NISTIR 6023

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The External Review of the NIST Precision Engineering Division's NAMT Project on Nanomanufacturing of Atom-Based Dimensional Standards Held at NIST on August 15, 1996

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arati Prabhakar, Director

Summary Report of the External Review of the Precision Engineering Division's NAMT Nanomanufacturing of Atom-Based Standards Project

Abstract

This report summarizes a workshop held on August 15, 1996, which provided an opportunity to U.S. industry in distributed and virtual manufacturing technologies to review and provide a critique of the Nanomanufacturing of Atom-Based Dimensional Standards Project. The information gained from the workshop will be incorporated into developmental project plans.

1. Introduction

The National Institute of Standards and Technology (NIST) has initiated a substantial program in research and development under the name of the National Advanced Manufacturing Testbed (NAMT). The program aims to address industry's needs for measurement and standards in a particular area of technology. As a part of the program, each individual project is being critiqued by knowledgeable people from industry, other agencies, and academia. This is to test the technical soundness of the project design as it relates to industry needs and the state of knowledge and practice in the field of the project. This external review work is one mechanism to provide such ideas for the subsequent definition of the project goals, objectives, and approaches.

2. Goal of the Workshop

The goal of this workshop, held at NIST on August 15, 1996, was to provide an opportunity for U.S. industry in distributed and virtual manufacturing technologies to review the Nanomanufacturing of Atom-Based Dimensional Standards Project and provide a critique of the program elements. The reviews helped to establish the quality and industrial relevance to ensure that the results meet the needs of the U.S. manufacturing community. The review benefitted NIST as a vehicle for reviewers to express their concerns and to make their needs known. The information gained from this workshop will be incorporated into the developmental project plans.

3. Basic Concepts of NAMT

A. The NAMT Program and Projects

The NAMT Program is designed to support the development of the NIST Manufacturing Engineering Laboratory's solutions to the standards and metrology issues of the new information-based manufacturing. The NAMT program is intended to be a showcase for the future of manufacturing. The NAMT will demonstrate how machines, software, and people can be networked together to achieve interoperability at all levels of a manufacturing enterprise. The NAMT contains a facility in which scientists and engineers from industry, NIST, academia, and other government agencies work together to solve measurement and standards issues in information-based manufacturing and develop the needed tests and test methods for industry that are part of NIST's mission.

The projects within the NAMT are characterized by: (1) collaborative industrial partners, (2) leading edge technologies, (3) development or use of advanced measurement technologies, (4) development of standards for manufacturing applications, (5) use of information technology, and (6) tasks and processes at multiple sites on-line. The results of the NAMT will be metrology techniques, interface standards, and other infrastructural technologies and standards.

The NAMT will accelerate efforts to develop components of a common information infrastructure for manufacturing, extending the capabilities of advanced computing, communications, and control technologies to multiple manufacturing applications and domains. It will leverage pools of manufacturing resources, including physical facilities, equipment, expertise, and software.

Presently, the NAMT has four projects:

- The *Nanomanufacturing of Atom-Based Dimensional Standards* project is focused on the distributed design, fabrication, and use of nanometer-scale dimensional artifacts.
- The *Framework for Discrete Part Manufacturing* is aimed at developing a consensus-based framework for the interoperability of distributed manufacturing systems.
- The *Development of Machine Tool Performance Models and Machine Data Repositories* project is creating a virtual manufacturing and inspection model and data repository to reduce the need for prototyping.
- The *Characterization, Remote Access, and Simulation of Hexapod Machines* project is aimed at measuring and extending the capability limits of parallel machines, and developing & evaluating techniques for open architecture control interface standards.

B. The Overall Themes of NAMT

Within the context of information-technology-based manufacturing, the current technical thematic focus of the NAMT projects is support of *distributed and virtual manufacturing.*

- By *distributed manufacturing* is meant the cooperation in the overall manufacturing process among functionally-specialized facilities at a variety of geographically -separated sites by means of modern computer and communications systems.
- By *virtual manufacturing* is meant both:

  - *real* manufacturing by *virtual enterprises* which come together by means of computer communications to produce a product or aspect thereof; and

- *virtual* manufacturing by means of comprehensive and realistically predictive simulation of designs, processes, and resulting products by means of computer quantitative modeling and qualitative animation.

C. The "*Nanomanufacturing*" Project and NAMT Themes

As is true with each of the other three NAMT projects, the "*Nanomanufacturing*" Project has, as a program principle, been designed to jointly support:

- the overall NAMT program objective of support to information-technology-based distributed and virtual manufacturing; and

- the lead Division's mission objective, which for the Precision Engineering Division is to provide, realize, and disseminate the international standard of length through length-measurement research and services.

As a result, the *Nanomanufacturing of Atom-Based Dimensional Standards* Project uses and supports the technology of:

- distributed fabrication and use of nanometer-scale dimensional artifacts
- computer modeling and simulation of mechanical systems and components
- remote teleoperation of Scanned Probe Microscopes (SPMs)
- all linked by means of advanced computers and communications for high-speed video, voice, and data transmission among collaborating institutions in industry, government, and academia.

4. Purpose of the Workshop:

The purpose of the workshop was to raise issues associated with the project's technical content and purpose as voiced by potential users and beneficiaries of the projected results. Comments/ideas were received from representatives from industry, other federal agencies, and academia. The industries included manufacturers of controller instruments, microelectronics and scanning probe microscopes. Table 1 shows the names of institutions and companies represented by those from outside of NIST. Appendix A lists the attendees and the organizations they represented.

Table 1. Companies/Institutions Represented
Advanced Technology and Research
Capital Vacuum
EMCOR
Huntington Labs
IBM - Thomas J. Watson Research Center
Kurt J. Lesker Company
Naval Research Laboratory
Texas Instruments
Topometrix
University of Maryland
University of North Carolina

5. Structure of the Workshop

The one-day workshop included a detailed overview of the NAMT Program and the Nanomanufacturing of Atom-Based Dimensional Standards Project. At the conclusion of each individual presentation, reviewers had an opportunity to respond to questionnaires designed by the Project Team. Members of the Project Team are listed in Appendix B. The Questionnaire is listed in Appendix C. An oral question-and-answer period followed the completion of the questionnaires. Two recorders captured the oral comments that occurred during the question and answer discussion period. Appendix D contains the oral comments. The reviewers' detailed answers are listed in Appendix E.

6. Principal Findings of the Workshop

A. Principal Conclusions

For most of the written questions, the individual reviewer's responses varied widely. For a few questions, however, the responses were so similar that, taken together, those responses formed clear majority opinions that are stated here as conclusions. These conclusions are:

1. *For achieving the degree of geometric perfection and size of features needed for high-accuracy reference standards to support future microelectronics and data-storage manufacturing, atom-based dimensional standards will be vital, necessary, and likely the only way to achieve that end.*

2. *The types of dimensioned features on these atom-based artifact standard includes linewidth, step height, roughness, and positional grids without a clear indication of the relative priority of each.*

3. *The measurement uncertainties for the atom-based artifacts stated as targets for the project are satisfactory.*

4. *The fabrication and use of such atom-based artifact standards carried out in a distributed manner using expensive specialty equipment at geographically separated sites will be a necessity in future manufacturing.*

5. *Development by NIST of a vacuum suitcase as a necessary means to support its particular needs in fabrication of atom-based artifact standards is justified.*

6. *Development by NIST of a vacuum suitcase as a technical end in itself, however, is questionable and would require greater definition of industry need as justification.*

7. *Capabilities to carry out remote diagnostics on SPMs, already important, will be increasingly more so in manufacturing industries.*

8. *There is an industry need for development of documentary standards governing controller, data, and operator interfaces for each component of the proposed program, especially for teleoperation of SPMs.*

9. *It would be a valuable contribution to have NIST and industry together draft strawman specifications to expedite the adoption of such standards.*

B. Issues Raised by External Reviewers

During open discussion following each segment of the overall project presentation (Appendix D) and the written responses of the individual reviewers to the specific written questions posed (Appendix E), reviewers asked questions or made statements that are here cast as issues concerning the project. These issues are shown in topical form under four headings; those associated with: 1) the atom-based artifacts; 2) the artifact transport system; 3) the remote teleoperation of SPMs; and 4) the justification and design of the project in terms of industry needs.

Each of these issues is to be addressed by the project team in the “Project Definition Document” to be developed subsequent to the workshop. Planned completion date of that document is December 1996.

I. Atom-Based Artifacts

- What type of traceability and/or accuracy is being pursued?
    - R&D on truly intrinsic standard (physical traceability to NIST not needed)?
        - What if companies can make their own?
        - What if companies use UHV but cannot make their own?
    - R&D on reference artifacts where physical traceability to NIST is needed?
- What type of uncertainty?
    - Absolute?
    - Relative?
- What types of dimensioned features?
    - Counted-atom linewidth?
    - Lattice step height?
    - Lattice-mismatch grid?
    - Lattice roughness?
- For each type of dimensioned-feature artifact:
    - How does it work, i.e. what is principle of generating geometry and dimension?
    - For what uses and specific manufacturing process(es) is it aimed?
    - What demand is there for it?
    - What is priority for its development?
    - What will be the sale price or cost to user?
    - What demands would its use place on:
        - Vendor?
        - Customer?
        - End user?
            - How would non-vacuum user use vacuum-based artifact?
- What are the materials issues for SEM applications?
    - For Separation by Implantation of Oxygen (SIMOX?)
        - How is charging to be avoided?
            - For thin layers?
            - For thick layers?
        - What about captured-charge centers near lines?
    - What will be stability of atom-based features?
        - What about thermal effects?
            - Increasing roughness?
            - Generation of defects?
    - What about more, different types of semiconductor material for research/testing?
    - What are the fundamental limits of atom-based geometry/dimensions?
- What industrial processes is each artifact aimed to control?
    - Lithography - critical dimensions?
    - Structure of Metal Organic Chemical Vapor Deposition (MOCVD) epitaxial layers?
    - What environments?
        - Non-vacuum processes?

- Vacuum processes and vacuum suitcase?
  - Where, which processes now being used by industry?
  - Where, which planned, projected in by industry?
- What is the cost and useful life of artifact
  - What is the planned useful life?
    - One-time certified “gold” standard?
      - Stable with time, handling, use?
      - Deterioration with time, handling, use?
    - Will they be recalibrated after use?
      - Will NIST do?
      - How will damage be factor in recalibration?
        - How to assure not damaged?
        - What to do if damaged?
    - Disposable?
  - Likely cost of artifacts?
    - Low?
    - High?
- What about pursuing alternative basis for generating need dimensioned features?
  - Crystal lattice?
  - Molecular structure?
  - Placing atoms in Si surface to create scale?
  - Laser-focused deposition?
- What about SPM instrument tips?
  - Will you develop formulas for tip preparation?
  - How to be sure tip is sharp enough todetect missing atoms in Linewidth artifact?
  - What about standardization of tip geometry?
  - What about standardization of tip holders?
  - Will you ship a tip with an artifact as an artifact-tip “reference material”

II. What artifact transport system will be needed for distributed nanomanufacturing?

- What is ultimately the technical need which determines the specific environment?
  - Contamination elimination?
  - Stability of atom-based features?
- What are the alternative environments for artifact itself? for mfg process being served?
  - Vacuum?
    - What level of vacuum?
      - UHV?
      - non-UHV?
    - What type of pumping can/will be used?
      - Active?
      - Passive dynamic?
        - Sorption?
        - Cryo?
      - None?

      - Controlled ambient?
        - Gas?
        - Liquid?
      - Uncontrolled ambient?
        - By using passivated surfaces?
        - By using freeze-thaw cleaning?
  - What are the types-configurations of transport systems based on application needs?
    - R&D fabrication and inspection (1)
    - Reuseable delivery to end user (2)
    - One-time-only disposable delivery to end user (3)
  - What are alternative size-configuations?
    - Integral with wafer-substrate (large as particular wafer)?
    - Insert to wafer-substrate (small)?
  - What are the specific industrial applications which determine needs?
    - SPM industry?
    - Microelectronics?
    - Data storage?
    - Biomedical?
      - Genetic engineering?
      - Gene mapping?
    - Nuclear?
    - Other?
  - What interfaces in the transport system need to be standardized?
    - What part of system needs them?
      - Vacuum system flanges?
      - Internal manipulator/transport mechanisms?
    - What standardized interfaces already exist?
      - Flanges?
      - Standard Mechanical Interface (SMIF) pod?

III. Remote Teleoperation of SPMs

  - What are standardized-interface needs?
    - Remote-control for diagnostics?
    - Data file formats?
    - Images?
  - What about standardization of instruments?
  - Is there a model from other industry applicable to SPM instruments?
  - What are the state-of-art technology challenges for robotic operation?
    - Sample loading?
    - Probe tip exchange?
    - Particle-contamination avoidance for robotics devices?
  - What is role of teleoperation/telerobotics within project goal/objective?
    - Within scope?
    - Needed for development of atom-based artifacts?

IV. Justification and Design of Project in Terms of Meeting Industry Needs

- Have related previous and current work been identified?
  - Exhaustive literature search?
  - Other documentary standards?
    - SEMATECH?
    - SEMI?
    - ASTM?

  - What other technology development taking/taken place?
    - At IBM?
    - At TI?
    - At universities?
  - What other knowledge about artifact standards?
    - SEMATECH Howard Huff on roughness standards?

- What determination of industry needs has been made?
  - Where is demand pull for:
    - Atom-based artifacts?
    - Vacuum suitcase?
    - Teleoperation of SPM?
  - Does SIA Roadmap envision in-vacuum mfg process, inspection process?
  - Shouldn't project be done with industry in consortium?

- What are economic benefits to industry?
  - Who will be the specific beneficiaries?
  - What is the time to pay-off for industry?
    - Research to yield some benefit in long-term?
    - Closer-in development with a near-term pay-off?
  - How can you demonstrate economic benefits?
    - ROI?

- What exactly are the project goals and their relation NIST mission?
  - Develop calibration artifacts ("measurements" - SI traceability)?
  - Drive standards process for interfaces ("voluntary standards")?
    - For SPM?
    - For vacuum suitcase?
  - Technology development, e.g., suitcase?
    - Already done at university?
    - Already available commercially?

The information gathered from the review will be used to define the projects' goals, objectives, and approaches. This redefinition process will more closely align the project to meet industrys' needs.

APPENDIX A

LIST OF ATTENDEES

Tony Barbera
Advanced Tech & Research

Marylyn H. Bennett
Texas Instruments, Inc.

Ken Bertken
Huntington Labs

Joe Cannon
Capital Vacuum

Zhe Chuan Feng
EMCOR

Joe Keller
Kurt J. Lesker Co.

Martin Peckerar
NRL

Dennis Sollon
Kurt J. Lesker Co.

Richard Superfine
UNC-Chapel Hill

Paul West
Topometrix

Kumar Wickramasinghe
IBM-TJW Research Center

Ellen D. Williams (Collaborator)
University of Maryland

APPENDIX B

PROJECT TEAM MEMBERS

- Technical Project Leader
  Clayton Teague

- Contributing Members
  Brad Damazo
  Joe Fu
  Janet Land
  Manfred Osti
  Bob Russell
  Fred Scire
  Rick Silver
  Keith Stouffer
  Vincent Tsai

- Artifact Task Leader
  Ted Vorburger

- Vac Suitcase Task Leader
  Dick Rhorer

- Teleoperation Task Leader
  Tom Wheatley

- Simulation Task Leader
  Ram Sriram

- Overall Project Leader
  Dennis Swyt

APPENDIX C

QUESTIONNAIRE

NAMT Overview

What is your reaction to the NAMT program focus on information-based manufacturing, particularly measurements and standards, for distributed and virtual manufacturing technologies?

Project Overview

1. What is your overall reaction to the proposed NIST project for "Nanomanufacturing of Atom-Based Dimensional Standards?"

What is your initial reaction to:

a. The notion of atom-based dimensional standards?
b. The notion that some such standards may need to live in vacuum?
c. The notion of the fabrication and use of such standards at different sites?
d. The notion of a vacuum-suitcase as a means of transporting such standard under vacuum?
e. The notion of telerobotics?

2. Do you see a need for new standards in the technologies which support distributed manufacturing (that is, in general, not specifically related to this project?)

3. What kind of things are you or your company doing that you think are important for us to know about on this project?

4. What other specific research in the proposed project area should NIST consider?

5. What is your assessment of the proposal to have industry and NIST draft a specification as a strawman to expedite the adoption of appropriate standards for each of the components of the proposed program?

6. Do you have any recommendations about how the project should be changed or redirected to meet the needs of industry better?

Atom-Based Artifacts

1. What kinds of things are you or your company doing concerning atom-based artifacts that you think are important for us to know?

2. What other specific research in the proposed area of Atom-Based Artifacts should NIST

consider?

3. This project aims to develop atom-based artifacts with the following priorities and uncertainties:

   First:Silicon single atom step height artifacts with 0.3 nm height and uncertainty of ±0.03 nm (2 std. dev.).
   Second: Atom-based linewidth artifacts with width of 300 nm and uncertainty of ±3 nm (2 std. dev.).
   Third: Lattice-mismatch grid artifacts with width on the order of 100 nm and uncertainty of ±1 nm (2 std. dev.).

   a. With respect to your needs, what do you think is the relative importance of each?
   b. With respect to your needs, are the target uncertainties appropriate, too large, or unrealistically small?
   c. What other types of artifacts should we be developing?
   d. Where would they fit in with the first three in importance?

4. We would like to work with you in developing the ______________________ artifacts.

5. We would like to test the ________________________ artifacts on our measuring equipment, which is ________________________.

6. Are there any gaps and limitations that we have overlooked? If so, what are your recommendations as how to address them?

7. Add any additional comments here.

Vacuum Suitcase

1. What kinds of things are you or your company doing relative to the vacuum suitcase concept that you think are important for us to know?

2. What other specific research in the proposed area of the vacuum suitcase concept should NIST consider?

3. How large a vacuum suitcase should we be considering?

4. With what specific types of analytical and fabrication equipment do you think the vacuum suitcase should be made to be compatible?

5. What pressure should we aim to achieve during operation of the vacuum suitcase?

10^{-6}, 10^{-7}, 10^{-8} Pascal or other?

6. Are there any gaps and limitations that we have overlooked? If so, what are your recommendations as how to address them?

7. Add any additional comments here.

Telerobotic Operation of SPMs

1. What kinds of things are you or your company doing concerning telerobotic operation of SPMs that you think are important for us to know?

2. What other specific research in the proposed area of telerobotic operation of SPMs should NIST consider?

3. What is your perception of the need for telerobotic operation of SPMs for a) the SPM industry? and b) this project?

4. What is your perception of the need for remote diagnostic capabilities on SPMs for a) the SPM industry? and b) this project?

5. What is your perception of the need for documentary standards for controller interface for a) the SPM industry? and b) this project?

6. What is your perception of the need for documentary standards for operation interfaces for a) the SPM industry? and b) this project?

7. Beyond supporting standards development, what can NIST do as a neutral party to encourage SPM manufacturers to allow greater user access to their hardware and software?

8. Are there any gaps and limitations that we have overlooked? If so, what are your recommendations as how to address them?

9. Add any additional comments here.

Industrial Collaborations

1. We would like to have you participate in this project in some way. Please comment about which of the following possibilities would be the most suitable and beneficial way for you to participate.

    a. Informal information exchange
    b. Intercomparison of research results
    c. Coordination of research activities
    d. Memorandum of understanding on cooperative work
    e. Formal Cooperative Research and Development Agreement

2. What changes would you recommend to make the project more beneficial to you?

3. What is the best strategy for us to use to get buy-in from your management for participation in this project?

4. What other organizations not represented today do you think would be interested in the NAMT Program in general and this NAMT Project in particular?

APPENDIX D

Notes for the External Review of PED NAMT:
Nanomanufacturing of Atom-Based Dimensional Artifacts
Reporters: John Kramer and Robert Russell

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This is a summary of the questions asked by the external reviewers of the PED NAMT Project, "Nanomanufacturing of Atom-Based Dimensional Artifacts," at the August 15, 1996 review session.

In preparing this summary, we make no claim to have recorded the questions and answers verbatim. Instead, we have tried to capture the essence of the discussion, giving proper credit to the various participants, and hopefully without ascribing points of view to individuals that they didn't intend to convey.

****

INTRODUCTION & NAMT OVERVIEW SESSION

Zhe Chuan Feng - What is the step height artifact you are showing in the slide? What are it's dimensions? How are they determined? Ted Vorburger - The dimensions on the plot are from the interferometric readings and capacitance gage readings of the instrument (Calibrated AFM) that took the image.

Marylyn Bennett - What is the time line for the project?
Dennis Swyt - Basically 5 years.

Paul West - Are we just looking at the microelectronics industries or are other industries like the recording industry or the traditional machine tool industry involved also?
Dennis Swyt - The microelectronics industry and the data storage industry are the main drivers. The basic physics underlying the technology for these industries is different than for the traditional machine tool industry and this drives us to atom-based artifacts. We have a good understanding of machine tool technology which we then apply to the microelectronics and data storage industries' metrology problems.

PROJECT OVERVIEW SESSION

Joe Cannon - You say one of your objectives is the "development of documentary standards for mechanical interfaces." What do you mean by documentary standards? Standards have already been developed. Dennis Swyt - The goal is to develop a standard way of hooking up vacuum suitcases to any vacuum system.

Paul West - Semiconductor fabrication is now done with air-based instruments. How are you going to take these specimens and use them to calibrate an in-air machines?
Dennis Swyt - We anticipate: (1) To fabricate atom-based artifacts, you need to work in vacuum. Then, (a) some may be stable out of vacuum, (b) some may need to stay in vacuum, (c) some may be viable in low vacuum or in a controlled environment. (2) In the future, fabrication may be done in vacuum.

Richard Superfine - Does the SIA Roadmap envision vacuum processing where you need to measure/inspect during the processing (i.e., in vacuum)?
Marylyn Bennett - Yes. TI has been investigating processing single wafers, face down, in vacuum. The process control must be done in vacuum. There are also vacuum cluster machines that are beginning to be used.
Dennis Swyt (to Marylyn) - Why in vacuum?
Marilyn - To guard against contamination. Also, with the thinner gate oxides they need to be grown in vacuum because the spontaneous air growth would drive them out of tolerance.

Marty Peckerar - Why limit yourself to UHV, why not controlled environments or lesser vacuum?
Dennis Swyt - It's the focus we have taken. What do you think about it? We need to find out if UHV is necessary or not.

Richard Superfine - It seems like there are three categories for developing processes. Those with fundamental science issues, those with engineering issues, and those that are answerable with today's technology. If the technology IS available, what is NIST's role? For example, the vacuum suitcase: We've done it. What you need is for manufacturers to agree on a standard. For example, teleoperation: We can do it--remote operation of control of a computer, since most instruments today are computer based. Is this the main question? "How can we get everyone to agree on the standard?"
Marylyn Bennett - Yes. We want standard methodology.
Dennis Swyt - Take an analogy with the classic machine tool industry as far as telerobotic operation is concerned. Most are based on proprietary controllers. Until recently there were no open architectures which promote modular solutions. Point solutions are available now, but we want to develop methodologies so that the solutions are easier.

Marty Peckerar - These are absolute standards. Relative standards may be good enough.
Dennis Swyt - This is a longstanding question for NIST. We recognize that internal relative standards are what industry uses day to day. Problems come up in commerce--when one company tries to buy components from another company. Also, industrial R&D drives us to absolute standards. They want to know if they are physically right. Also, the new emphasis on quality, ISO 9000, etc. The requirement is for traceability which drives us (as a national measurement lab) back to absolute accuracy. We have been driven to absolute accuracy by industry.

Joe Cannon - What is your concept of a suitcase? What size will it be?
Dennis Swyt - We're still working that out. Some designs would have to be moved around by a

forklift. Others may be around the size of a bread box.

Kumar Wickramasinghe - IBM tried the concept of a vacuum suitcase ten years ago and found that contamination is a big issue. The project was abandoned because of too much contamination from wafer to wafer. (Note: After the review, I (John Kramar) overheard Kumar saying that this was in a manufacturing, batch-processing, setting. He thought that from the cross-contamination standpoint, the concept would work okay for transporting standards.)

ATOM-BASED ARTIFACTS SESSION

Paul West - How does counted atoms work for line width?
Ted Vorburger - You literally count the atoms.

Marylyn Bennett - What are the projected uses for (a) the step-height and (b) the lattice mismatch standards?
Ted Vorburger - (a) Measure feature height (esp. flying height of magnetic R/W heads. 12 nm +/- 1%) (b) Squareness and pitch at the 100 nm level.

Paul West - Are we doing anything to standardize or characterize the tips? Are you developing formulas for tip preparation?
Ted Vorburger - Not in this project but in PED there are projects dealing with tip characterization.

Paul West - What about standardization of instruments? Is it important to use the right kind of tip to make use of the atom-based artifacts? Will tips need to be shipped with the artifact to insure proper use? Will tip holders need to be standardized across the various instrument manufacturers? How will you (consistently) get a sharp enough tip to locate the missing atoms in the line width artifact? (Note: this last question seems to be based on a misconception of what the line width artifacts will look like.)
Ted Vorburger - We don't believe it will be necessary to have a standardized tip to be able to use these artifacts.

Paul West - If the artifacts are coming back to NIST how are you going to insure that they don't get damaged by the people using them (i.e. What happens if someone runs a tip into the artifact?

Kumar Wickramasinghe - What about sub-nanometer roughness standards?
Ted Vorburger - We have thought about them and would like to develop them. Good ones are insensitive to probes, i.e., they are sine waves or square waves. There are some being developed at about the 5 nm level.
Kumar - We need 1 nm.
Ted - Maybe they could be produced by the careful control of optical- holographically produced gratings. Or maybe an array of lattice steps, evenly spaced.
Zhe Chuan Feng - How do you set the height scale on your single step Si artifact image?

Ted Vorburger - We measure it with the calibrated AFM.

Martin Peckerar - I assume the line width standard is made on SIMOX. How are you going to avoid charging? Captured charge centers in the oxide near the lines?
Marylyn Bennett? - How thick is the oxide? If it's thin enough, it's not a problem.

Summary (Robert Russell)
Some people weren't sure how the manufacturers of microelectronics were going to use the artifacts, especially since they would have to exist in UHV and many instruments are not UHV.

VACUUM SUITCASE SESSION

Ken Bertken - What are the size of the artifacts?
Dick Rhorer - Up front, we are designing for only a 2" wafer. We are still open to input.
Ted Vorburger - What is practical? Do we need to design for whole wafer size?
Ken - Do you need to handle wafers at all? Marylyn Bennett - You don't need the artifacts to be full wafer size. You can drop them onto a wafer and use a wafer handler to move them around.

Marylyn Bennett - (1) We would like for artifacts to be cheaper. (2) We are using 12" wafers for some things now and will be switching to them more and more, but many active fabs are still using 3" wafers, so if you want to be compatible with all wafer sizes, you will have to address that range. (3) SMIF Pods are a recognized standard for mechanical interfaces. Hitachi ships FE tips in vacuum. (4) Proposed pump-down times are way too long. Full wafers can be pumped down in 1-2 minutes. (5) Particulate contamination is as important as exposure to gases (like air). Take special care that your valves or pumping systems don't generate particulates.

Marty Peckerar- What about using controlled environments like inert gas or lower vacuum?

Joe Cannon - Are you looking at other areas for application like NASA, NIH?
Dennis Swyt - Our principal demand pull is from the microelectronics and storage technology industries.
Joe - Manufacturers might like to know if it could be a broader market.
Paul West - There may be some applications in genetic engineering research--gene mapping.

Paul West - From the vacuum suitcase, it is implied that this is going to be an in-vacuum standard interface. I have a perfect artifact in UHV, how is it going to make my product better? Measurements (today) aren't done in vacuum. Some things, like lithography, will never be done in UHV.
Kumar Wickramasinghe - Since many instruments are not in vacuum why UHV?
Ellen Williams - Could be a 2 step process where by you measure in air and then in vacuum.

Ken Bertken - If the suitcase is disposable, is the artifact therefore disposable?
Dick Rhorer - Probably not.

Marylyn Bennett - Have you looked into the cost of making these artifacts? If they are inexpensive (~$500) then there won't be a need to keep them for a long time or to ship them from system to system. If they're $20,000 each, that's different.

Richard Superfine - Since the artifacts will be based on intrinsic properties of countable numbers of atoms, made why can't the people who use them just make them at their site, as opposed to NIST shipping in this suitcase?

Paul West - People in this project need to spend a day on a manufacturing floor and become familiar with their equipment and processes.
Marylyn Bennett - Come on down. We'll suit you up.

Summary (Robert Russell and John Kramar)
Many thought that UHV was not needed and did not understand why we are pursuing it right away. They thought that we should look at alternatives. A mechanical interface standard appears to exist (SMIF pod), but it may not apply to vacuum transfers.

TELEROBOTIC OPERATION SESSION

Paul West - (Comment on open architecture) Competition is good if you are in a large market.
Dennis Swyt - ... and you're winning.

Superfine - Is there a model from another instrument industry that can be used?
Keith Stouffer - The machine tool industry (EMC).

Paul West - Topometrix uses an open architecture. Users can develop what they need (or buy if available). Note that SPM is a young and frothy industry relative to machine tools.

Kumar Wickramasinghe - How will you drive standards? It seems you are focusing on the SPM industry. Some manufacturers won't even talk to each other.
Paul West - Chromatography people have tried to get their industry together on these types of issues with varying success. I can put you in touch with some of these people to get their stories of how to deal with unwilling people. Laboratory Information Management System.

Richard Superfine - Just a standard data file format between the different SPM manufacturers would be useful. (Many agreed with this)
Ted Vorburger - Standards already exist for surface topography data files.

Paul West - SPM companies used to compete on controllers. They compete on other things now, so it should be becoming easier to promote open architectures.

APPENDIX E

Summary of Individual External Reviewers Written Responses to Questions Posed by Project Team on the Topics Shown

The following responses have been compiled from the completed questionnaires submitted by the external reviewers following the completion of the program, project, and sub-projects presentations and discussions described above. The responses to each question have been ordered in the compilation from what may be the most to the least positive or certain.

Initial reaction to the notion of atom-based dimensional standards:

- Great idea - probably needs standard probes.
- Vital project for future nanoscale manufacturing - standards are not available for metrology on the nanometer scale (examples: step height standards, width standards, artifacts for probe tip calibration for SPM).
- Probably the only way to go to achieve standards on this scale.
- Will be necessary.
- Will be necessary for IC dimensions.
- Very necessary.
- Certainly important, with the full range of fundamental science and technical problems.
- Must pay attention to relative as well as absolute dimensional or positional standards.
- Would be great if you could tie the standard to a process
- See the need for them especially for things like CD's, but think this is still very far-reaching due to all the technical difficulties.
- Guess that (such) "natural" standards will be the way to go. (Would like to understand the fundamental limitation or the stability of atom features 10^{-9} Pascal => 1 Monolayer/day; thermal effects promote roughness and defects).
- It is unclear what requirements this places on the customer, vendor, individual and its demonstrable accuracies in using these artifacts.

Other specific research in the proposed project area NIST should consider:

- Standard SPM probes, what Europe and Asia are doing in this area, identification of 5-10 processes needing this technology.
- NIST laser focusing to create precisely spaced arrays of deposited atoms very promising for some metrology.
- Overlay and alignment grids for mix-and-match lithography, where length standards are important.
- Sub-nanometer scale roughness standards.
- Set-up standards for AFM measurements to study atomic ordering and measurement methods and standards for MOCVD grown epitaxial layers

Initial reaction to the notion that some such standards may need to live in vacuum:

- Will have to live in vacuum for contamination and oxidation elimination.
- Either vacuum or an inert environment
- Quite likely, but consider possible molecular systems which would provide alternatives.
- Probably not, but if this is the only way to achieve contamination control, do it.
- Probably not practical.
- Not sure.

Initial reaction to the notion of the fabrication and use of such standards at different sites:

- A requisite for future manufacturing.
- Needed.
- A good idea if necessary (SPM probes are made this way routinely).
- Probably necessary (in order to be financially viable as some steps will need multi-million-dollar equipment).
- Need more specific discussion of some case where a company would have UHV capability to use standard, but not capability to create standard. Would NIST's role be creation of a guarantee of a standard?
- Concern about the ability to keep the artifact in a known state so it can be trusted.
- Don't see this as a huge marketable use.

Initial reaction to notion of vacuum-suitcase for transporting standards under vacuum:

- Needed.
- Concept could be viable for standards fabrication but not manufacturing use (IBM tried concept tried for manufacturing about a decade ago, found suitcase was a venue for contamination collection).
- Would require strong proof of need to get industry to make investment.
- TI developed one in the 1980's for the MMST program, IBM also developed one, and SMIF is the industry standard so this work is already in progress.
- Controlled ambient is probably the most important issue. Would like to see alternative but if vacuum is only way to achieve contamination control, do it.
- Not practical.
- What are the issues that NIST is addressing?

Initial reaction to the notion of telerobotics:

- Very important.
- Clear need in many cases (Possible for company to send item to be characterized to central site and do proprietary check remotely - competes with idea of vacuum suitcase).
- Useful.
- Good for limited applications.
- Most challenging technically for robotic operation of SPM: sample loading (Park Sci) (desktop), semiprobe tip exchange
- Not sure of this. (Probably need some kind of controlled ambient vacuum teleoperator for moving samples from one tool to another, but the robots make particles, no)

- Beyond the scope of this project, for driving interface standards for telerobotics, this is particularly important; however, not essential to accomplish the end goals of this project - fabrication of atom based standards.

Need for new standards in the technologies which support distributed manufacturing: (that is, in general, not specifically related to this project?)

- Yes
- Yes
- Probe tip calibration artifacts
- Not sure yet.

Things you think are important for us to know about on this project:

- Topometrix has three telerobotic projects: MS windows; reach out (as in distributed learning project); UNC VR project.
- Our company routinely use standards in manufacturing our SPM products
- I work on vacuum carrier & SMIF.
- Development of alignment techniques for AFM/STM (proximal probe) lithography
- IBM East Fishkill's vacuum suitcase experience which may or may not apply.
- ATR developing a commercial generic controller, which with strong emphasis on API's, openness, implementation on PC using Windows NT, might serve as a possible testbed for embracing telerobotic activities/APIs.
- MoCVD-grown GaN, In GaN, AlGaN, InSb, AlGaAs, InGaAs, InGaP, InGaAlP, InGaAsP, InAlP, PbZrTlO3 (PZT) BaSrTiO3---surface roughness in nano-scale, multi-layer (MQW, SL--) structures, cross section, interface phenomena.

Other specific research in the proposed project area NIST should consider:

- Standard SPM probes, what Europe and Asia are doing in this area, identification of 5-10 processes needing this technology.
- NIST laser focusing to create precisely spaced arrays of deposited atoms very promising for some metrology.
- Overlay and alignment grids for mix-and-match lithography, where length standards are important.
- Sub-nanometer scale roughness standards.
- Set-up standards for AFM measurements to study atomic ordering and measurement methods and standards for MOCVD grown epitaxial layers.

Proposal to have industry and NIST draft a specification as a straw man to expedite the adoption of appropriate standards for each component of the proposed program:

- Extremely important, including an industrial prototype and phased testing
- Essential.
- Seems essential to make it useful to the program.
- Good idea. Industry input is essential in defining the standards.
- With the few comments, I've made above, great.

- Good idea. How does this tie to other standards projects?
- OK, but NIST should either collaborate with or get information from SEMATECH, SEMI, ASTM, etc. to not duplicate efforts.

Recommendations on how project should be changed/redirected to meet the needs of industry better:

- Focus on details : who will use results, how; ROI for companies that buy them.
- Need to clarify long-term-research vs short-term-utilization benefits to industry [probably UHV atom standards are of use for the future and will not get favorable response from industrial scientists with immediate needs; short-term aspects such as height standards in magnetic read heads should be coordinated directly with potential users].
- Equal emphasis on absolute and relative standards, vacuum and controlled ambients.
- Do this activity as a consortium with much more industrial commitment (otherwise NIST may do really "great" things that do not get used).
- Get more and different types of semiconductor materials for your fabrication and testing investigation (EMCORE will be happy to be such a partner for materials such as MOCVD-grown GaN, etc).

Atom-Based Artifacts

Things you're doing concerning atom-based artifacts important for us to know:

- Specifically on atom-based artifacts for standards; Don Eigler at IBM Almaden moves atoms around in UHV and at low temperatures.
- Working on cleaning fabricated structures in UHV to obtain atomic resolution, very interested in Si/SIMOX structures.
- Using graphite and mica for air-based SPM, high-school-educated operators, know the practical aspects.
- Refer to answer in Project Overview i.e. "MOCVD-grown GaN, . . .
- STM lithography
- Nothing in this area.

Other research in the proposed area of atom-based artifacts should NIST consider:

- Fundamental limits of atom level details? Does this limit the applicability of a transportable standard?
- Other environments - gas, liquid?
- Please contact Dr. Howard Huff at SEMATECH (512 356-3500 main switchboard) for excellent input on roughness standards.
- The Japanese work "moving" atoms about the Si surface might be useful here. You can construct a kind of "vernier" (I think).
- Set-up standards for AFM measurements. To study atomic ordering and measurement methods & standards for MOCVD grown epitaxial layers.

Importance of following priorities and uncertainties relative to your needs:

1. Silicon single atom step height artifacts. . .
2. Atom-based line width artifacts with width of. . .
3. Lattice-mismatch grid artifacts with width . . .

- Good
- All useful.
- 2, 1, 3.
- 2,3,1
- 3 more important.

Stated target uncertainties relative to your needs:

- OK
- OK
- OK
- In the right ballpark.
- Appropriate, but tough to measure.

Other types of artifacts we should we be developing and relation to other three:

- Surface roughness - 2.
- Roughness standards - between 2 and 3.
- Single-atom-vacancy size, dislocation line width - not sure.
- Other "self-organized" systems with well-defined features like bio molecules - for all 3.

Artifacts on which we'd like to work with NIST:

- Step height surface roughness test in air
- Atom- patterned atomic optometric level artifact
- Unsure now

Artifacts would like to test in our own measuring equipment:

- Step-height and surface roughness in air SPM
- Atom-based standards and possibly step height in research-fab AFM.
- IC critical dimensions (CDs) in CD SXM
- SEM

Recommendations on things we should consider:

- Second project is very-very hard to achieve.
- A project on roughness standards would be welcomed by the silicon manufacturers, IC makers, and defect inspection/detection suppliers.
- Concerned about charging in your SIMOX test structure.
- Need to address the issue of how these standards can be used to calibrate a variety of instruments out in the manufacturing lines most of which don't operate under UHV.
- Measurement procedures should be standardized, parameters effecting measurement identified, how the measurement procedure used to control each effect specified.

- Include SPM tip in plans
- Develop plan for certifying the instruments at industrial sites.
- Keep me informed of these projects as I want to incorporate this into the materials characterization steering team which recommends future tools/requirements to TI.

Vacuum Suitcase

Things my organization doing relative to the vacuum suitcase important for us to know:

- Call me (214 927-3597) for contact on vacuum carrier TI developed.
- Our MOCVD systems have sample load-loop part similar to your vacuum suitcase.
- Nothing right now.
- Nothing yet.
- None

Other research in vacuum-suitcase area NIST should consider:

- Passive dynamic pumping, e.g. sorption or cryogenic, driving transport system.
- Use a gas or liquid.
- Surface-passivation-controlled artifacts
- Minimum vacuum practically required.
- Life expectancy of an artifact and how customer will know the artifact, after all of this handling, is still accurate.
- An exhaustive background-literature search before proceeding.
- Appears technology being developed does not address generic fundamental questions, but technical implementation issues not related to needs of identified customers.

The size of the vacuum suitcase we should be considering:

- Big enough for a 12" wafer.
- For the initial NIST use, whatever size you need.
- Small as possible to optimize handling, pumpdown.
- Don't know.
- How big is the substrate?

Analytical and fabrication equipment with which vacuum suitcase should be compatible:

- Pump for interface section or transfer arm should be part of static system.
- MBE, SEM
- Check on SMIF; interface and fab equipment already specified by SEMI, maybe ASTM.
- Standard surface-analytical types: Auger, UPS, XPS, etc.
- LEED, in-situ reflectance

Target pressure for operation of vacuum suitcase:

- 10^{-8} Pascal
- Probably $10^{-6 \text{ to } -7}$ Pascal
- Case-by-case analysis of needs with design upgradeable to different levels as required.
- Avoid vacuum transport by artifacts affordable enough for one per piece of equipment.

Recommendations on any overlooked in vacuum suitcase area:

- Need either mass spectrometer or ion gauge on the vacuum suitcase.
- Case-by-case analysis of needs with design upgradeable to different levels as required
- Controlled ambient rather than UHV should be pursued equally.
- Avoid vacuum transport by artifacts affordable enough for one per piece of equipment.

Additional comments:

- May used vacuum standards for R&D but practical to use in a manufacturing process?
- Look at possibility of passivation and surface-thaw cleaning at user site.
- Steve Robey of NIST synchrotron has built/used vacuum suitcases
- Since transfer to industry requires knowledge of start/end point applications, need to clarify alternative applications (in-house easiest).
- Contact Hitachi on how they transport field emission gun (FEG) tips in vacuum.
- Broaden the scope of applications for this project (including different industries).

Telerobotic Operation of SPMs

Things concerning telerobotic operation of SPMs important for NIST to know:

- Concerned with real-time control with loop times (user<--->instrument) on the order of < 10ms, which is very different type of control than traditional use of systems.
- Several projects - UNC/ASN
- Nothing in this area.
- Patterns generators for SPM lithography.
- ATR addressing issues of controller/ PC-platforms running under Windows
- NT dealing with APIs/hardware architecture with real-time diagnostic capability.
- Could your telerobotic system be fitted to a MOCVD system?

Other research in the area of telerobotic operation of SPMs NIST should consider:

- Robotic control of instruments is important to automate tip exchange and sample exchange. But this is very different issue from remote software operation.
- Security levels protocol
- University/materials scientists/biomedical industry have most potential use.
- Simultaneous control of multiple tips
- Connect to MBE or MOCVD systems.

Need for telerobotic operation of SPMs for a) the SPM industry; b) this project:

- Needed
- Important in SPM industry for tool diagnostics
- Applicability very high though need as perceived by the industry probably low.
- a) Growing b) Good
- Where an otherwise experienced user does not have access to an advanced SPM (UHV perhaps) or and advanced interface.
- Lithography systems
- Not a high use or priority in semiconductor industry
- Don't see the need for telerobotic operation to generate standards per se.

Need for remote diagnostic capabilities on SPMs for the SPM industry; this project:

- Absolutely essential for efficient diagnostics with system automation increased and skilled experts far from sites.
- Needed
- Yes
- Important but more a political than technical problem.
- Only small need in IC industry now; could become important in next 10 years or so.

Need for documentary standards for controller interface:

- Very important
- Needed
- Good
- Open architecture systems preferable to customers who wish to make advanced changes.

Need for documentary standards for operation interfaces:

- Very important
- Great need for operator interfaces to the display systems and to export data from the controllers for data event logging.
- Needed
- Good

What NIST can do as a neutral party to encourage SPM manufacturers to allow greater user access to their hardware and software:

- Users cry for standards, especially for analysis algorithms and data file formats.
- Tough due to competitive nature of SPM suppliers.
- Would be good if the SPM metrology equipment were certified against NIST standards - so that we can get the SPM manufacturers to open their architecture.
- Help industries to set up measurements, eliminate the non-type signals etc.
- Software standardization and robotic control are different issues that need to be defined.
- Very interested in taking part in SPM control software standards for in-house and remote generation.

Industrial Collaborations

Most suitable and beneficial way for you to participate:

Informal information exchange
- Best way for now.

Intercomparison of research results
- Don't have results to share at this time.

Coordination of research activities
- We would be happy to share our understanding of relevant issues in open architecture controller and telerobotic operations and to obtain insights from NIST in these areas relevant to the particular application of SPM's.
- Don't have research going on at this time.

Memorandum of understanding on cooperative work
- Not at this time
- Not at this point

Cooperative Research and Development Agreement
- Topometrix is interested in this project.
- Not at this point but downstream we'd be interested in a multitip controller program for proximal probe lithography downstream.
- Not at this time

Changes recommended to make project more beneficial:
- None
- What happened to TI, INTEL, IBM, NATIONAL, etc.
- NIST should learn how companies, suppliers, industries, universities operate day to day as did Mike Postek of NIST did for a SEMATECH project very successfully.

Best strategy to get buy-in from your management for participation in this project:
- Stay focused on long term, precompetitive technologies.
- Data to support the use of these projects in IC industry.
- What you have done - get us middle-level managers involved.

Organizations not represented today possibly interested in NAMT program/project:
- All semiconductor manufacturing companies
- Biomedical industry
- NASA, NIH, Nuclear
- Arizona State University - Dr. Ramakrishna

GLOSSARY

AFM	atomic force microscope
API	application protocol interface
cd	critical dimensions
MBE	molecular beam epitaxy
MOCVD	metal organic chemical vapor deposition
NAMT	National Advanced Manufacturing Testbed
NIST	National Institute of Standards and Technology
R&D	research and development
PED	Precision Engineering Division
ROI	return on investment
SEM	scanning electron microscope
SIA	Semiconductor Industry Association
SIMOX	separation by implementation of oxygen
SMIF	standard mechanical interface
SPM	scanning probe microscope
UHV	ultra high vacuum