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Standard Guide for Nanotechnology Workforce Education in Materials Synthesis and Processing[1]

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1. Scope

1.1 This guide provides a framework for a basic workforce education in materials synthesis and processing at the nanoscale, to be taught at an undergraduate college level. This education should be broad to prepare an individual to serve within one of the many areas in nanotechnology research, development, or manufacturing.

1.2 This guide may be used to develop or evaluate an education program for synthesis and processing applications in the nanotechnology field. This guide provides listings of key topics that should be covered in a nanotechnology education program on this subject, but it does not provide specific course material to be used in such a program. This approach is taken in order to allow workforce education entities to ensure their programs cover the required material while also enabling these institutions to tailor their programs to meet the needs of their local employers.

1.3 While no units of measurements are used in this practice, values stated in SI units are to be regarded as standard.

1.4 *This standard does not purport to address all of the techniques, materials, and concepts needed for materials synthesis and processing at the nanoscale. It is the responsibility of the user of this standard to utilize other knowledge and skill objectives as applicable to local conditions or required by local regulations.*

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E2456 Terminology Relating to Nanotechnology

E2996 Guide for Workforce Education in Nanotechnology Health and Safety

E3089 Guide for Nanotechnology Workforce Education in Material Properties and Effects of Size

2.2 *ISO Standards:*[3]

ISO/TS 80004-2 Nanotechnologies – Vocabulary – Part 2: Nano-Objects

ISO/TS 80004-8 Nanotechnologies – Vocabulary – Part 8: Nanomanufacturing Processes

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms related to nanotechnology in general, refer to Terminology E2456 and ISO/TS 80004-2.

3.1.2 For definitions of terms related to nanotechnology synthesis and processing in general, refer to ISO/TS 80004-8.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *additive processing, n*—adding a layer of new material, in order to leave a pattern of deposited material on the substrate. **ISO/TS 80004-8**

3.2.2 *materials processing, n*—the technique(s) used to transform industrial materials from an initial or intermediate state into modified or finished parts or products.

3.2.3 *materials synthesis, n*—process(s) or reaction(s) for building up a complex material or structure by the union of simpler compounds or elements.

3.2.4 *nanoparticle, n*—a nano-object with all external dimensions in the nanoscale where the lengths of the longest and

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

the shortest axes of the nano-object do not differ significantly.
ISO/TS 80004-2

3.2.5 *subtractive processing, n*—removal of material except where the surface is protected by the patterned resist.
ISO/TS 80004-8

4. Summary of Guide

4.1 This guide designates a list of nanoscale synthesis and processing subject areas relevant to nanotechnology workforce education. Selection of the areas is based on inputs from industry, nanotechnology educators and subject matter experts.

4.2 Within each subject area, important topics to be covered are listed specifically.

4.3 This approach provides both a broad education as well as in-depth emphasis for key subjects within the time constraints of an instructional course or program.

5. Significance and Use

5.1 The purpose of this guide is to provide, at the undergraduate college level, a basic educational structure in the synthesis and processing of nanoscale materials to organizations developing or carrying out education programs for the nanotechnology workforce. This guide helps to describe the minimum knowledge base for anyone involved in nanomanufacturing or nanomaterials research.

5.2 The basic education should prepare an individual for varied roles in the nanotechnology workplace. The material in this guide may require a post-secondary two-year science or technology background to be understood sufficiently.

5.3 Workers may transition in their roles in the workplace. Participants in such education will have a broad understanding of a complement of topics related to the infrastructure required for advanced research and manufacturing, thus increasing their marketability for jobs within as well as beyond the nanotechnology field.

5.4 Because nanotechnology is a rapidly developing field, the individual educated in nanotechnology needs to be cognizant of changing and evolving safety procedures and practices. Individuals should be aware of how to maintain an up-to-date understanding of the technology and have sufficient base education to enable the synthesis of emerging or evolving safety procedures and practices.

5.5 This guide is intended to be one in a series of standards developed for workforce education in various aspects of nanotechnology. It will assist in providing an organization a basic structure for developing a program applicable to many areas in nanotechnology, thus providing dynamic and evolving workforce education.

6. General Background Knowledge and Skills

6.1 Introductory algebra, chemistry, physics, and statistics at the college level.

6.2 The environmental, health, and safety (EHS) hazards presented by nanoscale materials can be very different from those presented by bulk materials. Students should have a basic understanding of the unique EHS factors when handling nanoscale materials (see Note 1).

NOTE 1—See Guide E2996 and the National Nanotechnology Initiative's webpage on recent EHS research[4] for more information.

6.3 Students should also have a basic knowledge of the physical and chemical properties of nanoscale materials (see Note 2).

NOTE 2—See Guide E3089 for details.

7. Concepts and Skills to be Covered

7.1 The methods relevant for workforce education in nanotechnology regarding synthesis and processing are given in Section 8, with important topics to be covered for each method listed specifically. Teaching of these topics should include comparing and contrasting different techniques. Additional methods or topics, or both, may be added on an as-needed basis.

7.2 Nanoscale synthesis and processing methods covered should include ones based on commonly used additive and subtractive material processing. Method selection is based on inputs from industry, nanotechnology educators and subject matter experts.

8. Synthesis and Processing Concepts and Techniques relevant to Nanotechnology Workforce Education

8.1 *Material Considerations*—Structure and basic processes that affect properties:
8.1.1 Crystal structure.
8.1.2 Defects.
8.1.3 Bonding.
8.1.4 Stress.
8.1.5 Diffusion.
8.1.6 Annealing.
8.1.7 Adhesion and delamination.
8.1.8 Aggregation, agglomeration, and suspension (see Note 3).

NOTE 3—These processes are applicable to nanoparticles.

8.2 *Concepts of Additive Processing:*
8.2.1 *Growth and Deposition Considerations:*
8.2.1.1 Nucleation.
8.2.1.2 Thickness control.
8.2.1.3 Uniformity.
8.2.1.4 Step coverage.
8.2.1.5 Homogeneous growth.
8.2.1.6 Heterogeneous growth.
8.2.1.7 Surface modification:
(1) Morphology modification.
(2) Chemical modification (see Note 4).

NOTE 4—For example, a method such as molecular self-assembly would fall under this category.

(3) Biological functionalization.

8.3 *Growth and Deposition Techniques:*

[4] Available from U.S. National Nanotechnology Coordination Office (NNCO), 2415 Eisenhower Ave., Alexandria, VA 22314, https://www.nano.gov/Highlights-Federal-NanoEHS-Report.

8.3.1 *Oxidation:*

8.3.1.1 Dry oxidation.

8.3.1.2 Wet oxidation.

8.3.1.3 High-pressure oxidation.

8.3.2 *Physical Vapor Deposition (PVD):*

8.3.2.1 Thermal and electron beam evaporation.

8.3.2.2 Sputter deposition.

8.3.3 *Chemical Vapor Deposition (CVD):*

8.3.3.1 Atmospheric Pressure Chemical Vapor Deposition (APCVD).

8.3.3.2 Low Pressure Chemical Vapor Deposition (LP-CVD):

(1) Vapor-Solid (VS) growth technique.

(2) Vapor-Liquid-Solid (VLS) growth technique.

8.3.3.3 Plasma Enhanced Chemical Vapor Deposition (PECVD).

8.3.4 *Atomic Layer Deposition (ALD):*

8.3.4.1 Thermal Atomic Layer Deposition.

8.3.4.2 Plasma Enhanced Atomic Layer Deposition (PEALD).

8.3.5 *Epitaxial Growth:*

8.3.5.1 Metal Organic Chemical Vapor Deposition (MOCVD).

8.3.5.2 Molecular Beam Epitaxy (MBE).

8.3.6 *Solution Based Deposition:*

8.3.6.1 Electrochemical deposition (plating).

8.3.6.2 Anodization.

8.3.6.3 Spin coating (see Note 5).

NOTE 5—For example, the deposition of a spin-on glass layer to form a planarizing dielectric or provide a dopant source in the fabrication of integrated circuits would fall under this category.

8.4 *Techniques for Fabricating Discrete Nanoparticles:*

8.4.1 *Nanoparticle Synthesis and Stabilization:*

8.4.1.1 Flame pyrolysis.

8.4.1.2 Laser ablation.

8.4.1.3 Wet chemistry:

(1) Bulk colloidal methods.

(2) Microfluidic synthesis using microreactors.

8.4.1.4 Mechanical attrition.

8.5 *Concepts of Subtractive Processing:*

8.5.1 *Etching Considerations:*

8.5.1.1 Selectivity.

8.5.1.2 Profile control:

(1) Aspect ratio.

(2) Anisotropic etching.

(3) Isotropic etching.

8.5.1.3 Etch rate.

8.5.1.4 Etch damage.

8.5.2 *Wet Etching:*

8.5.2.1 Chemistries.

8.5.2.2 Crystal plane orientation dependent etching.

8.5.2.3 Dopant control of etching.

8.5.3 *Chemical mechanical planarization* (see Note 6).

NOTE 6—The process is also known as chemical mechanical polishing.

8.5.4 *Dry Etching:*

8.5.4.1 Plasma generation:

(1) Optical emission and end point detection.

8.5.4.2 Plasma etching (no ion bombardment).

8.5.4.3 Reactive Ion Etching (RIE).

8.5.4.4 Sputter etching (ion milling).

8.5.4.5 Focused Ion Beam (FIB).

8.5.4.6 Dry etch systems:

(1) Inductively coupled plasma.

(2) Capacitively coupled plasma.

(3) Ashing systems.

(4) Sputter etch.

8.5.5 *Vapor etching* (see Note 7).

NOTE 7—For example, etching with vapors of hydrofluoric acid or xenon diflouride would fall under this category.

9. Keywords

9.1 nanotechnology; materials synthesis; materials processing; workforce education