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HIGHLIGHTS

Wenzhong SHEN, Yixin ZHAO, Feng LIU

Highlights of mainstream solar cell efficiencies in 2022

The world record power conversion efficiency (PCE) of both the single-junction silicon and perovskite/silicon tandem solar cells was broken in 2022, and the mass-production of the passivating contact and perovskite solar cells (PSCs) was also significantly developed in 2022. Continuing to the first viewpoint on the highest independently confirmed PCE of mainstream and emerging solar cells in 2021 [1], this paper highlights the certified PCE in 2022 of silicon, perovskite, and organic solar cells and analyzes the progress of each cell technology.

Silicon solar cells

Due to the advantages of high efficiency, low manufacturing cost, and high material reliability, as well as mature industry, crystalline silicon (c-Si) solar cells have been the leader for 40 years with the production of about 300 GWp in 2022 (over 95% of the photovoltaic (PV) market share). Si passivated emitter and rear cell (PERC) dominated the 2022 PV market with a mass-production averaged PCE of p-Si PERCs of approximately 23.5%. Although the PCE of Si PERCs was improved to have a theoretical limit of 24.5% in 2022, both the research and industry in the Si PV community focused on passivating contact concept of Si heterojunction (SHJ) and tunnel oxide passivated contact (TOPCon) solar cells. Table 1 lists the achievements of the SHJ and TOPCon solar cells during 2022. In 2022, the record PCEs of both Si SHJ and TOPCon solar cells were improved significantly to 26.81% and 26.4%, respectively. Especially, the PCE of 26.81% broke the long-time world record PCE of 26.7% in single-junction c-Si solar cells [2]. It also should be noted that these two over 26% PCEs were realized in large Si wafers and the PV industry was rapidly investing in the mass-production of the passivating contact solar cells in 2022. The efficiency difference of over 2.0% is the engine of the PV industry revolution from PERC to SHJ and TOPCon solar cells. The production of SHJ and TOPCon solar cells was about 20 GWp in 2022 and will be about 100 GWp in 2023. In 2022, the TOPCon technology, compatible to the PERC counterpart, was particularly interested in the PV industry due to its good cost performance. It is expected that the passivating contact solar cells will dominate the PV market in 5 years.

The SHJ solar cell has been maintaining the world's highest efficiency in the field of c-Si solar cells due to its effective carrier selective contacts and heterojunction interface characteristics. The SHJ solar cell is based on the structure of hydrogenated amorphous silicon (a-Si:H)/c-Si, which is prepared at a low temperature (< 200 °C). From Table 1, it can be found that the PV companies of Longi, SunDrive, and Maxwell have made significant contribution in efficiency increasing and cost decreasing efforts. As well known, the high PCE of the SHJ solar cells is based on the good passivation of the intrinsic a-Si:H (a-Si:H(i)), good optical and electrical properties of the doped a-Si:H, transparent conducting oxide (TCO) with a high transparency and mobility, and fine metal fingers, as well as high quality Si wafer with a high minority lifetime and a suitable thickness of 90–130 μm [3]. Longi has demonstrated a good passivation scheme through a triple-layer structure for the a-Si:H(i). The first high oxygen content (26.6%) buffer layer furthest passivates the c-Si surface dangling bonds, followed by the moderate oxygen content (24.7%) layer to effectively saturate the dangling bonds and reduce the

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Wenzhong SHEN (✉)
Institute of Solar Energy, and Key Laboratory of Artificial Structures and Quantum Control of the Ministry of Education, School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: wzshen@sjtu.edu.cn

Yixin ZHAO (✉)
School of Environmental Science and Engineering, and Frontiers Science Center for Transformative Molecules, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: yixin.zhao@sjtu.edu.cn

Feng LIU (✉)
School of Chemistry and Chemical Engineering, and Frontiers Science Center for Transformative Molecules, Shanghai Jiao Tong University, Shanghai 200240, China
E-mail: fengliu82@sjtu.edu.cn

Table 1 Summary of breakthroughs of SHJ, TOPCon, and PERC solar cells in 2022

Solar cell type	PCE/%	Area/cm^2	V_{OC}/mV	J_{SC}/(mA·cm^{-2})	*FF*/%	Test center	Report date	Description
n-SHJ	26.07	274.3	746.7	40.71	85.74	ISFH	Mar.	SunDrive/Maxwell copper plating
n-SHJ	25.40	274.5	749.3	39.75	85.28	ISFH	Mar.	Longi TCO without indium
n-SHJ	25.62	274.5	747.4	40.11	85.48	ISFH	Apr.	Maxwell reducing 50% indium and 55% silver (with copper)
n-SHJ	26.50	274.4	750.6	41.01	86.08	ISFH	Jun.	Longi multilayer passivation
n-SHJ	25.94	274.4	747.5	40.49	85.71	ISFH	Aug.	Maxwell/SunDrive reducing 50% indium and copper plating
n-SHJ	26.41	274.5	750.2	40.80	86.28	ISFH	Sept.	SunDrive/Maxwell copper plating
n-SHJ	26.81	274.4	751.4	41.45	86.07	ISFH	Oct.	Longi multilayer passivation
n-SHJ	26.09	274.3	749.6	40.52	85.90	ISFH	Dec.	Longi TCO without indium
p-SHJ	24.47	244.7	742.9	40.14	82.05	ISFH	Mar.	INES Ga-doped Si wafer
p-SHJ	25.47	274.3	747.6	40.66	83.80	ISFH	Mar.	Longi Ga-doped Si wafer
p-SHJ	26.12	274.3	750.2	41.09	84.76	ISFH	Sept.	Longi Ga-doped Si wafer
p-SHJ	26.56	274.1	751.3	41.30	85.59	ISFH	Oct.	Longi Ga-doped Si wafer
n-TOPCon	25.5	440	–	–	–	NIM	Mar.	Trina LPCVD
n-TOPCon	25.7	330	–	–	–	NIM	Apr.	Jinko LPCVD
n-TOPCon	26.1	330	–	–	–	NIM	Oct.	Jinko LPCVD
n-TOPCon	26.1	330	–	–	–	NIM	Nov.	Jolywood PVD
n-TOPCon	26.4	330	–	–	–	NIM	Dec.	Jinko LPCVD
p-PERC	24.5	440	–	–	–	NIM	Jul.	Trina

Notes. –: Not yet disclosed; ISFH: Institut fur Solarenergieforschung Hameln, Germany; NIM: National Institute of Metrology, China; INES: Institut National de l'Energie Solaire, France.

interface defects, and finally the low oxygen content (20.2%) layer to benefit for the carrier transport [4]. In the 26.81% world record PCE of SHJ solar cells by Longi, the n-type oxygen-alloyed hydrogenated nanocrystalline silicon (nc-SiO$_x$:H (n)) has been utilized for the window layer to enhance the optical transparency (reduce the parasitic absorption) and the response at short wavelength. The introduction of nanocrystalline silicon also improves the doping efficiency and therefore reduces the series resistance and contact resistivity (ρ_c) with TCO, beneficial for all the performance parameters of open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}), and fill factor (*FF*). Beginning with the nc-SiO$_x$:H (n) seed layer with a high nanocrystalline ratio through increasing PH$_3$, doping gas flow can further enhance both V_{OC} and *FF*. The back p-type a-Si:H has been replaced with p-type hydrogenated nanocrystalline silicon (nc-Si:H (p)) to improve the response at a long wavelength and also enhance both V_{OC} and *FF* due to the nanocrystalline characteristics [4]. High-efficient SHJ solar cells also require good TCO layers (both high transparency and mobility), fine screen-printing/copper plating metal fingers, and optical/electrical injection treatment.

In addition to the achievement of world record of 26.81% PCE in single-junction c-Si solar cells, there were three breakthroughs in the 2022 SHJ research and development. First, SunDrive and Maxwell cooperated on the copper plating and nanocrystalline technology and achieved a PCE of 26.41%. The grids could be 9 μm in width and 7 μm in height, which is advantageous in high-efficient SHJ solar cells. Replacing silver screen-printing by copper plating for SHJ solar cell metallization was a hot development direction in 2022, while the industrial application of copper plating should resolve the obstacles such as not cost-effective processes, complicated electroplating steps, long-term degradation, and reliability [1]. Secondly, Longi tried SHJ solar cells without indium in TCO layers to reduce the cost and avoid the shortage of the noble metal in the future. The highest efficiency reached over 26% to (26.09%). Maxwell also achieved good results in SHJ solar cells with reducing 50% indium and 55% silver paste (with copper). Thirdly, Longi demonstrated that the SHJ technology could also be applied in p-type (Ga-doped) Si wafers (p-SHJ) with a certified PCE as high as 26.56%. The multilayer passivation and nanocrystalline doped layer technology in SHJ with n-type Si wafers (n-SHJ) have been well adopted. These efficiency increasing and cost decreasing attempts will significantly prompt the industrialization of SHJ solar cells. The mass-production averaged PCE of SHJ was about 25% in 2022 and expected to be 27% in 5 years. Attention has also been paid in the Si PV community to the heterojunction back contact solar cell, a combination of SHJ structure with interdigitated back contact electrodes, to improve the efficiency up to 27.5%. For further development of SHJ solar cells, perovskite/SHJ tandem solar cells should be investigated to achieve a mass-production averaged PCE of over 30%.

On the other hand, n-type TOPCon (n-TOPCon) solar cell has already been considered as one of the most popular candidates of all the high-efficient c-Si solar cells for the theoretical efficiency limit of 28.7% with partial area passivating contact for both polarities, which is closest to the theoretical efficiency limit of c-Si solar cells of 29.43%. The concept of TOPCon solar cell was first proposed and demonstrated by the University of New South Wales (UNSW) in Australia in 1983 [5] and brought to public attention by Fraunhofer ISE in Germany in 2014 [6]. Table 1 lists the high-efficient n-TOPCon solar cells created by Trina Solar, Jolywood, and Jinko Solar in 2022, of which the latter two have achieved an excellent performance with a PCE of more than 26%. The n-TOPCon structure of present commercial interest consists of ultra-thin SiO_2 and phosphorus-doped polycrystalline silicon (poly-Si (n^+)), which possesses the advantages of a full-area passivation contact and compatibility with a high-temperature sintering process for existing PERC production lines. The application of TOPCon contributes to reducing the carrier recombination loss (J_0) and ρ_c to < 5 fA/cm^2 and < 2 mΩ·cm^2, respectively [7]. The large-scale development of n-TOPCon solar cells was realized in 2022 with a production capacity of 50 GWp and an expected annual production capacity of about 200 GWp in 2023.

At present, the mass-production efficiency of n-TOPCon solar cells is close to 25.0%. From the perspective of carrier recombination loss, the carrier recombination ($J_{0\mathrm{p,pass}}$ and $J_{0\mathrm{p,metal}}$) in the front passivation and metal contact regions of TOPCon solar cells can reach 15 fA/cm^2 and 500 fA/cm^2, respectively [8,9]. Due to the use of SiO_2/poly-Si (n^+) stack with the superior passivation and contact characteristics, the lower carrier recombination ($J_{0\mathrm{n,pass}}$ and $J_{0\mathrm{n,metal}}$) of 4 fA/cm^2 and 100 fA/cm^2 can be achieved in the back passivation and metal contact regions [9,10]. In the n-TOPCon cell technology development process, it is better to develop high sheet resistance (170–190 Ω/□) and shallow doping depth (0.3–0.6 μm) based on the current front boron diffusion with a doping profile of 120 Ω/□ and 1.1 μm, to solve the issues of the Shockley–Read–Hall recombination, Auger recombination, and transverse recombination of the carriers. The front $J_{0\mathrm{p,pass}}$ and $J_{0\mathrm{p,metal}}$ is expected to achieve 8 fA/cm^2 and 50 fA/cm^2 with the further superimposed selective emitter, multilayer passivation films with graded refractive index, and thinner metal finger technologies (finger width narrowed from > 30 μm to only 15 μm). On the back side, by improving the carrier selective transport ability of the ultra-thin SiO_2, using the gradient phosphorus-doped poly-Si layer and optimizing the doping ability and parasitic absorption of poly-Si, as well as enhancing the high-temperature sintering stability of the metal fingers, the rear lower $J_{0\mathrm{n,pass}}$ and $J_{0\mathrm{n,metal}}$ of 1 fA/cm^2 and 50 fA/cm^2 can be achieved. These are the ways to realize the conversion efficiency of n-TOPCon solar cells over 26.0%.

In the process of promoting n-TOPCon solar cells to increase cell efficiency and reduce manufacturing cost, there are currently three major technical challenges: laser boron-doped selective emitter, choice of the low-pressure chemical vapor deposition (LPCVD) or plasma-enhanced chemical vapor deposition (PECVD) technology, and metallization process for thinner poly-Si layer. Firstly, compared with the laser phosphorus-doped technique already widely used in PERCs, the laser boron-doped counterpart is more difficult due to the fact that the diffusion and segregation coefficients of the boron atoms are much lower than those of the phosphorus counterpart. Both the laser device and laser doping process need to be improved. Secondly, compared with the TOPCon structure by LPCVD, the tubular PECVD can achieve *in situ* doping in single-side wafers, almost no wrap-around with passivation of < 4 fA/cm^2 and low process cost. But the long-term stability of the PECVD process needs further verification. Finally, as is known that the thinner poly-Si (from 120 nm to < 80 nm thickness) has the advantages of both reducing the process time to increase production capacity and decreasing the parasitic absorption of rear poly-Si to improve the J_{SC}, the development of new metallization technology requires controlling the grain size and surface activity of Ag paste to reduce the damage to poly-Si layer and decreasing the diffusion of metal impurity ions into the passivation layer to reduce the carrier recombination, and continuing to explore a narrower finger width (⩽ 15 μm) and lower-temperature sintering process (temperature reduction of 20–80 °C). It is expected that the mass-production averaged PCE of n-TOPCon will be 26% in 2 or 3 years.

Perovskite solar cells

Metal halide perovskites possess unique optoelectronic properties and can exhibit a high photon-to-electron conversion efficiency. They can be processed to thin films through various feasible solution- or evaporation-based routes at a relatively low cost. Therefore, they have emerged as a promising class of materials for PV applications. On the one hand, considering the Shockley-Queisser limit that is posed for single-junction solar cells, perovskites with a bandgap of broad range and a high tunability endow them a suitable candidate as sub-cells in a multi-junction tandem configuration, which holds a good potential on achieving a higher efficiency. On the other hand, as the commercialization and mass-production of perovskite solar cells (PSCs) require the fabrication of high-quality perovskite films with a good uniformity and reproducibility in larger scales, enhancing the PCEs of large-area cells and modules has also become crucial to the field. Here, as listed in Table 2, the highest certified PCEs achieved in 2022 of perovskite-

Table 2 Summary of breakthroughs of single-junction and multi-junction perovskite-based cells and minimodules in 2022

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report date	Description
Perovskite (one-sun cell)	23.7	1.062 (da)	1.213	24.99	78.4	NPVM	May	USTC
Perovskite (minimodule)	22.4	26.02 (da)	1.127	25.61	77.6	NPVM	Jul.	EPFLSion/NCEPU
Perovskite/perovskite tandem (concentrator cell)	29.0	0.049 (da)	Not yet disclosed			JET	Dec.	2-terminal, NJU/Renshine
Perovskite/perovskite tandem (one-sun cell)	26.4	1.044 (da)	2.118	15.22	82.6	JET	Mar.	2-terminal, SichuanU/EMPA
Perovskite/perovskite tandem (minimodule)	24.5	20.25 (da)	2.157	14.86	77.5	JET	Jun.	2-terminal, NJU/Renshine
Perovskite/silicon tandem	32.5	1.014 (da)	1.980	20.24	81.2	JRC-ESTI	Nov.	2-terminal, HZB
Perovskite/organic tandem	23.4	0.055 (da)	2.136	14.56	75.6	JET	Mar.	2-terminal, NUS/SERIS

Notes. da: designated illumination area; NPVM: Chinese National Photovoltaic Industry Measurement and Testing Center; USTC: University of Science and Technology of China; EPFLSion: École Polytechnique Fédérale de Lausanne, Sion campus; NCEPU: North China Electric Power University; JET: Japan Electrical Safety and Environment Technology Laboratories; NJU: Nanjing University; SichuanU: Sichuan University; EMPA: Swiss Federal Laboratories for Materials Science and Technology; JRC-ESTI: European Solar Test Installation at Joint Research Centre; HZB: Helmholtz-Zentrum Berlin; NUS: National University of Singapore; SERIS: Solar Energy Research Institute of Singapore.

based solar cells and minimodules with varied scales, including single-junction devices and multi-junction tandems, are summarized and presented.

Like any other year in the past decade, the year of 2022 also witnessed many encouraging achievements on pushing the PCE of single-junction lead halide PSCs [11,12]. Although the record on small-area cell had still been held by Ulsan National Institute of Science and Technology (UNIST) at 25.7% before the end of 2021 [13], new records were set in 2022 for large-area one-sun cell (above 1 cm^2) and minimodule (a package of interconnected cells of area less than 200 cm^2). For the record set on 1-cm^2 cell by the University of Science and Technology of China (USTC), a certified PCE of 23.7% was achieved with a designated illumination area (da) of 1.062 cm^2 [14]. Meanwhile, the record set on minimodule was a collaborated work between École Polytechnique Fédérale de Lausanne, Sion campus (EPFLSion), and North China Electric Power University (NCEPU). The 26-cm^2 8-cell minimodule achieved a certified PCE of 22.4% [15,16]. Compared to the previous records on single-junction PSCs of larger areas, both of the new PCEs are accompanied by remarkably good J_{SC} values when enlarging cell area. Coupled with the well-maintained decent V_{OC} and FF values, high efficiencies were thus realized.

For the advancement on perovskite-based multi-junction tandem solar cells and minimodules, much exciting progress was also made in 2022. In the construction of a two-terminal all-perovskite tandem, the wide-bandgap top cell can select lead halide perovskites with the bandgap tuned to 1.65–1.80 eV; while for the narrow-bandgap bottom cell, mixed tin-lead perovskites can realize a suitable bandgap with a lower end of 1.2 eV. Over the year of 2022, new records were reported for all-perovskite two-junction tandems in three categories of varied cell areas. In March, a new record of 26.4% was set for 1-cm^2 cell by Sichuan University and Swiss Federal Laboratories for Materials Science and Technology (EMPA) [14]. Then in June, a record PCE of 24.5% on 20-cm^2 minimodule was reported by a research group in Nanjing University and Renshine Solar Co., Ltd. [12,17]. In December, the certified PCE on small-area all-perovskite tandem was updated by the same group, where a value of 29.0% for an area of 0.049 cm^2 was achieved with detailed parameters not yet disclosed [18]. Nevertheless, comparing the other two new records to the previous numbers, the improvement on overall PCE can be attributed to the substantial progress made on increasing V_{OC} and FF values, which are highly related to the strategic defect reduction and suppressed non-radiative recombination at the interfaces in those tandem structures.

Pairing perovskite sub-cells with the narrow-bandgap cells made from other more-developed materials is another promising route to enhance the overall PV performance. In many cases, the tandem device can significantly outperform either of the single-junction cell. Up to the present, the highest PCE of perovskite-based tandem solar cells has still been hold by the architecture of perovskite/silicon. The year of 2022 witnessed another two leaps on the efficiency of such cell in the scale of 1-cm^2 area, where both values exceeded the threshold of 30% [12,13], demonstrating the great potential of this multi-junction combination. The current record on the two-terminal perovskite/Si tandem was set in November by Helmholtz-Zentrum Berlin (HZB) as 32.5% [19], excelling the record of 31.25% reported in June [20] with some improvement on FF. The PCE of 32.5% established the new world record PCE in perovskite and/or c-Si based tandem solar cells. Another architecture with a new record reported is the perovskite/organic tandem. A certified efficiency of 23.4% was set on a cell area of 0.0552 cm^2 from the National University of Singapore (NUS) and the Solar Energy Research Institute of Singapore (SERIS) [14,21]. It is also worth noting that for the two-junction perovskite/Cu(In,Ga)(S,Se)$_2$ (CIGS) tandem, the technical details for the current record on a 1-cm^2 cell was disclosed in 2022 [22]. This PCE value of 24.2% was reported by HZB in early 2020 [23].

Compared to the previous record, the improvement on PCE was mainly attributed to the higher V_{OC}, which was attributed to a more suitable wide-bandgap of the triple-cation mix-halide perovskite, the favorable modification to charge carrier extraction [24], and the utilization of functional organic ammonium halide additives.

In summary, many notable milestones were achieved in 2022 on the efficiency of perovskite-based solar cells and minimodules, including both single-junction devices and multi-junction tandems. For the better development and commercialized promotion of PSCs, there still exist several critical issues that need to be further addressed, such as the improvement on long-term operational stability, the preservation of device performance for scale-up production, the consideration on cost, and the everlasting caution on environmental impact. Yet still, it is believed that with collaborated efforts from researchers in academia and the industry, perovskite-based solar cells hold a good prospect among PVs, and these challenges will be successfully tackled in the near future.

Organic solar cells

Organic solar cells (OSCs) based on bulk heterojunction (BHJ) structure have attracted much attention due to the advantage of potentially low-cost, flexibility, and semitransparency, showing a high potential for future use, especially in local environment such as new generation of building integrated PV and agriculture-integrated PV. Currently, the OSCs based on non-fullerene acceptors (NFAs) afford the highest efficiency about 20% [25]. The major advances are ascribed to the reduced energy loss and well-defined carrier transport pathway. Meanwhile, the extended absorption from NFAs toward the near infrared wavelength significantly enhances the light harvest. It should be noted that the current high efficiency OSC materials show an absorption extended to the solar radiation dip of around 950 nm, which delivers a J_{SC} of around 30 mA/cm^2. Further extending the absorption to 1100 nm (similar to the absorption cut-off of silicon materials) could significantly extend the J_{SC}, achieving the next step breakthrough in OSC performances. Although the non-fullerene acceptor based OSCs have good performances in V_{OC}, J_{SC} and FF, it should also be noted that fullerene acceptor materials, or other type of less crystalline donor or acceptor materials can be used in making a more efficient mixing region, showing improvement in faster exciton quenching and a higher V_{OC}, which is also an important direction to be examined in future research. In fact, the balance between the crystalline domain and the mixing domain has been the most important aspect in optimizing the OSC morphology. Key advances can be seen from the double-fiber morphology developed by Zhu et al. [26], or low concentration doping of secondary acceptors developed by Song et al. [27]. In the current stage, efficiency enhancement is still the main focus, and device stability and the manufacture of large-area modules are critical directions to be accelerated. The development of new and more stable photon active materials, more robust morphology, and better interfacial engineering is crucial.

In 2021 and 2022, the development of a new Y-family NFA L8-BO from the researchers in Beihang University promoted the rapid development of organic PVs [28]. The branched side chains induce improved molecular packing and optimized electronic structure, affording a higher PCE of over 18%. Important progresses in 2022 were mostly based on L8-BO, which are summarized in Table 3. Important processes will be briefly commented. The researchers in Zhejiang University (ZJU) utilized the sequential casting method (layer-by-layer, LBL casting) to manipulate the vertical phase segregation, and the PM6:L8-BO binary device afforded an improved PCE of 18.4% [29]. The researchers in the University of Chinese Academy of Sciences (UCAS) used a similar processing method, and prepared D18:L8-BO LBL binary device that showed a PCE of 18.9% [30]. It seems that LBL processing in producing vertical phase segregation can be a superior carrier extraction approach, which still need detailed confirmation. The researchers in ZJU reported a ternary mixture to regulate the trade-off between V_{OC} and J_{SC} by combining the symmetric−asymmetric NFAs to reduce energetic disorder and enhance blended thin film luminescence efficiency. An improved PCE of 19.12% was obtained [31]. This is the best case to show that slight variations in material structure could lead to a

Table 3 Summary of breakthroughs of organic solar cells in 2022

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report date	Description
Organic (thin film)	18.9	0.032	0.914	26.54	77.8	NIM	Jun.	UCAS
Organic (thin film)	19.12	0.045	0.892	26.88	79.73	NPVM	Aug.	ZJU
Organic (thin film)	19.23	0.031	0.891	26.70	80.84	NPVM	May	SJTU
Organic (thin film)	19.35	0.046	0.882	27.82	78.90	NPVM	Sept.	ZJU
All-polymer (thin film)	17.8	0.051	0.910	25.52	76.7	NIM	Dec.	WHU
Organic (minimodule)	14.13	19.31	5.805	3.50	69.57	NPVM	May	ZJU

Notes. NPVM: Chinese National Photovoltaic Industry Measurement and Testing Center; NIM: National Institute of Metrology, China.

drastic change in performances. The researchers in Shanghai Jiao Tong University (SJTU) proposed a double fibrillar network nanostructure, which is confirmed to be the desired morphology to guarantee high exciton dissociation and carrier transport [26]. The highly crystalline polymer D18 was introduced to balance exciton diffusion length and enhance carrier transport properties. Such strategy led to a reduced recombination rate, hence minimizing photon-to-electron losses and maximizing the power output in ternary devices, offering a high PCE of 19.23%. The quaternary strategy is also used to optimize the morphology, electronic structure, and light absorption [32]. The researchers in ZJU constructed PM6:BTP-eC9:L8-BO:BTP-S10 devices, by which the exciton separation, carrier mobility, and carrier lifetime were enhanced simultaneously, and an outstanding PCE of 19.35% was obtained [33].

All polymer solar cells (APSCs) have attracted much attention in 2021 and 2022, owing to their good light, thermal, and mechanical stability. The research group from the Institute of Chemistry of the Chinese Academy of Sciences (ICCAS) developed a new polymer donor named PQM-Cl. The negative electrostatic potential and low average local ionization energy distribution of the PQM-Cl surface enable an efficient charge generation and transfer process. When blended with a well-used polymer acceptor PY-IT, the PQM-Cl:PY-IT devices delivered an impressive PCE of 18.0% (not certified) with a superior *FF* of 80.7%, and the devices showed excellent mechanical and flexible properties [34]. In November, they further optimized the fibril network morphology of the active layer by tuning the polymer molecular weight and obtained a high PCE of 18.2% (certified to be 17.7%) [35]. In December, the researchers in Wuhan University (WHU) designed a narrow-bandgap chlorinated polymer acceptor PY-2Cl and incorporated it into the PM6:PY-1S1Se host blend. The introduction of PY-2Cl extended the light absorption, improved the molecular packing, solidified the blend microstructure, and suppressed the non-radiative recombination. Consequently, the PCE of the APSCs was improved up to 18.2% (certified to be 17.8%), and could maintain 77.5% of its initial PCE after continuous illumination for 3000 h at room temperature due to significantly suppressed the burn-in degradation [36].

Exciting progresses have also been made in OSC modules, which is important for commercial application. The researchers in Huazhong University of Science and Technology (HUST) reported an alcohol-dispersed formulation named PEDOT:F, which has good wetting properties and a low acidity. Based on PEDOT:F, fully printable OSC minimodules were fabricated, where 7 sub-cells were connected in series, showing a PCE of 13.07% with an area of 12.2 cm^2 [37]. The researchers in ZJU combined bilayer-merged-annealing (BMA) and blade-coating methods to fabricate the OSC minimodule. The BMA strategy could effectively resolve the dewetting issues between polar interlayer solution and non-polar BHJ blends to improve the film coverage. Meanwhile, the pinhole formation during large-area fabrication can be suppressed, beneficial to improve the performance and reproducibility of large-area OSCs. As a result, the PCE of the OSC minimodule achieves 14.13%, with the area of 19.31 cm^2 [38].

To conclude, significant progresses were made in 2021 and 2022 in all aspects, including increased efficiency, improved device stability, and large-scale module fabrication. For better development and commercialization, more emphasis should be laid on the research of device stability and the development of the module preparation method. It is believed that the efficiency of OSCs could be quickly elevated to 22–25%, and the performance of modules could achieve 18% in 3 to 5 years. A bright future for OSC technology can be expected.

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