

Performance Potential for Locally Contacted Perovskite Solar Cells

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In perovskite solar cells (PSCs), a common characteristic of highly effective interface passivation materials is low conductivity. Gains in voltage are thus often disproportionately offset by resistive losses. Local contact approaches can minimize this trade-off and have a proven track record in conventional silicon photovoltaics. Indeed, recent record efficiencies for centimeter-scale PSCs exploit architectures where the passivation layer partially covers the perovskite-transport layer interface. Herein, a three-dimensional numerical device model is used to determine practical performance limits to local contact geometries and consider both the optimum contact dimensions and the trade-offs involved in relaxing these dimensions for ease of fabrication. It is observed that the potential for substantial power conversion efficiency (PCE) increases with local contacts. In devices where power loss occurs solely through recombination at the contacted interface, PCE can be enhanced by up to 10% absolute compared to a full-area contact. However, optimum PCEs depend on contacts on the order of nanometers. It is shown that more fabrication-friendly micrometer-scale contacts still boost PCE, but the absolute enhancement falls short due to the relatively low bulk perovskite charge carrier diffusion length. This may ultimately motivate methods of interface engineering that produce “effective” local contact geometries at nanometer scales, such as via self-forming layers.

1. Introduction

An interlayer between the perovskite and transport layers is widely employed in solar cells to reduce interface defects and recombination losses. However, these materials often impede charge transport and thus are fabricated as thin as possible^[1] or modified with additives, as in the case of phenyl-*n*-butyric acid methyl ester (PCBM) blended into polymethylmethacrylate (PMMA) in perovskite solar cells.^[2] Another approach, which underpins the silicon (Si) passivated emitter rear cell (PERC) technology,^[3–6] incorporates local contacts in the passivating interface layer (Figure 1c). Charge transport to the charge-selective electrodes occurs at these local contacts, with the uncontacted regions highly passivating (and insulating). This approach has the benefit of relaxing thickness tolerances on the interface layer and widening the range of materials compatible with high efficiency, including passivating interface materials that could not be fabricated at tolerable thicknesses or with insufficient conductivity.

The maximum spatial separation of local contacts in Si PERC cells is roughly constrained by the minority carrier diffusion length of the silicon bulk, typically in the range of 0.5–3 mm in high-efficiency cells, although in some architectures a sheet diffusion or transparent conductive oxide layer contributes to lateral conductivity. Consequently, contact separation in high-efficiency local contact Si cells is on the order of $\approx 1,000 \mu\text{m}$.^[5,7] However, despite the significant progress made in Si solar cell technology, local contact geometries, or otherwise functionally equivalent structures, are only just being implemented into PSCs.^[8–11] The results are promising, with recent centimeter-scale records being set with this approach.^[9,10] Nonetheless, there remains an open question as to the performance potential and practical limitations of this architecture in PSCs, especially in the context of the vastly smaller charge carrier diffusion lengths, which are roughly three orders of magnitude smaller than monocrystalline Si.^[12]

A major advantage of local contact architectures is the wider range of high-quality interface passivating materials that are too resistive for full-area passivation. For example, Kirchartz et al. demonstrated the exceptional passivation ability of *n*-trioctylphosphine oxide (TOPO) on methylammonium lead

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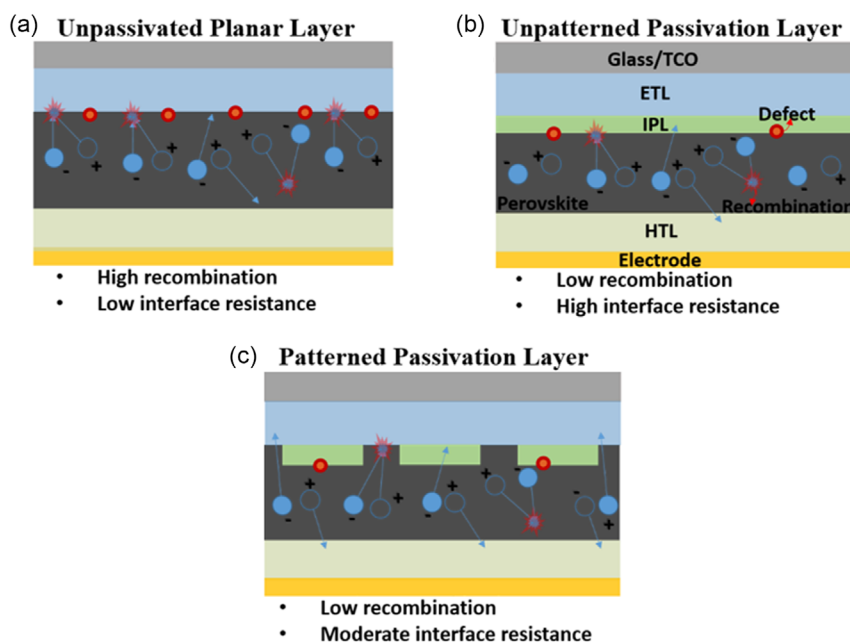


Figure 1. a) Schematic diagram of the device geometries of unpassivated planar layer, b) unpatterned passivated layer, and c) patterned local contacts, and their corresponding working mechanisms.

iodide. They observed that TOPO-passivated films exhibited high quantum efficiency and quasi-Fermi energy level splitting, affirming the suppression of nonradiative recombination.^[13] However, TOPO's high resistivity hinders charge transport, constraining fill factor (FF), and efficiency below theoretical limits determined from the device voltage.^[13,14] This can be attributed to a necessity to employ extremely thin layers to achieve functional conductance across the interface.^[15–20] An example of the trade-off is presented by Meng et al.^[18] who modified TOPO layer thickness and observed a negative correlation between voltage and FF. In principle, however, utilizing a thick TOPO layer with local contacts can achieve most of the passivation benefits while minimizing resistive losses.

The idealized geometry of a local contact structure is presented in Figure 1c. A regular two-dimensional array of apertures is fabricated in a continuous, insulating interface layer. Methods to achieve these local contacts depend on the length scales involved. For contacts on the nanometer scale, in a previous report,^[9] we introduced a nanostructured titania electron transport layer (ETL) consisting of nanorod arrays formed by the electron-beam lithography (EBL) method, which was then topped with a thin PMMA passivation layer. The nanorod arrays modified the spatial distribution of the passivation layer, establishing a nanoscale array of localized charge transport pathways. This approach provided both effective passivation and excellent charge extraction, resulting in a certified PCE of 21.6% and a high FF of 83.9% for a 1 cm² cell.

EBL techniques are unlikely to be suitable for industrial large-area fabrication, but in a related investigation, Peng et al.^[10] utilized a thick alumina (Al₂O₃) insulator layer with nanoscale openings between isolated islands of Al₂O₃ formed by Volmer–Weber (V–W) growth. By employing this “porous insulator contact”

strategy, they achieved a certified efficiency of 24.7% using only fractional passivation of the perovskite-transport layer interface. By moving to larger dimension contacts, on the order of micrometers, a recent study by Mao et al.^[11] used patterned lithium fluoride (LiF) insulator contacts to achieve a certified PCE of 24.95% on a small area using local contacts at both interfaces. This patterned LiF layer was created through thermal evaporation with a shadow mask featuring periodic circular openings. With local contacts on a single interface, Mao et al. achieved a PCE of ≈24%.

Therefore, experimental evidence makes clear that a local contact geometry is a viable path to enhance performance in PSCs across a range of contact sizes. Yet, an outstanding question is the practical achievable PCEs with these local contact geometries across a range of contact dimensions and at varying rates of recombination at the unpassivated, contacted region of the interface. This is particularly important in the design of micrometer-scale contacts, where such dimensions could open the possibility for more industrial-friendly fabrication techniques such as laser micromachining (ablation).^[21]

Therefore, in this work, we applied a three-dimensional (3D) numerical electronic–ionic drift-diffusion model of locally contacted PSCs to find the highest performing geometry that optimizes the trade-off between passivation and conductivity for local contact sizes ranging from nanometer to micrometer scale. We consider the influence of recombination rate at the local contact, perovskite absorber mobility, contact size, and separation. Other key electronic parameters of the device model, including contact resistivity, transport layers, and perovskite properties are based on previous simulation.^[9] We assumed that interface recombination occurs only at the perovskite/ETL contact, and that the passivating layer is both perfectly insulating and

passivating. Our simulation parameters were taken from our previous works^[9,22–24] and literature^[25–30] to ensure a coherent device model, as shown in Table S1, Supporting Information.

2. Results and Discussions

2.1. Design Selection and Working Principle

All device simulations were performed with a three-dimensional drift-diffusion model in COMSOL Multiphysics, as described previously.^[9] Key device parameters were defined with a view to tandem applications, thus, we focused on a relatively wide bandgap of 1.65 eV and assumed a generation current density of 23 mA cm^{-2} .^[29] For comparison, and to determine the optimal single-junction performance, additional simulations at 1.55 eV bandgap were also performed.

Figure 1 illustrates the working principle of the locally contacted passivation layer, in addition to the two limited cases of full-area interface passivated and unpassivated surfaces. In an ideal device, unimpeded selective charge transport of the appropriate majority carrier occurs at each interface. However, it is often the case that a bare interface between the perovskite and the charge-selective transport layer produces recombination-active defects that result in nonradiative energy losses (Figure 1a). Consequently, low majority carrier resistance is accompanied by high nonradiative recombination rates. To mitigate this issue, the introduction of an insulating passivation layer at the perovskite-ETL interface proves effective in reducing defect concentration, thereby lowering nonradiative recombination (Figure 1b). Yet, this passivation layer brings about an increment in interface resistivity and a subsequent reduction in the FF. Hence, we adopt a compromise wherein local contacts are created within the passivation layer to facilitate charge collection while minimizing the total unpassivated area of the cell (Figure 1c). This structural design relies on the perovskite absorber for lateral charge transport to these local contacts,

making carrier mobility and lifetime a crucial factor in achieving high FF and PCE.

2.2. Photovoltaic Performance of Planar Perovskite Solar Cells

To establish a baseline level of performance for comparison to local contact devices, we simulated a full-area contacted PSC with varying levels of contact recombination rates. The simulated photovoltaic performance of these structures is presented in Figure 2 and S2, Supporting Information considering a perovskite absorber of $5 \text{ cm}^2 \text{ Vs}^{-1}$. Figure S3, Supporting Information depicts analogous plots for Figure 2 and S2, Supporting Information, considering a perovskite mobility of $1 \text{ cm}^2 \text{ Vs}^{-1}$.

The magnitude of interface recombination at the contacted region of the perovskite-ETL interface is a critical parameter in determining the optimum local contact geometry. Our simulations model interface recombination via generalized Shockley–Read–Hall recombination through interfacial defects. Thus, several defect parameters are influential on the total recombination rate, including electron and hole capture cross sections, defect energy level, and areal density. In this implementation, we have assumed a midgap energy level for the traps, with capture cross sections of 10^{-15} cm^2 for both electrons and holes. The areal defect density ($N_{t,\text{surf}}$) is adjusted to explore a range of interface recombination.

Figure 2a displays the current–voltage curves at various contact defect densities. As these defect parameters are ultimately conditional on other defect properties, $N_{t,\text{surf}}$ is a proxy for different magnitudes of contact recombination rates. To establish reference values of $N_{t,\text{surf}}$, we performed simulations of a full area contacted PSC (Figure 1a). We identified values of $N_{t,\text{surf}}$ for which efficiency loss, relative to negligible interface recombination was 0.5, 3, and 10 percentage points (Figure 2). For the discussion to follow, these values of $N_{t,\text{surf}}$ are referred to as the low, medium, and high interface recombination scenarios,

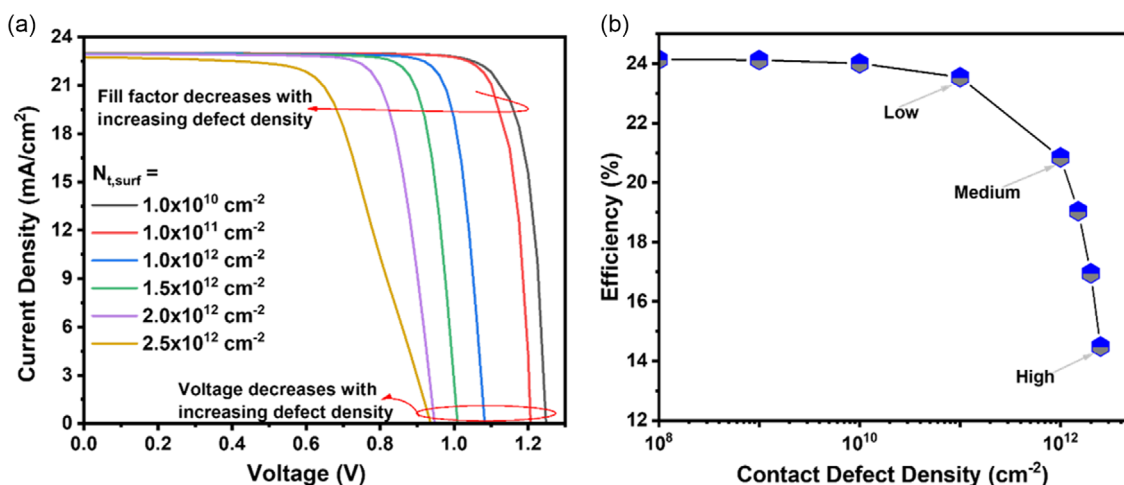


Figure 2. Simulated performance of unpassivated planar devices as a function of contact defect density at the perovskite-ETL interface, where the bulk perovskite has a charge carrier mobility of $5 \text{ cm}^2 \text{ Vs}^{-1}$. a) Current–voltage curves. b) Efficiency versus contact defect density. The contact defect density at 1.0×10^{11} , 1.0×10^{12} , and $2.5 \times 10^{12} \text{ cm}^{-2}$ signifies low, medium, and high recombination rate scenarios, respectively, as indicated.

respectively. Figure 2b shows the efficiency dependence on the contact defect densities. Figure S2a, Supporting Information illustrates the variation of FF with voltage at various contact defect densities. Figure S2b, Supporting Information demonstrates the dependency of current density on contact defect densities ranging from 1.0×10^8 to $2.5 \times 10^{12} \text{ cm}^{-2}$. The low recombination condition was selected as the threshold at which a reduction in PCE is first observed (in this model: PCE = 23.5% at $N_{t,\text{surf}} = 10^{11} \text{ cm}^{-2}$), while the high recombination condition was defined by a level at which interface recombination reduces device performance to a level that would be considered irrelevant for practical applications (PCE = 14% at $N_{t,\text{surf}} = 2.5 \times 10^{12} \text{ cm}^{-2}$).

2.3. Application of Local Contacts in PSCs

In this first instance, we consider in general the simulated impact of a local contact geometry on PCE across the full spectrum of $N_{t,\text{surf}}$ from low to high interface recombination. We consider the dependence of open-circuit voltage (V_{oc}), FF, and PCE on recombination and contact area. Figure 3 shows simulated data for local contact radii of 50 and 100 nm. As expected, we observe here the tension between recombination and resistance in a locally contacted device. For any given recombination rate, reducing the contact spacing (increasing the area fraction (AF) of the local contacts) decreases V_{oc} due to the larger recombination-active area of the interface. This motivates lower-contact AFs. However, if the pitch is too large, given electron and hole mobility in the perovskite, the FF decreases rapidly due to the excessive distance that carriers must diffuse in the perovskite bulk to the

local contacts. Consequently, for any given recombination rate, there is an optimum contact AF that maximizes the PCE. The relative gains in PCE from this trade-off are greatest at higher recombination rates ($N_{t,\text{surf}} \geq 10^{12} \text{ cm}^{-2}$), which emphasize the value of local contact geometries for more highly recombination-active contacted surfaces.

In addition, a comparison between the 50 and 100 nm contact radii shows that increasing the contact size limits achievable PCEs at higher values of $N_{t,\text{surf}}$. In both cases, we observe the expected trade-off between V_{oc} , which decreases with increasing AF and FF, which decreases with decreasing AF. The results of Figure 3 assume a perovskite mobility of $5 \text{ cm}^2 \text{ Vs}^{-1}$. In Figure S5, Supporting Information, we plot similar contour figures for a bulk mobility of $1 \text{ cm}^2 \text{ Vs}^{-1}$ and observe an overall lower achievable PCE at any given recombination rate and AF. This is a consequence of increased FF losses due to the higher bulk resistivity of the perovskite absorber, which must transport photogenerated electrons to the local contact regions.

We also note here that a comparison between circular and square contacts showed no significant influence on the contact shape on performance. At 10% contact AF, both square and circular contacts of the equivalent area have predicted PCEs within 1% relative difference (Figure S8, Supporting Information).

2.4. Design Guidelines for Local Contact Fabrication in Real-World Applications

Figure 4 plots simulated figures of merit for PSCs with local contact radii of 5, 50, 100, and 1000 nm as a function of AF. In the PCE plots of Figure 4a, we observe a clear peak in

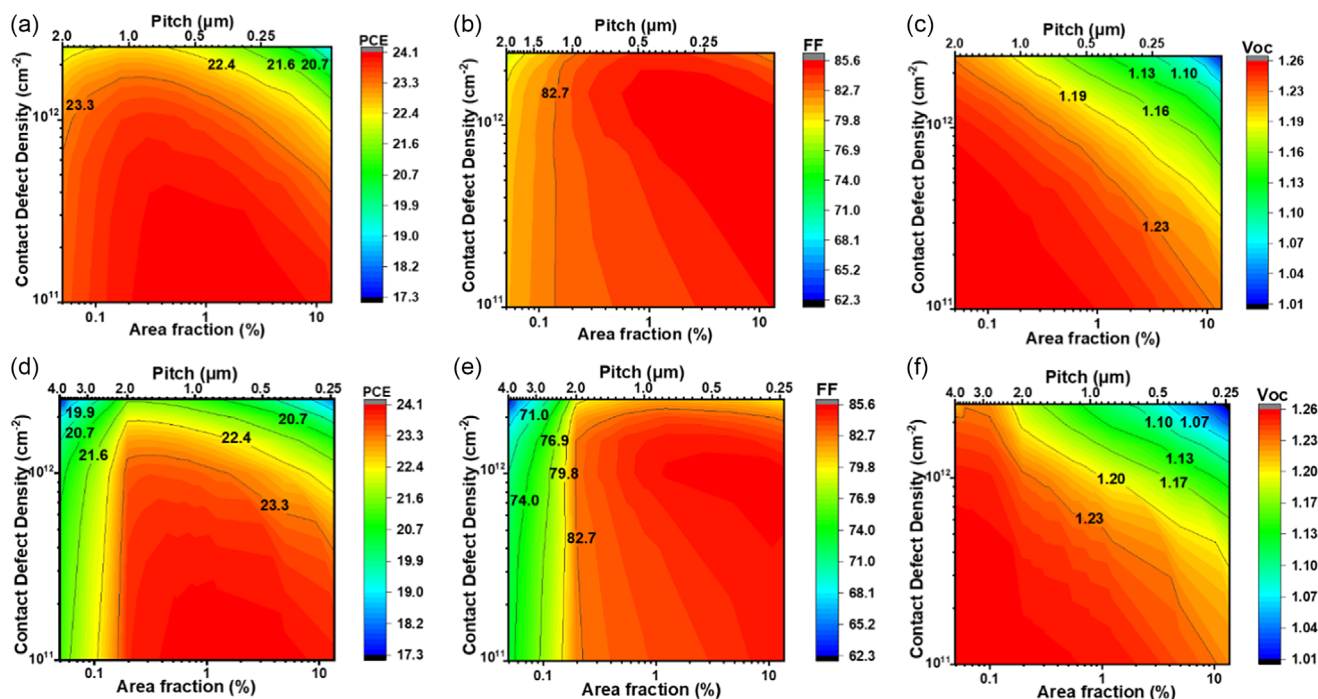


Figure 3. Photovoltaic parameters for contact defect density in the range of $1.0 \times 10^{11} - 2.5 \times 10^{12} \text{ cm}^{-2}$ for a) PCE, b) FF, c) V_{oc} using a local contact radius of 50 nm, and d) PCE, e) FF, and f) V_{oc} using a local contact radius of 100 nm. All figures are calculated at a perovskite charge carrier mobility of $5 \text{ cm}^2 \text{ Vs}^{-1}$.

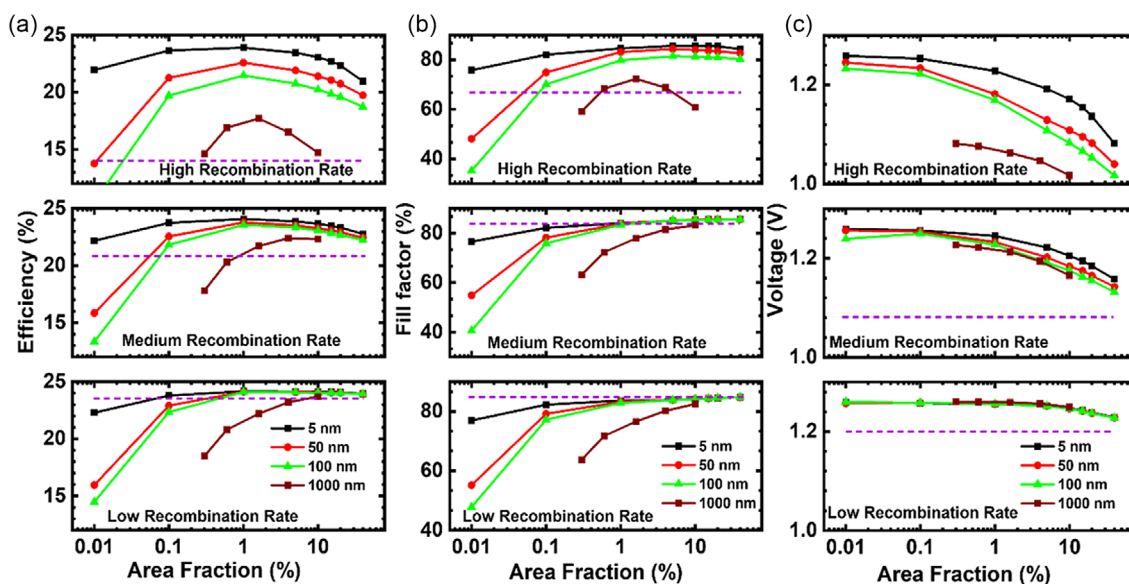


Figure 4. Impact of local contact AF, contact radius (r), and different contact defect density on the photovoltaic performance to denote the low, medium, and high recombination rate for a) efficiency, b) FF, and c) voltage at absorber mobility of $5 \text{ cm}^2 \text{Vs}^{-1}$. At a high recombination rate, the voltage extracted for the unpassivated planar device is 0.9 V.

efficiency at the optimum between FF and V_{oc} . The large drop in PCE for small contact fractions ($AF < 0.1\%$) is a function of the loss in FF as the contact separation results in measurable resistive transport losses in the perovskite bulk (Figure 4b). In Figure 4c, we observe that voltage drops continuously with increasing AF, indicative of the increase in the total AF of recombination-active contacts, which increases total recombination in the cell.

We also observe that it is possible for a local contact geometry to underperform the full area unpassivated contact. This occurs wherever FF losses due to recombination and bulk transport resistance exceed the gains in open-circuit voltage. Voltage is always higher, owing to the reduced recombination active surface area in the locally contacted structure, but low contact fractions (i.e., a greater separation between contacts) result in resistive losses that overwhelm the gains in voltage.

These simulations also demonstrate the absolute performance reduction that occurs for larger contacts at any given combination of contact recombination and the AF. This can be understood by considering the volume of the perovskite surrounding the contact. Recombination at the contact produces a minority carrier concentration gradient that results in a minority carrier diffusion current that flows toward the contact. Beyond a threshold position in the perovskite, photogenerated minority carriers will preferentially diffuse to the contact and will be lost to the external circuit thereby reducing overall efficiency. In supplementary Figure S9, we plot the two-dimensional current paths of photogenerated holes in our simulated devices. Larger local contacts expand the recombination-affected volume deeper into the perovskite absorber. For instance, a 5 nm radius local contact affects a region that extends 15 nm into the absorber, while the same region for a 100 nm radius contact extends to 220 nm. Consequently, the volume of the perovskite absorber losing photogenerated holes to recombination increases,

reducing cell voltage and FF despite a common AF. Additionally, the FF further declines due to the increased distance between contacts for a given AF. This ultimately points toward isolated local contacts at the nanometer scale are necessary to achieve maximum PCE gains from local contacts architectures.

The maximum achievable efficiency for each contact size, given a perovskite mobility of $5 \text{ cm}^2 \text{Vs}^{-1}$, is depicted in Figure 5. For a 5 nm radius, a PCE of up to 24% can be achieved at the optimum AF even at the highest recombination rate we considered. Indeed, the dimensions of the contact itself make

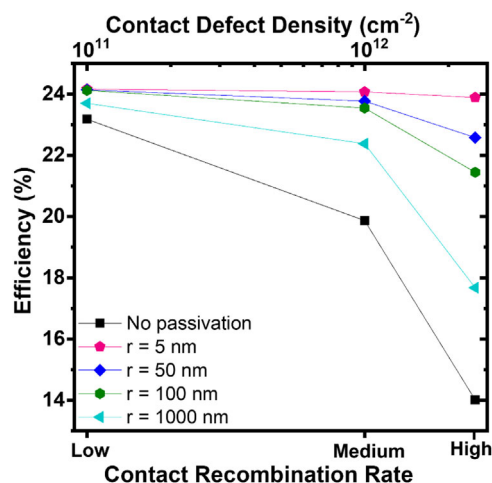


Figure 5. A plot of efficiency versus varied contact recombination rate for unpassivated planar and the different local contact radii (r) for the local contact geometry extracted at a perovskite mobility of $5 \text{ cm}^2 \text{Vs}^{-1}$ at optimized pitches.

the PSC relatively insensitive to interface recombination, a substantial advantage from the perspective of relaxing process control and expanding material choice. At the highest recombination rate, the local contact device is up to 10 percentage points more efficient than a planar, unpassivated device. As the contact radius increases, the achievable PSC falls, but up to $r = 1000$ nm, PCE still maintains a significant lead over the unpassivated device ($\approx 17.7\%$ vs $\approx 14\%$). These results underscore the advantages of the local contact geometry in enhancing PCE under higher recombination rates at the contacted interface.

As discussed above, these simulations emphasize the preference for the smallest possible local contacts, and demonstrate that there is still significant PCE headroom for the current record performance devices.^[10,11] For instance, Peng et al.^[10] achieved efficiencies of 24.7% and 21.65%, respectively, using bandgaps of 1.55 and 1.65 eV respectively. Mao et al.^[11] achieved efficiencies of 24.95% and 21.50%, using bandgaps of 1.54 and 1.65 eV, respectively. In comparison, our simulation model achieved a high PCE of 27.0% (Figure S11, Supporting Information) and 24.2% using bandgaps of 1.55 and 1.65 eV respectively. These results suggest that further optimization of the local contact geometry could potentially lead to an increase in PCE of over 2% absolute. However, achieving such diminutive hole arrays at an industrial scale may pose a challenge and in practice, achievable PCEs may be constrained by the realities of mass production.

For micrometer-scale regular array contact formation, laser patterning techniques can fabricate local contacts down to a radius of ≈ 10 micrometers.^[21] Based on our simulations, this would result in a PCE not significantly above a full-area contact for a device with high contact recombination. The work of Mao et al. showed a reasonable PCE of 21.5% incorporating local contacts with a diameter of 280 μm and a spacing of 20 μm . However, it is worth noting that the LiF passivation layer adopted by Mao et al. was not perfectly insulating and the measured fluorine distribution was indicative of a graded local contact structure, as opposed to the discrete low resistance/high recombination and high resistance/low recombination structure we considered here. Our simulations also suggest that recombination at the contacted interface was likely lower, as evidenced by the relatively high baseline PCE and the relatively small boost in PCE achieved with such large uncontacted regions. This would be equivalent to a contact defect density of $\leq 10^{12} \text{ cm}^{-2}$ (i.e., between the “low” and “medium” conditions in our simulations of Figure 5). These results suggest that in cases where the contacted interfaces produce only limited levels of recombination, micrometer-scale local contact methods may still be worth considering.

Another strategy is to adopt the chemical processes that result in nanometer-scale patterning of the interfacial passivation layer.^[10,31] Such a strategy would utilize techniques that create self-forming, discontinuous coverage by the passivation layer, thereby bypassing the intricate patterning step. For instance, our previous work has suggested that 2D perovskite surface layers may owe their efficacy to discontinuous coverage of the surface of the underlying 3D perovskite film.^[31] Whichever approach is taken, practical considerations should also guide implementation. For example, if the passivation layer is to be deposited before the perovskite absorber, it is important to

ensure that the perovskite can completely fill the local contact holes and make good electrical contact with the underlying transport layer. We also note that secondary advantages may result from patterned interface layers, such as an improvement in crystal quality of the deposited perovskite as observed by Peng et al.^[10] which can improve charge carrier mobility, lifetime, and overall performance. If the passivation layer is deposited onto the perovskite layer, then the fabrication method must not damage the perovskite, and the top transport layer must then be able to make adequate penetration into the local contacts.

Finally, it is crucial to highlight the importance of high mobility and low surface recombination at the passivated regions of the perovskite-transport layer interface in the successful implementation of local contact regimes, especially when employing patterning techniques. Improving bulk perovskite mobility will reduce the FF losses associated with increased contact separation and facilitate large local contacts in a regular array pattern.

3. Conclusion

In summary, our study simulated the comparative performance of unpassivated planar PSCs and those incorporating local contacts in an insulating passivation layer. Our findings highlight the efficiency potential for an optimized local contact geometry, which balances the trade-off between recombination and resistive losses. This optimization approach enables the development of high-efficiency PSCs, especially for nanoscale contacts, at any given recombination rate. Related to an unpassivated full-area contact geometry, optimal local contacts could increase PSC by up to 10 percentage points, effectively improving cell performance from impractical (14%) to a higher efficiency (24%) at a 1.65 eV perovskite bandgap. For a lower bandgap device ($E_g = 1.55$ eV), efficiency can reach up to 27%, for local contact recombination at the highest recombination rate we considered here. In addition, adopting a local contact strategy can expand the possible range of passivating interlayers that are too electrically insulating to include as continuous interface layers, such as TOPO.

The simulation findings also reveal that larger contacts on the micrometer scale, which may be more practical from an industrial perspective (i.e., suitable for fabrication via laser micromachining), have comparatively low-efficiency potential, albeit still above the fully-contacted, unpassivated architecture. Given the practical limitations on fabricating a regular array of nanoscale contacts over a large area, these results may motivate self-forming techniques which create effective locally contacted interfaces and have already demonstrated their efficiency potential in record PSC devices.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

contact defect concentration, insulating passivation layer, local contacts, patterned, perovskite solar cells, resistive loss, simulation

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- [1] T. G. Allen, J. Bullock, X. Yang, A. Javey, S. De Wolf, *Nat. Energy* **2019**, 4, 914.
- [2] J. Peng, Y. Wu, W. Ye, D. A. Jacobs, H. Shen, X. Fu, Y. Wan, T. Duong, N. Wu, C. Barugkin, H. T. Nguyen, D. Zhong, J. Li, T. Lu, Y. Liu, M. N. Lockrey, K. J. Weber, K. R. Catchpole, T. P. White, *Energy Environ. Sci.* **2017**, 10, 1792.
- [3] K. Catchpole, A. Blakers, *Sol. Energy Mater. Sol. Cells* **2002**, 73, 189.
- [4] A. W. Blakers, A. Wang, A. M. Milne, J. Zhao, M. A. Green, *Appl. Phys. Lett.* **1989**, 55, 1363.
- [5] A. A. Sabater, A. Fell, A. A. Brand, M. Muller, J. M. Greulich, *IEEE J. Photovoltaics* **2021**, 11, 1136.
- [6] M. A. Green, *Sol. Energy Mater. Sol. Cells* **2015**, 143, 190.
- [7] J.-S. Chiu, Y.-M. Zhao, S. Zhang, D.-S. Wu, *Sol. Energy* **2020**, 196, 462.
- [8] J. Wu, Y. Fang, D. Zhang, S. Zhang, J. Wan, R. Wen, X. Zhou, N. Fu, Y. Lin, *J. Mater. Chem. A* **2021**, 9, 14877.
- [9] J. Peng, D. Walter, Y. Ren, M. Tebyetekerwa, Y. Wu, T. Duong, Q. Lin, J. Li, T. Lu, M. A. Mahmud, O. L. C. Lem, S. Zhao, W. Liu, Y. Liu, H. Shen, L. Li, F. Kremer, H. T. Nguyen, D.-Y. Choi, K. J. Weber, K. R. Catchpole, T. P. White, *Science* **2021**, 371, 390.
- [10] W. Peng, K. Mao, F. Cai, H. Meng, Z. Zhu, T. Li, S. Yuan, Z. Xu, X. Feng, J. Xu, M. D. McGehee, J. Xu, *Science* **2023**, 379, 683.
- [11] K. Mao, F. Cai, Z. Zhu, H. Meng, T. Li, S. Yuan, J. Zhang, W. Peng, J. Xu, X. Feng, Q. Chen, J. Xu, *Adv. Energy Mater.* **2023**, 2302132, 1.
- [12] M. J. P. Alcocer, T. Leijtens, L. M. Herz, A. Petrozza, H. J. Snaith, *Science* **2013**, 342, 341.
- [13] Z. Liu, L. Krückemeier, B. Krogmeier, B. Klingebiel, J. A. Márquez, S. Levchenko, S. Öz, S. Mathur, U. Rau, T. Unold, T. Kirchartz, *ACS Energy Lett.* **2019**, 4, 110.
- [14] M. Stolterfoht, M. Grischek, P. Caprioglio, C. M. Wolff, E. Gutierrez-Partida, F. Peña-Camargo, D. Rothhardt, S. Zhang, M. Raoufi, J. Wolansky, M. Abdi-Jalebi, S. D. Stranks, S. Albrecht, T. Kirchartz, D. Neher, *Adv. Mater.* **2020**, 32, 2000080.
- [15] G. Huang, C. Wang, H. Zhang, S. Xu, Q. Xu, Y. Cui, *J. Mater. Chem. A* **2018**, 6, 2449.
- [16] W. Li, X. Lai, F. Meng, G. Li, K. Wang, A. K. K. Kyaw, X. W. Sun, *Sol. Energy Mater. Sol. Cells* **2020**, 211, 110527.
- [17] T.-H. Wu, G. D. Sharma, F.-C. Chen, *Processes* **2022**, 10, 1477.
- [18] W. Meng, J. Xu, L. Dong, J. Zhang, Z. Xie, J. Luo, B. Zhao, K. Zhang, A. Osvet, T. Heumüller, K. Forberich, M. Halik, N. Li, C. J. Brabec, *Sol. RRL* **2022**, 6, 2200378.
- [19] F. Palazon, D. Pérez-Del-Rey, S. Marras, M. Prato, M. Sessolo, H. J. Bolink, L. Manna, *ACS Energy Lett.* **2018**, 3, 835.
- [20] W. Meng, Y. Hou, A. Karl, E. Gu, X. Tang, A. Osvet, K. Zhang, Y. Zhao, X. Du, J. Garcia Cerrillo, N. Li, C. J. Brabec, *ACS Energy Lett.* **2020**, 5, 271.
- [21] C. Xu, Q. Li, Q. Wang, X. Kou, H.-T. Fang, L. Yang, *J. Power Sources* **2021**, 492, 229638.
- [22] D. Walter, A. Fell, Y. Wu, T. Duong, C. Barugkin, N. Wu, T. White, K. Weber, *J. Phys. Chem. C* **2018**, 122, 11270.
- [23] D. A. Jacobs, H. Shen, F. Pfeffer, J. Peng, T. P. White, F. J. Beck, K. R. Catchpole, *J. Appl. Phys.* **2018**, 124, 225702.
- [24] N. Mozaffari, D. Walter, T. P. White, A. D. Bui, G. D. Tabi, K. Weber, K. R. Catchpole, *Sol. RRL* **2022**, 6, 2101087.
- [25] M. D. Stamate, *Appl. Surf. Sci.* **2003**, 218, 318.
- [26] I. Anusca, S. Balčiūnas, P. Gemeiner, Š. Svirskas, M. Sanlialp, G. Lackner, C. Fettkenhauer, J. Belovickis, V. Samulionis, M. Ivanov, B. Dkhil, J. Banyas, V. V. Shvartsman, D. C. Lupascu, *Adv. Energy Mater.* **2017**, 7, 1.
- [27] J. Lim, M. Kober-Czerny, Y. H. Lin, J. M. Ball, N. Sakai, E. A. Duijnste, M. J. Hong, J. G. Labram, B. Wenger, H. J. Snaith, *Nat. Commun.* **2022**, 13, 1.
- [28] T. W. Crothers, R. L. Milot, J. B. Patel, E. S. Parrott, J. Schlipf, P. Müller-Buschbaum, M. B. Johnston, L. M. Herz, *Nano Lett.* **2017**, 17, 5782.
- [29] S. Rühle, *Sol. Energy* **2016**, 130, 139.
- [30] C. Wehrenfennig, G. E. Eperon, M. B. Johnston, H. J. Snaith, L. M. Herz, *Adv. Mater.* **2014**, 26, 1584.
- [31] M. A. Mahmud, T. Duong, Y. Yin, H. T. Pham, D. Walter, J. Peng, Y. Wu, L. Li, H. Shen, N. Wu, N. Mozaffari, G. Andersson, K. R. Catchpole, K. J. Weber, T. P. White, *Adv. Funct. Mater.* **2020**, 30, 1907962.