References to figures are given in italic type. References to table are given in bold type.

accelerometers 141
acid etch 199
acoustic drop ejection 33, 352
acrylate UV inks 101–3, 102
active electronics see electronic components, active
air bubbles 38
alginites 286, 296
aliasing 35
alkaline etch 199
aluminium oxide 6, 10
ammonia sensors 217
antennae (RFID) 260–3, 261, 264–5
anti-aliasing 35
aqueous inks 96–100, 210–11, 277
dyes 100
polymeric additives 100
asynchronous communication 267
azo dyes 97, 98

barium strontium titanate 6
batteries 214–15
bead formation
stable 128–30, 129
unstable 130–2
Bernoulli underpressure refilling 68–9
binary printers 20, 35
biocides 172
biomaterials 3, 151–2, 223–4, 275
alginites 287
applications

bioreactors 298
tissue engineering 297–8
see also tissue engineering
tissue printing 298
cells see cells
corrosion 285
drying behaviour 285
humoral factors 322
ink formulation 282
reactive inks 292–6
polymers 295
print heads 280–1
proteins 287–9
rapid prototyping 281–2
substrates 296–7
thermal inkjet for 279

bioreactors 298
biosensors 146–7
2,4-biphenyl-5,4-tertbutylphenyl-1,3,4-oxadiazole (PBD) 240
Boltzmann constant 125
Bond number 114
Boston Microsystems 145, 146
bubble-jet see thermal inkjet
Burroughes, Jeremy 238

cadmium selenide 108, 212
calcium acetate 99
Canon 349
capacitors 176, 214–15
capillary blood vessels 310
capillary forces 73
coaalescence 126
contact line motion 124–5
refilling 67–8
spreading 122–4
capital costs 162
carbon nanoparticles 165
carbon nanotubes (CNT) 106, 165–6, 166, 213–14, 239
Carnegie Mellon chemical sensor 144, 144, 146
Cassie-Baxter relation 123
Castle Island’s Worldwide Guide to Rapid Prototyping 328
Cavendish Laboratory 240
cells (biological) 275–6
attachment and growth 291–2
biocompatibility 292
cell-directing patterns 289
inks containing 290
matrix 276
multiple types 316–17
print heads 276–7, 290–1, 311–12
see also tissue engineering
cells (electrical) 214–15
cellulose ester 91
ceramics 31–2, 281
applications 10
deposition methods 6–7, 10
as substrate 173
see also lead zirconate titanate
cerium oxide 6
chalcogenides 216–17
chemical sensors 144–7
optimally based 148
chemoresistive materials 144
Chinese hamster ovary (CHO) cells 291
circuit breakers 176–7
coaalescence 128, 248, 284
bridge formation and broadening 126–7
droplet relaxation 127–8
coffee stain effect 11, 209, 221, 243–4
colourants 97–9
substrate interactions 99
complementary metal-oxide semiconductor (CMOS) process 220–1
complexity 42
computational fluid dynamics (CFD) 208
computer-aided design (CAD) 188–9, 321, 327
Conductive Inkjet Technology, Inc. 204
conductive inks 164–72
see also conductive polymers; metals
conductive polymers 105–6, 172, 221, 228
see also poly(3,4-ethylenedioxythiophene)
conductive tracks 5, 160–1, 163, 222
inks
dispersants 168–70
nanoparticle properties 164–8
materials 165–6
protective layers 174–5, 175
resistors 175–6
sintering 174–5
substrates 173
three-dimensional 163
see also electronic components; printed circuit boards
conductivity 162–3
contact angle 242–3
contact angle hysteresis 125–6
contact line motion 124–5, 130–1
contact line retraction 132–3
contacts 163–4
continuous inkjet (CIJ) 351
applications 28
drop generation 27–8
fundamentals 21–2
ink formulation 88
mask printing 12
metals 4
multiple jet 28
single-jet 27–8
copper 165, 203–4, 260
copper indium gallium selenide (CIGS) 216–17
copper zinc tin sulfide (CZTS) 216–17
corrosion, biological materials 285
costs 340, 361
cytokines 276
cytotoxicity 291
data formats and sources 321–2
Deerac system 280–1
degassing 38
DemaMatrix 289–90
denaturation 288
deposition maps 114–16
diamond 7
Dimatix printer 278
diodes 265, 271
direct deposition 9, 9
cells 319
   ceramics 10
   metals 4, 9
   polymers 10–11
dispersants 168–9
displays 212–13, 237–8, 345
   geometry 241
   ink formulation 243–5
   process reliability 246–9
dodecylbenzene sulfonate acid (DBSA) 217
drive-per-nozzle system 247
drop-on-demand (DOD) 1–2, 28–9
   binary 35
   droplet formation 89–95
electrostatic 33
   fundamentals 21–2
   piezoelectric 30–1
   thermal 29–30
   see also piezoelectric-actuated
   printing; thermal inkjet
droplet properties and behaviour
coalessence 126–8
deceleration due to elongational
   effects 70–1
deposition
   deposition maps 114–16
   unstable 120–1
   formation 21–2, 89–96, 248–9
   aerodynamic drag 90
   fluid behaviour drag 92
   piezoelectric print head 60–6
   impact 90–1, 114, 116–20, 348
   gravitational potential energy 117
   inkjet-sized drops 119–20
   millimetre-sized drops 116–19
   spreading 117
   placement 16, 345
   aerodynamic effects 347
   satellite formation 38–9, 90, 277, 348
   size 22, 23, 41, 201
   grey-scale printing 35–6
   volume 247, 248–9, 283, 345, 361
   spacing 40
   see also resolution
   speed/velocity 22, 37
   spreading
   heterogeneous substrates 123
   surface tension 23–4
   trajectory 346, 346
   see also ink formulation; substrate
   interactions; viscosity
drug delivery systems 152
drying behaviour 243
   biological materials 285
dust 126
dyes 97–9

Eastman Kodak 353–4
Eisler, Paul 184
electrohydrodynamic jet printing 210
electronic components
   active 208
   biological materials 224–5
   ink formulations 210–11
   memory storage 221
   organic LEDs 211–14
   photovoltaics see photovoltaics
   sensors 217–19
   substrate requirements 209
   transistors 219
   passive 159, 221–2
   applications 159–60
   capacitors 176
   circuit breakers 176–7
   electrostatic discharge 177–8
   fuses 176
   inductors and transformers 177
Index

366

electronic components (continued)
  passive filters 177
  resistors 175–6
  switches 177
  thermal management 178
  transistors 269
  see also conductive tracks

electronic interconnections 9

electronics industry 207–8

electrostatic discharge (ESD) 177–8

electrostatic spray printing 33–4, 34, 351, 352

elongation effects 70–1
  Escherichia coli 223, 296
  etch resist 197–202
  etching 9, 13–14, 14
  evaporation 132–4
  extrusion fabrication 281

  face shooter 30
  failure modes 37–8
  fifth pen approach 100
  flat-panel displays see displays
  flexible substrates 214
  flexstensional devices 356
  fluid properties
    surface tension 23–4
    viscosity see viscosity
    see also droplet properties and behaviour; ink formulation
  fullerene 215–16
  fuses 176–7

  gearwheels 11
  gelation 132
  gels see hydrogels
  gene chips 289
  glass 173
  globular proteins 287–8
  gold 5, 108, 144, 165, 165, 221
  graphene 221
  grey-scale printing 35–6, 201
  growth factors 322
  hard disk drives 153, 154
  HeLa cells 312
  Helmholtz resonator 47–8, 48
    multi-cavity 71–7
  Hewlett-Packard 349
  high-definition TVs (HDTV) 241
  high-frequency RFID 257, 262, 264–6
  human umbilical vein endothelial cells (HUVECs) 312
  humectants 170–1
  hydrogels 12, 286–7, 294, 296, 320–1
  in situ synthesis 223
  indium tin oxide (ITO) 213–14, 239
  inductors 177
  ink formulation 208
    added polymer 91, 93, 100
    aqueous inks 96–100
    biomaterials 282–9, 318–20
    conductive inks 164–72
    liquid medium 170–2
    continuous inkjet 88
    design considerations 95
    dispersants 168–9
    effect of polymer addition on rheological properties 91–2
    etch resists 199
    instability 37
    jetting sensitivity 359
    oil-based inks 101
    organic light-emitting diodes (OLED) 243–5
    phase change inks 101
    solvent-based inks 103–4
    surfactants 171
    UV cure processes 101–3
    see also droplet behaviour and properties; surface tension; viscosity
  inkjet printing
    advantages 2–3
    limitations 344–8
    principles 1–2
  insulin 289
integrated circuits (IC) 153  
see also conductive tracks; electronic components; printed circuit boards  
interconnects 125, 128, 221, 242  
International Energy Agency (IEA) 215  
inverse printing 9, 14–15  
iron oxide 221  

jettability 243, 280  
kinetic energy 61, 62  
Kodak Stream 354  
kogation 30  

Labcyte 280, 352  
laser direct imaging (LDI) 102–3, 188  
lead zirconate titanate (PZT) 6, 31, 221, 350  
legend printers 91  
lenses 148–9  
light-emitting diodes see organic light-emitting diodes  
light-emitting polymers (LEP) 150–1  
linear array print heads 46, 47  
Litrex printer 248  
low-frequency RFID 256–7  

machine integrators 192  
manufacturing 8, 223  
history of 3D printing 325–8  
limitations 16–17  
process requirements 40  
process selection 326–7  
see also solid freeform fabrication  
MapleDW 280–1  
Marangoni flows 135  
mask printing 9, 12–13, 101  
material deposition 3  
matrix print head 47, 47  
mechanical components 11  
melt printing 4  
Memjet 341, 358  
meniscus formation 73, 95  

metals 3–6  
conductive tracks 165  
direct deposition 4, 4  
fluid properties 24  
melt printing 3, 9  
nanoparticle suspensions 5, 9, 107–8, 221  
precursor printing 5  
ProMetal process 338  

micro-electro-mechanical systems (MEMS) 141–2, 340–1, 350–1  
advantages of inkjet 143  
assembly and packing 152–5  
bioactive 151–2  
chemical sensors 144–7  
limitations 142–3  
opto-electronic 142, 147–9  
resonant 145  
see also electronic components  
micro-gel beads 314–15  
micro-gel fibre 315  
micro-satellites 38  
micro-sieves 14, 15  
Microcraft JetPrint 191  
Microdrop Technologies 278  
MicroFab 278  
microwave RFID 257–8  
Moore’s law 259  
multiwall carbon nanotubes (MWCNT) 213  

nanoparticles  
biomaterials 285  
dispersants 169  
metallic 5, 107–8, 164–6, 221, 268–9  
particle shape 166  
nanotubes 166  
nickel 165, 165  
nonplanar surfaces 143  
nozzle-plate flooding 37  

Objet Geometries systems 330–2, 332  
ProJet 333
Ohnesorge number 25–6, 61, 89–90, 114
in deposition maps 114–16, 115
open-ended print head 48, 49
optical fibre sensors 146–7, 147
optoelectronics 142, 147–9
see also organic light-emitting
diodes; photovoltaics
Optomec 280
Orbotech Sprint printers 191
organ transplantation 307
organic light-emitting diodes (OLED)
106–7, 211, 238–9
display elements, containment and
solid content 241–3
for displays 212–13
ink formulation 243–5
for lighting 211–12
print defects 246–9
quantum dot 212, 214
substrates 239
see also displays
oscillatory motion 51–2
overprinting 41

paired emitter detector diode (PEDD)
217
papers 99, 214
passive electronics see electronic
components, passive
pattern formation 128
patterning 105
PEDOT see poly(3,4-ethylenedioxy-
thiophene)
phase change inks 101, 130, 132–3, 199, 295
phenyl-C_61_-butyric acid methyl ester
(PCBM) 104, 215
photodetectors 149, 217
photolithography 160–1, 190
phototool imaging 187
photovoltaics 106, 151, 215–17
phthalocyanine dyes 97, 98
Picofilter Inc. 352
piezoelectric actuated printing 30–1,
46–7
active electronics fabrication 211
actuation mechanisms 31–3
for cells and biopolymers 277–8,
279–80, 282–3, 290–1, 311
drop formation 60–1
characteristic frequency 61–2
elongational effects 70–1
negative pulse 64–6
positive pulse 62–4
dynamics
damping 66–7
large print head 53–4, 56–8, 57
long ducts 77–82
multiple pumps 71–7
pressure change in pump chamber
50–1
pulse formation 52–3
refilling 67–70
small print head 53–5, 54, 55
volume change in print head 50–1
ink formulation 89
for laboratory use 278
limitations 350
long duct theory
equations of motion 81
pulse response 81–2
meniscus formation 73
multi-cavity resonators 71–7
eigenmodes 76
resonance frequencies 76
negative pulse 54
proteins 288
pulse length 53
pump 50
pump chamber pressure 55, 56
valveless pump 78
pigments 98–9
pixels 241
pluripotent stem cells see stem cells
Poiseuille law 68
polyacrylamide 91
polyaniline (PANI) 173, 217
poly(ethylene imine) 99–100
poly(ethylene oxide) 91
poly(ethylene terephthalate) (PET) 108, 187
poly(3,4-ethylenedioxythiophene) (PEDOT) 173, 244, 245, 349
polyhedral oligomeric silsesquioxane (POSS) 240
PolyJet devices 330–2, 332
polymers
as aqueous ink additives 92–4, 100
biological 285–6, 294
coiled 286–7
globular proteins 287–9
deposition methods 7–8
dyes 98–9
effect on ink droplet formation 92–4
etching 14–15, 14
molecular weight degradation 94
organic conducting 105–6
for organic LEDs, performance assessment 244–5
in solvent-based inks 103–5
poly[2-methoxy-5-(2′-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) 91, 107, 208
poly(methyl methacrylate) (PMMA) 338
poly(para-phenylene vinylene) (PPV) 240
polypeptides 294
poly(phenylene ethylene)-poly(phenylene vinylene) (PPE-PPV) 211
polypyrrole 173
polysaccharides 286, 296
polystyrene 91
polythiophene 173
polyvinylidene fluoride trifluoroethylene (PVDF-TrFE) 217
poly(4-vinylphenol) (PVP) 219
powder bed printing 8, 15, 15, 335–8
pre-patterned substrates 209
prednisolone 289
pressure waves 72
print heads 343
   arrangements 41–2
   biological ink 290–1
biomaterials 280–1
   cell printing 276–7, 290–1, 311–12
cells (biological) 276–7, 290–1, 311–12
continuous inkjet 88
failure modes 37–8
future trends 357
linear array 46, 47
matrix array 47, 47
motion 39–42
nozzle size 41
open-ended 48, 49
piezoelectric 47–8, 48, 49, 277–8, 350
dynamics 49–60
small 53–5, 54, 55
thermal inkjet 88–9, 279
print quality 34–5
see also resolution
print speed 319–20
Printar LGP/GreenJet 191, 194–5
printed circuit boards (PCB) 102, 103, 183–5, 184
complexity 201
conventional manufacturing 185, 186
imaging 185–7
laser direct imaging 188
phototool imaging 187–8
data formats 188–9
design formats 188–9
etch resist 196–202
commercial implementation 202
requirements 198–9
flexible substrates 204
future possibilities 202–5
inkjet applications 189–90
disadvantages 196–7
legend printing 190–3
soldermask 194–6
multi-layer 203
print resolution 197–201
RFID tags 260
substrate preparation 200
vari-layer 205
see also conductive tracks
ProMetal RCT 338, 339
protective layers 222
proteins 287–9
pulse generation 90
PZT see lead zirconate titanate

quantum dots (QD) 212, 214, 240
radiofrequency identification (RFID)
tags 155, 252
conventional 256, 258–60
printed 263
antenna stage 264–5
antenna structures 260–3
applications 260
demonstrators 272
digital section 265–7
drawbacks of inkjet 261–2
implementation issues 270–2
materials 268
rectifier, power supply, clamp 265
transistors 269
standards and classification 256–8
13.56 MHz 257, 265
135 kHz 256–7
ultra-high frequency 257–8
ramp functions 58, 59, 74
rapid prototyping 326, 328
biomaterials 281–2
raster image processor 189
raw materials 160–1
Rayleigh-Plateau instability 24, 38–9, 130
reactive inks 292–6
rectification 265, 266
refilling 67–70
registration 198, 220
released layers 143
reliability 36–8, 198
organic LED manufacture 246–9
repair 198
resistors 5, 175–6
resolution 34–5, 39, 40–1, 40
biomaterials printing 283, 319
printed circuit board etch resist 197–201
solid freeform fabrication (SFF) 340
see also accuracy
resonant MEMS structures 145
reverse thermal gelation (RTG) 331–2
Reynolds number 25, 26, 61, 89, 114
satellite drops 38–9, 90, 277, 348
screen printing 190–1
selective laser sintering (SLS) 327–8
semiconductors 212–13, 219–20
as ink 106–7
stability 270
as substrate 149, 154–5
sensors 217–19
shear strain 24, 25, 91, 287, 291
silicon chips 258–60, 263
silicon nitride 11
silver 108, 165, 221
resin coated 210
Silverbrook Research 355
sintering 25–6, 185–6, 194
sol-gels 6–7
solar cells 106, 151, 215–17
solder bumps 9, 10
Solder Jet 153
soldermask 194–6
solid freeform fabrication (SFF) 160, 326–8
challenges 338–40
future trends 340–1
introduction of inkjet technology 329–30
laser-based 329
liquid-based
Objet Geometries PolyJet 330–2
Solidscape Inc. 333–5
market size 338–40
powder-based 8, 15, 335–8
resolution 340
for tissue engineering 313–14, 315–16
direct printing 319
high-speed 319–20
resolution 319
see also tissue engineering
solidification 132
Index 371

Solidscape Inc. 333–5, 335, 336
solute segregation 134
solvent-based inks 103–4
nanoparticle suspensions 170
solvents 219–20
inkjet etching 13–14
splashing 121
stem cells 292, 322
stent 152
stereolithography apparatus (SLA) 327
Stokes’ law 107
strain hardening 91
stream printing 354
substrate
biological applications 296–7
conductive tracks 172, 173
motion 39–42
surface energy 209
substrate interactions 113–14
bead formation
stable 128–30
unstable 130–1
capillarity-driven contact-line motion 124–5
capillary-driven spreading 122–4
coalescence see coalescence
contact angle hysteresis 125–6
droplet coalescence 126–8
evaporation 132–4
ink adhesion 199
solidification 132
see also droplet properties and behaviour, impact
superconducting quantum interference device (SQUID) 221
support materials 330–1
surface energy 117–18, 209
surface tension 23–4, 284
surfactants 171–2, 210
surfactants 63
switches 177
Taiwan Semiconductor Manufacturing Company 358
Taylor cone 33
Technology Partnership 356
text printing 28
textiles 173
thermal inkjet 29–30, 277
for biological materials 279, 279–80
effect on cells 290–1
proteins 287–9
ink formulation 88–9
limitations 348–50
thermal management 348
Thermal Inkjet Picofluidic System (TIPS) 279
thermo-cleavable solvents 104–5, 105
thin film deposition 17, 350
3D printing see solid freeform fabrication
3D Systems Inc 327
tissue engineering 297–8, 298, 307–8
3D printers 313–14
micro-gel beads 314–15
viscosity of materials 318–19
applications 319–22
current methods 309
data source linkage 321
inkjet printing feasibility study 310–12
multiple cell types 316–18
stem cells 322
see also cells
titanium oxide 11
Tonejet 356
transformers 177
transistors 219–20, 265, 269–70
trichlorobenzene 107
Trident heads 279
Trouton ratio 25
tumor cells 275
ultra-high frequency (UHF) RFID 257–8, 262–3
ultraviolet (UV) cure inks 101–3, 199, 285–6, 295, 330
ink formulation 101–3
Underwriters Laboratories 192
valveless pump 79, 79–81
van der Waals forces 168–9
vari-layer PCBs 205
vertical cavity surface-emitting laser
(VCSEL) 148, 149, 153
viscosity 24–5, 55–6, 89, 91, 348
biological materials 283–4, 318–19
droplet coalescence 126
effect of polymer addition 92–4, 93
energy dissipation 75
high 359
in piezo-driven print head 50
thermal inkjet 349
volatile organic compounds (VOC) 144
VoxelJet Technology GmbH 338

water 20, 23
viscosity 24–5
waveguides 150–1, 151
wax plate lamination 326–7
waxes see phase change inks

Weber number 25, 61, 114
in deposition maps 114–16, 115
droplet impact 119–20
solidification 132
Weissenberg number 93
Wenzel relation 123
wetting behaviour 123–4, 242–3
white light interferometry 249

Xaar 351
Xerox 352

yeast 283
Young equation 121, 127

Z Corporation printers 335–8, 337
Z-Corp process 16
Zimm non-free draining time 93
zinc sulfide 212