

Index

a

active materials 68, 98–101, 148,
208, 276
all solid-state asymmetric in-plane m-ECs
228, 229
aqueous polymeric gels 104–105
aqueous self-healing electrodes 271–272
automobile battery research and
development 8
autonomic healing 265

b

battery management system 263
bendability 95
bendable cells
flexible substrates and neutral plane
71–72
mechanical process 69–70
thickness effect 70–71
brittle materials 68
Bruggeman relation 156
bulk electrodes
advantages 152, 153
architecture 152
based on CNT conductive network
184
based on conductive polymer gels
191–193
with directional pore distribution
165–178
carbonized wood template method
168–172
3D printing of 173–175

ice templates method 172–173
iterative extrusion method
165–167
magnetic induced alignment method
168
disadvantages 152–153
fabrication methods 159–160
LiFePO₄-based 161
low tortuosity 155–157
performance evaluation 176–178
with random pore structure 160–165
cold sintering process 161–162
pressure-less high-temperature
sintering process 160–161
spark plasma sintering 162–165

c

calendering density 194
of electrode 149, 151–153
carbide-derived carbon 235
carbon based foam electrodes
CNT foams 181
CNT/graphene foam 181–182
graphene foam 179–180
carbon-based foam electrodes 189
disadvantages 189
carbonized wood template method
168–172
carbon nano tubes (CNTs) 33
carbon/polymer 3D m-LIBs 240
carbon/polypyrrole 3D interdigitated
configuration m-LIB 241
cellulose nanofibril paper 108

- chemical vapor deposition (CVD)
 - for CNT foam fabrication 181
 - graphene foam fabrication 179–180
 - C-LiFePO₄/C-PPy foam electrodes 192
 - CNT and graphene based flexible cells
 - 121–122
 - flexible CNTs/graphene composite films 125–127
 - free-standing films for ECs and LIBs 121–122
 - free-standing graphene and CNT films for LIBs 122–124
 - CNT foam
 - application 183
 - CNT foams 181
 - CNT/graphene foam 181–182
 - advantages 182, 187
 - CNT/graphene foam electrodes 182
 - CNTs 98
 - cold sintering process 161–162
 - commercial paper 108
 - compact graphene electrodes 188–189
 - conducting polymers, for electrochemical capacitors 42
 - conductive cellulose nanofiber fabrication 185
 - conductive nanofiber framework 185
 - conductive polymer based foam electrodes 191–193
 - conductive PPy/Fe₃O₄ gel framework 191
 - construction of
 - thermal-responding layer 274–276
 - construction principles of flexible cells 95
 - conventional cells 51, 263
 - architecture design procedures 50
 - disadvantages of
 - architecture 68–69
 - electrolytes 69
 - mechanical properties 67–68
 - electrode composite and size design process 51
 - electrode manufacturing process 51
 - electrolyte injecting and formation 51
 - mixing, coating, calendering and winding 51
 - performance requirements and design 50
 - cycle performance 77
 - cyclic voltammetry (CV) 77
 - cylindrical LIBs 16
- d**
- directional freezing method 172–174
 - double layer capacitance 5
 - dual-graphene-based lithium ion capacitor 22
 - dynamic covalent self-healing mechanism 264–265
- e**
- electric double layer capacitor (EDLC)
 - activated carbon for 40
 - carbon nanotubes for 41
 - graphene electrode material for 41
 - electric double-layer capacitors 9
 - electric double-layer capacitors (EDLCs)
 - charge storage mechanism 20
 - electrode materials for 18–20
 - Gouy-Chapman model 18–19
 - Helmholtz model 18
 - liquid ion electrolyte 19
 - solid/solid electrode interface 19–20
 - Stern model 19
 - electric double-layer miniaturized electrochemical capacitors, valuation methods for 210–211
 - electricity, advantages 2
 - electrochemical batteries 5
 - electrochemical capacitor (ECs) 6, 149
 - electric double-layer capacitors 18
 - electrolytes for 45
 - energy storage mechanism 9, 18
 - evaluation methods for 49
 - history of 8
 - vs. lithium-ion batteries 9, 10, 52
 - performance 18
 - separators for 45

- electrochemical deposition method, for
2D interdigitated cells 228–231
- electrochemical energy storage
application 3
classification of 4–5
development history 3–4
power vs. energy density 6–10
- electrochemical energy storage system 1
- electrochemical impedance spectroscopy
(EIS) 77
- electrochromic materials 267–268
- electrochromic oxides 267
- electrochromism
architecture of 287
characteristics 287
definition 286–287
LIBs 289–291
organic and inorganic 289
pseudocapacitor 287–289
transition metal oxides 288
tungsten oxide 288
- electrode manufacturing process 51
- electrode materials, for miniaturized cells
213–214
- electrodeposited carbon-coated
LiFePO₄/PPy material 193
- electrodeposition method 3D
interdigitated configuration cell
fabrication, 239–240
- electrolytes
for flexible ECs
aqueous polymeric gels 104–106
inorganic solid materials 106
non-aqueous polymer gel 106, 108
for flexible LIBs
inorganic solid-state electrolytes
102–103
solid-state polymer electrolytes 104
for miniaturized cells 214–215
- electrolytic deposition (ELD) 228–231
- electronic gadgets 67
- electrophoretic deposition (EPD)
228–231
- electrospinning 98
- energy generation 1
- ethoxylated trimethylolpropane
triacrylate (ETPTA) 104
- evaporation-induced compact GO
disadvantages of 189
- extrusion-based 3D printing technique
175, 224
- f**
- Faradaic capacitor 20
- Faradaic ECs 9
- Faradic reaction 287
- flexible cells
active materials
CNTs 98–99
graphene 99
low-dimensional materials 99–101
- bendable cells
flexible substrates and neutral plane
71–72
mechanical process 69–70
thickness effect 70–71
- construction of
stretchable cells based on
island-bridge architecture
129–131
stretchable cells based on wavy
architecture 127–129
- construction principles of 95
- conventional cells 67–68
- dynamic electrochemical performance
of
bending 83–85
bending characterization 78
conformability test 79
stress simulation by finite element
analysis 79–82
stretching 86–88
stretching characterization 78–79
- electrolytes 101
- electrolytes development 132
- innovative architecture designs 132
- integrated flexible devices 133
- mechanical performance improvement
131
- nonconductive substrates 107–121

- flexible cells (*contd.*)
 - packaging and tabs 132–133
 - static electrochemical performance of 76–77
 - stretchable cells 72–76
 - substrate materials
 - paper 97
 - polymer 96–97
 - requirements 96
 - textile 98
 - flexible CNTs/graphene composite films 125–127
 - flexible electronic technology 67
 - fluorine-modified graphene based m-ECs 226, 227
 - foam electrodes 151–153
 - advantages 153
 - architecture 152
 - carbon based with high gravimetric energy density 178–179
 - CNT foam 181
 - CNT/graphene foam 181–182
 - graphene foam 179–180
 - disadvantages 152
 - fossil energy 1
 - free-standing graphene and CNT films for LIBs 122–124
 - Free-standing graphene and CNTs films for SCs 121–122
 - freeze-drying method 179
- g**
- galvanostatic charge/discharge 77
 - gel polymer electrolyte 104
 - global energy consumption 1–2
 - graphene 99
 - based 2D interdigitated m-ECs 235
 - based m-ECs 226
 - compact electrode 188
 - composites 34
 - macroscopic structures 214
 - properties of 179
 - graphene foam
 - application 183
 - bidirectional freezing process 180
 - chemical vapor deposition method 179
 - design and compressive elasticity of 180
 - drying process 179
 - properties of 180
 - self-assembly of GO 179
 - graphite, for LIBs 29–31
 - gravimetric capacity exertion (c_p), of LIB material 150
 - gravimetric energy density, of electrodes 149–151
- h**
- hard carbon 31–33
 - heterogeneous Co_3O_4 /graphene foam 186
 - high-density bulk PANI/graphene bulk electrode synthesis 189, 190
 - high energy density cells
 - electrodes
 - gravimetric and volumetric energy density of 149–151
 - thick electrode, classification of 151–153
 - factors related to 154
 - strategies for 147–149
 - architecture design 148
 - materials and chemistry development 147–148
 - holey-graphene/ Nb_2O_5 foam 187
 - hybrid capacitors 21–22
 - charge storage mechanisms 21
 - dual-graphene-based lithium ion capacitor 22
 - and symmetric ECs 22
 - hybrid ECs 9
 - “hydrothermal lithiation” method 101
 - hyper-branched architecture
 - self-terminated oligomer 278
- i**
- ice templates method 172–173
 - inkjet printing technique 228
 - feature of 228

- planar m-ECs on paper substrates 228
 - thin and porous electrode films 228
 - inks with Newtonian behavior 222
 - inks with non-Newtonian behavior 222
 - inks with thixotropic/pseudoplastic behavior 222–223
 - inorganic amorphous sulphides 102
 - inorganic ceramic electrolytes 103
 - inorganic solid materials 106
 - inorganic solid-state electrolytes 102–103
 - in-situ electrode conversion, for 2D interdigitated cells 234–236
 - integrated electrochromic architectures for energy storage, electrochromic devices 287
 - integrated flexible devices 133
 - integrated self-powered smart sensor system 248249
 - integrated Si-based solar cells 248
 - integrated systems 247–249
 - interdigitated microelectrode array 244
 - Internet of Things (IoTs) 205
 - ionic blocking effect based thermal response electrodes 278–280
 - island-bridge architectures 75–76
 - iterative extrusion method, for electrode fabrication 165–167
- L**
- large volume variation materials/carbon foam 186–188
 - laser induced graphene based m-ECs 233
 - laser scribing, for 2D interdigitated cells 231–234
 - layered $\text{Li}(\text{Ni}_x\text{Co}_{1-x})\text{O}_2$ material 26
 - LiCoO_2 material 23–25
 - LiFePO_4 -gel foam electrode 192
 - LiFePO_4 material 27–28
 - LiMn_2O_4 polycrystalline thin films 217
 - Li-polymer 3D m-LIBs 247
 - liquid-alloy self-healing electrode materials 273–274
 - liquid electrolytes
 - for LIBs 42
 - for miniaturized cells 215
 - lithiation-delithiation processes 35–37
 - lithium ion batteries (LIBs)
 - conventional materials for 22–23
 - LiCoO_2 positive active material 23–25
 - LiFePO_4 material 27–28
 - LiNiO_2 and derivative 25–26
 - lithium-manganese-rich materials 28
 - material status of 22
 - negative materials 23
 - positive material properties 23
 - spinel LiMn_2O_4 26–27
 - vs. electrochemical capacitors 52
 - electrochromism 289–291
 - energy density 16
 - mechanisms of 16
 - principle of 15
 - lithium-ion batteries (LIBs) 6–10, 147
 - advantages 16–17
 - alloy-based materials 35–39
 - Chinese market shares 28–29
 - commercialization 7
 - cycle life 48
 - cyclic and linear carbonates in 43
 - disadvantages 17–18
 - for electric vehicles 8
 - vs. electrochemical capacitors (ECs) 9–10
 - electrodes for 153
 - electrolyte used in 42
 - energy and power densities 208
 - energy and power density 47–48
 - evaluation of 46
 - graphene for 34
 - graphene hybrid materials 35
 - gravimetric and volumetric energy density 46–47
 - history, current status and development 8
 - intercalation/deintercalation reaction materials 37
 - $\text{Li}_4\text{Ti}_5\text{O}_{12}$ based 37

- lithium-ion batteries (LIBs) (*contd.*)
 - metal lithium negative for 39
 - nanocarbon materials 33–35
 - nanosized silicon materials for 36
 - negative materials for
 - characteristics 29
 - Chinese market share 33
 - graphite 29–31
 - soft and hard carbons 31–33
 - porous carbon materials for 40–41
 - porous materials 36–37
 - properties 6
 - safety 48
 - separators for 45–46
 - silicon/carbon composite materials for 36
 - solid state electrolytes 45
 - thickness of electrodes 208
 - TiO₂ for 38
 - transition metal oxides in 37–39
 - lithium ion capacitor 22
 - lithium-manganese-rich materials 28
 - Li₄Ti₅O₁₂/graphene foam electrode 184
 - low-dimensional materials (LIBs)
 - architecture of 99
 - electrolytes
 - inorganic solid-state electrolytes 102
 - solid-state polymer electrolytes 104
 - MXene phases 100
 - low electronic conductive material/
 - carbon foam 182–186
- m**
- magnetic induced alignment method 168
 - magnetron sputtering process 216–217
 - mesocarbon microbeads (MCMB) 30
 - metal lithium negative, for LIBs 39
 - microchannel plated deposition method 245–247
 - micro encapsulation based self-healing system 265
 - microvascular self-healing systems 265
 - miniaturized cells
 - architectures of 212
 - classification of 206
 - 3D 208
 - development trends of 207–209
 - 2D interdigital configuration 212–213
 - 3D interdigitated configuration 212–213
 - 2D parallel plate configuration 212–213
 - 3D stacked configuration 212–213
 - with 3D stacked configuration 240–247
 - microchannel plated deposition methods 245–247
 - template deposition 241–245
 - electrode materials 213–214
 - electrolytes for 214–215
 - evaluation methods 209–210
 - examples of 206
 - fabrication technologies for 215–220
 - high performance 209
 - integration of 209
 - market of 206
 - performance of 207
 - polymer electrolytes 215
 - research and development 209
 - volume characteristics 210
 - volumetric energy density 205
 - miniaturized electrochemical capacitors (m-ECs) 206, 207
 - all solid state asymmetric in-plane 228, 229
 - based on carbide-derived carbon film 235
 - carbide-driven carbon 235
 - carbon materials 213
 - conducting polymers 214
 - evaluation methods for 211
 - graphene material for 213
 - laser scribed graphene electrodes for 232, 234
 - pseudocapacitive materials 214
 - screen printed 225
 - on a silicon wafer 235–236

solid-state 215
 using RuO₂ films 219–220
 miniaturized lithium ion batteries
 (m-LIBs) 205, 206
 evaluation methods for 211–212
 mask-assisted fabrication 226
 materials for 214
 screen printing 225
 solid-state 215
 using Li₄Ti₅O₁₂ anode and LiFePO₄
 cathode 226
 MoO_{3-x}-CNTs-cellulose nano fibers
 electrodes 111
 MoS₂@ CNT@GF foam 187
 multiwall carbon nanotubes (MWCNTs)
 34
 MXene phases 100
 MXene water-based ink 238

n

nanocarbon materials 68
 nano fibers of cellulose (NFC) 110
 nanosized silicon materials 36
 nanostructured 3D m-LIB fabrication
 243
 neutral plane 69
 nitrogen-doped graphene/Fe₃O₄
 hydrogels fabrication 186–187
N-methyl-2-pyrrolidone (NMP) solution
 279
 non-aqueous polymer gel 106, 107
 non-autonomic healing 265
 nonconductive substrates based flexible
 cells
 disadvantages of 108
 paper-based flexible cells 108–112
 physical methods 107
 polymer 117–120
 textiles-based flexible cells 112–117

o

on-chip thin film m-LIBs 217, 218
 organic and inorganic electrochromic
 materials 289
 oxide solid-state electrolytes 102

p

PANI/Au/paper electrode 111
 paper-based flexible cells 108–112
 paper substrate 97
 paraffin wax microspheres 279
 pseudocapacitor miniaturized
 electrochemical capacitors 211
 photolithography 239–240
 planar m-ECs using graphene materials
 fabrication 225
 plasma-activated sintering 162
 poly(3-decylthiophene) (P3DT) 278
 poly(ethylene oxide) (PEO) 104
 polyacrylic acid/uriedo-pyrimidinone
 (PAA-U_{py}) 271
 polydimethylsiloxane (PDMS) 96
 polydopamine (PDA) 279
 polyethylene naphthalate (PEN) 96
 polyethylene terephthalate (PET) 96
 polyimide (PI) 96
 polymer materials 68
 polymer substrates 96–97
 polymer substrates based flexible cells
 117–120
 polyurethane (PU) 96
 porosity adjustable graphene bulk
 electrodes 189, 191
 porous carbon materials, for LIBs 40
 porous electrodes, tortuosity of 157
 porous graphene foam fabrication 188
 porous materials 36
 portable electronics 52, 147
 positive temperature coefficient (PTC)
 materials 266
 pouch-type LIBs 16
 pressure-less high-temperature sintering
 process 160–161
 primary battery 5
 printing technology 107
 prismatic LIBs 16
 pseudocapacitance 5, 20, 21
 pseudocapacitor 20, 287
 pseudo-capacitors 9
 transition metal oxides for 41
 pulse electric current sintering 162

pyrolytic photoresist-derived carbon
electrode 234

r

renewable energy 1
renewable energy based electricity 3
renewable energy sector, employment in
2
renewable energy sources 10
RF magnetron sputtering 216–218
limitation 224

s

screen printing, for miniaturized cells
advantages 225
asymmetric m-ECs construction 225
description 224
design flexibility 224
graphene based 226
vs. RF magnetron sputtering 224
substrate patterning 224
using highly-conducting graphene ink
226
secondary batteries 5, 6
self-healing materials 264
self-healing silicon anodes 268
self-powered smart sensor system
248–249
shape-adapting cells 266
shape-memory alloys 265
shape-memory materials in LIBs and Ecs
alloy based thermal regulator 281–282
self-adapting cells 280–281
self-heating 283–285
self-monitoring 285–286
Si-based thin film electrodes 219
silicon/carbon composite materials 36
sintering, advantages of 165
Si particle/conducting polymer/CNT
hybrid material 193
smart cells
definition of 263
integrated electrochromic architectures
for energy storage 286
smart devices 263

smart materials
construction of
aqueous self-healing electrodes
271–272
ionic blocking effect based thermal
response electrodes 278–279
liquid-alloy self-healing electrode
materials 273–274
self-healing silicon anodes 268–271
thermal-responding layer 274–276
thermal response electrodes based
PTC effect 276–277
definition of 263–264
electrochromic materials 267
self-healing materials 264
shape-memory alloys 265
thermal-responding PTC thermistors
266
soft carbon 31, 32
solid-state polymer electrolytes 104
spark plasma sintering 162
spinel LiMn_2O_4 material 26
stage index 29
stage phenomenon 29, 30
static electrochemical performance 76
stencil-printed gel composite electrolytes
215–216
stretchable cells
innovative architecture 132
island-bridge architectures 75–76
wavy architectures
large-deformation buckling process
74–75
small deformation buckling process
72–74
stretchable cells based on island-bridge
architecture 129–131
stretchable cells based on wavy
architecture 127–129
Stretchable devices 95
stretchable m-EC array with integrated
strain sensors 248
substrate materials
flexible cells
paper 97

polymer 96–97
 requirements 96
 textile 98
 supercritical drying method 179

t

tandem m-EC bridging solar cell and gas sensor 248
 tap density 150
 tap density, for electrodes 149
 template deposition method, for
 miniaturized cells with 3D stacked configuration 241
 textiles-based flexible cells 112
 textile substrate 98
 thermally sensitive polymer-based
 polymer 279
 thermal regulator 266
 thermal-responding layer 274
 thermal-responding positive temperature coefficient (PTC) materials 266
 thick bulk electrodes 152
 thick electrodes 147
 thick LiFePO₄ electrode fabrication 186
 thin film 2D m-ECs 208
 thin film 2D m-LIBs 208
 thin film solid state m-LIBs 216
 3D conductive network 178
 3D foam electrodes 153
 3D in-plane miniaturized cell fabrication 236
 3D printing 236
 3D interdigitated configuration cell fabrication 239
 3D porous graphene film preparation 233
 3D printing process
 classification of 237
 defined 236–237
 3D interdigitated m-LIBs 238–239
 fused deposition modelling 237
 of m-ECs 238
 powder-liquid 238
 schematic illustration 237
 selective laser sintering 238

stereolithography 238
 for thick electrodes 173
 3D solid-state m-LIB
 architecture 242
 based on imprinted microelectrodes 243
 power performance 242
 tortuosity, in porous electrodes 156
 tortuosity, of porous electrodes
 numerical simulation 158–159
 X-ray tomography 157–158
 transition metal oxides 267–288
 transition metal oxides (TMOs), for
 pseudocapacitors 41
 true density 149
 tungsten oxide 288
 2D interdigitated cells
 electrochemical deposition method for 228
 fabrication technologies for 220–221
 in-situ electrode conversion 234–236
 laser scribing for 231
 performance evaluation 220–222
 printing technologies
 advantages 222
 classification of 222
 inkjet printing technique 228
 and rheological behavior 222–224
 screen printing 224
 2D parallel plate miniaturized cell fabrication 216
 2D planar miniaturized cells, fabrication of 220, 221

u

ultrahigh-voltage integrated m-ECs,
 graphene based 226, 227
 ureidopyrimidinone grafted polyethylene glycol (UPy-PEG-UPy) binders 271

v

vacuum filtration method 111
 volumetric energy density, of electrodes 149

W

wavy architecture 127

wavy architectures

 large-deformation buckling process

 74–75

 small deformation buckling process

 72–74

WO₃ 267

wood-derived all-solid-state

 electrochemical capacitor 172

W-RuO₂-based m-EC 219

X

Xerox paper 108

Y

Young's modulus 70

