

CHAPTER ONE: INTRODUCTION.....	1
STUDY BACKGROUND .....	1
STUDY GOALS AND OBJECTIVES.....	1
INTENDED AUDIENCE.....	2
SCOPE AND FORMAT .....	2
INFORMATION SOURCES AND METHODOLOGY.....	3
ANALYST CREDENTIALS.....	3
RELATED BCC RESEARCH REPORTS.....	3
BCC ONLINE SERVICES.....	4
DISCLAIMER .....	5
 CHAPTER TWO: EXECUTIVE SUMMARY.....	 6
<i>SUMMARY TABLE GLOBAL MARKET FOR ADVANCED     ELECTRONIC MATERIALS BY APPLICATION, THROUGH 2021 (\$     MILLIONS)</i> .....	  6
<i>SUMMARY FIGURE GLOBAL MARKET FOR ADVANCED     ELECTRONIC MATERIALS BY APPLICATION, 2010-2021 (\$     MILLIONS)</i> .....	  7
 CHAPTER THREE: OVERVIEW .....	 8
DEFINITIONS AND KEY CONCEPTS .....	8
ELECTRONICS.....	8
ELECTRONIC MATERIALS.....	8
NEW ELECTRONIC MATERIALS.....	8
NEW MATERIALS .....	8
<i>TABLE 1 NEW ELECTRONIC MATERIALS</i> .....	9
GRAPHENE .....	10
QUANTUM DOTS.....	10
PHOTONIC CRYSTALS.....	10
CARBON NANOTUBES.....	11
SUPERCONDUCTING MATERIALS.....	11
NANOWIRES .....	11
CONDUCTIVE AND SEMICONDUCTIVE POLYMERS.....	11
PHASE-CHANGE MATERIALS .....	12
MOLYBDENITE .....	12
APPLICATIONS .....	12
MARKET SUMMARY.....	13
<i>TABLE 2 GLOBAL MARKET FOR ADVANCED ELECTRONIC     MATERIALS BY MATERIAL TYPE, 2010–2021 (\$ MILLIONS)</i> .....	 13
<i>TABLE 3 GLOBAL MARKET FOR ADVANCED ELECTRONIC     MATERIALS BY MATERIAL TYPE, 2010–2021 (% OF TOTAL     MARKET)</i> .....	  14
 CHAPTER FOUR: GRAPHENE.....	 15

GENERAL DESCRIPTION.....	15
DEFINITION.....	15
OCCURRENCE AND PRODUCTION .....	15
Established Technologies .....	15
Scotch Tape Method.....	15
Epitaxial Method .....	16
Graphite Oxide Reduction Method .....	17
Experimental Approaches .....	17
Metal-Carbon Melt Method.....	18
Pyrolysis of Sodium Ethoxide Method .....	18
Production of Graphene from Carbon Nanotubes .....	18
Production of Graphene from Table Sugar.....	18
Dissolving Graphite in Chlorosulphonic Acid.....	19
Molecular Wedge Method .....	19
Radio Frequency Catalytic Chemical Vapor Deposition .....	20
PROPERTIES.....	20
APPLICATIONS AND END USES.....	21
<i>TABLE 4 POTENTIAL ELECTRONICS APPLICATIONS OF GRAPHENE</i> .....	21
<i>TABLE 4 (CONTINUED)</i> .....	22
COMPUTING .....	22
Transistors .....	22
Graphene Switches .....	23
Quantum Confinement in Graphene Nanoribbons .....	23
Field-Induced Modification of Graphene Structure .....	23
Ballistic Transistors.....	24
Graphene Nanomesh .....	24
Integrated Circuits .....	25
Graphene Interconnections .....	25
All-Graphene Integrated Circuits .....	25
DATA STORAGE .....	26
Graphene Spin Valve.....	27
Graphene Nanocable Memory Device.....	27
Graphene Nanoribbon Memory .....	28
Graphene Oxide-Based Memory .....	28
DISPLAYS .....	28
Roll-to-Roll Production .....	29
Spray Coating .....	29
Transfer Printing.....	30
Electrophoretic Deposition .....	30
Hybrid Graphene-Carbon Nanotube Film.....	30
COMMUNICATIONS .....	30

High-Speed Photodetectors .....	31
Amplifiers.....	31
Frequency Multipliers .....	32
ENERGY.....	32
Photovoltaics.....	32
Flexible Organic Photovoltaic Cells .....	33
Polymer Photovoltaic Cells Based on Solution- Processable Graphene and P3HT .....	33
Dye-Doped Graphite/Graphene Solar Cell.....	34
Capacitors .....	35
Capacitors (Continued).....	36
SENSORS AND IMAGING EQUIPMENT .....	37
Sensors .....	37
Chemical and Gas Sensors .....	37
Electrochemical Sensors .....	37
Mass Sensors.....	38
Nanopore Sensors .....	38
Radiation Sensors .....	39
Biosensors.....	39
Imaging Equipment.....	40
Graphene Frequency Multipliers.....	40
Graphene-Based Plasmon Amplifiers.....	41
Other Technologies .....	41
OTHER APPLICATIONS .....	41
MARKETS.....	42
SUMMARY .....	42
<i>FIGURE 1 TRENDS IN THE GLOBAL MARKET FOR GRAPHENE IN ELECTRONICS APPLICATIONS, 2010–2021 (\$ MILLIONS).....</i>	<i>43</i>
<i>TABLE 5 GLOBAL MARKET FOR GRAPHENE ELECTRONICS BY APPLICATION, 2010–2021 (\$ MILLIONS).....</i>	<i>44</i>
<i>FIGURE 2 GRAPHENE ELECTRONICS APPLICATION SEGMENTS (% OF TOTAL MARKET) .....</i>	<i>45</i>
COMPUTING .....	45
DATA STORAGE AND MEMORY .....	46
DISPLAYS .....	46
COMMUNICATIONS .....	46
ENERGY.....	47
<i>TABLE 6 GLOBAL MARKET FOR GRAPHENE ELECTRONICS IN ENERGY APPLICATIONS, THROUGH 2021 (\$ MILLIONS) .....</i>	<i>47</i>
Photovoltaics.....	47
Capacitors .....	48
SENSORS AND IMAGING EQUIPMENT .....	48

<i>TABLE 7 GLOBAL MARKET FOR GRAPHENE ELECTRONICS IN SENSING AND IMAGING APPLICATIONS, THROUGH 2021 (\$ MILLIONS)</i> .....	48
Sensors .....	48
IMAGING APPLICATIONS .....	49
OTHER APPLICATIONS .....	49
CHAPTER FIVE: QUANTUM DOTS .....	50
GENERAL DESCRIPTION .....	50
DEFINITION.....	50
PROPERTIES.....	50
OCCURRENCE AND PRODUCTION .....	51
Colloidal Synthesis .....	51
Epitaxy .....	51
Printed Quantum-Dot Films .....	52
APPLICATIONS AND END USES.....	52
COMPUTING .....	52
DATA STORAGE AND MEMORY .....	53
DISPLAYS .....	53
LIGHTING AND ILLUMINATION .....	54
COMMUNICATIONS .....	55
Optical Switches and Gates .....	55
Optical Amplifiers.....	56
Lasers .....	56
ENERGY.....	57
SENSORS AND IMAGING SYSTEMS.....	57
MARKETS.....	58
SUMMARY .....	58
<i>FIGURE 3 TRENDS IN THE GLOBAL MARKET FOR QUANTUM-DOT ELECTRONICS APPLICATIONS, 2010–2021 (\$ MILLIONS)</i> .....	58
<i>TABLE 8 GLOBAL MARKET FOR QUANTUM-DOT ELECTRONICS BY APPLICATION, THROUGH 2021 (\$ MILLIONS)</i> .....	59
<i>FIGURE 4 QUANTUM-DOT ELECTRONICS APPLICATION SEGMENTS, 2010-2021 (% OF TOTAL MARKET)</i> .....	60
COMPUTING .....	60
DATA STORAGE AND MEMORY .....	61
DISPLAYS .....	61
COMMUNICATIONS .....	61
<i>TABLE 9 GLOBAL MARKET FOR QUANTUM-DOT COMMUNICATIONS APPLICATIONS, THROUGH 2021 (\$ MILLIONS)</i> .....	61
Optical Switches .....	62
Optical Amplifiers.....	62
Lasers .....	62
LIGHTING AND ILLUMINATION .....	63

ENERGY.....	63
Photovoltaics.....	63
SENSORS AND IMAGING EQUIPMENT .....	63
<i>TABLE 10 GLOBAL MARKET FOR QUANTUM-DOT LEDS, THROUGH</i>	
<i>2021 (\$ MILLIONS)</i> .....	<i>63</i>
Biosensors .....	64
Image Sensors.....	64
CHAPTER SIX: PHOTONIC CRYSTALS .....	65
GENERAL DESCRIPTION.....	65
DEFINITION.....	65
PROPERTIES.....	65
Two-Dimensional Versus Three-Dimensional Crystals.....	66
Defects.....	66
Static Versus Tunable Crystals .....	66
OCCURRENCE AND PRODUCTION .....	67
Micromachining .....	67
Microlithographic Techniques.....	68
Layer-by-Layer Fabrication.....	68
Autocloning .....	68
Holographic Lithography.....	69
Multibeam Interference Lithography .....	69
Glancing Angle Deposition .....	69
Stack Methods.....	70
Low-Temperature Deposition.....	70
Self-Assembly.....	71
Opal Method.....	71
Other Self-Assembly Techniques .....	71
Drawing and Extruding .....	72
APPLICATIONS AND END USES.....	72
COMPUTING .....	73
DATA STORAGE AND MEMORY.....	73
PHOTONIC-INTEGRATED CIRCUITS .....	73
ADD/DROP FILTERS .....	74
MARKETS.....	75
SUMMARY .....	75
<i>FIGURE 5 TRENDS IN THE GLOBAL MARKET FOR PHOTONIC</i>	
<i>CRYSTALS IN ELECTRONICS APPLICATIONS, 2010–2021 (\$</i>	
<i>MILLIONS)</i> .....	<i>75</i>
<i>TABLE 11 GLOBAL MARKET FOR PHOTONIC CRYSTAL</i>	
<i>ELECTRONICS BY APPLICATION, THROUGH 2021 (\$ MILLIONS)</i> .....	<i>76</i>
<i>FIGURE 6 PHOTONIC CRYSTAL ELECTRONICS APPLICATION</i>	
<i>SEGMENTS (% OF TOTAL MARKET)</i> .....	<i>76</i>
<i>FIGURE 6 (CONTINUED)</i> .....	<i>77</i>
COMPUTING .....	77

DATA STORAGE AND MEMORY .....	77
COMMUNICATIONS .....	78
<i>TABLE 12 GLOBAL MARKET FOR PHOTONIC CRYSTAL-BASED COMMUNICATIONS DEVICES, THROUGH 2021 (\$ MILLIONS)</i> .....	78
Photonic Crystal Integrated Circuits.....	78
<i>TABLE 13 GLOBAL PHOTONIC IC SALES, THROUGH 2021</i> .....	79
Add/Drop Filters .....	79
<i>TABLE 14 GLOBAL OPTICAL ADD/DROP FILTER SALES, 2010–2021</i> .....	80
 CHAPTER SEVEN: CARBON NANOTUBES .....	 81
GENERAL DESCRIPTION .....	81
DEFINITION.....	81
OCCURRENCE AND PRODUCTION .....	81
Arc Discharge.....	81
Laser Ablation .....	81
Chemical Vapor Deposition.....	81
Flame Synthesis .....	82
PROPERTIES.....	82
APPLICATIONS AND END USES.....	83
COMPUTING .....	83
Interconnects .....	83
Transistors .....	84
DATA STORAGE AND MEMORY .....	85
DISPLAYS .....	85
OPTICAL COMMUNICATIONS.....	86
ENERGY.....	87
Photovoltaics.....	87
Carbon Nanotube Composite Photoactive Layer .....	87
Carbon Nanotube Transparent Electrode .....	87
Single-Nanotube Photovoltaics .....	87
Carbon Nanotube Concentrators .....	88
SENSORS AND IMAGING EQUIPMENT .....	88
Nanosensors.....	88
Imaging Equipment.....	89
OTHER APPLICATIONS .....	89
RFID Tags.....	89
MARKETS.....	90
SUMMARY .....	90
<i>FIGURE 7 TRENDS IN THE GLOBAL MARKET FOR CARBON NANOTUBE-BASED ELECTRONIC DEVICES, 2010–2021 (\$ MILLIONS)</i> .....	  90
<i>TABLE 15 GLOBAL MARKET FOR CARBON NANOTUBE-BASED ELECTRONIC DEVICES BY APPLICATION, THROUGH 2021 (\$ MILLIONS)</i> .....	  91

<i>FIGURE 8 CARBON NANOTUBE-BASED ELECTRONIC DEVICE</i>	
<i>APPLICATION SEGMENTS, 2010-2021 (% OF TOTAL MARKET)</i> .....	91
<i>FIGURE 8 (CONTINUED)</i> .....	92
COMPUTING .....	92
ENERGY.....	92
SENSORS AND IMAGING EQUIPMENT .....	92
<i>TABLE 16 GLOBAL MARKET FOR CARBON NANOTUBE-BASED</i>	
<i>SENSORS AND IMAGING EQUIPMENT, THROUGH 2021 (\$</i>	
<i>MILLIONS)</i> .....	93
Sensors .....	93
Imaging Equipment.....	93
OTHER APPLICATIONS .....	94
RFID Tags.....	94
CHAPTER EIGHT: SUPERCONDUCTING MATERIALS .....	95
GENERAL DESCRIPTION .....	95
DEFINITION.....	95
PROPERTIES.....	95
Conductivity.....	95
Tunneling.....	96
OCCURRENCE AND PRODUCTION .....	96
APPLICATIONS AND END USES.....	97
COMPUTING .....	97
Computing (Continued).....	98
COMMUNICATIONS .....	99
Filters.....	99
Filters (Continued).....	100
Antennas .....	101
SENSORS AND IMAGING EQUIPMENT .....	101
Superconducting Quantum-Interference Devices .....	101
<i>TABLE 17 SQUID END USES</i> .....	102
MARKETS.....	102
SUMMARY .....	102
<i>FIGURE 9 TRENDS IN THE GLOBAL MARKET FOR</i>	
<i>SUPERCONDUCTING ELECTRONIC DEVICES, 2010–2021 (\$</i>	
<i>MILLIONS)</i> .....	102
<i>FIGURE 9 (CONTINUED)</i> .....	103
<i>TABLE 18 GLOBAL MARKET FOR SUPERCONDUCTING</i>	
<i>ELECTRONIC DEVICES BY APPLICATION, THROUGH 2021 (\$</i>	
<i>MILLIONS)</i> .....	103
<i>FIGURE 10 SUPERCONDUCTING ELECTRONIC DEVICE</i>	
<i>APPLICATION SEGMENTS (% OF TOTAL MARKET)</i> .....	104
COMPUTING .....	104
COMMUNICATIONS .....	105
RF Filters.....	105

SENSORS AND IMAGING EQUIPMENT .....	105
SQUIDS .....	105
CHAPTER NINE: NANOWIRES.....	106
GENERAL DESCRIPTION.....	106
DEFINITION.....	106
PROPERTIES.....	106
OCCURRENCE AND PRODUCTION .....	106
APPLICATIONS AND END USES.....	107
COMPUTING .....	107
DATA STORAGE AND MEMORY .....	107
DISPLAYS .....	108
Field Emission Displays.....	108
Transparent Conductive Panels.....	108
ENERGY.....	109
Nanowire Photoactive Layer.....	109
Nanowire Transparent Electrode .....	110
COMMUNICATIONS .....	110
SENSORS AND IMAGING EQUIPMENT .....	110
MARKETS.....	111
SUMMARY .....	111
<i>FIGURE 11 TRENDS IN THE GLOBAL MARKET FOR NANOWIRE</i>	
<i>ELECTRONIC DEVICES, 2010-2021 (\$ MILLIONS)</i> .....	111
<i>FIGURE 11 (CONTINUED)</i> .....	112
<i>TABLE 19 GLOBAL MARKET FOR NANOWIRE ELECTRONIC</i>	
<i>DEVICES BY APPLICATION, THROUGH 2021 (\$ MILLIONS)</i> .....	112
<i>FIGURE 12 NANOWIRE ELECTRONIC DEVICE APPLICATION</i>	
<i>SEGMENTS (% OF TOTAL MARKET)</i> .....	113
MEMORY .....	113
DISPLAYS .....	114
ENERGY.....	114
<i>TABLE 20 GLOBAL MARKET FOR NANOWIRE-BASED</i>	
<i>PHOTOVOLTAIC MATERIALS, THROUGH 2021 (\$ MILLIONS)</i> .....	115
Photovoltaic Materials.....	115
Transparent Electrodes.....	115
SENSORS AND IMAGING EQUIPMENT .....	116
CHAPTER TEN: CONDUCTIVE AND SEMICONDUCTIVE POLYMERS .....	117
GENERAL DESCRIPTION.....	117
DEFINITION.....	117
PROPERTIES.....	117
OCCURRENCE AND PRODUCTION .....	117
Ink-Jet Printing.....	118
Screen Printing.....	118
Roll-To-Roll (Web) Printing.....	119



APPLICATIONS AND END USES.....	119
COMPUTING .....	119
MEMORY .....	119
DISPLAYS .....	120
LIGHTING AND ILLUMINATION .....	121
ENERGY.....	122
Organic Solar Cells.....	122
OTHER APPLICATIONS .....	123
MARKETS.....	124
SUMMARY .....	124
<i>FIGURE 13 TRENDS IN THE GLOBAL MARKET FOR POLYMER ELECTRONIC DEVICES, 2010–2021 (\$ MILLIONS)</i> .....	124
<i>TABLE 21 GLOBAL MARKET FOR POLYMER ELECTRONICS BY APPLICATION, THROUGH 2021 (\$ MILLIONS)</i> .....	125
<i>FIGURE 14 POLYMER ELECTRONIC DEVICE APPLICATION SEGMENTS (% OF TOTAL MARKET)</i> .....	126
MEMORY .....	126
DISPLAYS .....	127
LIGHTING.....	127
ENERGY.....	127
OTHER .....	128
CHAPTER ELEVEN: PHASE-CHANGE MATERIALS .....	129
GENERAL DESCRIPTION.....	129
DEFINITION.....	129
PROPERTIES.....	129
OCCURRENCE AND PRODUCTION .....	130
APPLICATIONS AND END USES.....	130
DATA STORAGE AND MEMORY .....	131
MARKETS.....	132
<i>FIGURE 15 TRENDS IN THE GLOBAL MARKET FOR PHASE-CHANGE MEMORY, 2010–2021 (\$ MILLIONS)</i> .....	133
<i>TABLE 22 GLOBAL MARKET FOR PHASE-CHANGE MEMORY, THROUGH 2021 (\$ MILLIONS)</i> .....	133
CHAPTER TWELVE: MOLYBDENITE.....	134
GENERAL DESCRIPTION.....	134
DEFINITION.....	134
PROPERTIES.....	134
OCCURRENCE AND PRODUCTION .....	134
APPLICATIONS AND END USES.....	135
COMPUTING .....	135
MARKETS.....	135
<i>TABLE 23 GLOBAL MARKET FOR MOLYBDENITE ELECTRONICS APPLICATIONS, THROUGH 2021 (\$ MILLIONS)</i> .....	135

CHAPTER THIRTEEN: COMPANY PROFILES .....	136
GRAPHENE .....	136
ADVANCED MICRO DEVICES .....	136
ANGEWANDTE MIKRO- UND OPTOELEKTRONIK GMBH .....	136
BASF SE .....	136
GLOBAL FOUNDRIES, INC. ....	137
GRAPHENE DEVICES LTD. ....	137
GRAPHENE SOLUTIONS LLC .....	138
GRAPHENE WORKS INC. ....	138
GRAPHENEA.....	138
HRL LABORATORIES LLC .....	138
INTERNATIONAL BUSINESS MACHINES CORP.....	139
NUPGA .....	139
SAMSUNG ELECTRONICS CO. LTD.....	140
SANDISK CORP. ....	140
TEXAS INSTRUMENTS INC. ....	140
QUANTUM DOTS .....	141
BIOCRYSTAL LTD. ....	141
CYRIUM TECHNOLOGIES INC. ....	141
EVIDENT TECHNOLOGIES .....	142
INNOLUME GMBH.....	143
INVISAGE TECHNOLOGIES.....	143
NANOCO TECHNOLOGIES LTD. ....	143
NANOCRYSTALS TECHNOLOGY LTD.....	144
NANOSYS INC.....	144
OMNIPV INC. ....	145
QD VISION INC.....	145
QUANTUM DOT CORP.....	145
PHOTONIC CRYSTALS.....	146
COLOSSAL STORAGE CORP. ....	146
LUXTERA INC.....	146
OMNIGUIDE INC.....	146
CARBON NANOTUBES.....	147
CARBON NANOTECHNOLOGIES INC. ....	147
CARBON NANOTECH RESEARCH INSTITUTE INC.....	147
NANOCYL SA .....	147
NANOLAB INC. ....	148
NANOSTRUCTURED & AMORPHOUS MATERIALS INC. ....	148
NANTERO INC. ....	148
SOUTHWEST NANOTECHNOLOGIES INC. ....	149
UNIDYM.....	149
SUPERCONDUCTORS .....	150
CRYOELECTRA GMBH.....	150
CRYOTON LTD.....	150

D-WAVE SYSTEMS INC.....	151
HYPRES INC. ....	151
ISCO INTERNATIONAL LLC .....	152
NEOCERA INC. ....	152
QUANTUM DESIGN INC. ....	153
SUPERCONDUCTOR TECHNOLOGIES INC. ....	153
NANOWIRES.....	154
CAMBRIOS TECHNOLOGIES CORP.....	154
CARESTREAM ADVANCED MATERIALS .....	154
CIMA NANOTECH .....	155
POLYMERS.....	155
ADD-VISION INC.....	155
E.I. DU PONT DE NEMOURS AND COMPANY .....	155
MERCK OLED MATERIALS GMBH .....	156
OSRAM OPTO SEMICONDUCTORS GMBH.....	156
POLYIC GMBH & CO.....	156
RITDISPLAY CORP.....	157
THIN FILM ELECTRONICS ASA.....	157
UNIVERSAL DISPLAY CORP.....	157
PHASE-CHANGE MEMORY .....	158
MICRON TECHNOLOGY INC. ....	158
MISCELLANEOUS .....	158
NEOPHOTONICS.....	158
CHAPTER FOURTEEN: PATENTS .....	159
<i>TABLE 24 U.S. PATENTS ISSUED FOR NEW ELECTRONIC</i>	
<i>MATERIALS (NUMBER OF PATENTS).....</i>	<i>159</i>
REFERENCES .....	160
REFERENCES.....	160
REFERENCES (CONTINUED) .....	161
REFERENCES (CONTINUED) .....	162