

Index

a

absorbable implantable devices 355
 accelerator parameters 212
 acoustic sensor 213–215
 active chemical/environmental sensors 219–222
 active motion sensor
 angle sensor 217
 characteristics 215
 linear displacement sensor 215–216
 omnidirectional sensor 217–219
 active sensors
 chemical/environmental sensors 219–222
 motion sensor
 angle sensor 217
 characteristics 215
 linear displacement sensor 215–216
 omnidirectional tilt sensor 217–219
 touch sensor 205
 single-electrode touch sensor 207–210
 static and dynamic pressure sensor 206
 tactile imaging sensor 206–207
 UV sensor 221–222
 vibration sensor 210
 acceleration sensor 212
 acoustic sensor 213–215
 direction sensor 213
 quantitative amplitude measurement 210–211

active touch sensor
 single-electrode touch sensor 207–210
 static and dynamic pressure sensor 206
 tactile imaging sensor 206–207
 active vibration sensor 210
 acceleration sensor 212
 direction sensor 213
 quantitative amplitude measurement 210–211
 actuators 253
 biomedicine
 biocompatible materials 261
 bladder illness curation 261–264
 drug delivery 264–267
 harvest energy 261
 industrial application 267
 electrospinning system 268–270
 syringe printing 270–271
 MEMS 253
 microfluidic manipulation 272
 droplet motion drive 272–274
 microfluidic transport 274–276
 optical system, laser controller 254–257
 tunable optical membrane 258–261
 air-cleaning system 387
 air pollution 235, 379, 385
 all-fiber based self-powered microsystem 326
 all-in-one energy harvesting 307
 flexible energy harvester 310–311
 multi-mechanism energy harvester 312–316

- all-in-one energy harvesting (*contd.*)
- triboelectric-electromagnetic-thermoelectric nanogenerator 309
- all-in-one power unit 307
- connection of TENGs and traditional circuits 316–320
- power management module (PMM) 316, 317
- TENGs and flexible supercapacitor integration 320–325
- all-in-one self-charging power unit 320, 325
- all-in-one self-powered microsystems
- actuators 328
 - energy storage units 307
 - fiber-based 326
 - hybrid energy harvesting 307
 - micro energy harvesting 307
 - micro/nanosensing 307
 - multiple functional electronic components 307
 - proceeding/responding 307
 - self-charging smart bracelet 328
 - smart display 307
- all-in-one shape-adaptive self-charging power unit 322
- aluminum (Al) foil 64, 272, 345
- ambient energy harvesting technology 3, 9
- angle sensor 217
- arch-shaped TENG 26–30, 52
- artificial intelligence (AI)
- electronic skin 368–371
 - flexible and stretchable self-powered smart systems 367
 - human-machine interface 374–376
 - robotic prosthetics 371–374
 - self-powered devices and technology 367
- Au NS electrode-based TENG (Au NS-TENG) 375
- b**
- backlight units (BLUs) 125
- battery-based power supply 345
- bending sensing 288–289
- β-cyclodextrin (β-CD) 380
- biodegradable polymers (BDPs) 355
- biodegradable triboelectric nanogenerator (BD-TENG) 355
- biomedical systems
- implantable medical device 339
 - self-powered electrical stimulation 353–354
- bladder illness curation 261–264
- blending conductive fillers 189
- bluetooth module 353, 361
- body sensor network (BSN) 352–353
- boron nitride 151
- c**
- capacitive load 78–80, 256, 259
- capacitive transformer 77, 81–83, 85, 90
- carbon nanotube (CNTs) 133
- applications 136–138
 - fabrication methods 133
 - bulk materials 134
 - surface materials 134–136
- carbon quantum dots (CQCs) 115–116
- cardiac monitoring 345–347, 364
- carnot efficiency 59
- catecholamines 382
- cathodic protection (CP) technology 391–393
- Center for Emergent Matter Science 102
- ceramics 8
- chemical exfoliation 153–154
- chemical sensor 219–220
- chemical synthesis 53–54, 390
- chemical vapor deposition (CVD) method 100, 134, 153
- Chinese Academy of Science 53, 70, 82, 90, 139, 235, 240, 254, 258, 268, 270, 293, 294, 340, 342, 344, 345, 347, 353, 355
- composite based conductive materials 189
- blending conductive fillers 189

- film embedded into stretchable elastomer 191–194
- composite materials 97, 102, 183, 199
- conductive composite 189–191
- conductive polymers 7, 121, 134, 183, 185, 189, 190
- contact-separation (CS) mode 19, 21, 272
- output performances 11
- working principle 10
- copper (Cu) 7, 26, 44–46, 49, 65, 155, 156, 196, 262, 263, 269, 364, 390
- cross-linked TENG (cl-TENG) 389
- Cu-coated polyethylene terephthalate (Cu-PET) 49
- cycles for energy output (CEO) 61
- cycles for maximized energy output (CMEO) 62
- d**
- dermis 281, 282, 373, 374
- dielectric optical electrode (DOE) 258
- 4-dimethylaminophenylazo (AAB) 384
- dopamine detection 382–383
- downy-structure-based TENG 352, 353
- droplet motion drive 272–274
- drug delivery 264–268, 274, 276
- dual hybrid power technology
- triboelectric–electromagnetic nanogenerator 233–234
 - triboelectric–photovoltaic nanogenerator 231–233
 - triboelectric–piezoelectric nanogenerator 228–231
- dual-mode triboelectric nanogenerator 374
- e**
- electrical operating cycles
- cycles for energy output 61–64
 - measurements 64–65
 - V – Q plot and characteristics 60–61
- electrical output signals 60, 77, 205
- electrification effect 9, 12, 14, 19, 21, 23, 368
- electrochemical polymerization system 389–390
- electrochemical reduction system 390–391
- electrodes 9–11, 14, 21–23, 26, 33, 35, 44, 45, 60, 67, 77, 97, 100, 113, 117, 123–126, 138, 143, 157–158, 184, 185, 190, 199, 210, 213, 217, 235, 258, 262, 266, 286, 288, 289, 294, 298, 320, 347, 350, 355, 362, 368, 373, 375
- electromagnetic effect 8, 233, 308
- electromagnetic repulsion 242, 243
- electromagnetic–triboelectric hybrid sensors 242, 245
- electronic devices and systems 177
- electronic skin 136–138, 368–371
- design 281–285
 - mechanical sensing 285
 - bending sensing 288–289
 - location sensing 289–290
 - pressure sensing 285–288
 - sliding sensing 288
 - strain sensing 290–294
- physiological sensing 294–301
- multimodal sensing 294–296
- physiological monitoring 296–297
- reliability 298–301
- signal transmission 298
- electronic-skin (e-skin) 138, 281, 282, 285, 286, 288, 289, 294–301, 369–371, 374
- electrospinning system 268–270
- electrostatic actuation 272, 274
- electrostatic vibrator switch 89, 90
- energy collection methods 234
- energy-conversion efficiency (ECE) 7, 8
- energy harvesting mechanisms 3, 227, 235, 239, 247, 307, 335
- energy storage module 366
- environmental monitoring/protection system
- self-powered electrochemistry system 388–391

- environmental monitoring/protection system (*contd.*)
- self-powered electrodegradation system
 - AAB degradation 384
 - methyl orange (MO) degradation 384–385
 - remove fly ash and SO₂ 385–386
 - seawater desalination (SD) 386–388
 - seawater electrolysis (SE) system 386–388
 - self-powered environmental monitoring system
 - heavy metal ions detection 383–384
 - phenol detection 380–382
 - SPAS 391, 392
- epidermis 138, 281, 282, 373
- f**
- fabrication methods
- carbon nanotubes 133–138
 - silver nanowires 142–145
- fabrication process 26, 42, 44–46, 48, 49, 52–54, 100, 107, 113, 124, 143, 166, 177, 198, 210, 220, 221, 390
- fast adapting (FA) 373
- fiber based conductive materials 195–196
- fiber-based hybrid nanogenerator (FBHNG) 240, 296
- fiber-based materials 97, 102
- field effect transistor (FET) 89, 98, 122, 151, 185, 288
- figure-of-merit (FOM) 7, 59, 66–73
- material 70–73
 - structural 67–70
 - of triboelectric nanogenerators 66–67
- finite element method (FEM) 61
- flexible and stretchable devices
- composite based conductive materials 189
 - blending conductive fillers 189–191
- film embedded into stretchable elastomer 191–194
- deterministic 3D assembly 167
- basic approach 169–172
 - freestanding 3D structures 175
 - morphable 3D structures 176–177
 - multilayer 3D structure 173–175
 - stress and strain engineering 172–173
- 3D Kirigami structure 172
- graphene 152–154
- from 1D nanomaterials
- carbon nanotubes 133–138
 - silver nanowires 142–145
 - ZnO nanowires 138–142
- polymer based conductive materials 183
- organic semiconducting nanowire 185
 - PANI 184
 - PEDOT:PSS 185
 - PPy 185
- textile based conductive materials 195
- fiber 195–196
- low-cost fabrication method 196
- single-electrode triboelectric nanogenerator 199
- supercapacitors 199
- from 3D assembly 177
- electronic devices and systems 177
 - interfaces with biological systems 178–180
- 3D bridge-island structure 167
- 3D nanomembrane 167
- 3D nanoribbons 166
- from 2D nanomaterials
- boron nitride 151
 - graphene 150–151
 - TMD 151
 - topographical thickness 149
- unconventional 3D structure design 165
- from 0D nanomaterials
- application 123–128

- carbon quantum dots 115–116
 gold nanoparticles 116–117
 patterning methods and application 121–123
 quantum dots 114–115
 thin film 117–121
 flexible electronics, structural design for 103–105
 flexible printed circuit board (FPCB) process 33, 87
 flexible printed circuit (FPC) manufacture 33, 44–45, 87
 fluorinated ethylene propylene (FEP) 12, 43, 65, 217, 269, 312
 four-mechanism hybrid generators 235–238
 freestanding 3D structures 175–176
 free-standing (FS) mode 19, 22–24, 59, 67, 69, 210, 268, 274
 freestanding triboelectric nanogenerator (F-TENG) 326
- g**
 Georgia Institute of Technology 70, 78, 81, 83, 136, 138, 139, 141, 142, 153, 206, 210, 219, 228, 286, 310, 322, 327, 332, 350, 360, 362, 366
 gold nanoparticles (AuNPs) 116–117, 383, 384
 graphene 150, 290
 application 157
 flexible and stretchable transparent electrodes 157–158
 nanogenerators 158–160
 synthesis
 chemical exfoliation 153–154
 epitaxial growth 153
 micromechanical exfoliation 152–153
 transfer 154
 mechanical exfoliation 154
 polymer assisted transfer 154–156
 roll-to-roll 156
 transfer free method 156
- h**
 heavy metal ions detection 383–384
 hemispheres-array-structured TENGs (H-TENGs) 368
 human-machine interface 134, 213, 289, 294, 298, 350, 367, 368, 374–376
 human skin 19, 24, 160, 281, 282, 285, 289, 301, 368
 hybrid nanogenerators 227, 234–236, 239, 240, 242, 247, 248, 296, 307, 310, 312, 313, 316, 331, 344
 hybrid sensing technology
 application 238
 electromagnetic-triboelectric hybrid sensors 242–247
 multiple hybrid sensors 247–249
 piezoelectric-triboelectric hybrid sensors 239–242
 dual hybrid power technology 227
 triboelectric-electromagnetic nanogenerator 233–234
 triboelectric-photovoltaic nanogenerator 231–233
 triboelectric-piezoelectric nanogenerator 228–231
 multiple hybrid power technology 234
 four-mechanism hybrid technology 235–238
 triple hybrid generator 234–235
 hypodermis 282
- i**
 implantable medical device
 cardiac monitoring 345–347
 iTEAS 347
 power sources of
 medical applications 344–345
 medical laser 342–344
 pacemaker 340–342
 TENG energy harvesters 340, 341
 versatile energy conversion and self-powered biomedical monitoring 350–351
 implantable triboelectric active sensor (iTEAS) 347, 350

- impressed current cathodic protection (ICCP) system 391
- indium tin oxide (ITO) 14, 43, 157, 209, 235, 270, 312, 342
- inductive transformer 77, 81–82, 90
- industrial pollution
- dopamine 382–383
 - heavy metal ions detection 383–384
 - phenol 380–382
- inkjet printing process 121–123
- inorganic thermoelectric generators 7
- intelligent agents 367
- Internet of Things (IoTs) 4
- PMU 364
 - self-powered device and technology 359
 - self-powered sensing nodes 360–363
 - vehicles and home appliances 359
 - wireless communication 363–364
- k**
- keel structure 347
- Kirchhoff's law 78
- kirigami based electrode 323
- kirigami paper-based supercapacitor (KP-SC) 322
- Korea University 90
- l**
- Landau–Levich equation 118
- Langmuir–Blodgett (LB) deposition 113, 120–121
- laser controller 254–257
- light-emitting diodes (LED) 98, 125, 126, 286, 384
- linear displacement sensor 215–216
- liquid crystal displays (LCDs) 126, 326
- liquid metal 24, 70–73
- liquid-metal-based triboelectric nanogenerator (LM-TENG) 70
- location ability 289, 368
- logic circuit 90, 209, 210
- m**
- machine-washable textile TENGs 49
- mass-fabrication technology 41
- chemical synthesis 53–54
- flexible printed circuit manufacture 44–45
- plasma treatment 51
- roll to roll process 45–46
- soft-lithography 41–44
- textiles manufacture 49–50
- 3D printing 46–49
- wrinkle-structured surface 51–53
- mechanical exfoliation 152–154
- medical laser 342–344
- 3-mercaptopropionic acid (3-MPA) 219, 383
- mesenchymal stems cells (MSCs) 354
- metal-based nanoparticles 97
- methyl orange (MO) degradation 384–385
- micro actuators 253, 255, 307
- microcontact printing process 122
- microelectromechanical systems (MEMS) actuator 97, 176, 253
- microenergy technologies
- electromagnetic effect 8
 - 5 technologies comparison 6
 - photovoltaic effect 7
 - piezoelectric effect 8–9
 - thermoelectric effect 7–8
- microfluidic transport 274–276
- micromechanical exfoliation 152–153
- micropyramid-patterned PDMS 374
- microsystem energy crisis 3–5
- multilayer 3D structures 173–175
- multiple energy harvesting mechanisms 235
- multiple hybrid power technology 234
- four-mechanism hybrid generators 235–238
 - triple hybrid generators 234–235
- multiple hybrid sensors 247–249
- n**
- nanogenerators (NGs) 227
- cardiac monitoring 345–347
- nanoimprinting 42–44
- nanomaterials 97–100, 113–128, 133–145, 149–161, 190, 321, 374

- nanoparticles (NPs) 97, 98, 113, 115–117, 139, 195, 206, 207, 383, 384
- nanostructured polytetrafluoroethylene (n-PTFE) 347
- o**
- omnidirectional tilt sensor 217–219
- one-dimensional (1D) nanomaterials 98, 133
- carbon nanotubes 133–138
 - flexible and stretchable electronics 133
 - silver nanowires 142–145
 - ZnO nanowires 138–142
- one-structural flexible energy harvester 310–311
- optical direction modulator 254
- organic materials 7–9, 14, 97, 100–102, 107, 180, 357
- organic nanogenerator 14
- organic semiconducting nanowire 185, 189
- organic thermoelectric generators 7
- output open-circuit voltage (V_{oc}) 207, 272
- oxide compounds 14
- p**
- packaged self-powered system 344, 345
- patterning methods 121
- inkjet printing process 121–122
 - microcontact printing process 122–123
 - screen printing process 121
- Peking University 22, 24, 41, 46, 51, 87, 135, 160, 196, 207, 213, 217, 228, 285, 322, 326, 364, 367, 368, 375
- photovoltaic effect 5, 7, 227, 231, 308
- physiological monitoring 285, 296–297
- piezoelectric and triboelectric hybrid nanogenerator (PTNG) 344
- piezoelectric coefficient 8
- piezoelectric constant 8
- piezoelectric crystals 8
- piezoelectric generator 8, 9
- piezoelectric materials 8, 138, 158, 160, 228, 231, 296
- piezoelectric-triboelectric hybrid sensors 227, 239–242, 249
- piezo-tribo-pyro-photo-electric effects 312
- plane-shaped TENG 24–26
- plasma treatment 51–54
- poly(methyl methacrylate) (PMMA) 121, 354
- polyaniline (PANI) 183, 184, 389
- polydimethylsiloxane (PDMS) 12, 14, 35, 42, 52, 134, 154, 206, 263, 293, 312, 341, 369, 375
- polydimethylsiloxane-silver nanowires (PDMS-AgNWs) 375
- polydopamine (PDA) 383
- polymer assisted transfer 154–156
- polymer based conductive materials 183
- organic semiconducting nanowire 185
 - PANI 184
 - PEDOT:PSS 185
 - PPy 185
- polymers 7–9, 14, 35, 54, 121, 122, 170, 183, 190, 355, 362, 389
- polymethyl methacrylate (PMMA) 54, 121, 153, 155, 156, 316, 354
- poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) 100, 183, 185
- polypyrrole (PPy) 183, 185, 369
- polytetrafluoroethylene (PTFE) 12, 35, 138, 242, 375, 380
- polyvinylidene fluoride (PVDF) 8, 71, 228
- porous CNT-PDMS 374
- power management
- capacitive load characteristics 78–80
 - capacitive transformer 82–83
 - circuit 87
 - inductive transformer 81–82
 - LC oscillation circuit 83–90
 - resistive load characteristics 78

- power management (*contd.*)
 theoretical model 77
 ultra-high voltages and impedance 81
 power management module (PMM) 87, 88, 316, 317, 326
 power management unit (PMU) 82, 83, 364
 power-transformed-and-managed TENG (PTM-TENG) 83
 power transmittance 77–80, 90
 pressure sensing 285–288, 368, 374
 pyroelectric nanogenerator (PyENG) 235, 310
 pyroelectric-piezoelectric nanogenerator (PPENG) 247
- q**
 quantum dots 114
- r**
 relative-sliding (RS) mode 14, 19, 21–22, 59
 reliability 22, 45, 51, 185, 290, 293, 294, 298–301
 resistive load characteristics 78–80
 resistive random-access memory (RRAM) 98, 371
 rolling friction enhanced freestanding triboelectric nanogenerator (rf-TENG) 390
 roll to roll fabrication process 45, 46
 roll-to-roll transfer 99, 100, 156
 rotor-shaped TENG 33, 35, 36
- s**
 sacrificial anode cathodic protection (SACP) 391
 sandwich-shaped self-charging power unit 322
 screen printing process 121
 self-charging smart bracelet 87, 326–328
 self-charging system 366
 self-driven active sensors 238
 self-powered analogue smart skin 368, 370
 self-powered anti-corrosion system (SPAS)
 mechanical energy 392–393
 wave energy 393–394
 self-powered electrical stimulation, in tissue engineering
 assisted neural differentiation system 353–354
 BD-TENG 355
 in vivo absorbable bioresorbable natural-materials-based TENGs 355–356
 self-powered electrochemical recovery system 391
 self-powered electrochemistry system electrochemical polymerization system 389–390
 electrochemical reduction system 390–391
 water electrolysis units 388–389
 self-powered electrodegradation system AAB degradation 384
 methyl orange (MO) degradation 384–385
 seawater desalination (SD) 386–388
 seawater electrolysis (SE) system 386–388
 self-powered environmental monitoring system, phenol detection 380–382
 self-powered human motion detection 328
 self-powered sensing nodes 360–363
 self-powered wireless body sensor network 352
 self-power technology 195
 short-circuit transferred charges (Q_{sc}) 60, 62, 79, 272
 signal transmission 285, 294, 298, 301, 364
 silicon mold 41, 42
 silver (Ag) nanowires 142
 applications 143–145
 fabrication methods 142–143
 single-electrode (SE) mode 19, 22
 single-electrode touch sensor 207–210

- single-electrode triboelectric nanogenerator (STENG) 199
- single-friction (SF) mode 22
- sliding sensing 288
- smart optical modulator (SOM) 258, 260
- smart skin 183, 281, 290, 368
- soft-lithography 41–43
- Stanford University 100, 134, 142, 157, 185, 285
- static and dynamic pressure sensor 206
- strain sensing 290–294
- stress and strain engineering 172–173
- stretchable electronics
- 3D structural design for 107
 - 2D structural design for 105–106
- stretchable strain sensor 186
- surface charge density 52, 53, 59, 66, 67, 70, 72, 73, 220, 242, 379
- syringe printing 270–271
- t**
- tactile imaging sensor 206–207
- tank-shaped TENG 33, 35
- teflon 12, 72, 142, 266
- textile-based conductive materials 195
- fiber 195–196
 - low-cost fabrication method 196
 - supercapacitors 199
- textile-based TENGs 24
- textiles TENG 49
- theoretical charging cycle 85
- thermal nanoimprinting 42–44
- thermoelectric effect 5, 7–8
- thermoelectric generators 7, 8
- thermoelectric (TE) module 312
- thermoelectric nanogenerators (ThNG) 227, 235, 309
- thin film by 0D nanomaterials 117
- casting 117–118
 - dip coating 118–119
 - Langmuir–Blodgett deposition 120–121
- 3D bridge-island structure 167
- 3D kirigami structure 172
- 3D nanomembranes 167
- 3D nanoribbons 166–167
- 3D plane-shaped design 26
- 3D printing 41, 46–49, 54, 113, 125, 190
- traditional polymers 183
- transfer free method 156
- transition-metal dichalcogenides (TMD) 100, 149, 151
- transmission electron microscope (TEM) 103, 189
- triboelectric–electromagnetic nanogenerator 233–234
- triboelectric nanogenerator (TENG) 3, 59
- arch-shaped 26–30
 - challenges 14
 - electrification effect 9
 - material progress 11–14
 - operation mechanisms 19–24
 - plane-shaped 24–26
 - principle 9–11
 - rotor-shaped 33–37
 - triboelectric series 11
 - triboelectrification effect 9
 - typical structures 24–37
 - wavy-shaped 33
 - zig-zag shaped 30–33
- triboelectric nanosensor (TENS) 264, 382
- triboelectric pair 9–11, 14, 22, 24, 26
- triboelectric–photovoltaic nanogenerator (TPNG) 231–233
- triboelectric–piezoelectric nanogenerator (TPiENG) 228–231, 235, 310
- triboelectric sensor 285, 360
- triboelectric series 11, 12, 14, 35, 70, 72
- triple hybrid generators 234–235
- tunable optical membrane 258–261
- 2D nanomaterials 100
- boron nitride 151
 - TMD 151
 - topographical thickness 149
- 2D plane-shaped TENG 26, 27

u

- ultraflexible 3D-TENG 48, 49
- under active bladder (UAB) 261
- University of Illinois 103, 105, 154, 166
- UV sensor 221–222

v

- variable $V'(x)$ 63
- vibration acceleration sensor 212
- vibration direction sensor 213
- voltage-total transferred charges ($V-Q$) 59, 60

w

- water electrolysis units 388–389
- wavy-shaped TENG 33
- wireless communication 285, 359, 363–364
- wireless power transfer (WPT) 8
- wrinkle-structured surface 51–53

y

- Yonsei University 103, 160, 195

z

- zero-dimensional (0D) nanomaterials 97, 113–128
- applications 123
 - electrodes 124–125
 - light-emitting diodes 125
 - transistors 125–128
- carbon quantum dots 115–116
- gold nanoparticles 116–117
- Langmuir–Blodgett deposition 120–121
- quantum dots 114–115
- thin film 117
 - casting 117–118
 - dip coating 118–119
- zig-zag shaped TENG 30–33
- zinc oxide (ZnO) nanowire (NW) 138
 - applications 141–142
 - synthesis 139–141