Diametric strategies for ultra-efficient photovoltaics

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A highly interdisciplinary Faculty in desert science, exploring fundamental and applied scientific issues
(Faculty founded 1977)
Ben-Gurion, Israel’s founding premier, appreciated the importance of science and of excellence in academia.
Strategies for performance enhancement in ultra-efficient solar cells:

a) Current densities ($J_{sc}$) are close to their basic limits.
b) Fill factors (FF) are also close to their basic limits.
c) Room for improvement: voltage (via $V_{oc}$), prompting:

**Strategy 1:** optical concentration (basis of concentrator PV)

\[ J(V) = J_{sc} - J_o \left( e^{\frac{qV}{nkT}} - 1 \right), \quad J(V_{oc}) = 0, \quad \text{so} \quad V_{oc} = \frac{nkT}{q} \ln \left( \frac{J_{sc}}{J_o} \right), \quad J_{sc} \propto \text{conc.} \]
Strategy 1: optical concentration (basis of concentrator PV)

Current status: High-performance optics and high-efficiency cells

Optics:

Affordable concentrators with $C \approx 1000 \times$ and optical tolerances $\approx 1^\circ$ are now available – so are precision dual-axis trackers.

$$J(V) = J_{sc} - J_o \left( \frac{qV}{e^{nkT}} - 1 \right), \quad J(V_{oc}) = 0, \quad \text{so} \quad V_{oc} = \frac{nkt}{Q} \ln \left( \frac{J_{sc}}{J_o} \right), \quad J_{sc} \propto \text{conc.}$$
Multi-junction solar cells: monolithic, series-connected

- Off-the-shelf availability
- Operating voltage of ~2.5-3 V
- Cell area of order 1-100 mm$^2$
- Efficiency peak at ~500-1000 suns
- $\eta_{\text{max}} \approx 40\%$ (in mass production)
- Requires tunnel diodes
- Requires current matching
- Series-resistance limited
Invention of the vertical-junction ("side-illumination") solar cell, for crystalline silicon: B. Sater, NASA [e.g., *Proc. 29th IEEE PVSE Conf.* (2002) 1019-1022]

Architecture: an integrally bonded stack of $\text{Si} \ p^+/n/n^+$ unit cells connected in series

Decouples photon and electron flows, *massively* lowering series resistance (high voltage $\rightarrow$ low current) and permitting numerous sub-cells per mm (but requires uniform illumination)

No metallization grid (no shading loss) or back contacts.

No bypass diodes.
First experimental results demonstrating efficiency increasing up to ~2500 suns for Si vertical-junction cells

Multiple-bandgap vertical-junction concentrator cells

Virtues: All the benefits of multi-junction cells, with

a) No need for tunnel diodes
b) Independent power conditioning of each stratum
c) Negligible series resistance (high efficiency)
d) High (separate) voltage for each tier (coming slides)
e) Tractable number of units per mm with *indirect* bandgap materials (width limited by minority carrier diffusion length)
Number of units per mm depends on material properties. Direct bandgap (III-V) semiconductors require a unit width of only a few μm (impractical).

*Indirect bandgap materials are optimized at tens of μm.*

<table>
<thead>
<tr>
<th>Junction</th>
<th>Width (μm)</th>
<th>Depth (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Si</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>GaP</td>
<td>15</td>
<td>80</td>
</tr>
</tbody>
</table>

Paucity of data for *indirect bandgap PV materials*, likely due to their being viewed as possessing inherently high series resistance, and hence unsuitable for high concentration.
Simulated performance of a 2-tier concentrator cell operating at $\geq 1000$ suns

A novel revival of indirect bandgap semiconductors for high-concentration solar cells – and the (ironic) unsuitability of direct bandgap materials
Simulated performance of a 3-tier concentrator cell operating at ≥ 1000 suns

A potential new paradigm for ultra-efficient concentrator cells
Photovoltaic performance enhancement by external recycling of photon emission

A. Braun, E.A. Katz, D. Feuermann, B.M. Kayes, J.M. Gordon
Energy & Env. Sci. 6 (2013) 1499-1503

Tackling solar cells in the dark
Strategy 2: Decrease $J_o$ (recombination current) by externally recycling photon emission. (How? To be described shortly.) $V_{oc}$ cannot distinguish between the two strategies.

Boost $V_{oc}$:

1. In the light, or
2. In the dark

\[ J(V) = J_{sc} - J_o \left( e^{\frac{qV}{nkT}} - 1 \right), \quad J(V_{oc}) = 0, \quad \text{so} \quad V_{oc} = \frac{nkT}{q} \ln \left( \frac{J_{sc}}{J_o} \right), \quad J_{sc} \propto \text{conc.} \]
Questions:

1) How can we evidence this effect experimentally?

2) Why has this effect not been observed previously?

Here: Experimental proof-of-concept with a convenient off-the-shelf optic

Future task: How to achieve it within a solar cell’s surface (below).

\[ FF = \frac{J_{mp} V_{mp}}{J_{sc} V_{oc}} \]

\[ V_{oc} = \frac{n k T}{q} \ln \left( \frac{J_{sc}}{J_o} \right) \]
Our photon trap (based on nonimaging optics – flow-line method for an extended source):

A hemi-ellipsoid

Light delivery and light probe (spectral emission) via the apex.

Vertical movement of the dome moderates the degree of photon recycling.
Why has measuring this effect proven elusive?

Answer: Unduly low external luminescent efficiency of all solar cells to date, i.e., dominant non-radiative losses.

That has now changed with Alta Devices’ thin-film 1-sun GaAs cell (world-record 28.8% efficiency for a 1-junction cell at 25°C and AM1.5G solar spectrum).

External luminescent efficiency 
\[ Q_e = \frac{J_{o,rad}}{J_o} \]

If our external photon recycling efficiency \( \equiv \eta_r \), then:

\[ V_{oc} = \frac{n k T}{q} \ln \left( \frac{J_{sc}}{J_{o,rad} \left( \frac{1}{Q_e} - \eta_r \right)} \right) \]
External luminescent efficiency: \( Q_e = \frac{J_{o,rad}}{J_o} \)

Photon recycling efficiency = \( \eta_r \)

\[
V_{oc} = \frac{n k T}{q} \ln \left( \frac{J_{sc}}{J_{o,rad} \left( \frac{1}{Q_e} - \eta_r \right)} \right)
\]

All cells to date had \( Q_e \leq 0.01 \), so \( \eta_r \) was immaterial. That has changed with Alta Devices (\( Q_e \approx 0.25 \)).

That notwithstanding, we can understand, at the outset, that even perfect photon recycling will generate only a modest voltage boost. (But that modest boost will be the first ever observed.)
External luminescent efficiency: $Q_e = \frac{J_{o,\text{rad}}}{J_o}$

Photon recycling efficiency = $\eta_r$

\[
V_{oc} = \frac{n k T}{q} \ln \left( \frac{J_{sc}}{J_o} \right) = \frac{n k T}{q} \ln \left( \frac{J_{sc}}{J_{o,\text{rad}}} \left( \frac{1}{Q_e} - \eta_r \right) \right)
\]

There is a thermodynamic limit for increasing $V_{oc}$ because $J_{sc}/J_o$ cannot be increased by more than a factor of $1/\sin^2(\theta_{\text{sun}})$.

Decreasing $J_o$: Even when $Q_e = 1 \rightarrow \Delta V_{oc} = 0.275$ V (at $T_{PV} = 25^\circ$C) since

$\eta_r \leq 1 - \sin^2(\theta_{\text{sun}})$ (Kirchoff’s Law for photon trapping) - complementary to the thermodynamic limit for flux concentration to increase $J_{sc}$.

(Accordingly, solar tracking is essential.)
A brief interlude for solar cell details:

Thin-film (a few $\mu$m thick) GaAs produced by epitaxial lift-off – plastic substrate

Fig. 2 (online colour at: www.pss-a.com) 1 $\mu$m 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).
Device Temperature: 24.7 ± 0.5 °C
Spectrum: ASTM G173 global
Device Area: 0.9989 cm²
Irradiance: 1000.0 W/m²

also confirmed in our lab measurements
Filtering out recycled Fresnel reflections off the cell

At short-circuit, radiative emission is essentially zero $\rightarrow$ recycled Fresnel reflections are measured.
Bottom line: Net $V_{oc}$ enhancement due to external photon recycling = 4 mV – remains unchanged at $T_{PV} = 50^\circ C$, and irradiance from 0.4 to 1.8 suns.

(First such demonstration, however modest in magnitude.)
Understanding *why* the performance enhancement had to be modest relative to the thermodynamic limit ($\Delta V_{oc}^{\text{max}} \rightarrow 275 \text{ mV}$, present 1-sun $V_{oc} = 1120 \text{ mV}$), but need not be in the future:

$\eta_r \rightarrow 1$ is challenging because $\eta_r$ includes absorption and reflection losses from the optic.

- **calculated**

![Diagram](image)

- **Our cell**
Our presentation related to a convenient table-top optic for proof-of-concept.

How might a viable, realistic angular-confinement micro-surface be envisioned for solar cells?

First proposals (from Cal Tech) based on nonimaging optics and supported with preliminary micro-fabricated units

New optics (from our lab): For next year's presentation
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Essentially eliminate series resistance losses:

a) No sheet resistivity component.

b) Photo-generated carriers crossing the junction are immediately collected by the vertical ohmic contacts.

c) Equal collection probability for excess carriers generated at any depth (hence improved spectral response mainly at shortest and longest $\lambda$).

d) Low series resistance even at high irradiance: due to effective photo-conductivity modulation throughout the bulk region.