Designation: E3089 − 22

Standard Guide for Nanotechnology Workforce Education in Material Properties and Effects of Size[1]

This standard is issued under the fixed designation E3089; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides a framework for a basic workforce education in material properties 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 unique material properties and their 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 guide, 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 material properties and applications. 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

2.2 *Other Standards:*[3]

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

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.

4. Summary of Guide

4.1 This guide designates a list of subject areas related to material properties and the effects of size that are 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 This guide establishes, at the undergraduate college level, the basic education structure for understanding the unique properties and applications of nanoscale materials as compared to bulk properties and applications of macroscale materials. It helps to describe the minimum knowledge base for anyone involved in nanomanufacturing or nanomaterials research and can be used by organizations developing or carrying out education programs for the nanotechnology workforce.

[1] This guide is under the jurisdiction of ASTM Committee E56 on Nanotechnology and is the direct responsibility of Subcommittee E56.07 on Education and Workforce Development.

Current edition approved Feb. 1, 2022. Published April 2022. Originally approved in 2017. Last previous edition approved in 2017 as E3089 – 17. DOI: 10.1520/E3089-22.

[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.

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 material properties and the effects of size, 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.

7. Concepts and Skills to be Covered

7.1 The subject areas and topics relevant for workforce education in nanotechnology regarding material properties are given in Section 8, and select examples of how a reduction of material or structure size to the nanoscale affect material properties are shown in Section 9. These should be covered in a manner wherein bulk and nanoscale properties are compared and contrasted.

7.2 Select examples of how nanoscale materials are utilized in a variety of applications are given in Section 10.

7.3 Additional subject areas, topics, and examples may be added on an as-needed basis.

8. Fundamental Material Properties

8.1 This section consists of topics that pertain to the basic properties of materials. These are considered to be essential for introduction in an undergraduate-level class to facilitate the subsequent understanding of how and why certain properties are affected when material or structure dimensions change from the macroscale to the nanoscale.

8.2 *Material Characteristics:*
8.2.1 *Structure:*
8.2.1.1 Crystalline material.

NOTE 2—Include discussion of Miller indices.

8.2.1.2 Non-crystalline material.
8.2.1.3 Allotropes and polymorphism.
8.2.2 Bonding.
8.2.3 Defects.
8.2.4 Phase diagrams.

8.3 *Physical Properties:*
8.3.1 Surface energy.
8.3.2 Melting temperature.
8.3.3 Diffusion.

8.4 *Mechanical Properties:*
8.4.1 Stress and strain.
8.4.2 Tensile and compressive strength.
8.4.3 Elastic and plastic responses.
8.4.4 Moduli.

NOTE 3—Include introduction to Young's, shear, and bulk modulus.

8.4.5 Hardness.

8.5 *Optical Properties:*
8.5.1 Reflection.
8.5.2 Refraction.
8.5.3 Absorption.
8.5.4 Transmittance.
8.5.5 Emission.

8.6 *Electrical Properties:*
8.6.1 Fermi level.

NOTE 4—This is to provide an overview for insight into electronic devices, corrosion, and batteries.

8.6.2 Conductivity.
8.6.3 Electronic transport.
8.6.4 Dielectric constant.

8.7 *Magnetic Properties:*
8.7.1 Ferromagnetism.
8.7.2 Diamagnetism.

9. Effects of Scale on Properties

9.1 While the subject of nanotechnology is generally associated with materials or structures having at least one dimension with a size approximately within the 1 to 100 nanometres (nm) range, it should be noted that the small size alone does not necessarily distinguish the technology. The uniqueness of nanotechnology arises when the nanoscale material or structure provides properties or phenomena different from those observed at the bulk or macroscale in the same material or structure, and these properties or phenomena can be utilized to achieve new or improved performances in a variety of applications.

9.2 Some of the different properties of nanoscale materials can be attributed to their significantly larger surface areas compared to those of a macroscale material with a similar mass

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

or volume. This ratio results in a large number of atoms being exposed to interact with the environment and surface effects become much more important. In other cases, unique and size-dependent properties appear because quantum mechanical effects can dominate at the nanoscale. The rest of Section 9 lists select examples to illustrate where properties change due to a size reduction. The list is not comprehensive, but does provide an overview on the effects of scale.

9.3 Lowering of melting temperature.

NOTE 5—This illustrates how surface effects become increasingly important as material dimensions are reduced.

9.4 Chemical reactivity changes due to scale.

NOTE 6—The catalytic efficiency of nanoparticles has been shown to vary by changing the particle size.

NOTE 7—Appropriate stabilization of the nanoparticles is necessary to provide effective catalysis. Common approaches include electrostatic stabilization and polymeric stabilization.

9.5 Ballistic conduction.

NOTE 8—This shows how electron transport deviates from the classical regime as material dimensions are reduced to below that of the electron mean free path.

9.6 Tunable wavelengths in light absorption and emission.

NOTE 9—Metals with different nanoscale diameters and semiconductor films with nanoscale thicknesses sandwiched between larger bandgap layers can be used to illustrate the size effect on optical properties.

10. Applications Enabled by the Use of Nanoscale Materials

10.1 This section contains select examples where nanoscale materials and structures are used in various fields to provide new or improved functionalities. The list is not comprehensive, but does provide an overview of such utilization.

10.2 *Mechanical Applications:*

10.2.1 Carbon nanotubes, having a very high tensile strength and light weight, are used to structurally reinforce composite materials in the aerospace industry.

10.2.2 Nanoparticles with spherical and polyhedral shapes can modify the friction mechanism and are used as additives to reduce friction in the petroleum industry. Their small size and multi-layered structure contribute towards improved wear resistance.

10.2.3 Nanoparticles made from polymerized styrene and butadiene are used as additives in the rubber mixture of a tire tread to reduce wear. The large number of surface binding sites on the nanoparticles improves the linking with the silica in the tread.

10.2.4 Silica nanoparticles are used to improve abrasion resistance in paints and coatings. Nanoscale silica is very hard and its small size increases the crosslinking density of reactive groups in resins.

10.3 *Optical Applications:*

10.3.1 Semiconductor layers with nanoscale thicknesses are used in quantum well lasers. Emission wavelengths different from that determined by the bulk bandgap can be achieved and tuned by adjusting layer thicknesses.

10.3.2 Structural changes at the nanoscale are used for the tuning of colors of materials or surfaces in displays and paints.

10.3.3 Nanoscale titanium dioxide is used in paints for UV-protection since it is a more effective UV absorber compared to microscale material.

10.3.4 Nanostructured coatings are used to improve performance in anti-reflection layers. Periodic features with dimensions smaller than the wavelength of light alter the refractive indices at interfaces and results in a reduction in reflections.

10.4 *Electronic Applications:*

10.4.1 *Devices and Circuit Components:*

10.4.1.1 Materials with nanoscale dimensions are implemented to further increase performance in active and passive components such as transistors and interconnects. For example, bandgap engineering with ultrathin layers can improve carrier mobility and highly conductive graphene sheets can be used for wiring material in integrated circuits.

10.4.1.2 The incorporation of nanoparticles and nanowires in solar cells results in higher device efficiency. The nanoscale material can capture more of the solar energy by enhancing light absorption through bandgap engineering or through a change in the light scattering mechanism.

10.4.2 In chemical and physical detection, sensor performance is enhanced through the use of nanoscale components and further miniaturization to evolve from Microelectromechanical systems (MEMS) to nanoelectromechanical systems (NEMS). The reduction in mass or increase in surface-to-volume ratio can lead to a higher resonance frequency and greater detection sensitivity, respectively, for example.

10.5 *Biomedical Applications:*

10.5.1 Many biological phenomena occur at the nanoscale, so it is synergistic with the use of nanotechnology for research and practical deployment in a wide variety of biomedical fields.

10.5.2 *Biological Applications:*

10.5.2.1 Fluorescent nanoparticles are used in tagging or labeling biomolecules for identification. The inherent small size and optical stability facilitate high resolution bio imaging, while the ability to functionalize nanoparticle surfaces with unique chemistry allows specific species to be targeted.

10.5.2.2 The use of magnetic nanoparticles can facilitate the detection of proteins. They enable the magnetic purification and enrichment of proteins from complex serum samples.

10.5.3 *Medical and Health Applications:*

10.5.3.1 The cellular uptake of inorganic nanoparticles such as gold is used for therapies such as the sensitizing, targeting or ablation of cancer cells. The nanoparticle size and surface functionalization can be tuned to target specific cells, while the metallic nature facilitates efficient coupling to a radio frequency source for non-invasive localized heating of the cells.

10.5.3.2 The cellular uptake of organic nanoparticles such as liposomes is used for drug delivery. Their wide ranging biochemical characteristics allow a broad spectrum of drugs to be encapsulated and transported to the targeted cells.

10.5.3.3 In health and beauty products, silver nanoparticles are added to bandages for their antibacterial properties and nanoscale titanium dioxide is used in sunscreen because of its high refractive index as well as strong UV light absorbing capabilities.