Nanometrology: Fundamental for Realizing Products at the Nanoscale

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Gaithersburg, MD 20899

Micro Nano Breakthrough Conference
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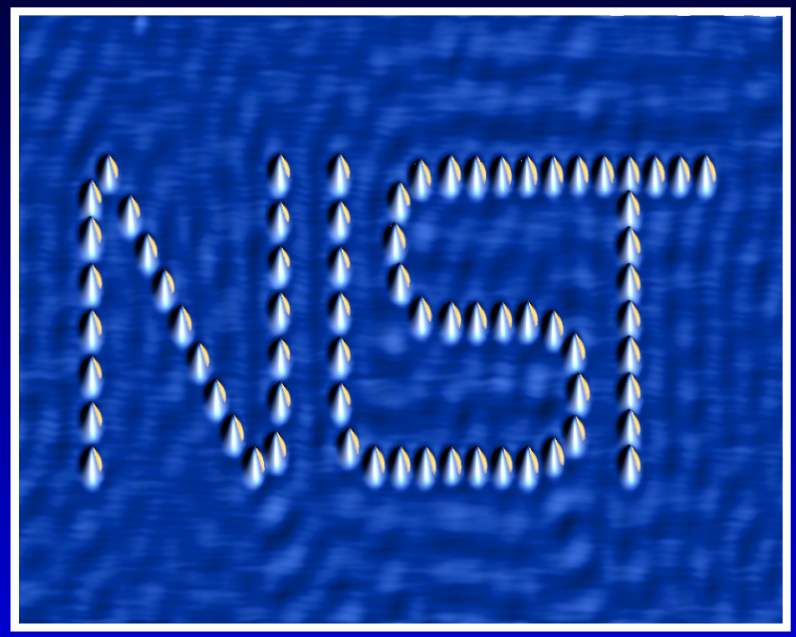
NIST
National Institute of Standards and Technology

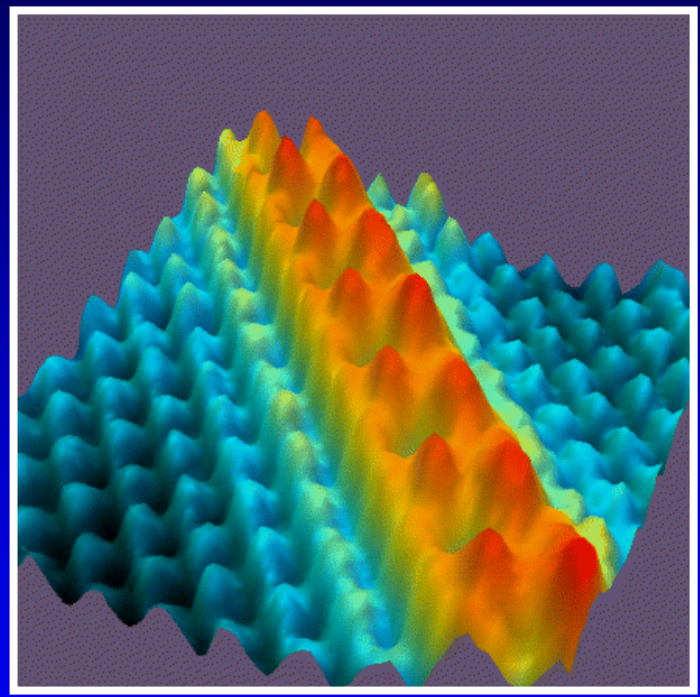
Nanotechnology



- Hype?
- Media buzz word?
- Technology?
- Or is it a:
  - Generic terminology for a large number of *potential* applications and products unified by the fact that they are composed of particles/structures <100 nm in size.
  - These particles may demonstrate special new properties because of their incredibly small size.

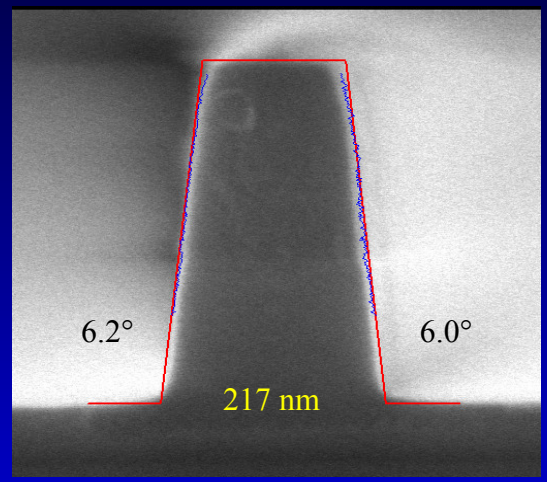
Nanotechnology to Nanoproducts

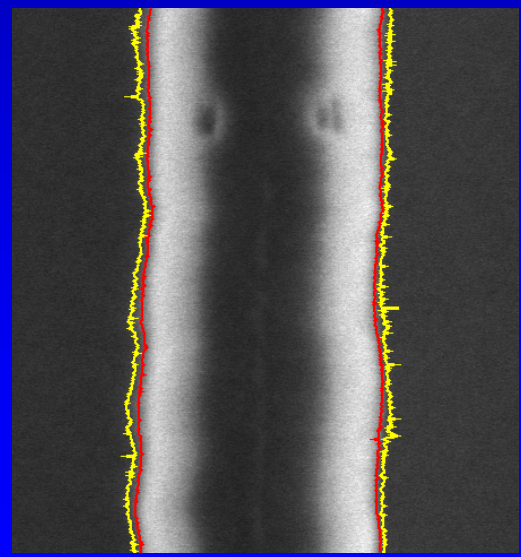
- Nanotechnology "resides" in a different world
- In this world, materials properties can dramatically change their characteristics
  - Where these changes occur is not fully known.
- Fulfilling the promise of nanotechnology *may* require the development of a new manufacturing infrastructure
  - similar to building the current semiconductor industry all over again.. for nanomanufacturing
  - or not …..*this is still not clear*



Nanomanufacturing

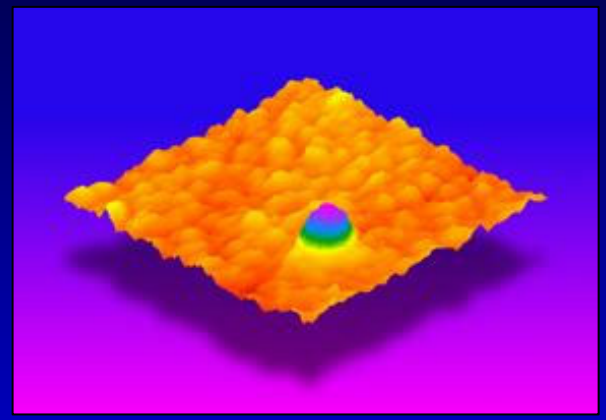
- "Top-down" nanomanufacturing exists today and has existed in several fields for some time
  - Semiconductor Industry
- Characterized by the implementation of various techniques to remove, add or redistribute atoms or molecules in a bulk material to create a final structure.
  - Lithography (patterning), deposition, etching
- But, as the semiconductor industry moves toward the 65-nm process node a paradigm shift is occurring:
  - Copper particles or interconnects in the region of 10's of nanometers may have completely different melting point and resistivity from the bulk copper.
  - At this scale grain size and surface roughness becomes dominant factors in the resistance of the line.
- The nanomanufacturing industry will be forced to cope with the new effects
  - Many which are yet unknown





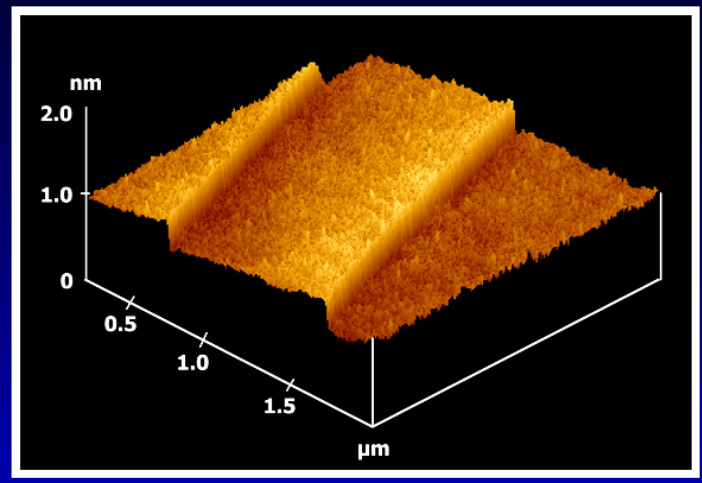
Nanomanufacturing

- "Bottom-up" nanomanufacturing is beginning to grow and show some promise
- Characterized by atomic and molecular scale directed assembly to create larger scale structures with engineered properties.
  - Chemical synthesis
    - Nanotubes and nanowires
  - Functional arrangement
    - Self assembly
  - Scanning or optical probe manipulation
    - AFM, STM with atomic resolution



- Ultimately, a combination of both "Bottom-up" and "Top-down" techniques may be required
- Successful and rapid development of this new infrastructure will help move nanotechnology out of the laboratory phase and into manufacturable products and devices.

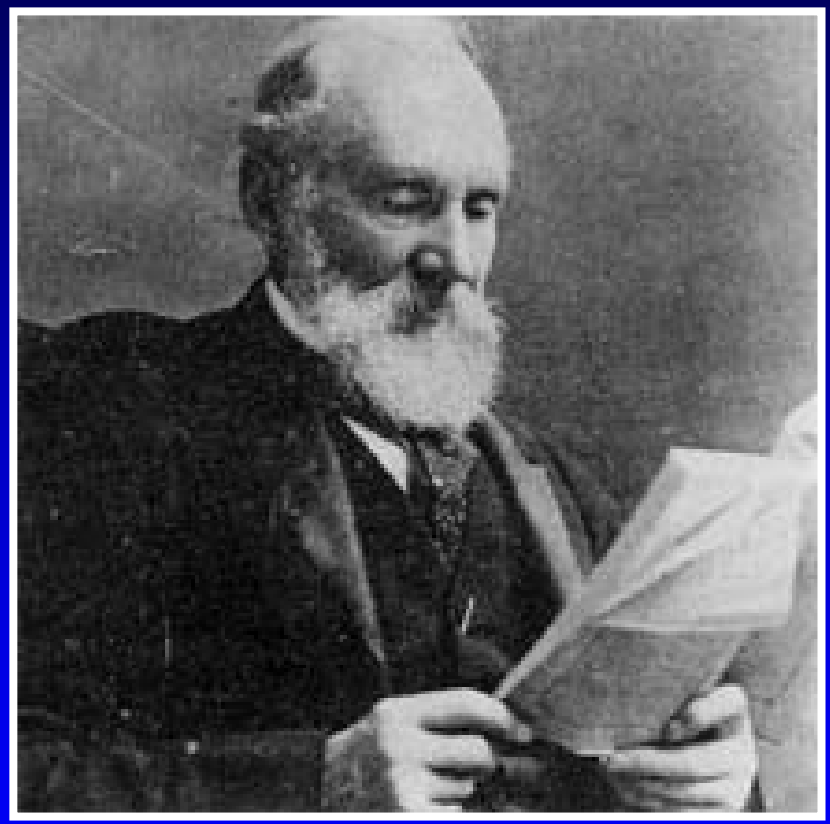
Nanotechnology



- For nanotechnology and nanoscience to realize its full promise, real products must be produced
  - some are beginning to appear.
- For this to occur in earnest, two significant infrastructural issues must be considered and addressed:
  - Process measurements (nanometrology)
  - Manufacturing/Nanomanufacturing
- NIST plays a critical and unique role in the evolution of nanotechnology into nanoscale products
  - NIST addresses both metrology and manufacturing-related issues
  - NIST is not concerned whether the metrology is related to top-down or bottom-up manufacturing it is the structure that has to be measured

Metrology

The science of measurement; a system of measures



"When you can measure what you are speaking about, you know something about it. But when you cannot measure it, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely advanced to the stage of science."

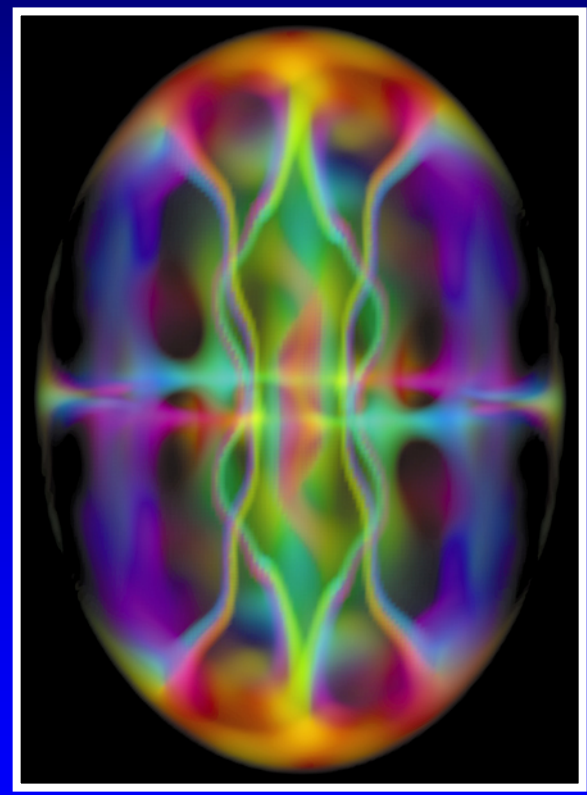
William Thomson, Lord Kelvin

NIST works closely with government, universities, and industry to develop the Nation's metrology infrastructure necessary for scientific, technical, and economic advances.

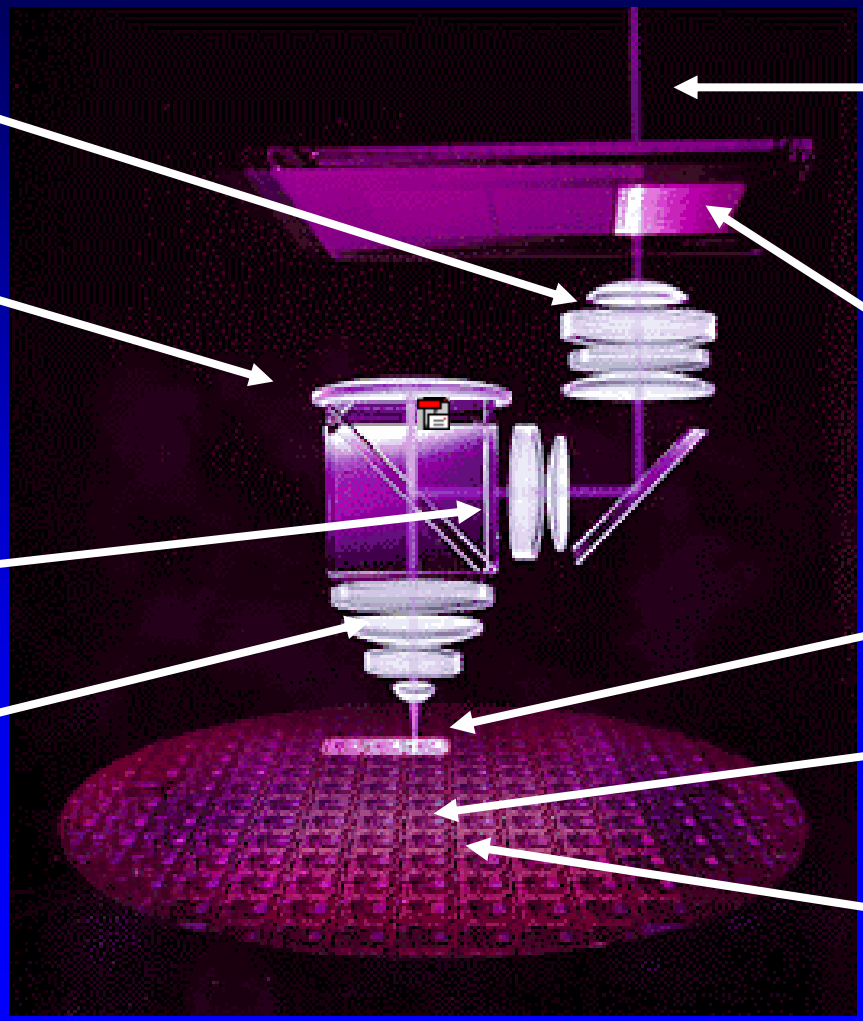
Metrology

The science of measurement; a system of measures

- Good metrology practice is more than just reading numbers from a data sheet.
- In order to measure a quantity accurately, it is necessary to fully study and understand the entire measurement process itself
- This may require multiple disciplines working closely together to achieve the final goal



NIST Measurements & Standards for Manufacturing -- an Integrated Approach



Light Scattering

Optical Properties

Index of Refraction of Gases

Index of Refraction of Materials

Laser Wavelength Standards

Mask Properties

Laser Power Measurements

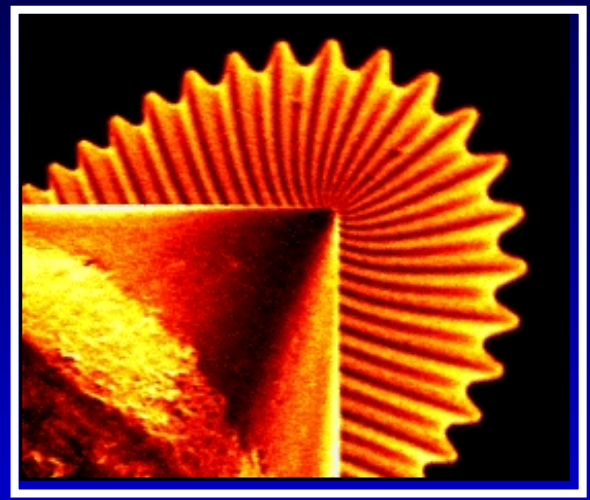
CD and Overlay

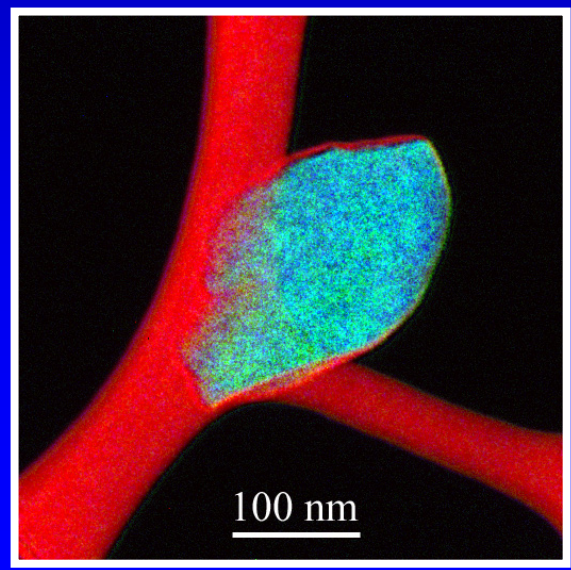
Instrument Testing and Improvements

NIST supports the entire lithography process to manufacture microelectronic devices

Measurements & Standards for Nanotechnology

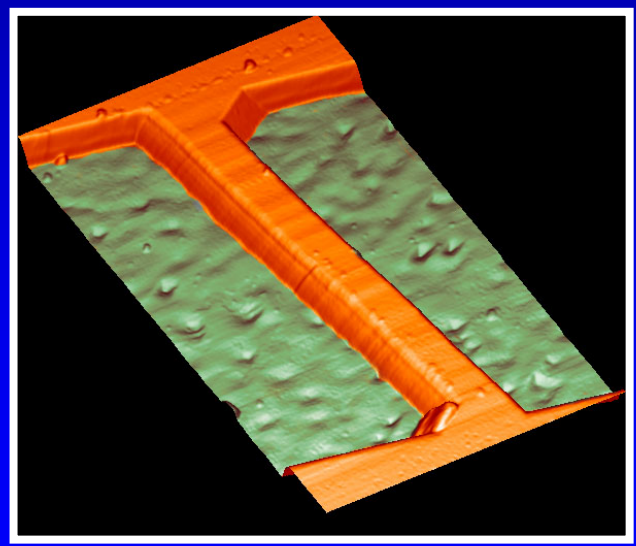
- Measurements are critical to developing complete understanding of any new phenomena
  - Only those things that can be measured can be fully understood.
  - By fully understanding the measurement process we understand the manufacturing process
- Nanometrology is needed to control fabrication, production, ensure product quality, and enable different parts to work together.
  - Sizes and tolerances
  - "If you can't measure it you can't make it"





Why new measurement science and technology?

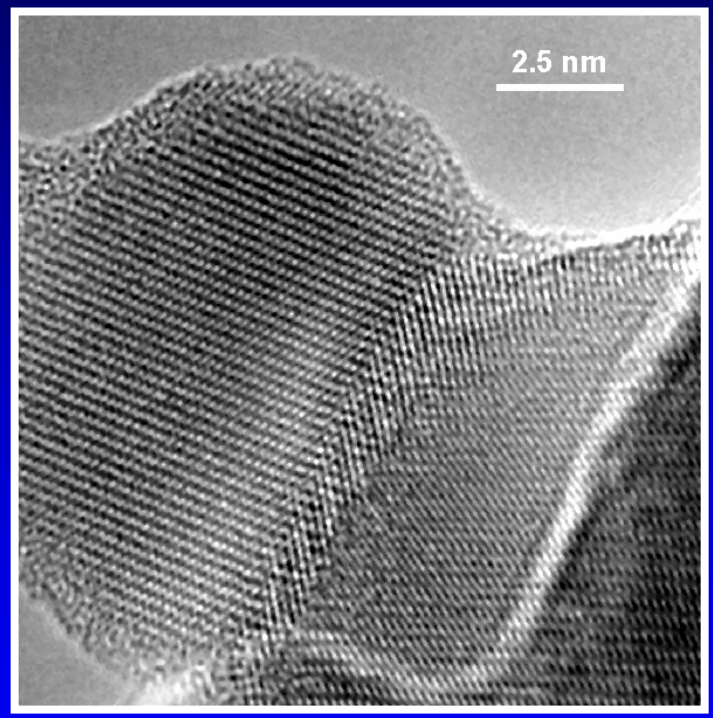
- Every physical property has some critical dimension associated with it…
  - the nature and behavior of the material or phenomena of interest depends on this critical dimension property
- These critical dimensions are in the nanometer range
- These dimensions must be measured
  - Critical property lengths
    - Transistor gate
    - Mean free path
    - Coherence length
    - Rayleigh and Mie scattering radii
    - Dislocation source length
    - Magnetic exchange length
    - Single domain size
    - Half-life diffusion length
    - …



It is NIST's Mission to develop the measurement science to address these dimensions, behaviors, and properties

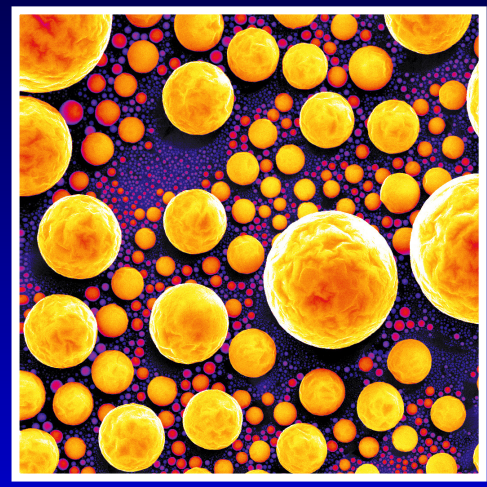
Nanometrology

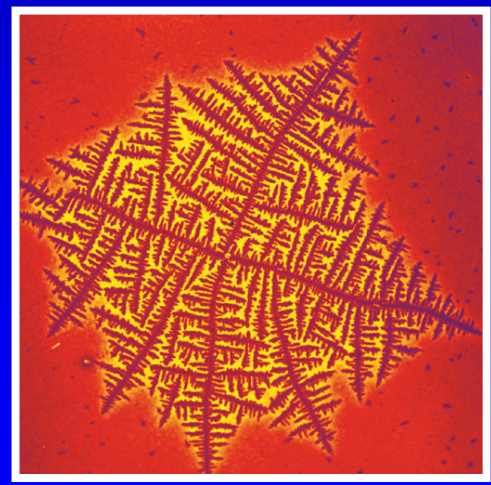
- Nanometrology involves the development of the techniques, tools and theory to measure those devices or the tolerances necessary for them to function properly at the atomic level
- Some of these techniques can be evolved from current top-down metrology
  - Semiconductor manufacturing
- Ultimately it may be necessary to measure the product or device atom-by-atom.
  - New methodologies must be developed



Measurements and Standards

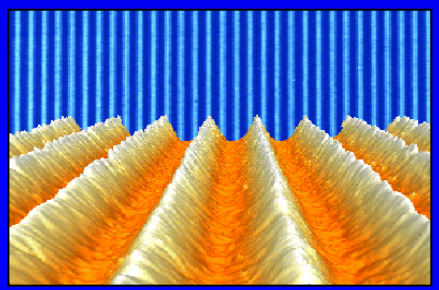
- The tiny size and complexity of nanoscale structures/objects makes the development of new nanometrology technologies more critical than ever.
- Development of new instrumentation
  - Qualification
  - Calibration
- Development of new measurement techniques
- Development of improved modeling
  - Understand the device
  - Compare theory and experiment
  - Build the nanodevice in computer first then…..fabricate
- Accurate measurements/standards





Infrastructure Development

- New measurements, standards, and data are needed to turn fundamental nanotechnology discoveries into new technologies, products and services:
  - Atomic scale measurements for length, mass, chemical composition, and other properties
  - Process measurements for manufacturing technologies to be used to assemble new devices at the atom or molecule level
  - Standard methods, data, and materials to transfer NIST measurement accuracy to industry and to assure the quality of the new nano-based commercial products

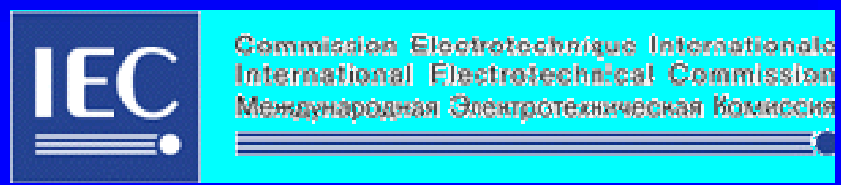


Traceability

- Along with infrastructural technology development, requirements for *traceability* for the potential of international trade arises
- Ensures that measurements are accurate representations of the specific quantity subject to that measurement.
- To prevent barriers to international trade, there must be “harmonization” of international standards

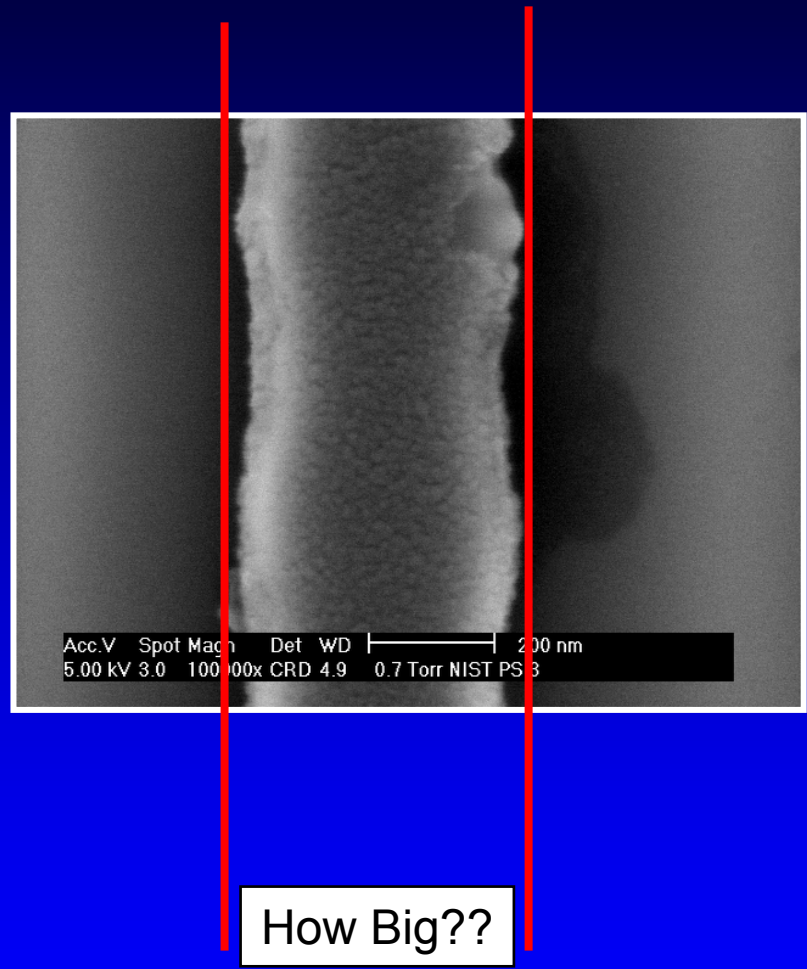
ORGANISATION INTERNATIONALE DE NORMALISATION

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION



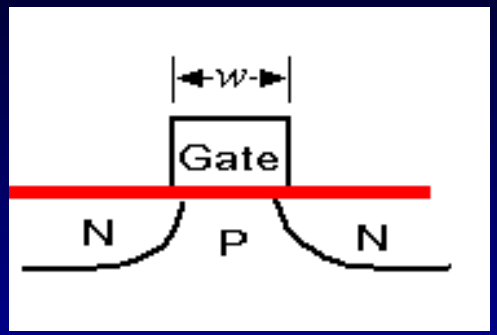
NIST's Technical Role

- Development of the measurement technology
  - What is measured
  - How it is measured
  - Determination of the limitations of the measurement process
- Development of new standards
- Development of uncertainty statement
  - Provides a means of comparison of metrology techniques
- Value of metrology
  - Economics of nanometrology



Metrology is Value Added

- It is often erroneously stated that "metrology is not value added to the product" but, today it is *becoming* a key enabler in a number of areas
- Metrology is a check and a balance in the nanomanufacturing process
- Metrology does provide an economic benefit
- It is often difficult to assess this economic benefit as it is often hidden and often forgotten



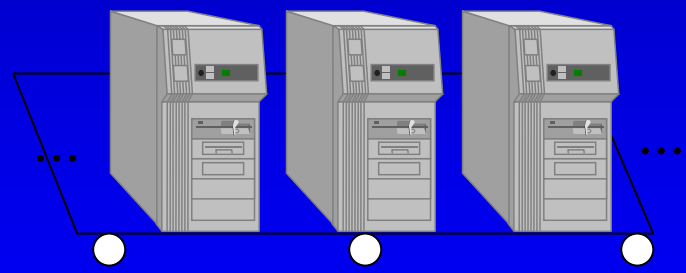
What's a Nanometer worth?

- Faster microprocessors fetch higher prices
- Narrower gate =>less capacitance => more speed
- For 180 nm gates, a 10 nm improvement in CD control was estimated to lead to an increase of $100 market value per microprocessor

"Under these assumptions, the value of CD control for the 180 nm generation of microprocessors exceeds $10 per nanometer."

C.P. Ausschnitt and M. E. Lagus, IBM Advanced Semiconductor Technology Center, Proc. SPIE Vol. 3332, p. 212 (1998).

1999 Worldwide PC sales exceed
113 million units
(Source: International Data Corp.)



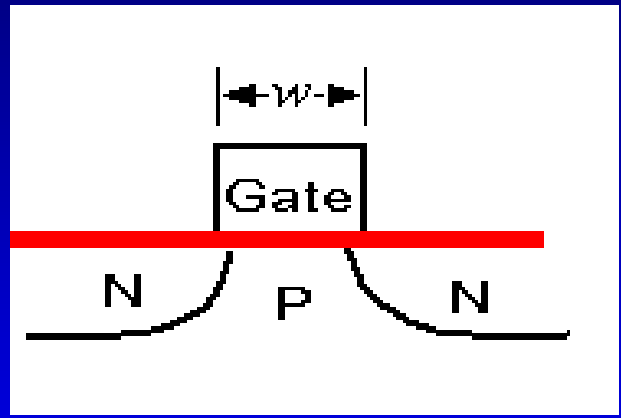
$>10^8$ units × $10/unit ≥ $1 billion/nm

It's a big industry, and small improvements yield big economic benefits.

Credit: John Villarrubia, NIST

What's a Nanometer worth?

**Even if the figure is only 10%
of that estimate - it is still a lot of money**



Through the nanometrology programs at NIST we work to assist industry to improve profitability through the development of new and innovative measurement capabilities for a vast array of applications

Unique NIST Facilities

Advanced Chemical Sciences Laboratory

Provides critical capabilities for nanobiotechnology and analytical chemistry research

NIST Center for Neutron Research

Most versatile neutron facility in the U.S. with over 1750 annual users

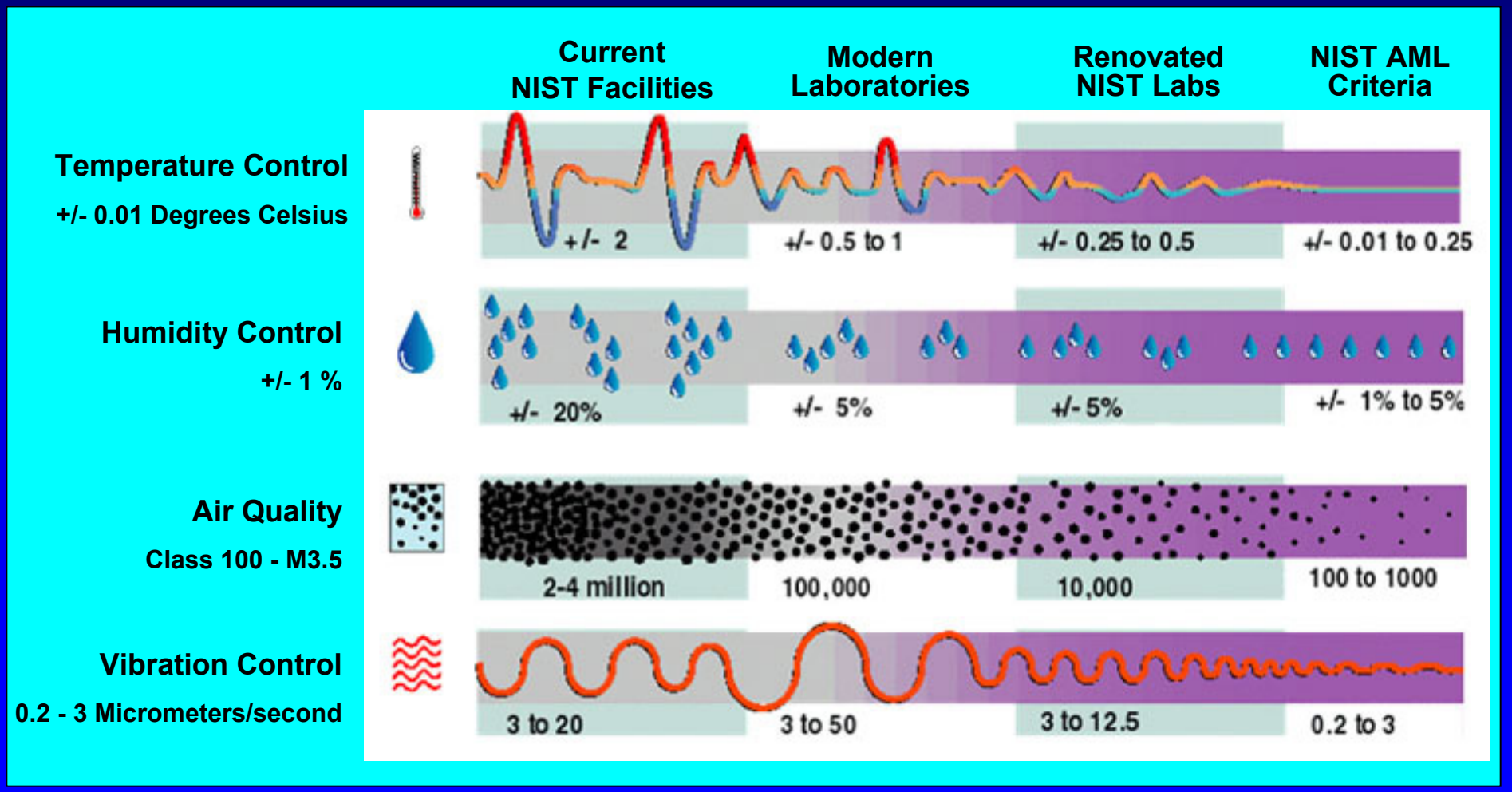
Unique NIST Facilities

Advanced Measurement Laboratory and
National Nanofabrication User Facility

World's premier nanometrology research facility
(air quality, temperature, vibration, humidity)

Critical Criteria - NIST AML

- Developed for advanced nanometrology
- Creates the most environmentally stable laboratory in the world.



State-of-the-Art & Next-Generation Measurement Capabilities to be Housed in the AML

Over 100 experiments are being moved into the AML

- Improved Standards Capabilities for next generation nanometrology requirements
  - Length standards ranging from nano to meso-scale
  - Mass, vibration, and pressure standards
  - Fundamental electrical standards
  - Optical and x-ray measurements and standards
- Chemical and physical characterization of three dimensional nano-scale structures and interfaces
- Imaging, characterization, and manipulation of matter at nano-scale, single atom, and molecular regimes
- Quantum information processing, advanced electron beam metrology instrument, optical tweezers, and Bose Einstein condensation

National Nanofabrication User Facility

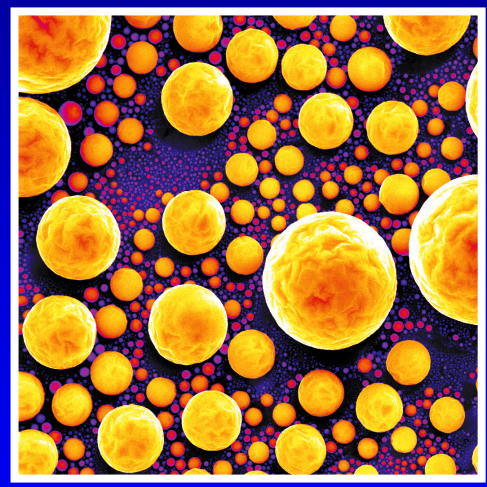
- The AML National Nanofabrication User Facility has approximately 18,000 sq. ft of Class 100 cleanroom space.
- Part of the NNUF will be a NIST-owned, shared access user facility.
- Part of the NNUF may be open for researchers to place research tools.
- The NNUF will have basic semiconductor processing to provide NIST and its partners with capability in fabricating prototypes of new test structures, electronic devices, measurement instruments, standard reference materials, MEMS, microfluidics, and bio-devices to and for the nanoscale.

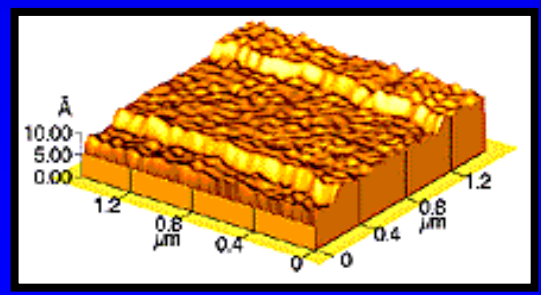
Manufacturing Engineering Laboratory Nanomanufacturing Program

Developing the Nanometrology Infrastructure for Nanomanufacturing

Goal:

- ***Develop and deliver timely measurements, standards, and infrastructural technologies that address identified critical U.S. industry and other government agency needs for innovation and traceable metrology, process-control and quality in manufacturing at the nanoscale.***





MEL Nanomanufacturing Program

Developing the Nanometrology Infrastructure for Nanomanufacturing

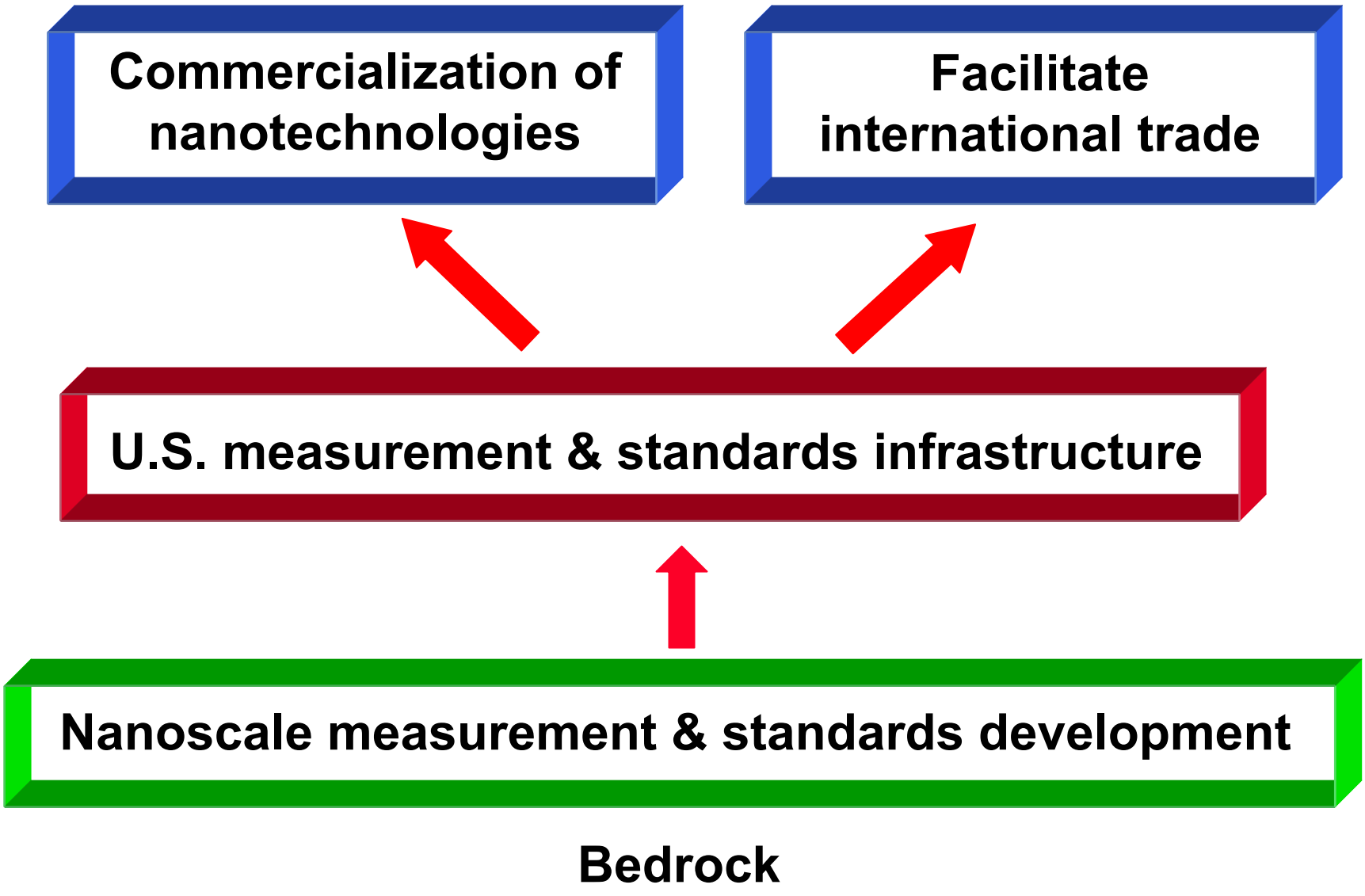
- **Fundamental themes:**
  - **Imaging and Metrology**
    - **SEM, AFM, Optics, Force, Atom-based**
  - **Nano-Fabrication**
    - **E-beam, SPM, Atom, Imprint, Nanomachining**
  - **Control and Assembly**
    - **High precision stages, optical tweezers**
  - **Information Technology**
    - **Integrated software engineering environment**

MEL Nanomanufacturing Program

Projects:

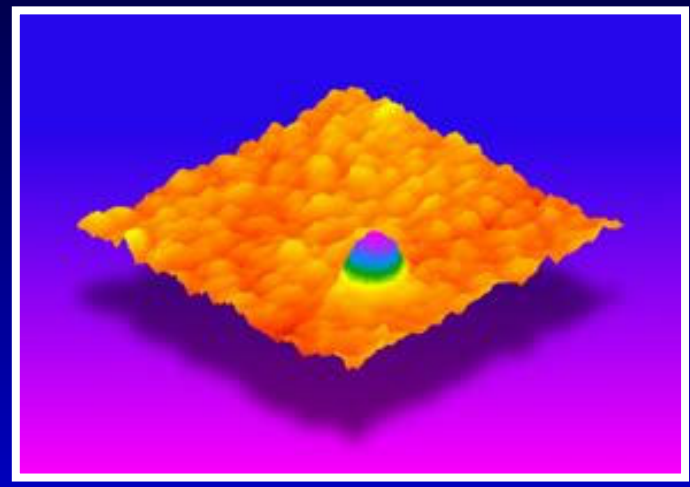
- Scanning Electron Microscope for Nanoscale Measurements
- Optical Metrology for Nanoscale Measurements
- Atom Based Metrology for Nanoscale Measurements and Standards
- Scanning Probe Microscopy for Nanoscale Measurements
- Force Metrology for Nanoscale Measurements and Standards
- Advanced Control Systems and Positioning for Nanoscale Measurements and Standards
- Optical Tweezers for Nanoscale Manipulation and Metrology
- Advanced Lithography for Nanoscale Measurements and Standards
- Development of Nanomachining Technologies for Nanomanufacturing
- Advanced Information Technologies for Nanomanufacturing

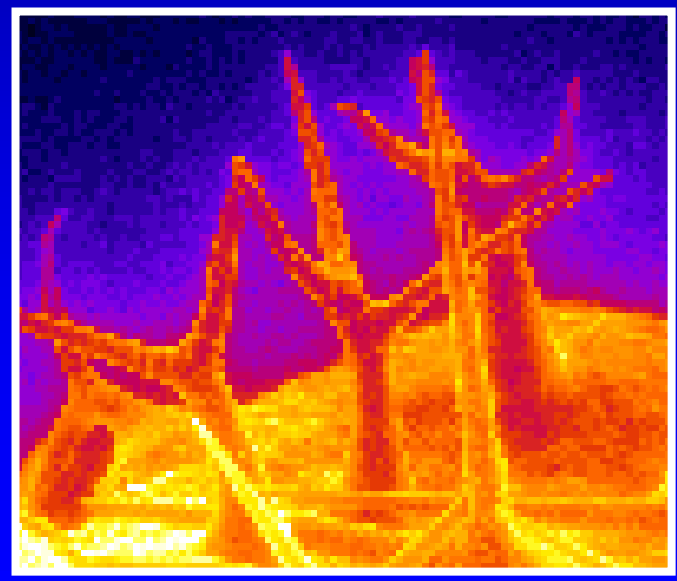
NIST's Role in Nanotechnology



Conclusion

- As the other agencies are developing specific nanoscale products and domain-specific technologies, NIST is available and interested in working with them to address the infrastructural metrology and manufacturing issues that are germane to their specific applications.





Thank You

Image:
Cobalt atoms on a copper surface
Courtesy of: Joe Stroscio

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