Towards high-efficiency solar cells: some like it hot

Krzysztof Kempa, Zhifeng Ren, and Michael J. Naughton

Ultrathin, amorphous silicon, solar cells provide a means to extract additional energy from ‘hot’ electrons, offering a route to a new generation of efficient photovoltaics.

If the earth receives enough solar energy in an hour to satisfy the world’s energy demand for a year, why does solar power account for only a very tiny fraction of that demand? Why don’t we all use solar energy? We are technically capable: present solar panels can convert anywhere from 5% to 40% of sunlight into electricity. Does solar just cost too much? If you include the opportunity cost of not going renewable, the answer should probably be ‘no.’ However, we have a tendency to defer the known and unknown costs, including those associated with global warming, to future generations. So, in the here and now, solar power is regarded as both inefficient and costly. Moreover, the more efficient a solar cell, the more it costs.

Hundreds of companies and research groups are working to develop more efficient and less expensive solar cells, but most are working on first- and second-generation photovoltaic materials (crystalline and noncrystalline thin film respectively) to improve performance or reduce the material required. A smaller number of groups is working instead on third-generation concepts,1 including novel architectures and physical phenomena that can potentially lead to dramatic increases in efficiency, ironically (yet beneficially) accompanied by significant reductions in material use and cost. One of these concepts involves the capture and harvesting of so-called ‘hot electrons.’

In every photovoltaic solar cell, incident photons from sunlight are absorbed by a semiconductor, such as silicon, and its energy given to an electron from a valence band of filled electron energy levels. This promotes the electron across a band gap to an unfilled conduction band where it is free to move about. When a p-n junction is formed by placing two types of semiconductors in contact, a voltage appears which sweeps this newly-freed electron out of the cell as electric current.

Figure 1. Plot of the measured dependence of the change in open circuit voltage $\Delta V_{oc}$ with light frequency as a function of absorber thickness in amorphous silicon solar cells. The inset is a photograph of a cell with a 10nm thick absorber. The dark circles are regions containing aluminum back contacts.

Some solar cells have band gaps too large for low-energy red light to be absorbed, while much of the energy from electrons freed up by high-energy blue light is lost as the electron is extracted. The surplus energy is converted to heat, as the overenergetic electrons interact with vibrations of the semiconductor lattice (called phonons) and cool to the bottom of the conduction band. Capturing the excess energy of these hot electrons before it is lost to heat is one of the small number of exotic phenomena that are thought to be capable of leading to solar cell efficiencies far above anything in existence today. Some predictions suggest 50–60% efficiencies are possible in cell architectures that are far thinner than state-of-the-art devices today, and thus potentially far less expensive.

Continued on next page
In order to search for these elusive hot electrons, we have fabricated a series of solar cells of different thickness, in this case using amorphous silicon (α-Si:H) p-i-n junction solar cells prepared with ultrathin p- and n-doped regions (5nm). The thickness, \( D \), of the intrinsic region varied between 5nm and 300nm. Current versus voltage data were taken under AM1.5 simulated sunlight, as well as under monochromatic light using red, green, and blue lasers. In these experiments, the quantity of interest is any difference between the open circuit voltages for different energies of incident photons. In other words, higher energy light (blue, 473nm) propels electrons further up into the conduction band than does lower energy light (red, 650nm), and so generates more hot electrons, and this should be manifested as a voltage difference \( \Delta V_{oc} = V_{oc}(\text{blue}) - V_{oc}(\text{red}) \).

Results from our experiments are shown in Figure 1, where we plot this \( \Delta V_{oc} \) (normalized by \( h\omega/e \), where \( h \) is a constant, \( \omega \) is frequency, and \( e \) is the electron charge) vs. \( D \) for fixed, short-circuit current density. Note that \( \Delta V_{oc} \) is nonzero for most film thicknesses, being positive for ultrathin junctions, and negative for thicker junctions (\( D > 30nm \)). Here, the increase of \( V_{oc} \) (that is, \( \Delta V_{oc} > 0 \)) with decreasing absorber thickness in ultrathin samples is due to an increase in the number of extracted hot electrons (a solid-state analog of the photoelectric effect\(^2\)), and a decrease of \( V_{oc} \) (\( \Delta V_{oc} < 0 \)) in thicker samples is associated with unextracted, and therefore thermalized (energy lost to heat), hot electrons. In our work, we also derived a formula to describe this phenomenological interpretation,\(^3\) represented by the line in Figure 1, which seems to follow the data quite well.

\[
\frac{e \Delta V_{oc}}{h \Delta \omega} = \frac{D_c}{D} + \alpha + \beta D
\]

where \( \Delta \omega \) is the difference in laser frequencies. The constant \( D_c \) is a type of critical distance between photogenerated carriers and the contacts below which hot carriers can escape and contribute to current, while constants \( \alpha \) and \( \beta \) are fitting parameters. This dependence is shown as the solid line in Figure 1. It is clear that the experimental data congregate around this line, confirming our interpretation.

The observation of a measurable hot electron effect in our junctions is facilitated by the exceptionally short carrier escape time, due to the nanoscopic scale of the junction thickness. We note also that the overall power-conversion efficiency of these ultrathin cells is enhanced by excess current (high electric-field effect) in addition to the excess voltage (hot-electron effect), approaching an efficiency of ~3% with absorbers only a fraction as thick as conventional cells.

In conclusion, we have found that the open circuit voltage \( V_{oc} \) in ultrathin α-Si p-i-n solar cells increases with light energy due to the extraction of hot electrons. This results from the solar cells being only a fraction as thick as conventional cells. Practically speaking, such ultrathin cells don’t collect much light, as evidenced by the semi-transparency seen in the photo in Figure 1, and so they are limited in how efficient they can be made (~3%). However, with an efficient light trapping scheme, this new phenomenon may be able to be more fully exploited.

We are now doing just that, employing a novel ‘nanocoax’ solar architecture that uniquely enables strong light collection while allowing for such ultrathin photovoltaic absorber layers,\(^4\) an architecture that could be a key to the future development of ultra-high-efficiency solar cells.

A. Herczynski, T. Kirkpatrick, J. Rybczynski, and Y. Gao contributed to this work.

Author Information

Krzysztof Kempa, Zhifeng Ren, and Michael J. Naughton
Boston College
Chestnut Hill, MA

The authors are professors in the Department of Physics at Boston College. In addition, Michael Naughton is the Evelyn J. and Robert A. Ferris Professor and department chairman, and is chief technology officer of Solasta Inc.

References


© 2010 SPIE