Perovskite/Si tandem solar cells: Fundamentals, advances, challenges, and novel applications

Yuanhang Cheng1 | Liming Ding2

1 Solar Energy Research Institute of Singapore, National University of Singapore, Singapore, Singapore
2 Center for Excellence in Nanoscience (CAS), Key Laboratory of Nanosystem and Hierarchical Fabrication (CAS), National Center for Nanoscience and Technology, Beijing, China

Abstract
The world record device efficiency of single-junction solar cells based on organic–inorganic hybrid perovskites has reached 25.5%. Further improvement in device power conversion efficiency (PCE) can be achieved by either optimizing perovskite films or designing novel device structures such as perovskite/Si tandem solar cells. With the marriage of perovskite and Si solar cells, a tandem device configuration is able to achieve a PCE exceeding the Shockley–Queisser limit of single-junction solar cells by enhancing the usage of solar spectrum. After several years of development, the highest PCE of the perovskite/Si tandem cell has reached 29.5%, which is higher than that of perovskite- and Si-based single-junction cells. Here, in this review, we will (1) first discuss the device structure and fundamental working principle of both two-terminal (2T) and four-terminal (4T) perovskite/Si tandem solar cells; (2) second, provide a brief overview of the advances of perovskite/Si tandem solar cells regarding the development of interconnection layer, perovskite active layer, tandem device structure, and light management strategies; (3) third, discuss the challenges and opportunities for further developing perovskite/Si tandem solar cells. This review article, on the one hand, provides a comprehensive understanding to readers on the development of perovskite/Si tandems. On the other hand, it proposes various novel applications that may bring such tandems into the market in a near future.

KEYWORDS
2-terminal, 4-terminal, innovative applications, interconnection layer, optical losses, perovskite bandgap engineering, perovskite/Si tandem solar cells

1 INTRODUCTION: THE MARRIAGE OF SI AND PEROVSKITE PHOTOVOLTAIC TECHNOLOGY

Solar energy is the most abundant and cleanest energy resource on the earth planet and the solar cell which can convert solar radiation into electrical power directly based on the photovoltaic effect is considered as the most appropriate way to use solar energy. The first solar cell based on a silicon (Si) p-n junction with 6% power conversion efficiency (PCE) was invented at the Bell Labs in 1954.1 Since then, Si-based solar cells have undergone decades of
development including device structure design, Si defects passivation, optical design, and wafer surface treatment,\textsuperscript{2–7} which boosts the device efficiency gradually to a world-record value of 23.3% for multicrystalline Si cell, 26.1% for single crystal Si cell, and 26.7% for Si-based heterostructure solar cell as shown in Figure 1.\textsuperscript{8} Further improvement in device PCE for Si-based single-junction solar cells becomes a bottleneck in this field since the device efficiency is approaching the Shockley-Queisser (S-Q) limit of 29% for a single-junction cell.\textsuperscript{9}

Most recently, an emerging photovoltaic (PV) technology based on organic–inorganic hybrid metallic halide perovskite materials (such as CH$_3$NH$_3$PbI$_3$) has shown great potential to realize higher PCE than that of Si single-junction cells.\textsuperscript{10} Such emerging perovskite solar cell (PVSC) is considered to be a superstar in PV field because, as shown in Figure 1, the efficiency growth rate of PVSCs is much faster than that of Si-based PV technology. On the one hand, the metallic halide perovskite materials have superb optoelectronic properties such as high absorption coefficient, long carrier diffusion length, high carrier lifetime, and small exciton binding energy.\textsuperscript{11–13} On the other hand, the perovskite PV technology attracts tremendous attention all over the world since the first report of perovskite-based dye-sensitized solar cell with device efficiency of 3.8% in 2009.\textsuperscript{14} Since then, significant efforts have been made in device structure optimization,\textsuperscript{15,16} perovskite composition engineering,\textsuperscript{17} perovskite crystal growth controlling,\textsuperscript{18,19} perovskite bulk and surface defects passivation,\textsuperscript{20} charge-transporting layer optimization,\textsuperscript{21,22} and device interface engineering\textsuperscript{23} to increase the device efficiency rapidly to a certified value of 25.5% within a decade of development.\textsuperscript{8} To have a clear understanding about the development of perovskite-based single-junction cells, we recommend some review articles on the topic of advances of both perovskite materials and PV devices to the readers.\textsuperscript{16,24–26} Although the PVSCs have experienced a rapid development in device efficiency these years, as shown in Figure 1, the efficiency increase rate becomes slower and it tends to reach a saturated value, indicating that the PCE of PVSC is also approaching its S-Q limit. According to the theoretical calculation, the efficiency limit of a perovskite-based single-junction solar cell is over 30% in an ideal condition without the angular restriction.\textsuperscript{27} Therefore, similar to Si-based single-junction solar cells, further pushing the device efficiency of perovskite-based single-junction cells becomes more and more difficult and it will never exceed the S-Q efficiency limit.

Despite the fast development of perovskite PV technology, the practical application of PVSCs is significantly limited by their small device area and poor device stability.\textsuperscript{28} Currently, the PV market is still dominated by the conventional Si technology (95%) and the thin film PV technology (5%). To further make the Si-based technology a more efficient PV converter, it has been proposed to combine a Si subcell with a relatively higher bandgap semiconducting material to form a multijunction solar cell, which is able to react with a wider solar spectrum and to enhance the overall device efficiency beyond the single-junction S-Q limit. For example, efficiencies over 33% have been achieved by combining Si bottom cell with III–V top cell in a tandem configuration.\textsuperscript{29}

Motivated by the tandem configuration, a few years ago, research scientists started to fabricate perovskite/Si tandem solar cells. In 2014, the first reported proof-of-concept perovskite/Si four-terminal (4T) tandem solar cell exhibited an overall PCE of 13.4% (6.2% of top cell and 7.2% of bottom cell) and the authors estimated that 31.6% PCE can be achieved with both optical and electrical optimization.\textsuperscript{30} In 2015, the first perovskite/Si two-terminal (2T) tandem solar cell was reported with an overall efficiency of 14.3%, and the simulation results also indicated that 32% PCE can be attainable with optimization of the transparent top electrode and interconnection layers between the top and bottom cell.\textsuperscript{31} The certified PCE of perovskite/Si tandem solar cells, as shown in Figure 1, increases dramatically from 23.5% in 2017 to 29.5% in 2020,\textsuperscript{8} exceeding the S-Q limit of Si single-junction cell, but it is still far from saturating. According to the reported optical and electrical analysis, the efficiency limit of perovskite/Si tandem cell is over 40%,\textsuperscript{32} indicating that there is still a room for boosting the device efficiency of tandem solar cells. Therefore, here, in this review paper, we will focus on the tandem solar cell concept developed with the combination of Si and perovskite-based PV technologies, including (1) a brief introduction of the working principle and development of 2T and 4T perovskite/Si tandem solar cells;
FIGURE 2  (A) Spectra response of perovskite top cell and Si bottom cell in a tandem configuration. (B) Illustration for the device structure of a 2T and 4T perovskite/Si tandem solar cell. (C) The equivalent circuit of a 2T and 4T perovskite/Si tandem solar cell under illumination. $R_s$ is the series resistance, $R_{sh}$ is the shunt resistance, $I$ is the output current, and $V$ is output voltage.

(2) identification of critical factors affecting device performance of the tandem cells such as interconnection layers, device architecture, perovskite film engineering, and optical management; (3) comments on the challenges and perspectives of perovskite/Si tandem solar cells. This review article provides not only a comprehensive understanding of the perovskite/Si tandems, but also several potential applications to bring such tandem PV technology into market in a near future.

2 WORKING PRINCIPLE OF PEROVSKITE/SI TANDEM SOLAR CELLS

Different from the single-junction solar cell whose efficiency is limited by its intrinsic optical bandgap, the tandem device combining semiconducting materials with different bandgaps are able to react with a wider range of solar spectrum, generating power greater than the S-Q limit. For example, as shown in Figure 2A, in a tandem configuration, the top solar cell with relatively wide bandgap absorbs photons with high energy (such as ultraviolet and visible light), while the bottom solar cell with relatively narrow bandgap harvests photons with low energy such as near infrared part of the solar spectrum. In this way, more photons can be absorbed and converted into electricity. In general, as shown in Figure 2B, the architecture of a tandem solar cell could either be a monolithically integrated device where the wide bandgap top cell is directly fabricated on top of the narrow bandgap bottom cell to form a series connection between the two subcells (2T tandem cell), or a mechanical stack where the two subcells are only coupled optically but electrically separated (4T tandem cell). Figure 2C shows the equivalent circuit of perovskite/Si tandem solar cells. As the subcells in a 2T tandem device are connected in series, current matching of the top and bottom cell is always required to ensure the overall device current is not limited by the subcell with lower current. On the other hand, the 4T tandem solar cells are not subject to current matching since the top and bottom cells are electrically separated. Therefore, either maximizing the top cell or improving the efficiency of bottom cell can boost the overall device performance of a 4T tandem.

Organic–inorganic hybrid perovskite materials are considered to be promising semiconductors for tandem devices because the bandgap of perovskite can be tuned within the range of 1.3 to over 2 eV via composition engineering.\textsuperscript{33,34} Previous calculation indicates that top cell with bandgap between 1.6 and 1.8 eV is perfect for crystalline Si (1.1 eV) bottom cell to construct a tandem...
### TABLE 1 Comparison of perovskite/Si 2T and 4T tandem solar cells

|                  | Optical coupling | Electrical coupling | Fabrication                                                                 | Advantages                                                                                                                                  | Disadvantages                                                                                           |
|------------------|------------------|---------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|
| **2T**           | Yes              | Yes, series         | Perovskite top cell is fabricated directly on the top of Si bottom cell.    | 1. It converts larger share of the solar irradiance to electricity;                                                                        | 1. Current matching between the subcells is required;                                                   |
|                  |                  | connection          |                                                                              | 2. It requires less processing step and less contact layers;                                                                             | 2. Solution-processed deposition may not be applicable to fabricate perovskite top cell on a textured Si bottom cell; |
|                  |                  |                     |                                                                              | 3. It provides larger output voltage than each of the subcell;                                                                         | 3. Lifetime of the tandem cell will be determined by the perovskite top cell since perovskite is not as stable as Si cell. |
|                  |                  |                     |                                                                              | 4. Less parasitic absorption from glass substrate.                                                                                       |                                                                                                         |
| **4T**           | Yes              | No                  | Perovskite top cell and Si bottom cell are fabricated separately.            | 1. It converts larger share of the solar irradiance to electricity;                                                                        | 1. More processing steps since the subcells are fabricated separately;                                   |
|                  |                  |                     |                                                                              | 2. Current matching is not required and the subcells can be optimized independently;                                                   | 2. Conductive glass substrate of perovskite top cell will cause optical losses due to its parasitic absorption. |
|                  |                  |                     |                                                                              | 3. Easy to maintain and fix by replacing a new subcell if it is not working;                                                           |                                                                                                         |
|                  |                  |                     |                                                                              | 4. The overall device efficiency is not sensitive to solar spectrum.                                                                   |                                                                                                         |

Device. Furthermore, the perovskite materials exhibit ultralow subbandgap absorption, which indicates that perovskite top cell is highly transparent at photon energies below its bandgap and reduces the optical loss for the bottom cell. Finally, since the perovskite layer can be made via solution-process or vacuum-based thermal evaporation, it is easy to fabricate perovskite top cell on the surface of Si bottom cell directly to form a 2T tandem device. Table 1 has summarized the comparison of 2T and 4T perovskite/Si tandem device including their advantages and disadvantages. On the one hand, for a 2T tandem, since the perovskite top cell is fabricated directly on top of Si cell, it requires less processing steps. However, more stringent requirements should be considered in terms of device fabrication as one subcell may impact the other one. In addition, the 2T cell requires strict current matching because the two subcells are electrically connected in series. Therefore, they are sensitive to the local climate conditions especially the irradiance spectra, given that the two subcells will be affected differently. On the other hand, for a 4T tandem, the perovskite and Si subcells can be fabricated independently, hence it is more flexible in terms of device fabrication. The subcells in a 4T device are not affected by each other because they are working independently. Therefore, 4T tandem devices are less sensitive to local climate conditions. Based on the above discussion, it is still too early to conclude which tandem configuration is more promising for future commercialization.

3 | OVERVIEW OF THE DEVELOPMENT OF PEROVSKITE/SI TANDEM SOLAR CELLS

Although the development of perovskite/Si tandem solar cells is less than a decade old, more and more efforts have been made regarding this research topic. In this section, we first establish the timeline for the progress made in perovskite/Si tandem solar cells. Second, we give a detailed discussion of the important works and identify key challenges in both 2T and 4T tandem devices, respectively.

As shown in Figure 3, the perovskite/Si 2T tandem structure had been proposed by Löper et al. as early as in 2014. The authors applied an optical model to predict the limiting efficiency of a perovskite/Si 2T tandem device which is 35.67% under the ideal condition with no parasitic absorption and 100% external quantum efficiency (EQE). Subsequently, the same group experimentally demonstrated a 4T...
tandem perovskite/Si tandem device with an efficiency of 13.4%. The authors predicted that the 4T tandem device would achieve over 30% PCE by reducing the optical loss with higher transparent contact.30 Later, another report from Bailie et al. introduced an Ag nanowire layer as a transparent electrode for perovskite top cell. The corresponding 4T perovskite/Si tandem device achieved a PCE as high as 17.0%.39 In early 2015, the first proof-of-concept 2T perovskite/Si tandem cell was fabricated and showed a stable efficiency of 13.7%. A thin Si-based interband tunnel junction was used as the interconnection layer between the top and bottom cell. The authors found that the perovskite top cell limited the 2T device efficiency and other transparent hole transporting layer was suggested to replace the spiro-OMeTAD layer to achieve higher device efficiency.31 Then in early 2016, a 1.74 eV wide bandgap perovskite was optimized by composition engineering. A 4T tandem device combined with a 1.74 eV perovskite top cell and Si bottom cell achieved an overall device efficiency of 25.2%, showing the great potential of tandem structure for pursuing higher efficiency.40 Later, an ultrathin Cu/Au metal bilayer was used as the transparent electrode for perovskite top cell, and the corresponding 4T perovskite/Si tandem cell exhibited an overall efficiency of 23.0%.41 Before 2017, more efforts were made to develop 4T perovskite/Si tandem cell because it is easy to fabricate by putting a semitransparent perovskite cell on the top of Si bottom cell. After 2017, more reports are focused on the 2T tandem structure by optimizing the interconnection layers, perovskite composition, and top transparent electrodes. For example, Fan et al. fabricated perovskite composition with various bandgaps for 2T tandem cells. It is found that 1.69 eV perovskite top cell matched well with Si bottom cell, achieving over 20% PCE for the 2T tandem cell.42 In the following years, the perovskite/Si tandem cells have experienced tremendous investigation through perovskite optimization, interface engineering, bottom cell optimization, tunnel junction or recombination later development, and also transparent top electrode development.43–46 2020 was a fruitful year when both the 2T and 4T tandem devices have made a big step for efficiency improvement. In the early of 2020, Helmholtz Zentrum Berlin (HZB) achieved a 2T perovskite/Si tandem solar cell with a certified PCE of 29.15%.47 However, Oxford PV has broken the world-record at the end of 2020 with a new certified efficiency of 29.5%, but details regarding the device structure and photovoltaic parameters have not been reported yet.8 For the 4T tandem device, with perovskite bandgap optimization and transparent top electrode development, a certified world-record efficiency of 28.2% has been achieved.48 It is expected that the device efficiency of perovskite/Si tandem solar cell will exceed 30% in a near future. It should be noted that the timeline in Figure 3 only includes some of the reports regarding the perovskite/Si tandem devices that are either the pioneering works, or the works with world-record efficiency. More reports on such tandem topic are summarized in Table 2.

4 | TOWARDS EFFICIENT PEROVSKITE/SI TANDEM SOLAR CELLS

4.1 | Interconnection layer for 2T tandem cells

The interconnection layer is a critical component of a 2T tandem device since it serves as both optical and electrical connection between the top and bottom subcells. Generally, a p-type layer in a solar cell is used to transport and extract positive holes, while the n-type layer is for
TABLE 2 Summary of the development of 2T perovskite/Si tandem solar cells

| Year | Tandem structure | Perovskite composition | Perovskite bandgap (eV) | Interconnection layer | Top electrode | Tandem PCE (%) | Reference |
|------|------------------|------------------------|-------------------------|-----------------------|--------------|----------------|-----------|
| 2015 | 2T | MAPbI_3 | 1.58 | n++ Si/p++ Si | Ag nanowire | 13.7 | 31 |
| 2015 | 2T | FAMAPbI_{1-x}Br_x | 1.62 | Sputter ITO | Sputter ITO | 18.0 | 49 |
| 2016 | 2T | MAPbI_3 | 1.58 | Sputter IZO | Sputter ITO | 21.2 | 52 |
| 2017 | 2T | FAMACsPbI_{1-x}Br_x | 1.69 | n++ Si/p++ Si | Sputter ITO | 20.57 | 42 |
| 2018 | 2T | FAMACsPbI_{1-x}Br_x | 1.69 | Sputter ITO | Sputter ITO | 22.22 | 50 |
| 2018 | 2T | CsRbFAMAPbI_{1-x}Br_x | 1.62 | Interlayer-free | IZO | 24.5 | 45 |
| 2019 | 2T | CsFAMAPbI_{1-x}Br_x | 1.63 | Sputter ITO | Sputter ITO | 25.2 | 53 |
| 2019 | 2T | CsFAMAPbI_{1-x}Br_x | 1.64 | Sputter ITO | Sputter IZO | 25.4 | 51 |
| 2020 | 2T | CsFAMAPbI_{1-x}Br_x | 1.63 | Sputter ITO | Sputter ITO | 25 | 54 |
| 2020 | 2T | CsFAMAPbI_{1-x}Br_x | 1.68 | Sputter ITO | Sputter ITO | 26.7 | 55 |
| 2020 | 2T | CsFAMAPbI_{1-x}Br_x | 1.68 | Sputter ITO | Sputter IZO | 25.7 | 56 |
| 2020 | 2T | CsFAMAPbI_{1-x}Br_x | 1.68 | Sputter ITO | Sputter ITO | 29.15 | 47 |
| 2014 | 4T | MAPbI_3 | 1.58 | NA | Ag nanowire | 13.4 | 30 |
| 2014 | 4T | MAPbI_3 | 1.58 | NA | Sputter ITO | 17.0 | 39 |
| 2016 | 4T | FACsPbI_{1-x}Br_x | 1.74 | NA | Sputter ITO | 25.2 | 40 |
| 2016 | 4T | MAPbI_3 | 1.58 | NA | Cu (1 nm)/Au (7 nm) | 23.0 | 41 |
| 2017 | 4T | RbFAMAPbI_{1-x}Br_x | 1.73 | NA | Sputter ITO | 26.6 | 44 |
| 2018 | 4T | CsFAPI_{1-x}Br_x | 1.77 | NA | Sputter ITO | 27.1 | 57 |
| 2019 | 4T | MAPbI_3 | 1.58 | NA | Sputter ITO | 25.5 | 58 |
| 2020 | 4T | CsFAPbI_{1-x}Br_x | 1.65 | NA | Sputter ITO | 25.7 | 59 |
| 2020 | 4T | CsFAMAPbI_{1-x}Br_x | 1.68 | NA | Sputter IZO | 28.2 | 48 |
| 2020 | 4T | FACsPbI_3 | 1.46 | NA | Cr (1 nm)/Au (7 nm) | 28.3 | 60 |

electron transporting and extraction. As shown in Figure 4A, in a 2T tandem configuration, it requires series connection between the two subcells. If the n-type layer of one subcell is connected directly to the p-type layer of the other subcell, a n-p junction will be formed between the two subcells, which will block the current flow between the two cells. To solve such connection issue, either a recombination layer or a tunnel junction layer should be inserted as the interconnection layer between the two subcells. As shown in Figure 4B, the first strategy to connect the two subcells in series is using a conductive layer which can transport both electrons and holes. Therefore, such conductive layer will provide recombination sites for electrons from one subcell and holes from another subcell. This strategy has been widely used to develop organic-based tandem solar cells with an ultrathin metal film as a conductive layer.61,62 Another effective strategy to connect the subcells in series is fabricating highly doped n++ Si/p++ Si tunnel junction as an interconnection layer as shown in Figure 4C. Generally, this strategy has been widely applied in Si-based tandem solar cell.63 The tunnel junction is made by highly doping the Si surface and it should be a thin layer so that the charge carrier can transport and recombine within this layer.

For a 2T perovskite/Si tandem solar cell, the interconnection layer requires not only good electrical properties for charge carrier transporting, but also decent transparency for infrared light absorption of Si bottom cell. Therefore, the thickness of interconnection layer is critical for the device performance. Werner et al. employed sputtered zinc-doped tin oxide (ZTO) as the interconnection layer between a mesoscopic perovskite top cell and a homojunction silicon bottom cell. They found ZTO thickness strongly influenced the current density–voltage (J–V) curve and EQE spectrum of the 2T tandem device. Since the interconnection layer is served for carrier recombination between the subcells, high vertical conductivity of the thin layer is not strictly required. The influence of ZTO thickness was mainly caused by the interference effect due to different refractive indices of charge-transporting layer and ZTO layer.65 Therefore, in another work, with well-matched refractive indices, the thickness of interconnection layer did not show an obvious effect on the tandem performance.52

The indium tin oxide (ITO) which is widely used as a transparent electrode in Si-based PV technology draws attention from researchers. For example, as shown in Figure 5A, Albrecht et al. employed a sputtered ITO layer as
the interconnection layer between the subcells.\textsuperscript{49} The Si bottom cell was made from a n-type Si wafer base, followed by plasma enhanced chemical vapor deposition for both intrinsic and doped a-Si:H layers. Then a thin ITO layer was sputtered on the top of p\textsuperscript{+} a-Si:H. For the perovskite cell fabrication, the n-type SnO\textsubscript{2} layer was deposited by atomic layer deposited (ALD) technique, followed by a perovskite layer coating, p-type spiro-OMeTAD layer deposition, MoO\textsubscript{3} evaporation, and top transparent ITO electrode deposition. The cross-section scanning electron microscope (SEM) image indicates that a flat and fully covered perovskite films can be achievable on a polished Si bottom cell via spin coating method. During device operation, the photogenerated holes in Si bottom cell will transport through the p\textsuperscript{+} a-Si:H to the ITO layer, while the photogenerated electrons in perovskite top cell will pass through the SnO\textsubscript{2} layer to reach ITO layer. Then the electrons and holes will recombine within the ITO layer, forming the current flow between the top cell and bottom cell. This is only an example to show the function of the ITO interconnection layer. As summarized in Table 2, there are also a lot of works that employed ITO as the recombination layer in 2T device configuration. Similarly, other transparent conductive metal oxides are also suitable to be the recombination layer such as aluminum-doped zinc oxide (AZO) or zinc doped indium oxide (IZO).\textsuperscript{56–68} Tunnel junction is another choice for the interconnection layer in 2T tandem devices. As shown in Figure 5B, Mailoa et al. fabricated the 2T tandem device starting from an n-type Si base. A p\textsuperscript{++} Si layer was then formed on the surface of n-type Si wafer by diffusion and a heavily doped n\textsuperscript{++} Si was deposited using plasma-enhanced chemical vapor deposition to form the n\textsuperscript{++}/p\textsuperscript{++} Si tunnel junction. The dopant concentration on the n\textsuperscript{++}/p\textsuperscript{++} Si interface was measured around 10\textsuperscript{19–20} cm\textsuperscript{−3}, indicating its high conductivity for carrier transportation and recombination as an interconnection layer. The perovskite top cell was directly fabricated on the top of n\textsuperscript{++} Si layer with a structure of ALD TiO\textsubscript{2}/mesoporous TiO\textsubscript{2}/perovskite/spiro-OMeTAD/Ag nanowire/LiF, where the Ag nanowire is the top transparent electrode and LiF is the antireflection layer for light trapping.\textsuperscript{31} As shown in Figure 5C, during device operation, the photogenerated holes from the n-type Si base will transport through the p\textsuperscript{+} emitter and photogenerated electrons from the perovskite layer will pass through the TiO\textsubscript{2} electron transport layer. The tunnel junction formed by the highly doped Si layer is narrow enough for charge carriers tunneling and recombination, ensuring current flow from top cell to bottom cell. Alternatively, Shen et al. have developed an interlayer-free 2T perovskite/Si tandem solar cell by ALD depositing TiO\textsubscript{2} directly on the top of p\textsuperscript{+} Si emitter without
forming an n++ / p++ Si interface as shown in Figure 5D. It is found that the ohmic contact was formed between the ALD TiO₂ layer and p-type Si, which can also facilitate the charge carrier recombination as the tunnel junction does. This interlayer-free concept was also realized by using ALD SnO₂ deposited on the surface of p⁺ Si emitter for 2T tandem devices. On the one hand, the SnO₂ layer acts as electron transporting layer for perovskite top cell. On the other hand, the SnO₂ layer forms recombination contact with p⁺ Si. In this way, the optical loss induced by the recombination layer and tunnel junction layer will be reduced. Furthermore, this interlayer-free concept was also employed in large-area (16 cm²) 2T perovskite/Si tandem cell with efficiency over 20%.

4.2 Device architecture of perovskite top cells

There are two main device structures for perovskite single junction solar cells named regular n–i–p structure and inverted p–i–n structure. For a regular n–i–p structure...
PVSC, the n-type electron transporting layer is deposited on the conductive glass substrate followed by a perovskite layer and a p-type hole transporting layer.\textsuperscript{71–74} On the contrary, the inverted p–i–n structure PVSC is fabricated from depositing p-type hole transporting layer on the conductive glass substrate followed by a perovskite layer and an n-type electron transporting layer on the top.\textsuperscript{51,75–78} For a 2T tandem device, the perovskite top cell is fabricated directly on the top of a Si bottom cell. As shown in Figure 6A, a perovskite top cell with regular n–i–p structure of SnO\textsubscript{2}/CH\textsubscript{3}NH\textsubscript{3}PbI\textsubscript{3}/Spiro-OMeTAD/ITO was used to form 2T perovskite/Si tandem cell. With such device structure, Zheng et al. achieved a PCE of 21.0% under reverse bias scanning with a $V_{oc}$ of 1.68 V, a $J_{sc}$ of 16.1 mA cm$^{-2}$ and a FF of 78%.\textsuperscript{69} It should be noted that the p-type spiro-OMeTAD hole transporting layer used in this structure has a thickness as high as 200 nm, which caused significant optical loss for both the top cell and bottom cell. It is expected to achieve higher device efficiency with this device structure by replacing the spiro-OMeTAD hole transporting layer which has strong absorption for the visible light.\textsuperscript{79}

Another alternative structure for 2T tandem device is using inverted p–i–n structure perovskite cell as shown in Figure 6B. Jošt et al. deposited a p-type PTAA layer directly on the surface of the interconnection layer. On the top of perovskite layer, an n-type top layer of fullerene C\textsubscript{60} was deposited by thermally evaporation. A thin SnO\textsubscript{2} buffer layer was then deposited via ALD technique to protect the soft C\textsubscript{60} layer during the sputtering process for IZO top electrode.\textsuperscript{80} From the SEM image, it can be seen that the top C\textsubscript{60}/SnO\textsubscript{2} layer in p-i-n structure is much thinner than spiro-OMeTAD in n–i–p structure, which is better for device light absorption. However, it is still hard to conclude which structure of perovskite top cell is better for 2T tandem device since both structures have been widely studied and decent efficiency have been achieved.\textsuperscript{46,50,81–83}

Different from the 2T configuration, a 4T tandem device only requires optical coupling between the subcells. Therefore, the perovskite cell and Si cell are fabricated separately and then put together to form a 4T tandem device. As shown in Figure 7A, Chen et al. fabricated a semitransparent perovskite top cell with regular n–i–p structure of Zr-doped In\textsubscript{2}O\textsubscript{3} (IZO) glass/SnO\textsubscript{2}/perovskite/spiro-OMeTAD/MoO\textsubscript{3}/IZO.\textsuperscript{48} It is found that the sputtered IZO coated glass substrate is more transparent than the commercial ITO glass substrate, which increases the transparency of the perovskite top cell and thus boosts the device performance of the bottom Si cell under the perovskite cell filter. Finally, the authors achieved a semitransparent perovskite top cell with a PCE of 19%. Thanks to the better transparency of IZO, the filtered Si bottom cell still exhibits a high PCE of 9.2%, leading to a champion efficiency of 28.2% for 4T perovskite/Si tandem device. Such IZO layer is further evidenced by Aydin et al. to be a high-performance top electrode for perovskite cell. Figure 7B shows the device structure of an inverted p–i–n structure.
perovskite cell of IZrO glass/NiO$_x$/perovskite/PC$_{61}$BM/ZnO nanoparticle/BCP/IZrO. The authors successfully improved device performance of the semitransparent perovskite top cell by optimizing the sputtering parameters for IZrO electrode. Compared to the commercial ITO electrodes, the device efficiency of the 4T tandem device with IZrO-based perovskite has increased from 23.3 to 26.2%. These works indicate that developing conductive transparent oxides (TCOs) with high conductivity but low parasitic absorption is an effective pathway to achieve highly efficient perovskite/Si tandem devices.

### 4.3 Optimization of perovskite films for tandem devices

In a tandem configuration, the wide-bandgap top cell and narrow-bandgap bottom cell are combined together to make the most of sunlight spectrum. Perovskite materials are considered to be promising for tandem devices due to their excellent optoelectronic properties and tunable bandgap. It has been demonstrated that halide and metal substitution can effectively change the bandgap of perovskite materials. Previous computational works indicate that a perovskite top cell with a bandgap in the range of 1.6–2 eV is suitable for forming tandem solar cells with Si bottom cell. Figure 8A shows the photograph of FA and FACs-based perovskite films with varied amount of Br component. The photograph show that the perovskite films present “yellowing” when increasing the Br concentration with the $x$ value higher than 0.3 for FAPb[I$_{(1-x)}$Br$_x$]$_3$ and 0.7 for FA$_{0.83}$Cs$_{0.17}$Pb[I$_{(1-x)}$Br$_x$]$_3$ films. The ultraviolet-visible absorption spectra also indicate that both kinds of perovskite films become more transparent with increasing the concentration of Br. After optimization, it is found that perovskite single junction solar cell with 1.74 eV bandgap is able to achieve a $V_{oc}$ of 1.2 V and PCE of over 17%. Combining with a Si bottom cell with 19% efficiency, the 4T device achieves an overall PCE of over 25%. As summarized in Table 2, perovskite films with bandgap in the range of 1.58–1.74 eV have been used for tandem solar cells. Furthermore, it can be seen that tandem cells fabricated by perovskite films with bandgap ranging from 1.6 to 1.7 eV successfully achieve overall efficiency over 25%.

Defects in solution-processed perovskite films are also another reason for the poor device performance of perovskite cell. For a crystalline material, the defects are usually localized at the film surface and grain boundaries. Therefore, various defects passivation and additive techniques have been employed to reduce the defects density in perovskite films and enhance the device performance. In a tandem solar cell, Chen et al. have shown that MACl and MAH$_2$PO$_2$ can promote the growth of perovskite grains. Figure 8B shows the grain morphology of the wide-bandgap (1.64–1.70 eV) perovskite films. It is found that the perovskite film without additives exhibits grains smaller than 200 nm, while both MACl and MAH$_2$PO$_2$ additives can boost the growth of perovskite film. In particular, the perovskite grain size can reach micrometer with the combination of MACl and MAH$_2$PO$_2$. The defects density of perovskite film can be effectively...
Figure 8 (A) Photographs, ultraviolet-visible absorbance spectra, and X-ray diffraction pattern of FAPb[I(1-x)Br_x]_3 and FA_{0.83}Cs_{0.17}Pb[I(1-x)Br_x]_3 perovskite films with different Br composition from x = 0–1. Reproduced with permission. Copyright 2016, American Association for the Advancement of Science. (B) Scanning electron microscope (SEM) images to show the grain size of the perovskite films formed from precursor solutions without and with additives. Reproduced with permission. Copyright 2019, Elsevier. (C) Top-view and cross-section SEM images to show the grain size and thickness of perovskite films.
reduced by enlarged grains since the grain boundaries have large amount of defects. As a result, the photocurrent of perovskite top cell is increased to match the current generated by Si bottom cell in the 2T perovskite/Si tandem solar cell. Finally, the tandem cell achieves a high $V_{oc}$ of 1.80 V and thus a PCE of 25.4%.95 On the other hand, the defects at device interfaces are also harmful to device performance. To reduce the effect of interfacial defects, Al-Ashour et al. designed a self-assembled monolayer (SAM) of Me-4PACz ([4-(3,6-dimethyl-9H-carbazol-9-yl)butyl]phosphonic acid) as a hole transporting layer. Such SAM can not only facilitate the hole extraction from perovskite layer, but also passivate the interfacial defects yielding an FF of up to 80% and a certified PCE of 29.15% in a 2T perovskite/Si tandem solar cell.47

In addition, Chen et al. have found perovskite film with grain size comparable to the film thickness is critical for photovoltaic performance of a tandem device. As shown in Figure 8C, the authors fabricated various perovskite films with different thicknesses ranging from 400 to 700 nm. In order to achieve large grains comparable to its film thickness, the authors used Lewis base additives to facilitate the growth of perovskite grains and thus reduce the trap density in the film. As a result, the electron-diffusion length of the thicker perovskite films can enhance to 2.3 μm. The corresponding semitransparent perovskite cell provides a PCE of 19.0%. In addition, by combining such high-efficiency perovskite top cell with a Si bottom cell, a 4T tandem device yields a PCE of 28.2%.48 These works provide an important clue for future study on tandem solar cells. On the one hand, the perovskite layer requires a thick thickness for charge carrier generation. On the other hand, thick perovskite film will reduce charge extraction from perovskite layer. Therefore, perovskite film optimization such as additive engineering, defects passivation, and solvent annealing methods may be effective for enhancing the quality of a thick perovskite film for tandem applications.

4.4 Reduction of optical losses

Optical loss has been identified to be one of the main factors determining the device performance of a 2T perovskite/Si tandem cell. Jiang et al. have applied a transfer matrix method to conduct optical analysis including parasitic absorption and reflection losses in semitransparent PVSCs with different device structures. It is found that the largest optical loss caused by reflection (such as front surface reflection and interface reflection) is higher than 11% for a 4T tandem device, while the largest reflection loss can reach more than 17% for a perovskite/Si tandem device with 2T configuration.94 In order to improve the device performance of a perovskite/Si tandem cell, effective strategies should be implemented to reduce the optical loss.

Altazin et al. have conducted simulation to evaluate the potential of 2T perovskite/Si tandem solar cells with different structures. The authors took a perovskite top cell with n–i–p device structure of IZO/e-conductor/perovskite/spiro-OMeTAD/MoOx/ITO as an example for the simulation. As shown in Figure 9A, structure A is a planar device structure with perovskite top cell deposited on polished Si bottom cell, structure B is a planar cell with a textured antireflection foil on the surface of the top ITO electrode, and structure C is a 2T perovskite/Si tandem cell made from a rear-side textured Si with a flat interface to the perovskite layer. The simulation results indicate that a front side antireflection film can increase the photocurrent of both perovskite top cell and Si bottom cell, while the rear side texture can only slightly increase the photocurrent of Si bottom cell. Therefore, deposition of MgF or LiF as an antireflection layer on the top transparent electrode to reduce front reflection loss has been adopted in various reports.101–104

Reducing optical loss has been widely used in experimental works. For example, recently, Bett et al. fabricated a 2T perovskite/Si tandem solar cell with the structure as shown in Figure 9B. A n–i–p structured perovskite top cell was fabricated on a Si bottom cell with rear-side texture. The front side of Si bottom cell was polished for top cell fabrication. A planar ITO layer was first sputtered on the surface of the Si cell as the interconnection layer followed by electron transporting layer and perovskite layer. The perovskite film with a bandgap of 1.7 eV was fabricated via solution process by controlling the concentration of Cs and Br component. The ITO top electrode is sputtered directly on the spiro-OMeTAD hole transporting layer without any buffer layers. To reduce the front surface induced light reflection, a thick MgF$_2$ layer is deposited on the transparent ITO electrode by thermal evaporation. The antireflection layer will enhance the light absorption of perovskite top cell while the rear-side texture will enhance the light absorption of the Si bottom cell. The final 2T tandem device shows a PCE of 21.6% with a high $V_{oc}$ of 1.837 V, a $J_{sc}$ around 15.2 mA/cm$^2$ and a FF of 75.3%.81–83 In this work, the overall current of the tandem cell is still limited by the perovskite top cell even it has a front antireflection layer which can effectively enhance the current of top cell. Therefore, it indicates that a possible way to further improve the overall performance of the tandem cell should be reducing the bandgap of perovskite to absorb and covert more photons into electrons.

To further reduce optical loss in a 2T tandem solar cell, a double-side textured Si bottom cell can be applied to increase light trapping within the device. As shown in Figure 9C, Hou et al. successfully fabricated a perovskite top
cell on a textured Si surface and achieved a decent device performance.\textsuperscript{56} The cross-section SEM image of the textured crystalline Si bottom cell indicates that the pyramids on the Si surface have an average size of 2 \( \mu \text{m} \), which is difficult for film deposition via a solution process. Previously, deposition perovskite film on a textured Si surface was completed by a two-step method. A thick PbI\(_2\) layer was deposited on the textured Si firstly by thermal evaporation, and then perovskite film was formed through reaction between PbI\(_2\) and solution-processed organic cation precursors.\textsuperscript{102} However, in this work, Hou et al. firstly conducted sputtering technique to deposit ITO interconnection layer and NiO\(_x\) hole transporting layer. It should be noted that since both the ITO and NiO\(_x\) layers are less than 20 nm, only vacuum-based technique such as sputtering is able to form such thin layers to follow the textured Si surface. To fully cover the rough surface of Si bottom cell by a solution-processed perovskite layer, the authors used concentrated perovskite precursor (1.65–1.75 M) to form a micrometer-thick perovskite layer. As discussed in the above section, larger grains size in comparison to its film thickness is required to achieve high device performance. Therefore, the authors conducted a solvent treatment on the perovskite film for grain growth to 2–4 \( \mu \text{m} \). On the top electrode, an antireflection layer of 140 nm MgF\(_2\) was used to reduce the optical loss. Finally, the 2T tandem device achieved a certified 25.7\% PCE with a \( V_{oc} \) of 1.78 V, a \( J_{sc} \) of 19.3 mA/cm\(^2\) and an FF of 75\%.\textsuperscript{56} The
high $J_{sc}$ of the tandem solar cell can be ascribed to not only the reduced optical loss, but also the relatively low bandgap (1.68 eV) of perovskite used in this study. In addition, another recent work has demonstrated that solution-processed doctor blade coating is also applicable to prepare perovskite top cell on a textured Si bottom cell. With a thick textured polydimethylsiloxane (PDMS) layer attached on the top transparent electrode to enhance light scattering, the optical path length of near-infrared light was extended within the Si bottom cell and the surface reflection loss was reduced. The corresponding 2T perovskite/Si tandem cell yields a high $J_{sc}$ over 19 mA/cm² and an overall device efficiency of 26%.106

5 | SUMMARY AND PERSPECTIVE

Developing perovskite/Si tandem solar cells is one of the hottest research topics in current PV field since the device efficiencies of perovskite and Si single-junction cells are approaching their S-Q limits. With several years development, perovskite/Si tandems have achieved a certified efficiency of 29.5% for 2T tandem cells and 28.2% for 4T tandem cells, exceeding both perovskite and Si-based single-junction solar cells. To provide a guideline for making high-performance perovskite/Si tandem solar cells, in the above sections, we first provide a comprehensive understanding on the device structures and working principles of both 2T and 4T tandem configurations. Then, a brief introduction on the development of perovskite/Si tandem solar cells is presented. We discuss how the interconnection layers, device structure, perovskite active layer, and device optical losses can determine the overall device performance. Various possible approaches have been provided to optimize the device component and reduce optical losses for improving tandem device performance. Finally, in this section, we intend to provide an outlook on future development of perovskite/Si tandem cells by proposing some potential applications of tandem cells in water splitting and energy storage, which is believed to bring high-efficiency perovskite/Si tandem solar cells into the market in the near future.

5.1 | Challenges for future tandem development

Transparent electrode is one of the most important components in both 2T and 4T tandem devices. It requires both high transparency and conductivity. Various transparent conductive materials have been employed as electrode for perovskite solar cells including thin metal layer, Ag nanowire, carbon nanotube, graphene, and TCOs.107–110 Among these, TCOs such as ITO has been evidenced to be a promising top electrode for semitransparent perovskite cells by significantly improving the device lifetime.111 Generally, the ITO made by industrial sputtering technique are widely used in Si-based PV technology. To achieve a highly transparent and conductive ITO layer, a high-temperature treatment at over 300°C is always required during sputtering or after sputtering process.111,112 However, perovskite films cannot survive under such high temperature condition.113 Therefore, low-temperature or room-temperature processed ITO has been developed for tandem solar cells. For n–i–p structured perovskite cell, room-temperature sputtered ITO has been developed directly deposited on the top of spiro-OMeTAD layer without loss of the device performance.114 However, for p–i–n structured perovskite cells, a robust metal oxide layer such as ALD SnO2 layer is applied as a buffer to protect the underneath organic layers such as fullerene based electron transporting layer during sputtering process, but such a buffer layer will cause optical loss in the tandem solar cells.115 Furthermore, a bare ITO layer with over 500 nm thickness is normally required to achieve desirable conductivity for efficient perovskite cells.116,117 However, such thick ITO electrode causes significant optical loss for the whole device due to strong parasitic absorption origin from the free carriers within ITO layer. To solve this issue, as shown in Figure 10A, a thin ITO layer (around 100 nm) with metal grid fingers has been designed to achieve both good transparency and conductivity.118 Figure 10B shows the optical loss and sheet resistance of various transparent electrodes such as ITO, IZO, AZO, fluorine-doped tin oxide (FTO), and Ag nanowire.118 It can be seen that all of the bare transparent electrodes have sheet resistance in the range of 10 to 100 Ω/sq and optical loss in the range of 2–12%. Once the bare transparent electrode is fabricated with metal grid, the sheet resistance can be significantly reduced to lower than 1 Ω/sq and the optical loss can be controlled below 5%. It should be noted that, on the one hand, the metal grid can improve the conductivity of transparent electrode, but on the other hand, it will cause optical loss by shadow effect. Therefore, optimization on the metal grid pattern should be investigated to balance the tradeoff between transparency and conductivity.

Another challenge in the development of perovskite/Si tandem device is upscaling the device area. Currently, the high-efficiency perovskite/Si tandem devices are fabricated with small area.47,56,95 Although there are some research groups reported tandem devices with active area over 10 cm²,69,101–104 it is still lagging behind the commercial wafer-based Si PV technology. Compared to the metal electrode, TCO-based transparent electrodes have much lower lateral conductivity and its effect on the device photovoltaic performance becomes significant with increasing
the device area. As shown in Figure 10C, Sahli et al. have designed Ag grid fingers to fabricate a 2T perovskite/Si tandem cell with an area of 12.96 cm². Thanks to the reduced series resistance by the Ag grid finger, the FF of such large-area tandem device is around 65% under forward scanning.103 In order to further improve the FF of large-area tandem cell, as shown in Figure 10C, Zheng et al. employed a new metal grid design for large-area (16 cm²) perovskite/Si tandem cell. With the new metal grid, the device exhibited an impressive FF of 76% under forward scan and 78% under reverse scan.70 However, the metal grids such as Ag fingers have been demonstrated to be detrimental for the stability of perovskite cell. The Ag atoms can pass through the ITO electrode by diffusion and then react with perovskite layer, resulting in the fast degradation of perovskite cells.119 In addition to the above-mentioned challenges, other issues, such as improving stability of perovskite cells and reducing production cost of the tandem cells,120,121 should be resolved before bringing the perovskite/Si tandem PV technology into commercialization.

5.2  Innovative applications of perovskite/Si tandem cells

There are some other possible research directions for future development of perovskite/Si tandem solar cells. For example, to upscale the tandem devices, Bailie et al.
CHENG and DING

FIGURE 11  (A) Illustration of a large-area perovskite/Si tandem module. Reproduced with permission. Copyright 2015, The Royal Society of Chemistry. (B) Illustration of a 3T perovskite/Si tandem solar cell. Reproduced with permission. Copyright 2019, Elsevier. (C) Schematic diagram of the solar-driven water-splitting system with a 2T perovskite/Si tandem solar cell. Reproduced with permission. Copyright 2019, Elsevier.

designed a 2T perovskite/Si tandem module as shown in Figure 11A. To realize the current matching between the perovskite top module and Si bottom module, the authors adjusted the cell sizes of perovskite cell and Si cell. Although this module design shows its potential in future PV market, more works such as large-area perovskite cell fabrication on Si bottom cell, transparent electrode fabrication, cells connection should be optimized to realize this prototype.

As discussed in the above section, the efficiency limit of a 2T perovskite/Si tandem is higher than a 4T tandem cell which requires an additional conductive glass substrate with strong parasitic absorption. However, current matching between the top and bottom cells is required for 2T tandem device. The current research on perovskite/Si tandem cells is still focusing on either 2T or 4T configurations. Most recently, Park et al. developed a 3T perovskite/Si tandem solar cell as shown in Figure 11B. The ITO interlayer between perovskite top cell and Si bottom cell serves not only as recombination layer, but also a common contact electrode for both cells. Such device structure, on the one hand, overcomes the requirement for precise current matching as a 2T tandem cell does. On the other hand, it effectively reduces optical losses by removing the usage of conductive glass substrate as a 4T tandem cell does. Another advantage is this 3T tandem cell can also be switched as a 2T device by probing the top electrode of perovskite cell and rear electrode of Si cell which yields an overall device efficiency of 23.5%. Another possible research direction for perovskite/Si tandem cell will be exploring innovative applications by combining perovskite/Si tandem cells with electrochemistry cells such as solar water splitting and solar flow battery. As shown in Figure 11C, Gao et al. developed a solar water splitting system driven by a perovskite/Si tandem cell with 18.7% solar-to-hydrogen conversion efficiency. As comment by Kim et al., this work is definitely a milestone in deployment of photovoltaic-electrochemical (PV-EC) system for solar hydrogen production, but more efforts should be made to further optimize both the tandem cell and electrochemistry cell for boosting the overall device performance. In addition, upscaling the PV-EC system, enhancing its life-span, and techno-economic analysis should be done to bring such
Another approach to combine perovskite/Si tandem cell with electrochemistry cell is developing solar flow battery. Li et al. have fabricated a solar flow battery device by coupling a high-efficiency perovskite/Si tandem solar cell with a redox flow battery. The overall solar-to-output electricity efficiency is around 20.1%. Together with this proof-of-concept solar flow battery, a recent review article also call on the collaboration between PV and battery filed for developing a solar energy conversion and storage (SECS) system. It is believed that future large-scale deployment of such SECS system will not only improve the overall energy efficiency, but also provide a buffer to stabilize the future electrical grids. The fast development of perovskite/Si tandem devices and their various innovative applications will push the commercialization of such PV technology in a near future.

ACKNOWLEDGMENTS

L. Ding thanks the National Key Research and Development Program of China (2017YFA0206600) and the National Natural Science Foundation of China (51773045, 21772030, 51922032, 21961160720) for financial support.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Yuanhang Cheng https://orcid.org/0000-0002-3062-9593
Liming Ding https://orcid.org/0000-0001-6437-9150

REFERENCES

1. Chapin DM, Fuller CS, Pearson GL. A new silicon p-n junction photocell for converting solar radiation into electrical power. J Appl Phys. 1954;25:676.
2. Jiang Y, Shen H, Pu T, et al. High efficiency multi-crystalline silicon solar cell with inverted pyramid nanostructure. Sol Energy. 2017;142:91-96.
3. Allen TG, Bullock J, Jeangros Q, et al. A low resistance calcium/reduced titania passivated contact for high efficiency crystalline silicon solar cells. Adv Energy Mater. 2017;7:1602606.
4. Richter A, Benick J, Müller R, et al. Tunnel oxide passivating electron contacts as full-area rear emitter of high-efficiency p-type silicon solar cells. Prog Photovolt Res Appl. 2018;26:579-586.
5. Zhong S, Dreon J, Jeangros Q, et al. Mitigating plasmonic absorption losses at rear electrodes in high-efficiency silicon solar cells using dopant-free contact stacks. Adv Funct Mater. 2020;30:1907840.
6. Hu X-G, Hou P-X, Wu J-B, et al. High-efficiency and stable silicon heterojunction solar cells with lightly fluorinated single-wall carbon nanotube films. Nano Energy. 2020;69:104442.
7. Ji W, Allen T, Yang X, Zeng G, De Wolf S, Javey A. Polymeric electron-selective contact for crystalline silicon solar cells with an efficiency exceeding 19%. ACS Energy Lett. 2020;5:897-902.
8. NREL Transforming Energy. Best Research-Cell Efficiency Chart. Photovoltaic Research. https://www.nrel.gov/pv/cell-efficiency.html
9. Ehrler B, Alarcón-Lladó E, Tabernig SW, Veeken T, Garnett EC, Polman A. Photovoltaics reaching for the Shockley-Queisser limit. ACS Energy Lett. 2020;5:3029-3033.
10. Green MA, Ho-Baillie A, Snaith HJ. The emergence of perovskite solar cells. Nat Photonics. 2014;8:506-514.
11. Chouhan L, Ghimire S, Subrahmanyam C, Miyasaka T, Biju V. Synthesis, optoelectronic properties and applications of halide perovskites. Chem Soc Rev. 2020;49:2869-2885.
12. Cheng Y, Yang Q-D, Xiao J, et al. Decomposition of organometal halide perovskite films on zinc oxide nanoparticles. ACS Appl Mater Interfaces. 2015;7:19986-19993.
13. Ma Y, Cheng Y, Xu X, et al. Suppressing ion migration across perovskite grain boundaries by polymer additives. Adv Funct Mater. 2021;31:2006802.
14. Kojima A, Teshima K, Shirai Y, Miyasaka T. Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. J Am Chem Soc. 2009;131:6050-6051.
15. Xue D-J, Hou Y, Liu S-C, et al. Regulating strain in perovskite thin films through charge-transport layers. Nat Commun. 2020;11:1514.
16. Meng L, You J, Guo T-F, Yang Y. Recent advances in the inverted planar structure of perovskite solar cells. Acc Chem Res. 2016;49:155-165.
17. Albero J, Asiri AM, Garcia H. Influence of the composition of hybrid perovskites on their performance in solar cells. J Mater Chem A. 2016;4:4353-4364.
18. Liu C, Cheng Y-B, Ge Z. Understanding of perovskite crystal growth and film formation in scalable deposition processes. Chem Soc Rev. 2020;49:1653-1687.
19. Cheng Y, Li H-W, Zhang J, et al. Spectroscopic study on the impact of methylammonium iodide loading time on the electronic properties in perovskite thin films. J Mater Chem A. 2016;4:561-567.
20. Xin D, Tie S, Yuan R, Zheng X, Zhu J, Zhang W-H. Defect passivation in hybrid perovskite solar cells by tailoring the electron density distribution in passivation molecules. ACS Appl Mater Interfaces. 2019;11:44233-44240.
21. Said AA, Xie J, Zhang Q. Recent progress in organic electron transport materials in inverted perovskite solar cells. Small. 2019;15:1900854.
22. Gu P-Y, Wang N, Wu A, et al. An azaaacene derivative as promising electron-transport layer for inverted perovskite solar cells. Chem Asian J. 2016;11:2135-2138.
23. Yang Z, Babu BH, Wu S, et al. Review on practical interface engineering of perovskite solar cells: from efficiency to stability. Solar RRL. 2020;4:1900257.
24. Zuo C, Bolink HJ, Han H, Huang J, Cahen D, Ding L. Advances in perovskite solar cells. Adv Sci. 2016;3:1500324.
25. Cheng Y, Ding L. Pushing commercialization of perovskite solar cells by improving their intrinsic stability. Energ Environ Sci. 2021;14:3233-3255.
26. Bisquert J, Qi Y, Ma T, Yan Y. Advances and obstacles on perovskite solar cell research from material properties to photovoltaic function. ACS Energy Lett. 2017;2:520-523.
27. Pazos-Outón LM, Xiao TP, Yablonovitch E. Fundamental efficiency limit of lead iodide perovskite solar cells. J Phys Chem Lett. 2018;9:1703-1711.
28. Lee S-W, Bae S, Kim D, Lee H-S. Historical Analysis of high-efficiency, large-area solar cells: Toward upscaling of perovskite solar cells. Adv Mater. 2020;32:2002202.
29. Cariou R, Benick J, Feldmann F, et al. III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration. Nat Energy. 2018;3:326-333.
30. Löper P, Moon S-J, Martin De Nicolas S, et al. Organic-inorganic halide perovskite/crystalline silicon four-terminal tandem solar cells. Phys Chem Chem Phys. 2015;17:1619-1629.
31. Mailoa JP, Bailie CD, Johlin EC, et al. A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction. Appl Phys Lett. 2015;106:121105.
32. Futscher MH, Ehrler B. Efficiency limit of perovskite/Si tandem solar cells. ACS Energy Lett. 2016;1:863-868.
33. Zhou Y, Jia Y-H, Fang H-H, et al. Composition-Tuned wide bandgap perovskites: From grain engineering to stability and performance improvement. Adv Funct Mater. 2018;28:1803130.
34. Bush KA, Frohna K, Prasanna R, et al. Compositional engineering for efficient wide band gap perovskites with improved stability to photoinduced phase segregation. ACS Energy Lett. 2018;3:428-435.
35. Manzoor S, Häusele J, Bush KA, et al. Optical modeling of wide-bandgap perovskite and perovskite/silicon tandem solar cells using complex refractive indices for arbitrary-bandgap perovskite absorbers. Opt Express. 2018;26:27441-27460.
36. Futscher MH, Ehrler B. Modeling the performance limitations and prospects of perovskite/Si tandem solar cells under realistic operating conditions. ACS Energy Lett. 2017;2:2089-2095.
37. Cheng Y, Liu X, Guan Z, et al. Revealing the degradation and self-healing mechanisms in perovskite solar cells by sub-bandgap external quantum efficiency spectroscopy. Adv Mater. 2021;33:2006170.
38. Loper P, Niesen B, Moon S-J, et al. Organic-Inorganic halide perovskites: Perspectives for silicon-based tandem solar cells. IEEE J Photovolta. 2014;4:1545-1551.
39. Bailie CD, Christoforo MG, Mailoa JP, et al. Semi-transparent perovskite solar cells for tandems with silicon and CIGS. Energy Environ Sci. 2015;8:956-963.
40. Mcmeekin DP, Sadoughi G, Rehman W, et al. A mixed-cation lead mixed-halide perovskite absorber for tandem solar cells. Science. 2016;351:151-155.
41. Chen B, Bai Y, Yu Z, et al. Efficient semitransparent perovskite solar cells for 23.0%-Efficiency perovskite/silicon four-terminal tandem cells. Adv Energy Mater. 2016;6:1601128.
42. Fan R, Zhou N, Zhang L, et al. Toward full solution processed perovskite/Si monolithic tandem solar device with PCE exceeding 20%. Solar RRL. 2017;1:1700149.
43. Schulze PSC, Bett AJ, Bivour M, et al. 25.1% High-Efficiency monolithic perovskite silicon tandem solar cell with a high bandgap perovskite absorber. Solar RRL. 2020;4:2000152.
44. Duong T, Wu Y, Shen H, et al. Rubidium multication perovskite with optimized bandgap for perovskite-silicon tandem with over 26% Efficiency. Adv Energy Mater. 2017;7:1700228.
45. Shen H, Omelchenko ST, Jacobs DA, et al. In situ recombination junction between p-Si and TiO 2 enables high-efficiency monolithic perovskite/Si tandem cells. Sci Adv. 2018;4:eaau9711.
46. Kim CU, Yu JC, Jung ED, et al. Optimization of device design for low cost and high efficiency planar monolithic perovskite/silicon tandem solar cells. Nano Energy. 2019;60:213-221.
47. Al-Ashouri A, Köhnen E, Li B. Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction. Science. 2020;370:1300-1309.
48. Chen B, Baek S-W, Hou Y, et al. Enhanced optical path and electron diffusion length enable high-efficiency perovskite tandems. Nat Commun. 2020;11:1257.
49. Albrecht S, Saliba M, Correa Baena JP, et al. Monolithic perovskite/silicon-heterojunction tandem solar cells processed at low temperature. Energy Environ Sci. 2016;9:81-88.
50. Qiu Z, Xu Z, Li N, et al. Monolithic perovskite/Si tandem solar cells exceeding 22% efficiency via optimizing top cell absorber. Nano Energy. 2018;53:798-807.
51. Liu X, Cheng Y, Liu C, et al. 20.7% highly reproducible inverted planar perovskite solar cells with enhanced fill factor and eliminated hysteresis. Energ Environ Sci. 2019;12:1622-1633.
52. Werner J, Weng C-H, Walter A, et al. Efficient monolithic perovskite/silicon tandem solar cell with cell area >1 cm 2. J Phys Chem Lett. 2016;7:161-166.
53. Mazzarella L, Lin Y-H, Kirner S, et al. Infrared light management using a nanocrystalline silicon oxide interlayer in monolithic perovskite/silicon heterojunction tandem solar cells with efficiency above 25%. Adv Energy Mater. 2019;9:1803241.
54. Yoon W, Scheiman D, Ok Y-W, et al. Sputtered indium tin oxide as a recombination layer formed on the tunnel oxide/poly-Si passivating contact enabling the potential of efficient monolithic perovskite/Si tandem solar cells. Sol Energy Mater Sol Cells. 2020;210:110482.
55. Kim D, Jung HJ, Park IJ, et al. Efficient, stable silicon tandem cells enabled by anion-engineered wide-bandgap perovskites. Science. 2020;368:155-160.
56. Hou Y, Aydin E, De Bastiani M, et al. Efficient tandem solar cells with solution-processed perovskite on textured crystalline silicon. Science. 2020;367:1135-1140.
57. Jaysankar M, Raul BAL, Bastos J, et al. Minimizing voltage loss in wide-bandgap perovskite for tandem solar cells. ACS Energy Lett. 2019;4:259-264.
58. Dewi HA, Wang H, Li J, et al. Highly Efficient semitransparent perovskite solar cells for four-terminal perovskite-silicon tandems. ACS Appl Mater Interfaces. 2019;11:34178-34187.
59. Ghariibzadeh S, Hossain IM, Fasel P, et al. 2D/3D Heterostructure for semitransparent perovskite solar cells with engineered bandgap enables efficiencies exceeding 25% in four-terminal tandems with silicon and CIGS. Adv Funct Mater. 2020;30:1909919.
60. Yang D, Zhang X, Hou Y, et al. 28.3%-efficiency perovskite/silicon tandem solar cell by optimal transparent electrode for high efficient semitransparent top cell. Nano Energy. 2021;84:105934.
61. Ameri T, Dennler G, Lungenschmied C, Brabec CJ. Organic tandem solar cells: a review. Energy Environ Sci. 2009;2:347-363.
62. Ameri T, Li N, Brabec CJ. Highly efficient organic tandem solar cells: a follow up review. Energy Environ Sci. 2013;6:2390-2413.
63. Rubinelli FA, Rath JK, Schropp REI. Microcrystalline n-i-p tunnel junction in a-Si/h/a-Si:h tandem cells. J Appl Phys. 2001;89:4010.
64. Li C, Wang Y, Choy WCH. Efficient interconnection in perovskite tandem solar cells. *Small Methods*. 2020;4:2000093.

65. Werner J, Walter A, Rucavado E, et al. Zinc tin oxide as high-temperature stable recombination layer for mesoscopic perovskite/silicon monolithic tandem solar cells. *Appl Phys Lett*. 2016;109:233902.

66. Werner J, Dubuis G, Walter A, et al. Sputtered rear electrode with broadband transparency for perovskite solar cells. *Sol Energy Mater Sol Cells*. 2015;141:407-413.

67. Kranz L, Abate A, Feurer T, et al. High-Efficiency polycrystalline thin film tandem solar cells. *J Phys Chem Lett*. 2015;6:2676-2681.

68. Lal NN, Dkhissi Y, Li W, Hou Q, Cheng Y-B, Bach U. Perovskite tandem solar cells. *Adv Energy Mater*. 2017;7:1602761.

69. Zheng J, Lau CJF, Mehrvarz H, et al. Large area efficient interface layer free monolithic perovskite/homo-junction-silicon tandem solar cell with over 20% efficiency. *Energy Environ Sci*. 2018;11:2432-2443.

70. Zheng J, Mehrvarz H, Ma F-J, et al. 21.8% Efficient monolithic perovskite/homo-junction-silicon tandem solar cell on 16 cm 2. *ACS Energy Lett*. 2018;3:2299-2300.

71. Jiang Q, Zhang L, Wang H, et al. Enhanced electron extraction using SnO2 for high-efficiency planar-structure HC(NH2)2PbI3-based perovskite solar cells. *Nat Energy*. 2016; 2:16177.

72. Zhou W, Zhen J, Liu Q, et al. Successive surface engineering of TiO2 2 compact layers via dual modification of fullerene derivatives affording hysteresis-suppressed high-performance perovskite solar cells. *J Mater Chem A*. 2017;5:1724-1733.

73. Elsman AM, Selim MS, Luo L, et al. Efficient and stable planar n-i-p perovskite solar cells with negligible hysteresis through solution-processed Cu, O Nanocubes as a Low-Cost Hole-Transport Material. *ChemSusChem*. 2019;12:3808-3816.

74. Jiang Q, Chu Z, Wang P, et al. Planar-Structure perovskite solar cells with efficiency beyond 21%. *Adv Mater*. 2017;29:1703852.

75. Liu T, Chen K, Hu Q, Zhu R, Gong Q. Inverted perovskite solar cells: Progresses and perspectives. *Adv Energy Mater*. 2016;6:1600457.

76. Bai Y, Meng X, Yang S. Interface Engineering for highly efficient and stable planar p-i-n perovskite solar cells. *Adv Energy Mater*. 2018;8:1701883.

77. Liu D, Wang Q, Traverse CJ, et al. Impact of ultrathin c 60 on perovskite photovoltaic devices. *ACS Nano*. 2018;12:876-883.

78. Cheng Y, Xu X, Xie Y, et al. 18% High-Efficiency air-processed perovskite solar cells made in a humid atmosphere of 70% RH. *Solar RRL*. 2017;1:1700097.

79. Liu Y, Zhang H, Zhang Y, et al. Influence of hole transport layers on internal absorption, charge recombination and collection in HC(NH2)2PbI3 perovskite solar cells. *J Mater Chem A*. 2018;6:7922-7932.

80. Jošt M, Köhnen E, Morales-Vilches AB, et al. Textured interfaces in monolithic perovskite/silicon tandem solar cells: advanced light management for improved efficiency and energy yield. *Energy Environ Sci*. 2018;11:3511-3523.

81. Bett AJ, Schulze PSC, Winkler KM, et al. Two-terminal perovskite silicon tandem solar cells with a high-Bandgap perovskite absorber enabling voltages over 1.8 V. *Prog Photovolt: Res Appl*. 2020;28:99-110.

82. Zheng J, Mehrvarz H, Liao C, et al. Large-Area 23%-Efficient monolithic perovskite/homojunction-silicon tandem solar cell with enhanced uv stability using down-shifting material. *ACS Energy Lett*. 2019;4:2623-2631.

83. Zheng L, Wang J, Xuan Y, et al. A perovskite/silicon hybrid system with a solar-to-electric power conversion efficiency of 25.5%. *J Mater Chem A*. 2019;7:26479-26489.

84. Aydin E, De Bastiani M, Yang X, et al. Zr-Doped indium oxide (IZRO) transparent electrodes for perovskite-based tandem solar cells. *Adv Funct Mater*. 2019;29:1901741.

85. Wang L, Yuan GD, Duan RF, et al. Tunable bandgap in hybrid perovskite CH3 NH3 Pb(3-y x y ) single crystals and phototodetector applications. *AIP Adv*. 2016;6:045115.

86. Liu Y, Zhang L, Wang M, et al. Bandgap-tunable double-perovskite thin films by solution processing. *Mater Today*. 2019;28:25-30.

87. Sutton RJ, Eperon GE, Miranda L, et al. Bandgap-Tunable cesium lead halide perovskites with high thermal stability for efficient solar cells. *Adv Energy Mater*. 2016;6:1502458.

88. Chen Q, Luo J, He R, et al. Unveiling roles of tin fluoride additives in high-efficiency low-bandgap mixed tin-lead perovskite solar cells. *Adv Energy Mater*;11:2101045.

89. Kulkarni SA, Baikie T, Boix PP, Yantara N, Mathews N, Mhaisalkar SB. Band-gap tuning of lead halide perovskites using a sequential deposition process. *J Mater Chem A*. 2014;2:9221-9225.

90. Ou Q, Bao X, Zhang Y, et al. Band structure engineering in metal halide perovskite nanostructures for optoelectronic applications. *Nano Mater Sci*. 2019;1:268-287.

91. Yang Z, Rajagopal A, Jo SB, et al. Stabilized wide bandgap perovskite solar cells by tin substitution. *Nano Lett*. 2016;16:7739-7747.

92. Wan Z, Ren S, Lai H, et al. Suppression of nonradiative recombination by vacuum-assisted process for efficient lead-free tin perovskite solar cells. *Adv Mater Interfaces*. 2021;8:2100035.

93. Bowman AR, Lang F, Chiang Y-H, et al. Relaxed current matching requirements in highly luminescent perovskite tandem solar cells and their fundamental efficiency limits. *ACS Energy Lett*. 2021;6:612-620.

94. Jiang Y, Almansouri I, Huang S, et al. Optical analysis of perovskite/silicon tandem solar cells. *J Mater Chem C*. 2016;4:5679-5689.

95. Chen B, Yu Z, Liu K, et al. Grain engineering for perovskite/silicon monolithic tandem solar cells with efficiency of 25.4%. *Joule*. 2019;3:177-190.

96. Akin S, Arora N, Zakeeruddin SM, Grätzel M, Friend RH, Dar MI. New strategies for defect passivation in high-efficiency perovskite solar cells. *Adv Energy Mater*. 2020;10:1903090.

97. Fu L, Li H, Wang L, Yin R, Li B, Yin L. Defect passivation strategies in perovskites for an enhanced photovoltaic performance. *Energy Environ Sci*. 2020;13:4017-4056.

98. Zheng X, Chen B, Dai J, et al. Defect passivation in hybrid perovskite solar cells using quaternary ammonium halide anions and cations. *Nat Energy*. 2017;2:17102.

99. Liu X, Cheng Y, Tang B, et al. Shallow defects levels and cations on internal absorption, charge recombination and collection in perovskite silicon tandem solar cells with efficiency beyond 21%. *Adv Mater*. 2017;29:1703852.

100. Chen B, Yu Z, Liu K, et al. Grain engineering for perovskite/silicon monolithic tandem solar cells with efficiency of 25.4%. *Joule*. 2019;3:177-190.
of organometal halide perovskite solar cells. *Nano Energy.* 2019;61:496-504.

101. Nogay G, Sahil F, Werner J, et al. 25.1%-Efficient Monolithic perovskite/silicon tandem solar cell based on a p-type monocrys-
talline textured silicon wafer and high-temperature passivating contacts. *ACS Energy Lett.* 2019;4:844-845.

102. Sahil F, Werner J, Kamino BA, et al. Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency. *Nat Mater.* 2018;17:820-826.

103. Sahil F, Kamino BA, Werner J, et al. Improved optics in monolithic perovskite/silicon tandem solar cells with a nanocrystalline silicon recombination junction. *Adv Energy Mater.* 2018;8:1701609.

104. Bush KA, Palmstrom AF, Yu ZJ, et al. 23.6%-Efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nat Energy.* 2017;2:17009.

105. Altazin S, Stepanova L, Werner J, Niesen B, Ballif C, Ruhistaller B. Design of perovskite/crystalline-silicon monolithic tandem solar cells. *Opt Express.* 2018;26:A579.

106. Chen B, Yu ZJ, Manzoor S, et al. Blade-Coated perovskites on textured silicon for 26%-Efficient monolithic perovskite/silicon tandem solar cells. *Joule.* 2020;4:850-864.

107. Rahmany S, Etgar L. Semitransparent perovskite solar cells. *ACS Energy Lett.* 2020;5:1519-1531.

108. Mujahid M, Chen C, Zhang J, Li C, Duan Y. Recent advances in semitransparent perovskite solar cells. *Infomat.* 2021;3:101-124.

109. Shi B, Duan L, Zhao Y, Luo J, Zhang X. Semitransparent perovskite solar cells: From materials and devices to applications. *Adv Mater.* 2020;32:1806474.

110. Yoon J, Kim U, Yoo Y, et al. Foldable perovskite solar cells using carbon nanotube-embedded ultrathin polyimide conductor. *Adv Sci.* 2021;8:2004092.

111. Jung J, Guo R. Optimized sputtering parameters for ITO thin films of high conductivity and transparency. In *Advances and Applications in Electroceramics II.* 2012:43-53.

112. Balasundaraprabhu R, Monakhov EV, Muthukumarasamy N, Nilsen O, Svensson BG. Effect of heat treatment on ITO film properties and ITO/p-Si interface. *Mater Chem Phys.* 2009;114:425-429.

113. Adil Afroz M, Ghimire N, Reza KM, et al. Thermal stability and performance enhancement of perovskite solar cells through oxalic acid-induced perovskite formation. *ACS Appl Energy Mater.* 2020;3:2432-2439.

114. Bett AJ, Winkler KM, Bivour M, et al. Semi-Transparent perovskite solar cells with its directly sputtered on spiro-octad for tandem applications. *ACS Appl Mater Interfaces.* 2019;11:45796-45804.

115. Cheacharoen R, Rolston N, Harwood D, Bush KA, Dauskardt RH, Mcgehee MD. Design and understanding of encapsulated perovskite solar cells to withstand temperature cycling. *Energy Environ Sci.* 2018;11:144-150.

116. Bush KA, Bailie CD, Chen Y, et al. Thermal and environmental stability of semi-transparent perovskite solar cells for tandems enabled by a solution-processed nanoparticle buffer layer and sputtered ITO electrode. *Adv Mater.* 2016;28:3937-3943.

117. Cheng Y, Xie C, Liu X, et al. High-power bifacial perovskite solar cells with shelf life of over 2000 h. *Sci Bull.* 2020;65:607-610.

118. Jacobs DA, Langenhorst M, Sahli F, et al. Light management: A key concept in high-efficiency perovskite/silicon tandem photovoltaics. *J Phys Chem Lett.* 2019;10:3159-3170.

119. Boyd CC, Cheacharoen R, Bush KA, Prasanna R, Leijtens T, Mcgehee MD. Barrier design to prevent metal-induced degradation and improve thermal stability in perovskite solar cells. *ACS Energy Lett.* 2018;3:1772-1778.

120. Fang Z, Zeng Q, Zuo C, et al. Perovskite-based tandem solar cells. *Sci Bull.* 2021;66:621-636.

121. Leijtens T, Bush KA, Prasanna R, Mcgehee MD. Opportunities and challenges for tandem solar cells using metal halide perovskite semiconductors. *Nat Energy.* 2018;3:828-838.

122. Park IJ, Park JH, Ji SG, Park M-A, Jang JH, Kim JY. A three-terminal monolithic perovskite/Si tandem solar cell characterization platform. *Joule.* 2019;3:807-818.

123. Li W, Zheng J, Hu B, et al. High-performance solar flow battery powered by a perovskite/silicon tandem solar cell. *Nat Materials.* 2020;19:1326-1331.

124. Karuturi SK, Shen H, Sharma A, et al. Over 17% Efficiency stand-alone solar water splitting enabled by perovskite-silicon tandem absorbers. *Adv Energy Mater.* 2020;10:2000772.

125. Park H, Park IJ, Lee MG, et al. Water splitting exceeding 17% solar-to-hydrogen conversion efficiency using solution-processed Ni-based electrocatalysts and perovskite/Si tandem solar cell. *ACS Appl Mater Interfaces.* 2019;11:33835-33843.

126. Gao J, Sahil F, Liu C, et al. Solar water splitting with perovskite/silicon tandem cell and TiC-supported Pt nanocluster electrocatalyst. *Joule.* 2019;3:2930-2941.

127. Kim JH, Kim YK, Lee JS. Perovskite tandems advance solar hydrogen production. *Joule.* 2019;3:2892-2894.

**AUTHOR BIOGRAPHIES**

Yuanhang Cheng received his PhD degree from the Department of Physics and Materials Science, City University of Hong Kong, in October 2017. He is currently working as a Senior Research Fellow at the Solar Energy Research Institute of Singapore (SERIS), National University of Singapore. His research focuses on perovskite solar cells.

Liming Ding got his PhD from University of Science and Technology of China (was a joint student at Changchun Institute of Applied Chemistry, CAS). He started his research on OSCs and PLEDs in the Olle Inganäs lab in 1998. Later on, he worked at the National Center for Polymer Research, Wright-Patterson Air Force Base and Argonne National Lab (USA). He joined Konarka as a Senior Scientist in 2008. In 2010, he joined
the National Center for Nanoscience and Technology as a full professor. His research focuses on functional materials and devices. He is an RSC Fellow, the nominator for the Xplorer Prize, and an Associate Editor for Science Bulletin and Journal of Semiconductors.

How to cite this article: Cheng Y, Ding L. Perovskite/Si tandem solar cells: Fundamentals, advances, challenges, and novel applications. SusMat. 2021;1:324–344. https://doi.org/10.1002/sus2.25