tools and devices segment is estimated to make up one third of the nano market, and within this sector, a large portion of products is expected to require highly precise dimensions.
***Technical Barrier to the Innovation*:** A key barrier to moving nanomanufacturing from the laboratory into the market place is the capability for well-understood, effective process control and product assurance.

***Stage of Innovation Where Barrier Appears*:** R&D (primary), Production (secondary)

***Measurement-Problem Part of Technical Barrier*:** In the nano regime, whereas many metrology forays have built up capability for addressing specific measurement needs, a truly versatile link to the SI unit of length is yet lacking. This versatility is critical for the flexibility to quickly address the quality-related metrology needs for yet-to-be-developed innovations and to shorten their time to market by enabling robust process controls.

Potential Solutions to Measurement Problem: A flexible, multi-probe, long-range, three-dimensional, coordinate measuring machine with nanometer accuracy must be developed for realizing the unit of length in this domain. This capability will provide traceability for industry-developed factory-floor and quality control lab metrology instruments, via NIST- or industry-developed calibration artifacts.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Airborne Contamination in Semiconductor Wafer Processing

Submitter: J. T. Hodges

Technological Innovation at Stake: Manufacturing of future generation semiconductor devices, having smaller physical feature size, higher speed, and lower cost, can be limited by the presence of airborne molecular contamination (AMC). Production yield is expected to be adversely impacted in 300 mm and larger diameter wafers. Numerous process steps in the production of semiconductor wafers utilize ultra-high purity gases, which can contain airborne molecular contamination. In the long-term, AMC concentration specifications required of gas suppliers by IC manufacturers will be below the 1 ppb level. Trace quantities of AMC in process gases also degrade manufacturing yield of integrated photonics devices and custom nanomaterials.

Economic Significance of Innovation**:** The semiconductor industry now represents nearly 1 % of the US GDP and in terms of value added is the largest manufacturing industry in the US and sustains high-wage jobs. The photonics industry (approximate $20 billion/yr), largely supporting telecom applications, is also a significant and growing sector, which relies on devices fabricated from wafers. A recent study [http://mph-roadmap.mit.edu/about_ctr/report2005/] indicates that for the optical communications industry to prosper, electronics and photonics must merge to generate a new breed of devices that will be manufactured in large volume at low cost to power devices with greater functionality, which increases consumer benefits. Given that a 1 % yield increase corresponds to approximately $1M per day increase in profits for a 300 mm fabrication facility, relatively small improvements in yield associated with improved metrology and process control improve profitability for IC manufacturers.

Technical Barrier to the Innovation**:** AMC must be controlled by specialty gas suppliers in high purity gases supplied to the semiconductor and photonics industries. Current measurement methods having the required concentration detection capability require expensive and bulky off-line instrumentation to characterize impurities in semiconductor process gases. Consequently, users rely on supplier-specified impurity levels in delivered gases, with no knowledge of the contamination level at the point of use.

Stage of Innovation Where Barrier Appears**:** Production

Measurement-Problem Part of Technical Barrier**:** More compact, flexible, in-line and/or *in situ* measurement systems are needed for high sensitivity contaminant concentration measurement at the point of use for contamination by species such as H_2O, CO, CO_2, CH_4, and NH_3. This is a challenging measurement at concentrations less than 1 parts-per-billion.

Potential Solutions to Measurement Problem: To address this issue, gas purity must be characterized by high accuracy, species-specific measurement techniques that are non-invasive, robust, reliable and able to clearly discriminate signal from contaminants within the process gas. Promising laboratory-level methods must be engineered to provide high-sensitivity process sensors capable of use in manufacturing environments. Diode laser instruments using optical absorption spectroscopy have been shown to provide quantitative gas purity measurements at the required levels, <1 ppb. Species selectivity is required and enabled by narrow bandwidth lasers and the high sensitivity afforded by resonant optical cavities.

Technology at Issue: Carbon Nanotube Identification

Submitter(s): John Lehman, NIST

Technological Innovation at Stake: Because of their strength, flexibility, and unique properties, carbon nanotubes (CNTs) are promising materials for application to a wide range of potential or improved products. As with any material, proper characterization and fitness-for-use testing are required for product scale-up. Simple, non-destructive and cost-effective tests for carbon nanotube identification and characterization are needed for manufacturing process optimization, safety regulation, process control and material enrichment.

***Economic Significance of Innovation*:** CNTs are a critical part of the nanotechnology infrastructure. Due to their special properties, they have applications in areas such as energy storage, molecular electronics, sensors, and materials. However, CNTs are expensive, costing $60-750/g depending on purity, and future prices need to be far less in order for them to appear in commercial products and to help nanotechnology realize its potential. Richard Smalley, Nobel prize recipient, identified cost reduction as the "single biggest limiting factor to quickly moving nanotubes into the marketplace." High costs are driven by low product yield, forcing producers to endure complicated, expensive purification processes. By providing new measurement tools, true process optimization can begin.

***Technical Barrier to the Innovation*:** Current manufacturing processes do not simply produce a single type of CNT. Instead, they inherently produce a mixture of CNT species, along with unwanted chemical impurities (3 - 50 %). Advanced, cost effective analytical techniques are needed so that CNT manufacturers, product developers, and regulatory agencies can truly "see" what they have.

***Stage of Innovation Where Barrier Appears*:** R&D, Production

***Measurement-Problem Part of Technical Barrier*:** Rigorous process control is not feasible today, because producers do not know what type of CNTs are in a given batch. Additionally, products differ between manufacturers, and CNTs from a single supplier can vary. Better control, which requires better measurement techniques, will yield better consistency. Quantitative data on chirality and diameter as well as semiconducting-to-metallic ratio determine the performance of field-emission devices, fuel cells, optical detectors and multifunctional composite materials.

Potential Solutions to Measurement Problem: New processes and screening techniques are needed to identify and characterize CNTs. One possible approach being explored at NIST is a two-tiered screening process, which matches characterization precision and accuracy with application needs. Tier 1 methods rapidly screen bulk CNTs for batch certification and high-volume products, such as polymer composites. Tier 2 methods quantify CNT species, including chirality, diameter, and defects - key attributes that dictate properties.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Multilayer film structures for electronics and optics industries

Submitter(s): Donald Windover

Technological Innovation at Stake: Multilayer, nanoscale, novel material, thin films with enhanced uniformity and reproducibility are key to achieving higher component densities, faster operating times, and more efficient energy usage in microelectronic devices. Some examples include high-k and low-k replacement of SiO^2 in both gate and interconnect applications and new "strain-enhanced" device substrates for the CMOS process.

***Economic Significance of Innovation*:** All advanced nano-devices and microelectronics structures, such as CMOS gate and interconnect applications, bio-chemical sensors, and flat-panel displays, use multilayer, nanoscale thin film structures in processing. Improvements in layer deposition control, therefore, could simultaneously impact multiple electronics industries. As an example, improved "in-process" monitoring of thin film deposition enhances device-manufacturing-yield increasing profits for the semiconductor industry (39 billion dollar US market / 166 billion dollar worldwide in 2004 according to SIA - http://www.sia-online.org).

***Technical Barrier to the Innovation*:** Repeatable deposition parameters for ultra-thin films (i.e., uniformity, thickness, surface roughness, and composition) are essential for reliable production and operation of semiconductors and electronics.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** Precision and repeatability in determination of film properties, calculation of correlations, and estimation of model and instrument error bounds all present current technical barriers requiring fundamental modeling of method and instrumentation, and calibration artifacts currently unavailable to industry.

Potential Solutions to Measurement Problem: X-Ray Reflectometry (XRR) provides the required determination of thickness, density, and roughness with high precision via model refinements of the structural parameters for certain material systems.

Technology at Issue: Novel Materials for Nanoscale Diffusion Barriers in Microelectronics

Submitter(s): Daniel Josell

Technological Innovation at Stake: To successfully achieve future generation devices, the microelectronics industry is examining a large number of nontraditional materials for applications at both the semiconductor device and the interconnect levels. These include new materials for gate-stack structures and wettable diffusion barriers for interconnect levels. Novel materials combinations for other nanoscale applications are also being developed. Successful implementation of new materials in nanoscale structures requires barrier layers to separate incompatible materials, e.g., inhibiting copper diffusion from interconnect levels to the wafer surface where the presence of copper destroys transistor operation. Efficiently evaluating the efficacy of these diffusion barriers is complicated by the number of potential materials systems and the low throughput and high cost of techniques presently used to quantify mass transport through diffusion barriers.

***Economic Significance of Innovation*:** Semiconductors, itself a large industrial sector ($213B worldwide market), is also an enabling technology that creates value and benefits for numerous other applications including military electronics, computing, industrial automation, telecommunications, and consumer electronics. Although this industry is faced with many technological issues, successful identification and development of new barrier materials is critical if the industry is to achieve devices manufacturing at the 35 nanometer level and below. Innovative materials can contribute to the advances needed in the semiconductor industry and the aforementioned industries that it directly impacts.

***Technical Barrier to the Innovation*:** There are a large number of potential materials systems that require investigation. While the electronics industry utilizes capacitor leakage structures for assessing barrier layer efficacy both rapid and inexpensive, cannot quantify mass transport and is useful for only a limited range of materials. For more general materials systems, the severity of some requirements, coupled with the length scales of interest, limit study to time-consuming, cost- and equipment-intensive approaches that impede examination of new materials.

Stage of Innovation Where Barrier Appears: Production

***Measurement-Problem Part of Technical Barrier*:** Absence of rapid and accurate approaches suitable for assessing mass transport through all classes of materials limits data available for predicting the long-term stability of nanostructures. Measurements of mass transport at the nanoscale utilizing standard x-ray diffraction equipment and multilayer specimen geometries coupled with thermodynamic and scattering analyses could substantially accelerate materials evaluation. Such an approach, while capitalizing on readily available instrumentation, would still require development of experimental methodologies and models for data interpretation. Combinatorial or high-throughput techniques would also needed for assessing diffusion through barrier materials in nano-structured devices to address the broad range of technologically relevant materials systems.

Potential Solutions to Measurement Problem: X-ray diffraction is ideally suited for rapid and accurate examination of nanostructure evolution. Development of thermodynamic and x-ray scattering models to interpret diffraction results from multilayered structures would permit universal, rapid evaluation of mass transport at nanometer length scales.

Technology at Issue: Next-generation optical microscopes

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: Advanced, beyond next generation, near- and far-field optical microscopy for wafer inspection. The International Technology Roadmap for Semiconductors (ITRS) anticipates high-volume manufacture of integrated circuits based on the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, existing instrumentation to inspect wafers with such features and with acceptable resolution are not suitable as in-line monitors.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Integrated circuits with higher densities increase computing speeds and reduce the costs of components for computing and many applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth of the semiconductor sector and impact in a negative manner other economic sectors that depend on advanced semiconductors.

Technical Barrier to the Innovation: Lack of high-resolution wafer inspection equipment for nanoscale devices and circuits. Device features already have nano-sized dimensions. Developing and manufacturing devices at these sizes requires wafer inspection instrumentation to verify that the wafers meet specifications, which are increasingly more stringent for each technology node of the ITRS, with acceptable tolerances before continuing with additional processing steps.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Optical microscopy has long been the most rapid means of imaging samples. Most lens designs for traditional optical microscopes do not use near-field light and thereby lose needed information about higher spatial-resolution details. High-resolution measurements are required to support advanced lens designs, especially for broadband light.

Potential Solutions to Measurement Problem: The new sub-diffraction limited super-lens, such as the silver super-lens shows promise for extension of far-field optical imaging to well below the traditional resolution limits. In addition to demonstration and commercialization of this technology to single wavelength optical microscopes, work should include extension of this lens for a single wavelength to lens for broadband light and to alternative approaches for higher spatial-resolution optical imaging.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Nano-Scale Drug Delivery

Submiter: S. Buntin, NIST

Technological Innovation at Stake: Nanoscale drug delivery systems and formulations engineered to provide more potent and targeted doses through higher bioavailability, ultimately affording highly effective treatments with fewer adverse side effects.

***Economic Significance of Innovation*:** In the year 2000, the share of the U.S. GNP attributed to healthcare costs was about 13 %, and forecast to rise to about 16 % in the year 2005. The fraction of total healthcare cost in 2000 devoted to drug expenditures was estimated at about 10 %, with the market size for drugs and drug delivery systems projected to grow from an estimated $47 billion in 2002 to $67 billion in 2006. Research is now focusing on innovative nano-particle systems to achieve higher dose efficiencies and potencies, thereby reducing drug expenditures in the future while simultaneously providing for improved health outcomes.

***Technical Barrier to the Innovation*:** Nanoparticle drug formulations, use of drug particles 1/100 the size of a red blood cell, can circumvent side effects and allowing for the facile transport into cells. For example, a 20 fold improvement was observed over conventional formulations for nanoparticle ampicillin in the eradication of Listeria, and Abraxane (American BioSciences, Inc), an albumin-bound nanoparticle anti-tumor agent, is much more effective in breast cancer treatment than conventional formulations, without solvent-induced side effects. For continued to development of such innovative drug formulations, new tools are needed to determine and assure quality and reproducibly. Control of particle size, composition and morphology for both organic-based pharmaceutical nano-particles and organic-inorganic hybrid nanostructures must be achieved for these new delivery systems. Further, the increasing design complexity of drug delivery formulations, comprising multiply layered polymeric biomaterials, exacerbates this challenge. Nanoparticle formulations typically allow drugs to have much higher potencies than conventional formulations by increasing availability of active agent in the blood stream. Most drugs have very low solubilities that severely limit their effectiveness and potency.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Particle measurement instruments currently available to the pharmaceutical industry lack the spatial resolution and compositional and morphological characterization sensitivity necessary to advance both discovery efforts and production of drug delivery devices employing nanoscale components. New or improved methods are needed for surface, near-surface (1-100 nm), and full 3D nanoscale characterization for drug development and in-line diagnostics for methods validation and quality assurance/control of manufacturing processes.

Potential Solutions to the Measurement Problem: New technologies, such as advanced mass spectrometric methods, sub-diffraction limited optical techniques and electron microscopies must be developed. These will then be the basis for protocols that include reference materials, calibration standards, and reference data supporting in-line manufacturing process monitoring for compositional and morphological characteristics critical to drug product efficacy that are needed to support clinical trials of nanoscale drug delivery systems, and ultimately widespread usage.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Directed Nanoscale Assembly

Submitter(s): Vivek M. Prabhu, Eric K. Lin

Technological Innovation at Stake: Controlling the placement of nanoscale units into designed structures and patterns through directed self-assembly processes; a grand challenge of nanotechnology. Self-assembly could enable the applications of the unique properties of nanoscale materials and structures with fabrication methods (in water or with biological materials) well-matched with exciting new applications.

***Economic Significance of Innovation*:** Directed assembly would facilitate nanofabrication of materials and applications orthogonal to those in the traditional semiconductor sector that could include biological functionality such as active biosensors or new devices such as large-area, flexible electronics. For example, in nanoscale electronics, the markets for nanomaterials, tools and equipment totaled approximately $1.8 billion in 2005 and are forecasted to reach nearly $4.2 billion by the year 2010. These applications open new markets with potential devices that currently do not exist.

***Technical Barrier to the Innovation*:** Directed self-assembly processes for the production of novel materials and devices have been demonstrated at a limited scale. However, these processes have not been developed in the context of large scale manufacturing or production. The infrastructure to determine objectively if the components can be self-assembled with sufficient fidelity and reproducibility has not been developed. Nanoscale materials suppliers and product developers will need a common set of metrics and methodologies to develop new technologies and facilitate commerce.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** New evaluation criteria and metrics unique to nanoscale directed assembly are needed to reach manufacturing design requirements. These quantities include selectivity, specificity, and registry of nanoscale building blocks. These quantities have been developed for biological assay such as in the development of DNA microarray technology, but new measurements, methodologies, and definitions are needed to quantify and validate nanoscale assembly to ensure confidence in their use in a manufacturing environment.

Potential Solutions to Measurement Problem: Initially, validation methods and concepts developed for biological technologies such as protein affinity or DNA microarrays may be adopted and adapted. For 1-D directed assembly of particles to surfaces and interfaces, quartz crystal microbalance (QCM) measurements can be combined with evanescent-wave fluorescence correlation spectroscopy (FCS) and fluorescence-resonance energy transfer (FRET) to probe assembly over a (2 to 10) nm length scale and a (100 ns to s) time scale. Selectivity can be quantified by comparing results on well-characterized material surfaces. New model test patterns in combination with fluorescence detection can be developed to evaluate selectivity, specificity, and registry of building blocks into fabricated, designed templates.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Strained-layer Engineering for High Performance Electronic and Optoelectronic Devices

***Submitter*:** Martin L. Green, Ward L. Johnson

***Technological Innovation at Stake*:** The introduction of strained layers into electronic and optoelectronic devices is being pursued by industry as a means of optimizing performance parameters such as electron mobility and optical emission wavelength. Further, scaling (adherence to Moore's Law) in Si microelectronics is an expensive proposition; however, through the use of strained Si layers, with their well documented higher carrier (electron and hole) mobilities, performance improvements may be achievable without scaling. Ken Rim of IBM has stated, "strain engineering replaced geometric scaling as the primary performance driver starting with the 90-nm technology node". Performance driven strain engineering will push devices close to the brink of mechanical failure, and it is essential to be able to characterize the strain and its distribution.

***Economic Significance of Innovation*:** The silicon microelectronics industry, is, at $750 billion, one of the largest sectors of the global (and US) economy. Continued innovations in Si microelectronics, especially those that improve device performance without scaling, are of immense importance. The establishment of new strain-mapping tools will promote U.S. industrial innovation and competitiveness by filling a void in measurement science and technology that is impeding the development of near-term and emerging electronic and optoelectronic devices.

***Technical Barrier to the Innovation*:** Strained silicon technology cannot be advanced independently of metrology improvements, as well as models for accurately predicting strain distributions. As stated in the International Technology Roadmap for Semiconductors 2005 (ITRS 2005), "although carrier mobility is already being improved by process-based stress, the inadequacy of stress metrology has become a greater issue." Efforts to proceed from simply manipulating strain, to true strain engineering, have been impeded by lack of characterization tools. Conventional X-ray and optical methods for determining strain attain resolutions of several hundred nanometers, inadequate for the sub-60 nm devices soon to be manufactured.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is no established approach for measuring the magnitude and distribution of strain with a resolution better than a few hundred nanometers. Techniques employing microbeam X-ray diffraction, and conventional micro-Raman spectroscopy, can achieve resolutions of only about 500 nm and 700 nm, respectively. To effectively map strain in device structures with sub-100-nm active regions, innovative measurement techniques must be developed with a resolution of ~15 nm.

***Potential Solutions to Measurement Problem*:** Two potential approaches are identified here for nanoscale mapping of strain: 1) tip-enhanced Raman spectroscopy (TERS) and 2) electron-backscatter-diffraction (EBSD). TERS potentially will extend the spatial resolution of strain measurements to 15-20 nm. However, reproducible TERS results have not yet been achieved with respect to either spatial resolution or signal strength, and quantitative determination of strain has not been accomplished.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Instrumentation for Measurement of Electrical Properties at the Nanoscale

Submitters: Alain Diebold, International SEMATECH, and C. Michael Garner, Intel

Technological Innovation at Stake: Measurements of electrical properties of nanoscale devices and structures at high and low frequencies require new instrumentation. Properties of interest include carrier mobility, resistivity, quantized conductance, and field induced mobility. The International Technology Roadmap for Semiconductors anticipates that new devices based on nanoscale properties will be needed sometime in the next 15 years.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Introducing integrated circuits with higher density increases computing speed and reduces the cost of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce the growth in the electronic sector.

Technical Barrier to the Innovation: Lack of methods for making ohmic contact with nanotubes and nanowires. Repeatable and reproducible measurements are very difficult.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Measuring and characterization with advanced nano-probe techniques electrical properties at the nanoscale are great challenges.

Potential Solutions to Measurement Problem: Develop refined nano-tips for nanoprobes and advanced non-contact methods.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: SEM and AFM Modeling for Semiconductor Electronics and Nanotechnology

Submitter(s): John Villarrubia

Technological Innovation at Stake: "Small" is often the essence in semiconductor electronics and emerging nanotechnology areas. In semiconductor electronics the state of the technology at a given time is customarily summarized by a single metric—the size of the "critical dimension" (the smallest feature size). Microprocessor speed and memory density depend directly upon the critical dimension. Inability to control (maintain reproducibility of) critical feature sizes is equivalent to inability to control essential properties of the product. Such process control is normally accomplished using a <manufacture> – <measure the result> – <determine manufacturing error> – <adjust inputs to correct errors> feedback loop. Measurement is an essential component of this control loop. The ability to manufacture products using feedback to maintain reproducible feature sizes is constrained by our ability (or lack thereof) to accurately measure those sizes.

***Economic Significance of Innovation*:** In semiconductor electronics smaller critical dimensions have demonstrable economic value. Higher density memory and faster microprocessors have greater value (and sell for a higher price) than their lower density or slower competition. Estimates have been made that each nanometer of reduction in transistor gate width produces a speed increase worth several billion dollars to the microprocessor segment of the economy alone. The value in less well established industries like the emerging nanotechnology industry are more difficult to quantify, but the potential for large economic value is widely recognized, as evidenced in well publicized government and private sector investments in this area.

***Technical Barrier to the Innovation*:** The ability to fabricate, manipulate, and see features at these small size scales are all new and challenging tasks. Image artifacts are at the same size scale as the needed accuracy. Modeling is needed to extract specimen geometric information from the AFM or SEM image. Models often do not exist. In cases where they do, accuracy has been demonstrated only for a very restricted set of materials and feature types.

Stage of Innovation Where Barrier Appears: R&D + Production

***Measurement-Problem Part of Technical Barrier*:** All microscopes have finite spatial resolution, set by the scale of the physical interaction between the microscope's probe and the sample. In an optical microscope the scale is set by the illumination wavelength. In an electron microscope it is generally set by the beam size and/or size of scattering volume. For existing microscope technologies, sub-micrometer (for light) or sub-10 nm (for scanning electron microscopes) are easily achievable. While more than adequate for macroscopic technologies, these scales are comparable to feature sizes for nanotechnologies and therefore not adequate.

Potential Solutions to Measurement Problem: (1) New microscopies with higher spatial resolution, (2) better use of existing resolution through models that allow correction of measurement artifacts and thereby correct interpretation of images, and/or (3) standard samples of known shape, size, and composition that permit experimental determination of measurement artifacts.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Micro-/Nano-Technology

Submitters: MEMS/NEMS Group [Craig McGray]

Technological Innovation at Stake: Micro-Electro-Mechanical systems (MEMS) is new technology based upon techniques borrowed from the semiconductor industry that make possible devices and machines like gears, motors, and springs so small their dimensions are best measured in millionths of a meter. MEMS devices are already commercial successes as accelerometers for automobile airbags, nozzles for ink jet printers; and projectors for high-end video displays. MEMS is forecast to produce a second semiconductor revolution that will drive growth in the U.S. economy for decades to come.

***Economic Significance of Innovation*:** The market in MEMS technology is currently valued at over $5 billion and is estimated to be growing at an annualized rate of 17 %. This market has much in common with the $ 200 billion integrated circuit (IC) industry, being comparable in size and growth at the present time to that of that industry in the 1980's.

Technical Barrier to the Innovation: There is inadequate technical knowledge and information existing to allow the MEMS industry to implement what is called the "fab-less" method of development and design of commercial MEMS devices that has been the basis for success in the IC industry. A fabrication facility is hugely expensive and iterations in manufacture of various prototype devices to achieve device performance and process yield is time consuming and costly. The fab-less alternative relies on sophisticated mathematical-computational modeling of devices and processes. These simulations, in turn, rely on the presence of a full characterization of the fabrication process to be used. While MEMS are fabricated by processes used and characterized for fabrication of ICs, those processes have not been adequately for MEMS which depend on the interaction of phenomena from a much larger set of physical domains (including electrical, mechanical, thermal, optical, fluidic, and others).

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** There is insufficient measurement data and the measurement methods to generate that data to adequately characterize a MEMS devices and their dependence on fabrication processes. Accurate data is needed for a large suite of material properties to be measured quickly within the manufacturing line, and at multiple locations across each wafer upon which multiple MEMS are fabricated, including:

Young's Modulus	*Stress Gradient*	*Thermal Coefs.*	*Microstructure*	*Damping*
Poisson's Ratio	*Contamination*	*Surface Charge*	*Residual Stress*	*Density*
Stiction	*Fatigue/Creep*	*Bond Strength*	*Surface Roughness*	*Sidewall Angle*

Potential Solutions to Measurement Problem: Direct measurement techniques for thin-film material properties; Compact models to calculate material properties from indirect measurements; Variation studies of material properties due to process parameters; Standard reference materials for film properties.

Technology at Issue: Nanomagnetic MRI Contrast Agents

Submitter(s): Stephen Russek

Technological Innovation at Stake: Engineering new types of contrast agents, understanding the nano-scale interactions of contrast agents with nuclear spins in biological systems, improving resolution to single-particle sensitivity, and measuring the functionalization and activation properties of the contrast agents are the key technical challenges. New classes of nanomagnetic contrast agents are being developed to dramatically extend the imaging modalities of magnetic resonance imaging (MRI). Contrast agents are being developed that target specific tissues, metabolic pathways, neural and cardiac functionalities. These new contrast agents will enable new types of imaging of molecular and neural activity and provide better diagnoses for a broad class of medical problems.

Economic Significance of Innovation**:** More than 25 million patients in the U.S. undergo MRIs each year. Doctors use contrast agents in about 30 percent of MRIs. Contrast agents increase the sensitivity and specificity of the scans, making it easier for doctors to deliver a diagnosis. The enhancement of the imaging and diagnostic capabilities that will result from the use of new contrast agents is expected to significantly increase the size of this industry, and expand early diagnostic capabilities for cancer, pathological brain structures (tumors, inflammation, ischemia), hepatic lesion detection and vascular visualization. Ultimately, future agents may allow visualization of therapeutic drug delivery for closer and earlier efficacy monitoring. The size of the MRI contrast agent market itself is expected to grow to several billion dollars per year. However, the economic impact through improved diagnoses and earlier treatment will be far larger.

Technical Barrier to the Innovation**:** The technical barriers to the development of better contrast agents are the ability to nano-engineer contrast agents that have high spin relaxivity, are non-toxic, and can be targeted to the desired organ or tissue. New types of contrast mechanisms must be developed to increase the sensitivity to enable imaging of individual contrast agents and their targets.

Stage of Innovation Where Barrier Appears**:** R&D, End Use

Measurement-Problem Part of Technical Barrier**:** New types of measurement tools are required to understand the detailed magnetic interaction of the contrast agents with nuclear spins in biological systems. New metrology is needed to understand how the functionalization of the contrast agents affects relaxivity properties. New metrology is required to understand and develop single particle tracking with MRI systems.

Potential Solutions to Measurement Problem: A coordinated effort is required between pharmaceutical companies, NIH funded research institutions, and metrology labs to develop the basic knowledge and metrology infrastructure required for more innovative and efficient development of contrast agents.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Atomic-precision imaging to aid in development of new materials

Submitters: USMS MEMS/NEMS Group, D. T. Read

Technological Innovation at Stake: Carbon-nanotube fiber-matrix composites is new form of material that promises to yield light-weight, ultra-high-strength components of a wide variety of products, from airplanes and satellites to flywheels for energy storage. Winning products will be the strongest and lightest, yielding high value for consumers and commanding premium prices for producers.

Economic Significance of Innovation: The current world-wide market for high-performance fibers, reported by the National Materials Advisory Board of the National Research Council, is $400 million (38 million pounds of material at just over $10 per pound), leveraging successively the markets for the fiber-composites, fiber-matrix-based components, and ultra-high-strength products based on them.

Technical Barrier to the Innovation: The extreme strength of carbon nanotubes points to fiber-matrix composite materials of great economic value. The key to optimum performance in a fiber-matrix composite material is the strength of the interface between the reinforcing fibers and the polymer matrix. Conventional methods developed for fabrication of fiber-matrix composites with larger, weaker fibers have not succeeded with the new ultra-fine, ultra-strong fibers. Proper dispersion of the fibers in the matrix is difficult and the fiber-matrix interface seems weak. Inability to know the atoms are in the as-manufactured material, how they move, and how they de-bond when the material is stressed impedes the ability to design fiber-matrix composites with adequately strong interfaces.

Stages of Innovation Where Barrier Appears: Research and development.

Measurement-Problem Part of Technical Barrier: Because the carbon-nanotube fibers are very fine, with diameters measured in tens of nanometers, conventional methods of relating the structure of the fiber-matrix interface to its strength are not sufficient to reveal the problems and point to solutions. The measurement problem is the inability to examine and debug the atomic-scale 3-dimensional structure of the nanotube-matrix interface. Conventional imaging, even by scanning electron microscopy (SEM) and atomic force microscopy (AFM) are insufficient to determine the exact structure of the interface and find out how its performance could be improved. Transmission electron microscopy (TEM) and scanned probe microscopy (SPM) are not well suited to this interface problem in non-crystalline materials.

Potential Solutions to Measurement Problem: What is needed is an instrument for atomic-level imaging of the fiber-matrix interface with capability to detect the location and define the chemical identity of each atom in the interface. Promising is a new type of Nano-Electrol-Mechanical (NEN) probe instrument with the capability to gradually erode a material surface and record the location and chemical identity of each atom as it is removed. The instrument looks capable looks like it could provide measurement data that could be compared with the intent of the design, for example, a chemical-bond diagram of the desired interface structure, and accelerate the development of commercially valuable high-performance materials.

Technology at Issue: Hard Disk Stack Metrology

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40 %. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50 %. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. The traditional technique used for measuring metal stacks in magnetic head fabrication, X-Ray Fluorescence (XRF), is essentially a bulk spectroscopy that is unable to determine layer structure on even a qualitative basis. Because XRF essentially detects only atoms/unit area, without an independent control of density, it cannot be used to monitor layer thickness. Reader stacks are beginning to include lighter metals and thin dielectrics. The local chemistry of these layers will be important to map and to control especially for Current Perpendicular to Plane (CPP) topologies. XRF is not as sensitive to light elements as we would like and it has no ability to probe the bonding structure of dielectric materials. Because XRF is reliant on reference standards that in turn must be characterized by destructive mass spectrometry techniques, ultimate accuracy is difficult to ensure on a regular basis.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** A production-grade calibrated metrology tool that can provide precise microstructural and local electronic information about the content and structure of metal and buried dielectric stacks of films with, in some cases, repeated layers as thin as 1 nm.

Potential Solutions to Measurement Problem: Possible approaches worth exploring include XPS, SIMS, GDMS, XRR, Soft X-Ray Emission, and variable energy microprobe.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Carbon Nanotubes (CNTs)

***Submitter*:** Ian M. Anderson

***Technological Innovation at Stake*:** Improvement of a wide variety of products through judicious substitution for conventional materials of CNTs, which exhibit unique properties: "the strongest fiber that will ever be made; electrical conductivity of copper or silicon; thermal conductivity of diamond; the chemistry of carbon; the size and perfection of DNA".

***Economic Significance of Innovation*:** CNTs have the potential to improve a host of composite materials across numerous economic sectors. Potential applications of CNTs range from reinforcing fibers for car bumpers to cathodes for flat panel displays, from storage materials for hydrogen fuel to conductive inks for rear-window defoggers.

***Technical Barrier to the Innovation*:** CNTs are not synthesized or supplied in pure form, but as a mixture of various CNTs, other carbonaceous species, and noncarbonaceous species. Suppliers of CNTs regularly adjust their synthesis routes to improve key specifications such as production rate, purity, length, and degree of aggregation. However, these supplier adjustments may alter the CNT batch properties, making them unsuitable for a target application of a given manufacturer.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** Currently, there is an absence of robust methods to characterize the distribution of species within a batch of CNTs. Manufacturers regularly qualify batches of various raw materials in their quality assurance (QA) laboratories, but protocols for the qualification of CNTs have yet to be devised. Ideally, a suite of measurements would be devised to quantify: the mass fractions of CNTs, other carbonaceous species, and noncarbonaceous species within a batch; the distribution of CNTs according to "chirality" (a characteristic unique to CNTs), the proportion of single-walled (SW) and various multi-walled (MW) tubes, and length; the levels and nature of defects within the CNTs; and the degree of aggregation. Specimen preparation protocols are also required to ensure that QA reproducibility is not compromised by improper handling. Specialized measurements should be available with rapid turn-around through dedicated government or commercial characterization laboratories.

***Potential Solutions to Measurement Problem*:** Specimen preparation protocols that mitigate damage of CNTs for QA measurements; reference materials (RMs) that quantify the characteristics of a batch of CNTs; measurement protocols that correlate these characteristics with quantifiable parameters, preferably obtained with equipment available within a manufacturer's multipurpose QA lab.

NIST National Measurement System Assessment
Case Study – Measurement Needs

***Technology at Issue*:** Toxicology of Nano-particles in Biological Systems

***Submitter*:** A. Fahey, NIST

***Technological Innovation at Stake*:** Product innovations that use nanoparticles is rapidly expanding in many sectors of the world economy with their incorporation into a wide range of products including cosmetics, pharmaceuticals, polymer composites, clothing, and microelectronics. Despite the potential gains from nanoparticle-based products, there is concern by many communities about their toxicity. The unique and diverse physico-chemical properties of nanoscale materials suggest that toxicological properties may differ from materials of same or similar composition but larger size. For example, nanoparticles may readily migrate through normal barrier tissues such as skin, enter into the blood stream and from there penetrate internal barrier tissues entering into organs like the brain.

***Economic Significance of Innovation*:** Between 1997 and 2003, worldwide government investment in nanotechnology rose from $432 million a year to just under $3 billion a year. Discoveries made in nanoscience and nanotechnology are expected to be a major driver of the world economy in the next decade. In a report entitled "The Next Small Thing," published in September 2001, Merrill Lynch quotes statistics that project the nano-structured materials market alone to be worth at least $5 billion/year and perhaps as much as $20 billion/year. However, despite the economic impact nanotechnology can yield through its novel properties, lack of sound toxicology of nanoscale structures in humans and animals has the potential to derail the acceptance of nano-structured materials in the marketplace.

***Technical Barrier to the Innovation*:** Effective and accepted methods to assess nanoparticle toxicity do not exist. Evidence demonstrating the migration of nanoparticles through barrier tissues in mammals has only recently been shown. New measurement methods are needed for both clinical effects of nano-structure incorporation in tissues and for characterization of nano-structures through out their life, i.e., before incorporation in tissues as well as following incorporation. It is expected that once incorporated in living tissues, nano-structures will change. Methods having the capability to determine such changes in-situ will greatly aid the understanding the evolution of nanostructures in the body.

***Stage of Innovation Where Barrier Appears*:** R&D

***Measurement-Problem Part of Technical Barrier*:** Development of usable dose metrics for nanoparticle toxicity is not possible without accurate methods to characterize nanoparticle properties such as composition, dimensional metrology, surface area, shape and structure. In addition the development of dose metrics will also depend on the ultimate fate of nanoparticles in biological tissues. Measurement methods sensitive to both the physical and chemical structure and properties of nano-structures are needed as a basis for assessing toxicological impact of nanoparticle materials in tissues.

***Potential Solutions to Measurement Problem*:** Develop a set of metrics that accurately characterize the toxicology of nanoscale materials. Develop methods to characterize nanoscale materials contained within biological tissues. Develop new measurement approaches for in-vivo and in-vitro of the properties of nano-structured particles and devices.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Next Generation Electrotechnical Products, Components, and Raw Materials

Submitter: J. R. Sieber, CSTL

***Technological Innovation at Stake*:** The RoHS, Restriction on Hazardous Materials, regulations recently adopted by the EU and other U.S trading partners impose significantly reduced maximum allowable concentrations of cadmium, mercury, lead, hexavalent chromium, and certain brominated flame-retardants in electrotechnical products. Current and future products and components, and their raw materials, are affected. Companies seeking market entry for consumer electronic and electrical products require stringent materials declarations from their suppliers at all levels of the supply chain.

***Economic Significance of Innovation*:** Some current raw materials will require significant reduction in proscribed compound content and new ones developed. RoHS regulations affect the worldwide market for electrotechnical products and their entire supply chain, a multi-$100 billion dollar per year market. U.S. companies are significant exporters and must comply by replacing components and designing new manufacturing processes to accommodate new or modified raw materials. Documentation of hazardous materials content is required to demonstrate compliances with RoHS requirements.

***Technical Barrier to the Innovation*:** Internationally recognized standards for documentation of supply chain compliance with RoHS regulations are needed. Proposed product safe lifetime labeling requirements are anticipated that will require implementation of new concepts and testing methods for materials degradation testing. New standardized analytical test methods and certified reference materials are needed to ensure that both raw materials and finished goods are compliant with the RoHS regulations.

***Stage of Innovation Where Barrier Appears*:** Marketplace

***Measurement-Problem Part of Technical Barrier*:** New test methods, and the concentration standards supporting them, are needed for raw materials, intermediate and finished goods. New or improved measurement methodologies and standards to support materials content compliance and product lifetime claims are needed. The global market requires international recognition of new test methods and content standards.

***Potential Solutions to Measurement Problem*:** Broad/International acceptance of measurements and standards supporting material content declarations, test methods that measure concentration of the RoHS substances in raw materials, intermediates, and finished products; new lifetime testing methods and the scientific/technological base supporting them, and certified reference materials (CRMs) pertinent to the methods and materials of test.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Magnetic Data Storage

Submitter(s): Theodore Vorburger

Technological Innovation at Stake: The continued miniaturization of recording density in the magnetic data storage industry relies on decreasing the spacing between the magnetic head and the storage medium. Improved speed and compactness of magnetic data storage devices comprises one of the innovation drivers of the successful and hugely important microelectronics industry.

***Economic Significance of Innovation*:** The push for large hard disk drive (HDD) storage capabilities on desktop computers and small portable products, such as, cell phones, PDAs, digital still cameras, and digital video cameras, could increase the HDD market from 372.2 million units in 2005 to 408.3 million units in 2006, according to a recent report of The Information Network (TIN). The HDD market is expected to grow from $3.3 billion in 2005 to $4.5 billion US in 2009 according to Gartner Dataquest. By meeting the roadmap, HDD's will satisfy anticipated multimedia library storage demands in micro and mobile devices. If the speed and compactness of magnetic storage does not continue to improve, then the development of improved products, such as computers, that use magnetic storage devices is hampered, and the vitality of the industries that provide those products is compromised.

***Technical Barrier to the Innovation*:** Decreasing the spacing between the magnetic head and the disk medium means decreasing the flying height of the slider with respect to the medium. However, both the head-medium spacing and the flying height become relatively more uncertain as the spacing decreases. The clearance between slider and medium is a problematical "width" dimension whose value also depends on the diamond like coating on the head and the lubricant coating on the medium. As the head-medium spacing decreases from 20 nm in 2003 to a projected 2.8 nm in 2013, industry may be able to make relative measurements of the various spacings and do this in a dynamic way, but the industry has called on NIST to provide calibrations for its measurements in order to determine the function of its storage technologies more accurately.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** In the 2005 Information Storage Industry Consortium (INSIC)-NIST Metrology Workshop held on October 20-21, 2005, the industry cited as its highest priority in the Head Disk Interface area an optical fly height measurement standard, which would simulate high density disk fly height conditions and materials that must fit existing fly-height testers. This would be a tapered air gap with a thin end of 2 nm to 5 nm and a thick end of 50 nm to 200 nm. There is currently no such available reference standard for hard disk drive (HDD) fly height measurement. This formal measurement need arising from a USMS Workshop echoes requests previously made directly to NIST by representatives of the Zygo Corporation. Zygo is a metrology supplier to this industry.

Potential Solutions to Measurement Problem: A transparent glass package with a tapered gap calibrated by phase shifting interferometry and refractometry.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanomanufactured Components in Complex Fluids

Submitter(s): Kathryn L. Beers

Technological Innovation at Stake: Industry is particularly eager to incorporate nanostructured components (e.g. nanoparticle and block copolymer assemblies, protein and peptide complexes, functional dendrimers and other engineered macromolecules) into their formulations because these additives promise unprecedented properties and performance, e.g., incorporation of biocides in coatings to produce self-cleaning surfaces, or addition of nanoparticles to cosmetics to improve feel, wear, and anti-aging effects.

***Economic Significance of Innovation*:** The majority of manufactured goods are so-called "formulations," products that are fabricated from a large number of components. Formulated products include paint and coatings, food, cosmetics, personal care products, and cleaning products among many others. Most often, the market for formulated products is driven by the ability to produce specialty materials with improved performance and tailored specifications, while reducing cost. Formulated complex fluids represent a large global market worth more than $150 B per year. The next generation of these products will possess value added by nanoscale components. Without the competitive edge to enable this innovation in the United States, enormous market share will be lost to competitors.

***Technical Barrier to the Innovation*:** The design and optimization of complex fluid formulations is an "art", which relies on individual knowledge to combine compiled experience and "trial-and-error" methods to arrive at optimal products. While many industries use formulation techniques in making and testing their products, there is no formal discipline in formulations based on first principles. Understanding interactions between nanostructured additives and complex mixtures, particularly the relationship between phase behavior, morphology, stability, and performance properties, including possible health effects is critical. However, there is no fundamental measurement platform on which to build the nano-metrology necessary to characterize the next generation of materials.

Stage of Innovation Where Barrier Appears: R&D

***Measurement-Problem Part of Technical Barrier*:** The performance and safety of these products depends on reliable nanomaterial feed stocks, robust processing methods and the stability of end products. Current formulation science has not advanced enough to handle these measurements, due to a historical reliance on individual knowledge and a lack of quantitative data collection or standard measurements.

Potential Solutions to Measurement Problem: Standard reference materials and new measurement methods to quantify purity, characterize quality, monitor processes and measure stability are necessary. For example, a high throughput platform to evaluate the solution properties of peptidic interfacial modifiers in the presence of other surfactants, changes in pH, salt and temperature using a combination of scattering, spectroscopy and imaging techniques would be integrated with evaluations of end-use properties, such as biocide activity, vector delivery, etc.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Spin Metrology Tools

Submitters: Alain Diebold and C. Michael Garner

Technological Innovation at Stake: The International Technology Roadmap for Semiconductors anticipates high-volume manufacture of integrated circuits using the 22 nanometer technology generation, which will have minimum features of ~ 10 nm by 2016. Early developers will start working on this technology within the next two years; however, metrology tools to determine properties of spins in semiconductors need to be developed so that industry may consider whether spins may replace charges as the basis for switches and transistor-like action at the end of the 2005 ITRS, that is by 2020.

Economic Significance of Innovation: The Semiconductor Industry Association's economic forecast calls for 2005 sales to increase by 6.8 percent to $227.6 B, followed by increases of 7.9 percent to $245.5 B in 2006, 10.5 percent to $271.3 B in 2007, and 13.9 percent to $309.2 B in 2008. Integrated circuits with higher density increase computing speeds and reduce the costs of components for computing and a wide range of applications. If the rate of technology innovation stops or slows dramatically, there will be a slowing in the introduction of new computing and consumer electronics and this will dramatically reduce growth in the semiconductor sector.

Technical Barrier to the Innovation: Lack of adequate metrology tools to characterize semiconductors, especially III-V compound semiconductors with polarized spins. Producing devices that use transport of polarized spin require new measurement methods that can detect injection of spin injection transport and decoherence of small quantities of electron spins and measure optical properties of materials used to polarize spins.

Stage of Innovation Where Barrier Appears: R&D

Measurement-Problem Part of Technical Barrier: Detection and mapping of small quantities of spin-polarized electrons in spin devices and mapping properties of spin polarized materials are very difficult.

Potential Solutions to Measurement Problem: Develop scanned probe methods that detect single electrons and their spins, based in part on measuring time-resolved Faraday rotation.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Hard Disk Sheet Magnetoresistive

Submitter: Marcos Lederman, Western Digital Corporation

Technological Innovation at Stake: Hard disk drive manufacturers are attempting to develop the next-generation computer hard disk drive systems (HDDs) that will attain the information storage capacities in terms of the Terabits-per-square-inch densities projected by the INSIC (Information Storage Industry Consortium) technology roadmap. These higher-capacity systems will provide users of computers with more memory, at faster retrieval rates, and at lower costs.

***Economic Significance of Innovation*:** The global disk storage market is $60B. The U.S. share is approximately 40 %. The data storage industry is large, and is significant for how it improves all other segments of the U.S. economy. For the period 2003-2008, all industries are increasing data stored at the compound annual growth rate of 50 %. Magnetic data storage is a multi-billion-dollar industry with hard disk drive shipments of more than 400 million units per year. Cost reductions due to improved production yields and increased benefit to users due to increased product capability and reliability; translate into hundreds of millions of dollars per year, with savings to consumers and increased sales and profits for industrial firms.

***Technical Barrier to the Innovation*:** Future-generation hard disk drives, with terabits-per-square-inch information densities, will require design tolerances that are beyond the current state of knowledge. In addition, new, superior instrumentation is required in order to achieve the requisite monitoring and control of the hard disk drive production processes. Current Perpendicular to Plane (CPP) magnetoresistive read sensors, such as Tunneling Magneto Resistance (TMR) sensors, used in newer-generation HDD magnetic heads, have substantially complicated the task of developing and monitoring the quality of sensor films. Contrary to earlier Current In Plane (CIP) sensors, were a simple 4-point resistance test would provide the MR coefficient and other essential film properties, the testing of these new sensors typically requires the fabrication of submicron- sized junctions, complete with lead and insulation layers. This time-consuming step is burdensome both at the development and production stage.

***Stage of Innovation Where Barrier Appears*:** Production

***Measurement-Problem Part of Technical Barrier*:** The goal is to develop a magnetoresistive measurement capability on blanket (unpatterned) TMR and CPP GMR films, down to resistance area products (RA) of the order of 0.1 Ohm-μm^2, such as will be needed for the development and production control of CPP read head sensors in the coming years. A related, and more immediate, need is for such a technique to allow the measurement of today's TMR sensors films, directly on device wafers, without the need to deposit special purpose structures on witness wafers.

Potential Solutions to Measurement Problem: The groundbreaking introduction of the Current In Plane Tunneling (CIPT) technique by D. C. Worledge and P. L. Trouilloud, and its commercialization by Capres A/S in Denmark, have already provided blanket film metrology for TMR films with RA above 1 Ohm-μm^2. An extension of the CIPT technique seems the most likely approach to the desired 0.1 Ohm-μm^2 metrology capability.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Scanning Electron Microscope Nanocharacterization

Submitter(s): Michael Postek

Technological Innovation at Stake: Nanocharacterization spans issues in physical and chemical metrology including force and length measurements, chemical composition determination, shapes of pores and particles, and 3D relationships of complex nanoscale components. The current state of the art might best be viewed as a multidimensional parameter space in which trade-offs are made between spatial resolution and sensitivity, chemical speciation and sampling volume, and speed of data acquisition and detection limits. Nanocharacterization will not be sufficient if these trade-offs continue to be necessary--to support the emerging nanotechnology industry, advances in SEM nanocharacterization will be required.

Economic Significance of Innovation**:** The National Science Foundation has stated in the 2001 publication *Societal Implications of Nanoscience and Nanotechnology* that "Nanoscale science and engineering will lead to better understanding of nature; advances in fundamental research and education; and significant changes in industrial manufacturing, the economy, healthcare, and environmental management and sustainability." NSF further predicts that the worldwide market of nanotechnology-related products will be the size of over $1 trillion annually in 10 to 15 years. In addition in its 2004 report, *Sizing Nanotechnology's Value Chain* LUX Research was even more optimistic indicating that in 2004 the value of nanotechnology related products was $158B and it is expected that this number would increase in the next 10 years 18x over to about $2.9T in revenue with 89 % of that being generated from new technologies.

Technical Barrier to the Innovation**:** Laboratory-based SEM instruments currently operate at levels below those needed for complex nanocharacterization with respect to spatial resolution, chemical sensitivity, speed of data acquisition, and signal to noise. For nanomanufacturing needs, SEM instrumentation is also insufficiently automated, robust, amenable to production environments, and affordable.

Stage of Innovation Where Barrier Appears: R&D and Production

Measurement-Problem Part of Technical Barrier**:** The priority challenges of nanoscale SEM characterization fall along four interrelated components of metrology: (1) the ability to characterize nanoscale structures in three dimensions, (2) the ability to acquire nanoscale data in a timeframe that supports timely interpretation of the results, (3) the ability to measure complex structures with nanoscale compositional heterogeneity, and (4) the ability to establish the dispersion of nanoscale materials.

Potential Solutions to Measurement Problem**:** Research is required, in collaboration with instrument manufacturers, to extend the capabilities to the upper theoretical limits of what can be realized in terms of spatial resolution, chemical sensitivity, speed of data acquisition, and signal to noise. Measurements at these length scales have not been done and much needs to be learned about specimen/electron beam interactions and effects upon the ultimate resolution possible and beam irradiation effects on nanometer sized samples. For example, the development and installation of aberration-corrected lenses for the SEM is anticipated have a positive affect on resolution and complex structural characterization ability.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Nanoscale Chemical Characterization of Advanced Materials

Submitter: Stephan Stranick, NIST

Technological Innovation at Stake: A broad range of future generation products and processes will be founded on reliable manipulation and tuning of material properties to take advantage of novel physical and chemical properties only available through use of nanoscale phenomena. Discovery of the mechanisms controlling these phenomena rely heavily upon nanoscale chemical characterization and chemical imaging. Real time, non-destructive, chemically specific visualization of nano-scale components and materials is critical to the development of these. Non-destructive, real-time, 3-D chemical imaging with nanoscale resolution will enhance progress in understanding nanoscale systems and will be a critical measurement capability necessary for the advance of nanoscale-based products.

Economic Significance of Innovation**:** Through advances in nanoscale chemical imaging, the U.S. will increase our basic understanding to implement "tuning" of advanced material's properties. An example of this found in the automotive industry is a class of engineered plastics, thermoplastic olefins, widely used in automotive fascia and bumpers. The US market for these materials in 2005 was $2.4 Billion and growing at a rate of almost 6 % annually. Optimizing this growth requires detailed nanoscale chemical information, so that manufacturers can tailor formulations to minimize expensive components, to the extent possible, without compromising performance. Here, high directional strength is often an important driver that make the new material's technologies more affordable, durable or environmentally friendly at good value. Ultimately, the resulting value creation and cost savings associated with optimization of thermoplastic products through advanced capability in nanoscale chemical imaging diagnostics is estimated to be in the 10- 20 % range annually.

Technical Barrier to the Innovation**:** Descriptions of nano-scale phenomena that allow engineering of materials properties are lacking. The success of investigations of the mechanisms controlling such systems are based on observation of material behavior, often in real-time and under conditions of use. Currently available chemical imaging techniques lack sufficient spatial resolution, chemical identification resolution, and/or the ability to probe into the bulk of the material so that observed behaviors attributed to bulk phenomena are not the result of interfacial behavior that may be very different.

Stage of Innovation Where Barrier Appears**:** R&D

Measurement-Problem Part of Technical Barrier**:** Currently most imaging of nanoscale objects is accomplished with either scanned probed microscopies or electron and ion microscopies. Electron and ion methods are primarily performed in vacuum environments and can depth profile samples to obtain chemical identification and quantification information using destructive methods, while scanned probe methods are strictly limited to surfaces. Non-destructive imaging techniques are needed that are applicable to a range of materials with nanoscale spatial resolution, sub-surface imaging capability, and the ability to distinguish both between chemically similar and dissimilar materials.

Potential Solutions to Measurement Problem: Linear and non-linear optical methods that couple chemically specific spectroscopies (infrared absorption and Raman) with advances in super-resolving optical elements (adaptive optics) to provide nanoscale chemical analysis. These photon based techniques would overcome the restrictions presently placed on electron and ion based chemical imaging techniques mentioned above.

NIST National Measurement System Assessment
Case Study – Measurement Needs

Technology at Issue: Self Assembly of Soft Nanomaterials

Submitter(s): Steven Hudson

Technological Innovation at Stake: The use of directed self-assembly in chemical, electronics, and pharmaceuticals industries to produce smart coatings, detergents, personal care products, (photovoltaic) circuits, and targeted drugs. Self-assembly, or bottom-up assembly, proceeds from the nano or molecular scale and is driven by natural interactions. To make practical devices on the nanoscale, directed self-assembly techniques that allow the assembly of complex systems composed of large numbers of nanoscale components will be necessary. Anticipated benefits of directed self assembly include smarter targeting and product design, enabling structures with greater functionality that tend to be defect-free and self-healing.

***Economic Significance of Innovation*:** Self assembly is prominent in a US chemical industry roadmap (www.ChemicalVision2020.org) that outlines a strategy to develop knowledge and tools that will alter management of the industry's $26B annual R&D investment and enable application-based design and pervasive use of nanomaterials. Current examples of self assembly are found in colloidal technology (e.g., washing detergent formulations) and pharmaceuticals (drug formulations). Future opportunities such as micro-injectable computer-chip heat-transfer fluids and virus-based drug delivery require the development of directed self assembly, which will enable smarter targeting and product design.

***Technical Barrier to the Innovation*:** Although man-made self-assembled nanomaterials do exist, they are still generally simple and poorly controlled. It is difficult to "order-up" a complex functional structure from simpler components because the needed interactions between the sub-components are not known.

Stage of Innovation Where Barrier Appears: R&D and production.

***Measurement-Problem Part of Technical Barrier*:** In order to develop well controlled self-assembled materials, we need the ability to measure the forces between the components or particles during the assembly process and measure the rates of assembly (and disassembly). Particle characterization methods (e.g., to measure the surface charge distribution) are necessary to ensure quality control. Further, rapid measures of the actual self-assembled structures and their response to stimuli (such as agitation, pH or temperature) are vital to establish design rules.

Potential Solutions to Measurement Problem: The measurement of interparticle forces by surface spectroscopic and microscopic methods will enable improved control over the assembly process and the measure of local and average assembly kinetics. Rapid screening methods by indirect scattering, direct visualization, and property measurements will enable quality control and process control. Efficient computational methods informed by these measurements will allow the development of design rules.