

# Preface

## **Electrophoretic Deposition of Nanomaterials**

Electrophoresis and dielectrophoresis have been used extensively in biology, chemistry, materials science, and bioengineering for the manipulation and processing of a variety of biological materials (proteins, cells, etc.), colloids, and other liquid phase objects. In parallel, electric field assisted deposition schemes, such as electrodeposition, electrochemical deposition, and electroplating, have been employed for a number of years in materials science, industrial materials processing, and thin film applications involving precious metal coatings, composite ceramic formation, and bio-active materials, various paints and dyes.

Recent research interest in nanoscience and nanotechnology has focused on discovering facile techniques to manipulate materials that historically have shown to be difficult to handle because of their size. In particular, nanomaterials pose a substantial challenge in their efficient handling due to their diminished size. Of the multitude of available techniques to control the distribution of these materials, the electrophoretic deposition (EPD) of nanomaterials appears to be ideally suited for the distribution and deposition of nanomaterials, providing a facile, expeditious means to produce tightly packed films of nanoparticle, nanotubes, and other nanostructured materials. EPD combines aspects of electrophoresis—the translation of charged particles, suspended in a solution, due to an ambient, direct current (dc) electric field—and dielectrophoresis—the locomotion of dipolar, polarizable, or charged particles, also in solution, due to alternating current (ac) or gradient electric fields—to deposit nanostructures onto conducting electrodes. In traditional EPD, a dc voltage is applied across the cell, thereby creating an electric field that transports charged particles to the electrodes where they deposit to form a cast film. The primary advantages of electrophoretic deposition as a technique to distribute, to aggregate, and to compose films of nanomaterials include site-selectivity, dense packing of the nanomaterials, size-scalability of the film, and marked control over the deposition thickness of the film. Thus, EPD can rapidly fabricate films comprising multiple monolayers of tightly packed nanomaterials, with short-range van der Waals interactions a stabilizing influence.

Electrophoretic deposition, first investigated in depth by Hamaker and Koelmanns in the 1940s and 1950s, has been applied to cast uniform layers of particles

on conducting surfaces. By applying a potential across the two electrodes, charged particles are transported to the appropriately biased electrode (e.g., negatively charged particles migrate to the anode) where they accumulate to form a cast film. Compact casts of nanocrystals, nanotubes, or nanoparticles have been fabricated by EPD from suspensions that contain polar and non-polar organic solvents, as well as water. An essential advantage of EPD is its significantly shorter cycle times relative to other wet-casting processes. Most large-scale deposition schemes, including Langmuir-Blodgett or evaporative self-assembly, are at least an order of magnitude slower than EPD. The ability to cast films at higher rates, as well as the potential to control nanocrystal mobility through the applied electric field, presents compelling advantages of EPD relative to the other techniques. For thin films of nanomaterials to be competitive with and to supplant bulk crystalline materials in optical, electronic, and magnetic applications, the facile and rapid production of ordered, homogeneous, densely packed, and topographically smooth nanomaterial films must be realized. The inability to cast ordered defect-free films at an industrial scale and at short cycle times remains a significant obstacle to the commercialization of nanocrystalline films.

EPD presents several additional advantages over other casting processes, such as evaporative self-assembly and Langmuir-Blodgett casting. EPD is *scalable*, as demonstrated by applications in the ceramics and coatings industries, where films are deposited onto substrates as large as automotive bodies (e.g., primer coating) and as small as nanoscale electrodes. The structure and properties of the cast film can be tuned to targeted values by manipulating process variables, such as applied dc and ac voltages, frequency, and nanocrystal surface chemistry, thereby affirming the flexibility of the process. Finally, by preparing suitable templates as deposition electrodes, *patterned* films can be cast. These combined characteristics make EPD the ideal deposition scheme to produce robust nanoparticle thin films.

The rapidly emerging nanomaterials market has motivated sectors of the metals, ceramics, electronics, and other industries to consider the incorporation of nanotechnology and/or nanomaterials into their products, techniques, and protocols. Commercial and industrial markets in Europe, Asia, and North America have demonstrated interests in using nanomaterials in device deliverables and other systems. Burgeoning research investment and developing markets in South America, Australia, and Africa are following these trends.

The ultimate goal of this book is to provide a comprehensive, integrated view of the basic research, materials science, and engineering of the deposition of nanomaterials via electrophoresis and a view of commercial and industrial applications associated with this technique. Further, this book will provide an invaluable, contemporary reference for the development of fundamental theory and experiment, advanced experimental and manufacturing techniques, and industrial applications of electrophoretic deposition of nanomaterials. This monograph represents contributions from a large breadth of the science and technology that are involved in this versatile deposition process, disciplines that include electrochemistry, materials science, physics, chemistry, chemical engineering, ceramics engineering, bioengineering, and electrical engineering, among others. This volume represents the initial

foray into illustrating a variety of characteristic components of this rapidly emerging field of nanoscience and nanotechnology.

This monograph begins with two chapters that overview the fundamental concepts, methodologies, equations, terms, and phenomena associated with electric field control and manipulation of colloidal particles (Paul J. Sides) and, more specifically, with the electrophoretic deposition of nanoparticles in polar solvents (Rodrigo Moreno and Begoña Ferrari). Subsequent chapters discuss various applications of electrophoretic deposition of nanoparticles, focusing on: non-polar solvent-based nanocrystal deposition (James H. Dickerson); carbon nanotube films and carbon nanotube-based composites (Aldo R. Boccaccini, Milo S. P. Shaffer, and Cengiz Kaya); advanced ceramics applications (Partho Sarkar, Debnath De, Tetsuo Uchikoshi, and Laxmidhar Besra; Rolf Clasen; and Saša Novak, Katja König, and Aljaž Ivekovič); solid state lighting and display devices (Jan B. Talbot); and electro-active materials applications (Li Tao, Chen Yanhong and Ma Jan).

Electrophoretic Deposition of Nanomaterials

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2012, XII, 376 p. 226 illus., 48 illus. in color., Hardcover

ISBN: 978-1-4419-9690-9