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High-efficiency Crystalline Silicon Solar Cells: A Review

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ABSTRACT Solar energy is a clean renewable energy resource that can be converted to electricity with photovoltaic (PV) technology without environmental damage. Solar energy can be transformed to electricity using a range of technologies, but crystalline silicon (c-Si)-based PV technology dominates in the PV market due to the high efficiency, long-term stability, reliability, and second most abundant (27%) material. Recently, c-Si solar cells achieved an outstanding efficiency of 26.7% through silicon heterojunction technology combined with an interdigitated back contact structure. Most industries and researchers are attempting to improve the efficiency further to reach the silicon limit. The dominant position of crystalline silicon solar cell in large-area electricity production and industrialization motivated us to write this review paper. This review paper covers the key factors that affect the efficiency, such as structure, process optimization, cost reduction strategies. In addition, some promising cell structures, such as PERC, IBC, HIT, and HBC solar cell, and their efficiencies are reported. Overall, this study provides a detailed idea to the new photovoltaic researchers regarding the solar cell structure, their efficiencies, and future potential of solar cells.

Key words Photovoltaics, Crystalline silicon solar cell, High efficiency, PERC, IBC, HIT, HBC

Nomenclature

V_{oc} : open circuit voltage, mV
J_{sc} : short circuit current density, mA/cm^2
FF : Fill Factor, %

Subscript

PERC : passivated emitter rear contact
PERT : passivated emitter rear totally-diffused
PERL : passivated emitter rear locally-diffused
IBC : interdigitated back contact
HIT : heterojunction intrinsic thin-layer
HBC : heterojunction back contact
Al_2O_3 : aluminum oxide
SiN_x : silicon nitride
a-Si:H : hydrogenated amorphous silicon
TCO : transparent conductive oxide

1. Introduction

Solar Energy is one of the greenest and cleanest renewable energy sources. The alarming situation related to global warming is the reason that solar

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energy replacing fossil fuels and being globally accepted. Also, it is abundant in nature. Still solar energy currently was expected to meet only 2.8% of the global energy demand because of the lack of technology and the expensive installation process.[1] Extensive research has been performed over the last few decades on solar energy harvesting by different techniques and using different materials to decrease the cost compared to conventional energy resources.[2,3] Among the solar cell materials, crystalline silicon has been extensively studied due to their high efficiency, long-term stability, reliability and low cost. According to reports the efficiency of commercial wafer-based silicon modules increased 12% to 17% in last ten years.[4] From Fig. 1, the reduction in the average price module and the increase in cumulative photovoltaic (PV) installation up to 2018 can be observed.[5] This curve also shows that the amount of PV installation has increased by 22.8% in recent years. Some novel technologies, such as screen printing, PERC, and surface texturing played a key role in the increasing efficiency of PV modules and the industries aimed the cost reduction. Since the beginning, c-Si was considered as the only long-term, sustainable, high-efficient material for solar cell. The efficiencies of best performing modules in laboratory is 24.4%. High concentrator technology has been brought up the module efficiencies up to 38.9%.[6,7] The renowned photovoltaics research institutes like University of New South Wales (UNSW), the Fraunhofer Institute of Solar Energy, and the Institute of Solar Energy Hamelin have reported the solar cell efficiency values of: 25%, 25.8%, and 26.1%, respectively.[8~10] Thus far, Kaneka Japan recorded the highest efficiency, 26.6%.[11] The technologies required to increase efficiency are highly expensive. It needs to be taken care of. But still progress in photovoltaic demands can be observed. The global cumulative photovoltaic installations were over 512 GW at the end of 2018 and global module production was 180 GW.[12] All these facts motivated us to write this review paper.

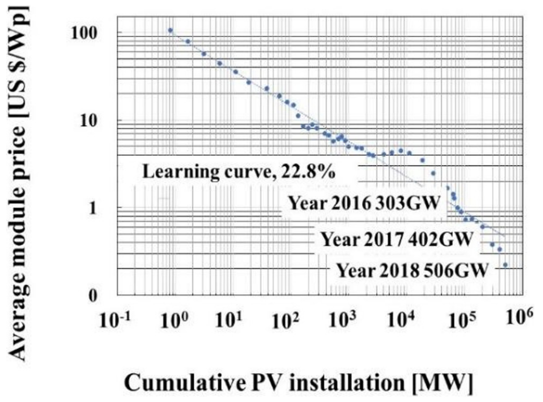

Fig. 1. Decrease of the average module price against the increase of cumulative PV installation

To achieve high efficiency, a solar cell requires an innovative cell structure, optimized light absorption, a large number of effective carriers with less carrier recombination loss, minimized electrode resistance, and area reduction. Apart from traditional back surface field solar cell, some developed technologies have led to the production of many high-efficiency crystalline solar cell structures like PERC, PERT, PERL IBC, HIT, HBC. Among them, the PERC, PERT solar cells show high efficiencies and they are cost effective too. As per reports PERC technology accumulated 20% of PV industry in 2017 which is expected to reach 50% by end of 2020.[13] Among others, IBC and HIT structures show very high efficiency but the technology to fabricate these structures is very expensive and high complex process are involved. In this review paper, we discussed the previous developments achieved towards high-efficiency solar cells and what current technologies are involved in further betterments. We reviewed the cell structures of PERC, IBC, HIT, and HBC solar cells, their potentials in efficiency based and industry-based areas, and the corresponding challenges.

2. Essential factors for improving the performance of high-efficiency solar cells

The solar cell performance is reduced by the several loss factors. We can categorize them into three groups, namely optical loss, thermalization loss, electrical loss. Fig. 2 describes the loss factors of a solar cell. The optical loss occurs due to shading, surface reflections. Approximately 72% of the incident light is absorbed at the cell.[14,15] It reduces the short circuit current density. Anti-reflection coating on the cell surface, surface texturing and light trapping, and minimization of the top contact coverage can reduce the optical losses. The thermalization loss occurs because crystalline silicon has approximately 1.1 eV of bandgap. But Tandem solar cells are one approach to increase the number of bandgaps, which further increases the efficiency. Next is recombination loss which occurs due to low passivation. It reduces the open circuit voltage effectively. "passivating layer" on the top surface can reduce the top surface recombination. Silicon is a semiconductor that is inferior to metals in terms of transporting current. Its internal resistance is high and hence electrical loss occurs. Electrical loss affects the FF of the cell. The FF reduces due to the presence of parasitic resistances. The cells are covered by a metallic contact grid to minimize the losses. Even so, some photons are still blocked by the grid.[16] Fig. 3(a), 3(b), and 3(c) depicts some technologies for reducing the optical, carrier and electrical losses. Among them Fig. 3(a) pyramid formation and double layer anti reflection coating is very useful to reduce surface reflection loss. Recent research work also suggests the uniformity in surface texturing which further minimizes the surface reflection. Another problem of shading loss can be overcome by fine pattern screen printing, the smaller the width of the metal grids, the lower the shading loss. Solar cell structures like IBC, emitter wrap through (EWT) cells show high efficiency due to the reduced shading

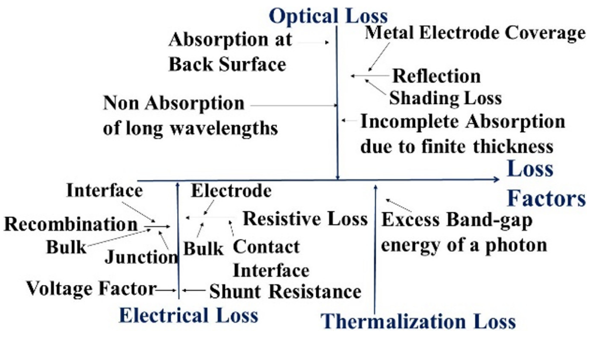

Fig. 2. Some Loss Factors of crystalline silicon solar cell

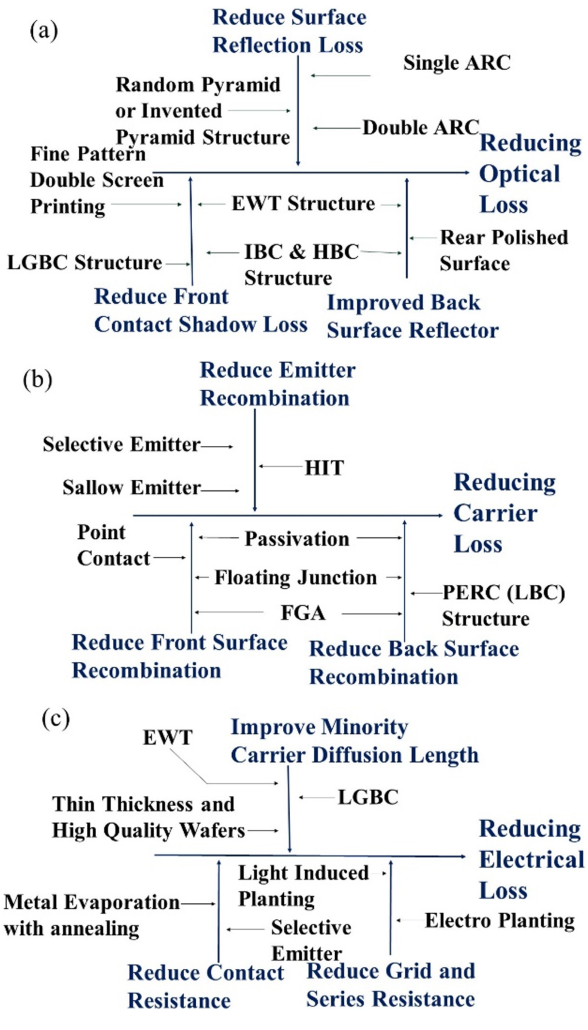

Fig. 3. Reducing (a) optical loss, (b) carrier loss, (c) electrical loss in solar cell

loss and improved back surface reflector. Fig. 3(b) suggests that carrier recombination loss can be optimized with technologies like improved passivation layers, forming gas annealing (FGA), floating junction etc. Also, selective and sallow emitter layers can reduce carrier recombination and increase V_{OC}. Another way of increasing efficiency and FF is to reduce electrical loss by minimizing series and contact resistance and improve minority carrier diffusion length. Fig. 3(c) suggests Technologies like Selective Emitter contact, light induced planting, laser grooved buried contact (LGBC), metal evaporation annealing can optimize the electrical loss which will further increase FF. The thin and high-quality wafers are mandatory for obtaining high efficiency.

3. Recent standing of high-efficiency solar cells

3.1 PERC solar cell

The PERC structure improves the ability of capturing light near the rear surface. It was first developed at the UNSW in 1983, and its design was published in a technical paper in 1989 with a then world record efficiency of 22.8%.[17] The PERC technology is easier to fabricate and cost-effective.

The standard back surface field cell architecture is fabricated with a metallic aluminum film on the rear side. In the PERC structure, optical and electrical losses can be reduced by adding a dielectric passivation layer on the rear side. Naturally, Al_2O_3/SiNx is applied as the rear passivation layer.[18] Al_2O_3 shows an outstanding passivation.[19] The Al_2O_3 layer followed by a deposited SiNx layer can improve the passivation effect. The SiNx layer protects the rear passivation film from metallization. Because the Al_2O_3 layer is thin, the SiNx layer compensates the rear passivation stack thickness and causes an internal reflection on the back of cell. Hence, the long-wave response is enhanced, and the short-circuit current is improved. Laser contact opening is frequently used to remove the dielectric passivation layer locally promoting the contact formation between Al and silicon. Fig. 4 shows the basic structure of PERC solar cell. A German manufacturer, Solar World, achieved an efficiency of 21.7% for PERC solar cells in 2016.[20] Trina Solar in China realized a record efficiency of 22.13% later that year.[21] The polysilicon PERC solar cell reached an efficiency of 21.25% on a large substrate (156 mm X 156 mm), but the record was soon broken by Jinko Solar which achieved an efficiency of 21.63%. In 2017, for the first time, Jinko Solar achieved an efficiency of over 22% for a polycrystalline solar cell, setting the record at 22.04%.[22] As per their most recent reports (2019), LONGI Solar has achieved the record efficiency of 24.02% for PERC structure.[23] The key improvements in PERC solar cells should be focused on advanced emitter structures, wafers with higher lifetime, multiwire in place of busbars, etc. The International Technology Roadmap of Photovoltaic showed that the global market share of the PERC technology grew above 20% in 2017 and predicted that in the upcoming ten years it will grow to more than 60%. Two main challenges in the improvement of PERC architecture are light-induced degradation (LID) and potential-induced degradation (PID). Sig-

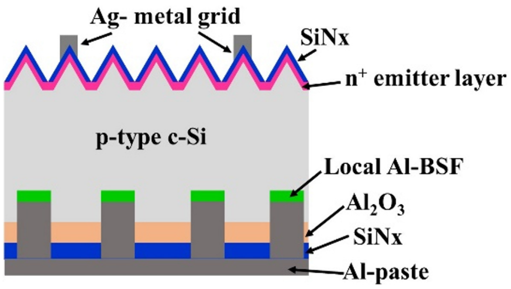

Fig. 4. PERC solar cell structure

nificant efforts are being undertaken to produce LID- and PID-free solar cells. Another two structures in PERx family are PERL and PERT cells which has drawn the attention due to its capability of reducing recombination loss and achieve high V_{OC} as well as high efficiency. These structures can be obtained by the deposition of poor recombination and insulating layer at the rear side followed by a local ablation in order to obtain metal contacts to the absorber. Though PERT and PERL structures are widely accepted still they require industrially feasible fabrication approach. The future research work on PERL and PERT cell should be focused on development of doping of emitter layer, local BSF process to achieve damage free high-quality fabrication of doped regions.

3.2 IBC solar cells

The IBC solar cell is one of the most important types of crystalline solar cells. One of its advantages is that it can help to develop a personalized concept that fits the energy requirements for localized conditions. IBC cells implement the following innovation: instead of placing the contacts in the front of the cell, they are placed on its rear side. This allows it to achieve a higher efficiency owing to the reduced shading on the front of the cell; simultaneously, electron-hole pairs generated by the absorbed light can still be collected on the rear side of the cell. The first IBC solar cell was developed at Stanford University in the 1980s and achieved an efficiency of 21.3%.[24] The IBC solar cell fabrication process involves a front surface texturing with random pyramids for efficient light trapping on the silicon wafers. The rear surface is polished. The front and back surface fields are formed by $POCl_3$ diffusion or ion implementation. The rear emitter pattern is defined by screen printing or lithography. Both the emitter and the back-surface field doping layers are located in an interdigitated structure on the back side of the cell. A schematic diagram of the IBC solar cell is shown in Fig. 5.

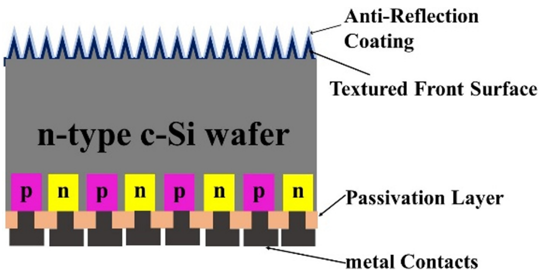

Fig. 5. IBC solar cell structure

The employment of all the rear contacts in the cell structure eliminates optical shading losses on the front side. This results in the increase in short-circuit current density and absorption capacity of the IBC solar cell. Other advantages are (1) the absence of front metal fingers that provide more space; (2) the decreased series resistance on the rear side; (3) the simpler module designs. The IBC solar cells are mostly fabricated on n-type silicon substrates with boron-diffused emitters.

To improve the light trapping effect, a pyramid structure is implemented with an anti-reflection coating layer. The thermal SiO_2 passivation layers at the front and the rear surfaces show a long-wave response and a reduced surface recombination. A metal electrode is formed, which realizes the point contact with the silicon substrate. The effective area of the absorption can be increased by eliminating the front grids and busbars. An increased effective area results in an increased photo-absorption capacity. However, this cell design still needs improvement. Several problems arise during the operation of multiple lithography. The costs become higher to avoid non-uniform distribution and high- temperature damage. The process can be simplified by a boron-doped diffusion mask layer and an interdigitated structure printed on the rear surface. Protections to avoid the non-uniform distribution and the high-temperature damage, however, increase the cost significantly. Furthermore, the screen-printing process is not accurate in terms of alignment, and it suffers from printing repeatability. To avoid these problems, doping via ion implementation is utilized worldwide, as it can precisely control the doping concentration and allows for the formation of uniform p- regions and n-regions along with a controllable junction depth. This doping technique requires a high annealing temperature, which is difficult to achieve in the PV industry. Laser doping techniques are used as alternative.[25] It gives uniform doping concentration and depth controllability, as well as pattern ability in the doping area. The selective doping area protects the entire silicon from suffering from high temperature damage. The other advantages of laser doping are the ability of laser texturing, laser ablation for contact opening, and laser-fired contacts in solar cell. The efficiency of IBC solar cells reached 21.3% in the first version. SunPower in 2010 achieved a record efficiency of over 24%.[26] SunPower recorded the highest efficiency of 25.2% for IBC structure in 2016.[27]

IBC cells are highly valued in applications where higher current values are needed, such as in CPV, solar race cars, and even in solar aircrafts. According to the International Technology Roadmap report in 2018, the IBC cells have an 8% share of the global market, which is expected to increase in the upcoming ten years by at least 5%.

3.3 HIT solar cells

The silicon heterojunction consists the intrinsic thin layer, which is the core of the HIT solar cell. A HIT solar cell is composed of a thin monocrystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. This cell was first designed and named by Sanyo Co. Ltd (now Panasonic Co. Ltd) in 1991. The advantage of this cell is that it can effectively separate the electron hole pairs. The hydrogenated amorphous silicon (a-Si(H)) layer has an excellent passivation effect on the crystalline silicon surface. It decreases the interface state density, thus reducing the surface recombination. These two properties allow the HIT solar cell to have a high open circuit voltage and a high efficiency. The other advantages of the HIT cell are as follows. (i) It has structural symmetry, which reduces the thickness of the cell and the production cost. The bifacial module consisting of these symmetrical HIT cells can absorb the light from both sides. Hence, the generating capacity can be increased. (ii) This solar cell design can be fabricated at low temperatures (below 200°C). (iii) There is large band bending between the amorphous Si and the crystalline Si. (iv) The crystalline Si surface exhibits excellent surface passivation. (v) It has good stability.

Fig. 6 shows a schematic diagram of the HIT solar cell. An intrinsic amorphous Si layer and a p-type amorphous silicon layer are deposited on the front side to form a p-n region. The back-surface field is composed of symmetrical stacked layers of intrinsic amorphous Si and n-type amorphous Si on the rear side. Finally, a metal electrode and TCO layers are formed by screen printing and sputtering, respectively.

The complete process is performed at a temperature

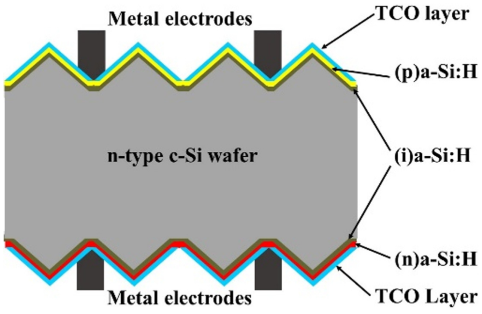

Fig. 6. HIT solar cell structure

below 200°C.[28] Since then, researchers have focused on the following aspects: (i) decrease in optical loss and electrical loss; (ii) cleaning of the c-Si wafer; (iii) development of high-quality wide-gap alloys and high carrier mobility; (iv) cost reduction in thinner wafers. Their effort resulted in an efficiency of 24.7% (V_{OC} = 750 mV, J_{SC} = 39.5 mA/cm^2, FF = 83.2%) in 2013.[29] In 2015, Kaneka recorded the highest efficiency, 25.1% (V_{OC} = 738 mV, J_{SC} = 40.8 mA/cm^2, FF = 83.5%) for a HIT solar cell.[30] Silevo Inc. fabricated a large-area solar cell panel (~239 cm^2) by using a tunneling oxide passivation layer. It achieved a conversion efficiency of 23.1% (V_{OC} = 739 mV, J_{SC} = 39.9 mA/cm^2, FF = 80.5%). The CESM in Switzerland and Meyer Burger achieved a higher conversion efficiency in the order of 22.4%~22.7%. The Shanghai Institute of Microsystem and Information Technology achieved an efficiency of 23.1% and has been pushing for further large-scale industrialization. The International Technology Roadmap for Photovoltaics acknowledged that the HIT solar cell has a technical potential for cost reduction, and its global market share can increase up to 10% in the upcoming years. However, to achieve this increase, the thickness of the Si wafer must be reduced, the TCO materials improved, and the metal electrode optimized.

3.4 HBC solar cells

The integrated back contact concept was applied to the heterojunction structure to develop the Hetero-junction Back Contact solar cell. The IBC solar cell has no shielding effect. Thus, its short circuit current density J_{SC} is high while a high-quality passivation is maintained. This results in a high open- circuit voltage. Fig. 7 shows a schematic diagram of the HBC solar cell. A passivation layer is deposited on the front surface of the c-Si wafer. It has a low surface recombination and a good transparency.

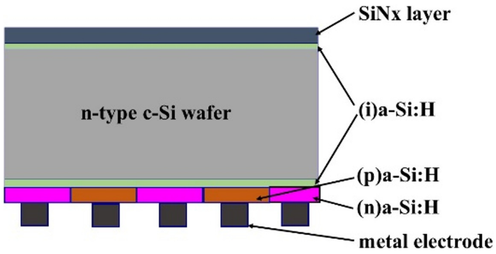

Fig. 7. HBC solar cell structure

Subsequently, an anti-reflective layer of silicon nitride is deposited. Afterwards, two stacking layers are deposited on the rear surface and, finally, grid electrodes are produced by an electroplating process on both the p-type and n-type layers. The rear grid electrodes can improve the fill factor of the solar cell greatly. The first designed HBC solar cell were fabricated by LG in 2012 which achieved an efficiency of 23.4% then.[31] Later, Sharp in 2014 and achieved a conversion efficiency of 25.1% (V_{OC} = 736 mV, J_{SC} = 41.7 mA/cm^2, FF = 82.0%).[32] At the same time, Panasonic designed a solar cell with and area of 143.7 cm^2, which achieved a conversion efficiency of 25.6%.[33] Kaneka Corporation recorded a conversion efficiency of 26.33% (V_{OC} = 744mV, J_{SC} = 42.3 mA/cm^2, FF = 83.8%) in 2016,[34] while the highest conversion efficiency for the HBC solar cell till date is 26.6% (V_{OC} = 740 mV, J_{SC} = 42.5 mA/cm^2, FF = 84.6%).[11] This 0.3% improvement has accredited to the increased fill factor.

4. Summary and perspectives

The crystalline Si is the predominant material in solar cells. Among the types of crystalline Si, the n-type crystalline silicon does not suffer from light-induced distortion resulting in high bulk carrier lifetime compared to p-type wafers. Hence, it can be considered as material having the potential to achieve a higher efficiency. New technologies, such as surface texture, full Al-BSF replacement, front and rear passivation improvement, photo-lithographically defined metallization, as well as thickness reduction, shallow junctions, antireflection coatings, selective emitters, and others have been developed to improve the efficiency. The HBC and IBC solar cells achieved an efficiency of 26.6% and 25.2%, respectively. Table 1 summarizes the fill factors and efficiencies of several high-efficiency structures. Fig. 8 shows the increase in efficiency over the last few years for the various cell structures. Despite the rapid development, these structures are still expensive in terms of device concepts and optical enhancement approaches.

Future research work will be aimed to the elimination of the thermal expansion mismatch, the reduction in the wafer thickness, the implementation of different module sizes, wafering technologies, wafer dimensions, and so on. Cost reduction in photovoltaic energy can underpin the utilization of renewable energy in commercially important areas. The Joint Research Centre of the European Commission reported an installed PV power capacity of 408 GW at the end of 2017, which could be tripled by 2023. The technological advances will ensure the competitiveness of PV power generation.

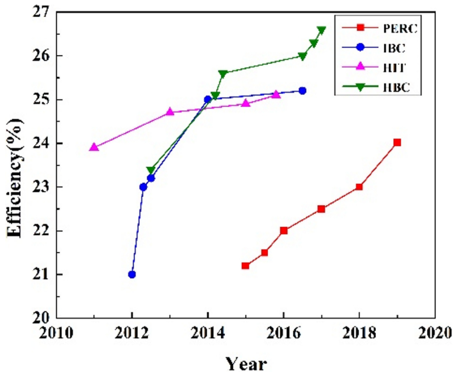

Fig. 8. Increase in efficiency with time for several solar cell structures

Table 1. Cell efficiencies measured under 1000 W/m^2 spectrum at 25°C for various high-efficiency solar cell structures

Structure	Wafer type	Fill factor	Efficiency	Description
PERC			24.02%	Longi[23]
IBC	n-type	82.7	25.2%	Sunpower[27]
HIT	n-type	83.5	25.1%	Kaneka[30]
HBC	n-type	84.6	26.6%	Kaneka[11]

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