

Routes for light management in monolithic perovskite/silicon tandem solar cells

Michel G. Rocha and Emiliano R. Martins

<https://doi.org/10.1109/JPHOT.2025.3591383>

Abstract—Fully-textured perovskite/silicon tandem solar cells have emerged as promising candidates for next-generation photovoltaics. The optical functions of full texturing, however, are not yet fully understood. A key challenge is the requirement for perovskite layer texturing, which often leads to increased electrical losses. Here, we elucidate the distinct optical roles of front and rear textures in tandem configurations using optical simulations and use these insights to propose a new architecture that eliminates the need for perovskite surface texturing. We demonstrate that our proposed structure achieves optical results comparable to those of fully-textured devices, while its planar perovskite layer has the potential to reduce electrical losses. The high optical performance also results in higher efficiency if a texture-induced voltage loss as low as 50 mV is assumed, which is about six times lower than the loss of fully-textured devices, thus enabling higher efficiencies within a simplified design. Our results show that perovskite texturing is not essential for optimal light management, thus opening the way to combine efficient light management with high electrical performance.

Index Terms—Perovskite/silicon tandem solar cells, Light management, Fully-textured cells, Light trapping, Planar perovskite, Electrical losses

I. INTRODUCTION

AS the efficiency of single-junction silicon solar cells approaches its theoretical limit [1] ($\sim 30\%$ [2]), increasing attention has turned to tandem solar cells (TSCs), which combine materials with distinct band gaps within a single device. Certified power conversion efficiencies (PCEs) of up to 34.6% have already been demonstrated [3], and their theoretical limits can be as high as 45.2% [4], [5].

Tandems based on a perovskite top cell and a silicon bottom cell hold great promise for low-cost, high-efficiency devices. Perovskites exhibit tunable band gaps [6], strong absorptance in the visible and near-UV spectrum [7], and carrier diffusion lengths exceeding their absorption depth [8], [9]. Perovskite materials are also inexpensive and composed of earth-abundant elements [10]. When combined with the low band gap of silicon, they enable broad-band light harvesting at low manufacturing costs [11].

Achieving high PCEs in TSCs, however, requires effective light management to direct the appropriate portions of the solar spectrum to each sub-cell [12], enhancing absorptance [13], [14] and minimizing reflection losses [15], [16]. This can be accomplished through photonic structures placed at intermediate interfaces [13], [17]–[19] or via optical impedance matching layers [20]. Various light-trapping and anti-reflection strategies have been proposed for perovskite/silicon tandem

solar cells (PSTSCs), such as Mie-resonance-based spectral splitting [21], nanosphere [22] and nanohole-array [23] diffractive structures, planar black silicon textures [24], and light management foils [25]. Among these, pyramidal texturing has emerged as a particularly effective solution, providing efficient light trapping and reducing reflectance [26]–[31].

The impressive optical gains achieved through pyramidal texturing in single-junction silicon cells have inspired extensive research on textured PSTSCs [32]–[38]. However, these textures introduce additional surface area and fabrication complexity, often resulting in elevated electrical losses that offset optical improvements [5], [32], [39], [40]. Consequently, the experimental efficiencies remain significantly lower than the theoretical predictions [4], [26]–[28].

Fully-textured PSTSCs — such as the structure illustrated in Figure 1(a) — have emerged as the most promising architecture for light management, with reported PCEs among the highest to date [30], [37], [38], [41]. The roles of anti-reflection and light trapping in such structures, however, are not yet fully understood. Moreover, there are significant challenges associated with full texturization, particularly regarding conformal deposition over steep textures and the resulting non-radiative recombination losses in the perovskite layer [40], [42], which can exceed 300 mV [5]. In particular, the benefit of texturing the perovskite interface remains controversial, as electrical losses may counteract the optical gains [39]. Furthermore, planar perovskite layers are increasingly regarded as a more reliable pathway toward scalable, high-quality, large-area cells [43], [44].

Here, we elucidate the optical role of pyramidal texturing in PSTSCs and show that effective light management can be achieved without perovskite texturing. We then use these insights to propose a simplified architecture that achieves comparable optical performance without requiring perovskite texturing. We show that the proposed design can outperform the efficiency of fully-textured PSTSCs when texture-induced voltage losses as low as 50 mV are assumed, which is at least six times lower than losses reported in the literature [5]. Our results show that perovskite texturing is not essential for optimum light management, thus opening the way for tandem cells with efficient light management and high electrical performance.

II. STRUCTURES, PARAMETERS AND METHODS

To elucidate the roles played by full texturing, we consider the tandem solar cell of Figure 1(a), which is representative of fully-textured cells [5], [29], [32], [36]. A planar stack, shown in Figure 1(b), is also considered as a reference. The

The authors are with the Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of São Paulo, São Carlos, SP 13566-590, Brazil (e-mail: michelgr@usp.br; erm@usp.br).

optical simulations are based on Rayflare [45], which employs a multimodal approach to model optical structures combining geometric and wave optics. The pyramidal textures in Figure 1 are modeled using a Phong scattering profile, which accounts for surface roughness and diffuse reflection [46]. The electrical properties of the cells are modeled by a two-diode equivalent circuit through Solcore [47]. We assume typical values for saturation currents J_{01} and J_{02} , ideality factors n_1 and n_2 , series resistance R_s and shunt resistance R_{sh} [48]–[50], as summarized in Table I.

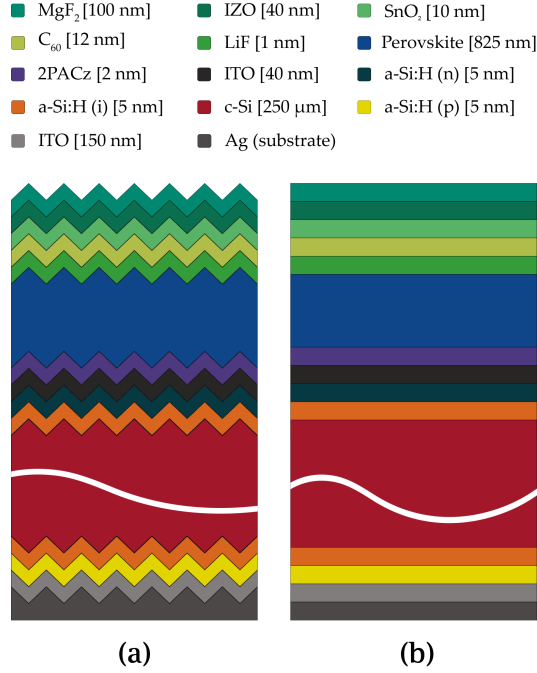


Fig. 1. Tandem cell architectures used for optical benchmarking: (a) fully-textured, state-of-the-art configuration; (b) planar reference.

The short-circuit current density (J_{sc}) of each subcell is calculated according to Eq. 1, where $\phi_{AM1.5G}$ is the AM1.5G solar spectrum, f_c is the collection efficiency of photogenerated carriers and $A(\lambda)$ is the spectral absorptance. The collection efficiency for perovskite is determined using Eqs. 2 and 3 [12], where k is the Boltzmann constant, T is the device operating temperature (298 K), W is the layer thickness, L_d is the minority carrier diffusion length (assumed to be $1 \mu\text{m}$ [8]), and V_{bi} is the built-in voltage, assumed equal to the perovskite band gap. The refractive indices of all materials are extracted from Refs. [51]–[53] (see Supplementary Information I, Figure S1). The optical data for the perovskite layer assumes a $\text{Cs}_{0.17}\text{FA}_{0.83}\text{Pb}(\text{I}_{0.83}\text{Br}_{0.17})_3$ composition [53], with a band gap of 1.63 eV.

$$J_{sc} = f_c q \int_{320 \text{ nm}}^{1200 \text{ nm}} \phi_{AM1.5G}(\lambda) A(\lambda) d\lambda \quad (1)$$

$$f_c = \frac{e^{\lambda_2^0/2} - 1}{\lambda_2^0/2} \quad (2)$$

$$\lambda_2^0 = \frac{qV_{bi}}{2kT} - \sqrt{\left(\frac{W}{L_d}\right)^2 + \left(\frac{qV_{bi}}{2kT}\right)^2} \quad (3)$$

TABLE I
TWO-DIODE MODEL PARAMETERS FOR THE SILICON AND PEROVSKITE SOLAR SUBCELLS

Solar Subcell	J_{01} (mA/cm ²)	J_{02} (mA/cm ²)	n_1 -	n_2 -	R_s ($\Omega\cdot\text{cm}^2$)	R_{sh} ($\Omega\cdot\text{cm}^2$)
Perovskite	3×10^{-18}	9×10^{-10}	1.3	2.0	0.4	3×10^3
Silicon	6×10^{-11}	5×10^{-6}	1.2	2.0	0.2	1×10^5

These parameters are then used to obtain the J – V characteristics of each subcell based on a two-diode model.

III. OPTICAL ROLE OF FULL TEXTURING

Figure 2 shows the reference stack A, the fully-textured stack B, and two additional stacks (C and D) used to help gain insight into the optical roles of front and rear texturing. All stacks have identical active layer thicknesses and optical properties, as outlined in Figure 1.

Figure 2(b) shows the short-circuit current density (J_{sc}) of the perovskite subcell as a function of its thickness for a planar (stack A — blue line) and fully-textured configuration (stack B — red line). The vertical arrow highlights the short-circuit current density enhancement in a typical tandem device with a $250 \mu\text{m}$ -thick silicon subcell [33], for which current matching is achieved with a perovskite thickness of 825 nm. Notice that the same current enhancement can be achieved simply by increasing the planar perovskite thickness to $\sim 1000 \text{ nm}$, which is within practical fabrication limits and comparable to carrier diffusion lengths. As the necessity of current matching in tandem cells fixes an upper bound for the useful perovskite current (here the upper bound is $\sim 20.8 \text{ mA/cm}^2$, which is close to the best state-of-the-art values obtained [1], [33]), it follows that the perovskite matching current can be achieved with thicker planar perovskite layers, with no need for light trapping, unless the silicon layer thickness is significantly increased beyond its typical values. This feature can be attributed to the combination of high absorption of perovskites and their long carrier diffusion lengths, which exceed $1 \mu\text{m}$ [8], [9] — check Supplementary Information II, Figures S2 and S3.

If light trapping does not play an essential role in perovskite absorption, then the question of the role of the front surface texturing arises. One possibility is that front texturing acts as an anti-reflection layer; however, interestingly, although pyramids have excellent anti-reflection properties, their performance in PSTSCs is not significantly superior to a planar AR coating (stack A), as shown in the inset of Figure 2(c), which compares the reflectance from stacks A and B.

The role of front texturing emerges when we compare the silicon absorption spectra of stacks A, B, C and D (Figure 2(c)). Note that the absorption spectra of stack A (blue line) and D (magenta line), which do not employ front texturing, are similar in the wavelength range between $\sim 700 \text{ nm}$ and $\sim 980 \text{ nm}$. The superior absorption of stacks B (red line) and C (black line) in this spectral region indicates the silicon light-trapping role of the front texture. In particular, note the two peaks at $\sim 800 \text{ nm}$ and $\sim 950 \text{ nm}$ for stacks A and D, which disappear for stacks B and C. These peaks arise

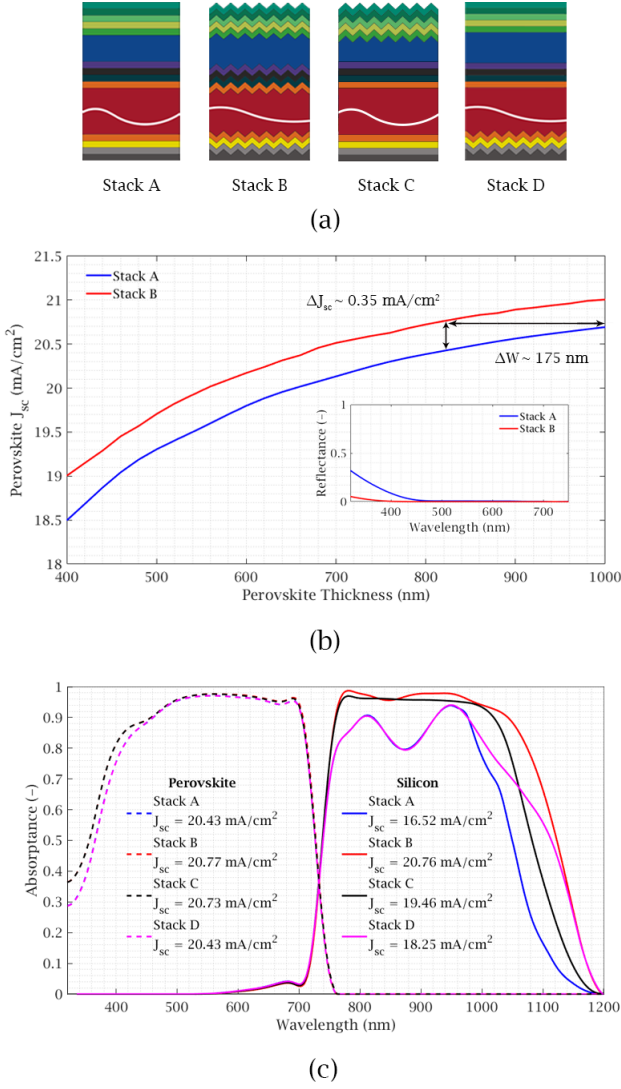


Fig. 2. Light management effects in a fully-textured PSTSC architecture: (a) device stacks considered for the optical characterizations; (b) short-circuit current density (J_{sc}) of the perovskite subcell for planar (stack A) and fully-textured (stack B) structures; inset: front-surface reflectance from stacks A and B; (c) spectral absorbance in the perovskite and silicon layers for stacks A–D.

from thin-film interference in the perovskite layer, and their vanishing in stacks B and C is consistent with the stronger scattering imposed by front texturing in the wavelength range between ~ 700 and ~ 980 nm. The role of rear texturing, on the other hand, is to trap light in the longer wavelength region (above 1000 nm), as seen by comparing the absorption of stacks C and D.

IV. PROPOSED STRUCTURE

Based on these insights, we propose a new light management scheme in which the perovskite layer remains planar, as illustrated in Figure 3. This scheme aims to optimize silicon absorption by combining front and rear texturing – the former targeting the ~ 700 nm to ~ 980 nm region and the latter targeting the region above 1000 nm. The silicon texturing follows conventional state-of-the-art parameters to ensure alignment with existing manufacturing techniques [54].

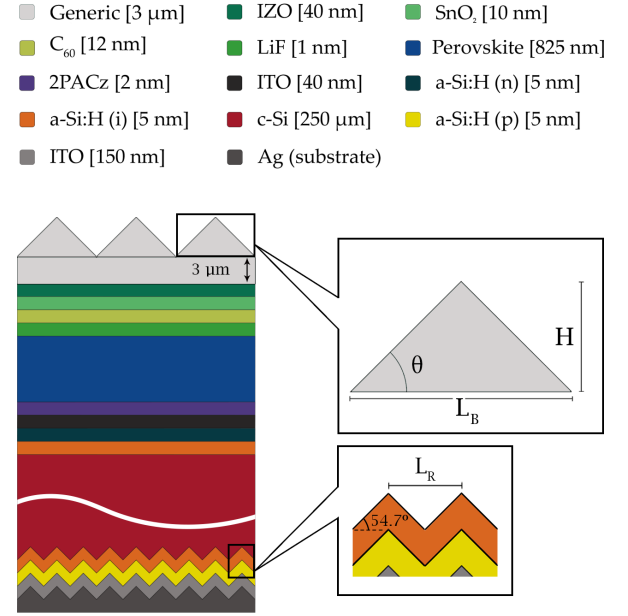


Fig. 3. Proposed structure. The top inset highlights the geometry of the anti-reflective front-side texture optimized here. The bottom inset shows the state-of-the-art pyramidal texturing used at the rear silicon interface, which remains unaltered in comparison to all previous textured stacks.

The anti-reflective parameters described in Figure 3 were obtained by optimizing the inclination angle θ of the front-side pyramids. Our simulations show that the scattering from the ARC pyramids is not fully diffuse. The height H of these pyramids was set to $3 \mu\text{m}$ to ensure compatibility with standard fabrication methods such as photolithography or laser interference lithography, which favor scalability [55]. A planar slab of the same material and thickness was placed under the texture as a buffer protecting the transport layers. We also assume that the front-side texture has a generic material with refractive index of $n_r = 1.4$, which is representative of the refractive indexes of materials commonly used in lithography, such as polydimethylsiloxane (PDMS) [55], [56]. The remaining layers follow the same architecture as Stack D in Figure 2 (a), consisting of a 40 nm indium zinc oxide (IZO) followed by 10 nm of tin oxide (SnO_2), a 12 nm of buckminsterfullerene (C_{60}) and a 1 nm lithium fluoride (LiF) interlayer. The 825 nm perovskite absorber is followed by a 2 nm layer of 2-(9H-carbazol-9-yl)ethylphosphonic acid (2PACz) and a 40 nm indium tin oxide (ITO) electrode, featuring the p-i-n architecture of the top perovskite subcell. As for the silicon subcell placed immediately below, it consists of a 5 nm n-doped hydrogenated amorphous silicon (a-Si:H (n^+)) layer followed by a 5 nm intrinsic a-Si:H (i) layer. The 250 μm crystalline silicon absorber is then followed by a 5 nm rear intrinsic a-Si:H (i) layer and a 5 nm p-doped a-Si:H (p^+) layer, forming a silicon heterojunction (SHJ). A 150 nm ITO electrode is deposited underneath followed by a silver (Ag) metal contact. The complete stack is depicted in Figure 3.

The inclination angle of the front-side pyramids, θ , was varied in the 20° – 70° range to maximize the short-circuit current density of silicon. As shown in Figure 4, the silicon subcell reaches a maximum of J_{sc} at the optimum angle of

$\theta = 44^\circ$. This angle entails a pyramid base length of $L_B \simeq 6.2 \mu\text{m}$. Interestingly, the silicon and perovskite currents are optimized by similar angles.

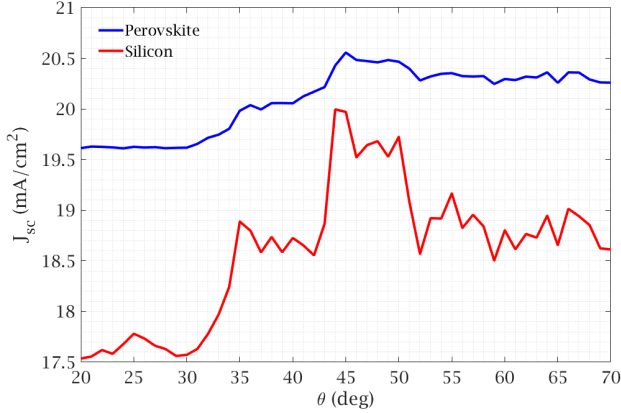


Fig. 4. Short-circuit current density (J_{sc}) as a function of the ARC pyramid inclination angle. The optimal angle of 44° maximizes both the silicon and perovskite currents.

The optical performance of the proposed structure is shown in Figure 5 alongside the fully-textured structure for reference. Both spectra correspond to current-matched cells, with optimized efficiencies of 32.15% and 32.94% for our structure and the fully-textured reference, respectively. These efficiencies, however, do not take into account parasitic losses, which are higher in the fully-textured solar cell [5], [39], [40]. An estimate of the impact of losses arising from perovskite texturing is shown in Figure 6(a), where $\Delta\eta$ is the absolute PCE difference between the proposed and fully-textured architectures, respectively. The dashed line, which peaks at around ~ 50 mV, marks the boundary where our structure outperforms the fully-textured solar cell. Conformal perovskite deposition on textured substrates has been shown to lead to severe interfacial recombination both at the electron transport layer (e.g., C_{60}) [5] and the hole transport layer (e.g. 2PACz) [39] interfaces, with experimental V_{oc} losses between 100 mV [40], [42] and 300 mV [5]. Thus, these results point to the benefit of light trapping schemes in which the perovskite layer is kept planar, such as the scheme proposed here. Indeed, taking these losses into account¹, our proposed structure has the potential to outperform current fully-textured solar cells across a wide range of silicon thicknesses, as shown in Figure 6(b), while also requiring thinner perovskite layers — see Supplementary Information III, Figure S4.

Finally it is worth noting that, while the precise size of the pyramidal textures is not critical [57], their inclination must be preserved, particularly for the ARC texture, as corroborated by Figure 4, which shows that the inclination angle itself plays a crucial role in effective light redirection.

¹To account for the drop in V_{oc} in the fully-textured cell, the ideality factor n_2 of perovskite was varied in the range of 2–2.3, with the corresponding recombination current J_{02} varying in the order of 10^{-10} to 10^{-8} mA/cm² [49], [50].

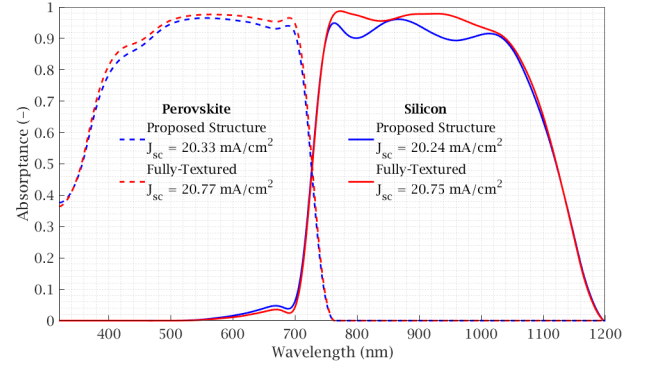


Fig. 5. Spectral absorbance in the perovskite and silicon subcells for the proposed and fully-textured architectures. The proposed structure maintains comparable optical performance while simplifying the top interface.

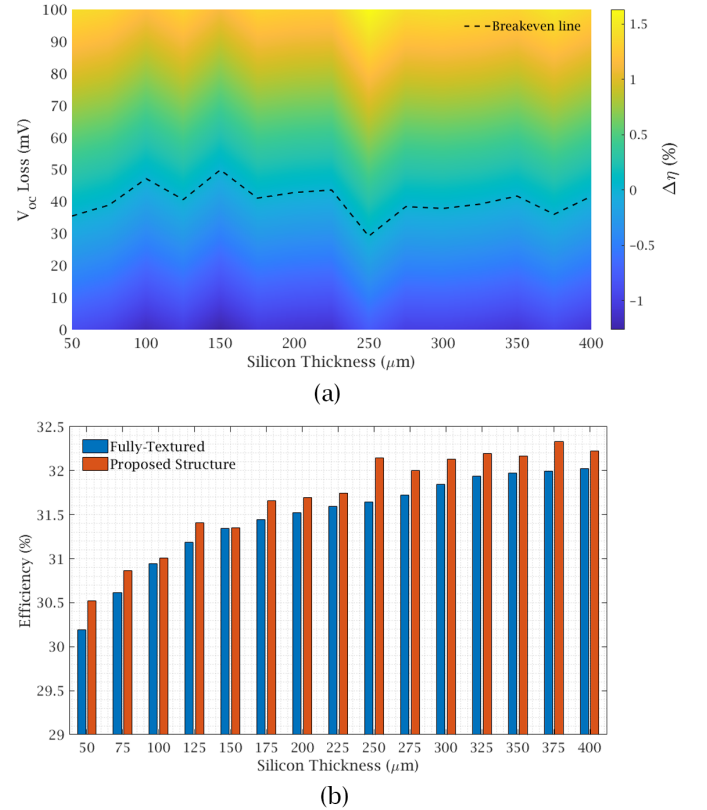


Fig. 6. Performance comparison between the proposed and fully-textured architectures; (a) difference between the efficiencies of the proposed and fully-textured architectures; the black dashed line marks the boundary where the efficiencies are equal; (b) absolute efficiency comparison between both architectures when a 50 mV V_{oc} drop is considered for the fully-textured cell.

V. CONCLUSIONS

In conclusion, we demonstrated that both front and rear texturing are essential to increase absorption in the silicon layer of perovskite/silicon tandem solar cells, but are not essential for perovskite light trapping. This insight led to the proposal of a light management scheme using a planar perovskite layer, thus promoting better electrical properties. The optical performance of this new architecture was shown to be comparable to fully-textured solar cells, yielding comparable efficiencies when a

V_{oc} penalty as low as 50 mV is assumed in the latter. Since these penalties can exceed 300 mV in fully-textured cells [5], we believe that our strategy can surpass the efficiency of current fully-textured designs and point to new directions for light management in tandem solar cells.

ACKNOWLEDGEMENTS

The authors acknowledge financial support from São Paulo Research Foundation – FAPESP (Grants. 2020/00619-4, 2021/06121-0) and the Brazilian National Council for Scientific and Technological Development – CNPq (307602/2021-4, 303820/2024-1). The Article Processing Charge (APC) for the publication of this research was funded by the Coordination for the Improvement of Higher Education Personnel (CAPES) – ROR identifier: 00x0ma614. For the purpose of open access, the authors have applied the Creative Commons CC BY license to any accepted version of the manuscript.

REFERENCES

- [1] M. A. Green, E. D. Dunlop, M. Yoshita, N. Kopidakis, K. Bothe, G. Siefer, D. Hinken, M. Rauer, J. Hohl-Ebinger, and X. Hao, "Solar cell efficiency tables (version 64)," *Prog. Photov. Res. Appl.*, vol. 32, pp. 425–441, Jul. 2024.
- [2] W. Shockley and H. A. Queisser, "Detailed Balance Limit of Efficiency of p - n Junction Solar Cells," *J. Appl. Phys.*, vol. 32, no. 3, pp. 510–519, Mar. 1961.
- [3] National Renewable Energy Laboratory (NREL), "Best research-cell efficiency chart," 2024, accessed: 01/28/2025. [Online]. Available: <https://www.nrel.gov/pv/cell-efficiency.html>
- [4] A. D. Vos, "Detailed balance limit of the efficiency of tandem solar cells," *J. Phys. D: Appl. Phys.*, vol. 13, pp. 839–846, 1980.
- [5] O. Er-raji, C. Messmer, A. J. Bett, O. Fischer, S. K. Reichmuth, F. Schindler, M. Bivour, O. Schultze-Wittmann, J. Borchert, M. Hermle, J. Schön, F. D. Heinz, M. C. Schubert, O. S. C. Schulze, and S. W. Glunz, "Loss Analysis of Fully-Textured Perovskite Silicon Tandem Solar Cells: Characterization Methods and Simulation toward the Practical Efficiency Potential," *Energy Environ. Sci.*, vol. 7, no. 2300659, 2023.
- [6] J. H. Noh, S. H. Im, J. H. Heo, T. N. Mandal, and S. I. Seok, "Chemical Management for Colorful, Efficient, and Stable Inorganic-Organic Hybrid Nanostructured Solar Cells," *Nano Lett.*, vol. 13, no. 4, pp. 1764–1769, Apr. 2013.
- [7] S. Albrecht, M. Saliba, J. P. C. Baena, F. Lang, L. Kegelmann, M. Mews, L. Steier, A. Abate, J. Rappich, L. Korte, R. Schlattmann, M. K. Nazeeruddin, A. Hagfeldt, M. Grätzel, and B. Rech, "Monolithic perovskite/silicon-heterojunction tandem solar cells processed at low temperature," *Energy Environ. Sci.*, vol. 9, pp. 81–88, 2016.
- [8] C. Liang, D. Zhao, P. Li, B. Wu, H. Gu, J. Zhang, T. W. Goh, S. Chen, Y. Chen, Z. Sha, G. Shao, T. C. Sum, and G. Xing, "Simultaneously boost diffusion length and stability of perovskite for high performance solar cells," *J. Nano Energy*, vol. 59, pp. 721–729, Mar. 2019.
- [9] S. D. Stranks, G. E. Eperon, G. Grancini, C. Menelaou, M. J. P. Alcocer, T. Leijtens, L. M. Herz, A. Petrozza, and H. J. Snaith, "Electron-Hole Diffusion Lengths Exceeding 1 Micrometer in an Organometal Trihalide Perovskite Absorber," *Sci. Rep.*, vol. 342, pp. 341–344, 2013.
- [10] H. Chung, R. Singh, L. Kumar, M. A. Alam, and P. Bermel, "Characterization and redesign of perovskite/silicon tandem cells," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 3625–3628.
- [11] C. D. Bailie and M. D. McGehee, "High-efficiency tandem perovskite solar cells," *MRS Bulletin*, vol. 40, pp. 681–685, Aug. 2015.
- [12] T. P. White, N. N. Lal, and K. R. Catchpole, "Tandem Solar Cells Based on High-Efficiency c -Si Bottom Cells: Top Cell Requirements for >30% Efficiency," *IEEE J. Photov.*, vol. 4, no. 1, pp. 208–214, 2014.
- [13] N. N. Lal, T. P. White, and K. R. Catchpole, "Optics and Light Trapping for Tandem Solar Cells on Silicon," *IEEE J. Photov.*, vol. 4, no. 6, pp. 1380–1386, 2014.
- [14] J. Li, K. Li, C. Schuster, R. Su, X. Wang, B. V. Borges, T. F. Krauss, and E. R. Martins, "Spatial resolution effect of light coupling structures," *Sci. Rep.*, vol. 5, no. 18500, pp. 1–8, 2016.
- [15] G. Yu, C. Shou, Z. Yang, H. He, Y. Zhang, W. Yang, M. Zhao, J. Sheng, G. Qin, and J. Ye, "Optical management of spacer layer of high-performance four-terminal perovskite/silicon tandem solar cells," *J. Sol. Energy*, vol. 228, pp. 226–234, Nov. 2021.
- [16] E. Raza and A. Z., "Review on two-terminal and four-terminal crystalline-silicon/perovskite tandem solar cells; progress, challenges and future perspectives," *Energy Reports*, vol. 8, pp. 5820–5851, 2022.
- [17] Q. Xu, Y. Zhao, and X. Zhang, "Light Management in Monolithic Perovskite/Silicon Tandem Solar Cells," *Sol. RRL*, vol. 4, pp. 1–16, 2020.
- [18] D. A. Jacobs, M. Langenhörst, F. Sahli, B. S. Richard, T. P. White, C. Ballif, K. R. Catchpole, and U. W. Paetzold, "Light Management: A Key Concept in High-Efficiency Perovskite/Silicon Tandem Photovoltaics," *J. Phys. Chem. Lett.*, vol. 10, pp. 3159–3170, Jun. 2019.
- [19] R. Santbergen, R. Mishima, T. Meguro, M. Hino, H. Uzu, J. Blanker, K. Yamamoto, and M. Zeman, "Minimizing optical losses in monolithic perovskite/ c -Si tandem solar cells with a flat top cell," *Opt. Express*, vol. 24, pp. A1288–A1299, Sep. 2016.
- [20] A. Martins, B. V. Borges, J. Li, T. F. Krauss, and E. R. Martins, "Photonic Intermediate Structures for Perovskite/ c -Silicon Four Terminal Tandem Solar Cells," *IEEE J. Photovolt.*, vol. 7, no. 5, pp. 1190–1196, Sep. 2017.
- [21] V. Neder, D. Zhang, S. Veenstra, and A. Polman, "Four-terminal perovskite/silicon tandem solar cell with integrated Mie-resonant spectral splitter metagrating," 2020.
- [22] J. Eisenlohr, B. G. Lee, J. Benick, F. Feldmann, M. Drießen, N. Milenkovic, B. Bläsi, J. C. Goldschmidt, and M. Hermle, "Rear side sphere gratings for improved light trapping in crystalline silicon single junction and silicon-based tandem solar cells," *J. Sol. Energy Mater. Sol. Cells*, vol. 142, pp. 60–65, Jun. 2015.
- [23] Y. Kuang, Y. Ma, D. Zhang, Q. Wei, S. Wang, X. Yang, X. Hong, and Y. Liu, "Enhanced Optical Absorption in Perovskite/Si Tandem Solar Cells with Nanoholes Array," *Nanoscale Res Lett*, vol. 15:213, pp. 1–6, Dec. 2020.
- [24] G. S. Arruda, J. Li, A. Martins, K. Li, T. F. Krauss, and E. R. Martins, "Reducing the Surface Area of Black Silicon by Optically Equivalent Structures," *IEEE J. Photovolt.*, vol. 10, no. 1, pp. 41–45, Jan. 2020.
- [25] M. Jošt, E. Köhnen, A. B. Morales-Vilches, B. Lipovšek, K. Jäger, B. Maccò, A. Al-Ashouri, J. Krč, L. Korte, B. Rech, R. Schlattmann, M. Topič, B. Stannowski, and S. Albrecht, "Textured interfaces in monolithic perovskite/silicon tandem solar cells: advanced light management for improved efficiency and energy yield," *Energy Environ. Sci.*, vol. 11, pp. 3511–3523, 2018.
- [26] D. Shi, Y. Zeng, and W. Shen, "Perovskite/ c -Si tandem solar cell with inverted nanopillars: realizing high efficiency by controllable light trapping," *Sci. Rep.*, vol. 5, no. 16504, pp. 1–10, Nov. 2015.
- [27] B. W. Schneider, N. N. Lal, S. Baker-Finch, and T. White, "Pyramidal surface textures for light trapping and antireflection in perovskite-on-silicon tandem solar cells," *Opt. Express*, vol. 22, no. S6, pp. A1422–A1430, Oct. 2014.
- [28] S. Foster and S. John, "Light-trapping design for thin-film silicon-perovskite tandem solar cells," *J. Appl. Phys.*, vol. 120, no. 103103, pp. 1–9, 2016.
- [29] F. Sahli, J. Werner, B. A. Kamino, M. Bräuninger, R. Monnard, B. Paviet-Salomon, L. Barraud, L. Ding, J. J. D. Leon, D. Sacchetto, G. Cattaneo, M. Despeisse, M. Boccard, S. Nicolay, Q. Jeangros, B. Niesen, and C. Ballif, "Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency," *Nat. Mater.*, vol. 17, pp. 820–826, Sep. 2018.
- [30] A. Al-Ashouri, E. Köhnen, B. Li, A. Magomedov, H. Hempel, P. Caprioglio, J. A. Márquez, A. B. M. Vilches, E. Kasparvicius, J. A. Smith, N. Phung, D. Menzel, M. Grischek, L. Kegelmann, D. Skroblin, C. Gollwitzer, T. Malinauskas, M. Jošt, G. Matič, B. Rech, R. Schlattmann, M. Topič, L. Korte, A. Abate, B. Stannowski, D. Neher, M. Stollerfoht, T. Unold, V. Getautis, and S. Albrecht, "Monolithic perovskite/silicon tandem solar cell with > 29% efficiency by enhanced hole extraction," *Science*, vol. 370, no. 6522, pp. 1300–1309, Dec. 2020.
- [31] P. Tockhorn, J. Sutter, A. Cruz, P. Wagner, K. Jäger, D. Yoo, F. Lang, M. Grischek, B. Li, J. Li, O. Shargaieva, E. Unger, A. Al-Ashouri, E. Köhnen, M. Stollerfoht, D. Neher, R. Schlattmann, B. Rech, B. Stannowski, S. Albrecht, and C. Becker, "Nano-optical designs for high-efficiency monolithic perovskite-silicon tandem solar cells," *Nat. Nanotechnol.*, vol. 17, pp. 1214–1221, Nov. 2022.
- [32] B. Chen, Z. J. Yu, S. Manzoor, S. Wang, W. Weigand, Z. Yu, G. Yang, Z. Ni, X. Dai, Z. C. Holman, and J. Huang, "Blade-Coated Perovskites on Textured Silicon for 26%-Efficient Monolithic Perovskite/Silicon Tandem Solar Cells," *Joule*, vol. 4, pp. 850–864, Apr. 2020.

- [33] E. Aydin, E. Ugur, B. K. Yildirim, T. G. Allen, P. Dally, A. Razzaq, F. Cao, L. Xu, B. Vishal, A. Yazmaciyan, A. A. Said, S. Zhugamali, R. Azmi, M. Babics, A. Fell, C. Xiao, and S. D. Wolf, "Enhanced optoelectronic coupling for perovskite/silicon tandem solar cells," *Nature*, vol. 623, pp. 732–738, 2023.
- [34] Y. Hou, E. Aydin, M. D. Bastiani, C. Xiao, F. H. Isikgor, D.-J. Xue, B. Chen, H. Chen, B. Bahrami, A. H. Chowdhury, A. Johnston, S.-W. Baek, Z. Huang, M. Wei, Y. Dong, J. Troughton, R. Jalmood, A. J. Mirabelli, T. G. Allen, E. V. Kerschaver, M. I. Saidaminov, D. Baran, Q. Qiao, K. Zhu, S. D. Wolf, and E. H. Sargent, "Efficient tandem solar cells with solution-processed perovskite on textured crystalline silicon," *Energy Environ. Sci.*, vol. 367, no. 6482, pp. 1135–1140, 2020.
- [35] E. Aydin, J. Liu, E. Ugur, R. Azmi, G. T. Harrison, Y. Hou, B. Chen, S. Zhumagali, M. D. Bastiani, M. Wang, W. Raja, T. G. Allen, A. Rehman, A. H. Subbiah, M. Babics, A. Babyigit, F. H. Isikgor, K. Wang, E. V. Kerschaver, L. Tsetseris, E. H. Sargent, F. Laquai, and S. D. Wolf, "Ligand-bridged charge extraction and enhanced quantum efficiency enable efficient n-i-p perovskite/silicon tandem solar cells," *Energy Environ. Sci.*, vol. 14, no. 8, 2021.
- [36] X. Y. Chin, D. Turkay, J. A. Steele, S. Tabean, S. Eswara, M. Mensi, P. Fiala, C. M. Wolff, A. Paracchino, K. Artuk, D. Jacobs, Q. Guesnay, F. Sahli, G. Andreatta, M. Boccard, Q. Jeangros, and C. Ballif, "Interface passivation for 31.25%-efficient perovskite/silicon tandem solar cells," *Science*, vol. 381, pp. 59–63, Jul. 2023.
- [37] B. P. Kore, O. Er-raji, O. Fischer, A. Callies, O. Schultz-Wittmann, P. S. C. Schulze, M. Bivour, S. D. Wolf, S. W. Glunz, and J. Borchert, "Efficient fully textured perovskite silicon tandems with thermally evaporated hole transporting materials," *Energy Environ. Sci.*, vol. 18, pp. 354–366, 2025.
- [38] S. Mariotti, E. Köhnen, F. Scheler, K. Sveinbjörnsson, L. Zimmermann, M. Piot, F. Yang, B. Li, J. Warby, A. Musiienko, D. Menzel, F. Lang, S. Keßler, I. Levine, D. Matrone, A. Al-Ashouri, M. S. Härtel, K. Xu, A. Cruz, J. Kurpiers, P. Wagner, H. Köbler, J. Li, A. Magedomedov, D. Mecerreyes, E. Unger, A. Abate, M. Stolterfoht, B. Stannowsky, R. Schlattmann, L. Korte, and S. Albrecht, "Interface engineering for high-performance, triple-halide perovskite-silicon tandem solar cells," *Science*, vol. 381, 2023.
- [39] Y. Wang, J. Hüpkens, S. Ravishankar, B. Klingebiel, and T. Kirchartz, "Loss analysis of halide-perovskite solar cells deposited on textured substrates," *Sol. RRL*, vol. 9, 2025.
- [40] Y. Shi, J. J. Berry, and F. Zhang, "Perovskite/silicon tandem solar cells: Insights and outlooks," *ACS Energy Lett.*, vol. 9, pp. 1305–1330, 2024.
- [41] J. Liu, Y. He, K. Ding, H. Zhang, Q. Li, L. Jia, J. Yu, T. W. Lau, M. Li, Y. Qin, X. Gu, F. Zhang, Q. Li, Y. Yang, S. Zhao, X. Wu, J. Liu, T. Liu, Y. Gao, Y. Wang, X. Dong, H. Chen, P. Li, T. Zhou, M. Yang, X. Ru, F. Peng, S. Yin, M. Qu, D. Zhao, Z. Zhao, M. Li, P. Guo, H. Yan, C. Xiao, P. Xiao, J. Yin, X. Zhang, Z. Li, B. He, and X. Xu, "Perovskite/silicon tandem solar cells with bilayer interface passivation," *Nature*, vol. 635, pp. 596–603, 2024.
- [42] F. Fu, J. Li, T. C.-J. Yang, H. Liang, A. Faes, Q. Jeangros, C. Ballif, and Y. Hou, "Monolithic perovskite-silicon tandem solar cells: From the lab to fab?" *J. Adv. Mater.*, vol. 34, no. 2106540, pp. 1–23, 2022.
- [43] X. Luo, H. Luo, H. Li, R. Xia, X. Zheng, Z. Huang, Z. Liu, H. Gao, X. Zhang, S. Li, Z. Feng, Y. Chen, and H. Tan, "Efficient perovskite/silicon tandem solar cells on industrially compatible textured silicon," *Adv. Mater.*, vol. 35, no. 2207883, 2023.
- [44] E. Aydin, T. G. Allen, M. D. Bastiani, A. Razzaq, L. Xu, E. Ugur, J. Liu, and S. D. Wolf, "Pathways toward commercial perovskite/silicon tandem photovoltaics," *Science*, vol. 383, no. 162, 2024.
- [45] P. M. Pearce, "RayFlare: flexible optical modelling of solar cells," *J. Open Source Softw.*, vol. 6, no. 65, 2021.
- [46] T. H. Fung, M. U. Khan, Y. Zhang, N. J. Wstern, D. N. R. Payne, and K. R. McIntosh, "Improved ray tracing on random pyramid texture via application of phong scattering," *IEEE Photonics J.*, vol. 9, pp. 591–600, 2019.
- [47] D. Alonso-Álvarez, T. Wilson, P. Pearce, M. Führer, D. Farrel, and N. Ekins-Daukes, "Solcore: a multi-scale, Python-based library for modelling solar cells and semiconductor materials," *J. Comput. Electron.*, vol. 17, pp. 1099–1123, 2018.
- [48] H. Hao, S.-T. Zhang, K. Wang, P. Yang, J. Wang, L. Yang, L. Lu, and D. Li, "Energy yield prediction of bifacial perovskite/silicon tandem photovoltaic modules," *Sol. RRL*, vol. 7, no. 2300218, pp. 1–10, 2023.
- [49] Y. Zeng, Z. Ding, Z. Liu, W. Liu, M. Liao, X. Yang, Z. Ying, J. Sun, J. Sheng, B. Yan, H. He, C. Shou, Z. Yang, and J. Ye, "Efficiency-loss analysis of monolithic perovskite/silicon tandem solar cells by identifying the patterns of a dual two-diode model's current-voltage curves," *J. Semicond.*, vol. 44, 2023.
- [50] D. Kiermasch, M. Fischer, L. Gil-Escrig, A. Baumann, H. K. Bolink, V. Dyakonov, and K. Tvingstedt, "Reduced Recombination Losses in Evaporated Perovskite Solar Cells by Postfabrication Treatment," *Sol. RRL*, vol. 5, no. 2100400, 2021.
- [51] PV Lighthouse, "Refractive index library," 2025, accessed: 01/28/2025. [Online]. Available: <https://www.pvlighthouse.com.au/refractive-index-library>
- [52] RefractiveIndex.INFO, "Refractive index database," 2025, accessed: 01/28/2025. [Online]. Available: <https://refractiveindex.info/>
- [53] H. Fujiwara, *Hybrid Perovskite Solar Cells: Characteristics and Operation – Appendix A: Optical Constants of Hybrid Perovskite Materials*. WILEY, 2021.
- [54] X. Tian, P. Han, G. Zhao, R. Yang, L. Li, Y. Meng, and T. Guo, "Pyramid size control and morphology treatment for high-efficiency silicon heterojunction solar cells," *J. Semicond.*, vol. 40, 2019.
- [55] M. C. Traub, W. Longsine, and V. N. Truskett, "Advances in Nanoimprint Lithography," *Annu. Review Chem. Biomol.*, vol. 7, no. 1, pp. 583–604, Jun. 2016.
- [56] Z. Ying, X. Yang, X. Wang, and J. Ye, "Towards the 10-year milestone of monolithic perovskite/silicon tandem solar cells," *J. Adv. Mater.*, vol. 36, no. 2311501, 2024.
- [57] O. Höhn, N. Tucher, and B. Bläsi, "Theoretical study of pyramid sizes and scattering effects in silicon photovoltaic module stacks," *Opt. Express*, vol. 26, no. 6, pp. A320–A330, 2018.