Atwater and Polman reply — We are grateful to Rau and Kirchartz for their thoughtful remarks on our Commentary[1], and hope this dialog will generate clarity in the physics of high-efficiency photovoltaics. Our Commentary identified several new design approaches and architectures using photonic structures to increase photovoltaic efficiency. It was driven by thinking about the design of solar cells with (i) high radiative efficiency, (ii) 1 sun unconcentrated (C = 1) operation and (iii) employing a light-collimating angle restrictor element (as opposed to a geometrical concentrator).

As Rau and Kirchartz[2] point out in their equation (2), the various design elements such as angle restriction, light trapping and improvement of external radiative efficiency are interdependent, a point that was also made in a number of the references cited in our Commentary. We agree that their equation (2) provides a physically complete description of the variation of open-circuit voltage with the extent of light absorption and external radiative efficiency over the entire range of radiative efficiencies ranging from QE << 1 to QE ~1. We also agree that the light-trapping effect indicated by the third term of our equation (1) is a factor that is of importance for cell design only in the non-radiative limit, and cannot provide an additional increase in open-circuit voltage in cells with very high radiative efficiency.

For cells with very high radiative efficiency, the external radiative efficiency is the central concept in minimizing voltage loss. We note that in the limit (i) of high radiative efficiency (QE ~1) but low photon recycling probability (p_r ~0), our expression for term 4, written in terms of internal quantum efficiency approaches their term 4 in terms of external quantum efficiency, $kT\ln(\mathrm{QE}) \sim kT\ln[\mathrm{QE}/(1 - \mathrm{QE} + (1 - p_r)\mathrm{QE})]$, but these two expressions will differ in the case where photon recycling is significant, so writing the fourth term in terms of external radiative efficiency produces the most general result.

In their last paragraph, Rau and Kirchartz assert that in the non-radiative limit, variations of the light-trapping factor I "by changes of ε_{out} (by angular restriction) or of A (by changing light trapping) as discussed in ref. 1 are counterbalanced in the correct equation (2) by denominators of terms 2 or 1, respectively." (ε_{out}, the etendue of incident photons; A, the cell absorptance.) Although true, this cancellation does not however imply that angle restriction has no influence on open-circuit voltage for cells in the non-radiative limit. By contrast, for example, for thin light-trapping cells in the non-radiative limit, V_{oc} can be increased by angle restriction via a reduced cell thickness w, rather than the ε_{out} term. That is, angle restriction allows w to be decreased while maintaining high absorbance and thus acts as a key light-trapping factor in this case. Indeed, Campbell and Green previously showed this concept in an analysis of silicon solar cells in the purely non-radiative limit[3].

Overall, we agree that the factors affecting cell open-circuit voltage are interdependent and there are subtleties in the interplay between these interdependent factors. That these factors can be dramatically influenced by nanophotonic design to increase the cell open-circuit voltage was the essential point that motivated our Commentary, a point that remains robustly true in light of this further analysis: new approaches to light management that systematically minimize thermodynamic losses will enable ultrahigh efficiencies previously considered impossible. This development takes advantage of recent advances in the control of light at the nanometre and micrometre length scales, coupled with emerging materials fabrication approaches. It can lead to single-junction solar cells with efficiencies >30% for silicon[3] and >35% for GaAs (ref. 4), well above the Shockley–Queisser limit for conventional cell designs. Moreover, these new designs enable parallel multijunction solar cells with efficiencies above 50%.

References

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