

Index

Note: *italic* page numbers refer to tables and **bold** page numbers refer to figures.

- a-Si:H *see* hydrogenated amorphous silicon
- absorption coefficient
 - amorphous silicon xx
 - cadmium telluride 279, 279–80, **285**
 - crystalline silicon xix–xx, 1
 - defect concentration from 189
 - hydrogenated amorphous silicon 173, 181–3
 - microcrystalline silicon 145–6
- aluminium induced crystallization 105–6
- amorphous silicon *see* hydrogenated amorphous silicon
- amorphous silicon cells
 - applications 227–9
 - largest array of modules 228, **229**
 - cell structure 204–7
 - design and efficiency 208–9
 - development overview xx, xxii–xxiii, 173–5
 - current production issues 175–6
 - films
 - device quality criteria 191
 - from hydrogen diluted silane 192–4
 - light induced degradation 211–12
 - light trapping 209–11
 - modeling 218
 - module fabrication 223
 - encapsulation and framing 225–6
 - monolithic integration of cell 225
 - plasma enhanced CVD systems 223–4
 - roll-roll production of flexible modules 226–7
 - shunt repair 225
 - transparent conductive oxide deposition 224–5
 - module performance 219–21
 - energy yield 221–3
- multijunction cells 212
 - current matching 214
 - spectrum splitting concept 215
 - tandem cells 215–18
 - triple junction 217–18
 - tunnel recombination junction 214–15
 - production capacity 223
 - superstrate and substrate configurations 207–8
 - transparent conductive oxides 209–11, 224–5
 - see also* hydrogenated amorphous silicon
- atomic layer deposition 262, 295
- back surface field 41, 72
- bandgap
 - acceptable range xix
 - amorphous silicon xx, 149, 180
 - tandem cells 215–16
 - cadmium telluride xxi, 277–8, 279
 - chalcopyrite cells xxi, 237, 265–6
 - crystalline silicon xx
 - group II–VI compound materials xxi
 - group III–V compound materials xx–xxi
 - low bandgap polymers 398
 - microcrystalline silicon 149
 - micromorph tandem cells 160
 - organic semiconductors xxi
 - silicon–germanium alloys 11, 12–15
- Bragg reflectors 18–19
- bulk heterojunction cells 387–8
 - active layer processing techniques 392–3
- buckminsterfullerene 388–91
- cell operational principles 391–3

464 INDEX

- bulk heterojunction cells *Cont.*
 - charge carrier mobility/recombination
 - CELIV, photo-CELIV and ToF techniques 399–401
 - photo-CELIV measurements of solar cells 412–17
 - regioregular MDMO–PPV copolymers 402–7
 - regioregular poly(3-hexylthiophene) 407–12
 - thickness dependence of
 - MDMO-0PPV/PCBM cells 418–21
- compounds commonly used in cells **392**
- conjugated polymers 387–8
 - interpenetrating network **391**
 - MDMO-PPV 388, **392**
 - MEH-PPV 389–91, **392**
 - regioregular MDMO-PPV copolymers 402–7
 - regioregular poly (3-hexylthiophene) 407–12
- development 388–91
- equivalent circuit model 406–7
- nanomorphology-property relationships 394–5
 - donor-acceptor "double cable" polymers 395–7
- photoinduced electron transfer 388–91
- photon harvesting, improving 397
 - less symmetrical fullerenes 398–9
 - low bandgap polymers 397–8
- power conversion parameters 393–4
- cadmium sulfide buffer 245, 261, 283–5
- cadmium telluride cells xxi, xxiv, 277–8
 - absorption coefficient **279, 285**
 - advanced cell structures and applications 293–4
 - back contact structure 288–90
 - bandgap 277–8, 279
 - buffering with cadmium sulfide 283–5
 - cadmium telluride, toxicity 291
 - cadmium telluride films
 - activation with chlorine 286–8
 - dopants **282**
 - electrical properties 281–3
 - grain boundaries 292–3
 - optical properties 279–80
 - physical properties **281**
 - cell characterization 298
 - C-V measurements 300–1
 - I-V measurements 298–300
 - quantum efficiency 301–2
 - structural, physical and chemical 302
 - cell thickness issues 292
 - efficiencies 277, **312**
 - environmental issues 290–1
 - impurities 291–2
 - modeling and computer simulation (SCAPS)
 - contact barrier 309–10
 - doping profile 310–13
 - parameter set **308**
 - psuedo two-dimensional simulation 313–14
 - two diode model 303–6
 - module and cell fabrication
 - commercial producers 297, 460
 - deposition techniques 294–6
 - series integrated modules 296–7
 - superstrate structure **xxiv**
 - window materials 285–6, **287**
- carbon dioxide sequestration 429–30
- carriers *see* substrates
- cell configuration *see* configuration
- chalcopyrite cells 237–9
 - absorber film
 - indium free 263
 - materials 237, 240
 - multisource evaporation process 240–2
 - sequential process 240–1, 242–3
 - sodium and film growth 243–4
- bandgaps xxi, 237, 265–6
- carrier density and transport 250–1
- cell concept 248–50
- chalcopyrite compounds in common use 239
- efficiencies 238, 251, 253
 - commercial modules 256
- loss mechanisms 251–2
- modules
 - advantages and potential 237–9
 - buffer 245, 261–3
 - cell structure and cross-section 239
 - diffusion layer and back contact 244, 263
 - monolithic integration and encapsulation 245–7
 - production process schematics **240, 244**
 - window fabrication and cost 245
- production and scaling up 254–7
 - cost estimations 257–8
 - energy payback time 238, 260

- module performance **256**, 258–9
 - raw material availability and recycling 259–60
- research and development issues 260
 - bifacial cells and superstrate cells 263–4
 - cadmium free cells 261–3
 - indium free absorbers 263
 - lightweight and flexible substrates 260–1
 - nonvacuum processing 264–5
 - novel back contacts 263
 - wide gap and tandem cells 265–6
- chemical vapor deposition 5
 - electron cyclotron resonance 11
 - hotwire 203–4
 - metal organic 262, 296
 - plasma enhanced 10
 - expanding thermal plasma 202–3
 - and hydrogenated amorphous silicon 173, 223–4
 - and microcrystalline silicon 134–5
 - and polycrystalline silicon 108–9
 - radio frequency 198–201
 - very high frequency 201–2
- reactor upscaling 25
 - batch type epitaxial reactor 28–9
 - continuous CVD reactor 25–7
 - convection assisted CVD 27, **28**
 - thermal atmospheric pressure 5, 41, 66–8
 - chemical yield (silicon conversion) 70
 - polycrystalline silicon cells 107–8
 - reactors 25–9, 71–2
 - silicon on ceramic substrates 72–5
 - silicon growth rate and $\text{SiHCl}_3\text{-H}_2$ 68–9
- chlorosilanes 66–9
- CIGS/CIS and related materials **xxi**, 237, **239**, 240, 243–4, 251
 - cell schematic **xxiv**
- close space vapor transport 8–9, **9**, 294–5
- commercial production
 - amorphous silicon cells 223–5
 - basic module concepts **xxv**, **xxvii**
 - challenges and future of photovoltaics *see* Terawatt Challenge
 - costs **xviii-xix**, 1–3
 - dye sensitized cells 382–3
 - growth rate of photovoltaics **xvii-xviii**
 - process flow schematics **2**, **76**
 - roll-to-roll process 226–7
 - stringing and laminating **xxviii**
 - website data 460
- conductive polymers 387–8
 - see also* conjugated polymers
- configurations, cell
 - bifacial 263–4
 - substrate and superstrate **xxiv**, **116**, 151, 152, 175
 - cadmium telluride **294**
 - chalcopyrite 263–4
- conjugated polymers, charge carrier
 - photogeneration in 325–6
- donor-acceptor interface 335–6
 - charge carrier generation and mobility 340–3
 - energetics and exiplexes 336–40
 - geminate electron-hole pair kinetics 343–5
 - nongeminate recombination of electron-hole pairs 345–9
- exciton dissociation 349
 - at donor-acceptor interface 353–7
 - and electronegative dopants 351–3
 - field assisted 327–8
 - Onsager-Braun model 349–51
- intrinsic photogeneration 326
 - electron-hole excitons 326–7
 - field assisted dissociation of excitons 327–8
- sensitized photogeneration 328
 - doping with electronegative sensitizers 328–32
 - Monte Carlo simulation 332–5
 - see also* bulk heterojunction cells
- copper indium gallium selenide *see* CIGS
- costs, production **xviii-xix**, 1–3
 - estimates and future of photovoltaics *see* Terawatt Challenge
- crystalline silicon cells (foreign substrate) **xxii-xxiii**, 39–41, 85–7
- cell fabrication schemes and options 75–7
 - passivation 77, 78–81
 - porosity of substrate 77
 - surface texturing 76–7
- cell performance
 - on ceramic substrates 82–5
 - efficiencies 82
 - high quality cell on SiSiC ceramic 85
 - large area wafer equivalents 81–2
 - mismatched thermal expansion coefficients 64–5, 84–5
 - on model (low cost) silicon substrates 78–81

466 INDEX

- crystalline silicon cells (foreign substrate) *Cont.*
 epitaxial absorber layer 41
 hydrogen passivation 78–81
 silicon deposition 68–75
 on ceramic substrates 73–5
 chemical yield (silicon conversion efficiency) 70
 growth rate and CVD 68–70
 requirements for photovoltaics 67
 research and development trends 71–3
 intermediate layer 44
 diffusion of impurities 47–8
 light trapping 45–7
 required characteristics 45
 seeding layer 41, 72, 73–5
 substrates
 low cost and model materials 43–4, 78–81
 polycrystalline silicon by CVD 72, 73–5
 required characteristics 42–3
 zone-melting on 64–6
 zone-melting recrystallization
 on ceramic substrates 64–6
 development and methods 48–51
 film growth and subgrain boundaries 51–3
 film microstructure and defects 55–6, 58–9
 grain size enhancement 53–5, 64–5
 lamp heated processors 59–64
 scan speed and cell performance 78–9, **80**
 see also epitaxial silicon cells
 crystallization, metal induced 105–6
 CuInS₂/CuInGaSe₂ and related materials xxi, 237, **239**, 240, 243–4, 251
 cell schematic **xxiv**
- dangling bonds xx, 177, 178, 190, **195**
 defect density 112–3
 amorphous silicon 178, 205
 and light soaking 190–1
 ZMR silicon 55–6, 58–9, **60**
 see also passivation
 density of states 179–80
 constant photocurrent method 187–8
 deep level transient spectroscopy 190, **191**, **192**
 defect concentration from absorption coefficient 189
 dual beam photoconductivity 188
 Fourier transform photocurrent spectroscopy 189
- modeling 180–1
 optoelectrical methods 187
 photothermal deflection spectroscopy 187
 space charge methods 190
- deposition technologies 4, 5
 atomic layer deposition 262, 295
 chemical deposition 245, 296
 close space vapor transport 8–9, **9**, 294–5
 electrodeposition 6–8, **7**, **8**, 296
 electron cyclotron resonance 11
 glow discharge technique 173
 high throughput/upscaling 24–5, 176
 batch type epitaxial reactors 28–9, 71
 continuous chemical vapor deposition reactor 25–7, 71–2
 convection assisted chemical vapor deposition 27, **28**
 liquid phase epitaxy reactors 29–32
 ion assisted deposition 9–10, **10**
 liquid phase epitaxy 6–7, 29–32, 110
 low energy plasma techniques 10–11
 multisource evaporation 241
 requirements for silicon photovoltaics 67–8
 screen printing and sintering 265, 296
 solution spray 296
 sputtering 242–3, 244, 245, 296
 see also chemical vapor deposition
 diffusion barrier 45, 47–8
 diffusion length 99–100
 doping 194–6
 dye sensitized cell *see under* nanocrystalline injection cells 364–5
- efficiencies
 amorphous silicon cells 39
 single junction 212, **213**, **216**
 tandem 215–16
 triple junction 216–17
 chalcopyrite cells 238, 251, 253, 256
 crystalline silicon cells (ceramic substrate) 82
 epitaxial silicon cells
 industrial type 23
 laboratory type 21, 22
 microcrystalline single junction cells 154–5
 micromorph tandem cells 160, 161
 nanocrystalline injection cells 363, 376–7
 electrodeposition 6–8, **7**, **8**, 296
 electron cyclotron resonance 11
 electron-hole pairs xxi, 343–5, 345–9

- energy distribution states *see* density of states
- environmental issues
- cadmium telluride cells 290–1
 - chalcopyrites cells 259–69, 261
- epitaxial silicon cells (silicon substrate) xxii, 1–4
- buried porous silicon reflectors 18–19
 - cost savings 2, 3
 - cross-section schematic xxii, 2
 - deposition technologies 4, 5
 - basic requirements for photovoltaics 67–8
 - close space vapor transport 8–9
 - electrodeposition from melted salts 6–8
 - electron cyclotron resonance 11
 - ion assisted deposition 9–10
 - liquid phase epitaxy 6, 29–32
 - low energy plasma techniques 10–11
 - upscaling/high throughput 24–32, 71–3
 - see also under* chemical vapor deposition
 - epitaxial lateral overgrowth 19–20
 - epitaxial ZMR silicon film
 - hydrogen passivation 78–81
 - open circuit voltage **80**
 - thickening 41, 55–6, **65**, 66–7, **66**
 - germanium-silicon structures 15–17
 - industrial cells 22–4
 - efficiency results 23
 - front grid contacted cell 24
 - local shunting paths **23**
 - novel lateral epitaxial **24**
 - production flow diagram **2**
 - laboratory type cells 21–2
 - efficiencies 21, 22
 - overview of main results 21
 - optical confinement 4, 17–20
 - silicon-germanium alloys 12–15, 16
 - substrates
 - choice xxii, 3
 - contamination by **4**
 - textured 11–12
 - epitaxy, liquid phase 6–7, 29–34, 110
 - excitons xxi, 326–7
 - dissociation 327–8, 349–57
 - exiplexes 336–40
 - extremely thin absorbers xxv, **xxvi**
- fullerines 388–91, **392**, 398–9
- germanium-silicon structures 15–17
- glow discharge deposition 135–6, 173
- Graetzel cell xxv, **xxvi**
- grain sizes (silicon) *see under* silicon
- heterojunction cells *see* bulk heterojunction cells
- hydrogenated amorphous silicon xx, 39, 133, 173
 - alloying 196–7
 - atomic structure 177–8
 - criteria for device quality films 191
 - density of states 179–80
 - determination 187–90, **191**, **192**
 - modeling 180–1
 - deposition techniques 197
 - expanding plasma CVD 202–3
 - hot wire CVD 203–4
 - radio frequency plasma enhanced CVD 198–201
 - very high frequency CVD 201–3
 - doping 194–6
 - electrical properties
 - ambipolar diffusion length 185–7
 - dark conductivity 183–4
 - photoconductivity 184–5
 - electron spin resonance 178
 - film structure and hydrogen diluted silane 192–4
 - hydrogen characterization by IR 178–9
 - metastability 190–2
 - optical properties 181–3
 - Staebler-Wronski effect 190–2
 - see also* amorphous silicon cells

hydrogenated microcrystalline silicon xx, 39–40, 133–4

 - multijunction cell schematic **xxiii**
 - see also* microcrystalline silicon cells

impurities, diffusion of 45–6, 47–8

indium tin oxide 151, 152

industry, photovoltaic *see* commercial production

intermediate silicon layers *see under* silicon

ion assisted deposition 9–10, **10**

Lambertian reflector 46, 98–9

laser crystallization 1, 104–5

light confinement *see* optical enhancement and confinement

light induced degradation *see* Staebler-Wronski effect

light trapping *see* optical enhancement and confinement

468 INDEX

- liquid phase epitaxy 6–7, 29–32, 110
 - lateral overgrowth **20**
 - morphology and topography **7**
 - reactor upscaling 29
 - batch type multiwafer 31
 - temperature difference method 30–1
- $\mu\text{c-Si:H}$ *see* hydrogenated microcrystalline silicon
- manufacture *see* commercial production
- metal impurities *see* transition metals
- metal induced crystallization 105–6
- microcrystalline silicon cells 133–4, 163–5
 - deposition technologies
 - high pressure depletion technique 136–7
 - hot wire technique 137
 - microwave plasma 137
 - plasma enhanced chemical vapor deposition 134–5
 - very high frequency glow discharge 135–6
 - microcrystalline defined 97
 - microcrystalline layers 1, 137–8
 - crystalline growth model 143–4
 - density state determination 187–90
 - doped layers 147–8
 - electronic transport properties 146–7, **148**
 - microstructural properties 138–41
 - nucleation and growth 141–3
 - optical properties 144–6
 - solar cells 148–9
 - light management 149
 - single junction cells 154–9
 - substrate choice 150–1
 - tandem amorphous/microcrystalline cells xxiii, 134, 159–64
 - transparent conductive oxides 150–4
 - micromorph tandem cells xxiii, 134, 159–61, 175
 - light induced degradation 161–4
- mobility gap 180
- modeling
 - cadmium telluride cells 303–14
 - density of states 180–1
 - exciton dissociation in conjugated polymers 349–58
 - hydrogenated amorphous silicon cells 218
 - kinetics of geminate electron-hole pairs 343–5
 - microcrystalline silicon growth 143–4
 - Monte Carlo and charge carriers 332–5
 - polycrystalline cells 100–1
- module manufacture *see* commercial production
- molybdenum 239, 244
- multicrystalline silicon
 - cells *see* silicon wafer cells
 - defined 97
- multijunction cells
 - current matching 214
 - spectrum splitting concept 215
 - tandem cells 215–18
 - triple junction cells 216–18
 - tunnel recombination junction 214–15
 - types and terminology **xxiii**, 212
- multisource evaporation 241
- nanocrystalline injection cells 363–4
 - charge carrier collection 371–4
 - charge separation and photons to current 369–71
 - interfacial electron transfer **370**, 373
- dye sensitized cells
 - commercial developments and field tests 382–3
 - efficiency 363, 376–7
 - increasing open circuit voltage 377–8
 - new sensitizers and redox systems 378–9
 - photocurrent action spectra 375–8
 - principle 364–5
 - solid state cells 379
 - stability 379–80, 379–82
 - tandem concept 384
- electrolyte
 - and charge carrier collection 372–3
 - redox cycles 365
- light harvesting by sensitizer layer 366–8
 - enhanced red and infrared response 368
- nanostructure
 - importance of 365–6
 - mesoscopic TiO_2 film **366**, **368**, **376**
- quantum dot sensitizers 374
- ruthenium polypyridyl complex dyes
 - adsorption at film surface 377
 - interfacial electron transfer 369–71
 - long term stability 379–82
 - structure **367**, **378**
- semiconductor film, mesoscopic **366**, **368**, **376**
 - conduction band electron motion **372**
 - effects of morphology on performance 375–6
 - electron injection into 369–71, 373

- and light harvesting 366–8
- photoinduced processes at surface **373**
- preparation 375
- nanocrystalline silicon xx, 134, 138–9, **140**
 - defined 97
- Onsager-Braun model 349–51
- optical enhancement and confinement 1
 - amorphous silicon cells xxiii, 209–11
 - cells, single junction 154–9
 - crystalline silicon xx
 - germanium-silicon structures 15–17
 - intermediate silicon layers 45
 - light trapping options 46–7, 76–7, 83, 209–11
 - microcrystalline silicon 149
 - reflectors 17–20, 121
 - Bragg 18–19
 - epitaxial lateral overgrowth 1–20
 - intermediate layer 45
 - Lambertian 46, 98–9
 - porous silicon interlayers 18–19
 - transparent conductive oxides 152
 - silicon-germanium alloys 12–15
 - texturing
 - glass 103
 - industrial epitaxial cells 22–3
 - microcrystalline cells 98, 152, 154
 - substrates 11–12
 - ZMR surfaces 47
 - organic semiconductors xxi
 - cells overview xxiv–xxv, **xxvi**
 - see also* bulk heterojunction cells; conjugated polymers
- passivation, hydrogen 77, 78–81, 113–14
 - amorphous silicon **177**, 178
 - polycrystalline silicon films 118, **119**
- photocurrent action spectra 375–6
- photovoltaic industry *see* commercial production
- plasma enhanced CVD *see under* chemical vapor deposition
- polycrystalline silicon cells 97–8
 - active layer formation
 - chemical vapor deposition 106–8
 - ion assisted deposition 109
 - liquid phase epitaxy 110
 - plasma enhanced CVD 108–9
 - solid phase crystallization 110–12
 - defect density and activity 112–15
 - diffusion length 99–100
 - initial polycrystalline film formation 103
 - nucleation control 103–4
 - seed layer approach 72, 73–5, 104–5
 - light confinement 98–9
 - modeling 100–1
 - solar cell and module processing
 - defect passivation 118, **119**
 - device structure 115–17
 - isolation and interconnection 118–20
 - junction formation 117–18
 - substrate choice 101–3
 - technologies and research
 - crystalline silicon on glass technology 121–2
 - general research 122–3
 - solid phase crystallization-hetero junction
 - with intrinsic thin layer 120–1
 - surface texture and enhanced absorption
 - with back reflector 121
- polycrystalline silicon defined 97, 134
- polymorphous silicon 194
- polysilicon *see* polycrystalline silicon
- production *see* commercial production
- quantum dot sensitizers 374
- reflectors *see under* optical enhancement
- ruthenium polypyridyl complex dyes *see under* nanocrystalline injection cells
- screen printing and sintering 265, 296
- silicon
 - grain sizes 97–8, 134, 194
 - and defect density 112
 - polycrystalline silicon 97–8
 - recrystallization of silicon 40, 49, 104–6, 110
 - silicon cell efficiency xxii, 1, 40, 97
 - layers, intermediate 41
 - chemical vapor deposition 72, 74–5
 - as diffusion barrier 45, 47–8
 - required properties 44–5
 - material definitions 97–8, 133–4, 194
 - wafers 1
 - see also* amorphous silicon; hydrogenated microcrystalline silicon
- silicon carbide 43, 45
- silicon cells *see* amorphous; crystalline; epitaxial; microcrystalline; polycrystalline; silicon wafer
- silicon nitride 43–4, 45

470 INDEX

- silicon oxide 44, 45
- silicon wafer cells xvii-xviii, xxii, 40
 cost reduction 1-3
 module concepts **xxvii**
- silicon-germanium alloys 12-15, 174
 dislocation and defect density 14
 efficiency comparison 16
 growth rate graphs **13**
 hydrogenated amorphous silicon 196-7,
 215-16
 internal quantum efficiency curve **15**
 structure and micrograph **12**
- solar cells
 overview xvii-xxix
see also bulk heterojunction; cadmium
 telluride; chalcopyrite; nanocrystalline
 injection; silicon cells
- solar energy, future of 428-31
- solid phase crystallization 110-12
- solution spray 296
- sputtering 242-3, 244, 245, 296
- Staebler-Wronski effect xxiii, 161-3, 175-6
 hydrogenated amorphous silicon 190-2,
 211-12
- STAR cells 121
- states *see* density of states
- Stranski-Krastonov growth 15
- substrates
 ceramic xxii, 1, 82, 102
 chemical vapor deposition of silicon on
 72, 73-5
 mullite 43, 83
 porosity issues 77-8
 silicon carbide 43, 44, **65**
 silicon nitride 43-4, 53, **66**, 82, 84, 102
 zirconium silicate 43, 44
 zone-melting recrystallization on 42-4,
 64-6
- for crystalline silicon ZMR cells 42-4, 78-81
- Czochralski silicon and multicrystalline silicon
 44, 54, 78-81
- for epitaxial silicon cells xxii, 3
- flexible by roll-to-roll process 226-7
- glass 39, 150, 208, 255
 polycrystalline silicon cells 101-3,
 121-2
- graphite xxii, 77
- intermediate silicon layer 41
- low cost and model silicon xxii, 3, 43-4
- metal 10, 154, 208
- metallurgical grade silicon 3, 25
- plastic 133, 260, 307-8
- silicon oxide 44, 45, 53, 54
- silicon ribbon 43, 44, 78
- stainless steel 150
- textured 11-12
- thermal expansion coefficients 64-5, 84-5,
 101-2
- Terawatt Challenge 427
 approach to estimating module costs 432-5
 BOM commonalities described and defined
 431-2, 435
 characteristics of thin film designs 453
 results of estimating module costs 435
 BOM commonalities, throughput/maturity
 levels for BOM commonalities
 439-40, **440**
 breakdown for active materials (nonBOM)
 438-9, **439**
 glass-to-glass modules BOM
 commonalities 435-8, **436**, **437**
 ground mounted, large systems 448, 449,
 450, 452, 453
 long term module costs for active materials
 (nonBOM) 444-6
 module efficiencies, evolution of 441-2,
442
 newer/alternate thin film technologies
 442-3
 projected total module evolution costs **447**
 relative technical risk of thin film
 technologies 443-4, **444**
 rooftop, commercial systems 448, 451,
 452, 454
 technology specific nonBOM costs 440-1,
441
 total module costs by technology 441,
441
- semiconductor materials, availability issues
 455-8
- website data for commercial modules 460
- world energy use and future needs 428, 431
 carbon dioxide sequestration 429-30
 challenges facing solar energy 429
- texturing *see under* optical enhancement
- thermal annealing 1
- thin film
 absorber materials xix-xxi
 defined xix
 technology overview xxi-xxix
- transition metal impurities 44, 47-8

- transparent conductive oxides 174, 175
 amorphous silicon cells 209–11, 224–5
 cadmium telluride cells 284, 285–6
 chalcopyrite cell 245
 microcrystalline silicon cells 150–4
 reflectors 152
- TREBLE cell 100–1
- VEST process 81
- window materials
 cadmium telluride cells 285–6, **287**
 chalcopyrite cells 245
 see also transparent conductive oxides
- zinc oxide 151, 152–3
- zirconium silicate 43, 44
- zone-melting recrystallization (silicon)
 development and methods 48–51
 and dislocation density 55–6
 electron beam ZMR 50
 film growth and subgrain boundaries 51–3,
 55, **56**
 characteristics 50
- oxygen solubility 53
 supercooling 52
- film microstructure and defects 55–6, 58–9
- grain size 49, 58
 enhancement 53–5, 64–5
- graphite stripe melting 50
- high speed recrystallized layers 56–7
 defect density 58–9, 60
 grain shape 58, **59**
 melting zone shape 57–8
- large area recrystallized wafer equivalents
 81–2
- laser ZMR 50, 51
- linear halogen lamp heating **49**, 50–1,
 59–60
 process control 62–3
 system setup 61–2
- scan speed and cell performance 78–9, **80**
- substrates
 ceramics 64–6
 low cost silicon 43–4
 properties and requirements 42–3
 thermal expansion coefficients 64, 65–6,
 84–5

With kind thanks to W. F. Farrington for creation of this index.

