

CHAPTER ONE: INTRODUCTION.....	1
STUDY GOALS AND OBJECTIVES.....	1
INTENDED AUDIENCE.....	1
SCOPE OF REPORT	2
INFORMATION SOURCES AND METHODOLOGY.....	3
ANALYST CREDENTIALS.....	4
RELATED BCC RESEARCH REPORTS.....	4
BCC ONLINE SERVICES.....	4
DISCLAIMER	5
CHAPTER TWO: EXECUTIVE SUMMARY.....	6
<i>SUMMARY TABLE GLOBAL MARKET FOR GRAPHENE-BASED</i>	
<i>PRODUCTS, THROUGH 2020 (\$ MILLIONS)</i>	6
<i>SUMMARY FIGURE GLOBAL MARKET FOR GRAPHENE-BASED</i>	
<i>PRODUCTS, 2009-2020 (\$ MILLIONS)</i>	7
CHAPTER THREE: OVERVIEW	8
GENERAL DESCRIPTION OF GRAPHENE	8
DEFINITION.....	8
HISTORY.....	8
OCCURRENCE AND PRODUCTION	9
Established Technologies	9
Scotch Tape Method.....	10
Epitaxial Method	10
Graphite Oxide Reduction Method	11
Experimental Approaches	12
Metal-Carbon Melt Method	12
Pyrolysis of Sodium Ethoxide Method	12
Production of Graphene from Carbon Nanotubes	12
Production of Graphene from Table Sugar	13
Dissolving Graphite in Chlorosulphonic Acid.....	13
“Molecular Wedge” Method	13
Radio Frequency Catalytic Chemical Vapor	
Deposition	14
PROPERTIES.....	14
<i>TABLE 1 GRAPHENE PROPERTIES</i>	14
Electronic Properties	15
Chemical Properties	15
Thermal Properties.....	16
Mechanical Properties.....	16
Optical Properties.....	16
RELATED SUBSTANCES.....	17
Graphite	17
Graphene Oxide	17

Carbon Nanotubes	18
Fullerenes	18
GRAPHENE APPLICATIONS AND END USES.....	19
<i>TABLE 2 POTENTIAL APPLICATIONS AND END USES OF</i>	
<i>GRAPHENE TECHNOLOGIES</i>	19
<i>TABLE 2 (CONTINUED)</i>	20
High-performance Computing	20
Data Storage	20
Communications	21
Thermal Management	21
Photovoltaic Cells	21
Sensors	21
Imaging Equipment.....	22
Displays.....	22
Capacitors	22
Structural Materials.....	22
Other Applications.....	22
MARKET SIZE AND SEGMENTATION.....	23
Market Size and Growth Trends	23
<i>FIGURE 1 TRENDS IN GLOBAL MARKET FOR GRAPHENE 2009-</i>	
<i>2020 (\$ MILLIONS)</i>	24
Applications	24
<i>TABLE 3 GLOBAL MARKET FOR GRAPHENE BY APPLICATION,</i>	
<i>THROUGH 2020 (\$ MILLIONS)</i>	25
<i>FIGURE 2 GRAPHENE APPLICATION SEGMENTS (% OF TOTAL</i>	
<i>MARKET)</i>	26
CHAPTER FOUR: GRAPHENE TECHNOLOGIES FOR HIGH-	
PERFORMANCE COMPUTING	27
SUMMARY.....	27
TECHNOLOGIES	27
TRANSISTORS	27
Graphene Switches.....	27
Quantum Confinement in Graphene Nanoribbons	28
Field-induced Modification of Graphene Structure.....	28
Ballistic Transistors.....	29
Graphene Nanomesh	29
INTEGRATED CIRCUITS	30
Graphene Interconnections	30
All-graphene Integrated Circuits.....	30
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	31
APPLICATIONS AND END USES.....	31
COMMERCIAL STATUS	31
MARKET	32

<i>TABLE 4 GLOBAL MARKET FOR GRAPHENE INTERCONNECTS, THROUGH 2020 (\$ MILLIONS)</i>	32
-------------------------------------------------------------------------------------------	----

CHAPTER FIVE: GRAPHENE TECHNOLOGIES FOR DATA STORAGE

APPLICATIONS.....	33
SUMMARY.....	33
TECHNOLOGIES.....	33
GRAPHENE SPIN VALVE.....	34
GRAPHENE NANOCABLE MEMORY DEVICE.....	34
GRAPHENE NANORIBBON MEMORY.....	34
GRAPHENE-OXIDE-BASED MEMORY.....	35
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	35
HIGH DATA DENSITY.....	35
Large On-Off Power Ratio.....	36
Wide Temperature Range.....	36
Radiation Resistance.....	36
COMMERCIAL STATUS.....	36
END USES AND APPLICATIONS.....	37
MARKETS.....	37

<i>TABLE 5 GLOBAL MARKET FOR GRAPHENE MEMORY APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	38
-------------------------------------------------------------------------------------------------	----

CHAPTER SIX: GRAPHENE TECHNOLOGIES FOR COMMUNICATIONS

APPLICATIONS.....	39
SUMMARY.....	39
TECHNOLOGIES.....	39
HIGH-SPEED PHOTODETECTORS.....	39
AMPLIFIERS.....	39
FREQUENCY MULTIPLIERS.....	40
PROPERTIES AND ADVANTAGES VS. COMPETING TECHNOLOGIES.....	40
APPLICATIONS AND END USES.....	41
COMMERCIAL STATUS.....	41
MARKET.....	41

<i>TABLE 6 GLOBAL MARKET FOR GRAPHENE COMMUNICATIONS APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	41
---------------------------------------------------------------------------------------------------------	----

CHAPTER SEVEN: GRAPHENE TECHNOLOGIES FOR THERMAL

MANAGEMENT APPLICATIONS.....	42
SUMMARY.....	42
<i>FIGURE 3 GLOBAL SALES OF GRAPHENE THERMAL MANAGEMENT APPLICATIONS, 2009–2020 (\$ MILLIONS)</i>	42
<i>FIGURE 3 (CONTINUED)</i>	43
TECHNOLOGIES.....	43

GRAPHENE NANOPATELET THERMAL INTERFACE	
MATERIALS	43
MULTILAYER GRAPHENE HEAT SPREADERS AND HEAT	
SINKS.....	44
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	45
END USES AND APPLICATIONS.....	45
COMMERCIAL STATUS	45
MARKETS.....	45
<i>TABLE 7 GLOBAL MARKET FOR GRAPHENE THERMAL</i>	
<i>MANAGEMENT APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	46
CHAPTER EIGHT: GRAPHENE TECHNOLOGIES FOR SOLAR	
PHOTOVOLTAIC APPLICATIONS.....	47
SUMMARY.....	47
<i>FIGURE 4 GLOBAL SALES OF GRAPHENE PHOTOVOLTAIC</i>	
<i>APPLICATIONS, 2009–2020 (\$ MILLIONS)</i>	47
TECHNOLOGIES	48
FLEXIBLE ORGANIC PHOTOVOLTAIC CELLS	48
POLYMER PHOTOVOLTAIC CELLS BASED ON	
SOLUTION—PROCESSABLE GRAPHENE AND P3HT	49
DYE-DOPED GRAPHITE/GRAPHENE SOLAR CELLS.....	49
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	50
END USES AND APPLICATIONS.....	50
COMMERCIAL STATUS	51
MARKETS.....	51
<i>TABLE 8 GRAPHENE TECHNOLOGIES FOR PHOTOVOLTAIC</i>	
<i>APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	52
CHAPTER NINE: GRAPHENE TECHNOLOGIES FOR SENSOR	
APPLICATIONS.....	53
SUMMARY.....	53
<i>FIGURE 5 GLOBAL SALES OF GRAPHENE-BASED SENSORS, 2009–</i>	
<i>2020 (\$ MILLIONS)</i>	53
TECHNOLOGIES	54
CHEMICAL AND GAS SENSORS.....	54
Electrochemical Sensors.....	54
Mass Sensors	54
Nanopore Sensors	55
RADIATION SENSORS.....	56
BIOSENSORS	56
DNA-sensitized Graphene Vapor Sensors.....	56
PROPERTIES AND ADVANTAGES VS. COMPETING	
TECHNOLOGIES.....	57
END USES AND APPLICATIONS.....	57
COMMERCIAL STATUS	57

MARKETS.....	58
<i>TABLE 9 GRAPHENE TECHNOLOGIES FOR SENSING APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	<i>58</i>
CHAPTER TEN: GRAPHENE TECHNOLOGIES FOR IMAGING	
APPLICATIONS.....	59
SUMMARY.....	59
TECHNOLOGIES	59
GRAPHENE FREQUENCY MULTIPLIERS	59
GRAPHENE-BASED PLASMON AMPLIFIERS	60
OTHER TECHNOLOGIES	60
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	61
END USES AND APPLICATIONS.....	61
COMMERCIAL STATUS	62
MARKET	62
<i>TABLE 10 GLOBAL MARKET FOR GRAPHENE-BASED THZ IMAGING TECHNOLOGIES, THROUGH 2020 (\$ MILLIONS)</i>	<i>63</i>
CHAPTER ELEVEN: GRAPHENE TECHNOLOGIES DISPLAY	
APPLICATIONS.....	64
SUMMARY.....	64
TECHNOLOGIES	64
ROLL-TO-ROLL PRODUCTION	64
SPRAY COATING	65
TRANSFER PRINTING.....	65
ELECTROPHORETIC DEPOSITION	65
HYBRID GRAPHENE-CARBON NANOTUBE FILM	66
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	66
END USES AND APPLICATIONS.....	66
COMMERCIAL STATUS	67
MARKET	67
<i>TABLE 11 GRAPHENE TECHNOLOGIES FOR DISPLAY APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	<i>68</i>
CHAPTER TWELVE: GRAPHENE TECHNOLOGIES FOR CAPACITIVE	
APPLICATIONS.....	69
SUMMARY.....	69
<i>FIGURE 6 GLOBAL SALES OF GRAPHENE CAPACITIVE APPLICATIONS, 2009–2020 (\$ MILLIONS)</i>	<i>69</i>
TECHNOLOGIES	70
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	71
END USES AND APPLICATIONS.....	72
COMMERCIAL STATUS	72
MARKETS.....	73

<i>TABLE 12 GRAPHENE TECHNOLOGIES FOR CAPACITIVE APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	73
CHAPTER THIRTEEN: GRAPHENE TECHNOLOGIES FOR STRUCTURAL MATERIAL APPLICATIONS	74
SUMMARY.....	74
<i>FIGURE 7 GLOBAL SALES OF GRAPHENE POLYMER COMPOSITES, 2009–2020 (\$ MILLIONS)</i>	74
TECHNOLOGIES	75
GRAPHENE-FILLED POLYMER COMPOSITES.....	75
Graphene-polystyrene Composites	75
Other Graphene-polymer Composites	76
<i>TABLE 13 TYPES OF CARBON NANOTUBE AND FULLERENE COMPOSITES AND THEIR PROPERTIES</i>	76
GRAPHENE MATRIX COMPOSITES.....	76
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	77
END USES AND APPLICATIONS.....	78
COMMERCIAL STATUS	78
MARKETS.....	79
<i>TABLE 14 GLOBAL MARKET FOR GRAPHENE POLYMER COMPOSITES, THROUGH 2020 (\$ MILLIONS)</i>	79
CHAPTER FOURTEEN: GRAPHENE TECHNOLOGIES FOR OTHER APPLICATIONS AND MARKETS.....	80
SUMMARY.....	80
<i>TABLE 15 GRAPHENE TECHNOLOGIES FOR OTHER APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	80
HYDROGEN STORAGE.....	80
TECHNOLOGIES	81
Oxidized Graphene Sheets	81
Other Developments.....	82
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	82
END USES AND APPLICATIONS	83
COMMERCIAL STATUS.....	83
MARKET	83
<i>TABLE 16 GLOBAL MARKET FOR GRAPHENE-BASED HYDROGEN STORAGE TANKS, THROUGH 2020 (\$ MILLIONS)</i>	84
ANTIBACTERIALS	84
TECHNOLOGIES	84
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES.....	85
END USES AND APPLICATIONS	85
COMMERCIAL STATUS.....	86
MARKETS	86

<i>TABLE 17 GLOBAL MARKET FOR GRAPHENE-BASED ANTIBACTERIAL APPLICATIONS, THROUGH 2020 (\$ MILLIONS)</i>	86
RFID TAGS	87
TECHNOLOGIES	87
PROPERTIES AND ADVANTAGES VS. OTHER TECHNOLOGIES	87
END USES AND APPLICATIONS	88
COMMERCIAL STATUS.....	88
MARKET	88
<i>TABLE 18 GLOBAL MARKET FOR GRAPHENE-BASED RFID ANTENNAS, THROUGH 2020 (\$ MILLIONS)</i>	89
CATALYST SUPPORTS	89
TECHNOLOGIES	89
Reduced Graphene Oxide-Supported Platinum Catalyst	89
Nitrogen-doped Graphene Nanoplatelet—Supported Catalyst.....	90
PROPERTIES AND ADVANTAGES VS. ALTERNATIVE MATERIALS	90
APPLICATIONS AND END USES	91
COMMERCIAL STATUS.....	91
MARKET	91
<i>TABLE 19 GLOBAL CONSUMPTION OF PLATINUM CATALYST MATERIALS AND NANOSTRUCTURED SUPPORT MATERIALS USED IN FUEL CELLS, THROUGH 2020 (\$ MILLIONS)</i>	92
<i>TABLE 20 GLOBAL MARKET FOR GRAPHENE CATALYST SUPPORT MATERIALS, THROUGH 2020 (\$ MILLIONS)</i>	92
CHAPTER FIFTEEN: INDUSTRY STRUCTURE	93
NUMBER AND SIZE OF COMPANIES.....	93
<i>FIGURE 8 GEOGRAPHICAL DISTRIBUTION OF COMPANIES WITH PRODUCTION OR ACTIVE R&D ACTIVITIES IN GRAPHENE (%)</i>	93
COMPANY PROFILES	94
ADVANCED MICRO DEVICES	94
ALLOTROPICA TECHNOLOGIES	94
ANGEWANDTE MIKRO- UND OPTOELEKTRONIK GMBH	95
ANGSTRON MATERIALS, INC.	95
BASF SE	95
CVD EQUIPMENT CORP.	96
DURHAM GRAPHENE SCIENCE	96
GENERAL MOTORS CO.....	96
GLOBAL FOUNDRIES, INC.....	97
GRAFTECH INTERNATIONAL, LTD.	97
GRAPHENE DEVICES, LTD.....	97
GRAPHENE ENERGY, INC.	98
GRAPHENE FRONTIERS	98

GRAPHENE INDUSTRIES, LTD.	98
GRAPHENE SOLUTIONS, LLC	99
GRAPHENE SUPERMARKET	99
GRAPHENE WORKS, INC.	99
GRAPHENEA.....	100
HARBIN MULAN FOREIGN ECONOMIC AND TRADE CO.	100
HRL LABORATORIES, LLC	100
INTERNATIONAL BUSINESS MACHINES CORP.....	101
NANOTEK INSTRUMENTS, INC.....	101
NUPGA	102
QUANTUM MATERIALS CORP.	102
SAMSUNG ELECTRONICS CO., LTD.....	102
SANDISK CORP.	103
TEXAS INSTRUMENTS, INC.	103
UNIDYM.....	103
VORBECK MATERIALS	104
XG SCIENCES, INC.	104
ZS GENETICS, INC.....	105
APPENDIX: PATENTS	106
PATENT ANALYSIS	106
TRENDS OVER TIME	106
<i>FIGURE 9 TREND IN NUMBER OF U.S. GRAPHENE PATENTS</i>	
<i>ISSUED ANNUALLY, 2003-2010.....</i>	<i>106</i>
<i>FIGURE 9 (CONTINUED)</i>	<i>107</i>
TECHNOLOGY TRENDS.....	107
<i>FIGURE 10 U.S. PATENTS FOR AND PATENT APPLICATIONS FOR</i>	
<i>GRAPHENE BASIC AND PRODUCTION TECHNOLOGIES VS.</i>	
<i>TECHNOLOGY IMPLEMENTATIONS (%)</i>	<i>107</i>
<i>FIGURE 10 (CONTINUED)</i>	<i>108</i>
<i>FIGURE 11 U.S. PATENTS FOR GRAPHENE APPLICATIONS BY</i>	
<i>TYPE OF APPLICATION (%)</i>	<i>109</i>
<i>FIGURE 11 (CONTINUED)</i>	<i>110</i>
IP PORTFOLIOS.....	110
<i>FIGURE 12 MAJOR GRAPHENE IP PORTFOLIOS (NUMBER OF U.S.</i>	
<i>PATENTS/PATENT APPLICATIONS).....</i>	<i>111</i>
<i>FIGURE 12 (CONTINUED)</i>	<i>112</i>
TYPES OF ENTITIES	112
<i>FIGURE 13 U.S. GRAPHENE PATENT HOLDERS/ASSIGNEES BY</i>	
<i>TYPE OF ENTITY (%).....</i>	<i>113</i>
NATIONALITIES.....	114
<i>FIGURE 14 U.S. GRAPHENE PATENT AND PATENT APPLICATION</i>	
<i>HOLDERS BY NATIONALITY (%)</i>	<i>114</i>
<i>FIGURE 14 (CONTINUED)</i>	<i>115</i>

SUMMARY OF RELEVANT PATENTS AND PATENT APPLICATIONS	116
ISSUED PATENTS	116
<i>TABLE 21 U.S. PATENTS ISSUED THROUGH DEC. 31, 2010 FOR GRAPHENE-RELATED INVENTIONS</i>	116
<i>TABLE 21 (CONTINUED)</i>	117
<i>TABLE 21 (CONTINUED)</i>	118
<i>TABLE 21 (CONTINUED)</i>	119
<i>TABLE 21 (CONTINUED)</i>	120
<i>TABLE 21 (CONTINUED)</i>	121
<i>TABLE 21 (CONTINUED)</i>	122
PATENT APPLICATIONS	122
<i>TABLE 22 U.S. PATENT APPLICATIONS PENDING AS OF DEC. 31, 2010, FOR GRAPHENE-RELATED INVENTIONS</i>	122
<i>TABLE 22 (CONTINUED)</i>	123
<i>TABLE 22 (CONTINUED)</i>	124
<i>TABLE 22 (CONTINUED)</i>	125
<i>TABLE 22 (CONTINUED)</i>	126
<i>TABLE 22 (CONTINUED)</i>	127
<i>TABLE 22 (CONTINUED)</i>	128
<i>TABLE 22 (CONTINUED)</i>	129
<i>TABLE 22 (CONTINUED)</i>	130
<i>TABLE 22 (CONTINUED)</i>	131
<i>TABLE 22 (CONTINUED)</i>	132
<i>TABLE 22 (CONTINUED)</i>	133
<i>TABLE 22 (CONTINUED)</i>	134
<i>TABLE 22 (CONTINUED)</i>	135
<i>TABLE 22 (CONTINUED)</i>	136
<i>TABLE 22 (CONTINUED)</i>	137
<i>TABLE 22 (CONTINUED)</i>	138
<i>TABLE 22 (CONTINUED)</i>	139