Combinatorial Investigation and Modelling of MoO₃ Hole-Selective Contact in TiO₂|Co₃O₄|MoO₃ All-Oxide Solar Cells

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A TiO₂|Co₃O₄|MoO₃ all-oxide solar cell produced by spray pyrolysis and pulsed laser deposition (PLD) onto a fluorine-doped tin-oxide (FTO) glass substrate with gold (Au) back contacts is demonstrated for the first time. A combinatorial approach is implemented to study the effect of molybdenum oxide (MoO₃) as a recombination contact and the influence of the cobalt oxide (Co₃O₄) light-absorber thickness on the performance of the solar cells. An increase of more than 200 mV in the open circuit voltage (Vₜₙ) is observed with a concurrent enhancement in terms of short-circuit current (Jₘₖ) and maximum power in comparison with TiO₂|Co₃O₄ devices without the MoO₃ layer. To understand the mechanism, full drift diffusion simulations are performed. The higher performance is attributed to elimination of a recombination process at the absorber/metal back-contact interface and surface passivation by the MoO₃ layer.

1. Introduction

Metal–oxide (MO) semiconductors are regarded as an emerging class of materials to address the growing demand of low-cost solar cells. Co₃O₄ is a very stable and earth-abundant metal oxide with intrinsic p-type conductivity and two optical band-gaps (~1.5 eV and ~2 eV) in the visible region. The p-type nature of Co₃O₄ thin films has been successfully exploited to form efficient heterojunctions in many applications, including solar photocatalysis, solar cells, supercapacitors, high-performance sensing devices, and cathode materials for rechargeable lithium batteries.

Co₃O₄ has a high work function (6.3 eV) and ionization potential (6.6 eV), which greatly limits the number of metals with appropriate energetic characteristics to act as effective contacts for hole extraction in devices. The addition of hole-selective contacts (HSC) and hole-selective materials allows for better extraction of holes. A potential hole-selective material is MoO₃ – an n-type semiconductor with a large electron affinity (~6.7 eV) and work function (~6.9 eV), which rules out any electron transport via the conduction band across the Co₃O₄|MoO₃ interface. However, the energy alignment between the conduction band minimum of MoO₃ and the valence band maximum of Co₃O₄ might be favorable for hole transfer from the Co₃O₄ valence band to the MoO₃ conduction band. Furthermore, little to no band bending is likely to occur at the interface due to the close proximity in work functions between these two materials. We predict that a similar mechanism will occur as reported by Schulz et al. for the case of NiOₓ/MoO₃ bilayers. According to this mechanism, MoO₃ can form the basis of a “charge recombination” layer. Thus, holes can be extracted very effectively via recombination at the Co₃O₄|MoO₃ interface and collected at the metal back contacts. Clearly, this makes MoO₃ a suitable candidate for use as a hole-selective contact (HSC).

Molybdenum oxide is widely used as a hole-selective contact (HSC) and has received significant attention for improving the performance and stability in organic and c-Si solar cells. MoO₃ as a HSC reduces charge recombination by suppressing exciton quenching as well as the resistance at the photoactive layer/anode interface in organic solar cells. The MoO₃ HSC also serves as an optical spacer for improving the light absorption, thereby enhancing the photocurrent.

Molybdenum oxide was considered a p-type semiconductor but recently ultraviolet photoemission spectroscopy studies have shown that it is an n-type semiconductor. With a high work function exceeding those of elemental metals, MoO₃ offers opportunities for hole contact in inorganic semiconductor materials with layered transition metal dichalcogenide semiconductors as well as carbon-based nanomaterials.

In this report we introduce molybdenum oxide, deposited by pulsed laser deposition, as a recombination contact in Co₃O₄-based all-oxide photovoltaic cells. The research methodology involves combinatorial device libraries that are characterized for...
their chemical, structural, optical, and electrical properties.\cite{26–28}
We show that a thin layer of MoO$_3$ inserted between the Co$_3$O$_4$ absorber and the metal back contact improves the photovoltaic performance. With the help of advanced modeling and calculations, we have demonstrated improvements in the performance by removing the surface recombination center and passivation on the oxide–metal back contact interface.

### 2. Results

Figure 1 shows schematic diagrams of the combinatorial TiO$_2$|Co$_3$O$_4$|Au and TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au device libraries. FTO-covered glass (Figure 1a) onto which a TiO$_2$ layer was deposited with a linear thickness gradient indicated in blue with the thickness profile of the corresponding layers displayed on the top (Figure 1b). The Co$_3$O$_4$ absorber layer was deposited by pulsed laser deposition (PLD) perpendicular to the TiO$_2$ thickness gradient with the thickness profile of the corresponding layers displayed on the top (Figure 1c). A grid of 13 × 13 100-nm thick metal circles (diameters of 1.8 mm) were deposited by sputtering onto the Co$_3$O$_4$ layer using a shadow mask which served as back contacts and cross-section of combinatorial PV device library (Figure 1d). A MoO$_3$ thin film was deposited onto the same Co$_3$O$_4$ layer with an additional grid of Au back contacts (offset to the original grid). It was deposited in a continuous thickness gradient perpendicular to the Co$_3$O$_4$ deposition profile using PLD with the thickness profile of the corresponding layers. The layers are displayed on the top and cross-section of combinatorial PV device library shown on top (Figure 1e). Back contact arrangement on the top and cross-section of combinatorial PV device library (Figure 1d and f).

Figure 1. Schematic representation of the preparation of combinatorial TiO$_2$|Co$_3$O$_4$|Au and TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au libraries. FTO-covered glass (Figure 1a) onto which a TiO$_2$ layer was deposited with a linear thickness gradient indicated in blue with the thickness profile of the corresponding layers displayed on the top (Figure 1b). The Co$_3$O$_4$ absorber layer was deposited by pulsed laser deposition (PLD) perpendicular to the TiO$_2$ thickness gradient with the thickness profile of the corresponding layers displayed on the top (Figure 1c). A grid of 13 × 13 100-nm thick metal circles (diameters of 1.8 mm) were deposited by sputtering onto the Co$_3$O$_4$ layer using a shadow mask which served as back contacts and cross-section of combinatorial PV device library (Figure 1d). A MoO$_3$ thin film was deposited onto the same Co$_3$O$_4$ layer with an additional grid of Au back contacts (offset to the original grid). It was deposited in a continuous thickness gradient perpendicular to the Co$_3$O$_4$ deposition profile using PLD with the thickness profile of the corresponding layers. The layers are displayed on the top and cross-section of combinatorial PV device library shown on top (Figure 1e). Back contact arrangement on the top and cross-section of combinatorial PV device library (Figure 1d and f).

Figure 2. X-ray diffraction patterns for the Co$_3$O$_4$|MoO$_3$ device film deposited onto compact TiO$_2$ on FTO-coated glass. The labelling of the XRD spectra correlates to the spatial position on the PV library, as shown in the image on the right. The main diffraction peaks marked by a pentagon are assigned to the Co$_3$O$_4$ polycrystalline phase with a cubic structure (Fm3m).
from 240 to 340 nm. This was followed by the Co$_3$O$_4$ absorber layer indicated in red (Figure 1c). A MoO$_3$ thin film was deposited onto the same Co$_3$O$_4$ layer with an additional grid of Au back contacts (offset to the original grid). It was deposited in a continuous thickness gradient perpendicular to the Co$_3$O$_4$ deposition profile using PLD and MoO$_3$ layer indicated in blue (Figure 1e) recombination contact layers, both with bell-shaped gradients perpendicular to each other. The thickness of the Co$_3$O$_4$ and MoO$_3$ layers changed from 40 to 250 nm (Figure 1c) and 35 to 65 nm (Figure 1e), respectively. Figure 1d and 1f show the back contact arrangement and the cross-section of the combinatorial PV device library.

Figure 2 depicts the X-ray diffraction patterns (XRD) for the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au device libraries along the MoO$_3$ thickness gradient as shown in the right hand image, where the numbers show the position in the PV library where the XRD pattern was recorded (right to left in the direction of decreasing MoO$_3$ thickness indicated by the arrow). The XRD measurements show pronounced peaks of MoO$_3$, Co$_3$O$_4$, and TiO$_2$ as indicated in the plots. The relative intensities of the Co$_3$O$_4$, and SnO$_2$ peak remain constant from right to left across the library, because the thickness of these layers remains constant in this direction.

Figure 3 depicts I–V characteristics of the TiO$_2$|Co$_3$O$_4$|Au and TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au device libraries in order to enable a comparison of the performance of the cells with and without the MoO$_3$ layer. The first noticeable difference between the two libraries is the number of active photovoltaic cells. A higher number of active PV cells are present in the TiO$_2$|Co$_3$O$_4$|MoO$_3$ library than in the TiO$_2$|Co$_3$O$_4$ library. Secondly, the open circuit voltage ($V_{oc}$) is significantly enhanced upon addition of the MoO$_3$ layer, from 450 to 660 mV (note the change of the voltage color scale). Thirdly, the region with the maximum short-circuit current ($J_{sc}$) which is confined to the thick absorber region of the TiO$_2$|Co$_3$O$_4$ device library (Figure 3c), moved to the thinner part of the absorber layer for cells that contain the MoO$_3$ layer (Figure 3d).

The maximum power point ($P_{max}$) and internal quantum efficiency (IQE) follow a similar trend to the one for $J_{sc}$. The fill factor (FF) values for the library with MoO$_3$ are higher than that without MoO$_3$.

### 3. Discussion

Figure 4 displays the various PV parameters ($V_{oc}$, $J_{sc}$, FF, IQE and $P_{max}$) as a function of the absorber (Co$_3$O$_4$) thickness for TiO$_2$|Co$_3$O$_4$|Au (blue dots) and TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au (green dots) to emphasize correlations between these parameters and the absorber layer thickness. For the TiO$_2$|Co$_3$O$_4$|Au device library there is clear trend where each parameter improves with increasing absorber thickness. Both the $J_{sc}$ and $V_{oc}$ of this library show no maximum point over the thickness range shown here, suggesting that thicker absorbers could provide higher performance. However, another library with a Co$_3$O$_4$ absorber layer thicker than 250 nm (not shown here) revealed a decrease in performance, mainly with respect to $J_{sc}$.

The photovoltaic behavior of the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au device library as a function of absorber thickness shows different trends to the library without the MoO$_3$ layer. In Figure 4a, $V_{oc}$ increases from 200 mV and reaches a peak value of 660 mV at an absorber thickness of 50–60 nm. At an absorber thickness of >60 nm, $V_{oc}$ starts decreasing with increasing absorber thickness and approaches a similar value to that observed in the TiO$_2$|Co$_3$O$_4$|Au device library. We also note a decrease in the $V_{oc}$ below 50 nm (Figure 4a), at the lowest absorber thickness. This may be associated with the pin holes that can correlate with the very low values of FF (Figure 4c). The FF increases with the increasing absorber thickness until reaching a maximum of 42% at an absorber thickness of 150 nm and then starts decreasing when the absorber thickness is further increased. The highest $J_{sc}$ value can be observed for the absorber with a thickness range of 50–60 nm (Figure 4c). The maximum power

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**Figure 3.** Maps of the open circuit voltage ($V_{oc}$), short circuit current ($J_{sc}$), internal quantum efficiency (IQE [%]), and maximum power point ($P_{max}$) as a function of cell position in the library, for devices with (right rows) and without (left rows) a MoO$_3$ recombination contact layer. Each map represents cells with an Au back-contact material.
point, \( P_{\text{max}} \) (Figure 4e), which is the product of the maximum voltage and current, follows the same trend as \( V_{\text{oc}} \) and \( J_{\text{sc}} \).

The IQE is an important parameter for this study and is defined as the ratio of the number of charge carriers that are photogenerated and collected in the solar cell to the number of photons that are observed by the cell. It provides a measure of the efficiency with which photons that are absorbed in the device can generate useful carriers that are collected at the contacts. The IQE is essentially normalized to the absorber thickness, enabling comparison between cells with different absorber thickness.

The improvement of the IQE with increasing thickness for the absorber layer in the TiO$_2$|Co$_3$O$_4$|Au device library suggests that the performance is limited by absorber surface/interface effects. In contrast to this, the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au devices show a reduction in similar parameters with increasing absorber thickness, indicating the limitation is bulk-like in nature. In particular we attribute this limitation to the known poor transport characteristic ability through diffusion associated with the cobalt oxide (Co$_3$O$_4$) absorber.

The combinatorial study of the libraries with and without MoO$_3$ layer point towards poor absorber transport properties. During the fabrication of metal oxides, the abrupt termination of the crystal at surfaces and interfaces leads to an array of atoms with dangling bonds that are highly reactive. Since these materials are grown in poor vacuum conditions, these atoms readily bond to contaminations in the ambient environment resulting in a highly disordered surface with a high density of recombination centers. The presence of these recombination centers at surfaces/interfaces is detrimental to absorber transport properties. Deposition of MoO$_3$ on the absorber layer could eradicate these traps and work as a passivation layer.

In light of the previous analysis, we can make the four following assumptions with regard to the main processes that affect the photovoltaic performance of the devices studied in this work. i) The decay of \( V_{\text{oc}} \) and \( J_{\text{sc}} \) observed at larger thicknesses for the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au devices suggests a sluggish extraction of the minority carriers (i.e., electrons) at the electron-selective contact (TiO$_2$|Co$_3$O$_4$). ii) Due to the band alignment properties of the Co$_3$O$_4$|Au and Co$_3$O$_4$|MoO$_3$ interfaces, we assume that surface recombination occurs at both interfaces. iii) A large density of surface states induces high recombination at the Co$_3$O$_4$|Au interface. iv) These inner bandgap states can be removed by using an interlayer of MoO$_3$, which enhances the photovoltaic performance. To corroborate these assumptions, we have elaborated two models, presented in Figure 5, one for the TiO$_2$|Co$_3$O$_4$|Au devices (Figure 5a) and the other one for the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au ones (Figure 5b).

According to hypothesis (i), we can assume that surface recombination occurs at the TiO$_2$|Co$_3$O$_4$ interface for both devices, which is modeled by the recombination velocity \( S_n \). Similarly, according to assumption (ii), we have modeled surface recombination at the Co$_3$O$_4$|MoO$_3$ (HSC) interface with the parameter \( S_p \). In agreement with assumption (iii), we have considered a density of surface states, \( N_s \), at the interface Co$_3$O$_4$|Au, where trap-assisted recombination can take place and induce current losses. Finally, hypothesis (iv) states that there is no such density of surface states at the Co$_3$O$_4$|MoO$_3$ interface and we assume that \( N_s = 0 \). The other processes that we consider are common factors in both models: light-induced generation of free carriers and bulk recombination at rates \( G \) and \( U_r \), respectively. The established modeling framework (Figure 5) allowed us to calculate the theoretical trends of \( J_{\text{sc}} \) and \( V_{\text{oc}} \) with the absorber thicknesses for both device configurations. Our calculations were performed using the full numerical drift-diffusion approach. The details of our equations are given in the Appendix (in the Supporting Information) and the results of our simulations are given in Figure 6.

Our simulations reproduce very well several of the features observed experimentally. Firstly, we can reproduce the current losses observed for the TiO$_2$|Co$_3$O$_4$|MoO$_3$|Au devices, which validates assumption (i). We therefore infer that these devices undergo slow extraction of the minorities (electrons) at the TiO$_2$|semiconductor contact. Since electrons cannot be extracted efficiently, a concentration gradient builds up between the interface and the bulk of the semiconductor where electrons diffuse and recombine. This effect becomes more important as the thickness of the semiconductor increases, because the probability...
of recombination is increased. Note that if the contacts would extract electrons perfectly (i.e., $S_n \rightarrow \infty$), no such drop would be observed. Instead, a current plateau would be reached (see Appendix, Supporting Information). It should also be remarked that the $J_{sc}$ drop does not depend on the presence of surface states (see Appendix). However, from the simulation shown in Figure 6a and from the experimental data it is clear that for the range of thicknesses used such a feature was not observed.

In addition, our simulations reproduce the overall effect of surface states on the absorber thickness dependence of $J_{sc}$ and $V_{oc}$, which thereby corroborates assumptions (iii) and (iv). It should be remarked that the effect of surface states becomes even more important when the Co$_3$O$_4$ thickness decreases. Indeed, in this case minority carriers are extracted at the Co$_3$O$_4$|TiO$_2$ interface, away from the recombination center. Since the solar cell is illuminated from the TiO$_2$ side, the effect of traps will be noticeable only if the recombination center is close to the Co$_3$O$_4$|TiO$_2$ interface, i.e., when the thickness of the Co$_3$O$_4$ layer is small.

It should also be noted that our model underestimates the $J_{sc}$ and $V_{oc}$ drops induced by the presence of the traps. This may be due to a band shift at the interface between Co$_3$O$_4$ and the hole’s selective contact. In particular, a high density of trap states may induce Fermi level pinning at the interface Co$_3$O$_4$|Au, which would change the position of the band edge and drastically influence the recombination rate at this interface. However, such an effect has not been taken into account here and is out of the scope of this paper.

4. Conclusions

We have demonstrated the improved photovoltaic performance of TiO$_2$|Co$_3$O$_4$|MoO$_3$ all-oxide heterojunction solar cells fabricated by spray pyrolysis and pulsed laser deposition. By appropriate work function matching between Co$_3$O$_4$ and MoO$_3$, which serve as a recombination contact, we have achieved an open-circuit voltage enhancement of over 200 mV with 50-nm thick MoO$_3$ as the hole-selective contact (HSC), which is a significant improvement compared to Co$_3$O$_4$|Au cells. Using a powerful...
combinatorial approach and calculations in this paper, we can adequately describe the behavior of TiO₂|Co₃O₄|Au and TiO₂|Co₃O₄|MoO₃|Au cells. Based on the advanced modeling and calculations proposed here, we have established that MoO₃ not only acts as an efficient HSC but also eliminates the surface recombination at the absorber/metal back contact interface and passivates the surface.

5. Experimental Section

Spray Pyrolysis of TiO₂: Commercially available fluorine-doped SnO₂ (FTO) coated glass substrates (Figure 1a) with a size of 71.2 mm × 71.2 mm, and a sheet resistance of 15 Ω cm⁻¹ (TEC 15, Hartford Glass Co. Inc.) were thoroughly washed with soap, rinsed with ethanol and de-ionized water, followed by drying under a dry air stream. Compact TiO₂ layers were deposited by spray pyrolysis, where the substrates were placed onto a Ceran hotplate (Harry Gestigkeit GmbH). A precursor solution of 0.1 M titaniumtetraisopropoxide and 0.1 M acetylacetone in ethanol and isopropanol (mixing ratio 1:1) was sprayed with a pneumatic spray nozzle (Spraying Systems Co.) onto the substrates at a hotplate temperature of 450 °C. The nozzle was mounted onto a commercial x-y-z scanner (EAS Gmbh).[22,28] and the precursor flow rate of 60 cm³ h⁻¹ was controlled by a syringe pump (Razel Scientific Instruments), while clean dehumidified compressed air at a flow rate of 6 L min⁻¹ was used as carrier gas. The x-y scan velocity was 30 mm s⁻¹, and the nozzle-to-substrate distance was approximately 6.9 cm. For combinatorial device fabrication a linear thickness gradient (Figure 1b) was produced using a series of spray cycles with a successively decreasing scan area.

Pulsed Laser Deposition of Co₃O₄: Co₃O₄ thin films were deposited onto compact TiO₂ layers with a continuous thickness gradient using a commercial pulsed laser deposition (PLD) system (Neocera) equipped with a Kr excimer laser with an emission wavelength of 248 nm (Coherent Compex Pro 102). The substrate was kept inside the PLD system by a custom-made sample holder with a built-in heater. A total of 30 000 incident laser pulses were applied to a commercial Co₃O₄ target (J. Kurt Lesker, purity 99.9%) at a repetition rate of 8 Hz. The energy of the laser was 90 mJ pulse⁻¹, corresponding to an energy density of 2 J cm⁻². Throughout the deposition the sample was heated to a temperature of 600 °C and maintained at a target-substrate distance of 53 mm and oxygen pressure of 3.3 mTorr. To attain a continuous thickness gradient, the deposition was carried out without sample rotation (Figure 1c).

MO₃ Pulsed Laser Deposition: A MoO₃ thin film was deposited onto the same Co₃O₄ layer with Au back contacts in a continuous thickness gradient perpendicular to the Co₃O₄ deposition profile using PLD (Figure 1e). In this way we could use the same Co₃O₄, without an additional deposition. A total of 10 000 incident laser pulses were applied to a commercial MoO₃ target (J. Kurt Lesker, purity 99.9%) energy of 90 mJ pulse⁻¹, at a repetition rate of 8 Hz. The energy of the laser was 90 mJ pulse⁻¹, corresponding to an energy density of 2 J cm⁻². Throughout the deposition the sample was heated to (400 °C) and maintained at a target-substrate distance of 72 mm and oxygen pressure of 33 mTorr. To attain a continuous thickness gradient the deposition was carried out without sample rotation.

Deposition of Electrical Contacts: For I–V characterization the FTO substrate served as a transparent conducting front electrode. A grid of 13 × 13 100-nm thick metal circles with a diameter of 1.8 mm were deposited by sputtering onto the Co₃O₄ layer using a shadow mask and served as back contacts (Figure 1d). To attain good electrical contact to the measurement system, the TiO₂ and Co₃O₄ layers were mechanically removed close to the library edges using a diamond pen, followed by ultrasonic soldering (MBR Electronics) of a thin frame of a soldering alloy around the device library.

After the deposition of a grid of gold contacts on Co₃O₄, the sample was rotated 90° and a thin MoO₃ layer was deposited (as described above) followed by an additional 13 × 13 grid of gold back contacts, offset laterally to form two sets of 169 cells (Figure 1f). [The advantage of this method is that it allows direct comparison between Co₃O₄ cells with and without the MoO₃, since both sets of cells utilize the same Co₃O₄ and TiO₂ layers.]

Structural Characterization: Structural characterization of the photovoltaic (PV) cell libraries were carried out prior to deposition of the back contacts. X-ray diffraction measurements were performed using a Rigaku Smartlab work station with a 9–2θ scan range from 15 to 70° on six different points along the MoO₃ thickness gradient.

Optical Characterization: Optical transmission and reflectance spectra were measured with a home-built mapping system, consisting of a computer controlled x-y scanning table) (Märzhäuser Wetzlar GmbH & Co. KG) in conjunction with a specular reflectance probe and two integrating spheres, connected by optical fibers to CCD array spectrometers (HR4000, Ocean Optics Inc.). Total transmittance (TT), total reflectance (TR), and specular reflectance (SR) were measured after the deposition of each layer.[27]

Thickness Analysis: The thickness of the TiO₂ layer was determined by using commercially available optical modeling software (CODE), 25 fitting simulated reflection and transmission spectra, in the spectral range 350–1000 nm, to the measured ones the TiO₂ thickness, d₁, as a fitting parameter. The simulation was based on the QJL interband transition model,[29] and it was validated on different samples by using cross-section scanning electron microscopy (SEM) with a focused ion beam (FIB). The Co₃O₄ thickness derived from the optical measurements was verified with the thickness determination from cross-section SEM measurements taken at the maximum thickness of the deposition profile. The measured and calculated thicknesses were in good agreement with each other with a difference of less than 5 nm.

Solar Cell Characterization: The I–V characteristics of all 169 solar cells were measured with a home-built automated scanning I–V system consisting of a Keithley 2400 source meter, an x-y scanning table (Märzhäuser Wetzlar GmbH & Co. KG) in conjunction with a motorized z-arm Olympus/Märzhäuser Wetzlar GmbH & Co. KG) and a laser pumped Xe lamp (LDLS, from Energetics Co.), which was coupled through an optical fiber to the scanning stage. The solar-cell device library was placed onto the x–y stage and mechanically clamped using metal clips, which also provided the electrical connection between the FTO via the soldered metal frame, and the source meter for electrical measurements (Keithley 2400). Temporary electrical contact to each individual solar cell was established by a gold-plated spring-loaded tip (Ingun Prüfmittelbau GmbH), mounted onto the motorized z-arm, touching the back-contact metal patch for the duration of the measurement. After each measurement was completed, the tip was lifted and the x–y scanning table moved the library to the next contact. For each point the I–V curve was measured twice, in ascending and descending scan direction, to exclude capacitive effects due to charge trapping. Solar cells that showed a difference of more than 15% in the open circuit voltage (Voc), short circuit current (Jsc), or the fill factor were not considered for further analysis, as well as I–V curves that showed less than three measurement points in the quadrant of photovoltaic action.[28,30]

Data Acquisition: LabVIEW programming was used to control the scanning system for optical and solar cell characterizations. Solar cell parameters were extracted by data extraction software. Matlab graphical software was used for the graphical data presentation.

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