nature portfolio

Peer Review File

Improved Silicon Solar Cells by Tuning Angular Response to Solar Trajectory

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors presented a strategic study on improving the efficiency of silicon solar cells by tuning their angular response to the solar trajectory. The manuscript was well-organized and clearly written, and presented a novel approach to improving solar cell efficiency by considering the angular response and sunlight directionality. The paper highlighted how exploiting sunlight directionality can exceed the long-assumed efficiency limit of 29.4% for silicon solar cells, potentially reaching efficiencies of over 30% with less than 100-µm Si thickness. This work is timely and provides significant insights that could guide future developments in commercial Si solar cell technology. The framework supporting the proposed efficiency improvements was robust and well-supported by extensive references. The manuscript makes a significant contribution to the field of photovoltaic research and addresses important questions regarding the efficiency limits of silicon solar cells. I recommend its publication in its current form. Here are my suggestions for the article.
1. The explanation of how sunlight directionality impacts efficiency limits is clear, however, further empirical data or simulations validating these theoretical predictions would strengthen the manuscript.
2. The discussion on light-trapping designs is insightful. However, it would benefit from additional examples of practical implementation and potential challenges in real-world applications.

Reviewer #2

(Remarks to the Author)
The publication “Improved Silicon Solar Cells by Tuning Angular Response to Solar Trajectory” by Green and Zhou is a very interesting paper that analyzes in detail the influence of directed solar radiation on the characteristics of solar cells. The work is solid and offers readers an interesting insight into the influence of the orientation of the incident light on the maximum achievable current.

Therefore, a publication of this paper would be possible, but I am not sure if the novelty of the paper is sufficient for a publication in Nature Communication and whether the conclusions which the authors draw from their study are too broad.

On the one hand, they want to show that the theoretical efficiency previously determined for crystalline silicon solar cells is too conservative, as these papers have assumed the Lambertian limit. In my opinion, however, using the well-defined Lambertian makes sense because the optical scenarios presented by Green et al. in Fig 4 f depend on geographical boundary conditions and the tracking mode of the modules. This would mean that the theoretical efficiency of solar cells would no longer be clearly defined and publications on this topic would get ambiguous. In addition, in some of the publications that analyze light trapping with optical structures allowing for light-trapping beyond the Lambertian limit such as https://www.nature.com/articles/s41598-020-68704-w.pdf
it was already stated that the silicon solar cell efficiency can be greater than 30% (see last sentence in the above paper). Therefore, the basic statement is not new. I would therefore suggest formulating the main statement of the paper (especially in the abstract) somewhat more cautiously and in particular not to claim that the theoretical efficiency limit has be corrected.

The second critical point is that most publications dealing with optical structures beyond the Lambertian limit are based on simulations. There are no convincing measurement results that it is really possible to achieve short-circuit currents beyond the Lambertian limit. Many of the suggested light-trapping structures require a structuring of the silicon surface which might

lead to higher surface recombination velocity and/or require a much more sophisticated/cost-intensive process technology than the already excellent current industrial standard. So I think the claim in the abstract " The present work provides a strategy for ongoing improvements in commercial cell efficiency …".
Furthermore, the review of papers dealing with light-trapping structures (beyond the Lambertian limit) is insufficient for a Nature paper.

Reviewer #3

(Remarks to the Author)
This paper thoroughly studied the improvement in limiting efficiency of solar cells through angular adjustment from an optical perspective, especially the relationship between the pathlength enhancement factor Z and the incident angle. It predicts that the Z factor may exceed 4n2 at certain incidence angles, which could potentially help to overcome the well-known theoretical limit of silicon solar cells（29.4%）. The authors consider the sunlight directionality, the light-trapping schemes, bifacial modules and the tracking strategies as a whole, theoretically demonstrating the possibility of elevated limiting efficiency bound by wise designs of texture and device structure. However, there are several issues with this paper:
1) The Z factor is solely obtained through theoretical derivation, and whether it can be achieved or exceeded 4n2 in practice is doubtful.
2) For the results of >30% efficiency, does the authors calculate the overall power output according to the whole area of the solar module? If the conversion efficiency is raised by changing the incident angle, it seems that the Z factor may increase, but will the output power of the unit solar module increase?
3) The results disclosed in this manuscript may have far-research implications on implementation of refined management photovoltaic plant, but less inspiration on solar devices especially when taking economy and feasibility into account.
4) The descriptions and the demonstrations look like a little bit difficult for readers to follow.
5) A more specialized journal, like 'Progress in Photovoltaics' is more suitable.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The additional references, especially the experimental paper on light-trapping structures, provide valuable support for the theoretical predictions and discussions in the paper. The improvement removed all weak points of the paper. Therefore, this article is recommended for publication in Nature Communications.

Reviewer #3

(Remarks to the Author)
I recommend to accept this manuscript because my comments have been well addressed.

<u>Authors' response (NCOMMS-24-47941-T)</u>
"Improved silicon solar cells by tuning angular response to solar trajectory"
by Green and Zhou.

We thank all 3 reviewers for their time and effort in reviewing our paper and for their constructive reviews. We have responded to all comments and recommendations (in blue below) and accordingly modified the manuscript, also breaking down our original figures and adding additional subheadings to allow a clearer reading. Both a marked-up and a clear copy with these changes have been resubmitted as requested.

<u>Reviewer #1</u>
The authors presented a strategic study on improving the efficiency of silicon solar cells by tuning their angular response to the solar trajectory. The manuscript was well-organized and clearly written, and presented a novel approach to improving solar cell efficiency by considering the angular response and sunlight directionality. The paper highlighted how exploiting sunlight directionality can exceed the long-assumed efficiency limit of 29.4% for silicon solar cells, potentially reaching efficiencies of over 30% with less than 100-µm Si thickness. This work is timely and provides significant insights that could guide future developments in commercial Si solar cell technology. The framework supporting the proposed efficiency improvements was robust and well-supported by extensive references. The manuscript makes a significant contribution to the field of photovoltaic research and addresses important questions regarding the efficiency limits of silicon solar cells. I recommend its publication in its current form.

We thank the reviewer for the positive comments, correctly identifying that the main contribution of the paper lies in describing an approach that allows *"improving the efficiency of silicon solar cells by tuning their angular response to the solar trajectory"*. We also agree that the *"manuscript makes a significant contribution to the field of photovoltaic research and addresses important questions regarding the efficiency limits of silicon solar cells."*

Here are my suggestions for the article.
1. The explanation of how sunlight directionality impacts efficiency limits is clear, however, further empirical data or simulations validating these theoretical predictions would strengthen the manuscript.
2. The discussion on light-trapping designs is insightful. However, it would benefit from additional examples of practical implementation and potential challenges in real-world applications.

We have addressed both suggestions by including several additional references including a compelling experimental paper *"Experimental comparison of light-trapping structures for silicon solar cells"* by Tobin and colleagues at Spire Corporation, as part of a Sandia Labs project, published soon after our past work confirmed the "beyond Lambertian" light trapping potential of cross-grooves. It compares experimental absorptance of bare wafers with assorted textures on front and rear. For these bare wafers, the cross-grooves showed appreciably stronger long wavelength absorption compared to randomly textured surfaces both sides, as used for HJT cells, and textured top, planar rear as for TOPCon. The advantage for perpendicular light was shown to be equivalent to an extra 1mA/cm^2 increase in current output for a 150-micron thick cell compared to the "both sides textured" case.

Reviewer #2

The publication "Improved Silicon Solar Cells by Tuning Angular Response to Solar Trajectory" by Green and Zhou is a very interesting paper that analyzes in detail the influence of directed solar radiation on the characteristics of solar cells. The work is solid and offers readers an interesting insight into the influence of the orientation of the incident light on the maximum achievable current.
Therefore, a publication of this paper would be possible, but I am not sure if the novelty of the paper is sufficient for a publication in Nature Communication and whether the conclusions which the authors draw from their study are too broad.

As noted by Reviewer #1, we believe the paper's novelty is in linking two different isometric projections not previously considered in this context, capturing angular properties of incident radiation and light-trapping performance. This provides new opportunities for cell design refinement and performance improvement for different applications, in the same way as solar module design is now customised for ground mounted and residential use. As below, this is also the first valid documentation of a silicon cell design with limiting efficiency over 30%, justifying the broad claims made.

On the one hand, they want to show that the theoretical efficiency previously determined for crystalline silicon solar cells is too conservative, as these papers have assumed the Lambertian limit. In my opinion, however, using the well-defined Lambertian makes sense because the optical scenarios presented by Green et al. in Fig 4 f depend on geographical boundary conditions and the tracking mode of the modules. This would mean that the theoretical efficiency of solar cells would no longer be clearly defined and publications on this topic would get ambiguous. In addition, in some of the publications that analyze light trapping with optical structures allowing for light-trapping beyond the Lambertian limit such as
https://www.nature.com/articles/s41598-020-68704-w.pdf
it was already stated that the silicon solar cell efficiency can be greater than 30% (see last sentence in the above paper). Therefore, the basic statement is not new. I would therefore suggest formulating the main statement of the paper (especially in the abstract) somewhat more cautiously and in particular not to claim that the theoretical efficiency limit has be corrected.

Unfortunately, the result cited, as with others from the same authors and simulation approach, are erroneous, as we recently established by full COMSOL EM simulation. We were concerned by high Z (pathlength enhancement) factors needed to fit their results, with values over 100,000 required for those in their most recent paper [Optics Express 32, 29795-29816 (2024)] (compared to COMSOL values <50): https://opg.optica.org/oe/fulltext.cfm?uri=oe-32-17-29795&id=554261
Prior to our simulations, we had corresponded with the authors attempting to locate the source of error. One possibility was that their published fit to Si optical properties gives zero and negative absorption coefficient values in the simulation range – the authors responding that 15 digits were used in the fit, not the 6 published. However, the above paper now provides the full 15 digits and zero and negative values still result in the 1195-1200nm range. The paper claims over 95% absorptance here when there is no absorbing medium in the structure! The problem originates from the finite difference time domain (FDTD) simulation approach employed, requiring long run times to ensure energy trapped in slow modes drains (before Fourier

transformation of the transient to give wavelength response). However, unwanted domain wall reflections limit available simulation time, resulting in premature termination while most energy is likely still trapped. The recent paper gave us the opportunity to document the above errors in more detail in the "Comments On" paper attached and now referenced in our paper. The authors may decide to withdraw earlier papers based on the clear errors. Fortunately, 29.4% is still regarded as the limit by most of the PV community and a strong statement that 30.1% is a new limit will likely cast doubt on these erroneous results even if not withdrawn.

In terms of appropriate efficiency limits, we agree the Lambertian provides a well-defined limit but, as we show, it actually represent a lower bound rather than a limit and there is nowhere further to go with it (oscillating around 29.4% for nearly the last 40 years). We also show, what was to us at least, a surprising geographical commonality for both fixed tilt and tracking systems, documenting an efficiency limit of 30.1% (as well as angular response) for a cell that would outperform Lambertian in annual performance. It is not a trivial challenge to go higher – a light-trapping scheme better than cross-grooves would be required and well worth knowing about.

The second critical point is that most publications dealing with optical structures beyond the Lambertian limit are based on simulations. There are no convincing measurement results that it is really possible to achieve short-circuit currents beyond the Lambertian limit. Many of the suggested light-trapping structures require a structuring of the silicon surface which might lead to higher surface recombination velocity and/or require a much more sophisticated/cost-intensive process technology than the already excellent current industrial standard. So I think the claim in the abstract " The present work provides a strategy for ongoing improvements in commercial cell efficiency …".
Furthermore, the review of papers dealing with light-trapping structures (beyond the Lambertian limit) is insufficient for a Nature paper.

We agree with the reviewer's first point – we are not aware of any experimental device that has exceeded the Lambertian 4n2 boost in practice. However, a scheme that has 8n2 theoretical limit is likely to perform better than one with 4n2 limit in practice, all else being equal. This justifies the exploration of high Z factor options. As above, we have now included reference to a compelling experimental paper describing a clear experimental advantage of cross-grooves as well as several other light-trapping references, to address the final point above.
Regarding surface recombination, our experience has been that slats give lower values than upright pyramids, where "rounding etches" are required, so while the reviewer might well be correct, things might also go in the opposite direction.
Regarding costs, while we take the reviewer's point, TOPCon is clearly more expensive than PERC that is more expensive than BSF, but this is the way the industry has evolved chasing the leverage provided by higher efficiency. The experimental performance gain already demonstrated for cross-grooves is a reasonable fraction of the gain from each of the above transitions.

Reviewer #3
This paper thoroughly studied the improvement in limiting efficiency of solar cells through angular adjustment from an optical perspective, especially the relationship between the pathlength enhancement factor Z and the incident angle. It predicts that

the Z factor may exceed 4n2 at certain incidence angles, which could potentially help to overcome the well-known theoretical limit of silicon solar cells（29.4%）. The authors consider the sunlight directionality, the light-trapping schemes, bifacial modules and the tracking strategies as a whole, theoretically demonstrating the possibility of elevated limiting efficiency bound by wise designs of texture and device structure.

We agree with many of the comments made by this reviewer, but the reviewer may understate the paper's contributions as "It predicts the Z factor may exceed 4n2 at certain angles" – we showed this back in 1986! Rather, we would describe the contribution more as "It predicts the Z factor may exceed 4n2 over a range angles typical of present key commercial applications and provides a technique for matching Z factor to the requirements of these applications".

However, there are several issues with this paper:
1) The Z factor is solely obtained through theoretical derivation, and whether it can be achieved or exceeded 4n2 in practice is doubtful.

As above, we agree with the reviewer here – we are not aware of any experimental device that has exceeded the Lambertian 4n2 boost in practice. However, a scheme that has 8n2 theoretical limit is likely perform better than one with 4n2 limit in practice, all else being equal. This justifies the exploration of high Z factor options.

2) For the results of >30% efficiency, does the authors calculate the overall power output according to the whole area of the solar module? If the conversion efficiency is raised by changing the incident angle, it seems that the Z factor may increase, but will the output power of the unit solar module increase?

Yes, any efficiency advantage would apply in principle to the whole module since light angles remain the same across present planar modules. Efficiency advantage may even increase in practice, since oblique angle diffuse contributions to output are attenuated by higher top glass reflection.

3) The results disclosed in this manuscript may have far-research implications on implementation of refined management photovoltaic plant, but less inspiration on solar devices especially when taking economy and feasibility into account.

Yes, this is what was said when we developed PERC cells back in the 1980s. However, the manufacturing capabilities of the industry are improving at a surprisingly rapid rate as evidenced by the recent transition from BSF, to PERC, to TOPCon and HJT and now to IBC, with all this driven by the drive to higher efficiency. The present work provides a path to further increase once these paths are exhausted. We note that making perpendicular slats is trivial compared to making a TBC, HBC or HTBC cell and that there are other simpler light-trapping approaches that can take advantage of our matching criteria.

4) The descriptions and the demonstrations look like a little bit difficult for readers to follow.

Yes, length constraints on the paper and the amount of information conveyed made some sections quite cryptic, although Reviewer #1 does state: “The manuscript was well-organized and clearly written”. We have rewritten sections and improved the layout and description, particularly in the final sections by breaking down the original Fig.4 and the associated description into separate sections with their own subheadings

5) A more specialized journal, like ‘Progress in Photovoltaics’ is more suitable.

Perhaps, but all articles in Nature Communications are open access and the journal reaches a far wider cross-section of the community, including even the photovoltaic community. Also, with the growing importance of photovoltaics in addressing climate change, photovoltaics are assuming a far higher profile within the Nature group of publications than in the past. In fact, use of the search term “photovoltaic” gets 191 hits for Nature Communications from 1 January to 23 October 2024 alone, many more than from ‘Progress in Photovoltaics’.

Reviewer #1 (Remarks to the Author):
The additional references, especially the experimental paper on light-trapping structures, provide valuable support for the theoretical predictions and discussions in the paper. The improvement removed all weak points of the paper. Therefore, this article is recommended for publication in Nature Communications.

Response: We again thank the reviewer for the time spent on assessing our work and for the supportive comments.

Reviewer #3 (Remarks to the Author):
I recommend to accept this manuscript because my comments have been well addressed.

Response: We also thank this reviewer for the time spent on assessing our work and for the supportive comments.