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Introduction to Nanofiber Materials

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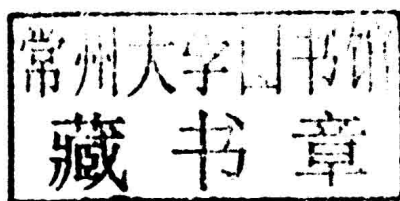
Introduction to Nanofiber Materials

FRANK K. KO

and

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Introduction to Nanofiber Materials

Presenting the latest coverage of the fundamentals and applications of nanofibrous materials and their structures for graduate students and researchers, this book bridges the communication gap between fiber technologists and materials scientists and engineers. Featuring intensive coverage of electroactive, bioactive, and structural nanofibers, it provides a comprehensive collection of processing conditions for electrospinning and includes recent advances in nanoparticle-/nanotube-based nanofibers. The book also covers mechanical properties of fibers and fibrous assemblies, as well as characterization methods.

Frank K. Ko is the Canada Research Chair Professor Tier 1 in Advanced Fibrous Materials and Director of the Advanced Fibrous Materials Laboratory, University of British Columbia.

Yuqin Wan is Research Associate in the Advanced Fibrous Materials Laboratory, Advanced Materials and Process Engineering Laboratory, University of British Columbia, Canada, and Associate Professor in the School of Textiles and Clothing, Jiangnan University, China.

Foreword

Professor Frank Ko is a recognized expert on the production, braiding and weaving of textile fibers, with strong interests in polymer science. He and I worked together in the mid 1990s, in a cooperative research effort supported by the US Army, on new polymer fibers, including nanofibers. Our complementary experience and knowledge were synergistic.

Early information about nanofibers made by electrospinning was sequestered in the research departments of a few filter manufacturers, and in the notebooks and memories of engineers from the former Soviet Union, who designed and manufactured gas masks. Since the 1930 patents of A. Formhals, little research on nanofibers was published except for a paper by P. K. Baumgarten in 1971 and papers by R. St. J. Manley in 1981, until my publications that began in 1995, with graduate student Jayesh Doshi.

Other polymer scientists soon began to develop their interests in electrospinning and nanofibers. The number of publications on nanofibers grew exponentially. By 2003, a paper on this subject, with mathematical models of co-author Alexander Yarin, was credited as “the frequently cited paper in a fast moving front of materials science,” a part of materials science previously left almost entirely to scientists in industrial textile fiber laboratories. Activity in the form of research and nanofiber manufacturing in the filtration industry, development of other useful products, and the establishment of startup companies, has ramified into a multitude of industries and now extends throughout the world.

Professor Ko presents fundamental knowledge that will enable students and other readers to create and use polymer, ceramic, carbon and metal nanofibers for a wide spectrum of purposes.

It is clear that the information in this book will be useful to researchers learning or working in the following areas.

- Filtration industry, a complex industry of rapidly growing scientific sophistication.
- Bioanalytical extracellular matrix material.
- Drug delivery in clinical medicine.
- Scaffolding for growth of implantable organs.
- Components of electronic devices.
- Selective transport of ions.
- Solar sails and other “gossamer” structures manufactured and used in interplanetary space.

Support of molecules and other tiny structures for examination in high resolution transmission electron microscopes.

For molecular scale observation of changes in molecular substances produce by energetic electrons (a great advance in radiation chemistry).

Development of smart textiles containing wearable computers and sensors.

The list of the things that are already being done with nanofibers in laboratories throughout the world is much longer, with fascinating possibilities yet to be articulated. This book provides a portal to the future, set in a context of polymers, fibers, textiles and materials science.

Darrell H. Reneker
The University of Akron

Preface

Polymeric materials in nanofiber form are of fundamental and practical importance.

Nanofibrous materials are the fundamental building blocks of living systems, from the 1.5 nm double helix strand of DNA molecules to the nanoscale fibres of sensory cells forming the extracellular matrices for tissues and organs. Considering the abundant evidence of nature's material design using nanofibers, it is reasonable to expect that the availability of nanoscale fibers having adjustable electronic, biological and mechanical properties will create the enabling technology for clean energy, clean environment, health care, microelectronics and nanoscience research. Inspired by these fibrous material designs in nature, coupled with the rapid development of research tools for nanotechnology fueled by substantial funding from Government programs such as the Multidisciplinary University Research Initiative (MURI) and by the National Science Foundation (NSF), a conducive environment was created in the 1990s for great strides in the new field of nanofiber technology. Specifically, in a MURI program sponsored by the Army Research Office (ARO), under the leadership of Professor Darrell Reneker, a versatile method was rediscovered for the formation of nanofibers by the electrospinning process. The MURI program has triggered unprecedented growth in nanofiber technology. I was fortunate to be involved in the ARO MURI program and enjoyed stimulating collaborations with Professor Reneker in the electrospinning of nanofiber yarns and the spinning of electrically conductive polymer into nanofibers with the late Nobel laureate Professor Alan MacDiarmid.

Benefiting from the experience gained in nanofiber technology from the MURI program, this book is an outgrowth of course notes designed by me for students enrolled in an NSF funded Research-Curriculum Development in Tissue Engineering (CRCD) Program led by Professor Cato Laurencin at Drexel University. The course was organized into ten lectures plus three laboratory sessions for students of diverse academic backgrounds including materials engineering, chemical engineering, mechanical engineering and biomedical engineering. Most of the students had no background in fibrous materials.

Building on the CRCD lecture notes, this book is organized into ten chapters. Chapter 1 provides an introduction to nanomaterials in general and nanofibers in specific. Chapter 2 presents an overview of polymer science with an emphasis on fiber forming polymers. Chapter 3 deals with nanofiber technology with a specific focus on electrospinning. Chapter 4 concerns process modeling of the electrospinning process and mechanistic modeling of nanofibrous assemblies that include yarn mechanics and

mechanics of nonwoven structures. In Chapter 5 we describe the various methods for the characterization of nanofiber materials. Chapters 6, 7 and 8 are devoted to functional nanofibers with Chapter 6 focusing on bioactive nanofibers, Chapter 7 focusing on electroactive nanofibers, and Chapter 8 focusing on structural composite nanofibers. In Chapter 9, various applications of nanofibers are presented and finally, in Chapter 10, the book concludes with an overview of the trend in nanofiber technology.

For various reasons the writing of the book was put on hold for a period of time until I moved to the University of British Columbia in Canada where I had the good fortune of having Dr. Lynn Yuqin Wan join the book project. With the dedicated participation of Lynn the book project was revived. As the book is based on the lecture notes delivered over the past decade, it draws heavily from the research results generated by my students, postdoctoral fellows and collaborators. I would like to thank them, in rough chronological order: Ali Ashraf, Manal Shaker, Ian Norris, Hoa Lam, Nic Titchenol, Haihu Ye, Afaf El-Aufy Jason Lyons, Jonathan Ayutsede, Milind Gahndi, Heejae Yang, Yoshihiro Yamashita, Sachiko Sukigara, Jie Xiong, Nasir M. Uddin, Takako Inoue, Chunhong Wang, Yuan Li, Jiashen Li, Lin Li Masoumeh Bayat, Wuyi Zhou, Nicole Lee, Justin Richie, Ian Dallmeyer, Phoebe Y. Li, Victor Leung, LiTing Lin and Ryan Huizing. Special thanks go to Professor Darrell Reneker for his generous sharing of the knowledge on electrospinning and to the late Professor Alan MacDiarmid who enthusiastically shared his knowledge in conductive polymers and helped to establish the area of electroactive nanofibers.

It must be noted that the research work of my group would not be possible without the sustained support of various funding agencies including the ARO, ONR, AFOSR, NSF, NASA, the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Foundation of Innovation (CFI). I would like to pay special tribute to the late Hidefumi Kato of Kato-tech who took my advice to build one of the earliest commercial Nanofiber Electrospinning Units (NEUs) and funded an extensive literature collection project in my laboratory that we utilize extensively in this book.

Finally I want to thank the editorial staff of Cambridge University Press, Production Editor Vania Cunha and Sarah Marsh (nee Matthews) Editor, Engineering, who patiently shepherded us through the completion of this book. Last but not the least I want to thank my daughter Jana Ko who patiently proofread the earlier version of the manuscript.

Frank K. Ko

Contents

	<i>Foreword by Darrell H. Reneker</i>	<i>page xi</i>
	<i>Preface</i>	<i>xiii</i>
1	Introduction	1
	1.1 How big is a nanometer?	1
	1.2 What is nanotechnology?	1
	1.3 Historical development of nanotechnology	2
	1.4 Classification of nanomaterials	5
	1.5 Nanofiber technology	5
	1.6 Unique properties of nanofibers	6
	1.6.1 Effect of fiber size on surface area	7
	1.6.2 Effect of fiber size on bioactivity	7
	1.6.3 Effect of fiber size on electroactivity	8
	1.6.4 Effect of fiber size on strength	9
	References	10
2	Fundamentals of polymers	13
	2.1 Polymeric materials	13
	2.2 Polymer flow, nonlinearity and heterogeneity	14
	2.2.1 Linear kinetics	14
	2.2.2 Nonlinear behavior	15
	2.2.3 Viscoelastic models	16
	2.2.3.1 The basic elements: spring and dashpot	16
	2.2.3.2 Maxwell model	18
	2.2.3.3 Voigt (Kelvin) model	19
	2.2.3.4 Four-element model	21
	2.3 Intrinsic structures of polymers	22
	2.3.1 Molecular bondings	23
	2.3.1.1 Van der Waals forces	24
	2.3.1.2 Hydrogen bonding	24
	2.3.2 Configuration and conformation	24
	2.3.2.1 Configuration	24
	2.3.2.2 Conformation	25

2.3.2.3	Other chain structures	26
2.3.3	Order and disorder	27
2.3.3.1	Amorphous and crystal structure	27
2.3.3.2	Orientation	27
2.3.3.3	Measurement of order and disorder	28
2.3.4	Molecular weight and molecular weight distribution	28
2.4	Thermal behavior	31
2.5	Polymer solutions	32
2.5.1	Solubility parameter	32
2.5.2	Solution viscosity	34
2.5.2.1	Intrinsic viscosity	34
2.5.2.2	Intrinsic viscosity and molecular weight	36
2.5.2.3	Measurement of intrinsic viscosity	37
2.6	Fiber, plastic and elastomer	38
2.7	Fiber formation	38
2.7.1	Melt spinning	38
2.7.2	Wet spinning	39
2.7.3	Dry spinning	40
2.7.4	Fiber properties	40
2.7.4.1	Polymer structure and fiber mechanical properties	40
2.7.4.2	Processing and fiber properties	42
References		43
3	Nanofiber technology	44
3.1	Nanofiber-forming technology	44
3.1.1	Conjugate spinning (island in the sea)	44
3.1.2	Chemical vapor deposition (CVD)	44
3.1.3	Phase separation (sol-gel process)	45
3.1.4	Drawing	46
3.1.5	Template synthesis	46
3.1.6	Self-assembly	46
3.1.7	Meltblown technology	46
3.1.8	Electrospinning	48
3.2	Electrospinning process	48
3.3	Processing parameters	49
3.3.1	Spinning dope concentration and viscosity	49
3.3.2	Applied voltage	51
3.3.3	Spinning dope temperature	51
3.3.4	Surface tension	51
3.3.5	Electrical conductivity	52
3.3.6	Molecular weight of polymer	52
3.3.7	Spinning distance	53
3.3.8	Spinning angle	54
3.3.9	Orifice diameter	54

3.3.10	Solvent boiling point	54
3.3.11	Humidity	55
3.3.12	Dielectric constant	56
3.3.13	Feeding rate	56
3.4	Melt electrospinning	57
3.5	Applications of nanofibers	57
3.5.1	Reinforcement fibers in composites	58
3.5.2	Protective clothing	58
3.5.3	Filtration	58
3.5.4	Biomedical devices	59
3.5.4.1	Wound dressing	60
3.5.4.2	Medical prostheses	60
3.5.4.3	Tissue scaffolds	60
3.5.4.4	Controlled drug delivery	60
3.5.5	Electrical and optical applications	61
3.5.6	Nanosensors	61
	References	61
4	Modeling and simulation	64
4.1	Electrospinning mechanism	64
4.2	Fundamentals of process modeling	64
4.2.1	Newton's law	65
4.2.2	Conservation laws	66
4.3	Taylor cone	66
4.4	Jet profile	67
4.5	Models	68
4.5.1	One-dimensional model	69
4.5.2	Three-dimensional models	70
4.5.2.1	Spivak–Dzenis model	70
4.5.2.2	Rutledge's model	71
4.5.2.3	Wan–Guo–Pan model	72
4.6	Application of models in parametric analysis	73
4.7	Computer simulation	74
	References	77
5	Mechanical properties of fibers and fiber assemblies	80
5.1	Structure of hierarchy of textile materials	80
5.2	Size effect on mechanical properties	80
5.3	Theoretical modulus of a fiber	81
5.4	Mechanical properties of nonwovens	83
5.4.1	Geometry of nonwovens	83
5.4.2	Deformation of nonwovens	85
5.5	Mechanical properties of yarns	86
5.5.1	Yarn geometry	87

5.5.2	Mechanical properties of linear fiber assemblies	89
5.5.2.1	Stress analysis	89
5.5.2.2	Strain analysis	91
5.5.3	Mechanical properties of staple yarns	92
5.6	Mechanical properties of woven fabrics	95
5.6.1	Woven fabric geometry	96
	References	99
6	Characterization of nanofibers	101
6.1	Structural characterization of nanofibers	101
6.1.1	Optical microscopy (OM)	101
6.1.2	Scanning electron microscopy (SEM)	102
6.1.3	Transmission electron microscopy (TEM)	105
6.1.4	Atomic force microscopy (AFM)	107
6.1.5	Scanning tunneling microscopy (STM)	109
6.1.6	X-ray diffraction	111
6.1.6.1	Wide-angle X-ray diffraction	113
6.1.6.2	Small-angle X-ray scattering	113
6.1.7	Mercury porosimetry	114
6.2	Chemical characterization of nanofibers	115
6.2.1	Fourier transform infra-red spectroscopy (FTIR)	115
6.2.2	Raman spectroscopy (RS)	118
6.2.3	Nuclear magnetic resonance (NMR)	120
6.3	Mechanical characterization of nanofibers	121
6.3.1	Microtensile testing of nanofiber nonwoven fabric	122
6.3.2	Mechanical testing of a single nanofiber	124
6.4	Thermal analysis	127
6.4.1	Thermogravimetric analysis (TGA)	128
6.4.2	Differential scanning calorimetry (DSC)	130
6.5	Characterization of other properties	133
6.5.1	Wettability and contact angle	133
6.5.2	Electrical conductivity	135
6.5.3	Electrochemical properties	136
6.5.3.1	Linear-sweep voltammetry and cyclic voltammetry	136
6.5.3.2	Chronopotentiometry	138
6.5.4	Magnetic properties	139
	References	142
7	Bioactive nanofibers	146
7.1	The development of biomaterials	146
7.2	Bioactive nanofibers	147
7.2.1	Nanofibers for tissue engineering	147
7.2.1.1	Extracellular matrices for tissue engineering	147
7.2.1.2	Nanofiber scaffolds for tissue engineering	148

7.2.2	Nanofibers for drug delivery	155
7.2.2.1	Drug delivery systems	155
7.2.2.2	Nanofibers for drug delivery	156
7.2.3	Nanofibers for biosensors	158
7.2.3.1	Biosensors	158
7.2.3.2	Nanofiber biosensors	159
7.3	Assessment of nanofiber bioactivity	160
7.3.1	Assessment of tissue compatibility	162
7.3.2	Assessment of degradation	162
	References	162
8	Electroactive nanofibers	166
8.1	Introduction	166
8.2	Conductive nanofibers	166
8.2.1	Conductive polymers and fibers	166
8.2.2	Fundamental principle for superior electrical conductivity	168
8.2.3	Electroactive nanofibers	169
8.3	Magnetic nanofibers	178
8.3.1	Supermagnetism	178
8.3.2	Supermagnetic nanofibers	179
8.4	Photonic nanofibers	181
8.4.1	Polymer photonics	181
8.4.2	Fluorescent nanofibers	183
8.4.3	Photo-catalytic nanofibers	185
	References	188
9	Nanocomposite fibers	191
9.1	Introduction	191
9.2	Carbon nanotubes	191
9.2.1	Structure and properties	191
9.2.1.1	Structure	191
9.2.1.2	Mechanical properties	195
9.2.1.3	Electrical properties	195
9.2.1.4	Thermal properties	196
9.2.2	Dispersion of carbon nanotubes	196
9.2.2.1	Purification	196
9.2.2.2	Mechanical dispersion	198
9.2.2.3	Chemical dispersion	199
9.2.3	Alignment of carbon nanotubes	204
9.2.3.1	Alignment of carbon nanotubes in solution	204
9.2.3.2	Alignment of carbon nanotubes in matrix	206
9.2.4	Carbon nanotube nanocomposite fibers	208
9.2.4.1	Methods for producing carbon nanotube fibers	209
9.2.4.2	Chemical vapor deposition	209

9.2.4.3	Dry spinning	211
9.2.4.4	Liquid crystal spinning	211
9.2.4.5	Wet spinning	212
9.2.4.6	Traditional spinning	213
9.2.4.7	Electrospinning	213
9.3	Nanoclay	214
9.3.1	Structure and properties	214
9.3.2	Clay nanocomposites	215
9.3.3	Nanoclay nanocomposite fibers	217
9.4	Graphite graphenes	219
9.4.1	Structure and properties	219
9.4.2	Graphene nanocomposites	221
9.4.3	Graphene nanocomposite nanofibers	221
9.5	Carbon nanofibers	222
9.5.1	Vapor-grown carbon nanofibers	222
9.5.2	Electrospun carbon nanofibers	224
9.5.3	Carbon nanofiber composites	225
	References	226
10	Future opportunities and challenges of electrospinning	239
10.1	Future of nanotechnology	239
10.2	Global challenges and nanotechnology	240
10.2.1	Nanofibers in energy	241
10.2.1.1	Electrodes and electrolytes in fuel cells or batteries	241
10.2.1.2	Supercapacitors	241
10.2.1.3	Dye-sensitized solar cells	242
10.2.1.4	Power transmission lines	242
10.2.2	Nanofibers in filtration	242
10.2.3	Nanofibers in biomedical engineering	243
10.3	Challenges	243
10.3.1	Mechanism analysis	243
10.3.2	Quality control	244
10.3.3	Scale-up manufacturing	244
10.3.4	Structural property improvement	252
10.4	New frontiers	253
	References	254
	<i>Appendix I Terms and unit conversion</i>	258
	<i>Appendix II Abbreviation of polymers</i>	260
	<i>Appendix III Classification of fibers</i>	262
	<i>Appendix IV Polymers and solvents for electrospinning</i>	263
	<i>Index</i>	265

1 Introduction

1.1 How big is a nanometer?

By definition, a nanometer, abbreviated as nm, is a unit for length that measures one billionth of a meter. ($1 \text{ nm} = 10^{-3} \mu\text{m} = 10^{-6} \text{ mm} = 10^{-7} \text{ cm} = 10^{-9} \text{ m}$.) Our hair is visible to the naked eye. Using an optical microscope we can measure the diameter of our hair, which is in the range of 20–50 microns (μm) or 20 000–50 000 nm. Blood cells are not visible to the naked eye, but they can be seen under the microscope, revealing a diameter of about 10 microns or 10 000 nm. The diameter of hydrogen atoms is 0.1 nm. In other words 10 hydrogen atoms can be placed side-by-side in 1 nm. Figure 1.1 provides an excellent illustration of the relative scales in nature. The discovery of nanomaterials ushered us to a new era of materials. We have progressed from the microworld to the nanoworld.

1.2 What is nanotechnology?

According to the National Science Foundation in the United States nanotechnology is defined as [1]:

Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1–100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size. The novel and differentiating properties and functions are developed at a critical length scale of matter typically under 100 nm. Nanotechnology research and development includes manipulation under control of the nanoscale structures and their integration into larger material components, systems and architectures. Within these larger scale assemblies, the control and construction of their structures and components remains at the nanometer scale. In some particular cases, the critical length scale for novel properties and phenomena may be under 1 nm (e.g., manipulation of atoms at $\sim 0.1 \text{ nm}$) or be larger than 100 nm. (e.g., nanoparticle reinforced polymers have the unique feature at $\sim 200\text{--}300 \text{ nm}$ as a function of the local bridges or bonds between the nanoparticles and the polymer).

Accordingly nanotechnology is the scientific field that is concerned with the study of the phenomena and functions of matters within the dimensional range of 0.1–100 nm. It is the study of the motion and changes of atoms, molecules, and of other forms of

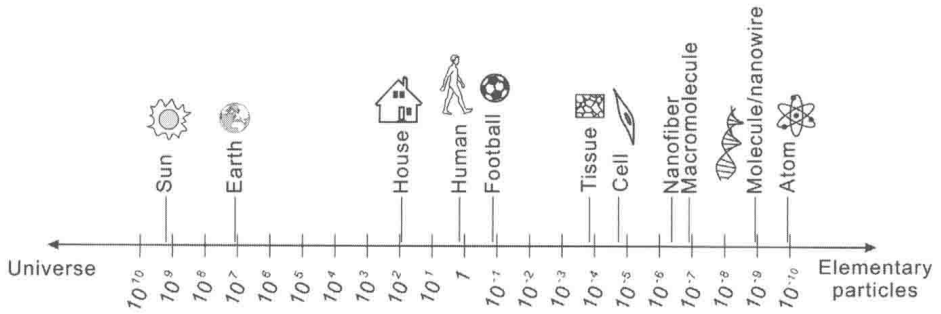


Fig. 1.1 Illustration of relative scale in nature. (The linear distance is indicated on this logarithmic scale in meters.)

matter. Nanotechnology, building upon the foundation of nanoscience, is concerned with the manufacturing of new materials, new devices and the development of research methodology and techniques for new technology.

Nanotechnology can also be referred to as the technology for the formation of nanomaterials and nanodevices, including the formation of nanostructural units according to a specific methodology to form macroscopic treatment (processing) of nanomaterials such as dispersion, forming technology as in the case of the formation of nanofibers and their composites.

Nanotechnology can be organized into three levels. The first level is molecular (atomic) nanotechnology wherein the molecules (atoms) are spatially organized in the nanospace in a repetitive manner. This in turn will create internally ordered nanostructures. Self-assembly and mineralization in biological materials are examples of molecular nanotechnology. The technology for controlling the morphology and uniformity of nanostructures is called the second level of nanotechnology. For example, in colloids and gels we do not concern ourselves with the order of arrangement of the molecule itself at the nanoscale. They form only morphologies of nanostructure of certain regularity. The third level of nanotechnology is concerned with the technology of the formation of nanoscale structures but is unable to control the degree of order of the molecules and atoms in the nanostructures. At the third level of nanotechnology the morphology and uniformity of the nanostructure are also uncontrolled [2].

1.3 Historical development of nanotechnology

Although the use of nanomaterials can arguably be traced back to over 1000 years ago when the smoke from a candle was used in China as ink, the first scientific discussion of nanotechnology is widely attributed to the 1959 Nobel Prize winning physicist Richard Feynman in his well known “There’s Plenty of Room at the Bottom” lecture at the California Institute of Technology (Caltech). In this lecture he boldly challenged his audience in his now famous statement.