Ultrathin (~30 μm) flexible monolithic perovskite/silicon tandem solar cells

Xinlong Wang a,b,1, Jingming Zheng a,b,1 Zhiqin Ying a,b,1, Meili Zhang a, Xuchao Guo b, Xin Li a, Meili Zhang a, Xuchao Guo a,b, Shiqian Su a, Jingsong Sun a, Xi Yang a,b, Jichun Ye a,b,*

a Zhejiang Provincial Engineering Research Center of Energy Optoelectronic Materials and Devices, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, China
b University of Chinese Academy of Sciences, Beijing 100049, China

1. Introduction

Ultrathin crystalline silicon (c-Si) solar cells, with less than 50-μm-thick c-Si wafers (approximately one-third of the thickness of commercialized c-Si solar cells), can capitalize on the success of bulk c-Si solar cells while being price competitive (low-capex and low-cost), lightweight, and mechanically flexible [1,2]. The power conversion efficiency (PCE) of flexible ultrathin c-Si solar cells has experienced a remarkable advancement, rising from 7.7% in 2013 to over 18.9% recently [3]. However, these values significantly lag behind the highest certified PCEs of 26.1% for flexible ultrathin c-Si solar cells [4] and 26.8% for rigid (130 μm) c-Si solar cells [5] and still fall below the PCEs of other flexible perovskite and organic thin-film solar cells (Fig. 1a) [6–9], thus limiting their potential for full exploitation. In addition, although thin silicon wafers offer improved flexibility, the inherent brittleness of silicon raises substantial concerns regarding mechanical durability. Moreover, the evolution of flexible c-Si solar cells faces a substantial challenge arising from the intricate balance between thickness and light harvesting efficiency. This challenge is further heightened by the sensitivity of c-Si solar cells to thickness variations, which is attributed to c-Si serving as an indirect optical bandgap semiconductor. Furthermore, regarding the persistent challenge arising from the inherent brittleness of silicon, there has been almost no notable progress in the development of flexible c-Si solar cells [10].

Constructing tandem solar cells using a combination of perovskite and ultrathin c-Si presents a promising path toward the cost-effective manufacturing of high-performance flexible photovoltaics. Although the PCE of rigid perovskite/silicon tandem solar cells has achieved 33.9% [11], there has been no concerted attempt to develop flexible perovskite/silicon tandem solar cells. The underlying cause can be attributed to the major obstacles encountered by ultrathin bottom c-Si, such as severe light absorption losses due to the reduced silicon thickness and strong surface reflection, ultimately leading to a decrease in short-circuit current density (Isc) in tandem devices. Considerable efforts have been focused on developing light-trapping methods for rigid perovskite/silicon tandem solar cells, including micrometer-sized...
pyramids and periodic texturization. However, the former suffers from limitations, with the performance of perovskite on pyramids being constrained by its restricted carrier diffusion length, substantial voltage deficit, and inadequate reproducibility, whereas the latter is plagued by intricate and expensive nanoimprint lithography techniques [12,13]. Alternatively, nanostructures have recently been demonstrated to be a promising light-trapping strategy that can simultaneously improve light absorption across a wide range of angles and wavelengths [14] and optimize perovskite film growth [15,16]. However, despite efforts to implement nanostructures as light-trapping strategies for single-junction c-Si and c-Si-based tandem solar cells [2,6,9,13,17,18], the utilization of nanostructures in flexible perovskite/silicon tandems and their impact on device flexibility have not yet been studied.

In this study, we demonstrated the first flexible perovskite/silicon tandem based on ultrathin (∼30 μm) silicon. It can be found that: (1) The wafer thickness had a crucial impact on the flexibility of silicon devices, with thinner c-Si wafers exhibiting increased flexibility. (2) The feature sizes of light-trapping textures can significantly affect the flexibility of silicon, with nanotextures hardly adversely affecting c-Si wafer flexibility. (3) The mechanical durability of the device can be enhanced by the capping of the perovskite top cells, which effectively alters the position of the neutral plane toward the silicon surface and mitigates tensile stress on the silicon surface. As a result, the flexible perovskite/c-Si tandem solar cells with a stabilized PCE of 23.6% (certified 22.8%) and a high power-to-weight ratio of 3.12 W g⁻¹ were successfully demonstrated. The flexible tandems also exhibit exceptional bending durability, with a maintained performance of 98.2% even after 3000 bending cycles at a radius of 1 cm.

2. Experimental

The details of the material synthesis and characterizations, device fabrications, and measurements are provided in the Supplementary materials (online).

3. Results and discussion

It is well known that the flexibility of c-Si strongly depends on its thickness [19]. By reducing the thickness of a wafer, its flexibility can be enhanced, and its manufacturing costs and capital expenditure can be reduced. However, there exists a trade-off between thickness and light harvesting efficiency due to the low light absorption coefficient of the indirect-bandgap c-Si. Thus, it is crucial to implement an advanced light-trapping strategy to improve the light absorption of silicon. Here, we measured the transmittance and reflectance spectra (Fig. 1b, c) of the silicon samples using different light-trapping strategies to characterize the light absorption properties. For double-side planar silicon, it was evident that the transmission loss in the infrared region increased significantly with decreasing thickness. The thinned double-side planar silicon also exhibited noticeable reflection losses in the wavelength range of 900–1200 nm. By comparing thinned double-side planar silicon with front-side planar silicon and back-side pyramidal silicon, we observed that the back-side pyramid structure effectively reduced the transmission and reflection losses in the infrared region. In addition, the introduction of front-side nanostructures led to a notable decrease in reflection loss across a wide spectral range for the thinned silicon sample. The slight enhancement in transmittance observed in the 1000–1200 nm wavelength range of the front-side nanostructured silicon can be attributed to the considerable reflection losses occurring in the front-side planar silicon.

Motivated by the efficient light trapping of the nanostructure, we fabricated single-junction flexible tunnel oxide passivated contact (TOPCon) bottom cells. The double-side TOPCon together with the surface nanostructure contributed to high-level surface passivation without sacrificing light trapping [16]. The corresponding device schematic was shown in Fig. 2a. The current–voltage (J–V) curves of the ultrathin planar and nanostructure c-Si devices were shown in Fig. 2b. The best-performing ultrathin nanostructure c-Si device delivered an open-circuit voltage (V_OC) of 626 mV, a J_SC of 34.3 mA cm⁻² and a fill factor (FF) of 77.3%, resulting in a PCE of 16.6%. By contrast, the champion ultrathin planar c-Si device showed a PCE of 12.9%, V_OC of 628 mV, lower J_SC of 26.8 mA cm⁻² and FF of 76.5%. The nanostructure device exhibited an increased PCE compared with the planar device mainly due to the higher J_SC. The increased J_SC and virtually unchanged V_OC indicated that the nanostructure strategy effectively enhanced light-trapping without detrimentally affecting passivation in the nanostructure device. The increased J_SC in the nanostructure device was further confirmed by the external quantum efficiency (EQE) measurement (Fig. 2c), where the calculated J_SC values of 33.7 mA cm⁻² for the planar c-Si device and 26.1 mA cm⁻² for the nanostructure c-Si device aligned closely with the J_SC values obtained from J–V scanning (<3% error).

To evaluate the suitability of ultrathin nanostructure bottom c-Si in the perovskite/silicon tandem, we developed monolithic flexible perovskite/silicon tandem solar cells. The corresponding schematic and cross-sectional scanning electron microscopy...
(SEM) images are shown in Fig. 3a, b, respectively. For the perovskite top cell, a self-assembled monolayer [2-(3,6-dimethoxy-9H-carbazol-9-yl)ethyl] phosphonic acid was introduced as the hole-transporting layer at the indium zinc oxide/perovskite interface [20]. The utilized perovskite active layer was a typical Cs$_{0.05}$(FA$_{0.83}$MA$_{0.17}$)$_{0.95}$Pb(I$_{0.82}$Br$_{0.18}$)$_3$ (FA: formamidinium; MA: methylammonium) featuring a bandgap of 1.63 eV (Fig. S1 online), which has previously exhibited to be a promising high-quality absorber with the remarkable stability, reproducibility, and high efficiency [21]. We further tested the ultraviolet–visible spectroscopy (UV–vis) absorption and steady-state photoluminescence (SSPL) spectra (Fig. S2 online) of the perovskite films to determine the perovskite bandgap. Both the Tauc plot obtained from UV–vis absorption spectra and the emission peak of photoluminescence for perovskite films revealed an optical bandgap of 1.63 eV. The $J$–$V$ curves of the best-performing monolithic planar and nanostructure flexible perovskite/silicon tandem device were showed in Fig. 3c. The planar flexible tandem, which had the front-side planar and the back-side pyramidal textured silicon bottom cell, exhibited a PCE of 16.8% (16.6%), with a $V_{OC}$ value of 1.72 V (1.72 V), a $J_{SC}$ of 12.5 mA cm$^{-2}$ (12.5 mA cm$^{-2}$), and a FF of 78.3% (77.2%) under the reverse (forward) voltage scan. By comparison, the nanostructure flexible tandem achieved a PCE of 23.7% (23.4%), with a $V_{OC}$ value of 1.73 V (1.73 V), a $J_{SC}$ of 17.1 mA cm$^{-2}$ (17.1 mA cm$^{-2}$) and a FF of 80.0% (79.1%) under the reverse (forward) voltage scan. The photovoltaic parameters based on the
eight devices suggest the good reproducibility of the nanostructure devices (Fig. S3 online). Both the devices have minor hysteresis between reverse and forward scans. The notable PCE enhancements in nanostructure tandem solar cells are primarily attributed to the improvement in \( J_{SC} \), confirming the light-trapping effect of the front-side nanostructure and the back-side pyramidal textures. The EQE measurements further emphasized the optical benefits of transitioning from a planar configuration to a nanostructured configuration (Fig. 3d), and the nanostructure flexible tandem showed integrated \( J_{SC} \) values of 17.1 and 19.9 mA cm\(^{-2}\) for the bottom and top cells, respectively, in line with the \( J_{SC} \) observed from the \( J-V \) measurements. By contrast, the integrated \( J_{SC} \) values of the planar flexible tandem for the bottom and top cells were 12.5 and 19.6 mA cm\(^{-2}\), respectively, indicating a severe current mismatch between the bottom and top cells. Moreover, we obtained stabilized PCEs of 23.6% and 16.5% by tracking the maximum power points (MPP) of the nanostructure and planar flexible tandem devices for 10 min, respectively (Fig. 3e), in good agreement with the \( J-V \) results. To validate our in-house measurement, we sent one of the devices to the Shanghai Institute of Microsystem and Information Technology for photovoltaic certification using dual-source, achieving a stabilized certified PCE of 22.8% (Fig. S4 online).

To the best of our knowledge, the certified stabilized PCE of 22.8% realized in this study denotes one of the highest performances ever reported for silicon-based flexible solar cells (Fig. S5 online), and is comparable to the best results reported for thin-film-based flexible solar cells (Table S1 online). The PCE, a key parameter directly related to power generation per unit area, serves as the primary metric for characterizing solar cell performance; however, in some applications, the limiting factor may be weight rather than available area. In such cases, the power-to-weight ratio becomes a more suitable metric to evaluate solar cell performance, particularly in scenarios where portable power is required, such as in aircraft, spacecraft, or personal backpacks where payload capacity is a critical consideration. Our flexible perovskite/silicon tandem devices, which are free from heavy glasses and back sheets, result in an extremely high power-to-weight ratio of 3.12 W g\(^{-1}\), which represents one of the current record values for photovoltaic technology (Fig. 3f). The power-to-weight ratios of these flexible perovskite/silicon tandem devices not only exceed that of 60-µm flexible c-Si and standard c-Si devices (0.43 and 0.02 W g\(^{-1}\), respectively) [10], but also demonstrate a favorable comparison with other power-generating technologies such as electric motors (0.3–8.4 W g\(^{-1}\)) and heat engines/heat pumps (0.03–10 W g\(^{-1}\) for a jet engine, excluding fuel) [22]. Additionally, the ratio of flexible perovskite/silicon is nearly four and eight times that of commercially available space-rated high-efficiency Si (0.82 W g\(^{-1}\)) and triple junction cells (0.39 W g\(^{-1}\)), respectively [23]. The remarkable power-to-weight ratio exhibited by our flexible perovskite/silicon tandem devices presents potential benefits for lightweight power sources with a high energy density (Table S1 online).

Nanostructure substrates have been reported as an effective method to optimize perovskite morphology, suppress nonradiative recombination, accelerate charge extraction, and inhibit phase separation in perovskite films [16,17,24]. In this section, we first explore the impact of nanostructure on the morphology of perovskite films. Atomic force microscopy measurements were conducted on both planar and nanostructure perovskite films (Fig. S6 online). Consequently, the mean grain size elongated from 260 nm for the planar perovskite film to 390 nm for the nanostructure perovskite film. Due to the deposition of perovskite using a spin-coating method, the root mean square surface roughness of planar and nanostructure perovskite films remains comparable. The cross-sectional SEM image (Fig. S7 online) reveals that the perovskite grown on a planar surface exhibits multiple stacked grains aligned in the longitudinal direction. By contrast, the perovskite film grown on a nanostructure surface displays individual grains uniformly distributed throughout the film thickness and the grain boundaries oriented perpendicular to the substrate, indicating a vertically aligned crystal growth pattern of perovskite on the nanostructure surface. To gain further insights into the recombination behavior, the transient photovoltage (TPV) decay curves were recorded under open-circuit conditions. As shown in Fig. S8 (online), in contrast to the planar devices, the nanostructure devices exhibit a superior TPV decay response with longer decay times, indicating a reduction in nonradiative recombination, consistent with the increased recombination resistance fitted in the impedance spectroscopy (Fig. S9 online). In addition, the impact of the nanostructure surface on perovskite charge extraction was investigated using SSPL and time-resolved photoluminescence spectra. In comparison to the planar sample, the SSPL spectra exhibited a higher quenching efficiency for the nanostructure sample (Fig. S10 online), indicating efficient hole extraction from the perovskite film [25]. The lifetimes of the nanostructure sample were calculated to have a fast decay of 2.8 ns, whereas the control sample exhibited a slow decay of 6.4 ns, confirming the dynamically faster hole extraction on the nanostructure surface, aligning well with the Mott–Schottky measurements (Fig. S11 online). Widely recognized, phase segregation imposes constraints on the potential open-circuit voltage and compromises the stability of wide-bandgap perovskites, thus seriously impeding the development of perovskite-based tandem devices [26]. We then performed the time-dependent PL spectra under 1 sun equivalent laser (532 nm) illumination to understand the role of the nanostructure surface on halide segregation in our 1.63-eV perovskites with a composition of \( \text{Cs}_0.05(\text{FA}_{0.83}\text{MA}_{0.17})_0.95\text{Pb}(\text{I}_{0.82}\text{Br}_{0.18})_3 \). As shown in Fig. S12a, b (online), we did not observe a significant change in the PL peak position within 30 min for both planar and nanostructure samples. When the bromine fraction on the X-site exceeds 20%, the alloyed I/Br phases segregate upon illumination, and photocarriers are funneled into the low-bandgap iodine-rich domains [27]. Consequently, we investigated the photostability of wide-bandgap perovskites with different compositions: \( \text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.82}\text{Br}_{0.18})_3 \) (\( E_G = 1.65 \text{ eV} \)) and \( \text{Cs}_{0.05}(\text{FA}_{0.83}\text{MA}_{0.17})_0.95\text{Pb}(\text{I}_{0.82}\text{Br}_{0.22})_3 \) (\( E_G = 1.68 \text{ eV} \)) (Fig. S12c–f online). In the 1.65-eV perovskites, the planar film showed only a slight peak shift to the lower-energy region, whereas the peak of the nanostructure film remained almost unchanged. However, for 1.68-eV perovskites, the PL spectra of the planar film displayed a very pronounced growing red shift from 738 to over 750 nm, corresponding to the formation of an iodine-rich phase under continuous illumination. By contrast, the PL peak of the nanostructure film showed only a minor shift, indicating a significantly lower extent of halide segregation compared to the planar film.

In order to assess device flexibility, an external force was employed to bend the samples using a bending tester (Fig. S13 online). The bending radius (\( R_b \)) was obtained by measuring the initial sample length without the external force and the change in length after applying the force, which resulted in the sample fracturing [19,28], as follows:

\[
R_b = \frac{L_0}{2\pi \sqrt{\frac{\Delta L}{d^2}} - \frac{\pi^2}{12}}
\]

where \( L_0 \), \( \Delta L \), and \( d \) denote the initial length of the bending sample, the change in sample length during the bending test, and the substrate thickness, respectively. We first investigated the effect of thickness on the c-Si wafers flexibility (Fig. 4a). By augmenting the planar c-Si wafer thickness from 20 to 60 µm, the \( R_b \) increased from ~5.1 to ~14.2 mm, indicating that the thicker c-Si wafer exhibits reduced flexibility. When the thickness was reduced to 30 µm, the wafers demonstrated excellent flexibility, with further thinning resulting in only marginal improvement in device flexibility. We
then fixed the silicon thickness to 30 \( \mu m \) and studied the impact of light-trapping texture feature sizes on the c-Si wafer flexibility (Fig. 4b). The \( R_b \) values of the planar and nanostructure c-Si were almost consistent, falling in the range 5.5–6.6 mm. In comparison, the surface pyramidal structure showed a much larger \( R_b \) value of \( \approx 13.4 \) mm. These results demonstrated that both thickness and texture feature sizes can significantly affect c-Si wafer flexibility. We also explored the influence of the perovskite top cells on the bottom c-Si wafers (Fig. 4c). In comparison to the \( R_b \) values obtained for the single-junction planar (\( \approx 5.8 \) mm) and nanostructure (\( \approx 6.2 \) mm) c-Si wafers, the tandems exhibited the reduced \( R_b \) values of \( \approx 4.9 \) mm for planar and \( \approx 4.5 \) mm for nanostructure tandems. The decreased \( R_b \) values observed in tandems can be attributed to the shifting of the neutral plane, which defines the position where the strains are zero [29,30], from the silicon bulk toward the surface (Fig. S14 online) [31]. Moreover, the flexibility enhancement is even more significant in the nanostructure tandem than in the planar tandem, which can be ascribed to the larger contact area and stronger interplay between the perovskite top cell and the c-Si wafers in the nanostructure tandem [16,17,32]. We further carried out bending durability tests for the planar and nanostructure flexible tandem devices. The planar flexible tandem cells retained only 88.7% of their performance after 3000 bending cycles with a bending radius of 1 cm (Fig. 4d). By contrast, the nanostructure tandem cells maintained 98.2% of the initial PCE after 3000 bending cycles. It is noteworthy that, if the radius of curvature was consistent, the flexed ultrathin silicon would either break immediately or remain largely unscathed even after multiple or prolonged flexing [33]. Thus, the
PCE decay for the flexible tandem was mainly caused by the top
perovskite subcells during the bending tests. This result can be con-
firmed by the top-view SEM of the flexible tandems before and after
bending cycles (Fig. 4e, f). The planar tandem showed a fracture sur-
face with multiple cleavage sites and a high density of microcracks
after bending, whereas the nanostructure tandem maintained
integrity, which can be ascribed to the enhanced interface adhesion
[16]. To assess the bending durability of transparent conductive
oxide (TCO), we conducted top-view SEM of the TCO films after
3000 bending cycles with bending radii of 1 and 0.5 cm. The TCO
film subjected to a bending radius of 1 cm after 3000 cycles exhib-
ted almost no cracks (Fig. S15a online). However, with a bending
radius of 0.5 cm, noticeable cracks and even instances of film
detachment were observed in the TCO film (Fig. S15b online). These
results indicate that the TCO film possesses better bending durabil-
ity than the perovskite film but falls short when compared to
silicon-based cells with a bending radius of less than 0.5 cm.

To estimate the long-term stability of the flexible tandem cells,
we investigated the operational stability of unencapsulated flexible
tandem cells by MPP tracking under simulated AM1.5 G solar illu-
mination (a xenon lamp without an ultraviolet filter and with a
delay equivalent to 100 mW cm⁻² in ambient air (without any
temperature and humidity controls), the temperature and humidity
during the test are shown in Fig. S16 (online). The unencapsulated
planar flexible tandem cell retained only 78.3% of its initial PCE after
100 h of MPP operation. The operational stability of the flexible pla-
nar tandem is comparable to that of rigid perovskite/silicon tan-
dems as previously reported [34]. By contrast, the unencapsulated
nanostructure flexible tandem cell retained 90.6% of its initial PCE
after 100 h of MPP operation (Fig. 4g). This stability is comparable
with the best results of rigid perovskite/silicon tandems [18]. Sev-
eral factors have been identified as contributing to the enhanced
operational stability of the nanostructure tandem, including the
reduced tensile stress inside perovskite, the high perovskite crys-
talline quality, and the hydrophobic characteristic of the nanostruc-
ture surface [16,17]. The enhanced operational stability of the
nanostructure tandem can also be attributed to the improved cur-
cent alignment between the subcells. This alignment prevents the
accumulation of excessive photoexcited charge carriers in the per-
ovskite layer, which can severely affect the stability of the perovskite-based tandems [35]. To compare the long-term stability of
rigid and flexible tandems and investigate the impact of the cur-
cent mismatch on the stability of the perovskite-based tandem
devices, we further conducted operational stability tests on unencap-
sulated rigid tandem cells at the MPP tracking under the similar
test situation (Fig. S17 online). Comparable with the flexible nano-
structure tandem, the rigid nanostructure tandem maintained 92.8%
of its initial PCE after 100 h of MPP operation. Notably, the oper-
aional stability of the flexible planar tandem is still much worse
than that of the rigid planar tandem, which retained 86.6% of its ini-
tial PCE after 100 h of MPP operation. The results reveal that the
current mismatch among the subcells could affect the long-term
stability of the perovskite-based tandems. In comparison to the
rigid planar tandem, significant current mismatch among the sub-
cells in the flexible planar tandem device has led to its inferior oper-
aional stability. It is worth noting that the flexible perovskite/
silicon tandem demonstrates a potential advantage in long-term
stability compared with the all-perovskite tandem, which is limited
by the stability of the low-gap tin-based perovskites due to the oxi-
dation of Sn²⁺ to Sn⁴⁺. In addition, for flexible all-perovskite tan-
dems, environmental stress factors such as moisture can have a
particularly detrimental effect on flexible PSCs, as flexible sub-
strates are more susceptible to water vapor transmission than silicon-
or glass-based substrates [6].

Despite the achievement of a certified stabilized PCE of 22.8% in
this study for the first flexible perovskite/silicon tandem solar cells,
the device performance still significantly lags behind the highest
certified PCE of 33.7% realized in rigid perovskite/silicon tandem
solar cells. Flexible perovskite/silicon tandem solar cells still have
great untapped potential in achieving an efficiency exceeding 30%
as efficiency limits of 10 μm flexible c-Si above 28.5% are predicted
[23,36,37], which is very close to the theoretical efficiency limit of
29.4% for rigid c-Si solar cells [15]. To further achieve the practical
feasibility of flexible perovskite/silicon tandem solar cells, several
factors must be considered, including flexibility, fabrication cost,
and lifespan. In terms of tandem device flexibility, although we
observed that the perovskite top cell provided stress compensation
for the c-Si bottom cell, the inherent rigidity of c-Si still imposes
constraints on its suitability for flexible photovoltaic applications.
Excitingly, recent reports have shown promising results in effect-
ively mitigating this issue through the implementation of an
edge-blunting technique, which entails modifying the pyramidal
structure in the marginal regions to enhance c-Si device flexibility
[10]. Moreover, the inherent brittleness and fragility of the per-
ovskite and TCO layers, along with their interfaces that are prone
to delamination, can substantially influence the flexibility of tan-
dem devices. The challenges related to the brittleness and delami-
nation of the perovskite layer can be mitigated by introducing an
aligned elastomer interlayer between the transport layer and the
perovskite layer [38], as well as by cementitious perovskite grain-
boundary passivation [39]. To avoid the performance degradation
caused by fragile TCO, numerous materials have been explored as
alternatives to conventional TCO for high-performance flexible
solar cells, such as Ag nanowires [8,40], carbon nanotubes [41],
and metal meshes [31,42]. Regarding the cost of device fabrication,
we employed the traditional thinning method through wet etching
to achieve flexible silicon cells for convenience. However, this
method is certainly not a cost-efficient approach. To mitigate the
cost of producing ultrathin silicon, an alternative economical
approach, known as “kerfless wafering”, can be implemented. This
process involves mechanically exfoliating a thin silicon film from a
thick wafer, using applied stress to obtain a wafer with a predeter-
mined thickness in the range of a few tens of micrometers [43,44].
Regarding the tandem device lifespan, the long-term operational
stability also plays a crucial role in determining the lifespan of flexi-
ble perovskite/silicon tandem devices. Consequently, it is neces-
sary to explore multiple strategies to achieve improved
environmental and operational stability for perovskite absorbers,
such as additive strategies [21,45,46] and the interface passivation
engineering [18,47]. In addition, effective encapsulation techniques
based on flexible devices should be employed to minimize the
impact of external factors [48]. Finally, we believe that the tandem
strategy for the combination of perovskite and ultrathin silicon
holds great potential for achieving cost-effective and industrially
viable flexible photovoltaics, and will contribute to a significant
growth of the flexible cell market in the near future.

4. Conclusion

In summary, we demonstrate the flexible perovskite/silicon
tandem solar cell with a certified stabilized PCE of 22.8% and a high
power-to-weight ratio of 3.12 W g⁻¹. In addition, we find that the
thickness and texture feature sizes can significantly affect the flexi-
bility of the c-Si wafers. The mechanical durability of the per-
ovskite/silicon tandem device can be improved by capping the
top perovskite cells. As a result, the flexible tandem devices exhib-
it improved bending durability and operational stability, retaining
98.2% and 90.6% of their initial PCE after 3000 bending cycles
and 100 h of MPP operation, respectively. This result represents a
significant milestone in the development of low-cost and high-
performance flexible photovoltaics, and is expected to generate a
significant interest in various flexible optoelectronic devices.
Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the Key Research and Development Program of Ningbo (2022Z151), the Key Research and Development Program of Zhejiang Province (2022C01215, 2024C01092), the China Postdoctoral Science Foundation (2023M743620), the Joint Funds of the Zhejiang Provincial Natural Science Foundation of China (LBMD24E020002), the Zhejiang Provincial Natural Science Foundation of China (LY24F040003), the National Key Research and Development of China (2018YFB1500103), and the National Natural Science Foundation of China (62204245, U23A200098).

Author contributions

Jichun Ye supervised the project. Xinlong Wang, Zhiqin Ying, Xi Yang, and Jichun Ye conceived and designed all the experimental work. Xinlong Wang, Zhiqin Ying, and Jingming Zheng fabricated the flexible silicon bottom cells and tandem devices. Xin Li, Meili Zhang, Xuchao Guo, Jingsong Sun, and Shiqian Su performed cell measurements. All authors contributed to the writing of the manuscript and to the analysis of the experimental results.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scihp.2024.04.022.

References

Xinlong Wang received his Bachelor degree from China University of Petroleum (East China) in 2019. He is currently a Ph.D. student at Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences. His research interest focuses on the stability and flexibility of perovskite/silicon tandem solar cells.

Jingming Zheng received her Bachelor degree from the Nanchang University in 2018 and received her Ph.D. degree from the University of Chinese Academy of Sciences. Now she is a postdoctoral fellow at Nankai University. Her current research focuses on high efficiency silicon solar cells.

Zhijin Ying received her Bachelor degree in material Science and Engineering in 2013 from Nanchang University and the Ph.D. degree from the University of Macau. Now she is a postdoctoral fellow at Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences. Her current research focuses on high-performance perovskite/silicon tandem solar cells.

Xi Yang received his Bachelor degree from China Jiliang University in 2008 and the Ph.D. degree in optics from Nankai University in 2013. He is currently an associate researcher at the Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences. His research focuses on perovskite/silicon tandem solar cells.

Jichun Ye received his Bachelor degree in materials Science and Engineering from University of Science and Technology of China in 2001 and the Ph.D. degree in materials science from University of California in 2005. In 2012, he joined the Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences as a professor and Ph.D. advisor. His research focuses on efficient crystalline silicon solar cells and perovskite/silicon tandem solar cells.
