

SOLAR CELL OPERATION IN DARK AND LIGHT;
THERMODYNAMICALLY-ATTAINABLE CONVERSION
EFFICIENCY;
AND CONCENTRATOR SOLAR CELLS.

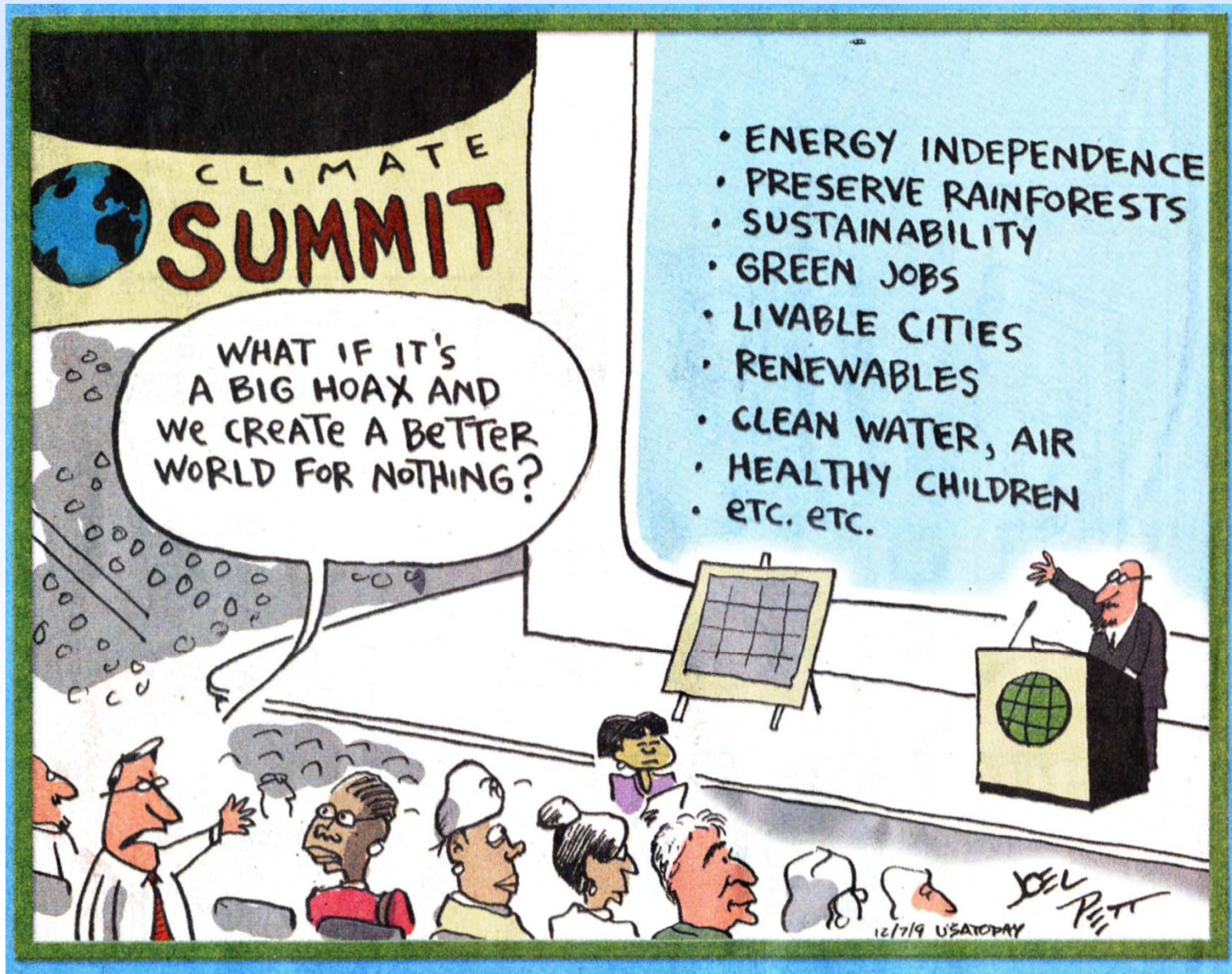
January 24, 2012

The University of Toledo, Department of Physics and Astronomy
SSARE, PVIC

Principles and Varieties of Solar Energy (PHYS 4400)
and
Fundamentals of Solar Cells (PHYS 6980)



Climate change – the great hoax?



On today's menu

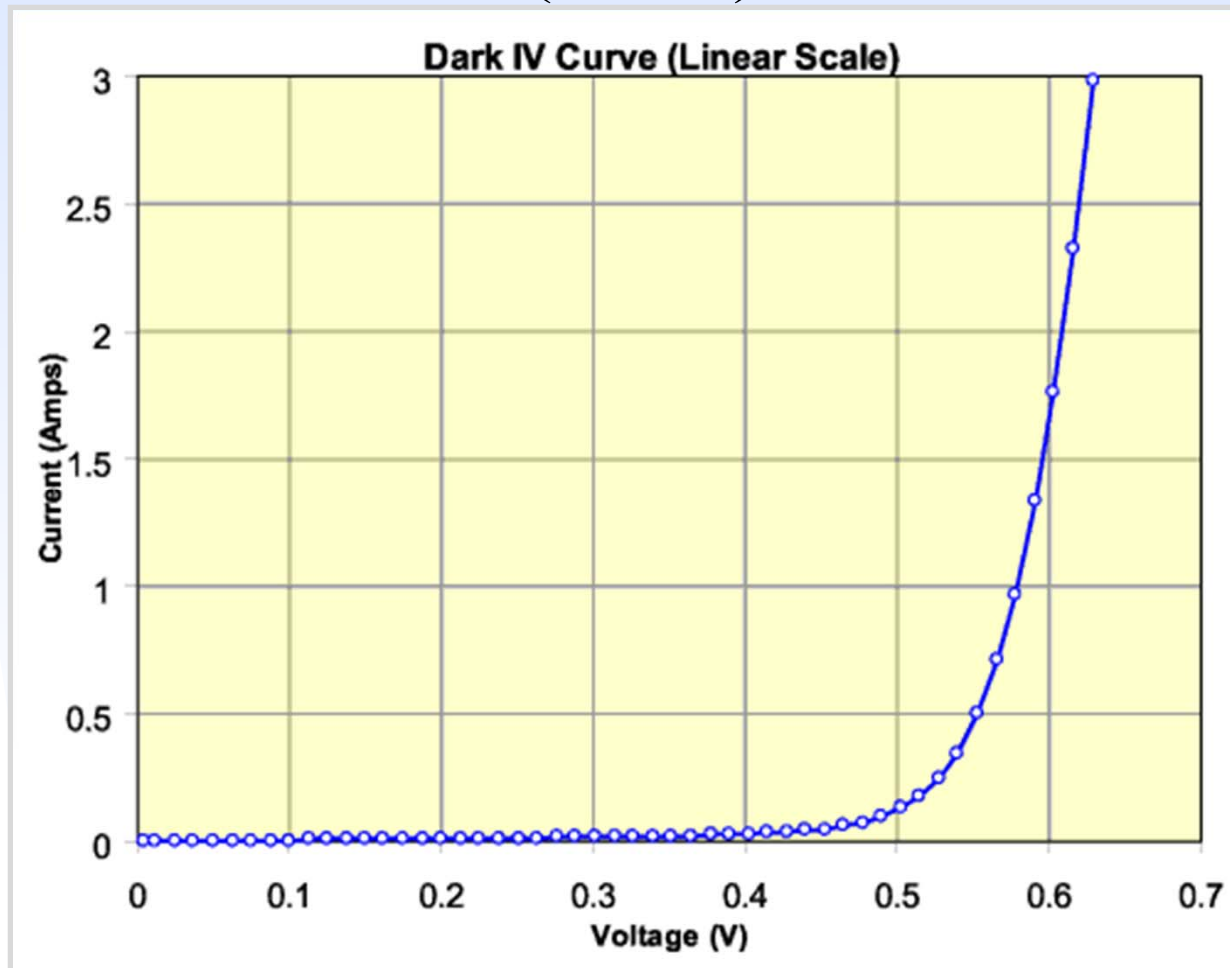
- revisiting J-V behavior
- types of solar energy conversion
- detailed balance:
 - solar cell in equilibrium (in the dark)
 - solar cell under illumination
- band gap influence on efficiency
- concentrator solar cells (effect on efficiency, practical considerations – tracking, direct insolation, thermal load)



J-V behavior in solar cells (basics)

Ideal Diode Law:
$$I = I_0 \left(e^{\frac{qV}{k_B T}} - 1 \right)$$

PVEducation.org



Igor Pro (analysis and graphing program)

Igor Pro software. You can use this software for any coursework as long as you're part of the P&A Dept.; the link to download the software installation package is here:

<http://www.wavemetrics.com/support/demos.htm>

Just download the IgorPro Demo (available for either Mac or Windows, and if you choose Mac, then Prof. Heben can assist you from the Mac perspective. Use this information for the activation:

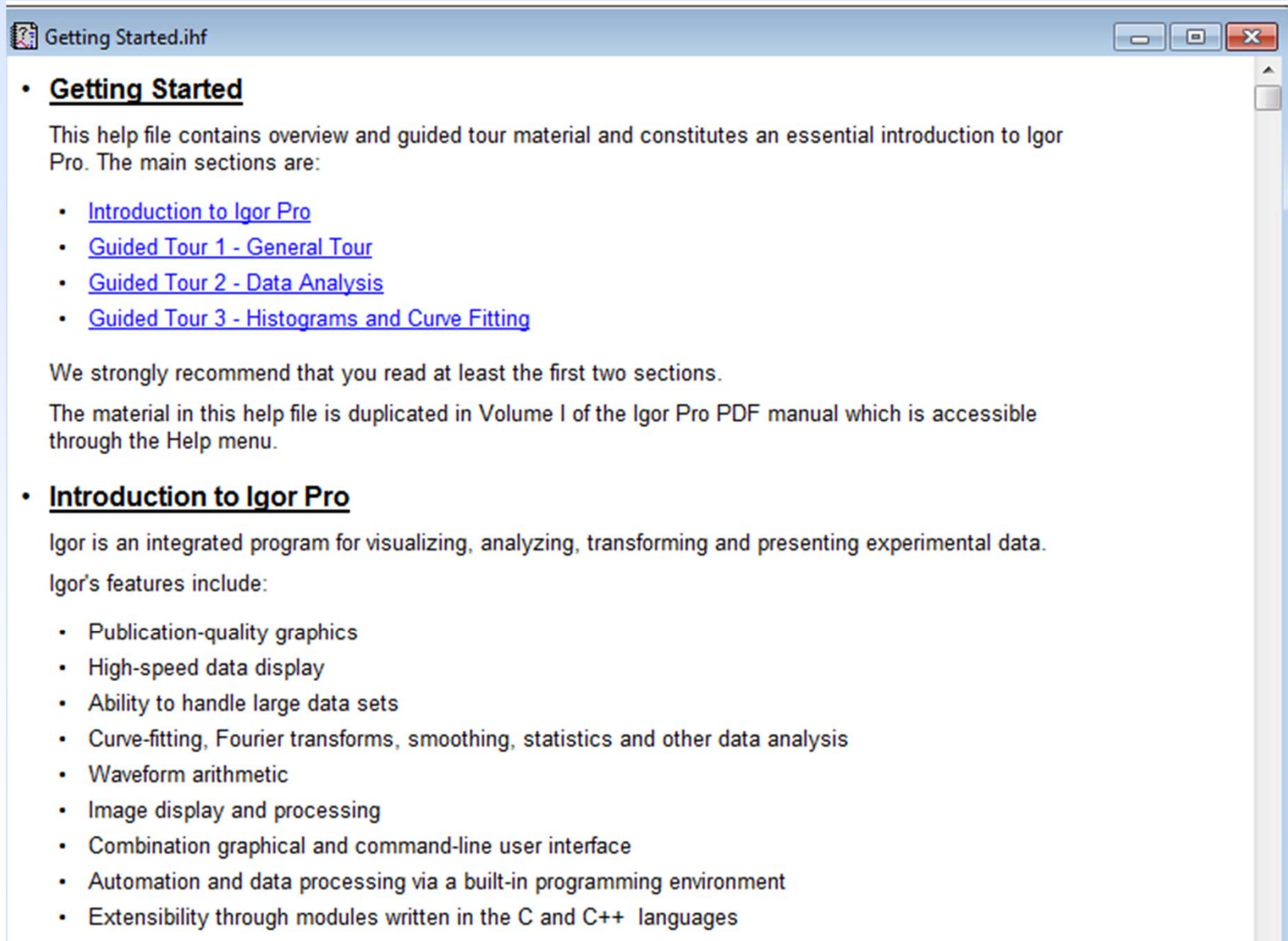
Serial Number: XXXXX. Activation Key: XXX-XXXX-XXXX-XXXX-XX

Note: The activation information will be deleted from the online lecture slides, so please make a note of it now.

To learn Igor Pro, take the time to carefully run through the "Getting Started introduction (under the Help menu).



Igor Pro (analysis and graphing program)



The screenshot shows a window titled "Getting Started.ihf" with standard Windows window controls (minimize, maximize, close). The content is as follows:

- **Getting Started**

This help file contains overview and guided tour material and constitutes an essential introduction to Igor Pro. The main sections are:

 - [Introduction to Igor Pro](#)
 - [Guided Tour 1 - General Tour](#)
 - [Guided Tour 2 - Data Analysis](#)
 - [Guided Tour 3 - Histograms and Curve Fitting](#)

We strongly recommend that you read at least the first two sections.

The material in this help file is duplicated in Volume I of the Igor Pro PDF manual which is accessible through the Help menu.
- **Introduction to Igor Pro**

Igor is an integrated program for visualizing, analyzing, transforming and presenting experimental data. Igor's features include:

 - Publication-quality graphics
 - High-speed data display
 - Ability to handle large data sets
 - Curve-fitting, Fourier transforms, smoothing, statistics and other data analysis
 - Waveform arithmetic
 - Image display and processing
 - Combination graphical and command-line user interface
 - Automation and data processing via a built-in programming environment
 - Extensibility through modules written in the C and C++ languages



J-V behavior in solar cells (basics)

Ideal Diode Law:
$$I = I_0 \left(e^{\frac{qV}{k_B T}} - 1 \right)$$

Applying this to a solar cell -- what's missing?

The ideal diode law describes the response of a diode to an applied voltage; it does not account for a *photocurrent*. The ideal diode's current is analogous to the dark current flowing in a solar cell. We can rewrite this as the dark current density:

$$J_{dark}(V) = J_0 \left(e^{\frac{qV}{k_B T}} - 1 \right)$$

Adding in the photocurrent, which flows opposite to the dark current:

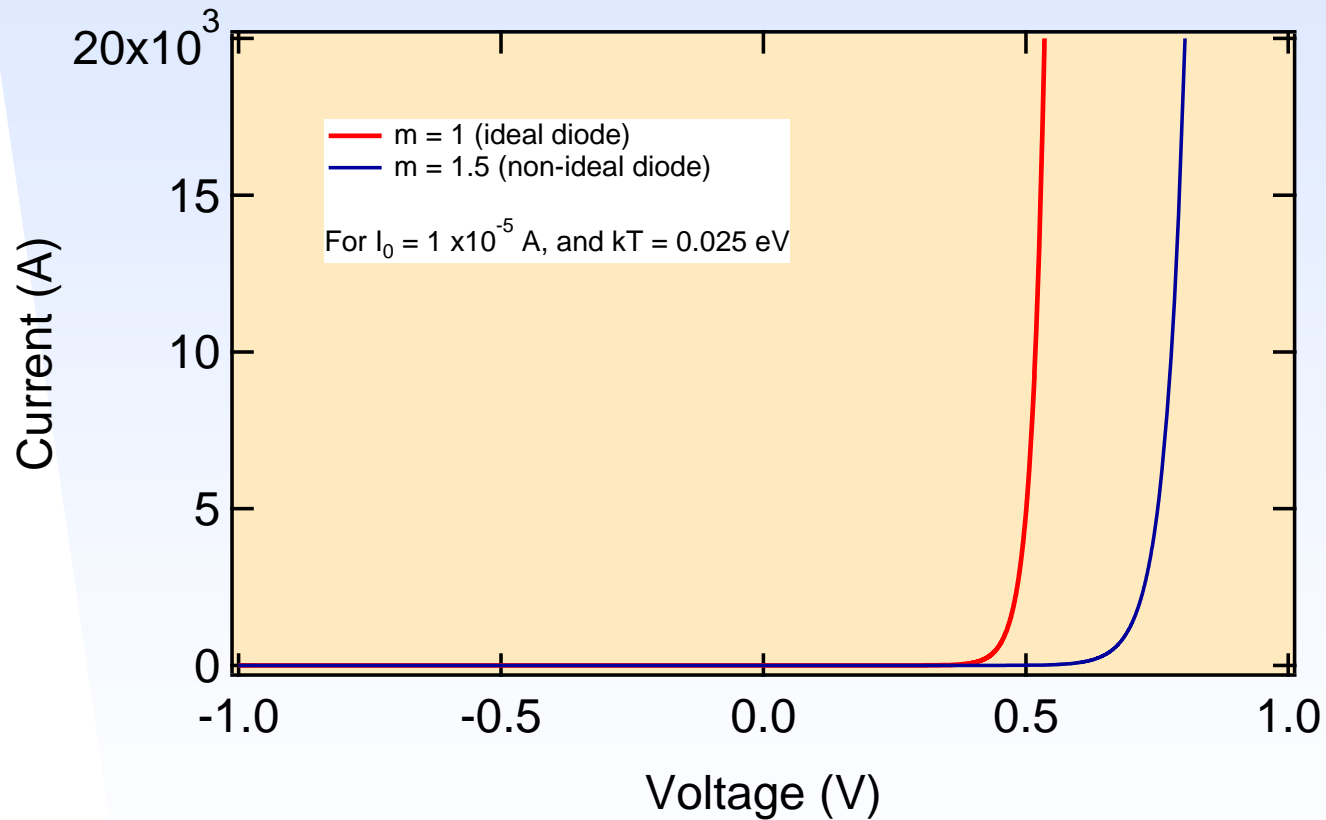
$$J(V) = J_{SC} - J_{dark}(V) = J_{SC} - J_0 \left(e^{\frac{qV}{k_B T}} - 1 \right) \quad \Rightarrow$$

$$V_{OC} = \frac{k_B T}{q} \ln \left(\frac{J_{SC}}{J_0} + 1 \right)$$

When the contacts are isolated $J(V) = 0$. Since J_{SC} increases with light intensity, one can see that V_{OC} also increases with light intensity (more later).



J-V behavior in solar cells (basics)



Ideal Diode Law:

$$I = I_0 \left(e^{\frac{qV}{k_B T}} - 1 \right)$$

Non-ideal Diode Law:

$$I = I_0 \left(e^{\frac{qV}{mk_B T}} - 1 \right)$$



Types of solar energy conversion

Photovoltaic: Absorbing photons from the Sun with $h\nu > E_g$ generates free electron-hole pairs; in this case the electronic potential energy is increased through a reconfiguration of the charge density. Photogenerated carriers are collected through electrodes, and electrical power can be extracted. Requires an energy gap such that $E_g \gg k_B T$. Semiconductors work well for this approach.

Solar thermal: Absorption of photons from the Sun increases the average thermal (kinetic) energy of the electrons and atoms, raising the temperature of the converter. The solar thermal converter can be used to drive an engine (e.g., steam turbine) to do work, in turn producing electrical power if desired.

Photochemical: Similarly to the case of photovoltaic conversion, in the case of photochemical conversion the absorbed photons raise the electronic potential energy; the photoexcited electrons then drive a chemical reaction. One prime example of this process is photochemical hydrogen production, which has proven to be an elusive task to accomplish through economical technologies.



Principle of detailed balance

Detailed balance

From Wikipedia, the free encyclopedia

In mathematics and statistical mechanics, a Markov process is said to show **detailed balance** if the transition probability, P , between each pair of states i and j in the state space obey

$$\pi_i P_{ij} = \pi_j P_{ji}$$

where P is the Markov transition matrix (transition probability), *i.e.*, $P_{ij} = P(X_t = j \mid X_{t-1} = i)$; and π_i and π_j are the equilibrium probabilities of being in states i and j , respectively.

For solar cells, detailed balance refers to the idea that in equilibrium, any process taking place also occurs in the reverse direction with an equal probability.



Principle of detailed balance (cont.)

JOURNAL OF APPLIED PHYSICS

VOLUME 32, NUMBER 3

MARCH, 1961

Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

WILLIAM SHOCKLEY AND HANS J. QUEISSER

Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California

(Received May 3, 1960; in final form October 31, 1960)

In order to find an upper theoretical limit for the efficiency of *p-n* junction solar energy converters, a limiting efficiency, called the *detailed balance limit* of efficiency, has been calculated for an ideal case in which the only recombination mechanism of hole-electron pairs is radiative as required by the principle of detailed balance. The efficiency is also calculated for the case in which radiative recombination is only a fixed fraction f_e of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and f_e as parameters, the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. The maximum efficiency is found to be 30% for an energy gap of 1.1 eV and $f_e=1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.

Detailed balance as applied to solar cells assumes that:

- charge carrier mobility: infinite (every photogenerated carrier is collected)
- every incident photon with $h\nu > E_g$ is absorbed
- every absorbed photon creates exactly one electron-hole pair
- (thermal) radiative emission = (thermal) photon absorption in the dark



Principle of detailed balance (cont.)

JOURNAL OF APPLIED PHYSICS 100, 074510 (2006)

Solar conversion efficiency of photovoltaic and photoelectrolysis cells with carrier multiplication absorbers

M. C. Hanna and A. J. Nozik^{a)}

National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401

(Received 25 May 2006; accepted 11 July 2006; published online 12 October 2006)

We calculate the maximum power conversion efficiency for conversion of solar radiation to electrical power or to a flux of chemical free energy for the case of hydrogen production from water

“There are four unavoidable losses that limit the solar conversion efficiency of a device with a single absorption threshold or band gap E_g :

1. **incomplete absorption**— photons with energy below E_g are not absorbed;
2. **thermalization** (carrier cooling) — the excess energy of carriers generated by absorption of photons with energy greater than E_g is usually lost as heat;
3. **thermodynamic loss** — the available energy, Gibbs free energy, or chemical potential of the thermalized excited states is always less than the internal energy, with the consequence that the photovoltage or output chemical potential must be less than E_g ; and
4. **radiative recombination** — a small fraction of the excited states radiatively recombine with the ground states at maximum power output.”



Principle of detailed balance (equilibrium, no illumination)

Consider a solar cell in the dark, which is in thermal equilibrium with its surrounding environment. A result (following from the analysis presented in *The Physics of Solar Cells* section 2.4.1 .) indicates that radiative losses (the cell's blackbody emission) will equal radiative gains (i.e., due to absorption of blackbody photons from the surrounding).

Since the cell's outgoing (emitted) photon flux must equal the incoming (absorbed) photon flux at equilibrium, one can deduce that the energy-dependent emissivity equals the energy-dependent absorptivity.



Detailed balance – under illumination

An illuminated solar cell absorbs photons at a rate G of:

$$G = (1 - R(E))a(E)b_s(E)$$

where b_s is the incident solar photon flux normal to the surface of the solar cell (see (2.2) in the textbook).

The emitted photon flux depends on the chemical potential $\Delta\mu$, the refractive index of the surrounding medium n_s , and the ambient temperature, T_a :

$$b_e(E, \Delta\mu) = F_e \frac{2n_s^2}{h^3 c^2} \frac{E^2}{e^{(E-\Delta\mu)/k_B T} - 1}$$

where $F_e = \pi \sin^2 \theta_c = \pi(n_0/n_s)^2$ and $\theta_c = \sin^{-1}(n_0/n_s)$; n_0 is the index of the surrounding medium -- see (2.12) in the textbook. Follows that the net photon absorption depends on:

$$j_{abs(net)} = q(1 - R(E))a(E)(b_e(E, \Delta\mu) - b_e(E, 0))$$

Light (non-equilibrium), and dark (equilibrium) contributions



Detailed balance – under illumination (cont.)

In the case of the limiting (highest possible) photocurrent, where all incident photons with $h\nu > E_g$ are absorbed and generate an electron which is ultimately collected, the short-circuit current is given by:

$$J_{SC} = q \int_{E_g}^{\infty} b_s(E) dE \quad (2.21)$$

where b_s is the spectrum of incident sunlight.

The limiting (lowest) dark current can be written as:

$$J(V) = J_{SC} - J_{dark} = J_{SC} - J_0 \left(e^{\frac{qV}{kT}} - 1 \right)$$

The limiting efficiency follows:

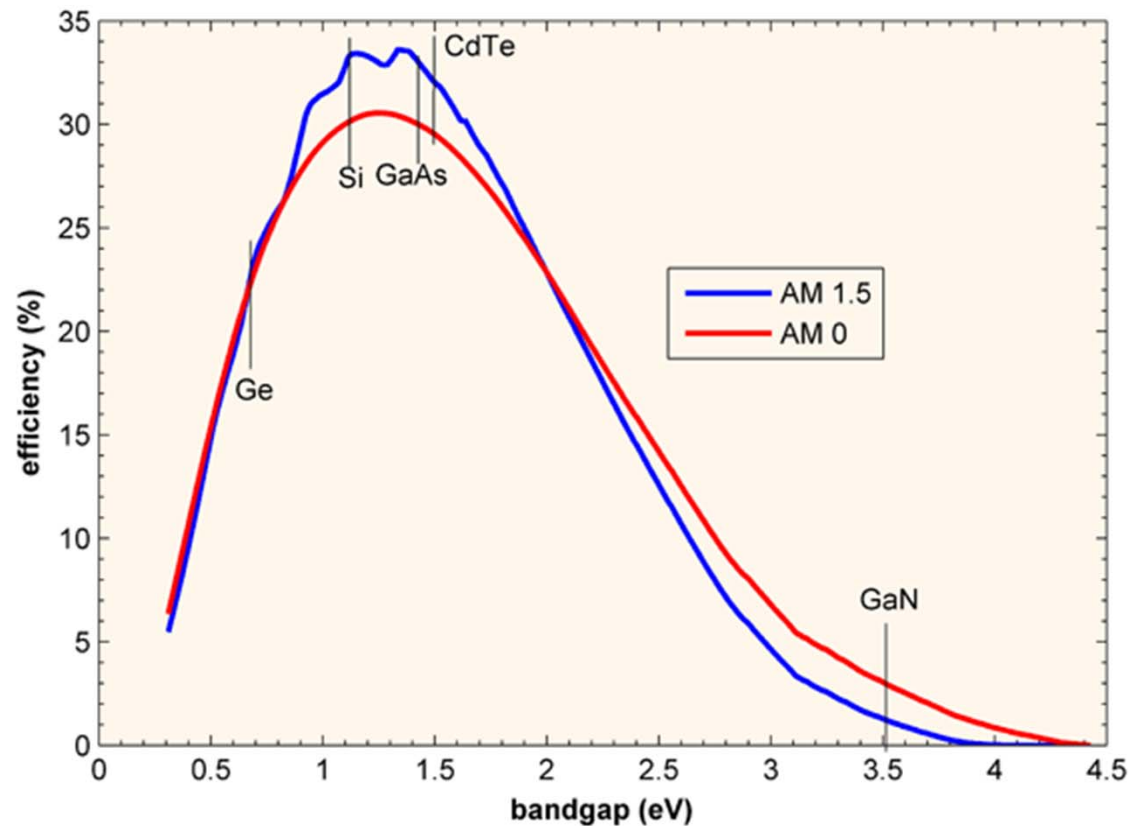
$$P_S = \int_{E_g}^{\infty} E b_s(E_S) dE \quad P = VJ(V) \quad \eta = \frac{VJ(V)}{P_S}$$

(Incident power)

One must optimize load resistance to operate at maximum power conversion efficiency.



Bandgap influence on efficiency



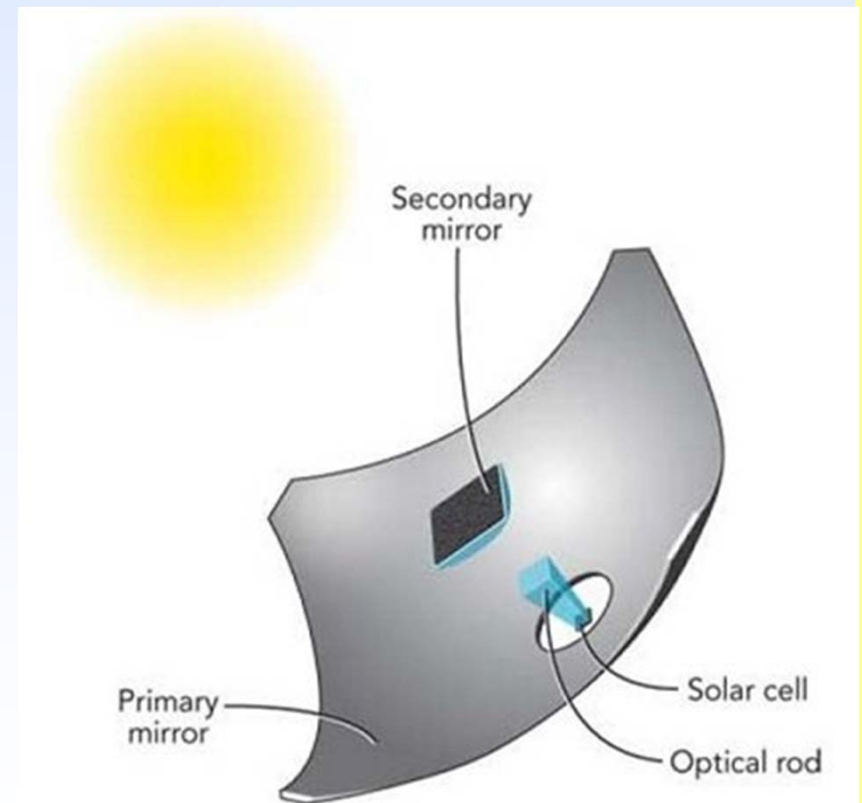
- Too large a bandgap, and you get insufficient absorption (GaN)
- Too narrow a bandgap, and you get insufficient photovoltage (Ge, PbS, PbSe)



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 \$10, which works out to \$100,000/m² (prices are likely 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.

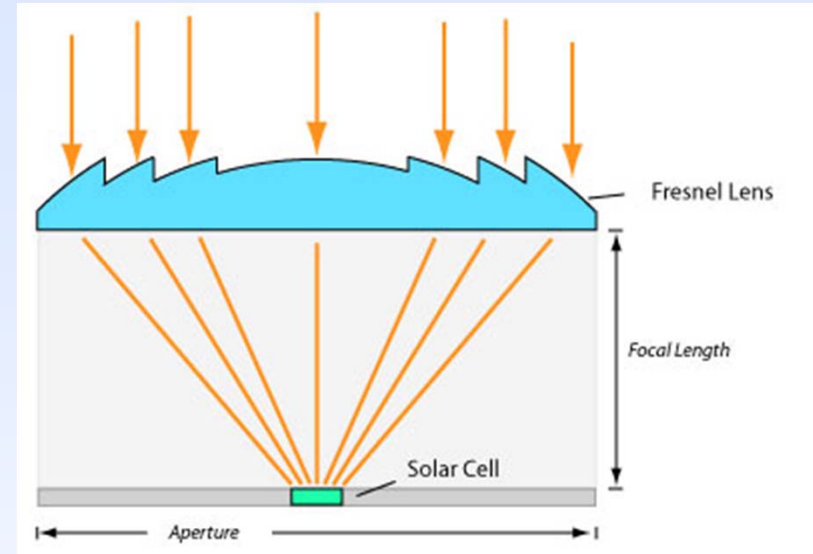
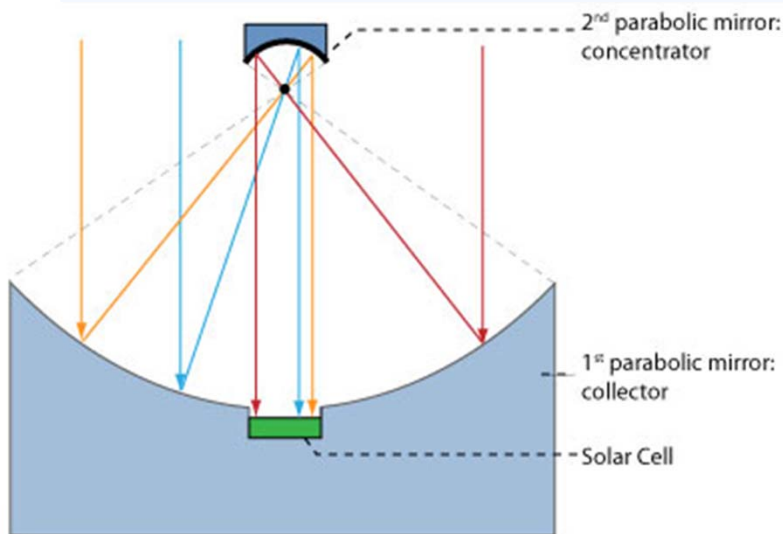


Concentrating solar cells (cont.)

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

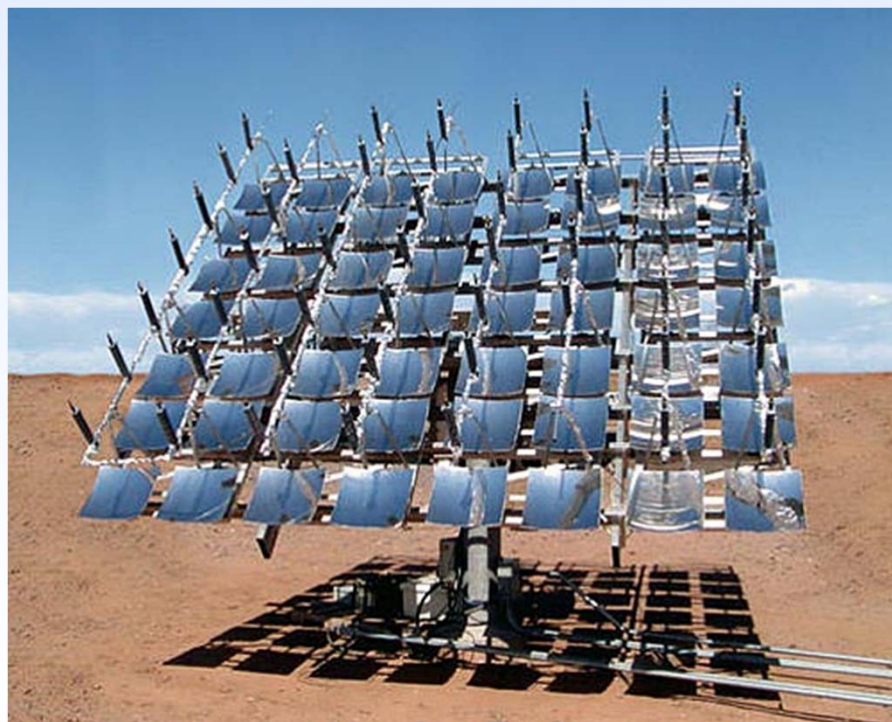
Named after the French physicist, comprises several sections with different angles; reduced weight and thickness compared to standard lens. Possible to achieve short focal length and large aperture while keeping the lens light. Constructed in a shape of a circle to provide a **point focus** with concentration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



Concentrating solar cells (cont.)

Some challenges for CPV...

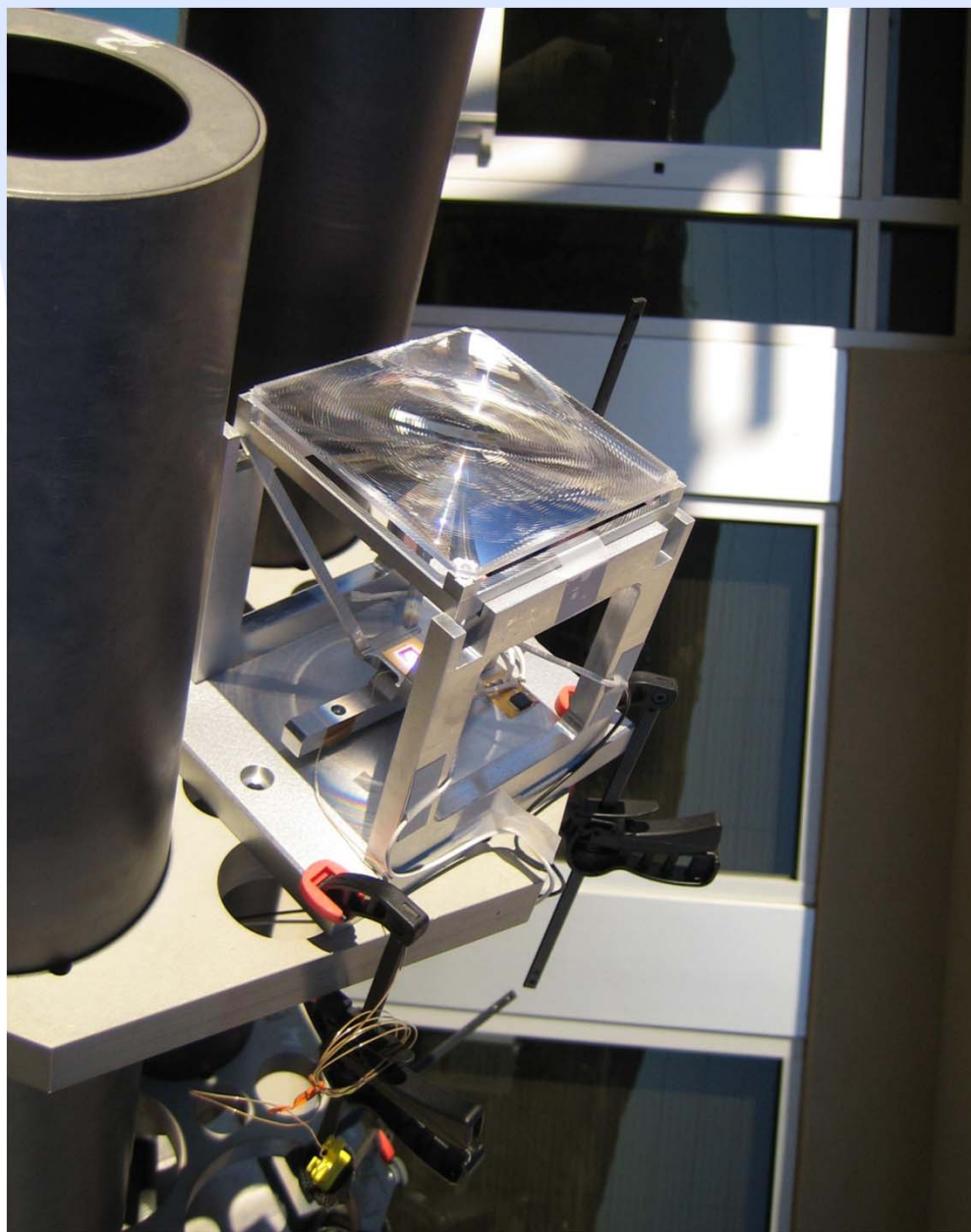
- Only direct insolation can be coupled into the receiver cells. The *indirect* portion, since it comes in from a variety of angles, cannot be focused correctly to be utilized. Scattered (diffuse) light is ~15% of the AM1.5G spectrum.
- Must use two-axis tracking technology for small receivers; for linear 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.



www.allamericanpatriots.com/photos/microdish-cpv-system



Concentrating solar cells (cont.)

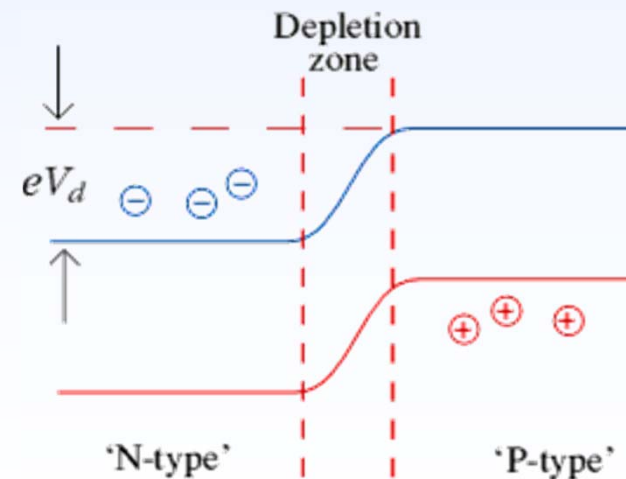


- Shown at left: Enfocus Engineering two-axis tracking CPV single-cell component, under test conditions at NREL.
- This component makes up one of many in an array that may be 10 x 8 , with 80 cells.
- Total *receiver* area of such a module would be 80 cm², and collect a total incident power at AM1.5G 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.)

Second, the slightly 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.

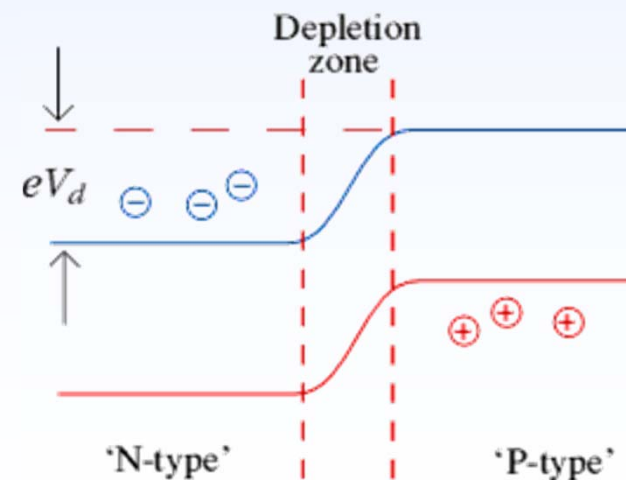
[J_{sc} is the short-circuit current density; V_{oc} is the open-circuit photovoltage; FF is the fill-factor, related to the optimization of the product of the voltage and the current.]

- 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, $p_{n_0} \gg n_{p_0}$:

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



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.

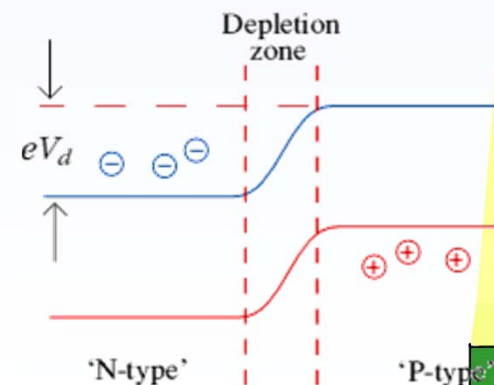
The photovoltage increases logarithmically. The photogenerated current increases linearly with concentration (X) and the net cell current is the photogenerated current minus the dark current. So when you put it all together:

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

$$V_{oc}(X) = mkT \ln((XJ_{sc}/J_0) + 1) \quad // \sim V_{oc}(\text{at 1 sun intensity}) + mkT \ln X$$

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.

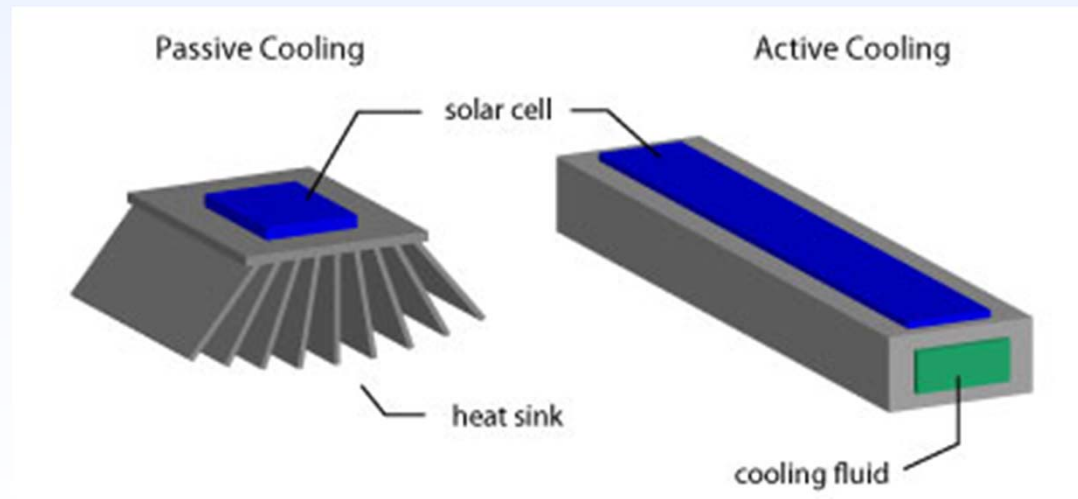


Concentrating solar cells (cooling)

Cooling

Most concentrating PV systems require cooling.

- **Passive Cooling:** Here, the cell is placed on a clad ceramic substrate with high thermal conductivity. The ceramic also provides electrical isolation.
- **Active Cooling:** Typically, liquid metal is used as a cooling fluid, capable of cooling from 1,700°C to 100°C.



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



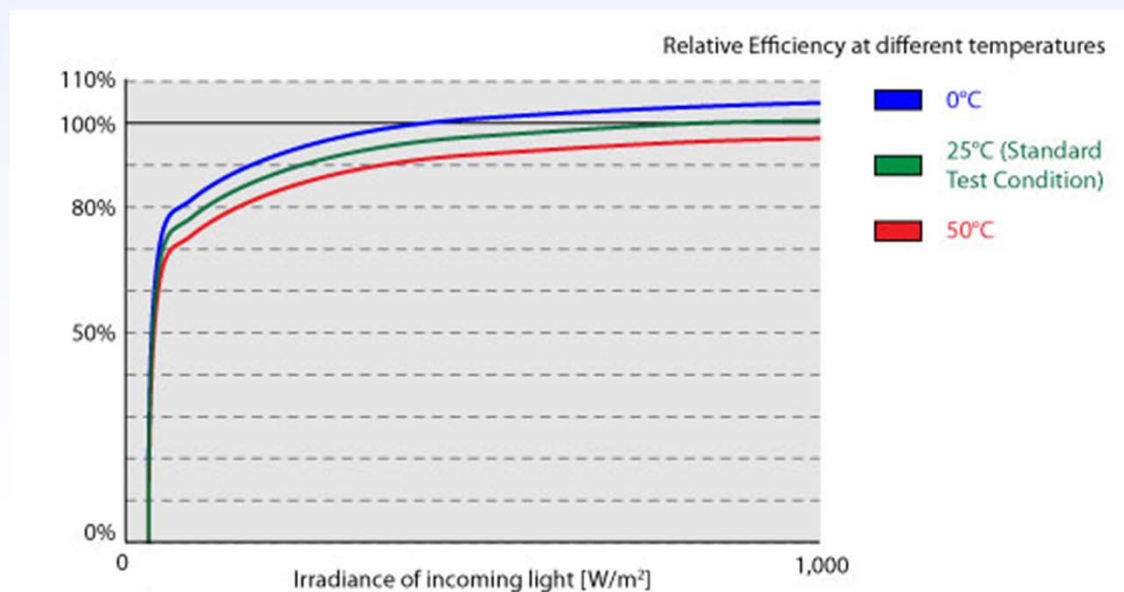
Concentrating solar cells (cont.)

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.



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



Increased efficiency under concentration (cont.)

