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Perspective

Effects of Masking on Open-Circuit Voltage and Fill Factor in Solar Cells

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Guidelines for the correct measurement protocol of novel photovoltaic technologies are becoming more frequent in literature as it is not straightforward how to accurately measure the true efficiency parameters of laboratory solar cells. This is particularly the case for small-area research devices, which are prone to overestimate the short-circuit current density due to edge effects of various types. The common recommended practice is therefore to utilize masks with well-defined apertures. Herein we show both experimentally and theoretically that this common practice, however, leads to erroneous determination of both open-circuit voltage and fill factor, which are figures of merit of equal importance to the short-circuit current density. Although the errors induced in voltage and fill factor by using a mask are generally smaller than what the errors in current can amount to when not using a mask, they are, on the other hand, omnipresent and can be quite well described.

Context & Scale

Research on novel solar cell materials, such as perovskites, is currently advancing at a tremendous pace, as they represent a very promising alternative to low-cost large-scale renewable electricity production. Yet, the power conversion efficiency of most materials still has room for improvement. To grasp what truly limits the values of short-circuit current, open-circuit voltage, and fill factors in solar cells, it is still necessary to disentangle the dynamics behind each of these parameters, independent of technology. Accurate and correct measurements of the values themselves are obviously therefore even more important. This photovoltaic method perspective provides a critical assessment of the currently recommended practice of implementing photomasks during the characterization of illuminated solar cells. We focus our study on perovskite solar cells, where the attention is currently needed, but the conclusions presented are valid for any photovoltaic technology.

Introduction

The concern of reporting accurate values of solar cell power conversion efficiency (PCE) has increased with the improved cell performances during the last years. The most frequent sources of contemporary photovoltaic (PV) measurement errors are usually found in spectral mismatch and erroneous estimations of the true area that takes part in generating the photocurrent.[1,2] Even though a set of routines and methods has been proposed[3–6] to circumvent these common measurement errors, the number of manuscripts reporting dubious or even erroneous efficiencies is still not negligible.[7] Overestimating the photocurrent generation by erroneous areas or unconsidered scattering or light piping effects led to the practice of cell masking first in the dye-sensitized solar cell community. In these highly light-scattering photovoltaic devices, the photocurrent was easily overestimated under illumination without the employment of photomasks. For perovskite solar cells, masking is also generally recommended for the same reasons, particularly for those based on mesoporous titanium dioxide. The now well-established effect of photon recycling[8] in high radiative efficiency perovskite films may in addition also guide more light into the active area from illuminated regions outside the electrodes. Accurate knowledge of true active area for generation and the reduction of excessive radiation are therefore necessary and also quite appropriately provided for by careful use of shadow masks during device characterization.[1,9–11] Several academic publishers have recently also started to request[12] that any submitted PV manuscript is now accompanied by a reporting form certifying if and how masking was employed during the measurements. Point 6 of the Nature publishing group checklist now requests authors to describe the mask/aperture used or to explain why a mask/aperture has not been used. It is also asked to specify if the measured short-circuit current density of the devices vary with mask/aperture area. These recommendations are highly justified to not let any exaggerated current density (and thus efficiency) claims pass through. Most solar cell certification institutes are also commonly employing masks when

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asked to certify high efficiencies of novel smaller laboratory cells. The contemporary focus of masking is thus put on its impact on short-circuit current density (J_{SC}) overestimations, often leading researchers to safeguard and choose masks with apertures noticeably smaller than the active device area to accommodate to these concerns. For the best perovskite photovoltaic devices, where only little now remains to be gained in actual photocurrent generation, the remaining improvements are, however, mainly to be expected in the open-circuit voltage (V_{OC}) and fill factor (FF). Correctly understanding and assigning the origin of V_{OC} and FF deficits in solar cells remains in fact one of the most essential aspects of photovoltaic research, independent of technology. Consequently, it is crucial to also measure these parameters as correctly as possible. What are, however, usually not considered sufficiently when employing masks under illuminated characterization are the induced effects on these equally relevant parameters of photovoltaic power conversion. Indeed, the photocurrent should not be allowed to be overestimated, but equal care must be taken to prevent errors in V_{OC} and FF determinations as a result of employing too small mask apertures. We therefore here deem it motivated to provide a method perspective on the outcome of masking on these parameters. Our contribution aims to convey that the common recommended practice of masking a solar cell in fact cannot unconditionally be endorsed. Sometimes masks with apertures much smaller than the device area are being employed, but this is categorically detrimental for the open-circuit voltage of the device. Masking with small apertures can in addition affect the fill factor substantially, and in different ways depending on what conditions the device is operating under. The chosen mask aperture size is thus crucial, to not over- or underestimate these two photovoltaic figures of merit. This is herein demonstrated by results from measured perovskite devices under different masking and illumination conditions coupled to simple analytical expressions for solar cells operating in different recombination regimes. Our perspective is thus focused on perovskite solar cells, but the general deductions are valid independent of photovoltaic technology, as supported by results provided in the Supplemental Information.

Results

We here choose to assess the influence of masking by studying a set of planar n-i-p $MAPbI_3$ solar cells employing doped organic charge selective layers. The manufacturing of these 500-nm-thick hysteresis-free cells is outlined earlier.[13] Figures 1A and 1B show the outcome of evaluating such a solar cell masked with three sets of apertures

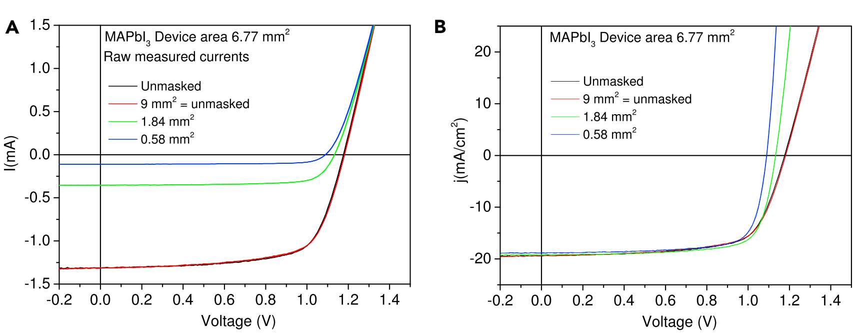

Figure 1. Double Sweep (Hysteresis-free) IV Curves at a Sweep Rate of 100 mV/s

(A and B) The figure shows current (A) and current densities (B) versus voltage for a planar n-i-p $MAPbI_3$ perovskite cell with a device active area of 6.77 mm^2 measured with three different mask apertures (one being larger than the active area, while two are smaller than the active area and densities are determined by dividing the current by the smaller of the two areas). Accounting for the generation area via the mask aperture provides the correct conversion into short-circuit current density in (B), but necessarily leaves you with a reduced open-circuit voltage, and an increased fill factor.

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when illuminated with a calibrated solar simulator. First, it must be noted that we see no discernable differences between a complete unmasked substrate and a 9 mm^2 mask (still larger than the overlap of the electrodes, which here always corresponds to 6.77 mm^2). This highlights that scattering or light piping effects are minimal in these specular reflecting planar perovskite solar cells. We also only observe minor impact on J_{SC} when then reducing the aperture to areas smaller than the device active area, and these changes are within the error margin originating from aperture area uncertainty. The most pronounced feature in Figure 1 is instead the clear impact of smaller masks on both V_{OC} and FF, which is also the main topic of this perspective. Both of these values are in fact erroneous, in terms of not actually being representative of the supposed reference AM1.5G 100 mW/cm^2 illumination conditions, which will be clarified in the following. We start by analyzing the quite straightforward influence of masking on the open-circuit voltage and later proceed with the more intricate effects on the fill factor. Finally, we discuss both parameters in terms of their combined impact on PCE.

Open-Circuit Voltage

The fundamental photovoltaic figure of merit of V_{OC} will always be erroneously underestimated when employing masks with an aperture area smaller than the electrode overlap area during illuminated cell characterization. This happens as the non-illuminated parts of any masked solar cells will still join in as volume for recombination, accordingly rendering the volume for recombination larger than the volume for generation. It is easy to acknowledge that any voltage provided by the cell exists all over the highly conducting electrodes and thus leads to a recombination current in the entire volume found between those electrodes. The total recombination current scales linearly with the area of the overlapping electrodes and is in the commonly used generalized Shockley diode equation, a simple exponential function of the voltage measured at those electrodes. Its value is hence not affected by any mask aperture size (apart from potential device temperature reductions due to partly working in the shadow). On the other hand, the volume for generation is defined by the area that is illuminated, and if using a mask, defined merely by the area of the aperture. So even if the total generation current equals the total recombination current at open-circuit conditions, the generation current density does not equal the recombination current density. This undesirable characterization condition will therefore inhibit the quasi-Fermi-levels from reaching its potential value and is thus not a fair way to estimate the true voltage potential of the PV material. In fact, with the above reasoning, the voltage provided by a masked cell should correspond to the voltage from an unmasked cell that is illuminated with an intensity reduced to the same amount as the masking area-cell area ratio. Our working postulate for this perspective thus simply advocates that masking will have the same effect on both voltage and fill factor as simply reducing the light intensity with a similar factor.

Based on this postulate, an analytical expression for solar cells not suffering from shunt resistances[14] or self-induced heating effects[15] can therefore be provided for the voltage reductions ΔV_{OC} that should occur with masking:

$$\Delta V_{OC} = \frac{nkT}{q} \cdot \ln(X) \qquad \text{with} \qquad X = \frac{A_{Aperture}}{A_{Device}}, \qquad \text{(Equations 1 and 2)}$$

where n is the diode ideality factor and kT/q is the thermal voltage. $A_{Aperture}$ is the area of the hole opening in the mask and A_{Device} is the device area defined by the overlapping area of the employed electrodes. In the common case of un-shunted solar cell operation, expressed by Equation 1, the reduction of V_{OC} will accordingly scale directly with the logarithm of the mask aperture such that cells with higher

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Table 1. Influence of Masking on the 1 Sun Characteristic Solar Cell Figures of Merit

	I_{SC} (μA)	J_{SC} (mA/cm^2)	FF	V_{OC} (V)	PCE %	ΔV_{OC} (mV) Measured	ΔV_{OC} (mV) Equation 1 with T_{ISO} = 300 K
Unmasked 6.77 ± 0.05 mm^2	1,312.77	19.39 ± 0.14	0.683	1.1820	15.7	–	–
Masked 1.84 ± 0.02 mm^2	353.16	19.19 ± 0.21	0.752	1.1338	16.4	−48.2	−52.3
Masked 0.58 ± 0.02 mm^2	109.53	18.88 ± 0.65	0.767	1.0905	15.8	−91.5	−98.6

Error margins are included for areas and J_{SC}.

ideality factors and measured at higher temperatures will suffer more in voltage losses upon masking (see Supplemental Information for the case of a Si photodiode). Accordingly, the value of the diode equilibrium recombination current I_0 has itself no influence on the extent of the induced masking voltage losses, only the isothermal (same with and without mask) device temperature and ideality factor matters. The logarithmic relation in Equation 1 thus leads to relatively small but nonetheless omnipresent underestimations in the open-circuit voltage. Bear in mind that the simple expression of Equation 1 will still be valid even if the cell suffers from series resistance losses. If a solar cell is, however, instead heavily shunted, the V_{OC} will no longer follow the outlined logarithmic relation of Equation 1 but will in the shunted voltage regime instead turn to drop linear with reduced masking area, but this is most often less relevant under 1 sun illumination conditions. More relevant is, however, the additionally induced temperature rise[15] that complicates the situation somewhat when illuminated with stronger (1 sun) light intensities. As a masked cell is partially operating in the shadow, it will be overall colder than an unmasked cell and the isothermal Equation 1 then becomes only an approximation, which will slightly overestimate the voltage drop due to masking. This is indeed the case for the 1 sun illuminated cell in Figure 1, where the theoretical isothermal expression slightly overestimates the measured voltage losses with 4 to 7 mV, as outlined in Table 1.

To certify our postulate that an isothermal reduction of illumination intensity has indeed the exact same effect on open-circuit voltage as masking does, we in Figure 2A plot the measured V_{OC} versus seven decades of illumination intensity for a 6.77 mm^2 cell with (black) and without (blue) a mask with a very small aperture of 0.436 mm^2 and accordingly with X = 0.0644. In the intermediate (isothermal 300 K) intensity regime at ~10^{-3} to 10^{-2} suns, the theoretical voltage losses from Equation 1 now fits perfectly with the measured voltage losses, both amounting exactly to 110 mV. The orange curve represents the black (masked cell) data just shifted in intensity, with the masking factor of 0.0644, which renders a seamless overlap with the unmasked lower intensity data in both the diffusion and the shunt-dominated part of the V_{OC} (suns) relation. The logarithmic diffusion part of the suns V_{OC} data allows us to also confirm that the ideality factor of 1.553 does indeed not change with masking, as opposed to that recently suggested in the work by Xu et al.,[16] and the two measurements can accordingly be fitted with the same equation, just shifted in intensity. Figure 2A therefore directly shows that a masked cell, with mask aperture smaller than the active area, is in fact never characterized under the assumed 100 mW/cm^2 reference solar intensities in terms of recombination, but instead at a reduced intensity corresponding to the aperture-device area ratio X. Although neglecting the temperature differences between masked and unmasked cells at the highest intensities, Equation 1 summarizes the general effect of masking on V_{OC}. The induced error in V_{OC} is, however, usually not as large as the example in Figure 2A, since this represents the outcome of the use of a very small mask. Figure 2B shows the induced relative error in V_{OC} as a function of employed mask aperture size (with respect to active device

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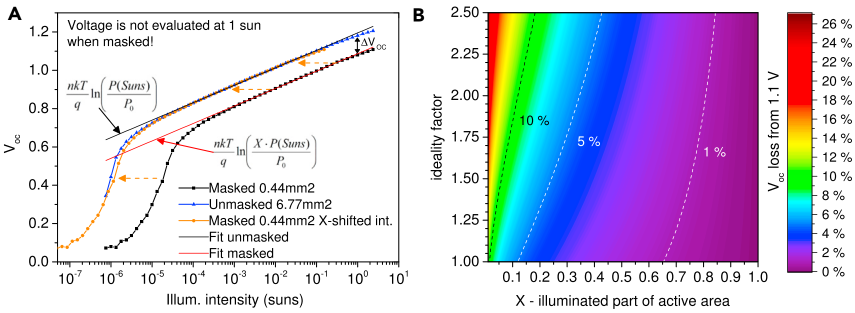

Figure 2. Effect of Masking on the V_{OC}

(A) The open-circuit voltage of a 6.77 mm^2 cell is here measured as a function of light intensity, with and without the utilization of a mask with a very small aperture of 0.436 mm^2. The fitted lines use the same equation with identical parameters apart from the inclusion of the masking aperture ratio X = 0.0644. Hence, it becomes clear that the voltage should actually not be described as being reduced at a particular light intensity with masking, but instead that the light intensity is simply incorrect. The graph thus highlights that a cell is not characterized under the believed 100 mW/cm^2 reference AM1.5G solar intensities in terms of recombination, when masked with a mask having an aperture smaller than the device area.

(B) The relative underestimation in V_{OC} as a function of masking ratio for different ideality factors starting from an unmasked V_{OC} of 1.1 V.

area) for different device ideality factors as outlined in Equation 1, assuming an unmasked V_{OC} of 1.1 V, which is representative for a high-quality perovskite solar cell. In general, it can be concluded that a relative error between 1% and 5% can be expected if 20% to 60% of the active area is shaded.

The quasi-Fermi levels of a masked solar cell are accordingly unable to reach their true sun illumination potential and the open-circuit voltage value is therefore always underestimated. The reason for this is simply that the steady-state charge carrier density present in a partly masked device can never be as high as in an unmasked one. To confirm this, we performed charge extraction measurements to compare the charge present in a masked and an unmasked cell at two different illumination intensities. Charge extraction measures the charge carriers stored in a photovoltaic device at a fixed illumination intensity/open-circuit voltage. This is realized by illuminating the device with continuous light, keeping it at open-circuit condition, to then rapidly simultaneously switching off the light and switching to short-circuit conditions and measure the resulting current pulse. By integrating the pulse, it is possible to determine the amount of charge stored in the solar cell at this prior steady-state V_{OC} condition. Figure 3 shows the obtained current pulses and their integrals, either unmasked (6.77 mm^2) or masked with an aperture of 2.06 mm^2, resulting in $X = 0.31$. A quite similar current pulse and

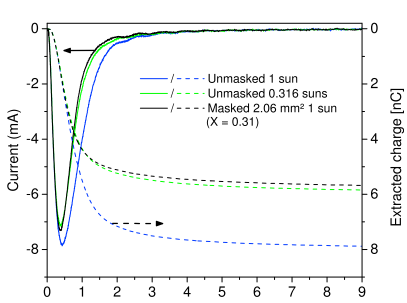

Figure 3. Charge Extraction Measurements

Charge extraction is here performed on an unmasked and 2.06 mm^2 masked cell. The number of extracted charge is quite similar in the masked cell as when the unmasked cell is illuminated with an intensity close to the ratio of the aperture and the device area.

integral value is obtained when instead evaluating the unmasked cell but with a reduced intensity very close to the masking aperture-device area ratio. As expected, the similarity concludes that the lower charge density resulting in reduced voltages in masked devices is not representative of 1 sun illumination conditions.

Fill Factor

For fill factors, the situation is slightly more complex, and different outcomes can occur with masking depending on in which regime of the recombination current curve we are evaluating the device. FF can accordingly both be over- and underestimated when using masks, but we emphasize that the most common case is an overestimation, due to the quite certain prevalence of device series resistance under 1 sun illumination conditions. In Figure 4, we show measured FF values of two planar $MAPbI_3$ solar cells, both affected by a typical series resistance of approximately 5 Ωcm^2, evaluated with and without masking under a similar large set of illumination intensities as in Figure 2A. The first device in Figure 4A has a very high shunt resistance (and therefore very low leakage current) as opposed to the second evaluated device in Figure 4B. The device in Figure 4A was evaluated with and without the presence of a mask with a small aperture of 0.436 mm^2, whereas the shunted device in Figure 4B was instead evaluated with a more reasonably sized 2.06 mm^2 mask aperture. The FFs were determined from the forward sweep, but due to the hysteresis-free character (Figure 1) of these devices, reverse sweep showed no noticeable difference (we are aware that this may generally not be the case for many other perovskite solar cells). To be able to also evaluate the effect of higher device series resistances, the I-V characteristics of the devices were also measured with an included external 60 Ω resistor (~4 Ωcm^2) in series. The FFs of both devices are indeed suffering from their series resistances at all intensities higher than ~0.1 suns and the losses are obviously also increased with the deliberately added external resistor. In Figure 4A, we see clearly how the FF of the 0.436 mm^2 masked device gets greatly overestimated when evaluated at "1 sun" illumination intensities, whereas the opposite is happening in the shunted regime <10^{-4} suns. In the intermediate diffusion limited intensity regime around 10^{-2} suns there are however only very minor differences, even with such a small mask aperture. However we again bear in mind that, in analogy with Figure 2A for V_{OC}, the measured values of FF of the masked devices are in essence just the same as the unmasked, but only shifted in intensity. To better recognize this implication in Figure 4, we clarify that the last black point in panel

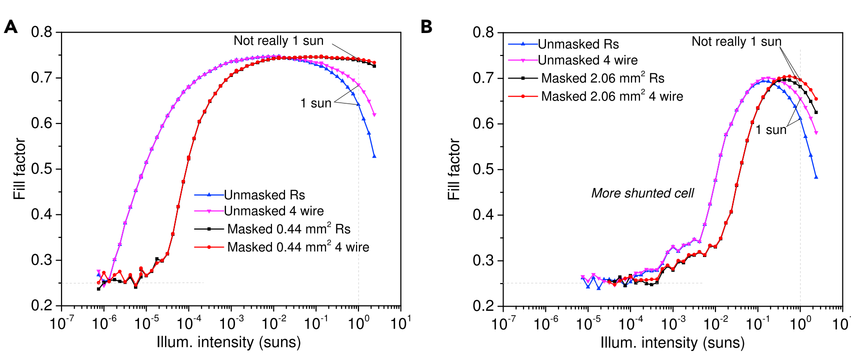

Figure 4. Measured FF as a Function of Light Intensity and Masking in Two Differently Shunted Perovskite Solar Cells

(A and B) The two cells are further evaluated with and without the presence of an additional series resistance of 4 Ωcm^2. The device in (A) is evaluated with a smaller mask than the device in (B), which is suffering more from a lower shunt resistance, forcing the FF to drop already at quite high light intensities. At 1 sun illumination, the FF of the masked cell is noticeably overestimated in both cases.

A (at 2.4 suns) equals a value on the blue curve lying in between the 10th and the 9th last point. As each intensity-step here corresponds to 75%, we conclude that the masking ratio X = 0.436/6.77 $\approx$ 0.065 is the same value as reducing the intensity 75% 9.5 times ($0.75^{9.5} \approx 0.065$). The same intensity offset goes for all other points in Figure 4A, whereas in Figure 4B, the larger mask aperture gives a ratio X = 0.31, which corresponds closer to four steps. This again concludes that also the FF is in fact not correctly determined under the assumed reference AM1.5G 100 mW/cm^2 illumination conditions, when employing a mask with aperture smaller than the area defined by the overlapping electrodes. In the Supplemental Information, the same is certified for a Si photodiode.

Theoretical Considerations on Fill Factor

Under 100 mW/cm^2 solar irradiance or comparable photon fluxes, a majority of present-day laboratory perovskite solar cells will quite certainly have entered a series resistance limited region. When using masks smaller than the device active areas one will, as outlined above, shift the operational maximum power point to a lower voltage value where the effect of series resistance is smaller and accordingly where the fill factor is getting larger. Under these quite common characterization conditions the masked device is indeed not under true reference sun illumination conditions in terms of recombination current densities, and the value of the series resistance affected FF will be erroneously overestimated. If solar cells are, however, instead operating in an intensity regime where the recombination current is fully ruled by the exponential diffusion part, there will, however, only be very small influences on fill factors with masking. If no other limitations are present, the FF in this regime can quite accurately be explained by an analog to Green's[17] theoretical FF expression and is here expected to slightly decrease with masking according to:

$$FF_{ideal,Masked} = \frac{\ln\frac{X \cdot I_{SC}}{I_0} - \ln\left(\ln\frac{X \cdot I_{SC}}{I_0} + 0.72\right)}{\ln\frac{X \cdot I_{SC}}{I_0} + 1}. \quad \text{(Equation 3)}$$

Here, I_{SC} is the unmasked (here assumed non-erroneous) short-circuit current of the device and X remains the aperture-device area ratio. This empirical expression for FF reduction due to masking is, however, as stated only valid in the intensity regime where the device is not suffering from either series or shunt resistances. It is further assumed that all other imaginable FF limitations, such as for example, space charge limited currents,[18] field dependent carrier generation,[19] distributed series resistance effects,[20,21] non-linear and light intensity dependent shunts,[22] are also not present. Similar, but slightly more complex as well as slightly less accurate, analytical expressions are also provided by Green for devices that in addition suffer from Ohmic resistive losses. We here therefore include one such approximate expression for fill factor alterations due to masking, based on Green's work for devices affected by Ohmic series resistance, as this condition is most common under 1 sun illumination.

$$FF_{Series,Masked} = FF_{ideal,Masked} \cdot \left(1 - \frac{R_S \cdot X \cdot I_{SC}}{\frac{nKT}{q} \cdot \ln\left(\frac{X \cdot I_{SC}}{I_0}\right)}\right), \quad \text{(Equation 4)}$$

where setting X = 1 will provide the FF of the unmasked but series resistance affected cell. Although an empirical approximation not at all accounting for all conceivable limiting features to fill factor, Equation 4 is still a quite relevant and

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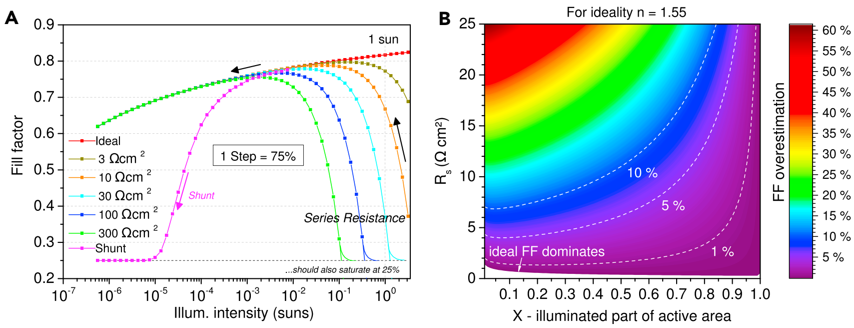

Figure 5. Calculated Masking Effect on FF

(A) The red curve originates from Green's empirical expression[17] (Equation 3) of how FF scales with V_{OC} in ideal solar cells. The other curves show the impact of various series resistances (Equation 4) as well as one (magenta) cell suffering from shunt resistance. Masking has effectively the same consequence as altering the illumination intensity such that one step in the graph data corresponds to either an intensity reduction of 75% or to the effect of using a mask with 75% aperture of the device active area.

(B) Calculated overestimation in FF as a function of mask aperture area-device area ratio X for various series resistances.

useful analytical expression for devices suffering from finite series resistance. Figure 5A shows how the FF of a theoretical photovoltaic diode (with ideality n = 1) suffers from both series and shunt resistance effects and is generally dependent on illumination intensity/masking. If the device is operating at the common high illumination intensities where R_s is present, the FF will increase noticeably with masking according to Equation 4. If, on the other hand, the device should already be operating under substantially reduced[14] light intensities, masking would here have a minor, but indeed opposite effect; marginally decreasing the FF according to the simpler ideal expression in Equation 3. Figure 5A includes the calculated FF of seven theoretical solar cells suffering from five different (some very high) series resistances and one low shunt resistance, and may therefore represent five differently conducting transparent electrodes and one leaky device. The red curve shows the ideal pure diffusion limited dependence, that is where the outcome of masking is defined by the simpler Equation 3. The magenta curve shows an identical device but in addition also is suffering from a shunt resistance. In this case, the FF will drop very rapidly with masking at intensities lower than $\sim 10^{-3}$ suns, to finally saturate at the Ohmic value of 25%, here occurring at 10^{-5} suns. The theoretical device presented in Figure 5A, showing a still reasonable series resistance of 10 Ωcm^2 (orange curve), has a fill factor of 0.667 at 1 sun illumination conditions if unmasked. Using the (not unrealistic) mask size with aperture of 75% of the device area will here, however, increase the fill factor to a value of 0.702. The effect of masking on FF can therefore be summarized as follows: if the device does not suffer from series resistance and "fairly large" mask is being used, the effect can almost be neglected. However, most laboratory solar cells do suffer noticeably from series resistance, most often due to the limited conductivity of the employed transparent electrode material, and quite pronounced overestimations in FF can easily be induced when using smaller mask apertures. Figure 5B displays the relative overestimation in FF, for a device (with n = 1.55) being illuminated with 1 sun intensity, as a function of mask aperture ratio X, for device series resistances ranging between 0 and 25 Ωcm^2 according to Equation 4. Already at series resistances as low as 4 Ωcm^2, the FF overestimation is already reaching 1% when only 10% of the active area is shadowed. It therefore highlights the necessity of employing masks with as large an aperture as possible.

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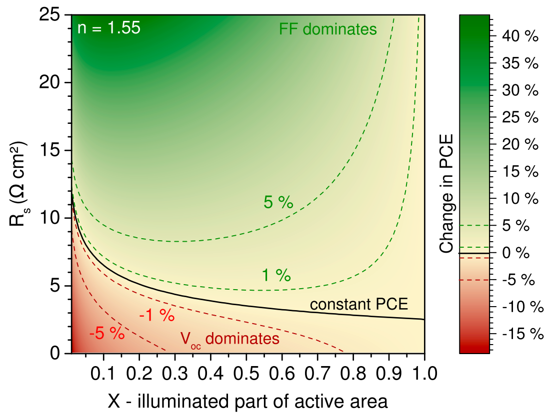

Figure 6. Total Masking Effect on Power Conversion Efficiency for a 1 Sun Illuminated Cell with n = 1.55

Neglecting possible J_{SC} alterations, the combined effect of the always present FF overestimations and V_{OC} underestimations leads to a fairly large "safe" region of allowable masking apertures. For devices with very low series resistances, the V_{OC} underestimation will dominate and render the total measured PCE with masking marginally lower than its true value, whereas for devices with higher R_S will instead noticeably overestimate the PCE as the mask is getting smaller.

Power Conversion Efficiency

The total induced effect of masking on the ultimate figure of merit for solar cell, namely the PCE, due to the here outlined effects on V_{OC} and FF, can hence also be summarized. As different technologies and geometries have already been shown to display very different J_{SC} dependency on masking area, we must here refrain from making any general statements on the influence on this parameter, that still embodies the original and highly justified motivation for masking, and can accordingly not conclude how PCE generally behaves with masking. We can nonetheless present the influence that the here evaluated parameters will together have on PCE by combining Equations 1 and 4 (details are found in the Supplemental Information). Figure 6 shows the product of the errors in V_{OC} and FF, for a device with unaffected J_{SC} and an ideality factor of 1.55, as a function of both series resistance and mask aperture ratio X. It can be concluded that the combined induced errors in PCE remain "acceptably small" as long as "fairly large" mask apertures are being employed, whereas devices with higher R_S will quite rapidly overestimate the PCE as the mask aperture is getting smaller. This combined effect is indeed what led to the observed behavior in Figure 1, where the PCE of the intermediate (1.84 mm^2) mask rendered the highest PCE, as with this mask aperture the FF is boosted more than what V_{OC} is suffocated. A similar overestimation of power conversion efficiency is demonstrated also for a Si photodiode in the Supplemental Information. We must, however, here emphasize that other limiting factors to FF, than the here accounted for series resistance and ideality factor, will have an additional influence on the relative change in PCE than what is summarized in the theoretical Figure 6. Although PCE can often be judged to not be heavily incorrect when using masks, we deem it justified to clarify that its constituents (FF and V_{OC}) can in fact be noticeably erroneous.

Accordingly, to minimize all effects outlined herein and to allow an as-truthful representation of the relevant open-circuit voltage as well as fill factor values, it is crucial to minimize the difference between any used mask aperture and the device area defined by the overlapping employed electrodes. This is, however, something that we believe is not generally common practice today, out of fear of overestimating

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the photocurrent generation. To alleviate and balance these two concerns, the best practice should be to still recommend the use of masks, but to employ masks with apertures as large as technically possible if one strives for accurate and correct values of V_{OC} and FF. Having masks with similar area as the active area, however, easily leads to substantial problems in alignment. The ultimate remedy is therefore to make both cell areas and aperture areas larger. Then, not only is alignment more easily achievable, but one also increases the accuracy in area determination and minimizes the relative influence of edge effects, such as for example excessive stray light.[23] For solar simulators with common collimation and devices using glass substrates with a thickness ≤ 1 mm^2, the employment of both masks and cell areas of approximately 1 cm^2 will obviously not impede the open-circuit voltage and fill factor noticeably and will simultaneously also not under- or overestimate the short-circuit current density. For smaller laboratory devices in which the short-circuit current density of unmasked cells is still noticeably larger than masked ones, we instead suggest measuring the cell first with a mask with a well-calibrated area smaller than the active area only to guarantee a good estimate of J_{SC}, and then to again measure the device with a mask slightly larger than the active area, which will provide more correct values of V_{OC} and FF. The final J-V curve, best representing the true performance of the cell, is then determined by normalizing the unmasked *J-V* curve to the masked current density value. As earlier already clarified,[9,10] it remains very motivated to ensure that substrate edges as well as other parts of the device are well masked to ensure not to overestimate J_{SC}, but let us not forget the impact of shadowed regions that inflate our FF and suffocate our potentially high photovoltage when using too small masks.

Outlook

This perspective aims at illuminating possibly overlooked aspects during the employment of photomasks in laboratory solar cell characterization. Our present study was focused on the novel field of perovskite photovoltaics, but the conclusions are valid independent of technology, as clarified in the Supplemental Information. We do not want to disparage the use of photomasks during device characterization, as it would most certainly lead to increased errors in current density determination. However, we have clearly demonstrated, both experimentally and theoretically, that masking has essentially the same effect on V_{OC} and FF as merely reducing the light intensity. Solar cells employing masks, with apertures smaller than the area defined by the overlapping electrodes, thus never allow correctly measuring V_{OC} and FF under the anticipated standard reference illumination conditions. V_{OC} will always be underestimated and FF will under common sun illumination conditions most often be overestimated with masking, due to the reduced influence of series resistance that is present, and the smaller the employed mask, the larger these errors become. Even if the effective combination of these two altered values often renders quite minute alterations to the more advertised parameter of power conversion efficiency, the individual values are still erroneous, and may hamper further development of novel photovoltaic technologies such as perovskite solar cells.

EXPERIMENTAL PROCEDURES

Full experimental procedures are provided in the Supplemental Information

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures and two figures and can be found with this article online at https://doi.org/10.1016/j.joule.2018.10.016.

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AUTHOR CONTRIBUTIONS

K.T. designed the study, which D.K., K.T., and L.G.-E. implemented experimentally. L.G.-E. manufactured the devices in Valencia, which D.K. and K.T. measured in Würzburg. K.T., D.K., and H.J.B. analyzed the data. K.T. wrote the paper, to which all authors contributed feedback and comments.

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