



Deposited via The University of Sheffield.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/231902/>

Version: Accepted Version

Article:

Blackburn, D., Hill, N.S., Sirbu, D. et al. (2025) Back-contact perovskite solar cells: progress, challenges and the future. ACS Applied Materials & Interfaces, 17 (39). pp. 54329-54340. ISSN: 1944-8244

<https://doi.org/10.1021/acsami.5c09718>

This document is the Accepted Manuscript version of a Published Work that appeared in final form in ACS Applied Materials & Interfaces, copyright © American Chemical Society after peer review and technical editing by the publisher. To access the final edited and published work see <https://doi.org/10.1021/acsami.5c09718>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Back-Contact Perovskite Solar Cells: Progress, Challenges and the Future

Dominic Blackburn¹, Nathan S. Hill², Dumitru Sirbu², David G. Lidzey^{1}*

¹ Department of Physics and Astronomy, Hicks Building, Hounsfield Road,
Sheffield S3 7RH, United Kingdom

² Power Roll Ltd, Jade Business Park, Spring Road, Seaham, SR7 9DR, United Kingdom

[*d.g.lidzey@sheffield.ac.uk](mailto:d.g.lidzey@sheffield.ac.uk)

Keywords: Solar-cell, photovoltaic, perovskite, module, back-contact, silicon, interdigitated, scale-up

Abstract:

Back-contact solar cells are a novel type of device architecture that have been used in combination with both silicon and perovskite semiconductors. Since 2016, the efficiencies of perovskite back-contact solar cells have risen from 6.5% to over 11%, with a wide variety of fabrication methods and device structures employed. This Spotlight on Applications article aims to highlight the benefits of back-contact solar cells over more routinely used planar counterparts and reviews recent progress made using perovskite materials. In particular, we show how the use of substrates patterned with embossed micro-grooves presents a facile route to back-contact solar-cell scale-up, with this approach recently used to create perovskite solar-cell modules consisting of hundreds of serially connected grooves having a stabilised efficiency of up to 12.8%. We conclude by discussing the challenges required to drive this technology towards high-volume manufacture and commercialisation.

Introduction:

Perovskite solar cells have been the subject of world-wide research and development over the last 12 years.^{1,2} Perovskites are crystalline materials that have the general structure ABX_3 , and due to their long charge-carrier diffusion lengths, high defect tolerance and direct band gap, have been used to create single-junction solar cells achieving power conversion efficiencies (PCEs) in excess of 26%.^{3,4} Indeed, the efficiency of single-junction perovskite solar cells now matches that of the highest performing silicon devices.^{5,6} Perovskites, can also be processed into thin-films from solution, allowing for a wide variety of scale-up deposition methods to be used in low-cost device manufacture. Here, scalable techniques such as spray, slot-die and blade coating have been used to fabricate devices, with PCEs in excess of 20% demonstrated.⁷⁻¹¹

Perovskite solar cells are usually fabricated from sequentially deposited planar films that are deposited onto a Transparent Conducting Oxide (TCO) contact. This approach is used to realise both n-*i*-p and p-*i*-n structured devices. Such a fabrication route combines the benefits of high repeatability and uniform film thicknesses together with compatibility with a range of deposition techniques. However, planar solar cell architectures come with some drawbacks; for example, parasitic optical absorption of incident light in the TCO and transport layers limits the maximum attainable short-circuit current (J_{sc}). Planar perovskite solar cells often make use of Indium Tin Oxide (ITO) as it combines high optical-transmission and high electrical conductivity, making it appealing for photovoltaic applications.¹² However, indium is an expensive metal that is usually obtained as a byproduct of zinc mining. In fact, at time of writing, indium is more valuable by weight than uranium.¹³ Indeed, the supply chain and suitability of materials used for next generation PV is often overlooked and this makes many of the advancements in academia unlikely to become widely applied in practical energy technologies. Here, we highlight a recent, comprehensive modelling study that has argued that for perovskite PV production to reach the point where it could supply TW of electricity, there are severe supply chain risks involved with a number of materials used; these include indium (used in transparent electrodes and in tandem interconnects), caesium (used in perovskite alloys) and gold (used in device contacts).¹⁴ For example, around 4,700 metric tons of indium would be required to generate 1 TW (peak) of electricity from perovskite PV. This is a substantial fraction of our current known reserves of indium (18,800 tons), and is larger than the annual indium production which (in 2019) was around 1000 tons. This leads to be a high supply criticality of indium with a 1 TW (peak) generation target requiring a 200% increase in current production.¹⁴

There are alternatives to the use of ITO; for example Fluorine-doped Tin Oxide (FTO) is also commonly employed as a conductive, transparent electrode, however the high sintering temperatures required to process FTO into a thin-film greatly inflate its fabrication costs. Furthermore, high-temperature processing conditions make it incompatible with thermally-sensitive plastic substrates; an issue that limits its applications – particularly when light-weight, flexible devices are required.

Back-contact solar cells are an alternative device architecture in which all charge-transporting materials are situated on the rear-side of the device. Critically, this approach reduces parasitic optical absorption, as the photoactive layer can be directly illuminated without light having to pass through any absorbing charge-transporting layers. Back-contact devices can also be more resilient to common pinhole defects that can often cause an electrical short-circuit in a solution processed device. Furthermore – as we show below - back-contact devices can be constructed

without the necessity to include any costly TCOs that are utilised in conventional planar devices. Taken together, back-contact devices represent an exciting new architecture for perovskite solar cells.

Back-contact solar cell devices typically use some type of patterned electrode structure, with the physical separation between electron and hole extracting contacts being on the order of the carrier diffusion length. This is fairly straightforward to achieve in silicon-based cells in which charge diffusion lengths can be on the order of hundreds of microns.¹⁵ This has led back-contact silicon devices to currently hold the single-junction efficiency record of over 27%.¹⁶ Silicon back-contact devices also have improved aesthetics as they do not include metal grid lines, giving them a uniform, sleek appearance that is of particular importance for building-integrated PV (BIPV) applications. Back-contact devices often also include passivated contacts and heterojunctions that also help to enhance their efficiency. It is clear however that the manufacture of such devices is more complex, as precise alignment is required of the rear contacts. Significantly, the wide-spread manufacture of silicon IBC devices will require some displacement of PERC devices (Passivated Emitter Rear Cell) which currently accounts for 60 - 70% of global production, and growing competition with TOPCon (Tunnel Oxide Passivated Contact) devices.

At present, there is a small but growing interest in the development of back-contact PV devices based on perovskites. Here, significant challenges exist as the patterning of appropriate electrode structures will require a higher resolution than is necessary with silicon, due to the fact that charge-carrier diffusion lengths in perovskites are of the order of hundreds of nanometres to 1 micron.² Nevertheless, as we show below, patterning over such length scales is possible and permits back-contacted devices to be realised in a way that would not be possible using other materials with much shorter charge diffusion lengths such as organic semiconductors.¹⁷ For this reason, the uptake of this technology in the thin-film PV sector has been relatively slow as the significant fabrication challenges requires the creation of very finely spaced electrode grids over relatively large areas.

In this Spotlight on Applications article, we firstly briefly discuss the development of back-contact architecture devices based on silicon, before reviewing progress on back-contact devices incorporating perovskite semiconductors. We focus attention on the various methods used to pattern the contacts used to extract electrons and holes from the device. We also discuss recent progress from a collaboration between researchers at the University of Sheffield and the UK company Power Roll Ltd who have developed a new type of perovskite back-contact

device. Finally, we discuss prospects for the scale-up and manufacture of perovskite back-contact solar cell technologies.

The Back-Contact Solar Cells Architecture

Solar-cells utilising an interdigitated back-contact (IBC) structure were first reported in the 1970's by Schwartz and Lammert as an alternative architecture for silicon solar cells.^{18,19} The basic device architecture is shown schematically in Figure 1a. Here, the p- and n-type contacts are arranged into an interdigitated 'finger' layout at the rear of the device, with these contacts separated by 18 μm . The rationale for this approach is that by placing extraction contacts to the rear of the device, any structures that would otherwise cast a 'shadow' over the light-absorbing silicon active layer (thereby reducing device efficiency) are removed. This approach also allows

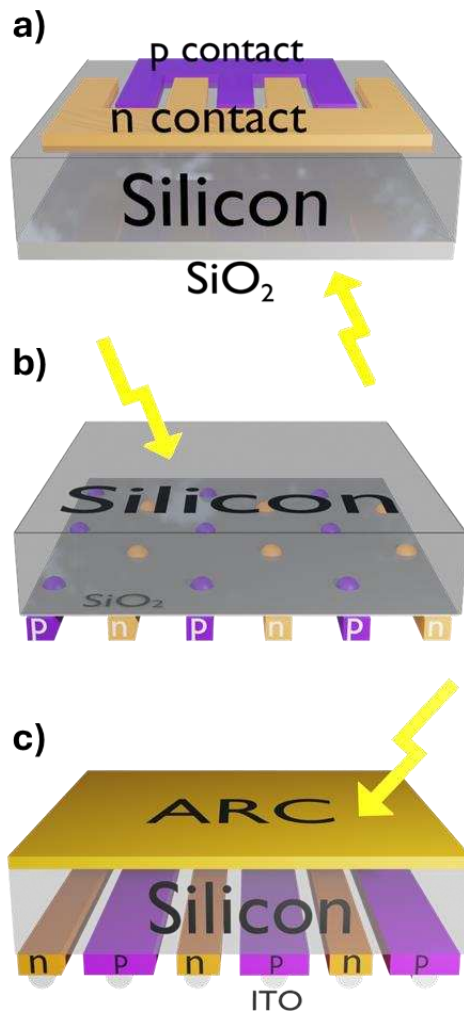


Figure 1: a) shows a schematic of the first reported interdigitated solar cell (Schwartz and Lammert); b) point-contact solar cell (Swanson *et al*); c) general architecture of a modern back-contact silicon solar cell. Not to scale.

thicker contact materials to be employed, thereby reducing series resistance. The main focus of initial work was to evaluate the effects of various factors on device performance via modelling. Simulations revealed that such structures had a high level of tolerance to changes in contact width and surface recombination velocity, but a low tolerance to changes in photo-absorber thickness for low bulk carrier-lifetimes. Devices were then fabricated and demonstrated PCEs between 11 and 15% at varying light intensities; a value that matched the highest performing certified efficiencies of crystalline silicon in the 1970's.⁵

In 1984, Swanson *et al* reported an alternative back-contact design called a point-contact solar cell, as shown schematically in Figure 1b.²⁰ Here, the interdigitated contact structure was replaced by n and p-type materials that instead made contact to the bulk silicon layer via a series of 'points' introduced through an insulating SiO₂ layer. Here, the small points of contact between the contacts and the silicon layer reduced the effects of recombination caused by defects

at the semiconductor-contact interface. Following further improvements, devices were reported in 1988 having an active area of 8.5 cm^2 with a PCE of 22.3%.^{21,22}

Since such early work, last few decades have witnessed a gradual increase in the efficiency of silicon IBC devices. This has been driven by both the development of effective light management strategies (optimisation of light absorption via Anti-Reflective Coatings (ARCs) (see Figure 1c))²³⁻²⁵ and a reduction in charge-carrier recombination.^{2, 26-29} By combining both effective light-management and amorphous silicon/crystalline silicon heterojunction approaches, IBC devices now demonstrate a PCE in excess of 26% with an active area of 180.4 cm^2 have now been demonstrated.³⁰

The IBC structure proposed by Schwartz and Lammert has now become the basis for some of the highest performing silicon devices. Most recently, 2025 saw a new record for silicon solar cell efficiency, with the company Longi reporting in a press-release a hybrid interdigitated back-contact (HIBC) device reaching certified PCE of 27.8% over an active area of 134 cm^2 . Readers interested in key stages in development of silicon-based IBC devices are referred to a full, recent review.³¹

We note similar work to develop IBC devices based on different semiconductor technologies. For example, significant performance has been demonstrated using Copper Indium Gallium Selenide (CIGS) based IBC devices with a power conversion efficiency demonstrated at 23.6%.³² Devices based on a CdTe - CdS mix have been reported having efficiencies of around 5.9%.³³⁻³⁵ Devices based on thin film technologies including organic and dye sensitized solar cells have also been reported. Here efficiencies are generally lower, with organic devices based on a blend of P3HT and PCBM demonstrating a PCE of 0.05%.³⁶ IBC DSSC devices have also been reported with typical efficiencies of 3.64%.³⁷ Rapid progress has also been made in the development of back-contact technologies based on lead-halide perovskites. We will focus on such progress in the following sections.

Back-Contact Perovskite Solar Cells

The last 10 years have witnessed rapid growth in the development of planar single-junction and tandem perovskite solar cells.^{1-4,38-40} However, in contrast to silicon back-contact solar cells in which layers can be deposited onto a silicon wafer, perovskites require a more sophisticated approach to create back-contact devices. Here, a significant issue derives from the shorter charge-carrier diffusion lengths in a polycrystalline perovskite film than in single-crystal silicon. For this reason, efficient perovskite back-contact devices will likely require electrodes that are patterned with spacings of around 1 μm or less. Furthermore, practical applications require devices to be created over macroscopic areas without introducing defects or short-circuits. This introduces a requirement for high precision, high yield lithography and patterning over large areas. Creating such patterned electrodes remains a major challenge in the field and is a topic that we discuss below.

Perovskites were first explored (2016) in back-contact solar-cell devices by Jumabekov *et al.*⁴¹ These devices were based on the interdigitated electrode structure originally pioneered by Schwartz and Lammert but featuring a

considerable update.¹⁹ Rather than alternating digits of each transport material, digits consisting solely of the hole-transport layer (HTL) NiO_x/Ni were deposited and patterned by photolithography. These were located on a continuous zinc oxide electron transport layer (ETL) that was separated from the HTL digits using an aluminium oxide insulating layer, as shown in

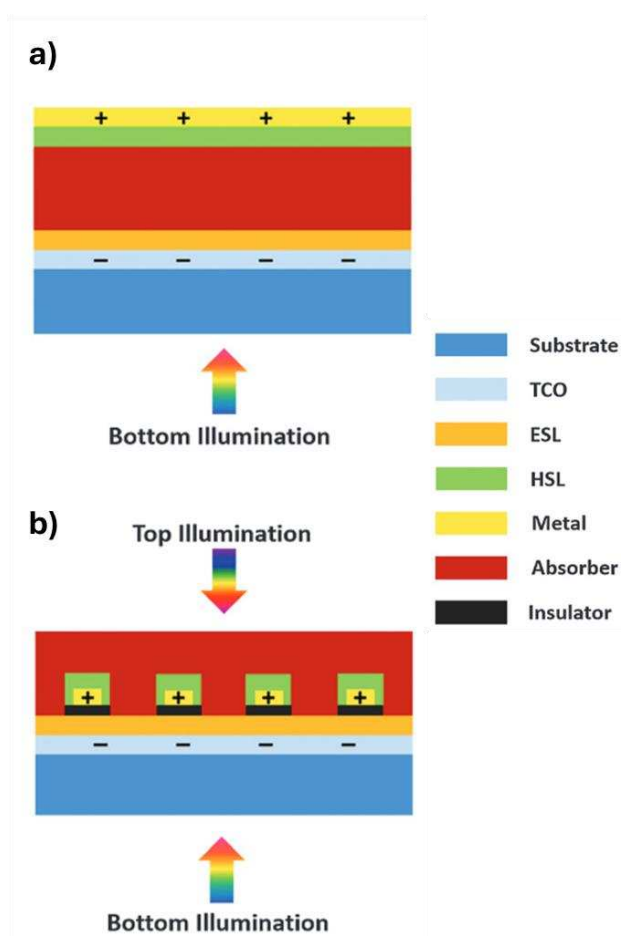
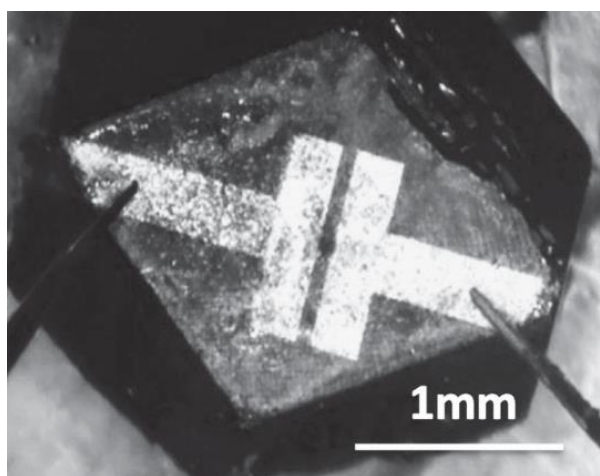


Figure 2: a) cross-sectional schematics of; a) planar; and b) quasi-interdigitated back contact solar cells

Reproduced with permission from Jumabekov *et al.* Copyright 2016 Royal Society of Chemistry

figure 2b. A perovskite film was then coated on top of this structured film to form a Quasi-InterDigitated Electrode (QIDE) device. The main rationale for replacing interdigitated contacts with a single digit contact separated from a planar electrode by an insulator was that this would reduce the possibility of structural defects formed during lithography. Such defects are expected to create electrical short circuits in the final device. In the QIDE device developed, the individual back-contact digits were separated by 2 μm , with champion devices achieving a PCE of 6.54% under ‘Top illumination’ and 3.52% following ‘Bottom illumination’ (see figure 2b) when subject to a J - V sweep.

In an attempt to emulate the architecture of a silicon back-contact solar cell in which contacts are directly patterned onto a silicon wafer, researchers have fabricated equivalent devices using perovskite single crystals.^{42,43} Here, the photovoltaic effect in such structures was first reported by Dong *et al* (see Figure 3), with a full, so-called “lateral”



*Figure 3: Microscope image of perovskite with evaporated gold electrodes forming a junction on one face of a single crystal (Dong *et al*)*

*Reproduced with permission from Dong *et al*.
Copyright 2016 Wiley*

perovskite solar cell reported by Liu *et al* in 2019. Briefly, a perovskite single crystal of 1 - 1.5 cm length was grown over the course of 30 minutes in an aqueous solution of lead acetate trihydrate and methylamine. A device with the architecture $\text{Au}/\text{BCP}/\text{C}_{60}/\text{MAPbI}_3/\text{Au}$ was then created by thermally evaporating separate contacts through a shadow-mask onto the surface of the crystal, with the separation between n- and p-type contacts being 50 μm . The devices realised had an active area of 0.05 mm^2 and a champion PCE of 5.9% recorded under 25 mW/cm^2 white light illumination. Subsequent work on lateral single crystal perovskite devices have seen efficiencies increase to 12.6% under AM1.5G illumination, with gains in efficiency resulting from improvements in crystal growth methodologies.⁴³ Single-crystal devices have also been reported to maintain over 99.7% relative efficiency over 200 hours illumination under nitrogen.⁴⁴

It is clear that an interdigitated or quasi-interdigitated back-contact device architecture has a potential weakness; if a fracture that occurs in a contact digit, this can lead to the formation of an electrically isolated region. For this reason, back-contact architecture devices are less resilient to damage or fabrication errors than their planar counterparts. This issue can however be addressed using a so-called “honeycomb” back-contact structure. This type of architecture is shown schematically in Figure 4a and was first pioneered by Hou *et al* in 2018.⁴⁵ In Hou *et al*’s work, a structure was constructed based on a planar TiO_2 ETL layer deposited onto a substrate. Optical lithography was then used to template a honeycomb-patterned electrode onto the ETL consisting of a resistive layer and Al/NiCoO_x HTL. Finally, a MAPbI_3 perovskite was spin-cast onto the structure, filling the pores. Here, the filled pores define the active area of the device as it is in this region that photogenerated charges can be extracted via the HTL or ETL. Champion PCEs of 5.4% and 1.5% were then reported in devices with pore diameters of $2.7\ \mu\text{m}$ and $8\ \mu\text{m}$ respectively. Photocurrent mapping

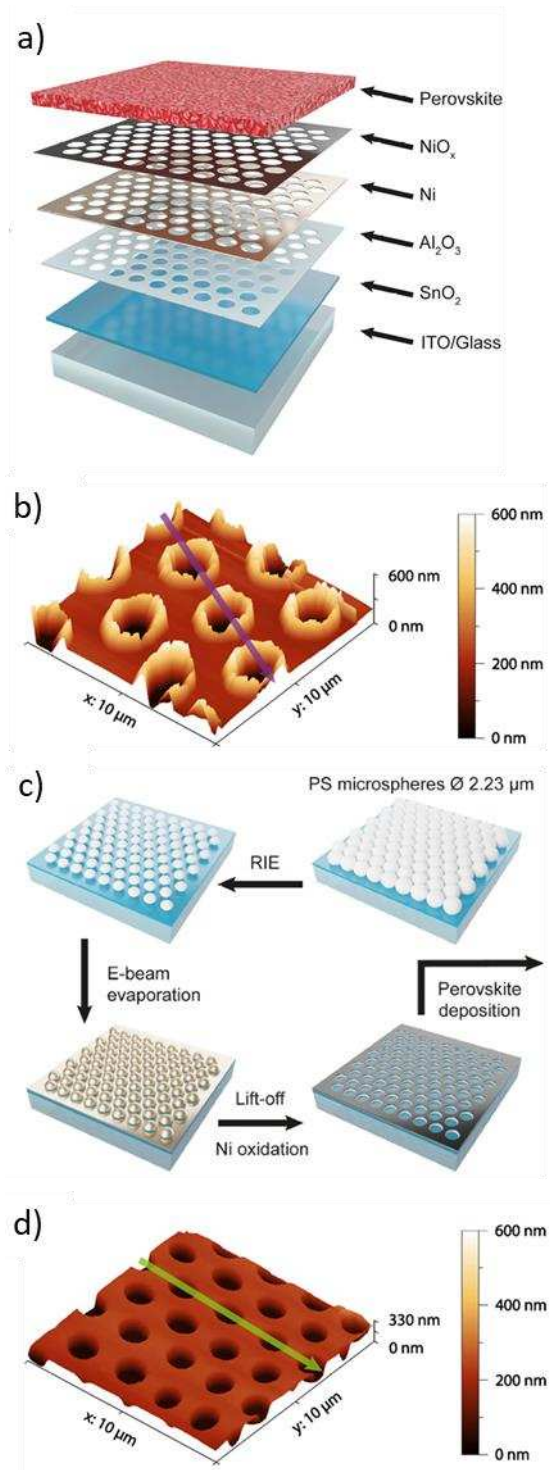


Figure 4: a) Layers in a honeycomb-type back-contact perovskite solar cell; AFM images of films fabricated by b) microsphere lithography and c) photolithography; d) Schematic for the use of polystyrene microspheres as a mask

Reproduced with permission from Deng *et al.*
Copyright 2022 Elsevier

was also used to directly image the individual honeycomb features. However, subsequent investigations found that the insulator layer in fact formed a “ring-like” structure around the pores, as shown in figure 4b, which in places caused the insulator to block electrical contact to the HTL. This led to a considerably rougher perovskite and likely obstructed charge extraction.⁴⁶

In 2022, Deng *et al* proposed a novel method to produce a honeycomb structure as illustrated schematically in Figure 4c.⁴⁶ Rather than using conventional photolithography to template the electrode, a monolayer of 2.23 μm diameter polystyrene nanoparticles were self-assembled into a honeycomb structure on the surface of planar tin oxide film using a technique termed ‘microsphere lithography’. Note that such self-assembly techniques are generally less expensive than photolithography, with practical manufacture processes based on solution self-assembly of microspheres for applications in photonics already explored.⁴⁷ Reactive ion etching was then used to reduce the size of the microspheres without modifying interparticle distances. The particles were then used as a shadow-mask and were able to pattern a 120 nm thick insulating film and a Ni/NiO_x HTL. Following the removal of the polystyrene microspheres by sonication in toluene, an array of 1.43 μm diameter pores were created on a 2.23 μm pitch. Critically the microsphere lithography process avoided the creation of “ring-like” defects formed when this structure was manufactured by photolithography as discussed above (see Figure 4d). A mixed cation perovskite was then spin-cast onto the patterned surface to fill the pores which formed a parallel array of back-contact devices. Upon testing, devices having an active area of 0.75 cm² reached a PCE of 8.98% (stabilising at 8.6%); a value that compared with 5.13% for controls in which direct photolithography was used to pattern a honeycomb. The improvement in efficiency of the microsphere patterned device over the photographically patterned control resulted from an increase in J_{sc} . Here it was speculated that the smaller pore pitch reduced the distance over which charge-carriers needed to travel before extraction, thereby reducing recombination effects.

In 2022, a new type of back-contact perovskite devices based on cracked-film lithography was developed by Prince *et al*.⁴⁸ Critically, this technique allowed small inter-electrode distances to be directly templated without the use of any photolithography. This process is shown schematically in Figure 5 and involved spin-coating a tin oxide ETL onto an ITO electrode. Onto this was then spin-cast a solution of 40 - 80 nm PMMA nanoparticles. The subsequent evaporation of the casting solvent led to the creation of a nanoparticle film that contained a dense mesh of “cracks”, having a width of around a micron (see Figure 5b). This film was then exposed to an O₂ plasma treatment for 2 hours which widened the cracks to over 2 μm . An

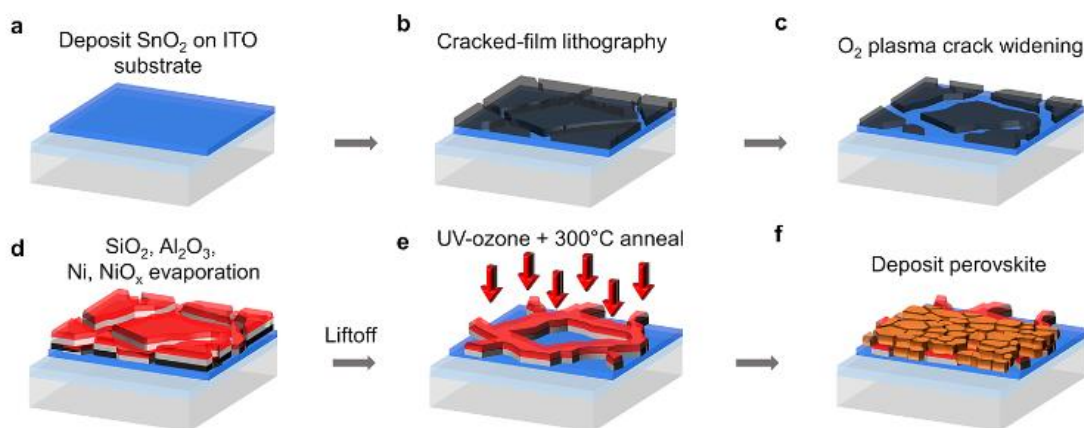


Figure 5: Schematic of the fabrication of back-contact perovskite solar cell by cracked-film lithography. Here, part (a) shows the starting substrate (SnO_2 coated on ITO). Part (b) shows the formation of a cracked network in a dried PMMA film deposited onto the SnO_2 . Cracks are then widened by exposure to an O_2 plasma (part (c)). Part (d) shows the substrate then sequentially coated with SiO_2 , Al_2O_3 , Ni and NiO_x , with the Ni / NiO_x being electrically isolated from the bottom SnO_2 /ITO contact. In part (e), lift-off of the PMMA is used to create the separated n and p-type contacts (SnO_2 and NiO_x respectively). Finally, part (f) shows the final structure, complete with a top perovskite active layer.

Reproduced from Prince et al, Copyright 2022, American Chemical Society

electrical insulator film was then evaporated onto the cracked surface, followed by a Ni/ NiO_x HTL transport layer. To create a back-contact structure, the PMMA nanoparticles were then washed off using an NMP-based solution. As can be seen in Figure 5e, this left the surface covered by an irregular mesh consisting of an insulator/HTL bilayer located on top of the ETL. A mixed cation perovskite was then spin-coated onto the mesh, with the gaps in the mesh acting as the active photocurrent-generating regions. Devices were fabricated from this structure having an active area of 0.06 cm^2 and demonstrated a champion PCE of over 6%. Here, a low fill factor was identified as being the primary efficiency loss.

In 2021, a new record efficiency for a perovskite back-contact perovskites was demonstrated by Lin *et al*⁴⁹ using the quasi-interdigitated structure first demonstrated by Jumabekov *et al.*⁴¹ The primary adjustment made to the structure was to use an ETL composed of both compact and mesoporous TiO_2 which was deposited onto an FTO-coated glass substrate. A series of $2 \text{ }\mu\text{m}$ wide Al_2O_3 /Ni/ NiO_x digits were then patterned onto the ETL using optical photolithography. A mixed-cation perovskite was spin-cast on the structure, with devices having an active area of 0.04 cm^2 achieving a champion efficiency of 12.3%. However, such devices suffered from considerable hysteresis which was attributed to interfacial recombination, with forward sweep PCEs of 6.2% reported. Despite this hysteresis, the devices were a notable improvement on the controls that simply utilised a compact TiO_2 ETL. Further work by Rietwyck *et al* then

characterised the diode ideality factor and photoluminescence emission from such devices using a number of methods.⁵⁰ Here, it was found that the mesoporous TiO₂ ETL significantly reduced non-radiative recombination and increased average device V_{oc} .

In 2023, Zhao *et al* demonstrated a highly efficient back-contact perovskite solar cell using a compositional engineering approach.⁵¹ Here, the objective was to increase charge-diffusion lengths in a perovskite using molecular additives, making charge-extraction via the patterned back-contact electrodes a more efficient process. Specifically, guanidine thiocyanate was added at up to 20 mol% to a MAPbI₃ perovskite with its effect on perovskite crystallinity and conductivity characterised. Using XRD rocking-curve measurements, it was confirmed that the (110) plane in the perovskite underwent a significant degree of out-of-plane alignment, with this effect being most prominent at 12.5 mol% additive concentration. It was found that this perovskite had increased charge-carrier lifetimes which was accompanied by an increase in grain size as measured by SEM. Back-contact devices having an active area of 0.04 mm² were fabricated using this perovskite and demonstrated a champion PCE of 11.2%. This efficiency was higher than control devices that did not incorporate the additive which had a PCE of 3.81%. This enhancement in PCE mainly occurred due to a large improvement in J_{sc} which occurred as a result of increases in charge-carrier lifetimes.

Non-radiative trap-assisted recombination is a major source of losses in perovskite solar cells, with such traps typically located at interfaces and grain boundaries. In a back-contact solar cell, it is expected that charge-carriers will need to traverse a number of grain boundaries before being extracted, with recombination at grain-boundaries a key loss mechanism. An investigation into the effect of grain size on device performance was carried out by Lin *et al*, making use of a solvent annealing approach to create back-contact devices incorporating perovskites having varying grain sizes.⁵² Interdigitated devices comprising digits having 5 µm separation were fabricated by photolithography using gold contacts and two different thiophenol-based self-assembled monolayers (SAMs) as the electrodes and transport materials respectively. A MAPbI₃ perovskite was then spin-coated on top of the patterned electrodes to complete the device. A solvent annealing step was applied to the perovskite using a DMSO/NMP vapour, tuning the average size of perovskite grains between 0.23 and 6 µm. As expected, it was found that devices based on materials having the largest grain sizes had the highest efficiencies, with devices having an active area of 0.04 cm² achieving a champion PCE of over 2%, compared to ~ 1.5% and ~ 1.25% for devices based on medium and small sized grains respectively. Time-resolved photoluminescence measurements identified an increase in the lifetime of a slow decay component associated with charges that had been extracted before recombining, and a

decrease in the lifetime of the fast component (associated with radiative decay in the perovskite) observed as the grain size increased. This implied that larger perovskite grains lead to more efficient charge extraction.

In summary therefore, a wide range of novel fabrication methods have been reported that can be utilised to template small inter-electrode distances commensurate with charge-carrier diffusion lengths. This has led to devices reaching champion efficiencies at time of writing of over 11%. However, whether the electrodes are templated by photo-, cracked film- or microsphere lithography, or evaporated directly onto a perovskite crystal, none of these methods have as yet, been demonstrated at scale or for solar modules. Here, fabrication has instead relied on the use of non-scalable deposition techniques (such as spin-coating) to deposit the active perovskite material. This both limits the maximum size of the devices realised and also leads to a degree of solution wastage. Some previous approaches have also required the application of high process temperatures or lengthy post-deposition processes that would add to both the cost and speed of manufacture should these devices scaled up. Clearly, further work is required for back-contact perovskite solar cells to be manufactured on a large scale. We address this issue and offer potential solutions later in this article.

Simulation Studies of interdigitated back-contact devices

Much of the work reported on back-contact perovskite solar cells discussed above dealt with unique device architectures, with researchers focusing on novel methods to template the necessary electrode structures. It is clear however that experimental work on back-contact devices is limited by fabrication challenges. For this reason, device simulation studies have also been carried out to explore the effects of various factors on the performance of such types of solar cell.

In 2018, the effect of a series of fabrication factors on the performance metrics of an interdigitated perovskite back contact device were numerically simulated by Ma *et al.*⁵³ It was found that while open circuit voltage (V_{oc}) and Fill Factor (FF) were largely independent of electrode width and separation, increases in either would lead to a reduction in J_{sc} and thus device PCE. Devices having simulated contact widths of 1 μm and inter-electrode distances of 0.1 μm corresponded to the highest efficiency devices explored in this computational study. The results of extensive simulations are shown in Figure 6, where device efficiency was explored as a function of varying electrode contact widths. Here, part (a) shows the effect of carrier lifetime on device efficiency, while part (b) shows the effect of simulated carrier mobility. The effect of the perovskite defect density and surface recombination rate was also established through modelling J - V curves. Here, it was found that for a defect density of $\leq 10^{18} \text{ cm}^{-3}$, there was little change in the shape of the J - V curve or device performance metrics. However, as the defect density increased above this value, significant losses in V_{oc} were observed; an effect attributed to band narrowing induced by the high defect concentration. In contrast, as the surface recombination velocity was increased from 1 to 10,000 cm s^{-1} , the J_{sc} decreased dramatically as

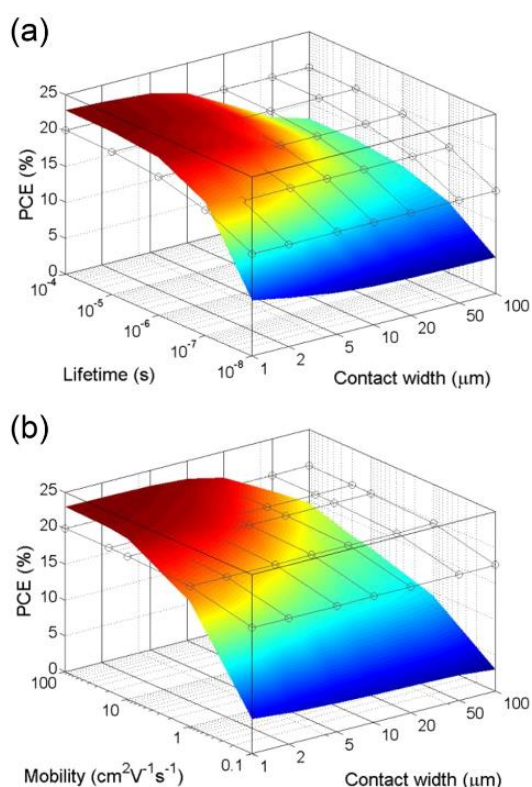


Figure 6: Variation in simulated PCE as a function of contact width and a) charge carrier lifetime or b) charge carrier mobility. Reproduced from Ma et al. Copyright 2018 American Chemical Society

would be expected. Finally, the effects of charge-carrier lifetime and mobility were explored as a function of the width of the contacts. It was found that for a contact width of 1 μm and current density of between 4.7 and 23.6 cm^{-2} , a reduction in carrier lifetime below 10^{-6} s , or a reduction in carrier mobility below $10 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ had a dramatic effect on PCE, reducing it by over 70%. Indeed, to maintain a high PCE, it was necessary to increase both carrier lifetime and carrier mobility as the contact width increased; a result consistent with carriers having to diffuse over longer distances before being extracted. Interestingly, the PCE appeared to saturate in all cases below the detailed balance limit, implying that additional loss processes must limit the efficiency of such devices.

Further investigations into photocurrent generation in back-contact perovskite devices were reported in 2020 by Shalenov *et al.*⁵⁴ Simulations were performed to model a quasi-interdigitated back-contact solar cell, with the effects of perovskite thickness, inter-electrode distance and insulating layer thickness explored. From an experimental viewpoint, it would be expected that a perovskite deposited over a substrate that has been patterned with interdigitated electrodes is likely to be characterised by significant variations in perovskite thickness over regions above the digits and between digits. Fortunately for device efficiency, however, simulations suggested that varying perovskite thicknesses over the interdigitated region between 0.5 and 2 μm had very little impact on performance metrics. However, for very thin films it is likely that insufficient light would be absorbed by the perovskite, leading to a low short-circuit current. Back-contact devices based on very thick perovskite films are also likely to have low efficiency, as charge carriers would be generated a significant distance from the back-contact electrodes, with recombination effects leading to a low short-circuit current.

The effect of inter-electrode distance was also simulated, with values between 0.42 and 1.05 μm explored. Interestingly, devices fabricated using electrodes with a 0.42 μm separation were characterised by lower J_{sc} values, although the reason for this was not discussed. Electrode separations above this value had little effect on the performance metrics. The insulating layer thickness (assuming constant combined perovskite and insulator thickness) was also found to

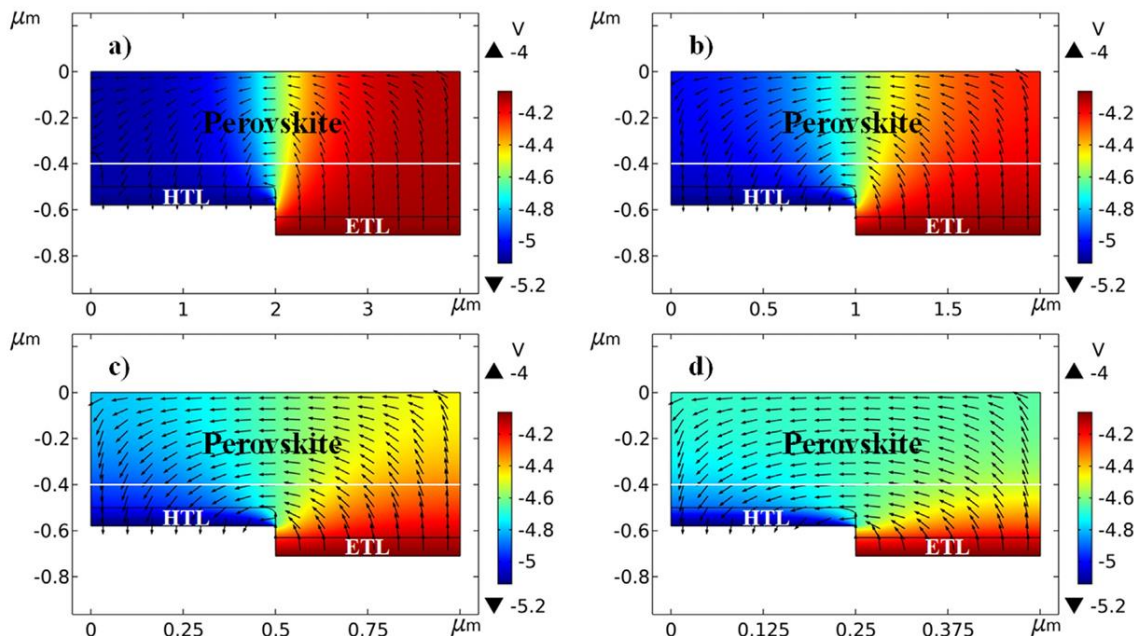


Figure 7: Simulated Electric field distributions for interdigitated back-contact perovskite solar cells with inter-electrode distances of; a) 4 μm ; b) 2 μm ; c) 1 μm ; d) 0.5 μm .

Reproduced with permission from Shalenov *et al.* Copyright 2020 Elsevier

have rather little impact on device efficiency for values between 0.05 and 0.2 μm . However, when this was increased to 0.4 μm , devices were characterised by a marked drop in J_{sc} . This was attributed to the reduced thickness of the perovskite layer above the digits leading to reduced light absorption. Simulations also investigated the effect of inter-electrode distance on the distribution of electric potential around the electrodes as shown in Figure 7. Here, it was found that for inter-electrode distances of $\leq 1 \mu\text{m}$, regions of highest potential occurred at the edge of the HTL and underwent considerable reduction towards the ETL. This implied that most efficient charge separation and collection occurs near the edge of the HTL. However, for larger separation distances, the distribution of electric potential varied considerably, with the region corresponding to the maximum being considerably larger. This suggests that a complex optimisation process is likely required for interdigitated devices, and that simply reducing inter-electrode distances may not be enough to maximise efficiency.

Groove-based back-contact perovskite solar-cells

The company Power Roll Ltd have developed a type of back-contact perovskite solar cell based on flexible, plastic substrates embossed by micron-width grooves. Note that the first experiments performed on this type of structure did not incorporate a perovskite photoactive layer, however for completeness we briefly describe such work as it provides important context for follow-up studies.

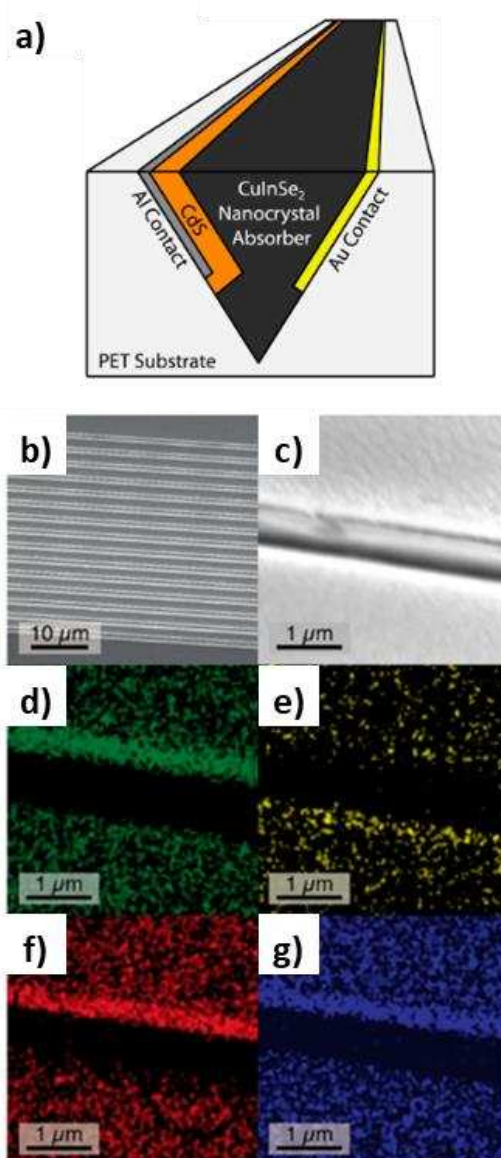


Figure 8: a) schematic of a single groove device; b) and c) SEM of patterned PET substrate; EDS SEM images of d) aluminium, e) gold, f) cadmium and g) sulphur respectively. Reproduced from Pernik et al. Copyright 2016 American Chemical Society

Micro-groove back-contact structures were first reported in 2016 by Pernik *et al* on a patterned polyethylene terephthalate (PET) substrate that was embossed with a series of V-shaped grooves (see schematic in Figure 8a and an SEM image in part b.⁵⁵ Following embossing, electron and hole transport layers were sequentially deposited via thermal evaporation onto the opposing walls of the grooves by evaporating different materials at a shallow, oblique angle with respect to the sample plane. This allowed one side of the grooves to be coated with a material, with the opposing wall remaining in shadow. By repeating this deposition and instead coating the opposing groove wall, it is possible to coat the two groove walls with separate ETL and HTL contacts.

Initial experiments explored grooves whose walls were coated with either Al/CdS (ETL) or Au (HTL), which were sequentially thermally evaporated. Into these grooves, a copper indium

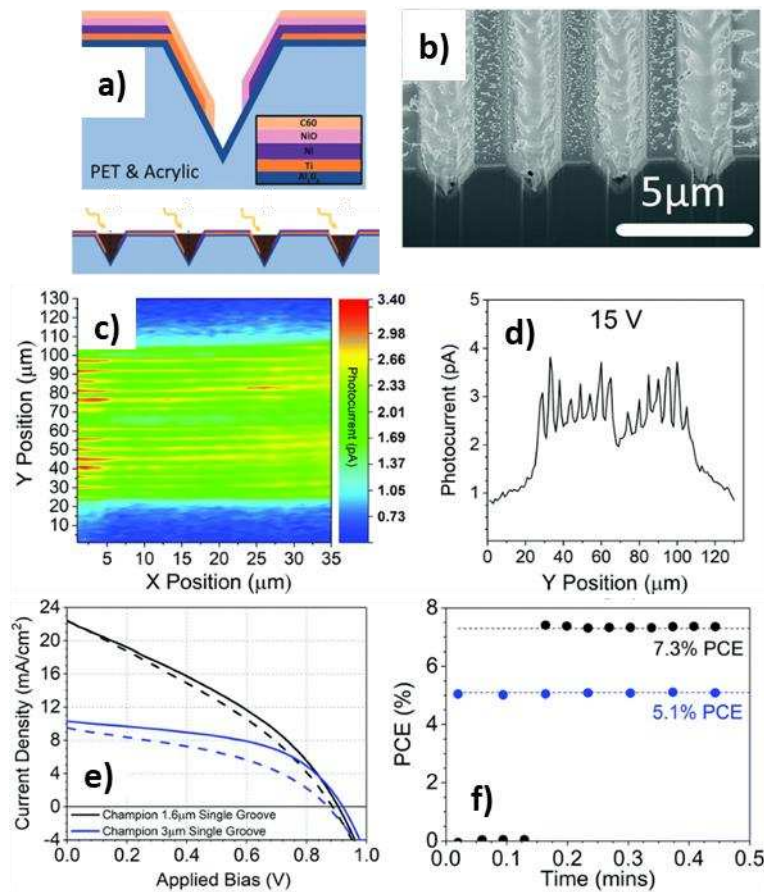


Figure 9: a) Schematic of a single groove and several grooves connected in series; b) FIB SEM cross sectional image of a cascade of coated grooves; c) Laser-Beam Induced Current image of a 16-groove cascade; d) integrated LBIC intensity across cascade in c; e) J-V curves of two different widths of groove for a single groove device; f) stabilised efficiency for champion single groove devices whose JV curves are reported in part e.

Reproduced from Wong-Stringer *et al*, available under CC-BY 4 licence.

selenide (CIS) photoactive layer was deposited by spray-coating, with devices created having the structure $\text{Al}/\text{CdS}/\text{CuInSe}_2/\text{Au}$. The directionality of the evaporation process was verified by EDS SEM measurements (see Figure 8d to g) that were able to demonstrate that each of the contact materials were primarily deposited on one of the groove walls for most of the materials evaporated, although the gold contact was not particularly visible within the grooves.

A mini-module consisting of three series-connected grooves was then constructed. Here, series connectivity between the grooves occurred via an overlap in the ETL and HTL at the apex of each groove. The grooves constructed each had an active area of $2.3 \times 10^{-4} \text{ cm}^2$, with the module tested by recording a J - V curve. Devices were found to have a champion PCE of 2.2%, with a lower PCE of 0.19% recorded when devices were instead illuminated through the substrate. A larger module consisting of 15 grooves was also tested; here the module efficiency was found to drop to 0.013%. It was suggested that the reduction in device performance resulted from the poor uniformity of the CIS across the grooves. It was proposed that by reducing the distance between the grooves, it should be possible to reduce the series resistance of the module and thereby increase device efficiency.

In 2019, our group reported back-contact groove-based solar cell containing a perovskite.⁵⁶ In these experiments, we used a device architecture consisting of $\text{Ti}/\text{C}_{60}/\text{perovskite}/\text{NiO}/\text{Ni}$, with devices formed within micron-width ‘V-shaped’ grooves embossed into a plastic film. The structure of the devices fabricated are shown schematically in Figure 9a, with an SEM image of the perovskite-filled grooves shown in Fig 9b. Again, grooves were connected in series via the overlap between the ETL and HTL at the apex of each groove.

In these structures, electron-beam (E-beam) evaporation was used to deposit all metal layers; this reduced the processing temperatures to less than 100°C and helped to limit any damage to the sensitive groove structures. A reactive E-beam deposition technique was also used to deposit metal-oxide films whereby the evaporated metal reacted with a low partial pressure of oxygen introduced into the deposition chamber. This allowed the stoichiometry of the metal oxide film to be controlled.^{57,58} After the deposition of the device contacts, a MAPbI_3 perovskite based on a formulation developed by Noel *et al* was spin coated onto the substrates.⁵⁹ This material precursor was chosen owing to its low processing temperature and compatibility with the plastic substrate material.

To confirm that the groove array was capable of producing a photocurrent, LBIC measurements were performed using a 635 nm laser focussed to a spot size of around 2 μm . A typical LBIC image recorded from a mini-module consisting of 16 series-connected groove devices is shown in

Figure 9c. It was found the photocurrent generation was fairly uniform across the grooves (see cross-section through the photocurrent image shown in Figure 9d, with negligible current generation recorded from the flat sections on either side of the grooves. Interestingly one groove near the middle of the mini-module generated a lower photocurrent, possibly indicating that it was operating near to short current. The photocurrent generated by the rest of the module verified the resilience of the device to non-functional grooves.

The efficiency of single grooves and mini-modules containing a different number of grooves was established by recording their *J-V* characteristics. A single 1.6 μm -wide groove was able to demonstrate a PCE of 7% (see Figure 9e) having a stabilised efficiency of 7.3% (see figure 9f). This reduced to 2.6% when fabricated into a module consisting of 16, 1.6 μm -wide grooves. A brief investigation was conducted into the shelf-life stability of the single-groove devices. It was found that following 150 days in dark storage under nitrogen, devices actually increased in efficiency from 4.0% to 5.0%. Taken together, these results indicated the potential of this type of back-contact architecture.

Following device development and optimisation, we have recently reported an improvement on previous work and have fabricated back-contact perovskite solar modules with each part of the process performed using fully scalable techniques.⁶⁰ Here, the ETL device contact additionally incorporated a tin oxide layer between the titanium and C_{60} . This was included as a result of a reported instability of the Ti/C_{60} interface which can undergo a reaction to form carbides even at room temperature in the solid state.⁶¹

The embossing pattern was also updated to reduce the width of grooves to 1.5 μm and change their shape from being ‘V-shaped’, to ‘U-shaped’. This was done primarily to make grooves easier to emboss with high fidelity and enhanced yield. The grooves were also organised into so-called ‘cascades’, each consisting of 362 series connected grooves. These cascades were separated from one another on the substrate by deep track-like features patterned on the surface termed ‘delineation features’ which acted as high-resistance pathways – see figure 10a. This electrically isolated adjacent cascades from one other without requiring any scribing steps that would typically add time and cost to the manufacturing process. Adjacent cascades could additionally be connected in parallel, with holes being extracted via a busbar at one edge of the substrate and electrons from the other edge. This allowed a module to be created consisting of 10’s of parallel-connected cascades, each made up of 362 series-connected grooves.

One component of our work is that modules are fully fabricated using roll-to-roll techniques. This approach has the benefit of a high throughput design that allows for a large number of devices to

be fabricated in a single coating run. The flexible substrates can also be spooled and unrolled with no detriment to device performance. To fabricate devices, several evaporation sources were directed at different angles to the substrate, allowing the opposing walls of the grooves to be sequentially coated with the ETL or HTL contacts. This both reduces the processing time required to coat the surface and reduces the energy costs associated with breaking vacuum between each deposition step. The perovskite active layer was also deposited by slot-die coating the substrate on a moving web.

The coated substrate was then characterised using a number of different techniques. Nano-focus X-ray fluorescence (XRF) mapping was used to image the grooves to explore the uniformity and directionality of the evaporation processes (see Figure 10b). Here, the presence of nickel (HTL) and titanium (ETL) located on opposite walls was verified, with a lead signal (corresponding to the perovskite) localised within the grooves. This confirmed cross-sectional SEM measurements (shown in Figure 10c), which was also able to reveal an overlap between the transport materials at the apex of the grooves. Interestingly, the integrated intensity of the lead fluorescence fluctuated across the grooves and indicated a higher lead concentration towards

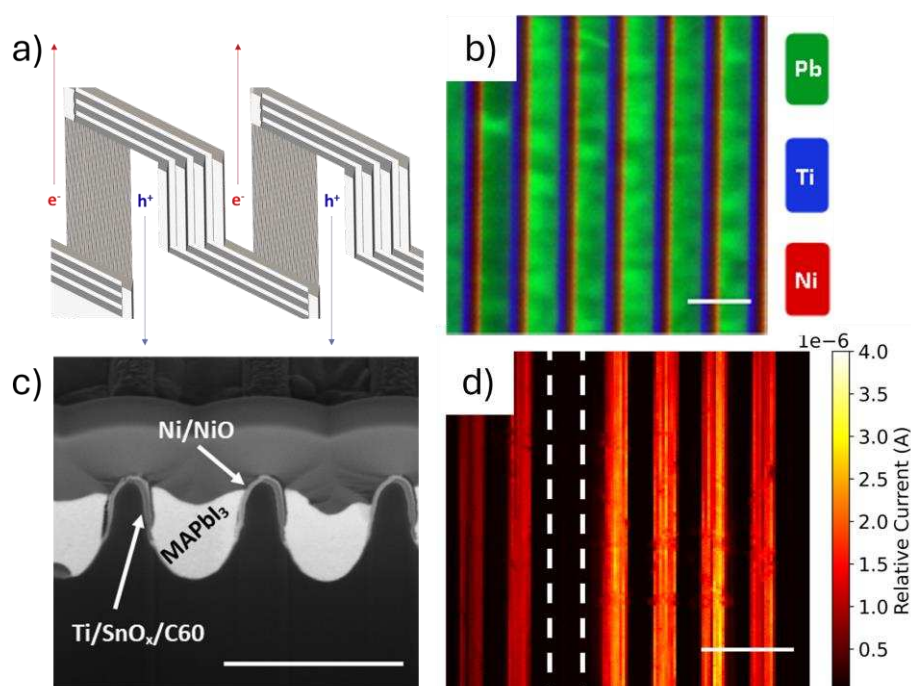


Figure 10: a) schematic showing charge-extraction in a groove device (not to scale); b) XRF mapping of several elements over a cascade of grooves (scale bar 2 μm); c) cross-sectional SEM of a groove cascade (scale bar 2 μm); d) Photocurrent mapping of a series of cascades (scale bar 500 μm)

Reproduced from Blackburn et al. Copyright 2025 American Chemical Society

the nickel-coated wall; this both suggested the presence of sub-surface voids, and also a varying efficiency of wetting of the groove walls during the precursor solution deposition process.

The photocurrent across a series of parallel connected cascades was imaged using a photocurrent mapping technique. Here, a typical current map is shown in Figure 10d. This was constructed by projecting a series of pixelated optical patterns at the substrate, with post-processing used to reconstruct a map of photo-current generation. Although the individual grooves cannot be observed owing to the relatively low magnification of the microscope, a relatively uniform photocurrent generation was observed across each cascade. However, one cascade, identified by the white dashed lines in Figure 10d, is clearly generating no measurable current. This was attributed to either poor electrical contact during measurement or to a short circuit within the cascade. Nevertheless, the rest of the cascades appear unaffected, suggesting that such groove mini modules are resilient to manufacturing defects.

Individual cascades from the coated web were tested and demonstrated an impressive champion PCE of 11.3% (device active area of 0.0689 cm²), which stabilised at 12.8% (having champion values of V_{oc} and J_{sc} of 373 V and 0.056 mA/cm² respectively). Interestingly, this high efficiency was achieved through back-illumination (i.e. light was directed at the groove through the plastic substrate). We note that this is not only the highest reported efficiency for a back-contact perovskite solar cell reported to date, but also the first demonstration of a back-contact perovskite device fabricated using fully scalable techniques. We emphasize that the laterally contacted transport materials and plastic substrate also allow for illumination from either side of the device, providing an inherently bi-facial device. We discuss the opportunities for bi-facial operation below.

The Future

The steady growth in the efficiency of both silicon and perovskite back-contact solar cells is charted in Figure 11. It is clear that there has been continued growth in the efficiency of perovskite devices over the last decade, however such devices are still to demonstrate the high efficiencies and stabilities routinely demonstrated by silicon-based technologies.

As we have outlined, one of the key challenges in creating high efficiency back-contact perovskite solar cells is creating surfaces patterned by electrodes whose separation approaches perovskite charge carrier diffusion lengths which are typically on the order of 100's of nanometres.² Such patterning must be achieved over large areas without introducing shorting pathways which otherwise limit efficiency. Although various approaches have been made to template such

structures, none of these have yet reached sub-micron length-scales. Evidently, further work should focus on the development and improvement alternative of fabrication methods to enable more efficient charge-extraction in these devices.

It is also clear that very few of the methods so far used to fabricate back-contact perovskite solar cells are consistent with scaled-up manufacture. Many of the techniques explored require lengthy solution processing steps to template the back-contact structures and are thus impractical to implement at scale. They also require time-consuming scribing steps to create device modules.

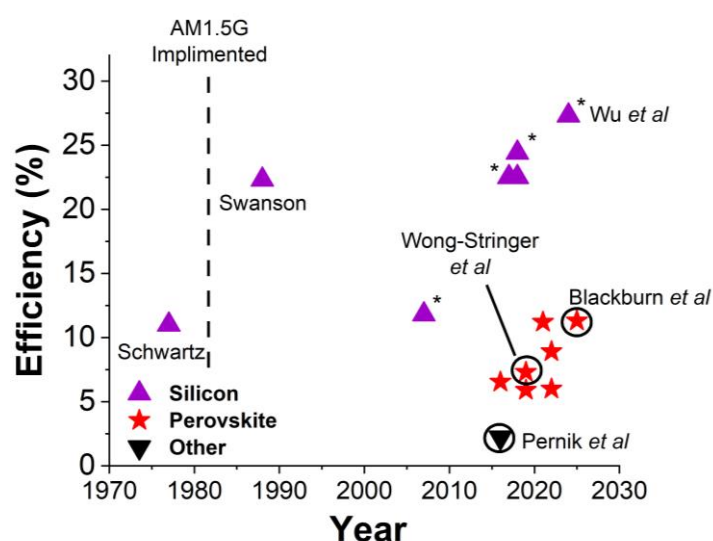


Figure 11: Major milestones in the efficiency of various back-contact architectures over time. Asterisks indicate certified efficiencies, points in circles indicate groove-based devices

This Spotlight on Application article has focused on work done in our collaboration to develop a new type of back-contact solar cell device based on a micro-groove embossed substrate that has been patterned using a directional coating technique. We believe this architecture solves many of the patterning and manufacturing challenges outlined above. The devices realised combine both high module efficiency (12.8% stabilised PCE), with a fully

scalable fabrication process that incorporated roll-to-roll slot-die coating. Critically, devices can be entirely constructed without the use of expensive and scarce metals such as indium. The light-weight nature of the fully-flexible plastic substrate should also allow modules to be applied to surfaces that cannot bear the weight typical of relatively heavy silicon-PV installations. This will be of particular importance for potential application in developing countries. As discussed above, our devices are bifacial. Here we expect opportunities for application in the emerging field of Agrivoltaics. For example, part of the surface of a glasshouse used for growing plants could be covered with PV modules. Here, part of the light entering the glasshouse that is not absorbed by the plants is expected to be scattered and then absorbed through the back-side of the PV modules. Whilst bifacial silicon photovoltaic panels could offer a similar yield in energy generation when used in this way, the often rigid and heavy panels may not be as easily interfaced

with non-load bearing structures (such as a polytunnel) and thus light weight flexible perovskite technologies are likely to find an advantage.

However, significant challenges remain before commercialisation. At present, the groove devices we have reported correspond to single cascade measurements that have been sectioned from a larger roll-to-roll coated web.⁶⁰ To create a commercial product, it is necessary to realise high efficiencies consistently and uniformly over a large area. Power Roll is now undertaking scale-up, creating 10 x 10 cm, fully roll-to-roll coated devices. We expect these to act as the building blocks of full-scale commercial modules.

Device stability is not a widely reported metric in many published reports of back-contact perovskite solar cells. For commercialisation, devices must clearly demonstrate an appropriate level of stability consistent with their intended application. At present, work is being undertaken at Power Roll to enhance device stability, with activity focusing on materials compatibility, intrinsic stability, surface passivation and encapsulation. Indeed, recent experiments have identified a number of routes to enhance operational stability; these include incorporating ultra-thin films of molecular materials at the ETL/perovskite and HTL/perovskite interfaces, together with capping the surface of the perovskite using a polymer barrier layer.

In addition to our recent work, we note other reports on the use of scalable methods (such as slot-die coating) to deposit the perovskite in a back-contact architecture.⁶² We emphasize that future work must focus on the use of scalable methods to fabricate back-contact electrodes with high precision and yield, with this being a critical step in the development of device modules. It will also be interesting to explore the use of other scalable techniques to deposit the perovskite active layer. Here, spray coating is of particular interest as it combines both high device efficiency and enhanced processing speeds.⁸

We suggest the following development activities should be explored to raise the current state-of-the-art power conversion efficiency from around 10% to over 20%. Such activities should also focus on improving operational stability to meet International Electrotechnical Commission (IEC) standards. We believe the following to be necessary;

1. Increased densification of interdigitated and back-contacted patterns, allowing greater geometrical fill factors to be realised.
2. Adoption of the most efficient, narrow band gap, stable perovskite formulations such as FAPbI₃. This will both help to improve device efficiency and stability.

3. The use of improved charge extraction layers and contacts to minimize charge carrier recombination and reduce unwanted electrochemical interactions.
4. Develop precise but scalable coating techniques allowing highly uniform thin films to be created. This is a critical part of increasing operational yield.
5. Utilise effective light management strategies such as anti-reflection coatings and surface layers to improve light harvesting.
6. Develop effective encapsulation strategies to prevent the ingress of moisture and oxygen.
7. Increase the conductivity of the electrodes to reduce series resistance and improve fill factor.

Conclusions

The development of back-contact perovskite solar cells is a growing research area that is likely to reach commercial viability in the coming years. Through reduced material costs and high-speed, low-cost processing via roll-to-roll coating and compatibility with flexible substrates, back-contact perovskites could find an important niche in the solar-cell market. There is however significant scope for further advances; here a promising architecture is that of micro-groove devices which we show can be fabricated using roll-to-roll processing and achieve efficiencies in excess of 12%. These devices potentially circumvent some of the issues that face traditional planar architecture devices, such as parasitic optical absorption in the charge transporting layers, a reliance on indium TCOs, an absence of the time-consuming scribing steps and the potential to increase energy yield through their inherent bi-faciality. Further work is however needed to enhance device efficiency and operational stability.

Acknowledgements

This work was partly funded by the Engineering and Physical Sciences Research Council (EPSRC) grant EP/V027131/1 (High-efficiency flexible and scalable halide-perovskite solar modules). D.B. thanks Power Roll Ltd who partly funded his studentship. Power Roll acknowledges a wide range of funding - in particular the Energy Catalyst 7 (40900) and Energy Entrepreneurs Fund 7 (EEF7018) grants. We extend our sincere thanks to the Power Roll operations team for their invaluable R&D, including testing, vacuum coating, printing, characterisation and QC.

Conflicts of Interest

D.G.L. is co-director of the company Ossila Ltd which retails materials used in photovoltaic research. Power Roll Ltd hold the following patents relating to the substrates used in this work:

Canada 2840327, China, 201180071841.6, 201480006419.6, Europe 2724380, EP 2951866, USA 14/264670, 14/764599, South Africa 2014/00531, Brazil BR1120150175007, Hong Kong 16103709.8, India 2812/KOLNP/2015, Japan 2015-555797, UK GB2487419.

References

- (1) A. Kojima, K. Teshima, Y. Shirai and T. Miyasaka, *Journal of the American Chemical Society*, 2009, 131, 6050-6051.
- (2) 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, *Science*, 2013, 342, 341-344.
- (3) Y. Zheng, Y. Li, R. Zhuang, X. Wu, C. Tian, A. Sun, C. Chen, Y. Guo, Y. Hua, K. Meng, K. Wu, C.-C. Chen. *Energy Environ. Sci.*, 2024, 17, 1153-1162
- (4) B. Jiao, L. Tan, Y. Ye, N. Ren, M. Li, H. Li, X. Lib, C. Yi, *Energy Environ. Sci.*, 2025, 18, 5437-5447
- (5) NREL, Best Research-Cell Efficiency Chart, (accessed January, 2025).
- (6) J. Zeng, Z. Liu, D. Wang, J. Wu, P. Zhu, Y. Bao, X. Guo, G. Qu, B. Hu, X. Wang, Y. Zhang, L. Yan, A. K. Y. Jen and B. Xu, *Journal of the American Chemical Society*, 2024, DOI: 10.1021/jacs.4c13356.
- (7) J. E. Bishop, J. A. Smith, C. Greenland, V. Kumar, N. Vaenas, O. S. Game, T. J. Routledge, M. Wong-Stringer, C. Rodenburg and D. G. Lidzey, *ACS Applied Materials & Interfaces*, 2018, 10, 39428-39434.
- (8) T. Thornber, O. S. Game, E. J. Cassella, M. E. O’Kane, J. E. Bishop, T. J. Routledge, T. I. Alanazi, M. Togay, P. J. M. Isherwood, L. C. Infante-Ortega, D. B. Hammond, J. M. Walls and D. G. Lidzey, *ACS Applied Materials & Interfaces*, 2022, 14, 37587-37594.

- (9) E. J. Cassella, E. L. K. Spooner, T. Thornber, M. E. O'Kane, T. E. Catley, J. E. Bishop, J. A. Smith, O. S. Game and D. G. Lidzey, *Advanced Science*, 2022, 9, 2104848.
- (10) M. Du, X. Zhu, L. Wang, H. Wang, J. Feng, X. Jiang, Y. Cao, Y. Sun, L. Duan, Y. Jiao, K. Wang, X. Ren, Z. Yan, S. Pang and S. Liu, *Advanced Materials*, 2020, 32, 2004979.
- (11) Z. Huang, X. Ge, Z. Liu, B. Shi, P. Wang, Y. Zhao and X. Zhang, *ACS Applied Energy Materials*, 2024, 7, 11683-11690.
- (12) J. Zhang, X. Hu, H. Li, K. Ji, B. Li, X. Liu, Y. Xiang, P. Hou, C. Liu, Z. Wu, Y. Shen, S. D. Stranks, S. R. P. Silva, H.-M. Cheng, W. Zhang, *Adv. Funct. Mater.* 2021, 9, 2104396
- (13) Uranium Marketing Annual Report, US Energy Information Administration, 2024.
- (14) L. Wagner, J. Suo, B. Yang, D. Bogachuk, E. Gervais, R. Pietzcker, A. Gassmann and J. C. Goldschmidt, *Joule*, 2024, 8, 1142-1160
- (15) D. K. Schroder, *IEEE Transactions on Electron Devices*, 1997, 44, 160-170.
- (16) G. Wang, Q. Su, H. Tang, H. Wu, H. Lin, C. Han, T. Wang, C. Xue, J. Lu, L. Fang, Z. Li, X. Xu and P. Gao, *Nature Communications*, 2024, 15, 8931
- (17) C. Longeaud, A.F. Allah, J. Schmidt, M. El Yaakoubi, S. Berson, N. Lemaitre, *Organic Electronics*, 2016, 31, 53-257
- (18) M. D. Lammert and R. J. Schwartz, *IEEE Transactions on Electron Devices*, 1977, 24, 337-342.
- (19) R. J. Schwartz and M. D. Lammert, Washington, DC, USA, 1975.
- (20) R. M. Swanson, S. K. Beckwith, R. A. Crane, W. D. Eades, K. Young Hoon, R. A. Sinton and S. E. Swirhun, *IEEE Transactions on Electron Devices*, 1984, 31, 661-664.
- (21) R. R. King, R. A. Sinton and R. M. Swanson, 1988.
- (22) R. R. King, R. A. Sinton and R. M. Swanson, *Applied Physics Letters*, 1989, 54, 1460-1462.
- (23) R.A. Sinton, Y. Kwark, J.Y. Gan, R.M. Swanson, *IEEE Electron Device Letters* 1986 EDL-7 567-569.
- (24) H. Savin, P. Repo, G. von Gastrow, P. Ortega, E. Calle, M. Garín, R. Alcubilla, *Nature Nanotechnology*, 2015 10 624-628.
- (25) S. Bhattacharya, S. John, *Scientific Reports*, 2019, 9, 12482.

- (26) G. Yang, A. Ingenito, O. Isabella, M. Zeman, *Solar Energy Materials & Solar Cells* 2016, 158, 84–90.
- (27) G. Yang, A. Ingenito, N. van Hameren, O. Isabella, M. Zeman, *Appl. Phys. Lett.* 2016, 108, 033903.
- (28) F. Haase, F. Kiefer, S. Schäfer, C. Kruse, J. Krügener, R. Brendel, R. Peibst, *Japanese Journal of Applied Physics* 2017, 56, 08MB15.
- (29) K. Masuko, M. Shigematsu, T. Hashiguchi, D. Fujishima, M. Kai, N. Yoshimura, T. Yamaguchi, Y. Ichihashi, T. Mishima, N. Matsubara, T. Yamanishi, T. Takahama, M. Taguchi, E. Maruyama, S. Okamoto, *IEEE Journal of Photovoltaics*, 2014, 4, 1433-1435.
- (30) K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, *Nature Energy*, 2017, 2, 17032.
- (31) M.K. Mat Desa, S. Sapeai, A.W. Azhari, K. Sopian, M.Y. Sulaiman, N. Amin, S.H. Zaidi, *Renewable and Sustainable Energy Reviews*, 2016, 60, 1516–1532 .
- (32) J. Keller, K. Kiselman, O. Donzel-Gargand, et al. *Nat Energy* 2024, 9, 467–478.
- (33) C. M. Hangarter, B. H. Hamadani, J. E. Guyer, H. Xu, R. Need, D. Josell, *J. Appl. Phys.* 2011, 109, 073514.
- (34) D. Josell, R. Debnath, J.Y. Ha, J. Guyer, M.A. Sahiner, C.J. Reehil, N.V. Nguyen, *ACS Applied Materials & Interfaces*, 2014, 6, 15972–15979.
- (35) C. M. Hangarter, R. Debnath, J.Y. Ha, M.A. Sahiner, C.J. Reehil, W.A. Manners, D. Josell. *ACS Applied Materials & Interfaces* 2013, 5, 9120-9127.
- (36) M. Kim, J.H. Park, J.H. Kim, J.H. Sung, S.B. Jo, M.-H. Jo, K. Cho K, *Adv. Energy Mater.*, 2015, 5, 1401317.
- (37) D. Fu, X.L. Zhang, R.L. Barber, U. Bach, *Adv. Mater.* 2010, 22, 4270-4274.
- (38) Z. Liu, R. Lin, M. Wei, M. Yin, P. Wu, M. Li, L. Li, Y. Wang, G. Chen, V. Carnevali, L. Agosta, V. Slama, N. Lempesis, Z. Wang, M. Wang, Y. Deng, H. Luo, H. Gao, U. Rothlisberger, S.M. Zakeeruddin, X. Luo, Y. Liu, M. Grätzel, H. Tan, *Nature Materials* 2025, 24, 252–259
- (39) K. Xiao, Y.-H. Lin, M. Zhang, R. D. J. Oliver, X. Wang, Z. Liu, X. Luo, J. Li, D. Lai, H. Luo, R. Lin, J. Xu, Y. Hou, H. J. Snaith and H. Tan, *Science*, 2022, 376, 762-767.

- (40) K. A. Bush, A. F. Palmstrom, Z. J. Yu, M. Boccard, R. Cheacharoen, J. P. Mailoa, D. P. McMeekin, R. L. Z. Hoyer, C. D. Bailie, T. Leijtens, I. M. Peters, M. C. Minichetti, N. Rolston, R. Prasanna, S. Sofia, D. Harwood, W. Ma, F. Moghadam, H. J. Snaith, T. Buonassisi, Z. C. Holman, S. F. Bent and M. D. McGehee, *Nature Energy*, 2017, 2, 17009.
- (41) A. N. Jumabekov, E. Della Gaspera, Z. Q. Xu, A. S. R. Chesman, J. Van Embden, S. A. Bonke, Q. Bao, D. Vak and U. Bach, *Journal of Materials Chemistry C*, 2016, 4, 3125-3130.
- (42) Q. Dong, J. Song, Y. Fang, Y. Shao, S. Ducharme and J. Huang, *Advanced Materials*, 2016, 28, 2816-2821.
- (43) Y. Liu, Q. Dong, Y. Fang, Y. Lin, Y. Deng and J. Huang, *Advanced Functional Materials*, 2019, 29, 1807707.
- (44) Y. Song, W. Bi, A. Wang, X. Liu, Y. Kang and Q. Dong, *Nature Communications*, 2020, 11.
- (45) Q. Hou, D. Bacal, A. N. Jumabekov, W. Li, Z. Wang, X. Lin, S. H. Ng, B. Tan, Q. Bao, A. S. R. Chesman, Y.-B. Cheng and U. Bach, *Nano Energy*, 2018, 50, 710-716.
- (46) S. Deng, B. Tan, A. S. R. Chesman, J. Lu, D. P. McMeekin, Q. Ou, A. D. Scully, S. R. Raga, K. J. Rietwyk, A. Weissbach, B. Zhao, N. H. Voelcker, Y.-B. Cheng, X. Lin and U. Bach, *Nano Energy*, 2022, 102, 107695.
- (47) O. L. Pursiainen, J. J. Baumberg, H. Winkler, B. Viel, P. Spahn and T. Ruhl, *Optics Express*, 2007, 15, 9553.
- (48) K. J. Prince, C. P. Muzzillo, M. Mirzokarimov, C. A. Wolden and L. M. Wheeler, *ACS Applied Energy Materials*, 2022, 5, 9273-9279.
- (49) X. Lin, J. Lu, S. R. Raga, D. P. McMeekin, Q. Ou, A. D. Scully, B. Tan, A. S. R. Chesman, S. Deng, B. Zhao, Y. B. Cheng and U. Bach, *Advanced Energy Materials*, 2021, 11, 2100053.
- (50) K. J. Rietwyk, X. Lin, B. Tan, T. Warnakula, P. Holzhey, B. Zhao, S. Deng, M. A. Surmiak, J. Jasieniak and U. Bach, *Advanced Energy Materials*, 2023, 13, 2200796.
- (51) B. Zhao, L. V. Gillan, A. D. Scully, A. S. R. Chesman, B. Tan, X. Lin, J. Liu, K. J. Rietwyk, S. Deng, C. Bailey, Y. B. Cheng, D. R. McCamey and U. Bach, *Angewandte Chemie International Edition*, 2023, 62.
- (52) X. Lin, A. S. R. Chesman, S. R. Raga, A. D. Scully, L. Jiang, B. Tan, J. Lu, Y. B. Cheng and U. Bach, *Advanced Functional Materials*, 2018, 28, 1805098.

- (53) T. Ma, Q. Song, D. Tadaki, M. Niwano and A. Hirano-Iwata, *ACS Applied Energy Materials*, 2018, 1, 970-975.
- (54) E. O. Shalenov, K. N. Dzhumagulova, A. Ng and A. N. Jumabekov, *Solar energy*, 2020, 205, 102-108.
- (55) D. R. Pernik, M. Gutierrez, C. Thomas, V. R. Voggu, Y. Yu, J. Van Embden, A. J. Topping, J. J. Jasieniak, D. A. Vanden Bout, R. Lewandowski and B. A. Korgel, *ACS Energy Letters*, 2016, 1, 1021-1027.
- (56) M. Wong-Stringer, T. J. Routledge, T. McArdle, C. J. Wood, O. S. Game, J. A. Smith, J. E. Bishop, N. Vaenas, D. M. Coles, A. R. Buckley and D. G. Lidzey, *Energy & Environmental Science*, 2019, 12, 1928-1937.
- (57) D. Blackburn, T. J. Routledge, M. O’Kane, E. J. Cassella, O. S. Game, T. E. Catley, C. J. Wood, T. McArdle and D. G. Lidzey, *Solar RRL*, 2022, DOI: 10.1002/solr.202200263, 2200263.
- (58) T. J. Routledge, M. Wong-Stringer, O. S. Game, J. A. Smith, J. E. Bishop, N. Vaenas, B. G. Freestone, David, T. McArdle, A. R. Buckley and D. G. Lidzey, *Journal of Materials Chemistry A*, 2019, 7, 2283-2290.
- (59) N. K. Noel, S. N. Habisreutinger, B. Wenger, M. T. Klug, M. T. Hörantner, M. B. Johnston, R. J. Nicholas, D. T. Moore and H. J. Snaith, *Energy & Environmental Science*, 2017, 10, 145-152.
- (60) D. Blackburn, N. S. Hill, C. J. Wood, T. Velusamy, B. A. Nieto-Díaz, C. Woolley, A. Brown, L. Zampelis, T. McArdle, M. Worth, T. Thornber, I. Albariqi, R. C. Kilbride, T. Yang, C. N. Hunter, G. J. Leggett, G. Koutsourakis, J. C. Blakesley, F. A. Castro, D. Beynon, T. M. Watson, D. Sirbu and D. G. Lidzey, *ACS Applied Energy Materials*, 2025, 8, 2219–2228
- (61) W. H. Wang and W. K. Wang, *Journal of Applied Physics*, 1996, 79, 149-152.
- (62) H. P. Parkhomenko, M. Mangrulkar and A. N. Jumabekov, *Coatings*, 2023, 13, 550.