Measurement Uniformity:

Why Standardization is Critical for Nanotechnology

Stephanie A. Hooker
Materials Science & Engineering Laboratory, NIST

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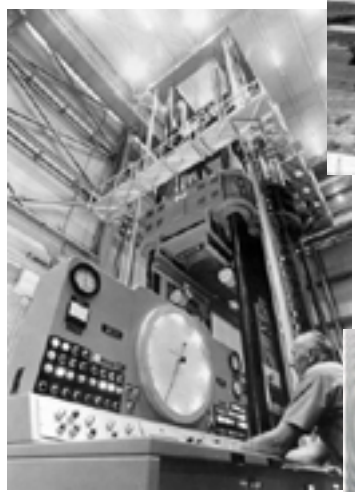
NIST Overview

- Premier U.S. Government agency for metrology
  - Standards
  - Practices
  - Measurement techniques
- Guided by national/economic priorities
  - Healthcare
  - Nanotechnology
  - Information/knowledge management
  - Homeland security
- Closely tied with industry & academia
- > 100 year history in standardization

NIST – A Historical Perspective

- Founded March 3, 1901
  - National Bureau of Standards
  - 1st Federal physical science research laboratory
  - 12 staff members
  - Focus on standardization
    - 1904 Baltimore fire
- Materials & chemistry research
  - Failure analysis
  - Purity characterization
  - Corrosion science
  - Property characterization
    - Silicon transistor



Staff Expertise

- Two well-equipped campuses
  - Gaithersburg, MD
  - Boulder, CO
- Highly experienced, multi-disciplinary staff
  - ~ 3000 staff specializing in:
    - Electrical engineering
    - Physics
    - Chemistry/chemical engineering
    - Materials science and engineering
    - Information technology
    - Manufacturing
    - Building & fire research
- Specialized test facilities
  - NIST Center for Neutron Research

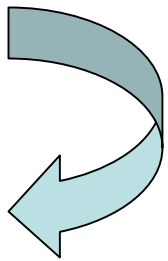
Agency Role in Nanotech

- Characterize new nanomaterials & devices
  - Dimensions, structure, performance, etc.
  - Blend of existing & new techniques, tools, and theories
    - In-situ, multiple layers, buried interfaces, …
    - 3-d, multiple properties, quantitative, distribution/mapping …
    - Bio-applicable, cellular, sub-cellular …
  - Create new standards for quality control

- Use nanotech to dramatically improve metrology
  - New measurement devices
    - Single photon sources/counters
    - Nanotube probes; bio MEMS/NEMS; etc.
  - New measurement standards
    - Voltage, capacitance, temperature
    - Optical power, energy

Why Carbon Nanotubes?

- Strong
- Lightweight
- Very high conductivity
  - Thermal
  - Electrical



- Lots of applications
  - Additives, reinforcements, & stand-alone devices
  - Energy, electronics, biotech, sensors, actuators, filtration, etc.
    - Low(er) tech (in-line painting of automobiles)
    - Very high tech (space structures)

Nanometrology Challenges

- Manipulation & handling
  - Isolation of a single nanostructure, or a small nano-cluster
  - Integration into a test platform
- Measurement resolution
  - “Average” vs. individual
- Linking structure with properties
  - Multiple, and possibly simultaneous, measurements

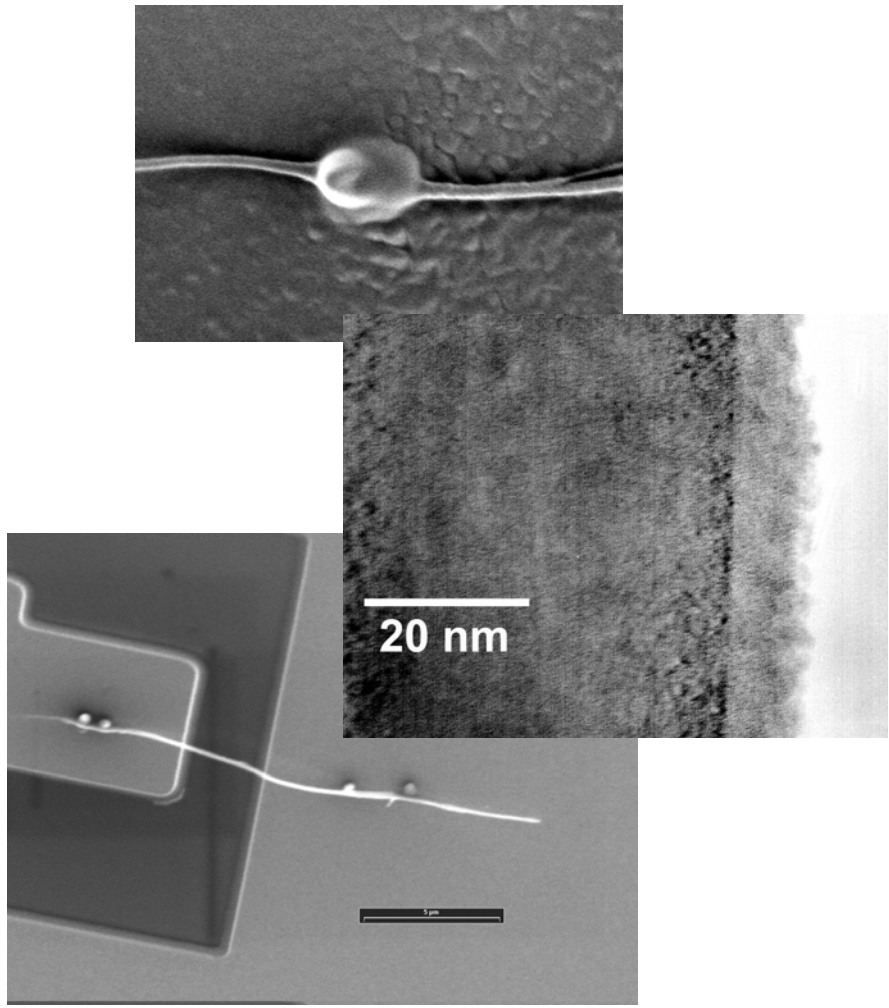
These are Even Trickier for Nanotubes …

- Lots of nanotube species exist
  - Different processes
  - Different types & configurations
- Complicated by defects, impurities, surface contaminants, and subsequent processing

- How do you know what you've got?
- Is what you have repeatable?
- Can you make it better? Or does it get worse?

Measuring Properties: Not Trivial Either

- Interfacing conventional and “near-perfect” materials
  - Contacts and interfaces are the “weak links”
  - Sources of measurement error
- Linking structure & properties on the isolated tube basis critical

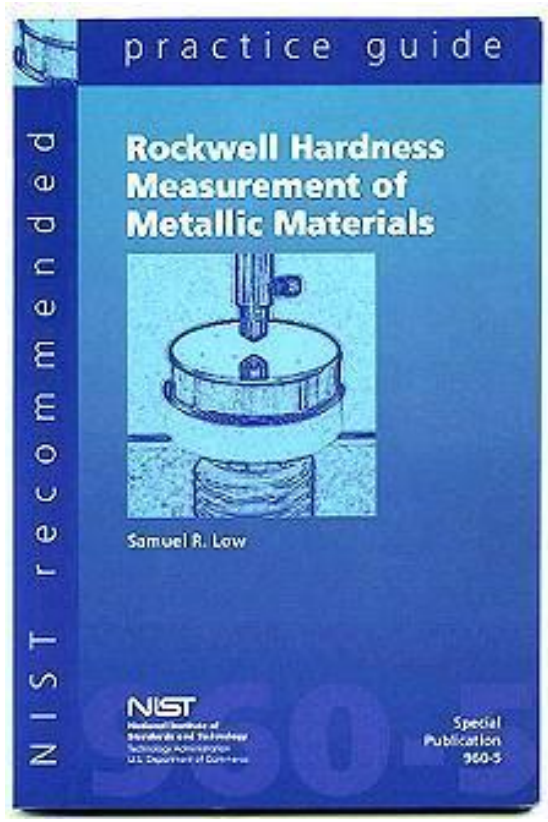


Standards Can Take Many Forms

- Documentary
  - Formal (ASTM, ISO, IEEE, ANSI)
  - Performance Specifications (Mil specs)
  - Agreed-upon Test Methods (Protocols)
- Reference Materials
- Evaluated Data and Data Delivery Mechanisms
- Recommended Practice Guides

NIST's "How to Measure" Book Series

- Recommended Practice Guides
- Targeted toward specific industrial challenges
- Practical, **user-friendly** guides
  - How to measure properly
  - What to measure
  - Which technique to use
  - How to interpret the results
- Designed to build consensus up and down the supply chain



Currently Available Guides

- Some of the more practical
  - ***Stopwatch and Timer Calibrations***
  - ***Surges Happen! How to Protect the Appliances in Your Home.***

- Some specific to materials science
  - ***Particle Size Characterization***
  - ***Fundamentals of Neutron Powder Diffraction***
  - ***Nomenclature in Dispersion Science and Technology***
  - ***Installing, Maintaining, and Verifying Your Charpy Impact Machine***
  - ***Capacitance Cell Measurement of Out-of-Plane Expansion of Thin Films***

Practice Guide Advantages

- Less formal than standards
- Based on state-of-the-art
- Easy to follow
- Broadly applicable
- Written in common lingo
- Includes the “tricks of the trade”
- Collaborative ---- even when we don’t agree
- Available soon!
- Available easily (web & hard copy)

Beyond State-of-the-Art

- As protocols are developed, we will likely see that all the questions have not been answered. We may need to:
  - Develop and qualify standard reference materials
  - Develop and qualify completely different techniques
  - Better learn how to separate tubes by species
  - Conduct round robin studies to bring out critical differences in existing protocols ---- “standardization”

- Teamwork is essential to achieve the above objectives!

Workshop Format

- Hand-selected group from industry, academia, and Government
- Invited lectures –
  - Protocols for qualifying nanotubes
  - New & existing measurement techniques
  - Ramifications of poor purity and/or dispersion
  - How you begin to work on the individual tube level
- Your role during the next 2 ½ days:
  - Think of the hard questions
  - Find the common ground
  - Consider & debate the remaining issues
  - Give us your honest thoughts