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Nanoscale Electrical Contacts: Standards and Measurements

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1. Introduction

The purpose of this paper is to suggest a possible framework for nanoscale contacts that the stakeholders in nano-electrotechnologies may follow to establish international standards with the goal of accelerating innovation in nano-electrotechnologies. Nanoscale contacts are expected to be challenges for many applications of nano-electrotechnologies. After defining nanotechnology and nano-electrotechnologies in the context of this paper, summary of likely business models and product opportunities for nano-electrotechnologies are given. The next section presents some generic questions and challenges about nanoscale contacts. The following section discusses five illustrative examples of metrology tools that require improved standards for assessing the performance and reliability of nanoscale contacts. And finally, the concluding section contains a few recommendations for action.

Key Words: Standards, Measurements, Nanoscale, Electrical Contacts, and Nano-Electrotechnologies

2. Nano-Eletrotechnologies Defined

There are many definitions of nanotechnology. The definition from the U.S. National Nanotechnology Initiative encompasses key aspects included in other definitions from around the world. *"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." [1]

Nano-Electrotechnologies are part of nanotechnology. They are often cross-sectional technologies with the potential for many cross-disciplinary applications. From the perspective of the International Electrotechnical Commission (IEC), nano-electrotechnologies [2] 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; fuel cells; and bioelectronic applications.

3. Business Models to Consider for Standards Development

The standards development efforts on nano-electro-technologies will often occur in the context of one or more of the following nano-electro-technical business models:

Traditional business model
Research and development supported in part by grants lead to new technologies for prototype product development followed by building manufacturing capacity, deployment and commercialization. This model may not be an appropriate one for nano-electro-technologies because it is very capital intensive and takes too long for commercialization with investors who often want financial success (positive returns on their investments) quickly.

Solution-looking-for-a-problem-or-market business model

Research and development lead to new technology that may have phenomenal commercial success or more likely may remain as an interesting technology sitting-on-a-shelf. Commercialization challenges are: 1) It usually takes a very long time to integrate a specific nano-electro-material into large-scale industrial processes that customers appreciate and want; 2) Market for specific nano-electro-material is limited even though the market for the application of the related technology may be large; and 3) Costs associated with scaling from the R&D prototype volumes to commercial manufacturing volumes are considerable. In the context of standards developers, this may not be an optimum model for nano-electrotechnology stakeholders.

Penetrate Existing Markets

Based on what the customer wants or on increased functionality for the given application: 1) Use core competencies in nano-electrotechnologies to penetrate existing markets and develop nano-electro-technical subassemblies directed at increasing functionality with lower cost per function for specific applications; 2) Build a large nano-electro-technical subassembly portfolio for a positive revenue stream; 3) While manufacturing some high-volume nano-electro-technical subassemblies, invest a reasonable portion of profits to develop unique processing capabilities that will maintain a diverse portfolio; 4) Establish joint ventures and partnerships from the start with organizations that are financially sound and already have access to large markets; and 5) Combine efficiently for all stages of subassembly development and commercialization the forces of market pull and technology push, with an emphasis on market pull.

4. Product Opportunities for Nano-Electrotechnologies

Nanoscale electrical contacts have diverse applications in many product categories. The 459 respondents to the 2008 NIST-Energetics-IEC TC 113 Survey to establish priorities for standards in nano-electrotechnologyies ranked the following 8 product categories in priority order and assigned energy and medical products the highest priority.[3]

Product Categories Listed in Priority Order [3]

1. *Energy (production, conversion, and storage)*
2. *Medical Products*
3. *Computers (PDA and similar, laptop, desktop, mainframe) and Computer Peripherals (printers, monitors/displays, etc.)*

4. *Telecommunication and Data Communications (wireless and wired-physical connection)*
5. *Security and Emergency Response Devices and Applications*
6. *Multimedia Consumer Electronics*
7. *Household and Consumer Applications*
8. *Transportation (sea/water, ground, air, space*)

5. Questions and Challenges

The commercial success of many nanoscale electrotechnical subassemblies for electrical, optical, and magnetic products and systems will require contacts or connections to micro- and macro-scale devices and systems. Present instrumentation to characterize and view in three-dimensions nanoscale contacts is not adequate for accelerating innovation and thereby commercialization. The standards and measurement methods associated with such instrumentation and the theories used to interpret measurement results make it difficult to assess performance, reliability, and durability of subassemblies with enhanced functionalities based on nano-electro-technologies.

Nano-Electrotechnologies stakeholders tend to prefer those standards for nanoscale contacts that are as technology and materials neutral as possible. Promoting standards that are too nano-electro-material and process specific may impede creativity and innovation. Those developing nano-electrotechnology standards will face challenges to achieve balances among standards for nanoscale contacts that are applicable to many applications (DC, AC, and RF) and that are applicable to only a few specific materials with limited applications, e.g., digital.

The performance, reliability, and durability of future nanoscale devices depend critically on gaining atom- and molecular-level and nanoscale-level understanding of contact formation and functionality in terms of carrier transport and electrical, optical, magnetic, chemical, and mechanical properties. Many questions arise.[4] These include:

How are electronic, optical, magnetic, chemical, and mechanical properties of the nano-electro-material affected by contacts?

How do molecules and nano-electro-materials respond when contacts are established?

What roles are played by the contact metal and alloys?

Are our theoretical understanding, computer simulations, and visualization methods such that we can predict the carrier transport and electrical (DC, AC, RF, analog, digital, and mixed-signal), optical, magnetic, chemical, and mechanical properties of nanoscale systems?

How will we separate electronic, optical, magnetic, chemical, and mechanical effects and record and measure detailed changes in such effects during the formation and lifetimes of contacts?

How will we answer these types of questions?

The instruments that will be used to answer these questions are expensive. Interpreting and extracting meaningful results from the large sets of data that they produce require considerable time and expertise from many disciplines. In principle, many instruments and techniques that could provide significant insights for research, development, deployment, and high volume manufacturing of nanoscale contacts do not deliver because often the results that they give lead to inadequate correlations among properties and dynamic behavior of contacts during formation and during their useful lifetime before failure. Standards and their associated measurements will play critical roles in enabling such validated correlations to advance innovation.

6. Economic Significance of Nanoscale Contacts

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 were to slow dramatically due perhaps to the performance, reliability, and durability of nanoscale contacts, there would be a slowing in the introduction of new computing and consumer electronics. This would in turn reduce growth in the semiconductor sector and would have a negative ripple effect in other sectors that depend on semiconductors. Such a decline would have considerable productivity implications for all global economic sectors that rely on semiconductors. Furthermore, if the nanoscale contact processes have unacceptable variations, the yield for circuits may become too low for traditional business models. This would dramatically increase the cost of products, make the new technology more costly, and reverse the 4 decade-old deflationary trend in the semiconductor industry - namely, the substantial decrease in cost per function with each new technology generation.

The U. S. National Science Foundation (NSF) 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 its 2004 report, *Sizing Nanotechnology's Value Chain* LUX Research was even more optimistic. It suggest that in 2004 the value of nanotechnology related products was $158B and that it expects this number would increase in the next 10 years by 18 times to be over about $2.9T in revenue with 89% of that being generated from new technologies.

7. Illustrative Examples of Standards and Measurement Needs

As illustrative examples of standards and measurement needs associated with nanoscale contacts, we list five standards needs concerning instrumentation for high resolution measurements of nanoscale contacts that are likely to be applicable to diverse nano-electro-technologies. These illustrative examples are from the international nanoelectronics industry. [5,6]

Example 1: 3-D Dopant Distributions

Need
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 that will have minimum features of ~ 10 nm by 2016. Early developers have started work on this technology. However, current instrumentation to measure 3D dopant distributions at the nanoscale is not capable of being used as in-line monitors for high-volume manufacturing.

There is a lack of adequate instrumentation to measure in real-time and in-line during high-volume manufacturing 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 volumes require characterization and metrology tools that give 3D dopant distributions and structural and material properties with atomic resolution.

Challenge
Develop enhanced standards for 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. The solution includes working to improve resolution of new characterization and metrology tools such as aberration-corrected STEM, LEAP, STEM, scanning capacitance microscopy, scanning transmission spectroscopy, conductive atomic force microscopy (CAFM), spreading resistance

measurements at the nanoscale, and secondary ion mass spectroscopy (SIMS) of small structures and thin films for dopant measurements.

Example 2: Structural and Compositional Analyses at the Nanoscale

Need
Advanced atomic mapping instrumentation for sub-22 nm structural and compositional analyses.

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. Structural and compositional analyses of carbon based materials such as organic molecules and carbon nanotubes are of considerable interest. The International Technology Roadmap for Semiconductors anticipates that new devices based on organic molecules or nanotubes may be needed to provide new device functions as complementary metal oxide semiconductors (CMOS) approach sub-20 nm technologies.

Current transmission electron microscope (TEM) and scanning electron microscope (SEM) technologies cannot measure the location of carbon atoms to analyze the growth and operation of devices based on these materials.

Characterization and metrology tools that measure structural and materials properties are just becoming capable of near atomic resolution, but often they can not measure the location of carbon, hydrogen and other light elements due to small scattering cross sections.

Challenge
Improve standards for precise atomic mapping instrumentation and for extracting by theory and computer simulations and visualizations parameters for assessing performance, reliability, and durability of nanoscale contacts. True atomic resolution in 3D must become routine for the entire range of materials and structures used in commercializing nano-electro-technologies. As stated in Example 1, characterization and metrology tools that are just becoming capable of near atomic resolution include aberration corrected transmission electron microscopes, local electrode atom probes, and other scanned probe microscopes such as atomic force microscopes, scanning potential microscopes, scanning near field acoustic microscopes, and scanning thermal microscopes. In addition to the hardware, standards to support the simulations and visualizations of massive amounts of data are required to gain better insights concerning the new phenomena associated with nano-sized contacts. Tomography of structural features must be extended to the much smaller dimensions beyond the presently available large feature sizes.

Example 3: Sub-10 nm Metrology Tools

Need
In-line for high-volume manufacturing and real-time measurement tools for sub-10 nm features [critical dimensions (CD)] to support patterning for integrated circuits (ICs).

Metrology tools to measure critical features are incapable of measuring sub-10 nm features precisely and accurately within the manufacturing line. Expensive wafers and other materials must be sacrificed to destructively analyze and to measure process dimensions outside of the fabrication facility. Only a few samples will be characterized per operation, so significant information will be lost on the variability of the nanoscale contact process in development.

Challenge
The integrated circuit industry requires processes that produce 100's of billions of features and nanoscale contacts uniformly across each wafer for each mask operation with a tight distribution of sizes. The inability to measure critical sub-10 nm features on a large number of features and wafers per lot will dramatically slow the development of integrated circuit technology.

Research and development on standards that will extend conventional e-beam based critical metrology tools. This would include aberration correction, brighter sources, and techniques to reduce dielectric charging on wafers.

Example 4: Scanning Electron Microscope Nanocharacterization

Need
Nanocharacterization spans physical and chemical measurements such as force and length measurements, chemical composition determination, shapes of pores and particles, and 3D relationships of complex nanoscale contact 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 nano-electro-technology industry. Advances in high-speed nanocharacterization techniques and instrumentation are required.

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

Challenge

The priority challenges for standards concern four interrelated abilities - components of measurements and theory: (1) the ability to characterize nanoscale structures in three dimensions, (2) the ability to acquire nanoscale data in a timeframe that supports timely and correct interpretations of the results, (3) the ability to measure complex structures with nanoscale compositional heterogeneity, and (4) the ability to establish the dispersion of materials used in nanoscale contacts.

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 ratios. 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 and regions of interest. For example, the development and installation of aberration-corrected lenses for the SEM is anticipated have a positive effect on resolution and complex structural characterization abilities.

Example 5: Single Molecule Junctions

Need
The basic idea in molecular electronics is using specially designed single molecules or larger molecular building blocks like carbon nanotubes to provide electronic functions in nanoelectronic devices. In contrast to integrated nanoscale contacts fabricated by top down wafer based processes, contacts to molecules are manufactured by bottom up growing and assembling processes based on individual contacts. Examples are single molecules assembled between separately fabricated metallic contacts (Figure 1) or carbon nanotubes placed on the top of planar conducting structures (Figure 2). The development of products based on molecular electronics devices requires precise control of growing and self-assembling mechanisms as well as a deep understanding of the charge transfer from bulk electrodes to the molecule or molecular building block and the charge transport through the molecule or molecular building block itself.

Challenge
Worldwide effort is ongoing to understand on a theoretical and experimental basis the charge transport in molecules and molecular building blocks as well as the charge transfer to metallic electrodes. Nevertheless, today the methods to derive basic properties from experimental measurements, theoretical models, and computer simulations are not standardized so that the comparisons of results are difficult. These difficulties occur in part from the design and controlled fabrication of the molecules, the molecular building blocks themselves, and the contacts to the outer circuit. The challenge is the development of a standard systematic approach to classify contacts and related characterization methods. Such a systematic approach may act as a guide to improve comparability of

results and therefore support and accelerate technical progress of this nano-electro-technology.

8. Recommendations and Conclusions to Consider

Use the collective wisdom of several IEC National Committees and other invited international technical experts to develop a consensus on how best to begin answering the above questions.

Develop a systematic approach to classify the design, experimental realization and characterization of nanoscale electronic contacts for top down and bottom up nanoelectronics:

> Integrated contacts in bulk materials (Key words:Top down fabrication, planar technology)
>
> Molecular building blocks assembled to electrical contacts (Key words: Reproducible fabrication of the molecular building blocks, cleaning, separation of metallic and semi conducting CNT's, assembling, self-assembling)

Develop guidelines for best practices, measurement methods, instrumentation, and standards so that reproducible comparisons of the performance, reliability, and durability concerning nanoscale contacts become quantitatively possible at all stages of the economic model and of the nano-electrotechnical cycle. These two sets of stages form the context in which nano-electrotechnology stakeholders work and have considerable overlap and many synergisms with each other:

> **Economic Model Stages:** The stages of the economic model that involve buyer-seller interfaces at each stage are Research, Development, Initial Deployment, Commercialization (large-scale, high-volume manufacturing), End Use by the customers and consumers, and End-of-Life (disposing and recycling).
>
> **Nano-Electrotechnical Cycle Stages:** The stages of the nano-electrotechnical cycle are Raw and/or Recycled Materials, Process, Subassembly, System Integration, Product, End Use, End-of-Life (Disposing and Recycling).

Consider a workshop with breakout sessions to begin building an international agreement on action plans for addressing the kinds of questions summarized in the above section on Motivation and Questions. Perhaps, the proposed workshop attendees would agree on determining which among the many instrumentation and theoretical approaches for eventual high volume manufacturing of nanoscale contacts have the highest priorities for the available limited resources.

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10. References

[1] NNI What is Nanotechnology?, http://www.nano.gov/html/facts/whatIsNano.html (January 2009)

[2] IEC TC 113 Strategic Policy Statement SMB 3649R, http://www.iec.ch/cgi-bin/getsps.pl/113.pdf?file=113.pdf (January 2009)

[3] H. S. Bennett, *Priorities for Standards and Measurements to Accelerate Innovations in Nano-Electrotechnologies: Analysis of the NIST-Energetics-IEC TC 113 Survey,* will be published in the NIST Journal of Research, Volume 114, Issue 2, March-April 2009. It is now available for download at http://www.nist.gov/eeel/semiconductor/upload/NIST_Energetics_Survey.pdf

[4] Talk given on 2 April 2007 at NIST by John J. Boland entitled "Nanoscale Contact Formation Dynamics." His co-authors are Borislav Naydenov, Peter Ryan and Luci Teague at the School of Chemistry and Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN), Trinity College, Dublin 2, Ireland.

[5] An Assessment of the United States Measurement System: Addressing Measurement Barriers to Accelerate Innovation, NIST Special Publication 1048, January 2007.
http://usms.nist.gov/usms07/appendix_b_usms_report_2006.pdf

[6] http://www.itrs.net/Links/2007ITRS/Home2007.htm