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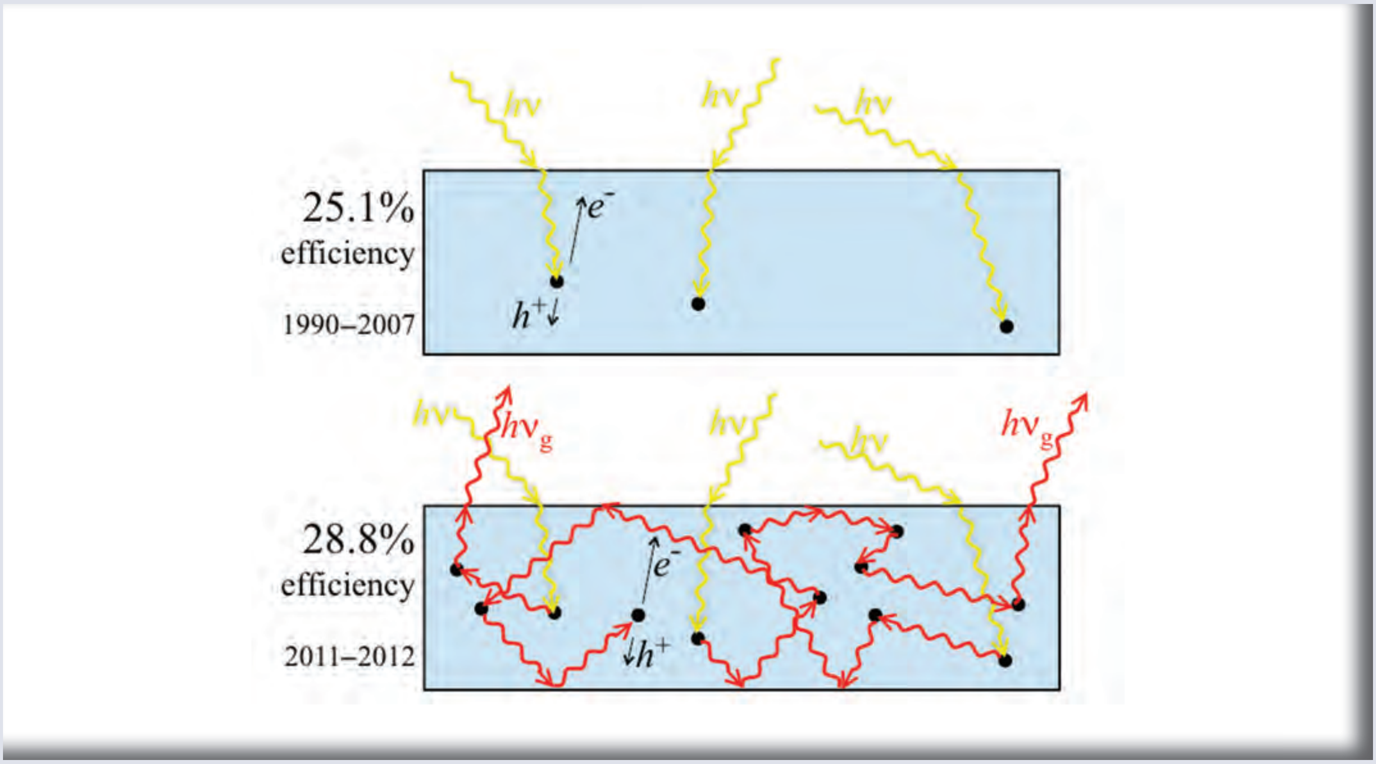
The Opto-Electronics of Solar Cells

Recent Advances in Colloidal Quantum Dot Photovoltaics



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Research Highlights

The Opto-Electronics of Solar Cells

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Abstract—Counter-intuitively, efficient external fluorescence is a necessity for achieving the highest possible solar cell efficiency. Why would a solar cell, intended to absorb light, benefit from emitting light? Although it is tempting to equate light emission with loss, paradoxically, light emission actually improves the open-circuit voltage, and the efficiency.

There has been great progress in solar cell efficiency, recently, as shown in Figure 1. After a long period of no improvement, the past two years have witnessed a surge to 28.8% efficiency [1] in the flat-plate, single junction, record. This is to be compared [2] with the Shockley-Quiesser [3] limit, 33.5% efficiency.

The idea that increasing light emission improves open-circuit voltage seems paradoxical, as it is tempting to equate light emission with loss. Basic thermodynamics dictates that materials which absorb sunlight must emit in proportion to their absorptivity. At open circuit, an ideal solar cell would in fact radiate out from the solar cell, a photon for every photon that was absorbed. Thus the external luminescence efficiency is a gauge of whether additional loss mechanisms are present. At the power-optimized operating bias point, the voltage is slightly reduced and 98% of the open-circuit photons are drawn out of the cell as real current. Good external extraction at open circuit comes at no penalty in current at the operating bias point.

On thermodynamic grounds, Ross derived [4] that the open circuit voltage is penalized by poor *external luminescence efficiency* η_{ext} as:

$$qV_{OC} = qV_{OC-\mathrm{Ideal}} - kT\,|\ln \eta_{ext}| \tag{1}$$

where η_{ext} is the probability of an internally radiated photon eventually escaping from the front surface of the cell. Equation (1) can be derived through the detailed balance method [2] of Shockley and Queisser (SQ). M. A. Green already inferred [5] the external luminescence yield, η_{ext}, of all the different historical solar cell materials, from their respective record $\{V_{OC\text{-ideal}} - V_{OC}\}$, employing eq'n. (1).

As solar efficiency begins to approach the SQ limit, the internal physics of a solar cell transforms. Shockley and Queisser showed that high solar efficiency is accompanied by a high concentration of carriers, and by strong fluorescent emission of photons. In a good solar cell, the photons that are emitted internally are likely to be trapped, re-absorbed, and re-emitted, leading to "photon recycling" at open-circuit. This leads to a very different physical picture of high efficiency solar cells, $>26\%$ efficiency, as illustrated in Figure 2.

To resolve the paradox of why external luminescence is good for solar cell efficiency, there are a number of different explanations:

1) Good external luminescence is a gauge of few internal loss mechanisms. At open circuit, an ideal solar cell radiates a photon for every absorbed photon. When electron-hole pairs recombine non-radiatively or when photons are absorbed without generating photocarriers within the active part of the device, both the external luminescence efficiency and the cell efficiency decrease.

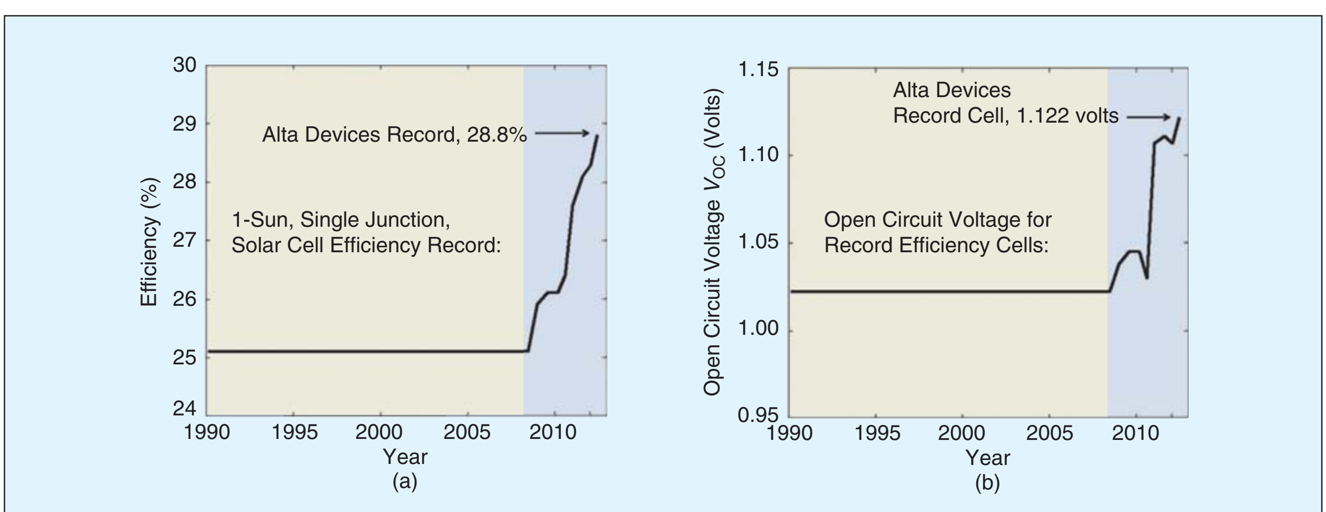

Figure 1. (a) The single junction, 1-sun, efficiency record, historically. (b) The open circuit voltage of the record solar cells.

2) External emission of photons into free space is unavoidable. All other losses can, in principle, be eliminated. Thus the total losses are at their very least, when external emission is the only loss mechanism. Maximum external emission is minimum total losses, which leads to the highest efficiency.
3) In un-textured cells, good external luminescence requires recycled photons, and re-absorption. Internal reabsorption recreates the electron-hole pair, effectively extending the minority carrier lifetime. The longer lifetime leads to a higher carrier density. Free energy, or voltage, increases with the logarithm of density.
4) The solar cell and the light-emitting-diode are equivalent, but reciprocal devices. Just as external emission leads to the most efficient light-emitting-diode, the most efficient solar cell maximizes external emission.
5) External luminescence is sometimes used as a type of contactless voltmeter, indicating the separation of quasi-Fermi levels in the solar material. This is sometimes employed as a contactless, quality-control-metric, in solar cell manufacturing plants. In this viewpoint, it is tautological: Good external luminescence actually IS good voltage, and therefore good efficiency.

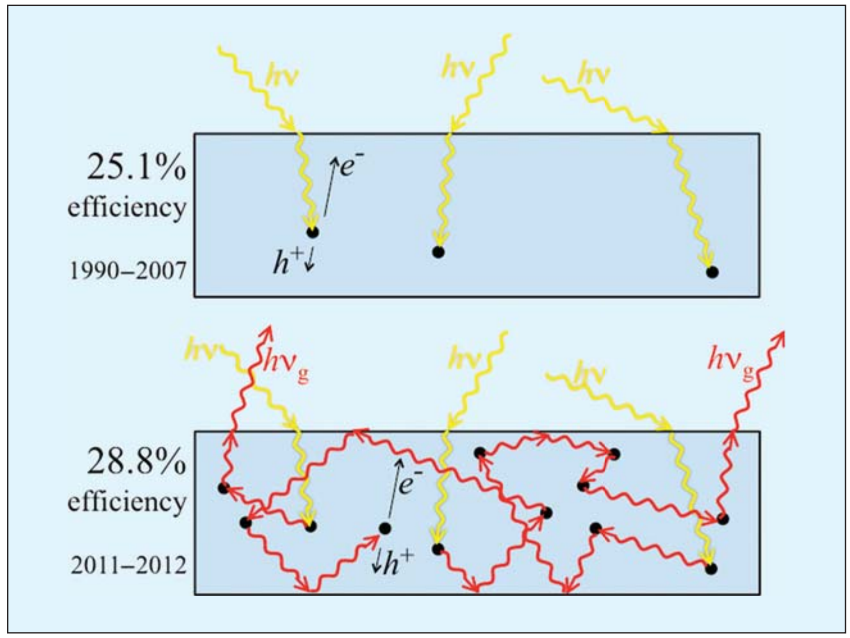

Figure 2. The physical picture of high efficiency solar cells, compared to conventional cells. In high efficiency solar cells, good luminescent extraction is a requirement for the highest open circuit voltages. One-sun illumination is accompanied by up to 40-suns of trapped band-edge luminescence, leading to the maximum external fluorescence efficiency.

This is the preferred explanation for the paradox:
Good external luminescence IS good voltage.

References

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Acknowledgement:

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