The Amazing past 3 years in PV: Any New Scientific Insights?

David Cahen and Pabitra K. Nayak[#]
Weizmann Institute of Science, Rehovot, Israel
([#] now @ Oxford Univ., UK; pknayakchem@gmail.com)

The remarkable advances over the past few years in performance of photovoltaic cells, including the advent of new absorber materials, allow us to take stock of how well we understand the real-world possibilities, and the limitations, of PV and if we can at all predict future progress.[1]

Apart from Si and InP, all cell types showed improved "best efficiencies".

All crystalline Si module types made major strides in cost reduction.

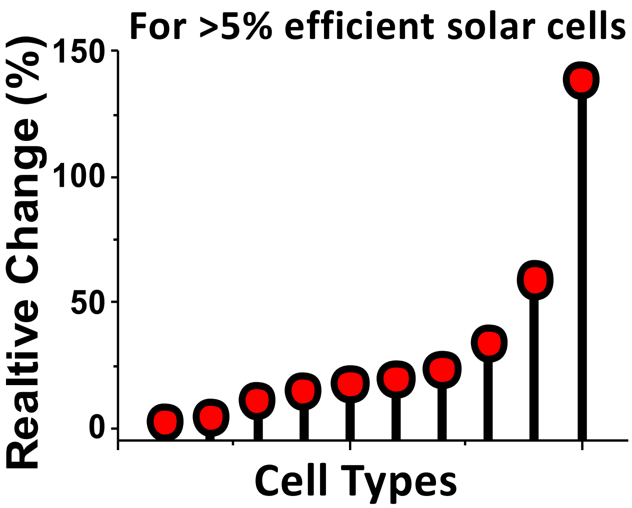
New cell types, e.g., sustainable chalcogenide, "perovskite" and quantum dot ones, appeared on the >5% efficiency scene.

Although all solar cells use the same basic principles, they differ in how they work, and the materials on which they are based are critical. Still, for all, the Shockley-Queisser (S-Q) limit serves as a benchmark, upper thermodynamic limit to the highest power conversion efficiency as it refers to *an idealized PV cell,* where the only loss pathway is radiative recombination; hence it helps to assess the potential for improved performance of real PV cells. As cells approach the S-Q limit, low luminescence quantum efficiency seems to be an important loss factor.

Real cells are, of course, non-ideal and the resulting additional constraints on efficiency must be understood and optimized for progress to be achieved. The best single crystal GaAs and (Ga,In)P solar cells closely resemble an ideal system and GaAs in fact exhibits an efficiency (after decades of research and development) close to the S-Q limit. At the same time a-Si cells show an extra loss of ≈600 meV, even after decades of research and development. The reason is clear: real world material parameters that are ignored in an ideal system pose additional limits.

Thus, while developments of GaAs-type cells tested the S-Q limit and showed better than ever its validity, the additional criterion of increased order for increased efficiency[2] has gained credibility from comparisons between recent results on different cells.

Also absent from the idealized cell are grain boundaries, which can determine the current and voltage efficiency in polycrystalline (PX) material-based solar cells by providing additional pathways of recombination and/or actual electrostatic barriers that lead to voltage loss. Even so, PX cells can perform very well and results for CdTe over the past years bring those cells in line with other well-developed ones, lending credence to the idea that the earlier formulated module/cell efficiency criterion (which implies that differences in chemistry and physics between cells and modules are mostly cell-type-independent[1]) holds water and is useful for gauging possible future technological developments.



The amazing 2011-2013 progress of nearly all solar cell types with possible or actual practical potential. Each dot represents a different cell type, using different materials. Not shown are the significant cost decreases of commercial cells, esp. multi/poly-

Most low-cost preparation processes yield materials with structural disorder and this disorder affects the electronic energies for electron (or hole) transport.[2] Tail states in the band gap, arising from dangling bonds, chemical impurities, band edge fluctuations and/or structural disorder also reduce cell performance by increasing non-radiative recombination of photogenerated carriers. We pay a price in terms of photovoltage due to energy dispersion in the band gap (instead of sharp band edges) as it limits the magnitude of quasi-Fermi level splitting.

Still, we have now materials that can be made with low cost, low temperature methods with "MOCVD-like" quality. Based on this and other considerations organo-metallic perovskites and CZTSS may well develop to yield high performance modules, considering the successes of CIGS and CdTe so far. For that, though, we will need more than flashy publications on ultra- to very- to just-small cells, with low lab yield; much work on preparation, fabrication, upscaling, yield and encapsulation is waiting, before a cell type can become a practical alternative for, or complement existing commercial cells. The jury is out if also here brilliant empiricism will lead our understanding or if the roles can be reversed (as was the case for single crystal Si & III-V cells).

---

(1) *Adv. Mater.* 23 (2011) 2870; 25 (2013) early view DOI:10.1002/adma.201304620
(2) *En. Env. Sci.* 5 (2012) 6022ץ