

Photovoltaics under concentrated sunlight

April 14, 2015

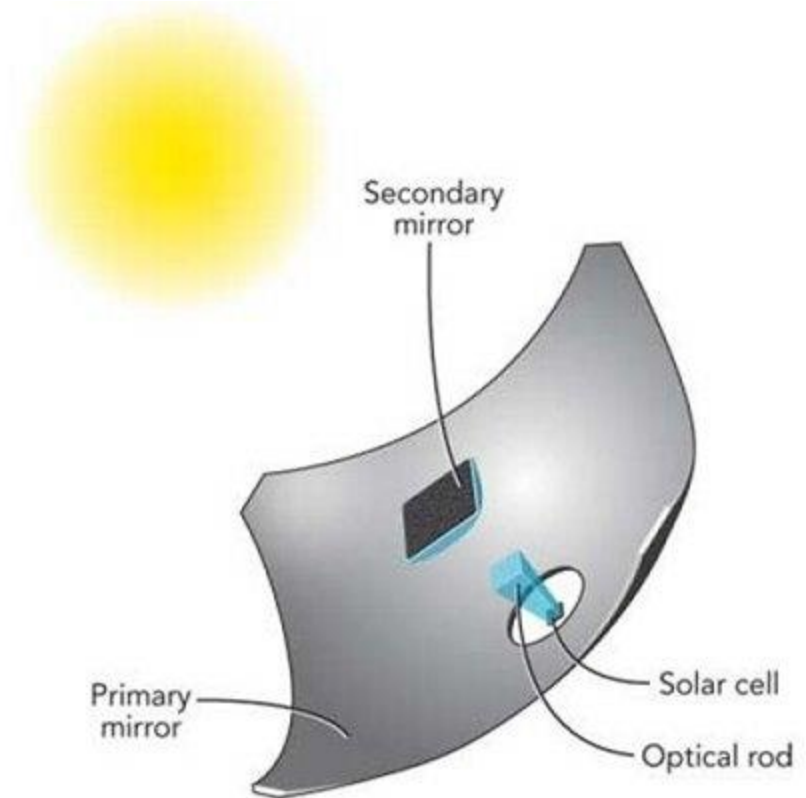
The University of Toledo, Department of Physics and Astronomy

Principles and Varieties of Solar Energy (PHYS 4400)

Concentrating solar cells

Why consider concentrating PV (CPV)?

- Multi-junction III-V solar cells offer >35% efficiency, but are expensive. A 1 cm² “receiver” can cost \$5, which works out to \$50,000/m² (prices are likely somewhat lower now).
- ~\$0.5/W_p for the cell alone
- Operating solar cells under concentration results in an improvement in solar power conversion efficiency.
- Concentrating optics cost much less than the receivers.
- Typical concentration factors are ~300x-1,000x.



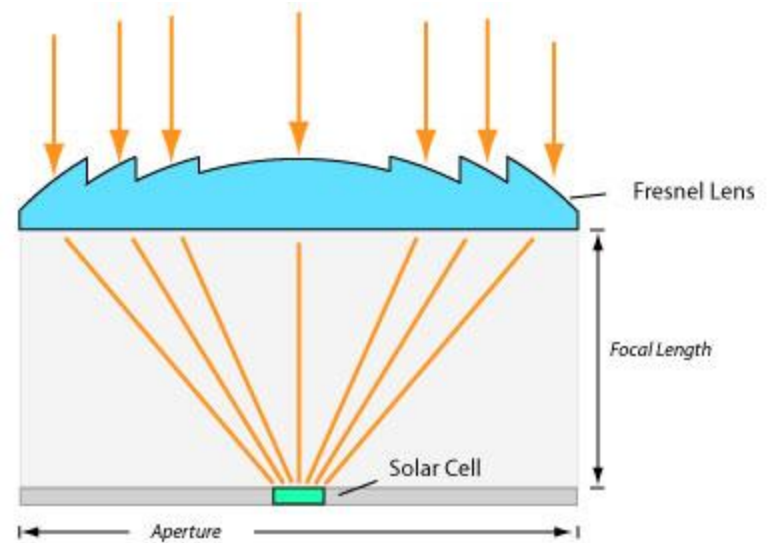
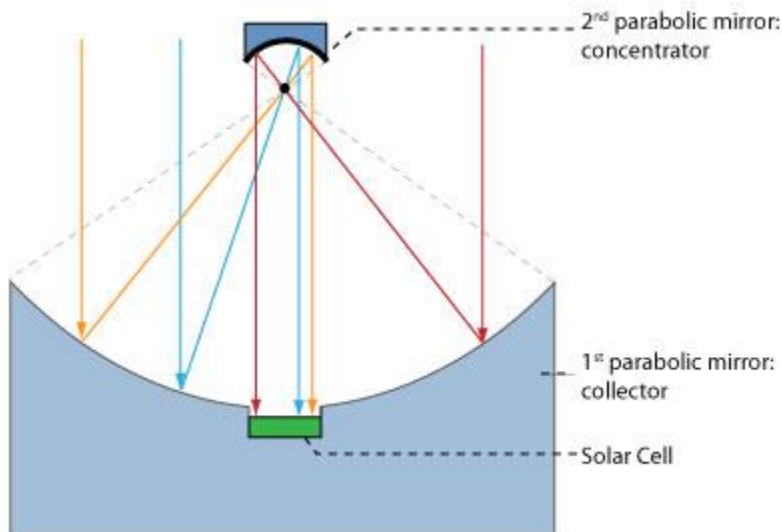
[Efficiency of concentrator PV cells.](#)

Concentrating solar cells (cont.)

http://www.greenrhinoenergy.com/solar/technologies/pv_concentration.php

Parabolic Mirrors

Incoming parallel light is reflected by the collector (the first mirror) through a focal point onto a second mirror. The second mirror (much smaller) is also a parabolic mirror with the same focal point -- it reflects the light to the center of the first parabolic mirror where it hits the solar cell. This configuration does not require optical (transmission) lenses. However, losses will occur in both mirrors. SolFocus has achieved a concentration ratio of 500x.



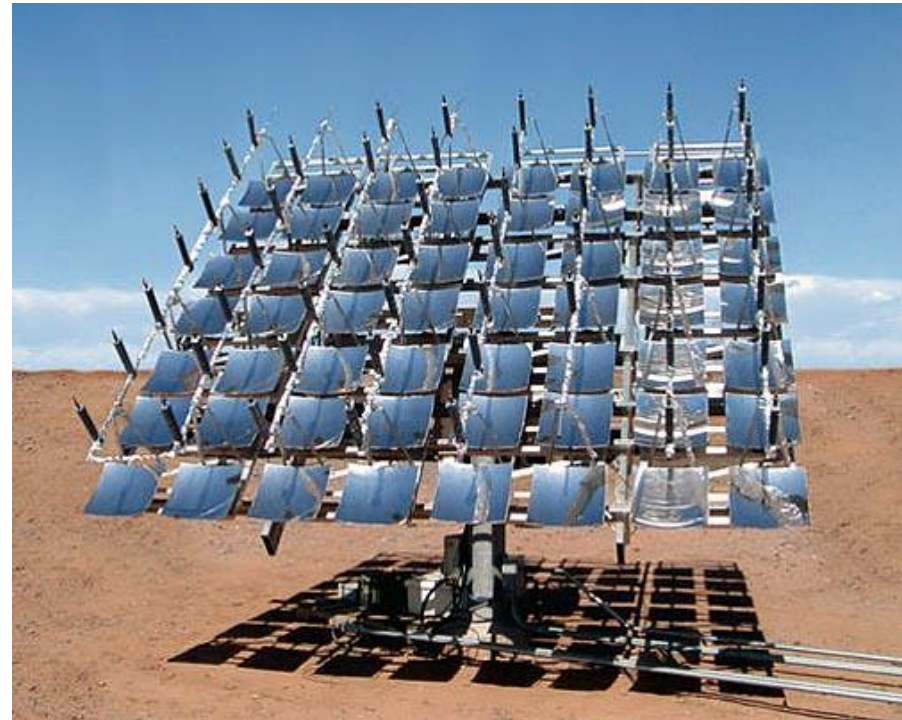
Fresnel Lens

Named after the French physicist, comprises several sections with different angles; reduced weight and thickness compared to standard lens. Possible to achieve short focal length and large aperture while keeping the lens light. Constructed in a shape of a circle to provide a **point focus** with concentration ratios of around 500, or cylindrical shape to provide **line focus** with lower concentration ratios.

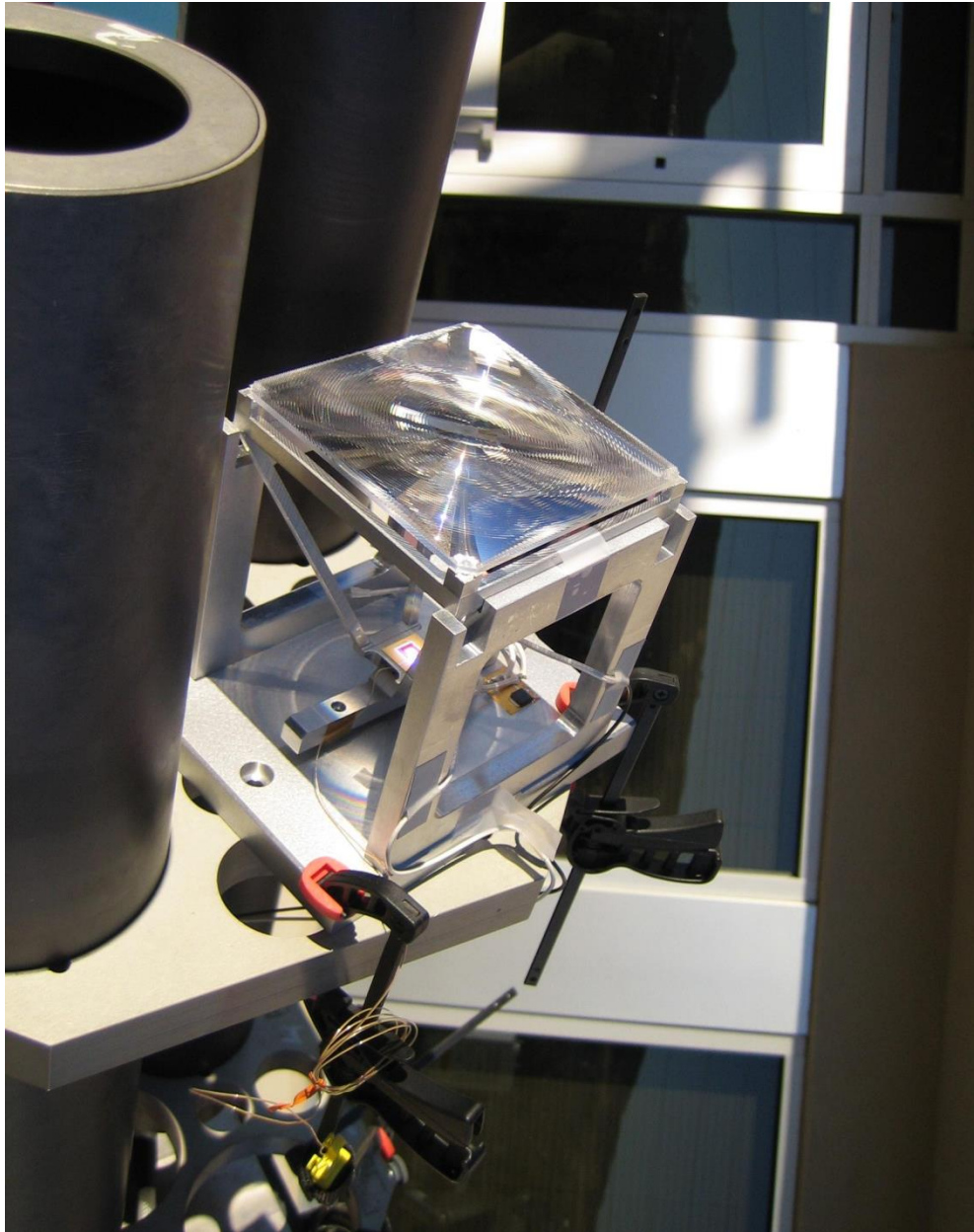
Concentrating solar cells (cont.)

Some challenges for CPV...

- Only direct insolation can be coupled into the receiver cells. The *indirect* portion, since it comes in from a variety of angles, cannot be focused correctly to be utilized. Scattered (diffuse) light is ~15% of the AM1.5G spectrum.
- Must use two-axis tracking technology for small receivers; for linear receivers, can use single-axis tracking, but concentration is much less.
- Thermal issues. The cell must dump a lot of heat, so one needs ideally a highly thermally-conducting contact and substrate to keep the cell cool under very intense sunlight.
- Typical concentration factors are ~300-1,000x (1000x = 1 MW/m²).
- Fresnel lenses yield chromatic aberration effects, creating inefficiency.



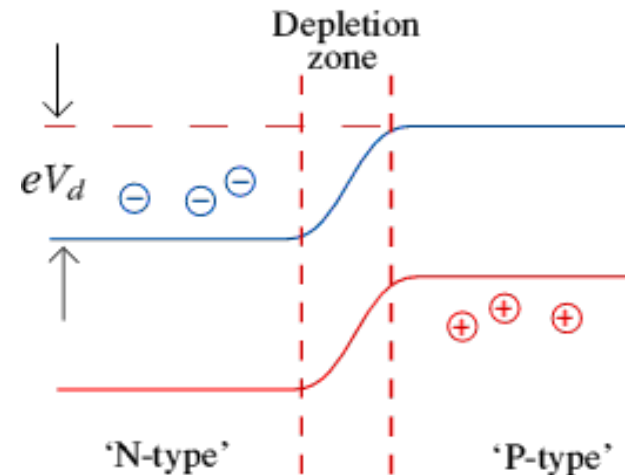
Concentrating solar cells (cont.)



- Shown at left: Enfocus Engineering two-axis tracking CPV single-cell component, under test conditions at NREL.
- This component makes up one of many in an array that may be 10 x 8 , with 80 cells.
- Total *receiver* area of such a module would be 80 cm², and collect a total incident power at AM1.5G of ~2.4 kW (assuming 300x concentration, so 2.4 m²).
- Conversion efficiency for the module of ~22% can be attained in practice → 528 W module.

Increased efficiency under concentration

The figure shows a standard p-n junction at open circuit. The left and right side consist of the same semiconductor material (i.e., same band-gap), just doped differently. Carriers within the depletion zone separate (e^- 's flow left, and h^+ 's flow right). The voltage V_d reduces actual operating voltage (under a resistive load) – i.e., the intrinsic band-bending actually reduces the photovoltage. Under illumination, however, the high carrier density causes the bands to move toward flattening (one can think of this as a saturation effect – at the limit of high carrier density, the materials will act like metals), thereby reducing the “loss” associated with the band-bending and increasing the photovoltage with increasing photogenerated carrier density.



Increased efficiency under concentration (cont.)

A more detailed explanation:

Assuming the absence of series resistance, increasing the sunlight concentration ratio, C , causes: (a) The value of J_{sc} to increase linearly with C ; (b) the value of V_{oc} to increase logarithmically with C , and (c) the value of FF to increase slowly.

Note: J_{sc} increases slightly and V_{oc} and FF drop strongly with increasing cell temperature.

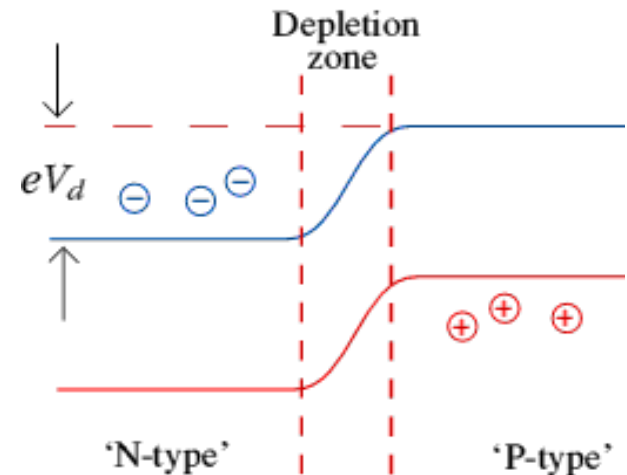
[J_{sc} is the short-circuit current density; V_{oc} is the open-circuit photovoltage; FF is the fill-factor, related to the optimization of the product of the voltage and the current.]

- Reverse saturation current:

$$J_s = q \left(\frac{D_h p_{n_0}}{L_h} + \frac{D_e n_{p_0}}{L_e} \right)$$

- Assume p⁺-n junction, $p_{n_0} \gg n_{p_0}$:

$$J_s \approx q \frac{D_h p_{n_0}}{L_h} = q \sqrt{\frac{D_h}{\tau_h}} \frac{n_i^2}{N_D} \propto \exp\left(-\frac{E_g}{k_B T}\right)$$



Increased efficiency under concentration (cont.)

The series resistance, however, can have a large effect. To preserve the solar efficiency, the effective series resistance must be reduced below about $(0.5/C) \Omega \text{ cm}^2$. So the bulk resistivities of the semiconductor layers as well as the contacts and grids become crucial.

With concentration, the photovoltage rises and (to a first approximation) the dark current (J_0) remains constant.

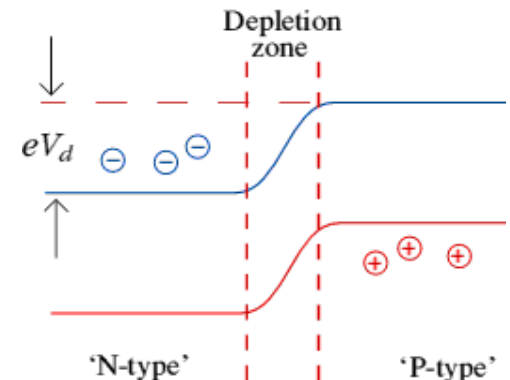
The photovoltage increases logarithmically. The photogenerated current increases linearly with concentration (X) and the net cell current is the photogenerated current minus the dark current. So when you put it all together:

$$J(V) = J_{sc} - J_0 \left(\exp\left(\frac{qV}{mkT}\right) - 1 \right) \quad // \text{ diode equation}$$

$$V_{oc} = mkT \cdot \ln\left(\left(\frac{xJ_{sc}}{J_0}\right) + 1\right) \quad // \sim V_{oc} \text{ (at 1 sun intensity)} + mkT \ln X$$

so V_{oc} goes up and $J(V)$ goes up and the efficiency increases.

Note that the current density drops at increased temperature, and although V_{oc} increases with T , the net result is reduced conversion efficiency. Efficient cooling is required to benefit from concentration.



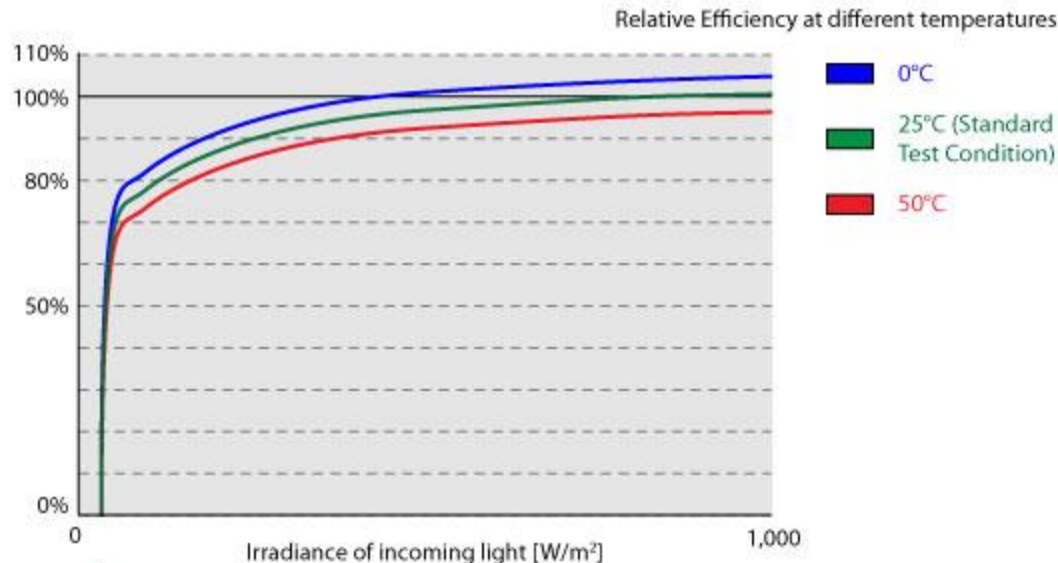
Concentrating solar cells (cont.)

Relative Module Efficiency (vs. Temperature)

Here is a typical curve for relative efficiency over the intensity of the incoming light for different temperatures. At 25°C and 1,000 W/m² the relative efficiency is 1.0, as these are the standard test conditions.

Nevertheless, the conversion efficiency is nearly constant over a wide range of intensities, only dropping sharply below about 10 % of the standard 1,000 W/m².

Changes in temperature cause the curve to shift upwards (if colder) or downwards (if warmer). Silicon is more sensitive to temperature changes than many thin-film materials.



Increased efficiency under concentration (cont.)

