Index

Note: page numbers in italics refer to figures; page numbers in bold refer to tables.

abrupt junction p-n diode, 70–1
absorption coefficients, 34, 148, 162, 163, 165
absorption depth, 176–9
absorption edge
  amorphous and crystalline silicon, 194, 196
  direct-gap semiconductors, 148, 149, 163
accelerating point charge, 125–9, 132
acceptor binding energy, 36–7
acceptor concentration see carrier concentration
acceptor doping, 36–7
acceptor level, 36
alkoxy-substituted poly para-phenylene vinylene (MEH-PPV), 258, 259, 260
alloy semiconductors, 56–9
  see also III-V alloy semiconductors; II-VI alloy semiconductors
Alq3, 267, 275, 279, 279
aluminium energy bands, 13
  substitution in silicon, 36–7, 36
aluminium antimonide, 57, 58
aluminium arsenide, 26, 57, 58
aluminium gallium arsenide LEDs
  double heterojunction, 228–34, 229, 230
  radiative efficiency, 237
aluminium gallium indium phosphide LEDs, 220, 226, 234–6
  bandgap versus lattice constant, 235
  emission spectra, 238
  forward intensity versus current, 240
  output intensity versus ambient temperature, 239, 239
  quantum efficiency, 244
aluminium gallium nitride, 241
  aluminium indium nitride, 241
aluminium nitride, 58
aluminium pastes, 188
aluminium phosphide, 26, 58
amorphous silicon, 195
  absorption coefficient, 165
a-Si:H, 193–5, 193
  band states, 193–5, 194
  generation/recombination currents, 103
  solar cell efficiency, 182
amorphous silicon thin-film solar cells, 192–9
doping, 195
  efficiency, 182, 197
open circuit voltage, 196
  substrate design, 195, 196
anode materials, OLEDs, 264, 270
anthracene-based dopant, 281, 282
antireflection layers, 165, 167, 191
anti-sites, 221–2
antisymmetric wavefunction, 138–9, 140, 142
arylidene-based dopant, 281, 281
atomic radius, 36
ATZL, 276, 279
Auger recombination, 222
avalanche breakdown, 97
back contact, solar cells, 172, 188–90
back reflectors, 196–7, 196
back surface field, 179, 180
back surface recombination velocity, 172
BAlg, 279, 279
band bending, 55, 55
  metal-semiconductor contacts, 105, 106
  band diagrams, 18, 26–9, 30
  band model, 71–2, 72
  band offsets, 113
band theory, 2–7
bandgap energy, 14–15, 14, 18, 26, 27
  alloy semiconductors, 57, 57, 58
  LED materials, 228, 229, 235, 235, 241
bandtails, 194
band-to-band transitions, 144–8
BGRVBL, 281, 282
bias voltage, 73–4, 74
binding energy
  acceptor, 36–7
  donor, 35–6
  exciton ionization energy, 132
  molecular excitons, 135
blackbody spectrum, 166
Bloch function, 5
Bohr magneton, 141
Boltzmann approximation, 22
Boltzmann distribution function, 16
bound excitons, 135, 143
Bragg Model, 8
Brillouin zones, 6–8, 6
built-in electric field, 71–2
bulk heterojunction organic solar cell, 286–8, 286, 287
Index

C-54STB, 280, 280
C$_{60}$, 288, 289, 290
Cadmium, toxicity, 200
Cadmium selenide, 58, 236
Cadmium sulphide, 58
CdTe/CdS structure, 199, 200
energy bands, 13
LEDs, 236
solar cell efficiency, 180, 200
Cadmium telluride, 58
band structure, 32, 33
CdTe/CdS structure, 199, 200
energy gap, 26
solar cells, 163, 182, 199, 200, 200
caesium fluoride, 272
candela, 149
capacitance, p-n junction diode, 115–16
carbon
$C_{60}$, 288, 289, 290
crystal structure, 28
energy gap, 26, 26
nanotubes, 290
see also diamond
carrier avalanching, 97
carrier collisions, 41
carrier concentration, 15–26
equilibrium and non-equilibrium, 44–5, 48
extrinsic semiconductors, 37, 38–9, 40
p-n junction diode, 88–91, 93, 101–4
selected semiconductor materials, 27
carrier drift velocity
solar cells, 163, 182, 199, 200
see also diamond
carrier generation/recombination currents, 101–4
carrier lifetimes, 44–5, 53
carrier mobility, 41, 42–3
carrier recombination, 34–5, 43–5, 50–1
hole current, 51, 51
p-n junction diode, 90, 92–3, 101–4
solar cells, 161
carrier transport, 40–8, 41
doping gradients, 46, 47
electron flux, 45, 56
LEDs, 223
solar cells, 160–1, 161
see also diffusion currents; drift currents
solar cells, 177–9, 178
carrier–voltage relationship
solar cells, 161, 201
cathode materials, OLEDs, 264, 268, 270
cathodoluminescence 124
CDBP, 279, 280
cerium-doped Y$_3$Al$_5$O$_{12}$ phosphor, 241
coumarin-based dopant, 280
crystal lattice
solar cells, 182, 199, 200
see also molecular systems
Cramer’s rule, 5
crystal defects, 53
crystal growth, 184–7
advanced processes, 191–2
liquid phase epitaxy (LPE), 225–6
metal–organic vapour phase epitaxy (MOVPE), 234
crystal lattice
periodicity, 5
vibrations
solar cells, 197, 199, 201
CuPc, 267, 271–2
current blocking layers, 223
current density
carrier transport in semiconductors, 41
diffusion currents, 45, 51, 53
solar cells, 161, 169, 174, 177, 178
current–voltage relationship
solar cells, 161, 161
czechralski growth process, 185, 186
damping term, 41
dangling bonds, 55, 55, 195
DBR (distributed Bragg reflector), 219, 244
DCDC, 281
DCIPP, 281
deep traps, 54
defect density, solar cells, 195
degenerate doping, 99
density of states function, 18–21
amorphous silicon, 193–4, 194
band-to-band transitions, 146–7
density of transitions, 146
depletion approximation, 78–83, 107
deployment region
solar cells, 161, 161
Dexter electron transfer, 144, 277
diamond
energy bands, 15
energy gap, 26
unit cell, 27–9, 28
dielectric constant, 36, 132
diffusion currents, 45–6
solar cells, 161, 169, 174, 177, 178
steady state diffusion, 51–2
diffusion equation, 50–3, 91
Index

311
Index

escape cones, LEDs, 223, 244
etching, solar cells, 187, 189
Euler’s formula, 130
excitons, 132–5
energy levels, 132–3, 133
energy transfer, 133, 143–4
molecular, 135, 141, 143–4
OLEDs, 269, 277
organic solar cells, 283–4, 285–6
external quantum efficiency, 228
extrinsic semiconductors, 35–40
eye sensitivity function, 149, 150
face-centred cubic (FCC), 28
Fermi energy, 14–15
extrinsic semiconductors, 37, 38–9, 38
intrinsic semiconductors, 24
traps, 54
Fermi–Dirac distribution function, 17, 17
Fick’s first law, 45
field ionization, 98
fill factor, 170, 197
fluorescence, 143, 277
fluorescent dopants, 279–82
Förster resonance energy transfer, 143–4, 277
forward bias, 73–4, 74, 76, 91, 92, 96–7
alternating current and transient behaviour, 115, 116
generation/recombination currents, 102, 103
LEDs, 218, 232
solar cells, 160–1
gallium aluminium arsenide, 57, 114
gallium arsenide, 57, 58, 114
absorption coefficient, 165
band structure, 29, 31, 32
carrier concentration, 25, 27
energy bands, 13
energy gap, 26
heterojunction, 114
LEDs, 35, 224, 226–7
photovoltaic absorption, 34
radiative efficiency, 237
surface recombination, 222, 222
gallium arsenide phosphide
GaAsP:N, 227, 227, 237
LEDs, 226–8, 227
radiative efficiency, 237
gallium arsenide solar cells, 163
efficiency, 180, 181, 182
triple junction, 201, 202
gallium indium arsenide, LEDs, 222
gallium indium arsenide phosphide, 165
gallium indium nitride, 56–7
energy gap as a function of lattice constant, 241
LEDs, 236–43, 238, 259, 240
gallium indium phosphide, 201, 201
gallium nitride, 58
band structure, 32, 32, 33
dislocation density on sapphire substrate, 236, 237
doping, 238
energy gap, 26
growth planes, 240, 243
LEDs, 236–42
radiative efficiency, 237
wurtzite, 28, 33
gallium phosphide, 58
absorption coefficient, 165
band structure, 32, 32
energy gap, 26
radiative efficiency, 237
recombination coefficient, 232
Gaussian surface, 80–1, 80
Schottky diode, 107
germanium
absorption coefficient, 163, 165
band structure, 31
carrier concentration, 27
crystal structure, 28
energy bands, 15
ergy gap, 26
recombination coefficient, 232
SiGe alloy, 56, 197
germanium solar cells
efficiency, 180
triple-junction, 201, 201, 202
gold, addition to silicon, 116
grain boundaries, multicrystalline silicon, 187
Grüneisen group velocity, 9
heavy holes, 29
heterojunctions, 113–15, 114
AlGaAs, 228–34
solar cells, 199–200
hexagonal close-packed (HCP), 28
high temperature region, 39, 40
highest occupied molecular orbital (HOMO), 264, 269, 274
hole injection layer (HIL), 268, 268, 269, 269, 271–2
hole transport layer (HTL), 266, 268, 269, 269, 273–4, 284
holes
density of states function, 23–4
effective mass, 43
quasi-Fermi energies, 48
sub-bands, 29
carrier concentration, 14–15, 14, 29
see also carrier concentration; carrier transport; electron-hole pair (EHP)
HOMO (highest occupied molecular orbital), 264, 269, 274
guest-host energy transfer, 277–9, 278
ideality factor, 103
imines, 276, 276
impact ionization, 98
indirect gap semiconductors, 32, 34
inorganic, 134
LEDs, 227–8, 227
photovoltaic absorption, 163, 164
recombination coefficient, 232
indium, energy bands, 13
indium antimonide, 26, 57, 58
indium arsenide, 58
indium gallium arsenide, 165
indium nitride, 58
indium phosphide, 57, 58, 165
indium tin oxide (ITO), 260, 264, 270
infrared (IR) radiation, 125, 217
inhomogeneous broadening, 221
insulators, energy bands, 13
interface traps, 53
intermediate temperature region, 37, 39, 40
intermolecular conduction, 257, 259
intramolecular conduction, 257
intrinsic semiconductors, 15
carrier concentration, 24
spatial dependence of energy bands, 41, 42
ionization energy, 35
sodium-based emitters, 282, 283
isoelectronic defects, 227
isophorone-based dopant, 281, 281
ITO (indium tin oxide), 260, 264, 270
JBEM, 281, 282
joint density of states function, 147
joint dispersion relation, 146
Kronig–Penney model, 3–7, 29
k-space, 20, 20
lambertian source, 225
large molecule materials see polymers
laser recrystallization, 199
lattice vibrations see phonons
LEDs see light emitting diodes (LEDs)
LEM (light emitting material), 266, 268, 269, 277
light absorption see photon absorption
light emitters, emission spectra, 150, 151
light emitting diodes (LEDs), 216–48
applications, 216–17
band diagram, 218
basic structure, 217–19, 219
carrier flows, 223
colour conversion, 240–2, 243
colour range, 216
crystallographic orientation, 240, 243
doping, 225, 227, 236, 238
efficiency, 150, 151, 218, 221, 234, 237
electrical contacts, 222
electron-hole pairs (EHP), 34
emission spectra, 150, 220–1, 220, 238, 243
escape cones, 223, 244
high-brightness high-power, 245, 246
lifetimes, 234
material non-uniformities, 221
non-radiative recombination, 221–3
operating temperature, 222, 239
optical outcoupling, 223–5, 223, 225, 224–7
output characteristics, 225, 226, 245, 247
output intensity versus ambient temperature, 239
photoluminescence, 114
photon emission rate, 147, 148
radiation pattern, 225, 226
reflectors, 218, 219, 225, 244
specifying, 245, 247
substrates, 219, 228, 234, 236
surface texturing, 244, 245
tilted walls, 244, 245
light emitting material (LEM), 266, 268, 269, 277
light holes, 29
liquid phase epitaxy (LPE), 225–6
lithium fluoride, 272
lithium fluoride/aluminium cathode, 268, 268, 269, 270
lithium oxide, 272
lithium-quinoilate complexes, 272, 272
low temperature region, 39, 40, 134, 134
non-radiative recombination, 43–5
non-uniformities, LEDs, 221
NPD, 267, 273–4
nitride alloy semiconductors, 58, 241
carrier concentration, 44
LPE (liquid phase epitaxy), 225–6
luminescence, 124
types, applications and efficiencies 124
see also photon emission
luminous efficacy, 149–50, 150
luminous efficiency, 150
LEDs, 218, 255
luminous flux, 149
luminous intensity, 149
LUMO (lowest unoccupied molecular orbital), 264, 269, 274, 276
magnetic field
accelerating point change, 126–7, 127
electron spin, 141
moving electric charge, 125, 126
majority carriers, 37
manganese dopant, 238
mercury selenide, 58
mercury telluride, 58
metal chelates, 275
metallurgical grade (MG) silicon, 185
metal-organic chemical vapour deposition (MOCVD), 234, 236
metal-organic vapour phase epitaxy (MOVPE), 234
metals
electrical conductivity, 13–14
semi-metals, 26
crystalline silicon, 182, 186–7, 187
efficiencies, 182, 200–3
minority carrier lifetimes, 44, 45
minority carriers, 37
MG (metallurgical grade) silicon, 185
microcrystalline silicon see polycrystalline materials
metal-organic vapour phase epitaxy (MOVPE), 234
metal-organic chemical vapour deposition (MOCVD), 234, 236
metal-semiconductor contacts, 104–13, 104
band-bending, 105, 106, 112
current flows, 108–11
Schottky diode, 106, 107–8
metal-semiconductor diode see Schottky diode
metal-vacuum interface, 108–11
MG (metallurgical grade) silicon, 185
microcrystalline silicon see polycrystalline materials
minority carrier lifetimes, 44, 45
minority carriers, 37
m-MTDATA, 267
MOCVD (metal-organic chemical vapour deposition), 234, 236
molecular doping, 277
molecular excitons, 135, 141, 143–4
molecular orbitals, 141
molecular systems, 135–41
momentum conservation, 34, 163
momentum space, 109, 109
moving electric charge see accelerating point charge
MOVPE (metal-organic vapour phase epitaxy), 234, 236
MS diode see Schottky diode
multicrystalline silicon, 182, 186–7, 187
multiple junction solar cells, 197, 198
absorption spectrum, 202
efficiencies, 182, 200–3
organic, 288
oxidation, 273
P1: TIXXYZ  P2: ABC
JWBK555-bind  JWBK555-Kitai  April 14, 2012  14:29  Printer: Yet to come
314 Index

n-type semiconductors, 35, 37
carrier concentration, 40
metal-semiconductor contact, 104, 105–6, 106
non-equilibrium dynamics, 44–5
quasi-Fermi energies, 48
see also n-type silicon
n-type silicon
Fermi level, 37, 38–9, 38
metal-semiconductor contact, 106–8, 111–12
quasi-Fermi energies, 49–50
ohmic contacts, 104, 112–13, 113
Ohm’s law, 41–2, 43
OLEDs see organic light emitting diodes (OLED)
oligomers see small molecule organic materials
open circuit voltage, 170, 171, 179–80, 196
operating lifetime
light emitting diodes (LEDs), 234
OLEDs, 265–6, 282
optical generation rate, 44
optical outcoupling, 223–5
optical generation rate, 44
 oxidation by holes, 114–15
oxide materials, 264, 270
organic light emitting diodes (OLED), 260–82, 265
anode materials, 264, 270
cathode materials, 268, 270–1
electron injection layer (EIL), 268, 268, 269, 269, 272–3, 272
electron transport layer (ETL), 266, 268, 269, 269, 275–6
emission colour, 277
fluorescent dopants, 279–82
hole injection layer (HIL), 268, 268, 269, 269, 271–2
hole transport layer (HTL), 266, 268, 269, 269, 273–4
host materials, 278–9
lifetimes, 265–6, 282
light emitting material processes, 276–8
packaging, 270–1
phosphorescent dopants, 282, 283
small molecule organic materials, 266–70
thickness, 260, 266
organic semiconductors, 254–76
congjugated systems, 255–9
electronic properties, 135
molecular excitons, 135, 141–4
solar cell efficiency, 182
organic solar cells, 283–90
bulk heterojunction, 286–8, 286, 287
materials, 288–90
planar heterojunction, 284–5, 285
single layer, 283–4, 284
oscillating dipole radiator, 128–32
oxadiazoles, 275–6
P3HT, 288, 289
PA (polyacetylene), 256, 256, 258
PANI (polyaniline), 264–5
PBD, 267, 275
PCBM, 288, 289
PECVD (plasma enhanced chemical vapour deposition), 193
periodic potential, 256, 257
p-n junction diode, 69–118
alternating current and transient behaviour, 115–16
band model, 72, 73
bridge rectifier, 71
built-in electric field, 71–2
capacitance, 115–16
carrier concentrations, 88–91, 95, 101–4
carrier flows, 86, 90–4, 94
carrier recombination, 90, 92–3, 101–4
cURRENT POTENTIAL, 75–7
contact potential, 72, 75–7, 82–3
contacts and Schottky barriers, 104–13
current–voltage relationship, 85–97, 97
depletion approximation, 78–83
depletion region, 78–83, 78, 79
diode current, 72–5, 73, 74, 76
equilibrium electric field, 81–2, 81, 82
equilibrium energy barrier, 76, 77
heterojunctions, 113–15, 114
logic gate, 71
quasi-Fermi energies, 91, 92, 102
reverse breakdown, 97–9, 98
symbol, 71
transistor region, 72, 78–83
polarization, LEDs, 239–40
poly para-phenylene vinylene (PPV) see PPV
polymer light emitting diodes (PLEDs), 260–7
polymer light emitting diodes (PLEDs)
photodiodes, 161–2, 162
photoluminescence efficiency, 259
photometric units, 148–52
photon absorption
absorption coefficients, 34, 148, 162, 163, 165
absorption constant, 148
absorption depth, 176–9
band-to-band transitions, 144–8
electron-hole pairs (EHP), 34, 44, 132, 134
excitons, 132–5, 134
heterojunctions, 114
molecular systems, 143
molecule-molecule process, 144
momentum conservation, 162, 164
quantum description, 130–2, 133
photoluminescence efficiency, 148–52
photon emission
accelerating point change, 125–32
excitons, 132–5
molecular excitons, 143
molecule-molecule process, 144
quantum description, 130–2, 133
photoluminescence efficiency, 148–52
solar cells, 162–3
photoluminescence efficiency, 148–52
sub-bands, 256, 257
transistor region, 72, 78–83
transistor region, 72, 78–83
thin-film solar cells, 199
polyethylenes, 255, 255, 258
polymers
conjugated systems, 255–9, 258
deposition techniques, 260
Index

molecular structure, 255, 255

see also organic semiconductors
potential barriers, 3–4
heterojunctions, 114
metal-semiconductor contacts, 104, 104, 107–8
organic semiconductors, 256–7, 264
p-n junction diode, 72, 74, 75, 76, 77
reverse breakdown, 98
solar cells, 161
potential wells, 10
heterojunctions, 114, 229–34
power
accelerating point change, 127–8
luminous flux, 149–50, 151
silicon solar cells, 181, 183–4
solar cells, 170, 171–2, 181, 183–4
Poynting vector, 127
PPV see poly para-phenylene vinylene (PPV)
PQT-12 288, 289
p-type semiconductors, 36, 37
metal-semiconductor contacts, 112, 113
non-equilibrium dynamics, 45
surface traps, 55, 55
see also p-type silicon
p-type silicon, Fermi level, 37, 38, 39
quantum efficiency, 228
quantum states, 2–3
excitons, 132–3
oscillating dipole radiator, 130–2
stationary point charge, 129–30
quantum well LEDs, 233–4, 240
quasi-Fermi energies, 48–50, 91, 92, 102
quaternary semiconductor alloys, 59
see also under the names of specific materials
quinacridone-based dopant, 280, 280
radiated energy per unit time, 127
radiation intensity, 127
radiative energy transfer, 144, 277
rapid thermal annealing, 198
reciprocal space lattice, 20–1, 20, 21, 109
recombination coefficient, 232
recombination time, 44
reduced zone scheme, 8, 9
relative dielectric constant, 36, 132
reverse bias, 74–5, 75, 91, 92, 93
alternating current and transient behaviour, 115–16
generation/recombination currents, 103
photon absorption, 161, 168
reverse breakdown, 97–9, 98
reverse saturation current, 75, 76
Richardson–Dushman equation, 111, 114
scattering time, 40, 42
Schottky diode, 106–12, 106
Schroedinger’s equation, 4, 136–7
screen printing, solar cells, 188, 189–91, 190
selenide semiconductors, 59
semi-metals, 26
separation of variables, 137
shallow traps, 54
sheet resistance, 190
short circuit current, solar cells, 170, 170, 171, 180–1
Siemens process, 185
silicon
absorption coefficient, 163, 165
band structure, 30, 32
carrier concentration, 24–5, 27
covalent bonds, 15
crystal structure, 28
doping, 35, 36–7, 36
energy bands, 12–13
energy gap, 26
photon absorption, 34
purification, 185
recombination coefficient, 232
recombination events, 147
solar-grade, 185
wafer preparation, 184–7
silicon germanium alloy, 56
silicon p-n junction diode
carrier flows, 86–8
contact potential, 77–8, 83–4
minority carrier concentration, 95–6
see also p-n junction diode
silicon ribbon technology, 191–2, 192
silicon solar cells, 198–9
amorphous silicon, 192–9
antireflection layer, 191
back contact, 172, 188–90
back surface field, 179, 180
crystalline silicon, 165–72, 166
design and analysis, 164–72, 166
doping, 188
efficiency, 180, 181, 182, 203
front electrode, 190–1, 190
front glass, 187–8, 180
multiple junction, 197–8
polycrystalline, 198–9
power output, 181, 183–4
silicon ribbon technology, 191–2, 192
surface texturing, 187–8, 188, 189
thickness, 34, 179, 191
types, 184
wafer preparation, 184–7
silicon wafers, 184–7, 191
silver pastes, 188, 190
simple harmonic radiator, 128–9
single crystal silicon
absorption coefficient, 165
production, 184–5, 191
solar cell efficiency, 181, 182
singlet states, two-electron atoms, 139–41, 140, 143
small molecule organic materials, 255
OLEDs, 266–70, 267, 268, 269
sodium oxide, 272
solar cells, 159–205
absorption constant, 148
advanced production methods, 191–2
carrier concentrations, 167–8, 168, 172–6, 174, 175, 177
carrier flows, 160–1, 161, 169, 177–9
carrier generation as function of depth, 176–9, 176, 177
concentrating solar systems, 203
current-voltage characteristic, 161, 162, 170, 170
design and analysis, 164–70
efficiency, 179–84, 180
finishing processes, 187–91
operating point, 161, 170, 170, 179–81
operating temperature, 181
optimal energy gap, 180, 181
photon absorption, 114, 162–3
potential barrier, 161
power output, 170, 171–2, 181, 183–4
Index

solar cells (Continued)
  wafer preparation, 184–7
  see also multiple junction solar cells; silicon solar cells;
  thin-film solar cells
solar spectrum, 164, 165, 166
soluble PPV derivatives, 259, 259
solution processing, 260
spatial density function, 139, 142
spatially extended electrons, 3
spatially extended energy states, 3
spectrum splitting, 197
spin, 12, 20
  hole sub-bands, 29
  net magnetic moment, 141
two-electron systems, 137–9, 140
split-off bands, 29
Staebler–Wronski effect, 195
stationary point charge, 125, 125, 129
storage delay time, 116
string ribbon growth method, 191, 192
superposition states, 129
sulphide semiconductors, 59
surface recombination, 222–3, 222
surface recombination velocity, 56, 172
surface texturing
  light emitting diodes (LEDs), 244, 245
  silicon solar cells, 187–8, 188, 189
surface traps, 53, 54–5, 55
symmetric wavefunction, 138–9, 140, 142
synchrotron radiation, 128
tandem cells, 197, 198, 201
TAZI 279
telluride semiconductors, 59
ternary semiconductor alloys, 56–9
  see also under the names of specific materials
thermal annealing, 198
thermalization, 133
thermionic emission, 108–11
thin-film solar cells, 172–6
  amorphous silicon, 192–9
cadmium telluride, 199
efficiency, 182, 192, 197, 199
  see also amorphous silicon thin-film solar cells
III-V alloy semiconductors, 56–9, 57, 58
  see also under the names of specific materials
III-V semiconductors
  anti-sites, 222
  crystal structure, 28
  energy bands, 13
  energy gaps, 26, 26, 241
  radiative efficiency, 237
  recombination coefficient, 232
  see also under the names of specific materials
time-dependent carrier concentrations, 44, 44
  tin, energy gap, 26, 26
  TPEI, 276, 276, 279
  TPD, 267, 273–4
  TPQ, 276, 276
  TPTE, 273
  tracking devices, 203
transition region, 72, 78–83
  transparent substrates, 234
  trap-assisted carrier recombination, 53
  traps, 53–4
  carrier generation/recombination, 102–3
  LEDs, 221–2
  reduction in recombination times, 116
  triarylamine, 273–4
  triphenylamine (TPA), 273
  triple-junction cells, 197, 198, 201, 201
  triplet states
    excitons, 143
    two-electron atoms, 139–41, 140
    tris(8-hydroxyquinolinato)aluminium see Alq3
  tunnel diodes, 100–1, 100
  tunneling junctions
tunneling of electrons
  metal-semiconductor contacts, 112, 112
  p-n junction diode, 99, 100
two-electron atoms, 135–41
II-VI alloy semiconductors, 58
  see also under the names of specific materials
II-VI semiconductors, 59
  anti-sites, 222
  crystal structure, 28
  energy bands, 13
  energy gaps, 26, 26
  LEDs, 236
  see also under the names of specific materials
two-layer cathode, 268, 270
ultraviolet (UV) radiation, 125, 217
valence band, 14, 14
  carrier concentration, 23–4
  holes, 14–15, 14, 29
  sub-bands, 29
vapour deposition, 266
varactor diode, 116
visible light spectrum, 124–5
visual sensitivity, 149
wafer bonding, 234, 236
wafer preparation, 184–7
wave packets, 128
wavefunctions, 4–7, 6, 7
  inside potential box, 11–12
  reduced zone scheme, 8, 9
  two-electron atoms, 136–9, 142
wavevector, 5
white-emitting LEDs, 240–2, 247, 278
wurtzite, 28, 33
  see also gallium nitride
YAG:Ce, 241
Zener diode, 97–9
zinc oxide LEDs, 236
zinc selenide, 26, 58
zinc telluride, 58
zincblende unit cell, 27–9, 28