The Opto-Electronic Physics Which Just Broke the Efficiency Record in Solar Cells

Green Photonics Symposium at Technion
Haifa, Israel,
April 23, 2014

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GaAs solar cells are the preferred technology, where cost is no objection: Space
The Epitaxial Liftoff Process:
Fig. 1  Schematic representation of the ELO process. a) The weight induced ELO process, b) ELO with a stabilized radius of curvature by guiding the temporary flexible carrier over a cylinder surface.

Fig. 2 (online colour at: www.pss-a.com)  1 µm thick GaAs film of 2 inch in diameter on a flexible plastic carrier (right hand side) after epitaxial lift-off from its substrate (left hand side).
GaAs
Courtesy of Alta Devices, Inc.
1-sun, single junction, solar cell efficiency record:

Altadena Devices record, 28.8%
Open Circuit voltage for record efficiency cells:

Alta Devices record cell, 1.122 volts
What is the ideal voltage $V_{oc}$ to expect, i.e. the Quasi-Fermi Level separation, chemical potential, or Free Energy?

$$\exp \left\{ \frac{\text{Free Energy}}{kT} \right\} = \left\{ \frac{\text{excited state population in the light}}{\text{excited state population in the dark}} \right\}$$

Boltzmann Factor

In molecules and quantum dots:

$$qV_{oc} = \text{Free energy} = kT \ln \left\{ \frac{\text{excited state population in the light}}{\text{excited state population in the dark}} \right\}$$

In semiconductors with mobile electrons & holes:

Free energy $= E_{Fc} - E_{Fv} = 2kT \ln \left\{ \frac{\text{electron density in the light}}{\text{electron density in the dark}} \right\}$
What is the voltage to expect, i.e. the Quasi-Fermi Level separation, chemical potential, or Free Energy?

Shockley-Queisser Limit (1961):

\[ qV_{oc} = kT \ln \left\{ \frac{\text{external Luminescent emission}}{\text{band \textendash} to \textendash band emission in the dark} \right\} \]

But in quasi-equilibrium:

\[ qV_{oc} = kT \ln \left\{ \frac{\text{incoming sunlight}}{\text{band \textendash} to \textendash band emission in the dark} \right\} \]
What is the operating voltage?

To extract current, voltage at contacts must be slightly lower than Voc

But, operating voltage linked directly to Voc

\[ V_{OP} \approx V_{OC} - \frac{kT}{q} \ln\left(\frac{qV_{OC}}{kT}\right) \]

We only need to understand the open-circuit voltage
Yes photons have entropy, S

Photon Free Energy = hν - TS
Photon Free Energy = hν - kT lnW

\[ qV_{\text{operating point}} = \]

\[ E_g - kT \left\{ \ln(\pi/\Omega_s) + \ln(4n^2) + \ln(qV_{\text{op}}/kT) - \ln(\eta) - \ln\left( \frac{1.4T_s}{T} e^{\frac{E_g}{kT_s}} \right) \right\} \]

Entropy due to loss of directivity information
Entropy due to incomplete light trapping
Free energy loss due to power-point optimization
Free energy loss due to poor \( \eta \equiv \) Quantum Efficiency

where \( \Omega_s \) is the solid angle subtended by the sun

nicest treatment:
Small bandgaps are particularly vulnerable to entropy:

After you subtract off all the entropy terms, you don't have much Free Energy left.

$$qV_{\text{operating point}} = 1.1\text{eV} - 0.8\text{eV} = 0.3\text{eV}$$

A lousy 0.3eV from all those big photons

In general we cannot afford to compromise with regard to quantum efficiency.
normal solar cells

new physics

high performing cells

Shockley-Queisser limit (single-junction)

33.5%

~25%

normal solar cells
25.1% efficiency
1990-2007

28.8% efficiency
2011-2012
What if the material is not ideal, and the electrons and holes are lost to heat before they can luminesce?

\[ qV_{oc} = qV_{oc\text{-ideal}} - kT|\ln\{\eta_{ext}\}| \]

The external fluorescence yield \( \eta_{ext} \) is what matters!

Only external Luminescence can balance the incoming radiation.
You may need an internal efficiency of $\eta_{\text{int}} = 99\%$
just to get an external efficiency of $\eta_{\text{ext}} = 50\%$

only $1/4n^2 = 1/50 = 2\%$
of the light escapes.
But this is really hard to do:
You may need an internal efficiency of $\eta_{\text{int}}=99\%$
just to get an external efficiency of $\eta_{\text{ext}}=50\%$
Efficiency vs. Rear Reflectivity,

GaAs 3μm

90% Rear Reflectivity Is Not Enough!
Latest 1 sun single-junction results from Alta Devices, Inc.

Expected to reach 34% dual junction, eventually.

\[ \begin{align*}
V_{oc} &= 1.1220 \text{ V} \\
I_{sc} &= 29.461 \text{ mA} \\
J_{sc} &= 29.677 \text{ mA/cm}^2 \\
\text{Fill Factor} &= 86.50 \% \\
I_{max} &= 28.557 \text{ mA} \\
V_{max} &= 1.0013 \text{ V} \\
P_{max} &= 28.593 \text{ mW} \\
\text{Efficiency} &= 28.80 \% 
\end{align*} \]
25.1% efficiency
1990-2007

28.8% efficiency
2011-2012
Counter-Intuitively, to approach the Shockley-Queisser Limit, you need to have good external fluorescence yield $\eta_{\text{ext}}$!!

Internal Fluorescence Yield $\eta_{\text{int}} >> 90\%$
Rear reflectivity $>> 90\%$

Both needed for good $\eta_{\text{ext}}$
For solar cells at 25%,
good electron-hole transport is already a given.

Further improvements of efficiency above 25% are all about the photon management!

A good solar cell has to be a good LED!

Counter-intuitively:
1. Thin-film cells are more efficient than the best wafer cells.
2. Solar cells perform best when there is maximum external fluorescence yield $\eta_{ext}$.

Why the record-setting Voltage?

Another way to look at this,
1. the recycled photons are not lost,
2. the carrier lifetime increases,
3. increasing carrier density
4. Increasing $V_{oc}$

This Photon-Recycling explanation is incomplete! Good external luminescence can be achieved with texturing and no-photon-recycling.
Paradox: Why is external luminescence is good for solar cell efficiency?

Reason #4; Luminescence IS Voltage:

External luminescence is sometimes used as a type of **contactless voltmeter**, indicating the separation of quasi-Fermi levels in the solar material. At quasi-equilibrium:

\[
\text{Luminescence} = (\text{Black Body}) \times \exp\left\{\frac{qV}{kT}\right\}
\]

(This is sometimes employed as a contactless, quality-control-metric, in solar cell manufacturing plants.)

This viewpoint is tautological:

Good external luminescence actually is good voltage, and therefore good efficiency.
What if the material is not ideal, and the electrons and holes are lost to heat before they can luminesce?

\[ qV_{oc} = qV_{oc-ideal} - kT|\ln\{\eta_{ext}\}| \]

Only external luminescence can balance the incoming radiation.

The external fluorescence yield \( \eta_{ext} \) is what matters!
Dual Junction Series-Connected Tandem Solar Cell

$$\begin{align*}
\text{Ga}_{0.5}\text{In}_{0.5}\text{P} & \quad V_{\text{OC}}=1.5\text{V} \\
\text{Solar Cell} & \\
\text{Tunnel} & \\
\text{Contact} & \\
\text{GaAs} & \quad V_{\text{OC}}=1.1\text{V} \\
\text{Solar Cell} & \\
\text{n}-\text{Al}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx2.35\text{eV} \\
\text{n}-\text{Ga}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx1.9\text{eV} \\
\text{p-Ga}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx1.9\text{eV} \\
\text{p}^+-\text{Al}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx2.35\text{eV} \\
\text{n}^+-\text{Al}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx2.35\text{eV} \\
\text{n}-\text{Al}_{0.5}\text{In}_{0.5}\text{P} & \quad \text{E}_g\approx2.35\text{eV} \\
\text{n}-\text{GaAs} & \quad \text{E}_g=1.4\text{eV} \\
\text{p-GaAs} & \quad \text{E}_g=1.4\text{eV} \\
\text{p-Al}_{0.2}\text{Ga}_{0.8}\text{As} & \\
\text{GaAs} & \quad V_{\text{OC}}=1.1\text{V} \\
\text{Solar Cell} & \\
\text{Ga}_{0.5}\text{In}_{0.5}\text{P} & \quad V_{\text{OC}}=1.5\text{V} \\
\text{Solar Cell} & \\
\text{Tunnel} & \\
\text{Contact} & \\
\end{align*}$$

All Lattice-Matched \( \eta \sim 34\% \) efficiency should be possible.
Latest 1 sun dual-junction results from Alta Devices, Inc.

Expected to reach 34% dual junction, eventually.
Conclusions:

1. Thin-Film GaAs of ~28% efficiency is in the process of scale-up for solar panels.

2. Opto-electronics can provide the motive power for automobiles.

3. The automotive power market is 10× bigger than the panel electricity market.