

# *Nanotechnology-Enabled Sensors*

**Kouros Kalantar-zadeh**

*RMIT University  
School of Electrical Engineering  
Melbourne, Victoria  
Australia*

**Benjamin Fry**

*RMIT University  
Biotechnology and Environmental Biology  
Melbourne, Victoria  
Australia*

# Contents

<b>Preface .....</b>	<b>i</b>
<b>Acknowledgments .....</b>	<b>ii</b>
<b>Chapter 1: Introduction .....</b>	<b>1</b>
1.1 Nanotechnology .....	1
1.2 Sensors .....	6
1.3 Nanotechnology Enabled Sensors .....	8
<b>Chapter 2: Sensor Characteristics and Physical Effects .....</b>	<b>13</b>
2.1 Introduction .....	13
2.2 Sensor Characteristics and Terminology .....	13
2.2.1 Static Characteristics .....	14
2.2.2 Dynamic Characteristics .....	17
2.3 Physical Effects Employed for Signal Transduction .....	20
2.3.1 Photoelectric Effect .....	21
2.3.2 Photodielectric Effect .....	27
2.3.3 Photoluminescence Effect .....	27
2.3.4 Electroluminescence Effect .....	31
2.3.5 Chemiluminescence Effect .....	34
2.3.6 Doppler Effect .....	34
2.3.7 Barkhausen Effect .....	36
2.3.8 Hall Effect .....	36
2.3.9 Nernst/Ettingshausen Effect .....	38
2.3.10 Thermoelectric (Seebeck/Peltier and Thomson) Effect .....	38
2.3.11 Thermoresistive Effect .....	42
2.3.12 Piezoresistive Effect .....	43
2.3.13 Piezoelectric Effect .....	46
2.3.14 Pyroelectric effect .....	47
2.3.15 Magneto-Mechanical Effect (Magnetostriction) .....	48
2.3.16 Magnetoresistive Effect .....	49
2.3.17 Faraday-Henry Law .....	51
2.3.18 Faraday Rotation Effect .....	54
2.3.19 Magneto-Optic Kerr Effect (MOKE) .....	55
2.3.20 Kerr and Pockels Effects .....	56
2.4 Summary .....	57

<b>Chapter 3: Transduction Platforms</b> .....	<b>63</b>
3.1 Introduction .....	63
3.2 Conductometric and Capacitive Transducers .....	63
3.3 Optical Waveguide based Transducers.....	66
3.3.1 Propagation in Optical Waveguides .....	67
3.3.2 Sensitivity of Optical Waveguides .....	69
3.3.3 Optical Fiber based Transducers .....	71
3.3.4 Interferometric Optical Transducers.....	72
3.3.5 Surface Plasmon Resonance (SPR) Transducers.....	74
3.4 Electrochemical Transducers.....	79
3.4.1 Chemical Reactions .....	80
3.4.2 Thermodynamics of Chemical Interactions.....	80
3.4.3 Nernst Equation.....	84
3.4.4 Reference Electrodes .....	97
3.4.5 Ion Selective Electrodes .....	90
3.4.6 An Example: Electrochemical pH Sensors.....	93
3.4.7 Voltammetry.....	94
3.4.8 An Example: Stripping Analysis .....	105
3.5 Solid State Transducers .....	106
3.5.1 <i>p-n</i> Diodes or Bipolar Junction based Transducers .....	106
3.5.2 Schottky Diode based Transducers .....	108
3.5.3 MOS Capacitor based Transducers .....	111
3.5.4 Field Effect Transistor based Transducers .....	113
3.6 Acoustic Wave Transducers .....	118
3.6.1 Quartz Crystal Microbalance.....	119
3.6.2 Film Bulk Acoustic Wave Resonator (FBAR).....	121
3.6.3 Cantilever based Transducers.....	123
3.6.4 Interdigitally Launched Surface Acoustic Wave (SAW) Devices .....	125
3.7 Summary.....	129
 <b>Chapter 4: Nano Fabrication and Patterning Techniques</b> .....	 <b>135</b>
4.1 Introduction .....	135
4.2 Synthesis of Inorganic Nanoparticles .....	136
4.2.1 Synthesis of Semi-conductor Nano-particles .....	136
4.2.2 Synthesis of Magnetic Nanoparticles .....	137
4.2.3 Synthesis of Metallic Nanoparticles .....	138
4.3 Formation of Thin Films.....	141
4.3.1 Fundamentals of Thin Film Deposition.....	141
4.3.2 Growth of One-Dimensional Nano-structured Thin Films..	143
4.3.3 Segmented One-Dimensional Structured Thin Films.....	150
4.4 Physical Vapor Deposition (PVD).....	151

4.4.1 Evaporation.....	151
4.4.2 Sputtering .....	158
4.4.3 Ion Plating .....	163
4.4.4 Pulsed Laser Deposition (PLD).....	164
4.5 Chemical Vapor Deposition (CVD) .....	164
4.5.1 Low Pressure CVD (LPCVD).....	168
4.5.2 Plasma-Enhanced CVD (PECVD) .....	168
4.5.3 Atomic Layer CVD (ALCVD).....	170
4.5.4 Atmospheric Pressure Plasma CVD (AP-PCVD) .....	172
4.5.5 Other CVD Methods.....	173
4.6 Liquid Phase Techniques.....	173
4.6.1 Aqueous Solution Techniques (AST).....	173
4.6.2 Langmuir-Blodgett (LB) method.....	176
4.6.3 Electro-deposition.....	179
4.7 Casting .....	182
4.7.1 Spin Coating .....	182
4.7.2 Drop Casting, Dip Coating and Spraying .....	184
4.8 Sol-gel.....	184
4.9 Nanolithography and Nano-Patterning .....	186
4.9.1 Photolithography .....	187
4.9.2 Scanning Probe Nanolithography Techniques .....	190
4.9.3 Nanoimprinting.....	191
4.9.4 Patterning with Energetic Particles.....	193
4.9.5 X-Ray Lithography (XRL) and LIGA .....	197
4.9.6 Interference Lithography .....	200
4.9.7 Ion Implantation .....	202
4.9.8 Etching: Wet and Dry .....	202
4.10 Summary.....	204
<b>Chapter 5: Characterization Techniques for Nanomaterials .....</b>	<b>211</b>
5.1 Introduction .....	211
5.2 Electromagnetic Spectroscopy.....	211
5.2.1 UV-Visible Spectroscopy .....	215
5.2.2 Photoluminescence (PL) Spectroscopy .....	219
5.2.3 Infrared Spectroscopy.....	223
5.3 Nuclear Magnetic Resonance (NMR) Spectroscopy .....	228
5.4 X-Ray Photoelectron Spectroscopy (XPS).....	232
5.5 X-Ray Diffraction (XRD).....	237
5.6 Light Scattering Techniques.....	240
5.6.1 Dynamic Light Scattering (DLS) .....	241
5.6.2 Raman Spectroscopy .....	245
5.7 Electron Microscopy.....	248

5.7.1 Scanning Electron Microscope (SEM).....	250
5.7.2 Transmission Electron Microscope (TEM).....	255
5.8 Rutherford Backscattering Spectrometry (RBS).....	259
5.9 Scanning Probe Microscopy (SPM).....	263
5.9.1 Scanning Tunneling Microscope (STM).....	264
5.9.2 Atomic Force Microscope (AFM).....	267
5.10 Mass Spectrometry.....	270
5.10.1 Matrix-Assisted Laser Desorption/Ionisation (MALDI) Mass Spectrometer.....	272
5.10.2 Time of Flight (TOF) Mass Spectrometer.....	273
5.11 Summary.....	274
<b>Chapter 6: Inorganic Nanotechnology Enabled Sensors.....</b>	<b>283</b>
6.1 Introduction.....	283
6.2 Density and Number of States.....	283
6.2.1 Confinement in Quantum Dimensions.....	284
6.2.2 Momentum and Energy of Particles.....	285
6.2.3 Reciprocal Space.....	286
6.2.4 Definition of Density of States.....	287
6.2.5 DOS in Three-dimensional Materials.....	287
6.2.6 DOS in Two-Dimensional Materials.....	289
6.2.7 DOS in One-Dimensional Materials.....	291
6.2.8 DOS in Zero-Dimensional Materials.....	291
6.2.9 Discussions on the DOS.....	292
6.2.10 Theoretical and Computational Methods.....	296
6.2.11 One-Dimensional Transducers.....	297
6.2.12 Example: One-Dimensional Gas Sensors.....	302
6.3 Gas Sensing with Nanostructured Thin Films.....	304
6.3.1 Adsorption on Surfaces.....	305
6.3.2 Conductometric transducers Suitable for Gas Sensing.....	307
6.3.3 Gas Reaction on the Surface - Concentration of Free Charge Carriers.....	313
6.3.4 Effect of Gas Sensitive Structures and Thin Films.....	319
6.3.5 Effects of Deposition Parameters and Substrates.....	322
6.3.6 Metal Oxides Modification by Additives.....	323
6.3.7 Surface Modification.....	325
6.3.8 Filtering.....	328
6.3.9 Post Deposition Treatments.....	328
6.4 Phonons in Low Dimensional Structures.....	329
6.4.1 Phonons in One-Dimensional Structures.....	330
6.4.2 Electron-Phonon Interactions in Low Dimensional Materials.....	334
6.4.3 Phonons in Sensing Applications.....	337
6.4.3 One-Dimensional Piezoelectric Sensors.....	338

6.5 Nanotechnology Enabled Mechanical Sensors.....	340
6.5.1 Oscillators based on Nanoparticles.....	341
6.5.2 One-Dimensional Mechanical Sensors.....	343
6.5.3 Bulk Materials and Thin Films Made of Nano-Grains.....	345
6.5.4 Piezoresistors.....	347
6.6 Nanotechnology Enabled Optical Sensors.....	348
6.6.1 The Optical Properties of Nanostructures.....	348
6.6.2 The Optical Properties of Nanoparticles.....	352
6.6.3 Sensors based on Plasmon Resonance in Nanoparticles.....	353
6.7 Magnetically Engineered Spintronic Sensors.....	356
6.7.1 AMR, Giant and Colossal Magneto-Resistors.....	357
6.7.2 Spin Valves.....	360
6.7.3 Magnetic Tunnel Junctions.....	361
6.7.4 Other Nanotechnology Enabled Magnetic Sensors.....	362
6.8 Summary.....	363
<b>Chapter 7: Organic Nanotechnology Enabled Sensors.....</b>	<b>371</b>
7.1 Introduction.....	371
7.2 Surface Interactions.....	372
7.2.1 Covalent Coupling.....	372
7.2.2 Adsorption.....	379
7.2.3 Physical Entrapment.....	380
7.2.4 Chemical Entrapment.....	381
7.2.5 Self-Assembly.....	381
7.2.6 Layer-by-Layer Assembly.....	384
7.3 Surface Materials and Surface Modification.....	386
7.3.1 Gold Surfaces.....	386
7.3.2 Silicon, Silicon Dioxide and Metal Oxides Surfaces.....	387
7.3.3 Carbon Surfaces.....	389
7.3.4 Conductive and Non-Conductive Polymeric Surfaces.....	390
7.3.5 Examples of Surface Modifications in Biosensors.....	401
7.4 Proteins in Nanotechnology Enabled Sensors.....	404
7.4.1 The Structure of Proteins.....	404
7.4.2 The Analysis of Proteins.....	409
7.4.3 The Role of Proteins in Nanotechnology.....	409
7.4.4 Using Proteins as Nanodevices.....	411
7.4.5 Antibodies in Sensing Applications.....	412
7.4.6 Antibody Nanoparticle Conjugates.....	418
7.4.7 Enzymes in Sensing Applications.....	420
7.4.8 Enzyme Nanoparticle Hybrid based Sensors.....	425
7.4.9 Motor Proteins in Sensing Applications.....	427
7.4.10 Transmembrane Sensors.....	428

xii Contents

7.5 Nano-sensors based on Nucleotides and DNA .....	436
7.5.1 The Structure of DNA .....	438
7.5.2 The Structure of RNA .....	441
7.5.3 DNA Decoders and Microarrays .....	442
7.5.4 DNA-based Sensors.....	449
7.5.5 DNA-Protein Conjugate-based Sensors .....	452
7.5.6 DNA Conjugates with Inorganic Materials .....	455
7.5.7 Bioelectronic Sensors based on DNA .....	459
7.5.8 DNA Sequencing with Nanopores .....	463
7.6 Sensors Based on Molecules with Dendritic Architectures.....	465
7.7 Force Spectroscopy and Microscopy of Organic Materials.....	467
7.8 Biomagnetic Sensors .....	469
7.9 Summary.....	470
<b>Index .....</b>	<b>482</b>
<b>About the Authors .....</b>	<b>491</b>