ADVANCES IN SOLAR PHOTOVOLTAIC TECHNOLOGIES AND THE ROLE OF PHOTONICS

Stéphane COLLIN[1,*], Oliver HÖHN[2], Christian M. WOLFF[3]

[1] Centre de Nanosciences et de Nanotechnologies (C2N), CNRS, Université Paris-Saclay, and Institut Photovoltaïque d'Ile-de-France, Palaiseau, France

[2] Fraunhofer Institute for Solar Energy Systems ISE, and Department of Sustainable Systems Engineering (INATECH), University of Freiburg, Freiburg, Germany

[3] Photovoltaics and Thin-Film Electronics Laboratory (PV- Lab), Institute of Electrical and Micro Engineering (IEM), École Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland

*** stephane.collin@cnrs.fr**

Solar photovoltaics (PV) is expected to play a crucial role in achieving carbon neutrality by 2050. The past 15 years have witnessed remarkable progress in both research and industry. This review provides an overview of current technologies, including dominant silicon PV, emerging perovskite materials, premium III-V semiconductors, and alternative thin-film technologies. We also introduce the main research avenues, with a particular focus on the emerging field of tandem solar cells and the role of photonics.

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Solar photovoltaics (PV) is expected to play a key role in the deployment of the renewable energies needed to achieve carbon neutrality by 2050 and comply with the Paris Agreement adopted in 2015. Over the last 15 years, solar energy has progressed at a lightning speed that no one had predicted: the capacity of PV installations worldwide has increased tremendously and overcome 1.5 TW, representing 5.5 % of the PV electricity share. From 2010 to 2024, the efficiency of PV modules has increased by 0.3–0.4% absolute per year to reach 22-23%, their price has fallen from over 1 €/W to 0.2 €/W, and the levelized cost of electricity of large PV systems has dropped from 0.31 $€_{2022}$/kWh to less than 0.05 $€_{2022}$/kWh [1]. Thanks to these changes, solar photovoltaics is now in a position to play a dramatic role in the energy transition.

These impressive gains are the consequence of large-volume manufacturing combined with advances in the technologies and processes. There is little doubt that the silicon PV, which dominates the current photovoltaic market, will continue to be improved over the coming years. Still, the best efficiencies are approaching the theoretical limits, and new architectures will be needed to achieve efficiencies over 30 %.

The operation of solar cells can be summarised in three stages: absorption of sunlight in a semiconductor and creation of electron-hole pairs (photon energy greater than the bandgap), thermalisation of charge carriers, separation and collection of charges through selective contacts (pn junctions or heterostructures). Under standard solar illumination (the so-called AM1.5G solar spectrum), the theoretical maximum conversion efficiency is 33% for a single junction (Shockley-Queisser limit). In practice, the record is 29.1% with 1-2 µm of GaAs, 27.3% with 120-150 µm of silicon, and around 23-24% for thin-film solar cells composed of 2-3 µm of Cu(In,Ga)Se_2 or CdTe. 1 µm-thick absorbers are typically sufficient for materials in the emerging perovskite family, and efficiencies over 25% have been demonstrated.

Tandem solar cells are considered the most promising technology to overcome the 33%-efficiency limit. The approach consists of combining two or more solar cells: a top cell with a wide bandgap absorbs high-energy photons, enabling energy conversion with reduced thermalisation losses (heat dissipation), and is transparent to low-energy photons. A straightforward route is to build upon the silicon technology by adding a wide-bandgap solar cell on top of the bottom silicon wafer, in a two-terminal (2T, monolithically integrated cells in series) or four-terminal configuration (4T, mechanically stacked, electrically independent). Perovskite is seen as the most promising candidate for low-cost tandem devices, but it still has several challenges to overcome. Other technologies are also being developed to contribute to the advancement of tandem cells, as potential alternatives to perovskite and for specific applications.

In the following, we draw an overview of the state of the art of the photovoltaic technologies and we introduce the main current research avenues, with particular emphasis on the role of photonics.

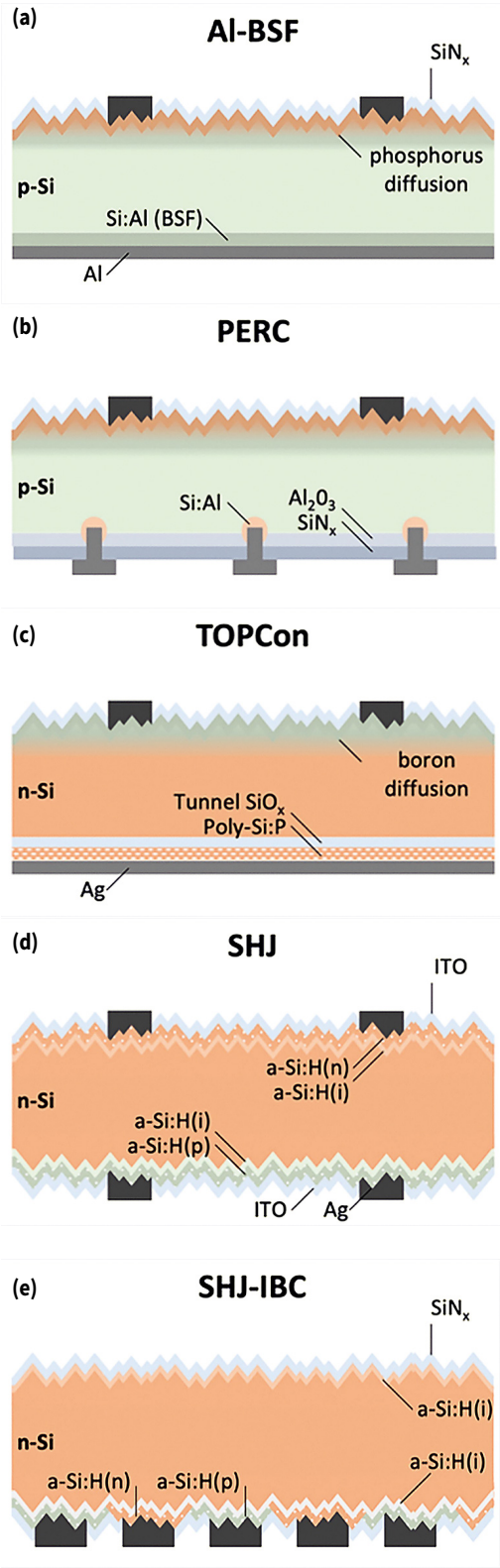


Figure 1. Main architectures for silicon solar cells: (a) aluminium-based back-surface field (Al-BSF), (b) passivated emitter and rear cell (PERC) (c) tunnel oxide passivating contact (TOPCon) at the rear side, (d) silicon heterojunction (SHJ), and (e) interdigitated back contacts (IBC) silicon heterojunction solar cell.

SILICON PHOTOVOLTAICS

Silicon is an indirect bandgap (1.12 eV) semiconductor with a low absorption coefficient, requiring typical wafer thickness of more than 100 µm for efficient absorption of near-infrared sunlight. This places strong constraints on the charge carrier diffusion length and surface recombination velocity.

For several decades and until the end of the 2010s, most silicon solar cells were made of p-type boron-doped wafers with surface texturing. A p–n junction was obtained by phosphorus diffusion at the front side, and the back contact was made with an aluminium-based back-surface field (Al-BSF) covering the full area. An anti-reflective coating (ARC) made of SiN_x:H was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the front side and contributed to surface passivation.

The architecture and manufacturing processes for silicon solar cells have undergone numerous developments, gradually moving from the laboratory to industry (see Figure 1) [2]. To reduce the impact of surface recombination at the rear Si/Al interface, the contact area can be reduced, and the remaining surface is passivated by dielectric layers, leading to the passivated emitter and rear cell (PERC) configuration. With this design, the optical reflectivity at the back side is also increased, allowing for wafer thickness reduction. PERC became the dominant silicon technology in the industry from 2019.

Improved surface passivation has increased the need for higher quality silicon wafers, resulting in the progressive shift from multi-crystalline to monocrystalline silicon grown by the Czochralski method in the 2010s, the replacement of boron by gallium in recent p-type Si wafers, and now a transition to n-type wafers, which exhibit a higher minority carrier lifetime. To avoid the recombination losses still occurring at the localized metal/silicon interfaces, two main strategies have been developed to

create full-area passivating selective contacts. These solutions need to provide both surface passivation (suppression of defects or field-induced repelling of minority carriers) and carrier selectivity (electrons/holes).

The TOPCon (tunnel oxide passivating contact) architecture combines a 1.0-1.5 nm thick silicon oxide layer for surface passivation and charge carrier tunnelling, with polysilicon contact layers (typical thickness >200 nm) highly-doped with boron (n-type) or phosphorus (p-type). Passivation of interfaces can be further improved using a hydrogenation treatment. For the front contact, the best compromise between transparency, passivation and conductivity is still the subject of ongoing research.

The second option is the so-called silicon heterojunction (SHJ) architecture. An intrinsic hydrogenated amorphous silicon (a-Si:H) layer (<10nm) provides excellent surface passivation and good conductivity and is topped with doped a-Si:H layers, both deposited by PECVD. The lateral transport of charge carriers towards the metal grid is partly ensured by an additional transparent conductive oxide (TCO) layer, typically indium tin oxide (ITO), which also acts as an ARC.

Both TOPCon and SHJ technologies are rapidly growing in the PV industry. The metal fingers typically have a width of less than 40 µm and are formed using screen-printing of silver pastes. To avoid grid-induced shadowing and parasitic absorption in the a-Si:H layers (bandgap 1.6-1.9 eV), interdigitated back contacts (IBC) have been the subject of long-standing developments. The IBC architecture has led to the highest efficiency; however, its industrialization still requires cost reduction and simplification. Interestingly, recent progress has benefited from laser technology, and the record efficiency of 27.3% was obtained with an IBC heterojunction silicon solar cell fabricated with an all-laser patterning process.

In addition to increasing efficiency, silicon consumption has been reduced (kerf losses and wafer thickness), from 16 g/W in 2004 to almost 2 g/W in 2023, and is one of the driving forces behind the reduction in manufacturing costs. Going further, an impressive 26%-efficiency was achieved in 2024 with a wafer thickness of only 57 µm, paving the way towards flexible silicon solar cells with high power-to-weight ratios. It is noteworthy that the remaining losses are mainly optical losses (see the section on photon management).

HALIDE PEROVSKITE

Halide perovskites are a (re-)discovered family of ionically bound compound semiconductors. Their common ground is that they share their generic crystallographic structure with $CaTiO_3$, the mineral named Perovskite in 1839 by Gustav Rose in recognition of the works of Lev Alekseyevich Perovski. In contrast to $CaTiO_3$ the class of halide ● ● ●

perovskite are not found in nature and were discovered as early as the 1890s, but it took another 100 years until the first semiconducting hybrid perovskites were reported. Since the first paper in 2009, reporting on halide perovskites as absorbers in solar cells, the research field has exploded and in the short time since then a plethora of new material compositions and applications have been discovered [3]. This was largely driven by the simplicity of fabrication of poly-crystalline thin-films, nano- and even single-crystals with staggering high optoelectronic quality using simple solution processing and low temperatures around 100°C.

Practically speaking the crystal structure ABX_3 can be modified to exhibit a controllably tuned bandgap anywhere in the range from 1.2 to 3.5 eV. To this end the A-site may contain cesium, or organic molecular cations such as formamidinium, methylammonium, or guanidinium, while the B-site is typically a divalent metal (Pb, Sn, Ge) combined with a halide (I, Br, Cl) on the X-site and mixtures thereof. What sets halide perovskites apart from most other semiconductors is their mix of very heavy and very light atoms, resulting in comparably low phonon energies that dampen rapid nonradiative recombination. In combination with moderate carrier mobilities in the range of 1 cm^2/Vs and comparably high absorption coefficients (10^4-10^5 cm^{-1}) due to their direct bandgap-nature, they are ideal for many optoelectronic devices and it is no surprise that highly efficient LEDs, FET, X-ray detectors (again due to the heavy atoms Pb, Sn), photodetectors and solar cells have been fabricated. In particular, solar cells have been evolving at an unprecedented speed, where efficiencies of close to 27% have been realized within 15 years of development. To put this into perspective: solar cells made from crystalline silicon or GaAs took 30-40 years of intense R&D to reach this level.

Beyond single-junctions, multi-junction devices are a natural "evolutionary step" for such versatile material systems and double- and triple-junctions have been realized with a large set of combinations (perovskite/perovskite/perovskite, perovskite/perovskite/Si, perovskite/perovskite, perovskite/CIGS, ...) with the most successful (so far) implementation being the combination with crystalline silicon (cross-sectional image of a cell from EPFL in the Figure 2).

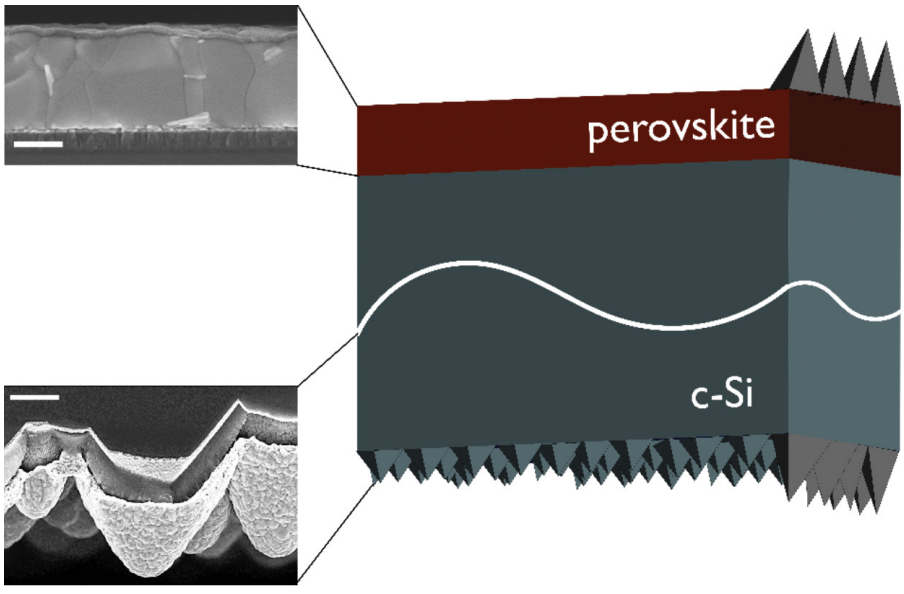


Figure 2.Simplified schematic of a perovskite tandem cell (right) with electron microscopy images of cross-sections of the perovskite top cell (top) and the silicon bottom cell rear-contact (bottom), scale bar = 500nm. Credit: Kerem Artuk & Deniz Turkay, EPFL.

In fact, this combo has reached an impressive efficiency of 34.6% in as little as 8 years since the first demonstration. This is a remarkable milestone since it is thereby the first dual-junction device configuration to beat the detailed balance limit of single-junction solar cells postulated by Shockley and Queisser. At the same time, the combination is of extremely high commercial appeal: crystalline silicon constitutes 97% of the global photovoltaics market share, and from an engineering point of view the perovskite top-cell could be considered little more than a few additional thin-film layers, and can likely be integrated into existing production lines.

The ionic nature of halide perovskites is, however, a double-edged sword. This property renders the material highly water-sensitive (they behave effectively like rock salt and can be dissolved in water) and prone to halide movement within the devices causing reversible (they counteract the built-in field, reducing the power output) and irreversible degradation (halides reacting with other species in the cell, *e.g.*, oxidizing the electrodes). At the same time, this is the reason for the ease of fabrication, making them comparably soft materials enabling flexible optoelectronics and resulting in remarkable self-healing effects. For example, after intense electron or proton irradiation, displaced atoms equilibrate rapidly, making them ideally suited for satellites. The remaining obstacle for this technology is – exaggeratedly speaking – it comparably low stability when in operation. With operational stability at elevated temperatures (~85°C) reaching several thousands of hours and a highly active academic and ever-growing industrial research community, it is not unlikely

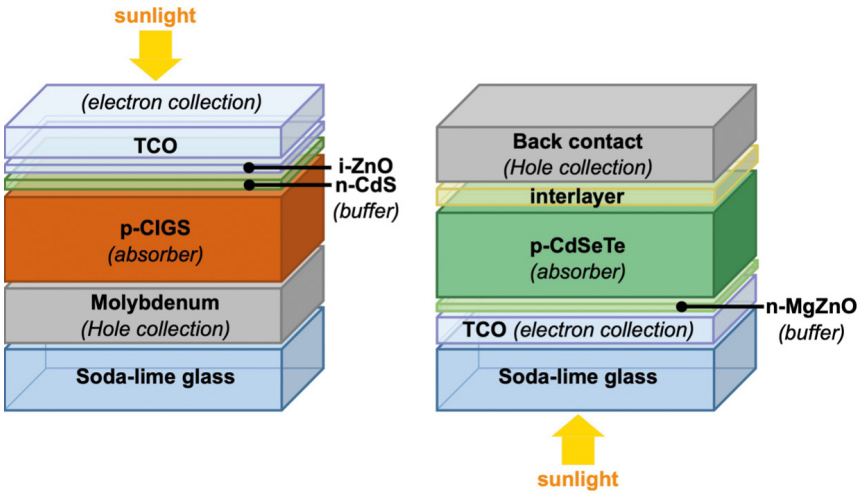


Figure 3. Sketchs of a CIGS solar cell (substrate configuration) and a CdTe solar cells (superstrate configuration).

that the remaining stability gap (compared to crystalline silicon) with a factor of 3-5x (annual degradation rate of c-Si is around 0.5-1% rel./year, for halide perovskites in the best cases ~3% rel./year) can be closed in the upcoming years.

III-V SINGLE-JUNCTION AND MULTI-JUNCTION SOLAR CELLS

Most III-V compound semiconductor materials, *e.g.* gallium arsenide (GaAs), are direct-bandgap semiconductors. III-V solar cells are typically realized by metal organic vapor phase epitaxy (MOVPE), molecular beam epitaxy (MBE), or hydride vapor phase epitaxy (HVPE), while MOVPE is the industrial standard today.

With an efficiency of 29.1% for a single-junction GaAs solar cell, III-V semiconductors have demonstrated the overall highest efficiency among single-junction solar cells. Due to their high radiative efficiency, the utilization of photon recycling is crucial and excellent rear side mirrors are required. In addition, III-V semiconductors offer the potential to realise multi-junction configurations. Adjusting the composition of ternary, *e.g.*, AlGaAs and InGaP, and quaternary compounds, such as GaInAsP, allows for tuning the bandgap of III-V semiconductor from < 0.7 eV to >2 eV by changing the composition.

III-V solar cells can either be used as stand-alone multi-junction solar cell or as top cells for *e.g.* silicon bottom solar cells. In silicon-based tandem solar cells, III-V solar cells are suited for both 2-terminal and 4-terminal operation. However, champion efficiencies of 2-terminal III-V-on-Silicon (record 36.1%) currently are higher than their 4-terminal counterparts.

All-III-V multijunction solar cells are used in space mainly, but can also be interesting in terrestrial applications such as unmanned aerial vehicles (drones), vehicle integrated PV, etc. One standard product has been a triple-junction GaInP/Ga(In)As/Ge solar cell on Ge substrate, however also a 4 junction is available for space. They often feature a distributed Bragg reflector below the Ga(In)As to allow for a thinner subcell. This is beneficial, as this cell suffers from degradation due to particle bombardment in space, and thus the lifetime of minority charge carriers decreases. A thinner subcell decreases the effect of this degradation and allows for a higher end-of-life-performance, which is the key measure for space solar cell efficiency. An alternative approach are so-called inverted metamorphic cells on a metal foil. Special about this cell concept is that the cells are grown invertedly, and the rear side of the device is directly accessible. In this way a rear side mirror can directly be implemented. Here, very high efficiency is possible, but the • • •

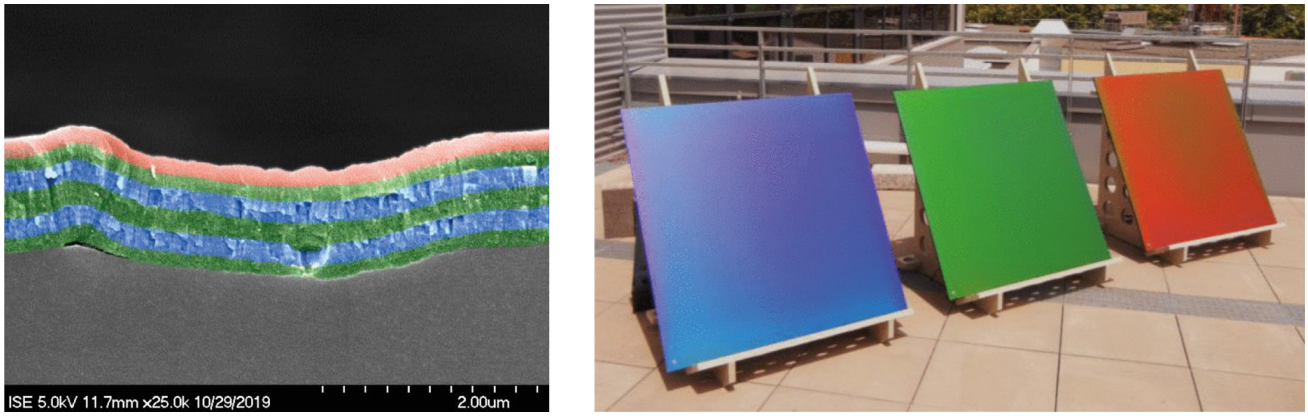


Figure 6. Coloured modules. (a) SEM cross section of the layer stack deposited on a textured glass surface to act as a narrow Bragg reflection filter with low angular dependence. The stack is made of SiN (green), TiO_2 (blue) and SiO_2 (coral). (b) The 1 m^2 modules exhibit with vivid colours, with power loss induced by reflected light of less than 6%. Credit: Fraunhofer ISE, reference [7].

required substrate lift-off is currently difficult and thus expensive.

For applications on earth, where high efficiencies or superior power-to-mass ratios are required, a two-junction GaInP/GaAs – also often grown invertedly – with rear side mirror is an interesting option. In these devices the mirror enhances absorption in the bottom cell, but even more importantly it severely improves photon recycling and thus the voltage of the device. The currently best device has an efficiency as high as 32.8% under the AM1.5g spectrum. A triple junction solar cell even allows for 37.9% and the overall highest efficiency under one sun was realized with a 6-junction solar cell and an efficiency of 39.2%.

While those multi-junction devices for one sun on earth are still a small niche, 4-6 junction solar cells are state of the art in concentrator photovoltaics (CPV). CPV are systems made of large lenses or mirrors to focus direct sunlight into tiny solar cells, with typical concentration factors up to x1000. Highest efficiency overall was reached with a wafer-bonded 4 junction solar cell with an efficiency of 47.6% under the AM1.5d spectrum (x665). The highest efficiency for a 6-junction solar cell currently is 47.1% (x143). While these cells are lab cells, 5-junction III-V solar cells based on Ge are industrially available for CPV. They are optimized for elevated (realistic) operating temperatures, and to account for the water absorption bands in the AM1.5d spectrum that are not present in the AM0 reference spectrum for space applications.

To further extend the use of III-V solar cells to terrestrial applications, the cost (typically of the order of 100 €/W for space applications) needs to be significantly reduced. Deposition rates beyond 100 µm/h have been demonstrated and are the subject of industrial pilots. To decrease material consumption and ultimately reduce costs, ultrathin solar cells utilizing multi-resonant photonic structures receive increasing attention. Using only 205 nm of active III-V absorber, efficiencies of 19.9% have been demonstrated with a single-junction GaAs solar cell (see the section on photon management).

POLYCRYSTALLINE CDTE AND CIGS THIN-FILMS

Thin-film solar cells made of polycrystalline inorganic semiconductors have been investigated for decades and have recently reached lab cell efficiencies over 23% [4]. They have been commercialized on a large scale, and offer a number of advantages: thin-film modules have a low levelized cost of energy, they can be produced over large surfaces with a high throughput, and they exhibit long-term stability and recyclability.

Thin-films are made of direct bandgap semiconductors with typical absorber thickness of about 3 µm. The two main representatives of this chalcogenide family are CdTe, a II-VI alloy which can incorporate Se, and $Cu(In,Ga)(S,Se)_2$ (CIGS), a I-III-VI_2 compound. Both are p-type semiconductors typically combined with n-type layers called "buffer" or "window" to form a p-n heterojunction, and transparent conducting oxide (TCO) layers as front or backside contacts (see Figure 3). CdTe and CIGS thin films are deposited on glass substrates at moderate temperatures between 450 and 600°C, resulting in polycrystalline, highly defective thin films.

The efficiency is hampered by the presence of defects in grain interiors and at grain boundaries. They originate from the crystal structure (stacking faults, vacancies), or the presence of extrinsic elements such as dopants. Several strategies have been developed over the years to passivate these defects and have led to significant efficiency improvements.

CdTe has a bandgap close to 1.5 eV. CdTe solar cells are fabricated in a superstrate configuration. The glass substrate is covered by a TCO layer (fluorine-doped tin oxide, a few hundreds of nanometres) and an n-type buffer layer made of MgZnO or CdS (a

few tens of nanometres). CdTe or CdSeTe is commonly deposited by close space sublimation or vapor transport deposition. After deposition, annealing at temperatures ranging from 350 to 500°C in $CdCl_2$ contribute to recrystallisation and passivation of grain interiors and grain boundaries. Cu doping has recently been replaced by group-V elements as As. The industry of CdTe PV is still growing and was able to keep costs competitive with Si modules. It is mainly located in the United-States and dedicated to utility-scale PV systems.

CIGS is fabricated in the substrate configuration. The CIGS thin film is usually deposited on a Molybdenum back contact using the so-called sequential process, sputtering, or the multi-stage co-evaporation method. The bandgap of CIGS can be tuned over a large range; record CIGS solar cells have an effective bandgap close to 1.15 eV. A composition gradient between the front and back contacts is typically used to increase the Ga content and the bandgap towards the back contact and repel electrons from the surface. An heterojunction is formed with an n-type CdS buffer layer (chemical bath deposition) or a high-bandgap Zn(S,O) layer a few tens of nanometres thick. Subsequently, an intrinsic ZnO layer and a TCO window layers are deposited. The incorporation of alkali elements (Na, K, Rb) has played a crucial role in the continuous increase in efficiency over the last decade, and the partial substitution of Cu by Ag has led to the record efficiency of 23.6% [5].

The CIGS PV industry has been historically active in Europe and Japan, but has struggled to keep up with the falling cost of silicon in recent years. There are hopes that the aesthetic appearance of thin-film modules and the potential use of lightweight flexible substrates such as polymer or metal foils for CIGS will make them attractive for building-integrated photovoltaics (BIPV) and new markets such as agri-PV or remote power applications such as electric vehicles and aircrafts.

Future research directions of both CdTe and CIGS are related to new applications and functionalities, such as bifacial cells. It is noteworthy that the realization of transparent back contacts and the reduction of absorber thickness to decrease the usage of Te in CdTe and In in CIGS are two important issues for both technologies. For tandem applications, wide-bandgap (>1.6 eV) CIGS solar cells still need substantial improvements, with current efficiencies around 16%. Research on CIGS is particularly active in Europe, with several ongoing projects involving most European groups in the field, on CIGS/Si tandem solar cells (SITA project) and ultrathin and bifacial CIGS thin-films (Hi-BITS project).

There are other potential candidates for large-scale, low-cost PV made of inorganic polycrystalline thin films with abundant and non-toxic elements. $Sb_2(S,Se)_3$ and kesterite $Cu_2ZnSn(S,Se)_4$ (CZTSSe) solar cells still have limited conversion efficiencies (<14.5%) but have demonstrated continuous progress in recent years and are still active research areas.

PHOTON MANAGEMENT

Sunlight absorption is the very first stage in the conversion process of solar energy into electricity. Among the wide range of semiconductor optical devices, one specificity of optics in solar cells lies in their very broad spectral range. A conventional silicon solar cell must absorb and convert photon energy between 1.1 eV and 4.1 eV, *i.e.* encompassing the entire visible spectrum and the near infrared. In conventional solar cells, most optical losses are found at short and long wavelengths. For example, high-energy photons are partially absorbed in the a-Si:H top contact layer of SHJ solar cells, triggering research in alternative materials such as MoO_x or TiO_x, and in the CdS buffer layer of CIGS solar cells, which can be replaced by the high-bandgap Zn(S,O).

At long wavelengths, highly reflective back mirrors and efficient light trapping are necessary to compensate for the steep drop in absorption coefficient near the bandgap and to allow for a reduction in the absorber thickness. As seen in the previous sections, the development of ultrathin solar cells is an active field of research, with potential benefits for carrier collection, material savings, and • • •

cost reduction [6]. Beyond the usual Lambertian scattering strategy, novel concepts for efficient light trapping combined with affordable fabrication processes are being investigated (see Insert 1).

OPTICS FOR TANDEM SOLAR CELLS

Emerging tandem solar cells raise new challenges. For instance, the textured surface of conventional silicon is poorly compatible with the low-cost, scalable deposition techniques currently being developed for perovskite solar cells. On the other hand, the deposition of perovskite on a flat silicon surface requires additional attention to achieve broadband

LIGHT-TRAPPING IN SOLAR CELLS

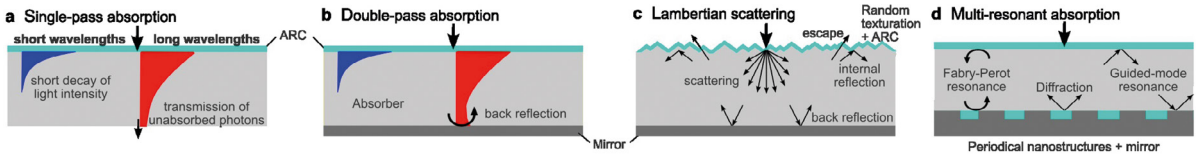


Figure 4. Main strategies and basic mechanisms to trap light in solar cells.

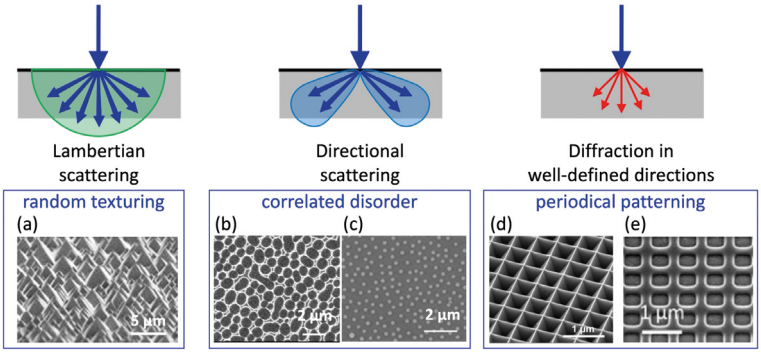
The presence of coatings, back mirror, roughness, textured or patterned surfaces can modify the way light enters the cell, propagates, scatters and is trapped in the absorber (see Figure 4). The optical path enhancement factor *F* is used as a figure-of-merit for light trapping, and absorption can be expressed by the generalized Beer-Lambert law: $A = 1-e^{-F\alpha d}$, where α is the absorption coefficient and *d* the thickness. *F*=1 for single-pass absorption with a perfect ARC, and *F*=2 with an additional perfect back reflector (double-pass absorption).

The first requirement to optimize sunlight absorption is the suppression of reflection at the front interface, about 30% for bare silicon or III-V materials. This is commonly achieved by a double-layer anti-reflection coating (ARC). Textured or rough surfaces also help suppress optical reflection by creating a graded effective refractive index.

To compensate for the drop of α near the bandgap, light-trapping is used to increase the optical path. The most common scheme is based on textured silicon surfaces obtained by chemical etching. The resulting randomly-positioned pyramids approximate Lambertian scatterers, whose upper limit is given by the Lambertian scattering model derived by E. Yablonovitch: $A=\alpha d/(\alpha d+1/F)$ and $F=4n^2\simeq 50$ (n: refractive index of the absorber). Actually, the Lambertian model is not a fundamental limit, and it could be exceeded by new light-trapping strategies (see Figure 5). Correlated disorder such as hyperuniform structures have emerged recently in the photonics community and offer new degrees of freedom to investigate the full range of possibilities between fully disordered structures such as currently used in silicon, and fully ordered patterns. Periodical patterning has already been successfully used in III-V/Si tandem solar cells and in ultrathin GaAs solar cells to achieve absorption enhancement via multiple resonances.

Low-cost fabrication processes are favoured in the search for new light-trapping solutions. They should enable the development of ultrathin solar cells with thickness 10 times lower than conventional solar cells without performance degradation, enabling material savings and cost reduction.

Figure 5. Scattering and diffraction effects and structures used to trap light in solar cells. (a) Chemical etching of silicon by KOH leads to randomly-positioned pyramids with well-defined angles, acting as a good approximation of Lambertian scatterers. (b,c) Recent advances in the physics of correlated disorder open new routes to achieve directional scattering using low-cost nanopatterning techniques such as polymer-blend (b) and colloidal (c) lithography. (d,e) Perfectly ordered structures fabricated by nanoimprint lithography result in diffraction in well-defined directions and absorption enhancement by multi-resonant effects: (d) inverted pyramids chemically etched in silicon, and (e) nanogrid made from sol-gel-based material. Credit: Images from CNRS.



suppression of optical reflection. Additionally, the entire stack of the top cell must be transparent to long-wavelength photons. This rules out the use of narrow bandgap semiconductors or highly-doped TCO, which would exhibit parasitic absorption of free carriers in the near infrared. In the 4T configuration, the additional TCO and the shading induced by the front and backside grids of the top cell impose additional design and material constraints. Finally, the luminescent coupling between the different cells has already been evidenced with III-V materials and should be taken into account in high-efficiency tandems, and the introduction of innovative light trapping structures to reduce the thickness of tandem solar cells has been little explored.

COLOURED MODULES

Coloured PV is an attractive option for building integrated PV applications (BIPV). However, it is obvious that optimal absorption of sunlight would results in black PV modules, and the performance cost of introducing colour is expected to be high. A solution inspired by the vivid structural colours of the Morpho butterfly was developed recently at the Fraunhofer ISE, achieving highly saturated, angularly stable colours with a remarkable performance loss of only 6% [7]. A narrow-band reflection filter is obtained through interference effects in a multilayer stack deposited on a textured glass substrate, and the central wavelength can be easily tuned to provide the desired aesthetic appearance (see Figure 6). Since the structural colour is created in the cover glass of the PV module, it is compatible with all PV technologies.

CONCLUSION

Silicon will remain the dominant technology for the next few years, with a continuing shift towards TOPCon and heterojunction technologies. Many research groups and a few industries are actively working on the next generation of solar cells, which will probably take the form of silicon-based tandem solar cells. Perovskite is considered the most promising candidate for low-cost tandem devices, but it still faces numerous challenges before possible large deployment at low-cost. Thin films technologies and III-V solar cells are mature technologies commercialized in small markets. They are also active fields of research and could contribute to research advances towards low-cost tandem solar cells. Photonics will continue to play a central role in the development of photovoltaics, particularly in the optimization of tandem solar cells, in the reduction of material usage and costs without sacrificing performance, and in the realization of visually appealing modules.

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