PHOTOVOLTAICS

An alternative 'Sun' for solar cells

Nanophotonic structures can be used to engineer efficient solar thermophotovoltaic systems.

Shanhui Fan

Some energy scientists have ambitions as astronomical engineers. Their goal is to convert solar energy into electricity by primarily tailoring the solar irradiation rather than optimizing the photovoltaic element of a device. This sort of solar engineering was first proposed in 1979 by Richard Swanson, then an electrical engineer at Stanford University. He introduced the concept of solar thermophotovoltaic (STPV) systems[1], in which an intermediate element is placed between the sunlight and the solar cell (Fig. 1). The intermediate element includes a black absorber — a material that can absorb the entire solar spectrum — on the side that faces the Sun. When exposed to sunlight, the element heats up and generates thermal radiation that is emitted through the other side, which is directed towards the photovoltaic cell. The fundamental advantage of this design is that virtually all solar energy could be converted into electricity. But despite their conceptual simplicity, STPV devices have performed below expectations and efficiencies have struggled to reach 1%. Writing in *Nature Nanotechnology*, Evelyn Wang and colleagues at the Massachusetts Institute of Technology now report[2] an STPV device that can achieve an efficiency of 3.2%.

Typical single-junction solar cells generate electricity by directly absorbing sunlight through a semiconductor layer of fixed electronic bandgap. The solar spectrum is, however, broad: photons with energy below the bandgap are not absorbed and cannot be converted; photons with energy above the bandgap do contribute to energy conversion by generating electron–hole pairs, but these quickly relax to the band edges losing some of their initial energy. The combination of these two intrinsic loss mechanisms defines the Shockley–Queisser limit, which states that a single-junction cell cannot have efficiencies exceeding 41% (ref. 3).

In a way, the Shockley–Queisser analysis indicates that the efficiency limit of solar cells has less to do with the cell itself and more to do with the Sun. If the Sun emitted only photons with energy immediately above the bandgap of the semiconductor, for example, both loss mechanisms in the Shockley–Queisser analysis would be eliminated. As a result, the same single-junction cell would approach an efficiency of 95% (ref. 4), the highest allowed by the second law of thermodynamics.

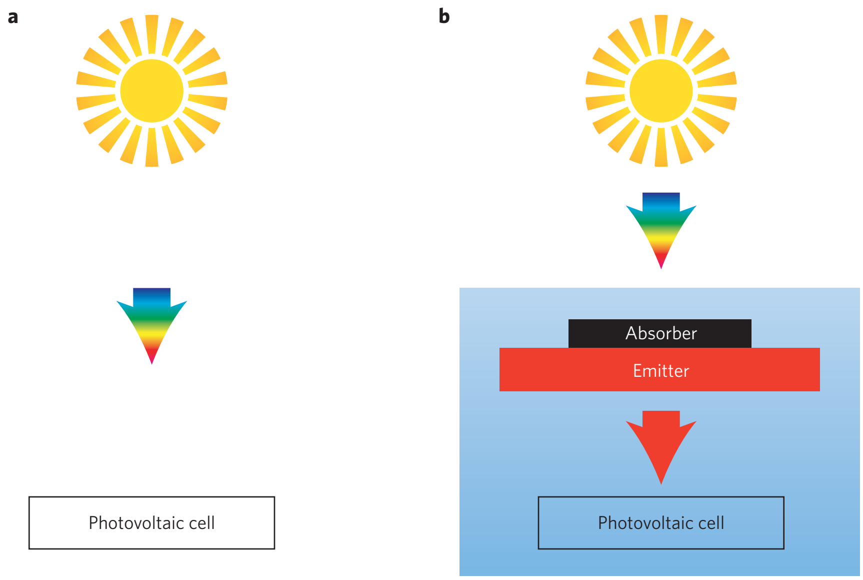

Figure 1 | Working principle of a solar thermophotovoltaic system. **a**, A standard photovoltaic cell is directly exposed to sunlight. **b**, In an STPV system, an intermediate material is placed between the Sun and the photovoltaic cell. The intermediate material absorbs the sunlight, heats up and generates thermal radiation that is emitted towards the photovoltaic cell.

Of course, we don't have a choice of the Sun that we live under. But the STPV concept allows scientists to create an alternative 'Sun' for the solar cells. Solar thermophotovoltaics is attractive from the efficiency limit perspective. Because the absorber in the intermediate element can be designed to absorb the entire solar spectrum, all sunlight can be used for energy conversion. At the same time, the photovoltaic element is interfaced only with the intermediate element. Therefore, both the design of the photovoltaic cell and the irradiation source can in principle be controlled, optimized and engineered. In particular, the emitter side of the intermediate element can be designed to generate narrow-band thermal radiation tailored to the bandgap of the solar cell. Using a single-junction cell and considering the solar radiation incident on the STPV system is the same as assumed in the Shockley–Queisser analysis, an ideal intermediate material could boost the overall system efficiency to 85%, more than double the Shockley–Queisser limit[4].

The STPV concept is attractive also from a practical point of view because, compared with traditional solar–thermal systems for electricity generation, it lacks moving parts, such as turbines, and can be relatively easily combined with existing thermal storage devices to achieve highly efficient and non-intermittent electricity generation from sunlight. This scenario is particularly attractive in the context of 'concentrated solar power' plants[5], where solar energy is first converted to heat, which in turn is used to generate electricity.

Despite all the theoretical and practical advantages of an STPV system, no experiments have demonstrated an efficiency that is competitive with single-junction solar cells. Early experiments used bulk tungsten or graphite as the intermediate layer. These materials were chosen because of their high melting or sublimation temperature. However, they do not offer much spectral control in their thermal emission and the efficiency of the devices was below 1% (ref. 5). In recent years, building on the experimental developments of tailoring thermal emission using nanophotonic structures[6–8], theoretical works have predicted efficiency enhancement beyond the Shockley–Queisser limit using nanophotonic structures as the intermediate element[9,10].

The work of Wang and colleagues is an impressive demonstration of a nanophotonic STPV system. The absorber is made of vertically aligned multiwalled carbon nanotubes and provides near-complete absorption over the broad solar spectrum. The emitter includes a one-dimensional photonic crystal made of multilayers of Si and SiO_2, with thicknesses optimized to achieve spectral matching between the thermal emission and the absorption spectrum of the InGaAsSb semiconductor of the photovoltaic cell. The photonic crystal provides a cut-off in the thermal emission right at the bandgap of the InGaAsSb, strongly suppressing sub-bandgap thermal radiation. The intermediate element and the photovoltaic cell are integrated in a vacuum environment to minimize parasite heat loss due to convection and conduction. Using a Xe-arc light as a simulator for solar light, the intermediate element is heated up to a temperature of approximately 1,300 K, and the resulting system demonstrates a light-to-electricity efficiency of 3.2%; a significant improvement compared with previous STPV systems.

Wang and colleagues have probed important parameters that control the efficiency of their device. One of them is the area ratio, that is, the ratio between the absorber and the emitter areas of the intermediate element. Some of the light absorbed by the intermediate element is emitted back towards the Sun as thermal radiation. This loss mechanism can be greatly reduced by increasing the area ratio, improving thermal efficiency. However, increasing this ratio also lowers the temperature of the emitter, decreasing the radiation power generated per unit area of the emitter. The MIT group found that an optimal efficiency can be reached by setting the area ratio to 7.

Although the efficiency remains substantially lower than what can be achieved by single-junction solar cells, Wang and colleagues estimate that efficiencies approaching 20% may be within reach with further optimization of their STPV design. These results should stimulate future efforts to incorporate nanophotonic concepts in STPV design for exerting fine control of the absorption and emission processes of the intermediate layer[6–8,11,12]. The key to efficient solar-energy conversion may well lie in controlling the light that reaches the photovoltaic element. ❐

Shanhui Fan is at the Department of Electrical Engineering and the Ginzton Laboratory of Stanford University, California 94305, USA.
e-mail: shanhui@stanford.edu

References

1. Swanson, R. M. *Proc. IEEE* **67,** 446–447 (1979).
2. Lenert, A. *et al. Nature Nanotech.* **9,** 126–130 (2014).
3. Shockley, W., Queisser, J. *J. Appl. Phys.* **32,** 510–519 (1961).
4. Harder, N.-P. & Würfel, P. *Semiconductor Sci. Technol.* **18,** S151–S157 (2003).
5. Datas, A. & Algora, C. *Prog. Photovoltaics Res. Applications* **21,** 1025–1039 (2013).
6. Lin, S.-Y. *et al. Phys. Rev. B* **62,** R2243–R2246 (2000).
7. Greffet, J.-J. *et al. Nature* **416,** 61–64 (2002).
8. Liu, X. *et al. Phys. Rev. Lett.* **107,** 045901 (2011).
9. Rephaeli, E. & Fan, S. *Opt. Express* **17,** 15145–15159 (2009).
10. Bermel, P. *et al. Opt. Express* **18,** A314–A334 (2010).
11. Yu, Z. *et al. Nature Commun.* **4,** 1730 (2013).
12. De Zoysa, M. *et al. Nature Photon.* **6,** 535–539 (2012).

NANOPARTICLE ASSEMBLY

Building blocks for tumour delivery

Supramolecular structures composed of inorganic nanoparticles and DNA strands can efficiently target tumours and then be disassembled for ease of elimination from the body.

Hak Soo Choi

The ideal targeted contrast agent should vanish after lighting up at the specific target site in the body[1]. Similarly, the ideal cargo vehicle, be it nanoparticles or molecular assemblies, should deliver biomedical imaging, diagnostic, or theranostic agents to the target site and then be eliminated from the body[2]. Writing in *Nature Nanotechnology*, Warren Chan and colleagues at the University of Toronto now report Lego-like nanoassemblies made from single-stranded DNA and gold nanoparticles that are large enough to be delivered to tumour sites via the enhanced permeation and retention (EPR) effect[3]. Once the assemblies have reached their target, they degrade into the original building blocks, which are then small enough to be eliminated through the kidneys.

The use of DNA in the nanoassemblies provides several useful features: it allows robust and modular architectures to be built through the programmability of its sequences; it allows different diagnostic probes to be loaded, which can be used for imaging techniques such as positron emission tomography, single photon emission computed tomography, magnetic resonance imaging, or optical imaging; and it allows the delivery of theranostic agents into different sites to be controlled through the attachment of targeting moieties.

Inorganic nanoparticles have been widely used in biomedical applications for bioimaging, diagnostic and theranostic purposes[2]. Although the US Food and Drug Administration treats (or regulates) nanoparticles like any other diagnostic or therapeutic agents (for example, small molecules)[2] the clinical translation of such nanoparticles is fundamentally limited because of the (potential) differences in their uptake and clearance from the body. In particular, most nanoparticles exhibit high uptake in the liver and gastrointestinal tract once they are administered, resulting in their slow complete elimination (through hepatobiliary clearance). For this reason, direct elimination from the kidneys to the bladder (renal clearance) is the preferred route for removal of the unbound targeted nanoparticles in order to reduce nonspecific background uptake in the major organs[4]. Larger nanoparticles are more effective when taking advantage of the EPR effect but their persistence could be toxic. Smaller nanoparticles are less likely to be taken up by passive targeting, but are eliminated quickly from the body. Chan and colleagues manipulate both of these properties to create degradable nanoassemblies.

To improve biodegradation and renal clearance, the researchers assembled gold nanoparticles using DNA building blocks and decorated their surface using polyethylene glycol (PEG). The structures