

Index

- 1.2-eV $\text{FA}_{0.75}\text{Cs}_{0.25}\text{Sn}_{0.5}\text{Pb}_{0.5}\text{I}_3$ bottom cell 530
 1.8-eV $\text{FA}_{0.6}\text{Cs}_{0.4}\text{Pb}(\text{I}_{0.65}\text{Br}_{0.35})_3$ top cells 533
 1.8-eV $\text{FA}_{0.83}\text{Cs}_{0.17}\text{Pb}(\text{I}_{0.5}\text{Br}_{0.5})_3$ top cell 530
 1.22-eV $\text{FA}_{0.7}\text{MA}_{0.3}\text{Pb}_{0.5}\text{Sn}_{0.5}\text{I}_3$ bottom cell 533
 1.22-eV $\text{MASn}_{0.5}\text{Pb}_{0.5}\text{I}_3$ 530
 1.25-eV $(\text{FASnI}_3)_{0.6}(\text{MAPbI}_3)_{0.4}$ bottom cell 532
 1.25-eV GA-passivated $(\text{FASnI}_3)_{0.6}(\text{MAPbI}_3)_{0.4}$ bottom cell 528
 1.63-eV $\text{Cs}_{0.05}\text{FA}_{0.8}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.85}\text{Br}_{0.15})_3$ 528
 1.75-eV $\text{FA}_{0.8}\text{Cs}_{0.2}\text{Pb}(\text{I}_{0.7}\text{Br}_{0.3})_3$ top cell 532
 1.75-eV $\text{FA}_{0.8}\text{Cs}_{0.2}\text{Pb}(\text{I}_{0.7}\text{Br}_{0.3})_3$ top cells 532
 1.77-eV $\text{FA}_{0.8}\text{Cs}_{0.2}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3$ top cell 533
 1.82-eV $\text{MA}_{0.9}\text{Cs}_{0.1}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3$ top cell 530
- a**
- absorption coefficient 5, 6, 9, 29, 37, 52, 91, 106–111, 135, 138, 209, 216, 262, 277, 281, 289, 328, 329, 342, 373, 375, 380, 495, 541
 ABX_3 perovskite crystal 2, 264, 417
 ABX_3 perovskite unit cells 254
 A-cation 253, 254, 256, 257, 260–264, 267–271, 339, 357
- AC poling of MAPbI_3 196–197
 adamantanes 418
 Al_2O_3 34, 37, 46, 301, 320, 418, 487, 488
 alkyl diammonium-based perovskites 45
 all-inorganic perovskites 50–52
 all-perovskite tandem solar cells (APTSCs) 2-T 528–533
 4-T tandem configuration 527–528
 limitations and challenges of 533–534
 amino-alkyl compounds 416
 ammonium salt passivation methods 357
 ammonium salts 358, 359
 tetra-ammonium zinc phthalocyanine 45
 amorphous SiO_2 418
 amplitude parameter 542
 anti-coupling behavior 267
 antiferroelectrics 175
 antimony (Sb)-based halide perovskites 52
 $\text{APb}(\text{Br}_x\text{I}_{1-x})_3$ 516
 apparent capacitances 443
 atomic force microscopy (AFM) 179–180, 231, 234, 240, 365
 atomic layer deposition (ALD) 350, 484, 530
 Auger coefficient 216
 Auger recombination 209, 210, 216, 217, 327, 334, 335, 378, 496
 average photon energy (APE) 494

b

- backward/reverse scan 14, 50, 342, 343, 356, 430, 442, 444, 487, 533
 band bowing 254, 264, 268, 269
 band gap
 band gap energy 208
 basic perovskites 103
 below-bandgap loss 463
 determination 142
 MAPbI_3 , analysis of 101
 perovskite alloys, variation in 105
 band structures 35, 97, 98, 102, 115, 123, 128, 132–141, 160, 174, 207, 208, 220, 254, 256, 264, 377
 barium titanate (BaTiO_3) 178
 bathocuproine (BCP) hole blocking layer 518
 BaTiO_3 perovskite, charge neutrality of 67, 195
 Beer's law 108
 bifacial solar cells 469
 bimolecular radiative recombination coefficient 215
 bimolecular recombination 215, 216, 218, 222, 223, 379
 blackbody radiation 16, 292, 296, 311–316, 321, 471
 blue shift 254, 266, 270, 364, 476
 Boltzmann constant 151, 209, 218, 292, 311, 470, 497
 bonding diagram, of isolated $[\text{PbI}_6]^{4-}$ cluster 142
 bowing effect 13, 254, 396–398, 521, 522
 Bragg–Brentano measurement geometry 189
 broadening parameter 99, 542
 bulk-heterojunction (BHJ) 362, 404
 butanediamine iodide (BEAI_2) 45
 butylammonium bromide (BABr) 519
n-butylammonium iodide (BAI) 520
N-butylammonium iodide (*n*-BAI) 360
4-tert butylpyridine 354

c

- calcium titanate 32, 375
 capacitive effects 187, 440, 442–444
 carbon-based PSCs 45
 carrier concentration effect, on Hall mobility 155
 carrier diffusion length 10, 22, 34, 36, 37, 144, 146, 151, 164, 207, 223, 224, 263, 277, 340, 375, 404, 405, 488, 526
 carrier lifetime 6, 7, 10, 123, 139, 151, 158, 165, 207, 217, 218, 224, 285, 297, 299, 303, 344, 345, 347, 360, 378–379, 399, 403–405, 522, 525, 526
 carrier mobility, of MAPbI_3 155
 characterization method, variation of 156–159
 effective mass effect 160–161
 maximum mobility determination 161–164
 temperature dependence 159
 carrier–phonon interaction 7, 216
 carrier properties, of MAPbI_3 153
 carrier concentration effect on Hall mobility 155, 156
 self-doping 153–155
 transport properties 166
 carrier transport characterization, principles of 152
 cathodoluminescence (CL) 208
 center cation
 cubic perovskite phase tolerance factor 256–258
 optoelectronic property variations 263–268
 solar cell performance 268–271
 thin film stability 258–263
 $\text{CH}_3\text{NH}_3\text{I}$ 231
 $\text{CH}_3\text{NH}_3\text{PbI}_3$ thin film 210, 222
 chalcogenide-halide mixed perovskite (MASbSI_2) 52
 charge carrier dynamics 173, 203
 charge-carrier recombination 173, 203, 345, 377, 378, 391

- charge transport materials 30, 353–356
 chemical vapor deposition (CVD) 350,
 352, 401
 chemiluminescence 208
 clamping 178, 187, 188
 classical Shockley diode equation 435
 composition engineering 385
 conduction band minimum (CBM) 36,
 97, 132, 264–267, 278, 282, 396, 398
 conductive (p-doped) silicon wafer 198
 contact potential difference (CPD) 191,
 192, 231, 286, 287
 continuity equation 496
 conversion efficiency 3, 16, 17, 29, 31,
 101, 207, 260, 269, 270, 285, 295,
 302, 309, 318, 327, 332, 334, 339,
 375, 377, 405, 415, 430, 463, 509,
 563
 copper indium gallium selenide (CIGS)
 474, 509
 creeping poling 195, 197–201
 crystalline silicon (Si) 52, 482, 488, 489,
 499, 509
 Cs-based inorganic perovskites 49
 Cs-based lead perovskites 48
 $\text{Cs}_{0.05}\text{FA}_{0.8}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3$
 optical constants of 556
 Tauc–Lorentz parameters of 558
 $\text{Cs}_{0.05}\text{FA}_{0.8}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.8}\text{Br}_{0.2})_3$
 optical constants of 555
 Tauc–Lorentz parameters of 556
 $\text{Cs}_{0.05}\text{FA}_{0.8}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.95}\text{Br}_{0.05})_3$
 optical constants of 554
 Tauc–Lorentz parameters of 555
 $\text{Cs}_{0.05}(\text{MA}_{0.17}\text{FA}_{0.83})_{0.95}\text{Pb}(\text{I}_{0.83}\text{Br}_{0.17})_3$
 415
 $\text{Cs}_{0.05}\text{MA}_{0.45}\text{FA}_{0.5}\text{Pb}_{0.5}\text{Sn}_{0.5}\text{I}_3$ bottom cells
 533
 $\text{Cs}_{0.1}\text{FA}_{0.9}\text{PbI}_{2.9}\text{Br}_{0.1}$ 353
 $\text{Cs}_{0.15}\text{FA}_{0.85}\text{PbI}_3$
 phase changes with temperature 85
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3$
 optical constants of 552
 perovskite 519
 Tauc–Lorentz parameters of 553
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.7}\text{Br}_{0.3})_3$
 optical constants of 551
 Tauc–Lorentz parameters of 552
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.8}\text{Br}_{0.2})_3$
 optical constants of 549
 Tauc–Lorentz parameters of 550
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.9}\text{Br}_{0.1})_3$
 optical constants of 548
 Tauc–Lorentz parameters of 549
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{1-x}\text{Br}_x)_3$ thin films 167,
 168
 $\text{Cs}_{0.17}\text{FA}_{0.83}\text{PbI}_3$
 optical constants of 546
 Tauc–Lorentz parameters of 547
 $\text{Cs}_y\text{FA}_{1-y}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3$ thin films 166,
 167
 $\text{CsFAMAPb}(\text{I},\text{Br})_3$ triple-cation perovskite
 112
 $\text{CsFAPb}(\text{I},\text{Br})_3$ 331
 CsGeI_3 387
 CsPbI_2Br -based dopant-free HTM
 photovoltaic cell 50
 CsPbI_3 258
 crystal structures 76
 phase changes with temperature 85
 CsPbI_3 crystal structure 75
 $\alpha\text{-CsPbX}_3$ perovskites 416
 $\text{CsRbFAMAPbI}_{3-x}\text{Br}_x$ 487
 CsSnI_3 380
 cubic ABX_3 perovskite structure 67,
 68
 cubic perovskite phase tolerance factor
 256–258
 Curie temperature 175, 176
 current matching 20, 328, 331, 333, 466,
 469, 473, 486, 493, 497

d

- damp heat tests 421–422, 527
 dark current density 470, 472
 deep carrier traps 144, 146
 deep electronic traps 445
 defect engineering 153
 defect passivation 297, 357, 406
 defect physics 123, 144–147

- defect tolerance 36, 37, 54, 147, 207, 215, 475, 520
 density functional theory (DFT) 123, 230, 396
 assumptions and limitations 126–128
 basic principles 124–126
 calculations 69
 crystal structures 128–131
 description 124
 electronic structure calculation 124
 exchange-correlation energy functional 126
 hybrid perovskites
 band gap determination 142
 band structures 132–134, 136
 center cation effect 143
 crystal structures 128
 defect physics 144–147
 density of states (DOS) 139–140
 direct–indirect issue 134–139
 effective mass 140–141
 halide anion effect 143–144
 organic center cations 131
 spin-orbit coupling (SOC) interaction 128
 many-electron system
 electronic properties of 124, 125
 electronic structures of 125
 density of states (DOS), hybrid perovskites 139–140
 detailed balance limit 475, 476
 diaminoethane (DAE) 51
 diffused front ($p+$ / n)c-Si homojunction 487
 diffuse horizontal irradiance (DHI) 494
 diffusion length 6, 10, 22, 34–37, 123, 144, 146, 151, 164–166, 207, 223, 224, 263, 266, 277, 285, 340, 345, 357, 375, 378–379, 383, 388, 391, 392, 399, 400, 403–406, 488, 524–526
 N,N -dimethylformamide (DMF) 350, 384
 dimethyl sulfoxide (DMSO) 350, 384, 389
 direct Auger recombination 216
 direct band gap semiconductors 219
 direct-gap formation, of hybrid perovskites 134
 direct normal irradiance (DNI) 494
 donor–π–acceptor-type(D–π–A)
 molecules 47
 doped/undoped organic ILs 530
 double-reflection model (DRM) 329, 330
 Drude-type free-carrier absorption 157
 dual AC resonance tracking
 piezoresponse force microscopy
 (DART-PFM) 183
 dye-sensitized solar cells (DSSCs) 29, 33, 373, 437
- e**
- effective mass 9, 36, 118, 132, 140–141, 156, 160–162
 effective PL lifetime $t_{1/e}$ 214, 215
 efficiency limit
 for cells with more junctions 474
 for four-terminal tandem solar cells 470–472
 for two-terminal tandem solar cells 472–474
 Einstein relation 151, 314
 electrical model 496–498
 electroluminescence (EL) 33, 208
 electron backscatter diffraction (EBSD) 189–191
 electron beam-induced current (EBIC) 164, 165, 285, 365
 electron-hole recombination energy 209
 electron transfer layers 260
 electron transport layer (ETL) 1, 2, 223, 234, 277, 328, 350, 353, 355, 356, 374, 441, 449, 487
 elementary charge 218, 434, 467, 470
 ellipsometry 5, 6, 92, 96, 101, 102, 104, 106–113, 157, 259, 291, 541
 energy yield calculation 465, 493–499
 ethylene diammonium diiodide (EDAI₂) 391
 exciton annihilation 374

- excitonic properties of hybrid perovskites 117–118
 external quantum efficiency (EQE) 102, 110, 218, 287, 289, 315–317, 362, 486, 487
 extinction coefficient 93, 541, 544, 545, 547, 548, 550, 551, 553, 554, 556, 557, 559–561
 extrapolated sub gap absorption 262
- f**
- $\text{FA}_{0.55}\text{MA}_{0.45}(\text{Sn}_{0.55}\text{Pb}_{0.45})\text{I}_3$
 optical constants of 558
 Tauc–Lorentz parameters of 559
- $\text{FA}_{0.75}\text{Cs}_{0.25}\text{Pb}(\text{I}_{0.3}\text{Br}_{0.7})_3$ perovskite top cells 530
- $\text{FA}_{0.75}\text{Cs}_{0.25}\text{Sn}_{0.5}\text{Pb}_{0.5}\text{I}_3$ 524
- ($\text{FAPb}_{0.6}\text{Sn}_{0.4}\text{I}_3$)_{0.85}($\text{MAPb}_{0.6}\text{Sn}_{0.4}\text{Br}_3$)_{0.15}-based PSCs 527
- (FASnI_3)_{0.6}(MAPbI_3)_{0.4} bottom cell 528
- (FAPbI_3)_{0.7}(CsSnI_3)_{0.3} 524
- (FAPbI_3)_{0.7}(CsSnI_3)_{0.3} perovskite 524
- (FAPbI_3)_{0.95}(MAPbBr_3)_{0.05} 415
- (FAPbI_3)_{0.97}(MAPbBr_3)_{0.03} 415
- (FAPbI_3)_{1-x}(CsSnI_3)_x 524
- (FASnI_3)_{1-x}(MAPbI_3)_x perovskites 522
- (FASnI_3)_x(MAPbI_3)_{1-x} perovskites 261, 262
- $\text{FA}_{1-y}\text{Cs}_y\text{Sn}_x\text{Pb}_{1-x}\text{I}_3$ 522
- FA/Cs-based mixed Sn-Pb perovskites 522
- FACs($\text{I}_x\text{Br}_{1-x}$)₃ 485
- FAGEI₃ 387
- FA/MA-based mixed Sn-Pb perovskites 522
- FAMACsPb($\text{I}_x\text{Br}_{1-x}$)₃ 485
- (FA, MA, Cs)(Sn, Pb)(I, Br, Cl)₃ 401, 403
- FAPb($\text{I}_{1-x}\text{Br}_x$)₃ thin films 167, 168
- FAPb($\text{I}_{1-x}\text{Br}_x$)₃ 516
- FAPbI₃ 248–250
 bandgap of 40
 crystal structures 76, 129
 cubic structure at room temperature 75
- DFT optimization 129
 Goldschmidt tolerance factor 43
 lattice parameters 130
 vs. MAPbI₃ 40, 41
 optical constants of 545
 phase changes with temperature 85
 Tauc–Lorentz parameters of 546
 thermal stability 40
- FAPbI₃ perovskite 234
- FASnI₃ 384–386, 390
- FA_xMA_{1-x}SnI₃ 385–387
- ferroelasticity 174–176
- ferroelectric insulators 176, 183, 195
- ferroelectric poling of MAPbI₃
 AC poling 196–197
 creeping poling and switching events 197–200
 macroscopic effects of poling 200–201
- ferroelectric solar cells 173
- ferroelectricity 174
 atomic force microscopy 179–180
 charge carrier dynamics 203
 crystallographic considerations 174–178
 definition 174
 electron backscatter diffraction (EBSD) 189–191
 ferroelectric poling of MAPbI₃ 195–196
 Kelvin probe force microscopy 191
 MAPbI₃ thin films 178–179, 183–188, 193–195
 piezoresponse force microscopy 180–183
 pitfalls during sample measurements 201
 polarization orientation 191–193
 transmission electron microscopy 188
 X-ray diffraction (XRD) 189
- ferromagneticity 174
- field effect transistors (FETs) mobilities 159, 198, 377
- fill factor (FF) 3, 41, 42, 203, 237, 303, 309, 347, 361, 387, 432, 437, 485, 487, 497, 499, 514, 563

- fill factor (FF) (*contd.*)
- film fabrication methods 389
- first principles method 35, 39, 124, 230
- fluorine-doped tin oxide (FTO)-coated glass substrate 518
- fluoro-silane 418, 421
- formamidinium lead iodide (FAPbI₃) 1, 71, 91, 128, 151, 277, 309
- forward bias to short circuit (FB-SC) 242
- forward scan 14, 370, 430, 437, 442, 448
- 4-T all-perovskite tandem solar cells 527–528
- four-terminal tandem solar cells 467–468
- efficiency limit for 470
- Fröhlich interaction 162, 221, 222
- fullerene-based ESL 518
- g**
- GASCN passivated (FASnI₃)_{0.6}(MAPbI₃)_{0.4} low-bandgap cells 532
- generalized gradient approximation (GGA) 97, 127
- Gibbs free energy 255, 261–263, 265, 268, 270
- Goldschmidt tolerance factor 42, 67, 256, 257, 340, 341, 343, 344, 347, 375
- grain boundaries (GBs) 153
- crystallography and chemical bondings 229
- definition of 229
- disordered or amorphous 229
- electrical properties 234, 237, 239, 240
- electronic properties of 229, 230
- impact of 229
- ion migration
- charge separation 244
 - enhanced ion transport 241–244
 - KPFM measurement 241
 - light current and voltage (I–V) characteristics 241
 - role of 244–246
 - potential barriers 231–234
 - stability
- MAPbI₃ hydrated phase 247–248
- of FAPbI₃ 248–250
- grain-boundary engineering 22, 304
- grain interiors (GIs) 230
- grain size and composition dependence 448
- grazing incident small-angle X-ray scattering (GISAXS) 364
- grazing incident wide-angle X-ray scattering (GIWAXS) 364
- guanidinium bromide (GABr) 302, 404, 519
- guanidinium thiocyanate (GASCN) 403, 525
- GW method 128, 133
- h**
- halide perovskites 207
- absorbers, compositional design of 40–41
- advantages 30
- Hall measurements 152, 153, 164, 381, 384
- Hartree–Fock (HF) method 127
- n-hexyl trimethylammonium bromide (HTAB) 300, 301
- high efficiency tandem solar cells 52–54
- high-energy (short-wavelength) photons 467
- highest occupied molecular orbital (HOMO) 39, 283, 354, 392
- highly absorptive, doped Spiro-OMeTAD film 484
- high-quality 1-μ m-thick mixed Sn-Pb perovskite films 532
- hole transfer 223, 260
- hole transport layer (HTL) 1, 2, 207, 223, 277, 328, 353, 374, 412, 432, 441, 488, 491
- hole transport material (HTM) 33, 34, 46, 47, 49, 231, 342, 354, 380, 453
- homogeneous broadening 211
- hot antisolvent treatment (HAT) 389
- HSE06 127, 128, 132–134

- hybrid chemical vapor deposition (HCVD) 352
- hybrid organic-inorganic perovskite 339, 361–362
- hybrid perovskite polycrystalline absorbers 1
- hybrid perovskite single cells 15, 324, 325
- hybrid perovskite solar cells advantages 3, 12
band gap tunability 12–13
high V_{oc} 13–16
low temperature coefficient 16
- band alignment 281–283
- band diagram of device simulation 283–285
experimental observation 285–287
refined analyses 287
- challenges 16
improved stability, requirement of 17–19
- large-area solar cells 19–20
- Pb and Sn compounds, toxicity of 20–22
- characteristics, variation of 4
- cross-sectional image 3
- crystal quality 413–415
- current density–voltage ($J-V$) characteristics 14
- damp heat tests 421–422
- defects and grain-surface ion migration, and passivation 417–419
- degradation at interface with metal oxides 420
- development 3
- formamidinium lead iodide 277
- high conversion efficiencies 11
- methylammonium lead iodide 277
- multiporous-layered-electrode perovskite solar cells 420–421
- normalized conversion efficiency variation 16
- operation 2
- operational principle and basic structures 278–281
- refined analyses carrier generation and loss 287–291
e-ARC software 295
power loss mechanism 291–295
- scanning electron microscope 2
- V_{oc} loss factors 296
- grain boundary effect 303–304
- interface effect 297–300
- passivation effect 300–303
- water-stable and MA-free perovskites 415–417
- hybrid perovskites 207 *see also* MAPbI₃
absorbers 91
advantages 7
bandgap of 101–106
characteristics 5
charge neutrality of 67
charge transfer mechanism 223–224
cubic symmetry 67
degradation and healing of 222–223
description 1, 67
exciton binding energy 118
feature of 123
lattice parameters 71–75
light absorption properties 91
octahedral factor 81
phase change by temperature 84–86
phase change with temperature 85–86
physical properties 4
refined structures of 86–88
semiconducting properties 1
 α spectra 92
structures, space group and lattice parameters 74
tolerance factor 81–84
- hybrid perovskite thin film 75, 157, 166, 209–213
- hydrazine (N₂H₄) 390
- hydrazinium chloride (N₂H₅Cl) 390
- hydrazinium tin iodide 389
- hypophosphorous acid (HPA) 390
- hysteresis in $J-V$ characteristics characteristics 437–442
- issues 453

- hysteresis in J - V characteristics (*contd.*)
- mechanistic and microscopic origin of hysteresis 442–452
 - solar cell 431–437
- i**
- ideal JV curve under illumination 434, 435
 - illumination model 439, 494, 496, 498
 - imbalanced electron/hole transport 445
 - impurity scattering 161, 221
 - indene-C60 bisadduct (ICBA) 393, 519
 - indirect Auger recombination 216
 - indirect-gap formation 134, 135, 139, 151
 - indium tin oxide (ITO) 38, 380, 464, 468, 478, 484, 518
 - inhomogeneous broadening 211
 - inorganic A cations 347–349
 - inorganic $\text{CsPb}(\text{I}_{1-x}\text{Br}_x)_3$ perovskites 516
 - inorganic HTMs 47
 - inorganic perovskites 48, 49, 52, 416
 - interband Auger recombination 216
 - interdigitated back contact (IBC) bottom cells 465, 468, 483, 499
 - interface dependence 449
 - internal quantum efficiency (IQE) 218, 287, 288
 - intrinsic carrier concentration 138, 377, 398–399, 521
 - intrinsic stability 31, 40, 44
 - intrinsic structural stability of perovskites 42
 - inverse/converse piezoelectric effect 174
 - inverted hysteresis 441, 442, 448
 - ionic radii 2, 43, 51, 79, 80, 256, 257, 340, 376, 398
 - ion migration 31, 44, 46, 95, 187, 194, 212, 222, 230, 241–246, 258, 344, 362, 411, 413, 417–419, 448
 - isopropyl alcohol (IPA) 389
- j**
- J_{sc} deficit 326, 406
 - j th Tauc–Lorentz peak 542
- k**
- Kelvin probe force microscopy (KPFM) 191, 231, 285, 287, 445
 - Kohn–Sham equation 124, 125, 128
 - Kramers–Kronig integration 113, 542
 - Kubelka–Munk function 102
- l**
- Lambert–Beer law 495
 - Langevin model 378, 379
 - large-area solar cells 19–20
 - lateral piezoresponse force microscopy (LPFM) 181, 182, 185
 - lead-free perovskites 48–52
 - lead halide perovskites 29, 30, 33–37, 39, 213, 220, 224, 411, 412, 416, 418, 422
 - lead thiocyanate ($\text{Pb}(\text{SCN})_2$) 270, 403, 492
 - lead zirconate-titanate ($\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$) 178
 - light-absorbing layer 223
 - light-induced I_2 molecule 417
 - light-intensity independence 447
 - light management 464, 469, 482, 483, 492
 - light trapping 482, 485, 486
 - local density approximation (LDA) 127, 144
 - LO-phonon scattering model 101, 161, 163, 168
 - Lorentz shape function 208
 - loss function 99
 - low-bandgap mixed Sn-Pb PSCs 524–526, 530, 533, 534
 - low-bandgap perovskite solar cells
 - critical issues of 525–527
 - current state of 524–525
 - mixed Sn-Pb perovskites 521–524 - low-energy (long wavelength) photons 467
 - lowest unoccupied molecular orbital (LUMO) 392
 - luminescence coupling 471–473
 - luminescent-coupling efficiency 471
 - Lyddane–Sachs–Teller relation 101

m

- MA-based perovskites 345, 346
macroscopic effects of poling 200–201
 $\text{MA}_{1-x}\text{FA}_x\text{Pb}_{0.75}\text{Sn}_{0.25}\text{I}_3$ perovskites 521
MA free perovskite solar cells 416
 MAGeI_3 387
many-body problem 124, 125
 $\text{MAPb}(\text{Br}_{1-x})_3$ 212
 $\text{MAPb}(\text{I}_{0.6}\text{Br}_{0.4})$ perovskites 520
 $\text{MAPb}(\text{I}_{1-x}\text{Br}_x)_3$ 516, 518
 MAPbX_3
 high-frequency dielectric constant 95
 static dielectric constant 95
 $\text{MAPbBr}_{3-x}\text{Cl}_x$ 211
 $\text{MAPbBr}_{3-x}\text{I}_x$ nanocrystals 212
 MAPbBr_3 , optical constants of 560, 561
 MAPbI_3 254, 258, 259, 339, 342, 345
 α phase 68, 69
 α spectra 92, 109, 110, 112, 113, 116, 138
 α variation, interpretation of 108–111
 band alignment 143, 144
 bandgap analysis of 101–103
 bandgap calculation 135
 band structure 132–141
 band structure 35, 132–141
 β phase 69
 carrier diffusion length, lifetime and mobility 164
 carrier mobility and lifetime 36, 164, 165
 carrier mobility, temperature dependence 159
 carrier properties of 153–155
 carrier scattering by an harmonic lattice vibrations 162, 163
 conduction band 36
 critical point analysis 102, 103
 crystal structural phases 68, 70
 crystal structure 69, 129
 crystal symmetry 68
 density of states 139–140
 DFT calculation
 carrier concentration/Fermi level 146
 ionic bonding 147
 transition energy levels of defects 145, 146
 vacancy-type defects 145
 DFT optimization 129
 dielectric function 93–96
 effective mass 140–141
 E_g values 102
 electronic structure, theoretical modeling of 39
 ellipsometry measurements 108
 vs. FAPbI_3 40, 41
 IR peak positions 99
 lattice parameters 129, 130
 nanocrystals 3
 vs. mixed perovskites, crystal structure 43, 44
 optical constants 543
 optical measurements, principles of 107–108
 optical transitions 97, 98
 Pb and I wave functions 143
 photophysical properties of 35
 photovoltaic properties 30
 polaron formation 162, 163
 spectral shift calculation of 114
 ε_2 spectrum 99
 Tauc–Lorentz parameters 542
 temperature effect on absorption properties 116–117
 thin films
 carrier concentration and Hall mobility 154
 carrier diffusion length, lifetime and mobility 164
 energy separation, Fermi level vs. valence-band maximum 153, 154
 transmission/reflectance (T/R) measurements 106, 107
 Urbach analysis 114, 115
 valence band 36
 variation of MA^+ reorientation time 88
 XRD calculations 70, 71
 XRD diffraction peaks 72

- MAPbI₃-based solar cell device 223
 MAPbI₃ β phase 68
 MAPbI₃/quartz sample, PL time decays of 158
 MAPbI₃/SiO₂ 224
 MAPbI₃/TiO₂ 224
 MASnI₃ 383, 384, 387
 MASn_xPb_{1-x}I₃ perovskites 521
 MASn_xPb_{1-x}I₃ 401, 402
 Matthiessen's rule 161
 maximum achievable current density 496, 497
 maximum power point (MPP) tracking 42, 201, 270, 430, 467, 524
 Me₄NBr surface passivation 358, 360
 mechanistic and microscopic origin of hysteresis 442–452
 mechanoluminescence 208
 mesoporous TiO₂ 2, 35, 279, 355, 365, 374, 384, 389, 441, 487
 metal-halide perovskites 29, 439, 446, 453, 474–476, 509, 510, 534
 methylammonium (MA) 29, 67, 179, 339, 510
 methylammonium lead iodide 277, 510
 α spectra 91
 conduction band minimum (CBM) 97
 crystal structures 128–131
 dielectric function 93
 light absorption 93
 DFT calculation 97
 feature 94
 IR region 98
 THz region 99–101
 visible/UV region 96–98
 optical transition analysis 97
 polycrystalline thin films
 photoluminescence intensity 7
 structural changes 18
 solar cells
 absorption coefficient spectra 5, 6
 crystal structure 5
 fundamental properties 8–11
 optical properties 8
 ϵ_1 spectrum 95
 valence band maximum (VBM) 97
 microwave conductivity (MC) 152, 217
 mid-contacted three-terminal solar cell 468
 mixed B-cation hybrid organic-inorganic perovskite solar cells 361–362
 mixed-cation hybrid perovskites
 of CsFAPb(I,Br)₃ 75
 tolerance factor (t) of 82–84
 mixed halide perovskite MAPbX₃ 211
 mixed I-Br perovskites 15, 516–520
 mixed Sn-Pb perovskites 516, 520–527, 532, 533
 mixed tin (Sn)-lead (Pb) perovskite 509
 mobile ions 11, 31, 41, 178, 179, 446, 447, 449–454
 modified forward (dark) currents 448
 molybdenum tris(dithiolene) complex 360
 monolithic 2-T tandem cells 515
 monolithic two-terminal solar cells 466–467
 multi-cation hybrid organic-inorganic perovskites 339, 341
 multi-cation hybrid perovskite solar cells
 basic characterization of 362–365
 cation selection in
 inorganic A cations 347–349
 organic A cations 345–346
 FA 341
 fabrication
 charge transport materials 353–356
 emerging fabrication technologies 350–353
 traditional fabrication approach 349–350
 mixed B-cation hybrid organic-inorganic perovskite solar cells 361–362
 Pb-based 341–344
 Sn-based perovskite materials 344–345
 surface passivation 357–360
 multi-junction solar cells 463, 469–474, 500

- multijunction tandem solar cells 509, 511, 512
- multiporous-layered-electrode perovskite solar cells (MPLE-PSC) 420–421
- n**
- nanoscale X-ray fluorescence (n-XRF) 365
 - nanotextures 482
 - narrow bandgap cell 377, 396
 - narrow bandgap perovskites 377
 - n-i-p configuration 281, 299, 374, 385, 401, 524
 - n-i-p MAPbI₃ solar cells 283
 - n-i-p solar cells 279
 - non-capacitive origins 443, 453
 - non-centrosymmetry 174
 - nonradiative interface recombination 300
 - nonradiative recombination 46, 146, 207, 209, 210, 215, 216, 219, 220, 222–224, 229–232, 292–294, 296, 300, 303, 304, 318, 327, 359, 360, 374, 476, 485, 525
 - non-silicon-heterojunction bottom cells 480, 483
 - n-type CdS absorber 490
 - n-type c-Si cells 487
 - n-type, double-side polished float zone (FZ) c-Si wafer 484
 - n-type Si homojunction bottom cell 487
 - nuclear magnetic resonance (NMR) 88, 348
- o**
- octahedral factor 81, 257, 376
 - OMeTAD 47, 354
 - omnidirectional PL spectroscopy 219
 - one-diode model 497
 - one-electron approximation method 124
 - open-circuit voltage 3, 37, 38, 55, 114, 165, 218, 309, 383, 432–435, 477, 488, 497, 499, 514, 563
 - optical absorption coefficient 36, 37, 209, 216, 342
- optical constants
- of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.6}Br_{0.4})₃ 556
 - of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.8}Br_{0.2})₃ 555
 - of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.95}Br_{0.05})₃ 554
 - of Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})₃ 552
 - of Cs_{0.17}FA_{0.83}Pb(I_{0.7}Br_{0.3})₃ 551
 - of Cs_{0.17}FA_{0.83}Pb(I_{0.8}Br_{0.2})₃ 549
 - of Cs_{0.17}FA_{0.83}Pb(I_{0.9}Br_{0.1})₃ 548
 - of Cs_{0.17}FA_{0.83}PbI₃ 546
 - of FA_{0.55}MA_{0.45}(Sn_{0.55}Pb_{0.45})I₃ 558
 - of FAPbI₃ 545
 - of MAPbBr₃ 560
 - of MAPbCl₃ 561
 - of MAPbI₃ 543
 - optical gap 52, 542
 - optical interference effect 108, 289
 - optical model 107, 108, 111, 291, 311, 315, 320, 321, 325, 328–330, 494–496, 498
 - optical properties, of hybrid perovskite materials 111
 - variation with center cation 111–112
 - variation with halogen atom 112–114
 - optical transition analysis, for MAPbI₃ 97
 - organic A cations 339, 340, 345–346
 - organic HTMs 34, 47
 - organic–inorganic halide perovskite (OIHP) 229
 - organic–inorganic metal halide perovskite solar cells (PSCs) 509
 - organic metal halide (OMH) perovskites 173, 178, 509
 - organolead halide perovskite crystal 411, 416, 418
 - organolead-halide perovskite solar cells (PSCs) 411
 - oxide vs. halide perovskites 29
- p**
- passivated emitter and rear locally diffused design 482
 - passivated emitter rear contact (PERC) 469, 482

- passivation effect 300, 302, 328, 357, 359, 391, 453
- Pauli exclusion principle 126
- Pb and Sn 12–14, 17, 20–22, 51, 262, 264, 339, 397, 534
- Pb-based hybrid perovskite thin films 166
- Pb-based multi-cation hybrid perovskite solar cells 341–344
- Pb-based perovskite cells 279, 290
- Pb-based perovskite film quality 51
- Pb-containing hybrid perovskites 128
- Pb halide perovskites 378, 379
- PbI₂, crystal structures 75, 76
- PCBM/MAPbI₃/quartz sample, PL time decays of 158
- peak transition energy 542
- Perdew, Burke, and Ernzerhof (PBE) scheme 127
- perovskite 375–376, 413
- perovskite absorber layer 1, 3, 14, 255, 268, 270, 278, 279, 347, 348, 354, 357, 359, 362, 373, 406, 486, 514, 516, 518, 519, 524, 526
- perovskite alloys, bandgap variation in 105–106
- perovskite-based photovoltaic cell performance 33
- perovskite-chalcogenide tandem solar cells 489–493
- perovskite crystal structure 32, 40, 79, 123, 255, 256, 258, 260, 262, 264, 268, 339, 341, 406, 417
- perovskite films 31, 35, 40, 42, 45, 47, 51, 52, 234, 236, 240, 241, 249, 255, 256, 261, 263, 271, 298, 303, 342, 343, 349–351, 353, 357, 364, 385, 389, 391, 397, 401, 403–405, 486, 492, 519, 520, 522, 523, 525, 526, 532, 534
- perovskite-silicon tandem solar cells 463, 464, 479, 482–489, 498, 499
- perovskite/silicon 2T tandem solar cell 484
- perovskite-Si tandem cell 53
- perovskite solar cells (PSCs) 339, 429 energy diagram of 39 layered architectures of 38 moisture resistance 46 open circuit voltage 38 stabilizing strategy 41–48
- perovskite unit cell 82, 129, 191, 253, 254, 264
- phenethylammonium iodide (PEAI) 302, 359, 492
- phenyl C₆₁ butyric acid methyl ester (PCBM) 239, 518
- phenylethylamine iodide (PEAI) 45
- photoconversion efficiency (PCE) 229
- Cs₂TiBr₆ 52
- MASbSI₂ 52
- of Sn-based perovskites 51
- triple-junction tandem cells 53
- photocurrent density 30, 53, 380, 432, 435, 470, 471, 473, 486–488, 493
- photoluminescence (PL) 151, 152, 208, 364
- hybrid perovskite thin film 209–213
- material and device characterization 222–224
- overview of 208–209
- quantum efficiency 218–220
- temperature-dependent PL 220–222
- time-resolved PL of hybrid perovskites 213–218
- photophysical properties of MAPbI₃ 35
- photovoltaic devices
- based on metal halide perovskite semiconductors 29
 - historical background 32–34
 - working principle of 37–40
- photovoltaic (PV) technology 509
- phthalocyanine (Pc) derivatives 47
- physical vapor deposition (PVD) 350
- piezoelectric crystal 174
- piezoresponse force microscopy (PFM) 179–184
- p-i-n solar cell 279, 304, 432
- pinning 178, 187, 188, 350, 384
- planar SnO₂ 441

- planar TiO_2 441
 Planck constant 162, 209, 470
 PL quantum yield (Q_{PL}) 297–299
 PL time decays of MAPbI_3 /quartz sample 158
 PL time decays of PCBM/ MAPbI_3 /quartz sample 158
 PL time decays of spiro-OMeTAD/ MAPbI_3 /quartz sample 158
 $Pm3m$ space group 253
 Poisson equation 496, 498
 polaron 162, 163
 poly[bis(4-phenyl)(2,4,6-trimethylphenyl) amine] (PTAA) HSL 518
 polycrystalline MAPbI_3 thin films 8, 185, 187, 188, 190, 191
 polycrystalline OIHP solar cells 229
 poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT + PSS) HSL 342, 524
 polyethylene-imine 418
 polymer hole transporting materials 48, 49
 polymer (poly(bithiophene imide)) (PBTI) 418
 $(p+)$ polysilicon/silicon oxide/(n)c-Si passivated front junction 487
 polystyrene 418
 power conversion efficiency (PCE) 30, 37, 339, 377, 430, 474, 509
 halide perovskite-based photovoltaic cells 31
 MAPbI_3 -based photovoltaic cell 30
 perovskite solar cells 30
 power loss mechanism 278–283, 291–294
 p-type CIGS absorber 490
 p-type hole selective layer (HSL) 514
 pyroelectric crystal 175
- q**
 quadruple cation-based perovskite 40
 quantum efficiency 102, 110, 207, 209, 218–220, 287, 288, 315, 362, 486, 487, 495
 quantum mechanical problems 125
 quasiparticle self-consistent GW (QSGW) 36, 396
 quaternary ammonium halides (QAJs) 357
- r**
 radiative recombination coefficient 8, 138, 215, 216
 Rashba splitting effect 97, 115, 135, 137, 138
 rate dependence of hysteresis 441, 447
 RbCsMAFA quadruple-cation perovskite 348
 Rb-doped CsFAPbI_3 perovskites 41
 reduced basis method 499
 refined hybrid perovskite structure centre cations orientation 86–87
 organic center cations relaxation 88
 refractive index 8, 9, 93, 209, 318, 495, 541, 544, 545, 547, 548, 550, 551, 553, 554, 556, 557, 559–561
 remanent polarization 177, 201
 resistance 20, 45–48, 197, 197, 203, 234, 292, 318, 320, 324, 327, 334, 335, 357, 393, 430, 432, 434–437, 443, 466, 482, 489, 497, 499
 resonance-enhanced sf-PFM 183, 185
- s**
 scanning photocurrent microscopy (SPCM), of MAPbI_3 single crystals 165
 scan rate 437–445, 447, 448, 450
 secondary phase materials 22, 68, 71, 75–77, 167
 self-doping 146, 153–155, 379
 semiconductor-based emission cooling 211
 sequential deposition method 389
 series-parallel connected tandem solar cell 468, 469
 Shannon ionic radii 256, 257
 s-shaped JV curves 435
 s-shape/s-kink 435

- Shockley equation 470, 472, 497
 Shockley–Queisser (SQ) limit 315–318, 376, 474, 511
 blackbody radiation 313–315
 conversion efficiencies 309, 310
 detailed balance theory 509
 EQE spectrum 315–317
 free software 335–336
 maximum efficiency 310
 perovskite single cells
 EQE calculation method 321–323
 performance-limiting factors of
 hybrid perovskite devices 325–327
 single solar cells 323–325
 thin-film limit 318–321
 physical model 311–313
 Sn–Pb perovskite solar cells 393–396
 tandem-cell
 devices 331–334
 EQE spectra calculation 329–331
 optical model and assumptions 328–329
 realistic maximum efficiency 334–335
 Shockley–Queisser (SQ) theory 6, 13, 15, 311, 563
 Shockley–Read–Hall (SRH)
 recombination 52, 434, 496
 Shockley–Read–Hall model 209
 short-circuit current density 3, 111, 309, 435, 470, 495, 497, 514, 563
 short circuit to forward bias (SC-FB) 242
 silicon heterojunction (SHJ) solar cells 464, 483
 silver (Ag) back electrode 485, 518
 silver bismuth halide 52
 single-carrier trapping 215–217, 223
 single-cation perovskites 339, 341, 345, 347
 single-frequency piezoresponse force microscopy (sf-PFM) 183
 single-junction silicon solar cells 482, 485
 single-junction solar cells 37, 261, 376, 377, 393, 396, 463, 466, 470, 474, 493, 496, 497, 509, 511–513
 single-monovalent-cation perovskites 516
 Sn-based all-inorganic perovskites 51
 Sn-based multi-cation hybrid perovskite solar cells 344–345
 Sn-based perovskites 12, 13, 18, 21, 23, 51, 128, 345, 377
 Sn-containing perovskite alloys
 $(\text{MASn}_x\text{Pb}_{1-x}\text{I}_3)$ 75
 Sn–Ge mixed PSCs 387–388
 Sn halide perovskites 377–380, 383, 389, 391
 Sn + Pb B-cation perovskites 268
 Sn + Pb perovskites 266
 Sn–Pb perovskite solar cells
 bowing effect 396–398
 physical properties
 carrier lifetime and diffusion length 399
 intrinsic carrier concentration 398–399
 Shockley–Queisser (SQ) limit 393–396
 status of
 device engineering 404–406
 efficiency of 395, 400
 $(\text{FA}, \text{MA}, \text{Cs})(\text{Sn}, \text{Pb})(\text{I}, \text{Br}, \text{Cl})_3$ 401–403
 $\text{MASn}_x\text{Pb}_{1-x}\text{I}_3$ 401
 photovoltaic parameters 381
 use of additives 403–404
 Sn perovskite solar cells
 CsSnI_3 380–383
 device engineering and lattice relaxation 391–394
 doping effect of large organic cations 390–391
 FASnI_3 384–386
 $\text{FA}_x\text{MA}_{1-x}\text{SnI}_3$ 385–387
 film fabrication methods 389
 MASnI_3 383–384
 Sn–Ge mixed PSCs 387–388

- 2D/3D FASnI₃ 387
use of reducing agents 389, 390
- soap-structured crystal 419
- solar cell architecture 269, 287, 310, 327, 334, 440, 448
- solar-cell efficiency limit 309, 563
- solar cell materials
bulk modulus 160
effective mass of electrons and holes 160
electron and hole mobility 160
- solution-based crystallization, of perovskite materials 31
- solution coating process 29
- solution-processed CH₃NH₃PbI₃ thin film 213, 217
- spiro-OMeTAD/MAPbI₃/quartz sample, PL time decays of 158
- spiro-OMeTAD/MoO_x buffer/sputtered ITO stack 487
- spin-orbit coupling (SOC) 97, 126–127, 135, 521
- Stokes shift 208–210, 219, 224
- subgap absorption characteristics 114–116
- sulfobetaine zwitterions 416
- surface passivation 357–360, 364, 388, 399, 404, 405, 418, 519, 520
- surrogate modelling methods 498
- t**
- tandem solar cells
bifacial solar cells 469
device architectures 513–514
efficiency limits of multi-junction solar cells 469–470
electrical model 496–497
energy yield calculation 498–499
four-terminal 467–468
illumination model 494
mid-contacted three-terminal solar cell 468
monolithic two-terminal solar cells 466–467
optical model 494–496
- PCE of 514–516
perovskite-chalcogenide 489–493
perovskite-silicon 482–489
perovskites as materials 474–477
series-parallel connected 468
temperature model 498
three-terminal 468
use of 511
- Tauc–Lorentz dielectric function model 113, 541
- Tauc–Lorentz parameters
of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.6}Br_{0.4})₃ 558
of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.8}Br_{0.2})₃ 556
of Cs_{0.05}FA_{0.8}MA_{0.15}Pb(I_{0.95}Br_{0.05})₃ 555
of Cs_{0.17}FA_{0.83}Pb(I_{0.6}Br_{0.4})₃ 553
of Cs_{0.17}FA_{0.83}Pb(I_{0.7}Br_{0.3})₃ 552
of Cs_{0.17}FA_{0.83}Pb(I_{0.8}Br_{0.2})₃ 550
of Cs_{0.17}FA_{0.83}Pb(I_{0.9}Br_{0.1})₃ 549
of Cs_{0.17}FA_{0.83}PbI₃ 547
of FA_{0.55}MA_{0.45}(Sn_{0.55}Pb_{0.45})I₃ 559
of FAPbI₃ 546
of MAPbI₃ 544
- Tauc–Lorentz peaks 96, 97, 541, 542
- temperature coefficient 12, 16, 498
- temperature dependence 84, 156, 159, 213, 220, 221, 439, 447
- temperature-dependent PL properties 220–222
- temperature model 498
- terahertz (THz) spectroscopy 152
- ternary bismuth halide perovskite materials 51
- 2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene (Spiro-OMeTAD) HSL 518
- thermalization loss 463, 511, 516
- thermally evaporated MoO_x buffer 484
- thermodynamic equilibrium 255
- thin films 178
secondary phases 75–77
stability 258–263
- three-terminal (3T) tandem solar cells 468
- Ti(IV)-based halide perovskites 52
- Tiedje–Yablonovitch limit 495

- time-resolved PL 207, 213–218, 223, 364
- tin halide perovskite solar cells
carrier lifetime and diffusion length 378–379
intrinsic properties 377–378
tandem solar cells 377
- tin oxide 244, 379, 468
- tolerance factor 256, 257
of APbX₃ 83
calculation 79
- cations in APbI₃ perovskite system 43
of hybrid perovskites 79–82
of mixed-cation perovskites 82–84
- triple-cation-mixed α -phase perovskites 83
- top cell 12, 13, 15, 16, 23, 49, 53, 54, 113, 270, 327–329, 331–335, 463–465, 467–474, 476, 477, 481, 483–492, 495, 496, 499, 509, 511, 513, 516, 518, 527, 528, 530, 532, 533
- toxicity of Pb and Sn compounds 17, 20–22
- traditional fabrication approach 349–350
- transmission electron microscopy (TEM) 188
- transparent conductive oxide (TCO) 2, 278, 318, 468, 478, 514
- transport equation 496
- trifluoroethylamine (FEA)-modified perovskites 45
- bis(trifluoromethane)sulfonimide lithium salt (Li-TFSI) 354
- triple cation perovskite 40, 42, 112, 236, 237, 343, 347, 349, 357, 359, 363, 364, 488
- triple-junction tandem cells 53
- triple-or quadruple-cation perovskites 341
- truxene core-introduced OMeTAD derivative 47
- 2-D crystal 418–419
- 2-D perovskite crystal 419
- 2D/3D FASnI₃ 387, 388
- 2-T all-perovskite tandem solar cells 528–533
- 2-T mechanically-stacked APTSCs 530
- 2-T monolithic APTSCs 530
- 2T perovskite/CIGS solar cells 490
- 2T perovskite/CIGS tandems 489–491
- 2T perovskite/SJH tandem solar cell 484–486
- two-terminal tandem solar cells 468, 469, 472–474, 499
- typical meteorological year (TMY) 494
- U**
- ultrathin ALD SnO₂/Au ILs 533
- Urbach analysis, for MAPbI₃ 114, 115
- Urbach energy 8, 9, 114, 137, 210, 262, 263, 265, 268, 311, 474
- V**
- vacuum-deposited MAPbI₃ bottom cells 530
- valence band maximum (VBM) 36, 97, 153, 264–267, 278, 282, 345, 396, 398
- van Roosbroeck–Shockley relation 208, 210, 216
- Varshni's law 220
- vertical piezoresponse force microscopy (VPFM) 181, 182
- virtual current 313
- V_{oc} deficit 37, 326, 327, 406, 517–519
- V_{OC}-to-bandgap loss 476
- W**
- wafer-based silicon solar cells 468
- Wannier equation 118
- water-stable and MA-free perovskites 415–417
- wide-bandgap cell 396
- wide-bandgap halide (WBH) perovskite layer 300, 301
- wide-bandgap perovskite solar cells
critical issues of 519–520
current state 518–519
mixed I-Br perovskites 516–518

Windows-based free computer software (e-ARC software) 295, 335

of MAPbI_3 71
of PbI_2 77
X-ray photoelectron (XPS) 398

X

X-ray diffraction (XRD) 189, 383
of CsPbI_3 77
of FAPbI_3 77
of hydrate phases 77

Z

zero-valence iodide 417
zinc oxide 468, 490
zinc phthalocyanine 45, 440
zinc-tin oxide (ZTO)/ SnO_2 /ITO ILs 530

