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HIGHLIGHTS

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Highlights of mainstream solar cell efficiencies in 2023

This article continues our highlights last two years [1,2] on the highest independently confirmed mainstream (silicon, perovskite, and organic) solar cell efficiencies in 2023. The world record power conversion efficiency (PCE) of the single-junction silicon and perovskite/silicon tandem solar cells has reached over 27% and close to 34%, respectively, in 2023. We have also witnessed the rapid mass-production development of the silicon passivating contact and silicon back contact solar cells, as well as further progress with perovskite solar cells (PSCs).

Silicon solar cells

2021 is the first year of China's carbon neutrality program. With the advantages of high conversion efficiency, mature cell process and low cost, crystalline silicon (c-Si) solar cells play an important role in achieving the goal of carbon neutrality. By 2023, China's installed renewable energy capacity has exceeded 1.4 × 10^9 kW, accounting for more than 50% of the country's total installed power generation capacity and historically surpassing the installed thermal power capacity. Photovoltaic (PV) power generation accounts for the largest proportion of installed renewable energy capacity. With the c-Si solar cell production of 450–500 GW in 2023 (over 98% of the global PV market share), the mainstream product of the PV market in 2023 is still the passivated emitter and rear cell (PERC). However, as PERC solar cells gradually approach the efficiency limit of 24.5%, PV industry has focused on two higher-efficient passivating contact cell structures, namely silicon tunnel oxide passivated contact (TOPCon) and heterojunction (SHJ) solar cells. We have witnessed the rapid mass-production development of TOPCon and SHJ solar cells in 2023, with the annual production of 105–115 GW and 7–8 GW, respectively. Table 1 lists the achievements of the TOPCon and SHJ solar cell efficiencies during 2023. By combining with laser doping selective emitter (LDSE), laser enhanced contact optimization (LECO) and optical trapping technologies, c-Si TOPCon solar cells have been reported with conversion efficiency of 26.89% over a large 182 cm × 182 cm area [3]. The SHJ solar cells by adopting the interdigitated back contact (namely, HBC) have reached the high cell efficiency of 27.09% with an all-laser patterning process [4].

The TOPCon solar cell has already been considered one of the most popular candidates among all the high-efficient c-Si solar cells for the theoretical efficiency limit reaching 28.7% [5], which is closest to the theoretical efficiency limit of c-Si solar cells of 29.4% [6]. As normally implemented, the TOPCon structure consists of ultra-thin SiO_2 and phosphorus-doped polycrystalline silicon (poly-Si(n^+)), which possesses the advantages of full-area passivation contact and compatibility with high-temperature sintering process for existing PERC production lines [7]. 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 carrier recombination for non-contact region ($J_{0n,pass}$) and metal contact region ($J_{0n,metal}$) of 2.7 and 50 fA/cm^2 can be achieved [8]. We have highlighted the excellent performance of TOPCon solar cells with conversion efficiency over 26.0% in 2022 [2], although some concerns that the fill factor (FF) of

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these cells may be overestimated due to non-optimal probe configurations [9].

As the efficiency of TOPCon solar cells continues to improve, recombination losses caused by front-sided contact have become the primary limiting factor for efficiency [10]. To reduce the front recombination loss, a common method is to apply LDSE on the front side [11], which has characteristics of cell processing at room temperature, easy control of doping distribution, high scanning accuracy and flexible scanning pattern [12]. Compared to existing technologies, the LDSE not only reduces carrier recombination in the emitter region and improves surface passivation, increasing open-circuit voltage (V_{OC}) by 5–8 mV [13], but also reduces the contact resistivity (ρ_c) of the metal electrode, thereby improving the FF. Although LDSE has a great improvement, it is estimated that recombination of metal region remains as high as 600–1000 fA/cm^2, which is still too high in comparison with the rear SiO_x/poly-Si. Thus, the state-of-the-art LDSE technology is insufficient to further increase the efficiency of TOPCon solar cells. To overcome the shortcomings of LDSE, local SiO_x/poly-Si structure is applied to the metal contact zone on the front-side, i.e., poly-finger technology. Compared to LDSE, the poly-finger structure can avoid direct contact between c-Si and metal electrodes, thereby greatly reducing J_0. In addition, this structure enables selective collection of carriers, reducing the probability of electron-hole recombination and extending the effective minority carrier lifetime. Simulation results indicate that the n-type Si solar cells with poly-finger structure achieve an increase by 4.8 mV in V_{OC} and 0.39% in efficiency compared to those of LDSE [14].

The LECO process is another highly favored technology in the industry in 2023. Applying a high intensity laser pulse to the metal contact area of cell surface, the local high density current generated will significantly reduce the contact resistance. Because of the decrease of sintering temperature, the cell interface passivation is not damaged, which makes the c-Si solar cell obtain higher V_{OC} and FF [15]. Studies have shown an interdiffusion of the Ag and c-Si material as the underlying root cause for improved local contact resistivity. The metal finger lines of the solar cell do not change after the LECO treatment. Note that the cells suffering from multiple finger interruptions cannot be fixed by LECO. Moreover, cells which show local shunts, e.g., overfired cells, are often difficult to be processed by the LECO treatment. The reason is that the driving force for the contact improvement due to LECO is the local induced current, which can not appear on cells with very low parallel resistance. The efficiency gain of TOPCon solar cells after employing LECO is generally between 0.15%–0.37% with proper handling [16]. Meanwhile, the TOPCon solar cells treated by LECO show no signs of light and elevated temperature induced degradation (LeTID).

In 2023, we have two observations for the mass-production of the TOPCon solar cells: ① More attention has shifted to the plasma-enhanced chemical vapor deposition (PECVD) on account of its technical advantages such as the fast film forming rate, compatibility with *in situ* doping and good single-sided deposition. As we know, the low-pressure chemical vapor deposition (LPCVD) process is considered one of the first TOPCon cell technologies for mass production [17], which has solved technical problems such as coating uniformity and doping profiles distribution. However, the LPCVD is also associated with the challenges of the longer process time and the more complex post-cleaning process, followed by the higher cell production costs. The PECVD technique was first employed by the Fraunhofer Institute for Solar Energy Systems (FhG-ISE) to prepare the TOPCon structure in 2018 [18]. The existing research mainly includes, e.g., the poly-Si layer doped with carbon to suppress the blistering, the heavily phosphorus-doped poly-Si (poly-Si(n^{++})) deposited to remove the Fe-atoms, the selective poly-Si(n^{++}) served to provide the excellent surface passivation, etc. The proportion of PECVD has reached 30% in the poly-Si deposition technologies of TOPCon solar cells in 2023, and it will exceed the capacity of LPCVD within two years. ② Chinese leading solar companies urge fast mass-production of the TOPCon-related back contact solar cells. As we know, Si interdigitated back contact solar cells have been commercialized for more than 20 years. However, the annual production of the back contact solar cell is limited to less than 1 GW due to its complexity and high-cost. Nevertheless, both the PERC/TOPCon hybrid and pure TOPCon back contact solar cells have been mass-produced with the annual production of 8–9 GW in 2023. This kind of back contact solar cell development is

Table 1 Summary of the achievements of TOPCon, SHJ and HBC solar cells in 2023

Solar cell type	PCE/%	Area/cm^2	V_{OC}/mV	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report month	Description
n-TOPCon	26.7	330	–	–	–, *	NIM	Apr.	Jolywood PVD
n-TOPCon	26.89	330	–	–	–, *	NIM	Oct.	Jinko LPCVD
n-SHJ	26.60	274.3	750.4	41.14	86.18	ISFH	May	SunDrive/Maxwell Copper plating
n-HBC	27.09	243.0	742.5	42.62	85.60	ISFH	Dec.	LONGi Laser patterning

Notes: ISFH—Institut fur Solarenergieforschung Hameln, Germany; – denotes not yet disclosed; * denotes possibility of overestimation; NIM—National Insititute of Metrology, China.

significant, since the annual production is even larger than that of the SHJ solar cells, taking advantage of mature and low-cost full laser patterning technologies.

Compared to the TOPCon solar cells, bifacial passivating contact enables the SHJ solar cells to feature superior carrier electrical transport characteristics and ultimately higher efficiencies. LONGi found [19] that the new p-type hydrogenated nanocrystalline Si (p-nc-Si:H) contact layer has lower activation energy than traditional hydrogenated amorphous Si (p-a-Si:H), which is conducive to optimizing the interfacial barriers for hole transport, thus presenting a lower contact resistance. As the surface passivation level of SHJ solar cells is gradually enhanced, the surface recombination is relegated to a secondary position while Auger recombination process plays a dominant role in the verification of the ideal factor of less than 1 [6]. The contact resistance and surface recombination of the SHJ consisting of p-nc-Si:H were reduced to 5 $m\Omega\cdot cm^2$ and 0.5 fA/cm^2, which increases the V_{OC} and FF to 751.4 mV and 86.07%, respectively. Moreover, the laser transfer metallization process was introduced to reduce the grid shading from 2.8% to 2.0%, achieving a short-circuit current density J_{SC} of up to 41.16 mA/cm^2. Finally, a certified efficiency of 26.81% was obtained by optimizing the hole contact layer and front optical design in 2022 [2].

In 2023, the SHJ research witnessed a breakthrough in the exploration of copper plating. The extensive consumption of low temperature silver paste contributes significantly, accounting for approximately 30% of the total processing cost. Maxwell and SunDrive jointly achieved a 26.41% [2,20] and later 26.60% efficiency in SHJ solar cells by utilizing copper plating, representing the best efficiency for copper-metallized SHJ solar cells. They have developed an advanced seedless copper plating technology to obtain high quality copper electrodes characterized by narrow width, low volume resistivity and low contact resistivity. Replacing screen-printed silver electrodes with copper-plated electrodes resulted in a 0.43% improvement in the certified efficiency of the M6-size SHJ device. The work provides an effective strategy for high-throughput SHJ solar cell fabrication that can accelerate the mass-production of SHJ solar cells. However, some challenges need to be overcome before industrial adoption, such as cost-effectiveness, complex electroplating steps, reliability and long-term degradation [21].

In pursuit of ultimate silicon solar cell efficiency, researchers are turning their attention to the HBC solar cell, a fusion of the SHJ solar cell with back contact electrodes. Compared with traditional bifacial SHJ solar cells, HBC cells have neither metallization nor the need for transparent conductive oxide (TCO) layer at the front. In December 2023, LONGihas announced a 27.09% certified efficiency record [4] of single-junction PV device based on HBC solar cells. A high current density J_{SC} of 42.62 mA/cm^2 has been achieved in the record HBC cell, higher than the best current density achieved for bifacial SHJ cells. To address the cost constraints associated with patterning processes, LONGihas abandoned the expensive photolithography process and instead innovatively adopted an all-laser patterning process for HBC solar cell fabrication. Another advantage of HBC cells over bifacial SHJ solar cells is the reduced usage of TCO layers. Through continuous technological improvements, LONGi has developed an ultra-thin TCO layer with reduced indium usage. The indium usage of the 27.09% efficiency record cell is one fifth of that of traditional bifacial SHJ solar cells. LONGihas also realized indium-free HBC solar cells with a certified efficiency of over 26.9%. Due to the huge advantages in efficiency and cost, HBC solar cells are expected to be the next generation of industrialized technology in a few years.

Perovskite solar cells

The remarkable development on metal halide perovskite PVs over the past decade has showcased their great potential as the next generation of mainstream solar cells with high efficiency and low fabrication cost. The exceptional optoelectronic properties that rooted in the materials' chemical and structural nature ensure the continuous improvement on the devices' PCE. In the year of 2023, it is truly encouraging that such efficiency enhancement has not only been reflected on single-junction PSCs toward the Shockley–Queisser (S–Q) theoretical efficiency limit, but also the multi-junction perovskite/silicon tandem devices of varied scales. While the high efficiency of tandem cell has proved the technical feasibility of utilizing sub-cells with complementary bandgaps, the scaling up of device area have revealed the notable progress on processing with good scalability and reproducibility, which is critical for mass production and commercialization. Here in Table 2, breakthroughs that were achieved in 2023 on the certified PCEs of single-junction and multi-junction perovskite-based cells and minimodules are summarized.

The year of 2023 is another one that witnessed many efforts on pushing the PCE of single-junction PSCs [22], which can be largely attributed to the bettered crystallization control of the perovskite thin film and carefully tuned interfacial contact in device. The record on small-area cell (aperture area: 0.05–1 cm^2) had been hold by researchers from Ulsan National Institute of Science and Technology (UNIST) as 25.7% since late 2021 [23,24] and improved to 25.8% by the same group in November, 2022 [22]. The technical details on the fabrication of the 25.7%-PCE cell was disclosed in early 2023 [24]. Volatile alkylammonium chlorides were added to the precursor of formamidinium lead iodide ($FAPbI_3$), which

Table 2 Summary of breakthroughs of single-junction and multi-junction perovskite-based cells and minimodules in 2023

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report month	Description
Perovskite	26.0	0.0746 (da)	1.190	26.00	84.0	JET	Mar.	ISCAS
Perovskite	26.1	0.0513 (da)	1.201	25.73	84.6	NPVM	May	USTC
Perovskite	26.1	0.0493(da)	1.174	26.13	85.2	Newport	Jul.	NWU/UT
Perovskite	24.35	1.007 (da)	1.159	25.60	82.1	NPVM	Apr.	NUS/SERIS
Perovskite	25.2	1.0347 (da)	1.162	26.39	82.0	Newport	Sep.	NWU
Perovskite/silicon tandem	33.2	0.998 (da)	1.962	20.97	80.7	JRC-ESTI	Mar.	2-terminal, KAUST
Perovskite/silicon tandem	33.7	1.0035 (da)	1.974	20.99	81.3	JRC-ESTI	May	2-terminal, KAUST
Perovskite/silicon tandem	33.9	1.004 (da)	1.966	20.76	83.0	NREL	Sep.	2-terminal, LONGi
Perovskite (minimodule)/silicon (cell) tandem	28.4	63.98 (da)	1.21/0.648	21.9/14.3	78.7/81.4	AIST	Jan.	4-terminal, Kaneka
Perovskite/silicon (large) tandem	28.6	258.14 (t)	1.909	19.11	78.3	FhG-ISE	May	2-terminal, Oxford PV

Notes: All measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C; da denotes designated illumination area; t denotes total area; JET—Japan Electrical Safety and Environment Technology Laboratories; JRC-ESTI—European Solar Test Installation at Joint Research Centre; AIST—Japanese National Institute of Advanced Industrial Science and Technology; KAUST—King Abdullah University of Science and Technology; NPVM—National PV Industry Measurement and Testing Center, China; NREL—National Renewable Energy Laboratory, US.

could modify the crystallinity and morphology of the fabricated perovskite film for defect reduction, leading to the high efficiency when coupled with charge transport layers of good quality. Meanwhile, over the year of 2023, another three records on small-area cell have been set. The first one exceeded the threshold of 26.0% in March from Institute of Semiconductors, Chinese Academy of Sciences (ISCAS) [25,26]. Then two respective research teams reached 26.1%, one from University of Science and Technology of China (USTC) [27,28], and the other is a collaboration between Northwestern University (NWU) and University of Toronto (UT) [27,29]. Since these PCE records are almost tied to each other, they all possess comparably good V_{OC}, J_{SC} and FF values for assurance on the overall high performance. It is also worth noting that, the PCE of the inverted (p-i-n) device configuration has been greatly boosted in 2023, considerably owing to the development of utilizing self-assembled monolayers (SAMs) of molecules like [4-(3,6-dimethyl-9H-carbazol-9-yl)butyl] phosphonic acid (Me-4PACz) and [2-(3,6-dimethoxy-9H-carbazol-9-yl)ethyl] phosphonic acid (MeO-2PACz) as the hole-selective layer by itself or coupled with other metal oxides and polymers [30–34]. As the inverted structure holds advantages over the conventional n-i-p structure on long-term operational stability and more feasible processing, future breakthrough on single-junction cell can count on the more meticulous tuning within either one of the device configurations.

For the case of perovskite single-junction one-sun cell (above 1 cm^2) of slightly larger area, two efficiency increments have been achieved since the last record [2,23]. One certified in April as 24.35% with a designated illumination area (da) of 1.007 cm^2 by National University of Singapore (NUS) and Solar Energy Research Institute of Singapore (SERIS) [35], followed by one in September as 25.2% by Northwestern University on an area of 1.0347 cm^2. Both of the new PCEs are accompanied with improved J_{SC} and FF values when compared with the previous record, with the decent V_{OC} value well maintained. Meanwhile, the PCE record set on minimodule (a package of interconnected cells with an area less than 200 cm^2) is still the 22.4% from 2022 of a 8-cell, 26-cm^2 minimodule [27,36].

The high tunability on the chemical composition and bandgap of metal halide perovskites has yielded the material an ideal candidate as sub-cell in multi-junction solar cells and modules [37]. To maximize the utilization of the solar spectrum, the structures to tandem with not only include the more-developed silicon cells, but also another perovskite sub-cell with matching bandgaps. In the case of double-junction all-perovskite tandem cells, lead halide perovskites with wide bandgap of 1.65–1.8 eV can function as top cell and collect the high-energy photons, while the bottom cell of mixed lead-tin (Pb–Sn) perovskites can realize a suitably narrow bandgap as low as 1.2 eV for absorption of the remaining photons of low energy. Compared to our last report, new records on two-terminal, all-perovskite tandems of varied cell areas have been set from researchers in Nanjing University and Renshine Solar Co., Ltd. As the records were certified by the end of 2022, they are not listed in Table 2 but are worthy of discussing here. A 29.1% efficiency was reported for a 0.049 cm^2 small-area cell, which should be accredited to the concerted interfacial engineering of all functional layers [25,38]. Technical details on a previous record of 28.5% for small-area all-perovskite tandem cell has also been disclosed in 2023 [39]. In the work, 3D/3D bilayer perovskite SHJ with type-II band alignment was rationally constructed at the interface between Pb–Sn perovskite and electron transport layer to tackle the challenges on processing compatibility. The suppressed non-radiative recombination and facilitated charge extraction yield the

Pb–Sn bottom cell with good V_{OC} and FF, thus leading to high PCE of the entire tandem. For the other record on 1-cm^2 one-sun cell, the certified efficiency has been advanced to 28.2% with substantial improvements on V_{OC} and J_{SC} values from the previous record.

To date, the highest PCE record of perovskite-based solar cells is held by perovskite/silicon tandem consisting of a perovskite top cell and a c-Si bottom cell. With the milestone of 30% successfully achieved in 2022, another three leaps on the efficiency of 1-cm^2 cell have been realized in 2023, pushing the current PCE record to as high as 33.9% [22,27] and surpassing the theoretical S–Q limit of any single-junction cell. All based on two-terminal configuration, the first two records set in 2023 were reported from KAUST as 33.2% in March [40] and 33.7% in May [25,41], but excelled by the 33.9% reported from LONGi in September [42]. In fact, from the technical perspective of PV promotion, constructing double-junction tandems between the fast-developing perovskite and the market-dominating silicon has been recognized as one of the most promising routes for further PCE enhancement with cost-effective manufacturing, hopefully translating to a reduction on levelized cost of electricity (LCOE) [43,44]. In this context, encouraging progresses have also been made with perovskite/silicon tandems of larger scales. A combined record efficiency of 28.4% was reported in January from researchers in Kaneka on four-terminal, 64-cm^2 device, which was mechanically stacked by a 32-cell perovskite minimodule on a single silicon cell [25,45]. In May, a certified efficiency of 28.6% on 258.14 cm^2 of even larger area was achieved by Oxford PV with a two-terminal perovskite/silicon tandem architecture [25,46]. The commercial size of this cell well demonstrates the gradual realization of enlisting such technology among the next-generation high-efficiency solar cell for practical deployment.

In all, a handful of notable milestones have been achieved in 2023 on the efficiency of perovskite-based single-junction and multi-junction cells and minimodules. For the further PCE advancement, and more importantly, the translation from laboratory research to industrial production, ensuring operational stability, reproducibility and reliability, as well as the exploration of environmental-friendly processing routes are all paramount but pressing goals. Nevertheless, it is with good faith that the ambition will be accomplished in the near future with the continuous collaborated efforts from academia and industry.

Organic solar cells

Organic photovoltaics (OPVs) represent a transformative technology in the realm of renewable energy, offering unique advantages such as mechanical flexibility, light weight and cost-effective production. The ability of OPVs to be fabricated using solution processing on flexible substrates has spurred intensive interest, driving the quest for improved efficiency and stability of devices and mini-modules. The highest reported efficiencies for organic solar cells (OSCs) based on non-fullerene acceptors (NFAs) were over 19% in a single-junction [22,47] and exceeding 20% in a tandem configuration [48]. Currently, the Y-family materials, which have gained popularity in the field, exhibit an extended absorption range encompassing the solar radiation dip around 950 nm. This extended absorption enables the generation of a J_{SC} of approximately 28 mA/cm^2, comparable to that of gallium arsenide (GaAs) and PSCs. The transport properties of OPV are effectively optimized to construct the double fibril network morphology and to carefully deal with the mixing phase, thus, an FF of approaching 82% was obtained [49]. However, the V_{OC} (0.92 V) is about 20% lower than that of GaAs (1.12 V) and perovskite (1.17 V) [22], which is the critical parameter that limits the PCE of OPV device. The address this issue, suppressing the non-radiative recombination has been a prominent focus of current research endeavors [50]. It is clear that the community is still at the early stages of understanding the fundamental factors controlling non-radiative recombination processes and drawing upon the experience gained from organic light-emitting diodes (OLEDs) could be valuable. Furthermore, the utilization of hot excitons presents an additional point of consideration. This term denotes excitonic states of elevated energy that exhibit an energy surplus relative to their counterparts in thermal equilibrium. The segment of energy loss associated with E_g $-qV_{OC,S\text{–}Q}$ (with E_g the bandgap) might be substantially reduced provided that these hot excitons have the capacity to dissociate directly. Despite the efficiency enhancement, the stabilization of devices and the advancement of manufacturing techniques for large-area modules constitute pivotal directions in which acceleration is imperative, which are critical for transitioning from laboratory-scale successes to commercially viable technologies, thereby necessitating concerted research and development efforts to overcome the existing technical and scalability challenges.

In the year 2023, the esteemed Y-family NFA, L8-BO, developed by researchers at Beihang University [51], continues to spearhead advancements in efficiency. This molecule exhibits a commendable fibril-like crystalline structure that facilitates efficient charge transport. It serves as a foundational platform enabling further refinement through molecular engineering, device structural optimization and processing technique enhancement. Important progresses are delineated in Table 3, and pertinent methodologies will be succinctly addressed. The team at the Institute of Chemistry, Chinese Academy of Sciences (ICCAS), has integrated the weakly crystalline PBDB-TF into the PBQ$_x$-TCl:eC9-2Cl-based

Table 3 Summary of the achievements of organic solar cells in 2023

Solar cell type	PCE/%	Area/cm^2	V_{OC}/V	J_{SC}/(mA·cm^{-2})	FF/%	Test center	Report month	Groups
Organic (thin film)	19.1	0.062	0.886	26.99	79.7	NIM	Jan.	ICCAS
Organic (thin film)	19.41	0.046	0.880	27.74	79.55	NPVM	Mar.	ZJU
Organic (thin film)	19.22	0.033	0.914	26.61	79.0	NREL	Apr.	SJTU
All-polymer (thin film)	18.59	0.031	0.945	26.26	74.95	NPQT	Jul.	SJTU
Organic (minimodule)	15.7	19.31	0.877 [a]	24.31[a]	73.4	JET	–	ZJU
Organic (submodule)	14.5	204.1	31.60	0.615	74.6	FhG-ISE	Nov.	FAU/FZJ

Notes: [a] The minimodule contains 7 cells, and the V_{OC} and J_{SC} here are reported on a 'per cell' basis. – denotes not yet disclosed. NPQT—National Photovoltaic Product Quality Inspection & Testing Center, China.

system to refine the formation of optimal fibrils of PBQ$_x$-TCl and eC9-2Cl. This approach is in harmony with the design principles we proposed in 2022 to establish a double fibril network morphology [49]. This strategy has proven to be a promising avenue in achieving superior transport properties, extending exciton and carrier diffusion lengths. Consequently, an impressive FF of 81.14% and a PCE of 19.5% were recorded in the laboratory, with the NIM, Beijing, certifying a PCE of 19.1% [48]. In March, researchers at Zhejiang University (ZJU) employed a mixed diluent strategy to equilibrate charge generation and recombination in OPV devices. They selected a quaternary mixture of PM6:BTP-eC9:BTP-S17:BTP-S16, leveraging the improved miscibility of BTP-S17 with BTP-eC9 and its expansive band gap to enhance V_{OC} potential. Concurrently, the broad absorption spectrum of BTP-S16 ensures efficient charge generation. This formulation yielded a laudable laboratory PCE of 19.76%, with certification from the NPVM, Fujian, at 19.41% [47]. In April, the team in Shanghai Jiao Tong University (SJTU) set a new benchmark on the Best Research—Cell Efficiency Chart from the NREL, USA, elevating the record from 18.2% to 19.2%. The corresponding PCE, derived from a 10-min steady-state test, comprised a V_{OC} of 0.914 V, a J_{SC} of 26.61 mA/cm^2 and an FF of 79.0% [22]. The associated research, awaiting publication, is anticipated to concentrate on the refinement of the mixing phase within the double fibril network paradigm, incorporating novel processing techniques. Additionally, all-polymer solar cells (APSCs) have also demonstrated significant progress in 2023. Utilizing the polymeric acceptor PY-IT, researchers in SJTU have amalgamated thermal annealing, solvent vapor annealing, and the introduction of the solid additive DIB to engineer an optimized nano-sized donor-acceptor fibrillar network. This approach has yielded an unprecedented laboratory efficiency of 19.06%, with certification from the NPQT, Chengdu, at 18.59%. Crucially, the release of DIB has been observed to alter the surface elastic modulus, inducing the formation of micro-sized wrinkle structures. Remarkably similar to surface pyramidal texturing in silicon solar cells, this effect contributes to reduced light reflection and an enhanced light reception angle, culminating in a 30% increase in power generation [52]. This study is a perfect example of how scientific experiments and real-world uses can come together. We think that this kind of research, which combines discoveries made in the laboratory with practical applications, is the way forward.

In the realm of OPV modules, the year 2023 has witnessed significant advancements surpassing the achievements of 2022, signaling a promising trajectory for commercial viability. In 2023, ZJU reported 15.7% minimodule PCE [27]. A notable enhancement in the FF to 73.4%, up from 69.57% in 2022. An additional groundbreaking development has emerged from Friedrich-Alexander Universität Erlangen Nürnberg (FAU), where the efficiency record for OPV submodules has been elevated to a remarkable 14.46%. This milestone has been authenticated by the FhG-ISE in Germany and has been duly recognized in the Champion Photovoltaic Module Efficiency Chart from NREL [53]. Although the detailed publication of this work is forthcoming, *PV-Magazine* has unveiled that the submodule encompasses 38 serially connected cells, encompassing an area of 204.1 cm^2. It is reported that the FAU team has ascribed this notable improvement in efficiency to three fundamental facets of their research initiative: the employment of superior active materials; laser patterning that minimized inactive areas on the surface and enhanced interconnects; and the use of simulations to establish more uniform coatings [54]. Collectively, these innovations have led to a high V_{OC} of 31.60 V and an FF of 74.6%, marking a substantial progression in large-scale OPV module fabrication.

To conclude, the recent advancements in the field of OPV modules are indicative of the rapid progress that is bridging the gap between experimental research and commercial application. The year 2023 has been particularly noteworthy, with significant strides made in enhancing the efficiency and manufacturability of OPV modules, as evidenced by the collaborative efforts of research institutes worldwide. It is believed that the efficiency of OPVs could be elevated to 22%–25% in the near future, and the performance of modules could achieve 18% in 3–5 years. Concurrently, the best OPV device could afford an extrapolated T_{80} lifetime of over 25000 h [55] at room temperature, based on 1000 h indoor testing. In Shanghai, the average time for sunlight irradiation is 1100–1300 h annually, that means the lifetime of the currently best small-area OSC may approach the standard for Si solar cells of over 25 years according to IEC-61215 [56]. A bright future for OPV technology can be expected and more efforts are echoed.

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