Welcome to SSC2010!

The 1st Solar Student Conference in Israel

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26-29 April 2010, Beit Daniel, Zikhron Ya'akov
(some of) the

VERY BASIC CONCEPTS OF

Photovoltaics

Isaac Balberg

Physics

Hebrew University of Jerusalem

with some additions / modifications by

me

AERI and M&I

Weizmann Institute of Science
In the beginning... בראשית
Energy levels of the hydrogen atom
The hydrogen molecule

\[ \text{H} + \text{H} \rightarrow \text{H}_2 \]
The hydrogen molecule

$H + H \rightarrow H_2$

Level splitting

Potential energy $U$

$U_A$, $U_S$

4.52 eV

0.074 nm = $r_0$

0.2 nm
From atomic levels to bands

$E$: distance between atoms where system’s energy is minimized
Filling the bands in solids

- Insulator (a): Allowed bands, Forbidden bands, Empty conduction band, Wide forbidden band, Filled valence band
- Metal (b): Empty states, Filled states
- Semiconductor (c): Thermally excited electrons, Narrow forbidden band, Holes in valence band
Fig. 2.9. (a) Diamond-type lattice. Each atom forms covalent bonds with four nearest neighbours at the corners of a regular tetrahedron.
(b) Two-dimensional representation of the diamond-type lattice.
Electrons and holes in semiconductors

Doping of semiconductors

[Diagram showing the arrangement of silicon atoms with boron and phosphorus dopants, indicating the presence of holes and free electrons.]
Electrons and holes in semiconductors

Formation of n-type semiconductor

Figure 5.9. An n-type semiconductor: (a) schematic lattice; (b) donor levels at absolute zero; (c) donor levels at room temperature
Formation of p-type semiconductor

Figure 5.10. A p-type semiconductor: (a) schematic lattice; (b) acceptor levels at absolute zero; (c) acceptor levels at room temperature
Formation of p-n junction
Charges, Fields and potential in the p-n junction

(a) x=0

(b) p

(c) $\rho(x)$

(d) $E(x)$

(e) $\phi(x)$

Depletion Layer
The energy diagram of the p-n junction
The p-n junction

\[ I = 0 \text{ actually means} \]

\[ I_{\text{diffusion}} = -I_{\text{drift}} \]
The p-n junction under forward bias

# of carriers that can diffuse over the potential barrier has increased by the Boltzmann factor \( \exp(qV/kT) \) so that

\[
I_{\text{diffusion}} = I_0 \exp(qV/kT)
\]

\( I_0 \sim \text{same as in equilibrium} \)

We define \( I_{\text{drift}} = I_0 (\mu_{\text{min}} \text{ or } D_{\text{min}}, \tau_{\text{min}}) \)
The p-n junction under forward bias

\[ I = I_0 \left[ \exp\left(\frac{qV}{kT}\right) - 1 \right] \]

\[ V_D = E_g - (E_c - E_F)_p - (E_F - E_v)_n = \frac{kT}{q} \ln\left(\frac{N_d N_a}{n_i^2}\right) \]

Due to the increase in \( V \), the current increases and the diffusion current is the dominant one in the circuit.
The p-n junction under reverse bias

Reverse current saturates @ \( I_0 \)

for \( V < 0 \),

\[ I = -I_0 \left[1 - \exp\left(\frac{qV}{kT}\right)\right] \]

For small \( |V| \),

\( I_0 \) is maintained while large \( |V| \) causes "breakdown".
Forward & reverse bias in p-n junction

A graph showing the I-V characteristics of a p-n junction, with labels for leakage current and reverse breakdown.
The photoelectric effect
Electron-hole pair generation by light in a semiconductor
The trick in making a photovoltaic cell is to continuously sweep the loose, wandering electrons out of the cell as fast as they are produced, and use them as electric power before they have time to affix to wandering holes. If this happens, the solar energy that was imparted to the electron in knocking it loose is lost as heat.
What a Semiconductor can do

\[ p-n \text{ junction} = \text{photocurrent} \]
The p-n junction under illumination

If the junction is illuminated, $I_L$ is the drift current that is added to $I_0$, due to electron-hole generation.

Illumination yields a drift photocurrent, $I_L$

\[ I_L = I_L(\tau, \mu, F(\alpha(\lambda))) \]
The p-n junction under illumination

\[ I = I_0[\exp(qV/kT) - 1] - I_L \]

Hence

\[ V_{oc} = \frac{(kT/q)\ln[I_L/I_0 + 1]}{2} \]

@\( V_{oc} \) the I_{diff} has increased so much that it cancels \( I_0 + I_L \)

\( \Rightarrow V_{oc} \) is determined by the light-induced drift current.
Anatomy of the p-n junction

**Fig. 9.** Breakdown of the processes taking place in a representative photovoltaic junction. It is assumed that the light is incident on the n-type end.
Solar Cell Recap
Conventional p-n junction

Absorb light.
Absorbed light creates carriers.
Carrier collection, by diffusion, drift.

after textbooks & R. Collins, CSM
Solar Cell Recap

a) Before contact

b) Thermal equilibrium

c) Upon illumination - charge separation
Solar Cell Recap
Conventional p-n junction + I-V characteristic

Absorb light.
Absorbed light creates carriers.
Carrier collection, by diffusion, drift.

after textbooks & R. Collins, CSM
Voc = 0.602 V

Jsc = 26.7 mA/cm²

FF = 73.3%

η = 11.8%
The equivalent circuit and the current in the non-ideal case (the load-line)

\[ I = \{I_0[\exp[q(V - IR_s)/kT] - 1]\} + (V - IR_s)/R_p - I_L \]
I-V characteristic of PV cell

Load line

Operating point

$V = IR_L$

$R_p$  

$R_s$

Sample PL0710/2  
Oct 30, 1998  
tape aperture, black dye

Area = 0.1863 cm$^2$

$Irradiance = 1000$ Wm$^{-2}$

$V_{oc} = 0.7210$ V

$I_{sc} = 3.824$ mA

$V_{max} = 0.5465$ V

$I_{max} = 3.552$ mA

$J_{sc} = 20.53$ mA cm$^{-2}$

$P_{max} = 1.941$ mW

Fill factor = 70.41 %

Efficiency = 10.4 %
\[ \eta(\lambda) \equiv \frac{I_p(\lambda)}{qN(\lambda)}, \quad N(\lambda) = \text{impinging photons} \]
Internal Quantum (or collection) Efficiency

\[ Y(\lambda) \equiv \eta(\lambda)/T(\lambda) \equiv I_p(\lambda)/qN(\lambda)T(\lambda), \quad N(\lambda)T(\lambda) = \text{entering photons} \]
A schematic of a Solar Cell
Inside a Solar Cell

Solar cell efficiency (\%) = \frac{\text{Power out (W) x 100}}{\text{Area (m}^2\text{) x 1000 W/m}^2\text{)}

10\% efficiency = 100 W/m\(^2\) or 10 W/ft\(^2\)
Current Types of PV Cells

Primarily based on solid-state electronic material systems

**Elemental Semiconductors** •
Single or multi-crystal -
Polycrystalline -
Amorphous thin film -

**Inorganic Compound Semiconductors** •
Single crystal -
Polycrystalline thin film -

**Organic Compounds** •
Polycrystalline film -
interpenetrating network
Nanocrystalline film; -
dye-sensitized

- \( \text{Si, Ge} \)
- \( \text{GaAs} \)
- \( \text{InP} \)
- \( \text{CdTe} \)
- \( \text{CuInSe}_2 \)
- Phenylene-Vinylidene ++
- Ru dye-TiO\(_2\)
Best measured research cell efficiencies:

\(~ 35\% \text{ III-V triple junction cell} \cdot (~ 41.5\% \text{ IV + III-V cells, with concentration})\)

\(~ 25\% \text{ single crystalline Si} \cdot \)

\(~ 20\% \text{ single junction PX thin films (CIGS, Si)} \cdot \)

\(~ 11\% \text{ dye sensitized solar cells (DSSC)} \cdot \)

\(~ 4.5 (\rightarrow 6?)\% \text{ organic PV} \cdot \)

**Definition of efficiency:**

\[
\eta = \frac{\text{Electrical Power}_{\text{OUT}} \times 100\%}{\text{Solar Radiative Power}_{\text{IN}}}
\]
## Possibilities for Technological Progress

<table>
<thead>
<tr>
<th>BEST commercial module /cell</th>
<th>Eff. (%)</th>
<th>Manufacturer</th>
<th>Technology rated / minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>72%</td>
<td>Single-crystal Si non-standard junction SunPower</td>
<td>17.7 / 16.3</td>
<td></td>
</tr>
<tr>
<td>69%</td>
<td>Single-crystal Si non-standard junction Sanyo</td>
<td>17.0 / 15.3</td>
<td></td>
</tr>
<tr>
<td>63%</td>
<td>Single-crystal Si non-standard junction BP</td>
<td>15.5 / 13.5</td>
<td></td>
</tr>
<tr>
<td>68%</td>
<td>Multi crystal Si standard junction Kyocera</td>
<td>14.4 / ??</td>
<td></td>
</tr>
<tr>
<td>63%</td>
<td>Single-crystal Si standard junction Shell</td>
<td>13.3 / ??</td>
<td></td>
</tr>
<tr>
<td>62%</td>
<td>EFG(ribbon) Si standard junction Schott</td>
<td>13.2 / 11.9</td>
<td></td>
</tr>
<tr>
<td>56%</td>
<td>CIGS Würth Solar</td>
<td>11.0 / 10.3</td>
<td></td>
</tr>
<tr>
<td>57%</td>
<td>CdTe First Solar</td>
<td>9.4 / 8.3</td>
<td></td>
</tr>
<tr>
<td>64%</td>
<td>a-Si, single junction Mitsubishi</td>
<td>6.4 / ??</td>
<td></td>
</tr>
<tr>
<td>53%</td>
<td>a-Si, triple junction Uni-Solar</td>
<td>6.4 / 5.7</td>
<td></td>
</tr>
</tbody>
</table>
Optical Problems for Quantum conversion of solar energy

In Solar Cells Most Solar Energy is "Wasted" as Heat

In any system with concentration, most of the diffuse radiation is "lost"
Power loss distribution for (old) Si cell at AM1.5

Engineering achievement of 25 years

grid coverage, reflection losses, spurious absorption

why is this so?

Shockley-Queisser limit

Engineering achievement of 25 years

quantum efficiency

$E_g > qV_{oc}$

fill factor

final cell $\eta$

Martin Wolf (1971)
Photovoltaic Conversion is a Quantum (threshold) Conversion Process

Solar Energy Spectrum in Solar Cells Most Solar Energy is “Lost” as Heat!!!
Single p-n junction solar cell

Energy

high energy photon - partial loss

low energy photon - total loss

useable photo-voltage (qV)

space

O. Niitsoo
Effect of bandgap / optical absorption edge on maximal possible PV conversion efficiency for single band gap / absorption edge system

- Theoretical limits as function of bandgap for AM 1.5 spectra, and "best cell efficiencies" for some cells.
- NOTE how close Si cells are to their maximum!

Prince, *JAP* 26 (1955) 534
Loferski, *JAP* 27 (1956) 777
Shockley & Queisser *JAP* (1961)
Towards higher efficiency

Harvest more photons

Maximum Current Density Available
in 1 Sun @ AM 1.5G

Spectral Photon Flux Density
\( \left( 10^{14} \text{ photons/sec-cm}^2 \right) \)

from B. Kippelen, Georgia Tech
What can we do?

Better utilization of sunlight: Photon management: Multi-bandgap, multi-junction photovoltaics

Four-junction device with bandgaps 1.8 eV/1.4 eV/1.0 eV/0.7 eV
Theoretical efficiency > 52%
Photon Management ➔ multi-junction device structures

Thermodynamic Efficiency Limits
non-concentrated Sunlight (AM 1.5)

<table>
<thead>
<tr>
<th># of Junctions</th>
<th>Efficiency</th>
<th>Optimum $E_G$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30%</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>42%</td>
<td>1.9 - 1.0</td>
</tr>
<tr>
<td>3</td>
<td>49%</td>
<td>2.3 - 1.4 - 0.8</td>
</tr>
<tr>
<td>4</td>
<td>53%</td>
<td>2.6 - 1.8 - 1.2 - 0.8</td>
</tr>
<tr>
<td>infinite</td>
<td>68%</td>
<td></td>
</tr>
</tbody>
</table>
Optical Problems for Quantum conversion of solar energy

In Solar Cells Most Solar Energy is “Wasted” as Heat

In any system with concentration, most of the diffuse radiation is “lost”
Improve performance using concentrated sunlight

Inverted Metamorphic Multijunction (IMM)

1.8 eV GaInP
1.3 eV GaAs
Transparent GaInP grade
Metamorphic 0.9 eV InGaAs

but ... **diffuse** (scattered) radiation lost upon concentration
The Photovoltaic (PV) effect: Generalized picture

Metastable high and low energy states

Absorber transfers charges into high and low energy state

Driving force brings charges to contacts

Selective contacts

(1) cf. e.g., Green, M.A., *Photovoltaic principles*. Physica E, 14 (2002) 11-17
p/n vs. excitonic solar cells

**INORGANIC**
- high dielectric constant
- minority carrier device

**ORGANIC**
- low dielectric constant
- excitonic device
- includes jiggling & wiggling

\[ E_B = -\frac{m^*e^4}{(4\pi\varepsilon_0)^22\hbar^2\varepsilon^2} \]

\( \varepsilon \) dielectric constant

from B. Kippelen, Georgia Tech
Physics of excitonic solar cells

Heterojunction
Requires interfaces, “selective”, for both excitons and charge carriers

From B. Kippelen, Georgia Tech
PV future Summary

PX and nX solar cells
Relax material requirements?

Painted / self-assembling solar cells
Simple fabrication of large areas

PHOTON (LIGHT) MANAGEMENT
Simplify spectral splitting to ↓ price e.g.,
Find how to use diffuse light @ low conc.
Summary

1) Change of charge carriers energetic state by light
2) Carriers and doping in semiconductors
3) The p-n junction in the dark
4) The p-n junction under illumination
5) The concepts of $I_{sc}$ and $V_{oc}$
6) The concepts of Efficiency and Fill factor
The End
The concept of the quasi-Fermi levels
Formation of bands
The concept of the Fermi level
The concept of the Fermi level
Photoexcitation in the p-n junction
The Heterojunction
Complex Heterojunctions
External Quantum Efficiency

Fig. 8. Spectral dependence of the quantum efficiency for a CdS/CdTe heterojunction cell prepared by vacuum evaporation of CdS on single crystal CdTe. [From Mitchell et al. (47).]
Energy levels of the hydrogen atom
Energy Bands in Solids

Figure 4.23. Energy band scheme for various classes of material
The simplest model for the determination of $I_m$ and $V_m$ 

(R$_s$ = 0, R$_p$ = $\infty$) 

$P = VI = V\{I_0[\exp(qV/kT)-1]-I_L\}$ 

dP/dV = 0 

$\rightarrow V_m = V_{oc}-(kT/q)\ln[qV_m/kT+1]$ 

$I_m = I_0\{\exp(qV_m/kT)-1\}-I_L$ 

$P_m \equiv V_m I_m$
The practical concepts

The Fill factor

\[ ff \equiv \frac{I_m V_m}{I_{sc} V_{oc}} \]

\[ ff = F(I_0, I_L, R_s, R_p) \]

\[ ff(0, \infty) = F(I_0, I_L, 0, \infty) \]

\[ ff(R_s, R_p) \approx ff(0, \infty)[1 - I_{sc} R_s/V_{oc} - V_{oc}/I_{sc} R_p] \]

The energy conversion efficiency of the cell

\[ \eta \equiv \frac{I_m V_m}{P_{rad}} \]
The equivalent circuit and I-V characteristic of a solar cell compared to a diode.
The real cell

- Thickness of the solar cell: approx 0.3 mm
- Thickness of the n-semiconductor layer: approx 0.002 mm

Diagram:
- Anti-reflection film
- Contact
- Consumer
- p-n-junction
- p-semiconductor layer
- Rear metal contact
- n-semiconductor layer
p-i-n and p-n Heterojunctions

Figure 2. The energy scheme of the two most common configurations for carrier separation in thin film solar cells: (a) the p-i-n homojunction (here with Ag and Indium–tin oxide electrodes), usually used for a-Si:H cells, (b) the p-n heterojunction (with Mo and tin oxide electrodes) usually used for CIS cells.
Basic Optics relevant to energy collection

S. G. Lipson
Technion
Part I: Geometrical Optics of Solar Concentration
Use of solar and geothermal energy is subject to thermodynamic limits. I am going to concentrate on the classical optics limitations.

This is all very basic material, much of which you will already know!

At the end I will add some practical aspects supplied by Jeff Gordon, Ben-Gurion University.
The dream.

Consider a source at $T_1$ radiating energy which is then concentrated into a sufficiently small area that it can raise it to temperature $T_2 > T_1$. We could then return the heat to the source (losing no energy) and get work out at the same time.

We have created Perpetuum Mobile
Radiation concepts

- Radiative flux (power) $\Phi$ in W
- Exitance $M$ in W.m$^{-2}$
- Radiance, Intensity $J$ in W.m$^{-2}$.sr$^{-1}$
- Spectral Radiance $I(\lambda)$ in W.m$^{-2}$.sr$^{-1}$µm$^{-1}$
  or $I(\nu)$ in W.m$^{-2}$.sr$^{-1}$Hz$^{-1}$
Planck’s law

A body can radiate a maximum spectral radiance at frequency $\nu$ in frequency interval $\delta\nu$ given by $I(\nu) \, \delta\nu$ where

$$I(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$
\[ I(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \]
Emissivity

The ratio between Planck’s $I(\nu)$ and observed $I(\nu)$ is called “emissivity” $\varepsilon(\nu)$, and Planck’s law indicates that $\varepsilon(\nu) \leq 1$.

Kirchhoff’s law relates absorptivity $\alpha(\nu)$ and emissivity: $\varepsilon(\nu) = \alpha(\nu)$ (uses same argument as the “perpetuum mobile”)
Homework Problem 1

What would be the optimum $\varepsilon(\lambda)$ for the paint of a solar water heating panel?
How could you make such a paint?
Lambertian source

If a source appears equally bright from all directions (black-body, ideal scatterer, etc), the irradiance at a distant plane must vary with angle as \( \cos \theta \), because of the foreshortening of the apparent area of the source.

\[
A \cos \theta
\]
Now we want to show that no optical system can produce an image with radiance greater than the source. This will solve the “perpetuum mobile” paradox.
Consider a basic perfect optical imaging system, forming an image of a grating.
Diffraction grating equation gives for period $h$

$$\frac{m \lambda}{n_1} = h_1 \sin \theta_1$$

$$\frac{m \lambda}{n_2} = h_2 \sin \theta_2$$

$$m \lambda = n_1 h_1 \sin \theta_1 = n_2 h_2 \sin \theta_2$$

$$n h \sin \theta \equiv \text{Étendue or optical invariant}$$
In 3 dimensions, the optical invariant is

\[ n^2A \sin^2 \theta \]
For example, for the sun, angular diameter $0.5^\circ=0.008$ rad, what aperture is optimal for a 100cm$^2$ solar cell?:
For example, for the sun, angular diameter $0.5^\circ = 0.008$ rad, what aperture is optimal for a $100\text{cm}^2$ solar cell?:

Sun diameter $D$; Aperture radius $R$;

$$\alpha = \frac{D}{L}, \quad \theta_1 = \frac{R}{L} = \frac{R\alpha}{D};$$

$$A_{\text{image}} \sin^2 \theta_2 = \frac{\pi D^2}{4} \sin^2 \theta_1 = \frac{\pi R^2 \alpha^2}{4} = \frac{1}{4} \alpha^2 A_{\text{aperture}}$$

for $\theta_2 = \frac{\pi}{2}, A_{\text{image}} = \frac{1}{4} \alpha^2 A_{\text{aperture}}$.

for $\alpha = 0.008$, $\frac{A_{\text{image}}}{A_{\text{aperture}}} = 1.6 \times 10^{-5}$

If $A_{\text{image}} = 10^{-2}\text{m}^2$, $A_{\text{aperture}} = 625\text{ m}^2$
The Abbe sine law

Note, in passing, the Abbe sine law for aberration-free imaging. If we considered all the orders of diffraction $m$ in this imaging system:

\[
\frac{m \lambda}{n_1} = h_1 \sin \theta_{1m}; \quad \frac{m \lambda}{n_2} = h_2 \sin \theta_{2m};
\]

\[
\frac{\sin \theta_{2m}}{\sin \theta_{1m}} = \frac{n_1 h_1}{n_2 h_2} = \text{const.}
\]

The ratio of the sines of the angles in object and image space is constant
Abbe sine law

This is not obeyed by a thin lens, for example, where the ratio of the tangents is constant.

\[ \tan \theta_1 = \frac{h}{u}; \quad \tan \theta_2 = \frac{h}{v}; \quad \frac{\tan \theta_1}{\tan \theta_2} = \frac{v}{u} = \text{const.} \]
Now let’s get back to our dream system
Consider a Lambertian source of area $A$

\[ \Phi = AI(\lambda, T) = AP(\lambda, T) \int_0^\theta \cos \theta d\Omega \]

\[ = AP(\lambda, T) \int_0^\theta 2\pi \cos \theta \sin \theta d\theta \]

\[ = AP(\lambda, T) \pi \sin^2 \theta \]
= \pi P(\lambda, T) \text{ times the Optical Invariant }

Conservation of energy requires that the flux \( \Phi \) be conserved (or decay by absorption), so \( P(\lambda, T) \) can not increase, i.e.

\[ T_2 \leq T_1 \]

No perpetuum mobile!
Homework problem 2

But couldn’t the dependence of the optical invariant on refractive index $n$ be used to increase the radiance, and therefore create perpetuum mobile?
Effect of aberrations

Aberrations always cause the image area to increase due to blurring, so that $T_2 \leq T_1$ again.

Various creative ideas arose, which allow aberrations to be eliminated around the edge of the image at the expense of the centre, so that ideal conditions can be achieved.
An ideal optical system:
Aplanatic system eliminates spherical aberration and coma
And so C is a perfect image of B, since no approximations have been made about small angles (i.e. no spherical aberration or coma)

Snell: \( \sin \theta_1 = n \sin \theta_2 \)

Euclid's sine rule: \( \frac{R}{n \sin \theta_2} = \frac{R}{\sin(\angle ACO)} \)

so \( \angle ACO = \theta_1 \)

and \( \angle ABO = \theta_2 \) (sum of angles in \( \Delta \))
Immersion lens:

This *aplanatic system* is used in almost all high power oil-immersion microscope objectives.

Can be used as an ideal radiation concentrator, but can not work with parallel rays from an infinitely distant source, so needs additional (perfect?) optics. Example later.

Also used as a concentrator for photon detectors, to increase the S/N (by decreasing the detector area needed)
Homework problem 3:

An aplanatic system is made with a material having **negative** refractive index (say, $n = -2$). What would its focusing properties be?
A Compound Parabolic Concentrator used to eliminate aberrations around the edge of a finite region (2-D picture; 3-D is more complicated)

- A parabola focuses rays parallel to its axis exactly to a point.
- Rays from one edge of source collector axis
- A parabola focuses rays parallel to its axis exactly to a point.
- Every ray from the source entering the aperture hits the collector somewhere.
Part II: The photo-electric effect, limited.

- Atmospheric absorption of radiation
- Cut-off frequency.
Atmospheric Absorption
Solar Spectrum

The diagram shows the spectral irradiance (W/m²Ăľ) versus wavelength (Ăľ) and includes different curves:

- Solar irradiation curve outside atmosphere
- Solar irradiation curve at sea level
- Curve for blackbody at 5900 Â°C

The curves are labeled with various gases:
- O₃
- H₂O
- O₂H₂O
- H₂O, CO₂

The wavelength range is from 0 to 3.2 Âľ.
Photo-electric effect in a semiconductor

A photon strikes the material.

If its frequency is greater than the cut-off $\nu_0$, where $h \nu_0 = E_g$, the photon is absorbed and an electron-hole pair is created;

If its frequency is less than $\nu_0$, the photon is not absorbed, but transmitted by the material.
In a p-n junction

The electron and hole separate because of the electric field in the junction, but the potential difference $\Delta V$ cannot be greater than the band gap $E_g$.

So the electrical energy created per photon must be less than $E_g$. 

\[ \Delta V < E_g \]
So total electrical energy that the photocell can supply is less than
\[ h \nu_0 \, n(\nu_0) \]
where \( n(\nu_0) \) is number of photons with frequency greater than \( \nu_0 \)

There are also intrinsic losses, such as recombination radiation, which reduce this energy further.
Planck curve for number of photons per frequency interval (5000K)
Integrated number of photons above frequency $\nu_0$ for Planck curve (at 5000K)
37% of total received energy

Optimizing the power for a single solar cell
We can use the fact that a semiconductor is transparent to frequencies below the band-gap, and stack solar cells in series. If they are connected electrically in series, all have to deliver the same current.
Example: 3-junction cells currently in commercial production
Improving the efficiency of a compound cell (crystalline and micro-crystalline Si)

- Broad-band anti-reflection coating
- Transparent glass substrate
- Roughened conducting transparent (ITO) electrode
- Shorter wavelength α-Si p-i-n junction layer
- Conducting multilayer reflects shorter wavelengths only
- Longer wavelength μ-crystalline Si p-i-n junction
- Back contact metal electrode
Optimizing the power for several solar cells in series (same current)
The bottom line:

When intrinsic losses (radiative recombination and re-emission into full $2\pi$ solid angle) are taken into account, the limiting quantum efficiency for the solar spectrum, using a large number of stacked solar cells, is found to be 72% at ambient temperature, compared to 37% for a single cell (Henry, 1980).
Part III: Some practical aspects

Advanced solar cells can be expensive, but if the concentration ratio is sufficiently large (>1000), the collecting optics will still dominate the cost.

Band gap and efficiency fall with temperature

Tracking systems are needed if concentration is used, but are not overwhelmingly expensive.
Connecting cells in series

• The output voltage of a solar cell is about 1v.
• To collect the output economically, individual cells must be connected in series, to provide higher voltage (say, 30v)
• But all cells then carry the same current, which is that of the weakest cell
• What if a solar cell array is partially shadowed at some time of day?
• This problem needs a solution!
Recent progress: (acknowledgement to Jeff Gordon, BGU)

Advanced semiconductor devices (multi-junction solar cells)

eff. \( \approx 40\% \) but only at high solar flux

+ (A few mm in linear dimension)

High-flux optical design (immersion lens):
hundreds to thousands of suns*
at high collection efficiency (85-90%)

(*1 sun = ambient direct sunlight

\( = 1 \text{ mW/mm}^2 = 1 \text{ kW/m}^2 \))

Miniaturized high-flux ultra-efficient solar cell concentrators
with feasible power production densities of 1 W/mm\(^2\) (1 MW/m\(^2\))

(*1 sun = ambient direct sunlight

\( = 1 \text{ mW/mm}^2 = 1 \text{ kW/m}^2 \))
Two motivations for concentrating sunlight

1) **Economic**: Expensive absorber is $1/C$ of the total system most of which is then affordable, practical (but clever) optics.
First-generation high-flux designs: Tailored optics

Achieve the fundamental compactness limit (1/4), as well as co-planarity (of the primary and secondary mirrors) for ease of fabrication

No spherical aberration or coma.
Near the thermodynamic limit for max. conc. / max. acceptance angle (tolerance)

Net flux = 500 suns = 50 W/cm²

1.0 cm²

\( \eta \approx 30\% \)
2). Solar cell efficiency can increase with concentration (basic photodiode behavior) provided the cell has adequately low internal resistance.
High-flux probe of photovoltaic cell properties

10,000-sun mini-dish (20 cm) fiber-optic concentrator
1.0 mm fiber, square 100 mm² 3-junction cell

Localized irradiation probe up to 10,000 suns (10 W/mm²) on a disc of 1.0 mm diameter

Such mapping has elucidated cell physics (e.g., tunnel diode and metal grid designs) - already being implemented for new generations of concentrator solar cells.
7 kW array (unit for multi-MW systems)

1 cm$^2$ cells
Motivation for progressively smaller cells:

1. Intrinsically higher cell efficiency (lower internal resistance)

2. Feasibility of thin, planar, all-glass concentrators, with inexpensive mass production, and barely more mass (per unit area) than common window glass

3. Adoption of precision micro-fabrication and assembly techniques common in the semiconductor industry
Problem of line-spacing of metallic electrodes
Simple approximation to a 1-D parabolic concentrator.
Sources I used:

Monolithically Stacked Multi-Junction Cells for Concentrated Photovoltaic

New aspects of tunnel diode transitions in multi-junction photovoltaic cells

A. Braun, B. Hirsch, E.A. Katz, J.M. Gordon, 🌍
Department of Solar Energy & Environmental Physics, Blaustein Institutes for Desert Research, Ben-Gurion Univ. of the Negev, Sede Boqer Campus, Israel

W. Guter, and A.W. Bett 🇦🇪
Fraunhofer-Institut für Solare Energiesysteme, Freiburg, Germany
• Sede Boqer campus of Ben-Gurion University of the Negev

• Blaustein Institute for Desert Research
  – Ecology, hydrology, desert architecture, sociology, agriculture physics of the environment
• Optic design (non imaging and imaging)
• Solar energy based material synthesis (collaboration with WIS)
• Studies of photovoltaic under high concentrations
Introduction

• Concentrated photovoltaics (CPV) is one of many options to make PV affordable, competitive and thus a realistic source of energy

• Achieve higher efficiencies at lower price
  – Higher efficiencies by using multijunction cells at high levels of concentration
  – Lower price by concentrating the sunlight
Monolithically stacked multi-junction solar cells

- Different sub-cells with decreasing band gap
- Each sub cell is utilizing different part of the sun spectrum

- Monolithically stacked
- Series connection
  - Lower output current
  - Requires current matching
  - Tunnel diodes between sub-cells

Maximum efficiency grows with concentration

Theoretical limit for energy conversion

• Detailed balance analysis
• Results depend on the band-gaps selection of the different sub-cells
  • Changes with: spectrum, temperature, concentration, cell design
• Efficiency increases with number of junctions and with light intensity
• Maximum efficiency of 86% is calculated for infinite number of junction under maximum concentration
Challenges (on the way to the 86% efficiency)

Find the right materials –
- Optimized band-gaps for current matching
- Equal lattice constants

Find modified new materials or move to metamorphic approach (graded buffer layers grown between lattice miss matched layers)
Metamorphic designs:
GaInP/GaInAs/InGaAs inverted solar cell with 40.8% efficiency


---

• More than 3 junctions

InGaAsP/InGaAs

R.R. king et al., Bandgap Engineering in High–Efficiency Multijunction Concentrator Cells, International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen, 1-5 May 2005, Scottsdale, Arizona
Characterization

• Deduce the parameters of the different junctions from a lumped device with two terminals

• Establish the correct reference spectrum. Complicated for large number of junctions under concentration
- Higher intensities
  - Series resistance decreases FF
  - Metallization pattern, decrease cell size to sub mm scale
  - Tunnel diodes for high currents, new material requires new tunnel diodes
## Achievements

<table>
<thead>
<tr>
<th>Year</th>
<th>Laboratory</th>
<th>Efficiency (%)</th>
<th>X (suns)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>Varian/Stanford Sandia</td>
<td>29.6</td>
<td>330</td>
<td>GaAs /Si: four terminals, mechanically stacked</td>
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<tr>
<td>1989</td>
<td>Boeing</td>
<td>32.6</td>
<td>100</td>
<td>GaAs /GaSb: four terminals, mechanically Stacked</td>
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<td>1991</td>
<td>Spire</td>
<td>27.6</td>
<td>255</td>
<td>GaAs single junction</td>
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<td>1994</td>
<td>NREL</td>
<td>30.2</td>
<td>160</td>
<td>GaInP /GaAs: two terminals, monolithic</td>
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<td>2001</td>
<td>Fraunhofer ISE</td>
<td>31.3</td>
<td>300</td>
<td>GaInP /GaInAs: two terminals, monolithic</td>
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</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Efficiency</th>
<th>Area (cm²)</th>
<th>Material</th>
<th>Details</th>
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<tbody>
<tr>
<td>2003</td>
<td>Sharp Corp.</td>
<td>36.0</td>
<td>500</td>
<td>GaInP/GaInAs/Ge: two terminals,</td>
<td>AM1.5G spectrum</td>
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<td>2005</td>
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<td>600</td>
<td>GaInP/GaInAs/Ge: two terminals,</td>
<td>monolithic</td>
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<td></td>
<td>Azur</td>
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<td>2005</td>
<td>Spectrolab</td>
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<td>236</td>
<td>GaInP/GaInAs/Ge: two terminals,</td>
<td>low-AOD spectrum</td>
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<td>2006</td>
<td>Spectrolab</td>
<td>40.1, 40.7</td>
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<td>GaInP/GaInAs/Ge, LM and MM</td>
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<td>2008</td>
<td>NREL</td>
<td>40.8</td>
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<td>GaInP/GaInAs/Ge, LM</td>
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</table>
New aspects of tunnel diode transitions in multi-junction photovoltaic cells

Fundamental phenomena, related to all monolithically stacked multi-junction photovoltaic cells

Tunnel diodes:

- Essential part of monolithically stacked multijunction solar cell

- Tunnel Junctions electrically connect between the valence band of one sub-cells and the conduction band of other

- Upper limit for the tunneling current density, \( J_P (J_{\text{Peak}}) \)
$J_p = \text{upper limit for the tunneling current density}$

$J_{SC} < J_{\text{Peak}}$

$J_{SC} > J_{\text{Peak}}$

PV manufacturer aim is to have: $J_{SC(\text{max})} < J_p$
Tunnel diode transitions have been construed as a characteristic of the entire cell - independent of flux distribution.

“what happens when $J_{SC} > J_P$ only at a fraction of the solar cell?" 

In CPV the cells often witness an inhomogeneous flux maps.
Experimental setting:
Localized irradiance up to 10,000 suns (10W/mm²) using fibers of diameter 2.0, 1.0, 0.6 and 0.2 mm.
ISE concentrator cell

a) A triple junction cell

b) A single junction cell, (top junction of the 3J cell) with an underlying tunnel diode produced specifically for tunnel diode assessment

2.0 mm diameter
Representative results – Exceeding the maximum tunneling current density (3J cell, 1.0mm diameter fiber at the cell’s center)

\[ J_p > 830 \text{ suns (under localized irradiation)} \]
• Repeating the experiment using fibers with different diameters (degree of localized irradiation) – we found that the value of $J_p$ varies with the fiber diameter

• 3J cell 1.0 cm², with measured $J_p$ equivalent to 3200 suns (when irradiated with 1.0mm fiber)
The graph shows the relationship between fiber diameter (mm) and photocurrent density ($J_p$ in mA/mm$^2$) for different types of solar cells.

- **3.14 mm$^2$ triple junction cell**
- **3.14 mm$^2$ single junction cell**
- **100 mm$^2$ triple junction cell**

The lower bound for a 0.2 mm fiber is indicated.

- **1000 suns**
- **650 suns**
- **>7300 suns**

The image also includes a close-up view of a solar cell with a diameter of 2 mm and a tick mark indicating 10 mm for scale.
Interpreting the results:

- $J_P$ is controlled by the injection rate (per unit area) of majority carriers into the tunnel diode.
- Under homogeneous illumination the entire cell experiences a TDT when $J_{SC} > J_P$.
- Under localized irradiation, excess majority carriers can spread laterally due to drift and diffusion.
- Excess majority carriers can tunnel through the diode but over an area greater than that of the localized irradiation.
Interpreting the results:

- The effect of the electron spreading on $J_p$ increases as radiation is more localized

- Spreading distance is estimated to be at the order of $10^1 – 10^2 \mu m$

- Analogous to current spreading in LEDs
Summary

a) CPV is here, but so are its unique challenges

b) Tunnel diode transitions delimits the irradiance range for efficient operation

c) Many concentrator system deliver inhomogeneous flux maps

d) Tunnel diode transitions are not uniform outright phenomena

e) Pronounced dependence of $J_p$ on the degree of localized irradiation
Summary

e) True for different cell architecture, should be universally observable

f) Majority carriers spreading

g) Measurements of tunnel diode $J_P$ at uniform illumination gives a lower bound to $J_P$

h) Modeling of MJ PV cells needs to be revised to account for the spreading mechanism

i) Cell and optics design – robustness to deviations from design conditions
New aspects of tunnel diode transitions in multi-junction photovoltaic cells

A. Braun, B. Hirsch, E.A. Katz, J. M. Gordon
Department of Solar Energy & Environmental Physics, Blaustein Institutes for Desert Research, Ben-Gurion Univ. of the Negev, Sede Boqer Campus, Israel

W. Guter, A.W. Bett
Fraunhofer-Institut für Solare Energiesysteme, Freiburg, Germany

![Diagram showing current density (J_p) vs. fiber diameter (mm)]

- Lower bound for 0.2 mm fiber
- 3.14 mm² triple junction cell
- 3.14 mm² single junction cell
- 100 mm² triple junction cell

2 mm
Thank you
Tunnel diodes

- avoid p-n-p structure
- Leo Esaki (1958), Nobel prize (1973)
- Highly doped layers

- 5 to 10 nanometer thick
  - Transparent, Beer-Lambert law:
    \[ I = I_0 e^{-\alpha x} \]
  - Increased tunneling probability

Simon M. Sze
Devices, 3rd ed.
• Upper limit for the tunneling current density, $J_p$
• Above $J_p$, the tunnel diode enters a region of negative differential resistance and we move from low resistance tunneling to high resistance thermal diffusion

Tunnel diodes in solar cells

• Until now, $J_p$ was considered as a characteristic of the entire cell with no documentation about the dependence of $J_p$ on the degree of localized irradiation

• Our experimental evidence for the dependence of $J_p$ on the degree of localized irradiation

• Practical point – concentrating PV systems may have inhomogeneous flux map

Research objective

• To explore the tunnel diode characteristics of new commercial triple junction solar cells under different localized illumination patterns and search for effects of the degree of the localized irradiation on the value of $J_p$
solar cells under study

- A single junction, GaInP cell with an underlying tunnel diode
  - Produced specifically for tunnel diode assessment
  - Active area of 3.14 mm², Non-uniform metallization
  - Reported threshold just above 600 suns


• Temperature dependence of the tunnel diode $J_p$
  • 1.0mm fiber located at the center of the cell
  • Temperature range: $T=25 \rightarrow 90^C$

The cell was thermally bonded to thermoelectric controller
• $J_p$ decreased at 6% in this temperature range
• The dependence of $J_p$ on the degree of localized irradiation cannot be explained merely as a temperature effect

3-junction 3.14mm$^2$ cell using a centered 1.00mm fiber at fixed intensity
• **Tunnel diode transition dependence on the tunnel diode area**

  • Dark $I-V$ curves of isolated n-GaInP/p-GaAs tunnel diode structures with diameters of 1.4, 2.2 and 2.9 mm.
  • $J_p$ is independent of diode area (within our measurement standard deviation of ±8%).
• Explain the results for the set of measurements with different fibers where $J_p$ decreased with the increase of fibers diameters
Discussion: Majority carriers spreading

• How large is $r_{spreading}$?

\[
J_p = \frac{I_P}{\text{Effective Area}}
\]

• Redraw the graph for $J_p$ with increasing spreading distances (with degree of localized irradiation)

• Accounting for $r_{spreading}$ of up to 200 microns fully resolve $J_p$ dependence on the degree of localize irradiation
LEDs analogy

- Analogous to current spreading in LEDs
  - experimentally demonstrated current-spreading length of up to 100 microns in III-V alloys LEDs
  - LEDs with a current-spreading layer: $L_s$ decreases as $J$ is increased
  - LEDs with a current-blocking layer: $L_s$ increases with $J$


- The two modes of behavior correspond to the spreading of majority carriers in the two regimes of photovoltaic tunnel diode operation: below or above $J_p$
Temperature –

- 25 to 35 degrees above ambient for (well designed) passive cooled CPV system

- 4-6% (relative) decreasing in the efficiency in compare with 25C data, the magnitude of the degradation is decreasing with concentration

- Not worse than typical (passive cooled) flat panel
Non-uniform irradiation

- In the “one optic one cell” approach we don’t need to worry about current mismatching
- Tunnel diode maximum tunneling current increases for highly localized irradiation


24th European Photovoltaic Solar Energy Conference, Hamburg
Impact of the Thomson effect on concentrating photovoltaic cells

Nimrod Ari *

* Prof. Kribus’s research group
Tel-Aviv University
Faculty of Engineering
School of Mechanical Engineering
In collaboration with the Porter School of Environmental studies
April 2010

DOI: 10.1016/j.solmat.2010.04.004
Photovoltaic conversion

---

**Figure 1**

Electron and Current Flow in Solar Cells

- Photons
- Electrons
- n-Silicon
- p-Silicon
- Holes
- Current Flow Direction
- Positive Contact
- Negative Contact
- Electron Flow

---

Sunlight -> Photons -> n-Silicon (n-type)

- Current Flow Direction: Electron Flow
- Positive Contact

p-Silicon (p-type) -> Holes

- Current Flow Direction: "hole" flow
- Negative Contact

**Load**

---

Front contact grid

Back contact

---

**Diagram**

- Photons
- n-type
- p-type
- Front contact grid
- Back contact
- Load
- Current
- Sunlight

---

**Diagram**

- Photons
- n-type silicon
- p-type silicon
- Junction

---

**Diagram**

- Electrons
- Negative Contact
- Positive Contact
- Electron Flow
- "hole" flow
Photovoltaic systems
Cogeneration

- Concentrating Photovoltaic (CPV) + thermal (CPVT) technology
- Better overall conversion efficiency and reduction in system costs
Gap
between theory & experiment

CPV cells achieve less than theoretical efficiency

Yamaguchi 2003
Thermoelectric effects

Seebeck

Peltier
William Thomson, Lord Kelvin (1824-1907)

Scotland, Glasgow, Dec 17th, 1856

“Sir, I take the liberty... a thermal effect, reversible with the direction of the current, must be produced by a current through an unequally heated conductor...

- a convection of heat by electricity in motion.”
Thermoelectric effects

• In 1854, the thermodynamic relationship between the Seebeck and Peltier: additional heat in a conductor - Thomson heat.
CPV-module operational conditions’ illustration

\[ \nabla T \]
Analysis

\[ \dot{q} = \rho j^2 + \frac{dk}{dT} \nabla T^2 - T \frac{dS}{dT} \nabla T \cdot j \]

- Joule term
- Heat transfer term
- Thomson term

\[ -T \frac{dS}{dT} \nabla T = \rho j \]

Effective resistivity

\[ \rho_T = -T \frac{dS}{dT} \nabla T / j \]
Thomson equivalent series resistance

A new component in cell modelling!

Photocurrent generators and diodes

could either be positive or negative!
Thomson impact on conversion efficiency

Measured efficiency

\[ \eta_M = \eta_P - l_S - l_T \]
Results

• non-negligible impact that should be considered in cell modeling

• increases cell electrical conversion efficiency by: 0.22%

• comparable to typical series resistance and equivalent to a reduction in series resistance of: 18.3%

• significance increases approx in proportion to the concentration

10,000 suns ... 2.2 %
Results

• If the cell polarity were reversed: a reduction in cell efficiency of twice the amount i.e. 0.44% relative to the measured efficiency for the n-over-p cells and equivalent to an increase of 38% in series resistance.

• The Thomson effect should also be found in other high power optoelectronic devices.

• In one Si substrate LED, 0.32% loss in LED efficiency at 350K

• If the LED polarity were reversed .. an increase in LED efficiency of twice the amount i.e. 0.64%
Manipulate the effect by:

- Cell polarity
- Cell operating temperature

Detect the effect experimentally:

- Evaluate cell performance while changing \( \nabla T \) (constant conditions; control top and bottom cell temperature, etc.)
The End

Thank you.
Non-imaging optics and a novel solar concentrator

Alex Goldstein and Jeffrey M. Gordon
Dept. of Solar Energy and Environmental Physics
The Jacob Blaustein Institutes for Desert Research
Ben-Gurion University of the Negev
Sede Boqer Campus
• **Why concentrate?**
  – Economics: PV cell is most expensive element
  – Potential of higher efficiencies at higher concentration

• **But there is a physical limit to concentration of light**
Thermodynamic concentration limit for 3D systems

Examples of point-focus (3D) systems

Fundamental trade-off between acceptance angle ($\theta_{in}$) and concentration
For $\theta_{in}=4.7\text{ mrad}$ and $\theta_{out} = \pi/2$ radians in air, $C_{geom, \text{ max}} \approx 45,000$
Thermodynamic limit of concentration

- What is Etendue?

\[
E = \iiint n^2 d(Area \, A)\, d(\text{projected solid angle} \, \Omega)
\]

- For axisymmetrical systems – one (radial) positional parameter (X) and one angular parameter (P), simplifies to:

\[
E = \iint n^2 dXdP
\]
Thermodynamic limit of concentration

The area is contracted, and by etendue conservation, the angular spread must increase.

\[ E = \iiint n^2 dX dP \]
**Imaging / Non-Imaging optics**

**Fig. 1** Rays emerging from \((A(B))\) are focused on \((A'(B'))\) in an imaging system. Imaging formation is worthless in a nonimaging optical system whose goal is the maximum efficiency of light transfer. Thus, in a nonimaging system the rays emerging from \(A\) and \(B\) must impinge at any point of the interior of the target.
Advances in solar concentrator optics

1970: Classical Non-Imaging Optics (NIO)

- First time thermodynamic limit is approached at high efficiency
- Edge-ray principle: Extreme In, Extreme out

CPC Disadvantages
- High aspect ratio at high concentration
- Cannot handle gaps
Advances in solar concentrator optics

- **Aplanatic optics**
- **Double-tailored “3rd Generation” NIO**
  
  - **Large inherent gaps and reasonable aspect ratio**
    
  - Performs well only for $\theta_{in} < 20$ mrad
  
  - Higher optical tolerance $\rightarrow$ cheaper optical systems

![Diagram of Concentrator Optics](image-url)
- **New dual-mirror design method**
  - Based on the Simultaneous Method of Surfaces (SMS)
    - General numerical method (Minano & Benitez) 1992
    - Also used in many previous dual contour designs, e.g. lenses

- **Toolbox**
  - NIO’s edge-ray principle
  - Snell’s Law (Mirrors)

- **Next: Recursive Design Method**
• **Input:**
  - Design acceptance angle ($\theta_{\text{in}}$)
  - Surfaces’ starting points
  - Receiver position

• **Output:**
  - Symmetric 2D design
  - Revolve around optic axis to get axi-symmetric 3D concentrator for one-optic one-cell dual-axis tracking

In reality: 3% shading
• **Classification**

  – **Six basic classes, similar to aplanat classification (Ostromourov et al, 2009)**

  • Based on:
    – Absorber up/down facing
    – Vertices position \((s, k)\)

  • SMS contours become aplanats in the limit of small acceptance design angle (Minano & Benitez, 1997)

  • 2 physically invalid classes (Total of 8)

  – **Now: the basic classes…**
Up-facing absorber

Concentrator Optics Background

Dual Mirror Design Method

Classification Scheme

Examples of Practical Concentrators

\[ A \]
\[ s > 0, k > 0 \]

\[ B[1] \]
\[ s < 0, k < 0 \]

\[ C \]
\[ s < 0, k < 0 \]
<table>
<thead>
<tr>
<th>Concentrator Optics Background</th>
<th>Dual Mirror Design Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification Scheme</td>
<td>Examples of Practical Concentrators</td>
</tr>
</tbody>
</table>

**Down-facing absorber**

- **D**
  - \( s > 0, k > 0 \)

- **F**
  - \( s < 0, k < 0 \)

**Diagram**

- **E[1]**
  - \( s < 0, k < 0 \)

- **E[2]**
  - \( s < 0, k < 0 \)
Examples of practical concentrators

- Most promising classes for CPV applications:
  - B[2] (Wineglass) with SMS lens
  - A with terminal concentrator
Tolerance angle ($\theta_t$)

- $\theta_t$: Off-axis angle ($\theta_{\text{off axis}}$) at 90% efficiency
- CPV industry typically requires $\theta_t \geq 1$ deg

Fundamental Tolerance Limit (Gordon & Feuermann, 2008)

- $\theta_{\text{max}} = $ Largest $\theta_{\text{off axis}}$ at which 100% efficiency theoretically possible
B[2] (Wineglass) with SMS lens

Assuming realistic values for industrial CPV:

3D $C_g = 760X$

$\theta_s = 10$ mrad

$\theta_t = 1.22$ deg

Efficiency at $\theta_{max} \geq 80$

Absorber outside optic

Aspect ratio = 1.31
Class A with dielectric terminal concentrator

3D $C_g = 480X$

$\theta_s = 10 \text{ mrad}$

$\theta_t = 1.22 \text{ deg}$

Efficiency at $\theta_{\text{max}} \geq 80\%$

Absorber outside optic

Aspect ratio $= 0.27$

3% shading
Non-imaging optics and a novel solar concentrator

Alex Goldstein and Jeffrey M. Gordon
Dept. of Solar Energy and Environmental Physics
The Jacob Blaustein Institutes for Desert Research
Ben-Gurion University of the Negev
Sede Boqer Campus

Thanks to my research group: Daniel Feuermann & Natalia Ostromouev, Eugene Katz, Dotan Babai, Avi Braun, Efrat Greenwald, Baruch Hirsch, and Heylal Mashal
Vertical Solar Cells
For CPV Systems

R. Pozner\textsuperscript{1}, G. Segev\textsuperscript{1}, A. Kribus\textsuperscript{1},
R. Sarfaty\textsuperscript{2}, and Y. Rosenwaks\textsuperscript{1}

\textsuperscript{1}Tel Aviv University
\textsuperscript{2}Ort Braude College
The Vertical Junction

A) Better Optimization Capabilities

B) Tolerance For Non-uniform Illumination

C) Ideal For High Concentration
Better Optimization Capabilities
Better Optimization Capabilities

Horizontal Junction

Vertical

Collection probability independent of wavelength

Uniformly wide spectral responses

More degrees of freedom in optimization
SRH Lifetime Optimization

![Diagram showing the optimization of SRH lifetime with varying parameters such as width, AR, N+, P, P+ Contact, and H. The graph on the right illustrates the efficiency with contours of SRH lifetime in seconds across different widths.](image-url)
Bulk Doping Optimization

![Diagram showing bulk doping optimization with a 3D model and a contour plot for efficiency. The diagram illustrates the doping levels and widths, with contour lines indicating efficiency levels.]

- **Bulk Doping** [cm$^{-3}$]
  - 50
  - 100
  - 150
  - 200

- **Width** [μm]
  - 10
  - 15
  - 20
  - 100

- **Efficiency**
  - Contour plot with labels 14, 16, 18, 20
Tolerance for non-uniform illumination
CPV System

The graph shows the normalized efficiency of CPV systems with Homogenizer length [mm]. The data points indicate the performance of horizontal and vertical modules with and without Homogenizer.

- **Horizontal module + Homogenizer**
- **Vertical module + Homogenizer**
Ideal For High Concentrations
Main Resistance Components

Vertical

Horizontal
Photoconductivity

\[ \sigma(x, y) = \sigma_0(x, y) + \sigma_{ph}(x, y, C) \]

\[ \sigma_0(x, y) \ll \sigma_{ph}(x, y, C) \]

\[ \sigma \text{ changes significantly with illumination} \]

\[ \sigma_0(x, y) \gg \sigma_{ph}(x, y, C) \]

\[ \sigma \text{ hardly changes with illumination} \]
VJ under Concentrations

Efficiency [%] vs Concentration

- Amonix
- Vertical Junction
- Sun Power Chipsize cell
- Sater
Better Optimization Capabilities

Tolerance for non-uniform illumination

Ideal for concentration

Thank You
Series Resistance

\[ R_s = 20 \, \Omega \cdot \text{cm}^2 \]
The optimization of:

Single Vertical Junction  
Vertical Module  
Vertical cell for concentrations

Leads to:

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<tr>
<th></th>
<th>1sun BSR=0</th>
<th>1sun BSR=1000</th>
<th>1000suns BSR=0</th>
<th>1000suns BSR=1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSR=10</td>
<td>&gt;160</td>
<td>60-80</td>
<td>50-70</td>
<td>45-60</td>
</tr>
<tr>
<td>FSR=100</td>
<td>80-120</td>
<td>50-70</td>
<td>40-60</td>
<td>45-60</td>
</tr>
<tr>
<td>FSR=500</td>
<td>30-50</td>
<td>40-50</td>
<td>35-50</td>
<td>40-60</td>
</tr>
</tbody>
</table>
Fig. 1. Historical progress of single-crystal silicon solar cell efficiencies. The"Stanford record" (4.1% conc.) and the"Stanford" record (9.1% conc.) are encircled.

- Record Devices-2008

- Best Research-Cell Efficiencies

- Multijunction Concentrators
  - Three-junction (2-terminal, monolithic)
  - Two-junction (2-terminal, monolithic)
- Single-Junction GaAs
  - Single crystal
  - Concentrator
  - Thin film
- Crystalline Si Cells
  - Single crystal
  - Multicrystalline
  - Thin film
- Thin-Film Technologies
  - CuInGaSe2
  - CuTe
  - Amorphous Si:H (stabilized)
  - Nano- / micro-poly-Si
  - Multi-junction polycrystalline
- Emerging PV
  - Dye-sensitized cells
  - Organic cells (various technologies)
The module current output will be restricted by the least illuminated cell.
Homogenizer length [mm]

Normalized module efficiency

- Regular cell based module
- VMJ based module
(Module + Homogenizer) efficiency

Maximum power Point Voltage [V]

Normalized system efficiency

No Homogenizer
H=17.5 [mm]
H=20.9 [mm]
H=24.9 [mm]
H=35.1 [mm]
BrightSource Energy

➢ Our business:
  ▪ Developing and building utility-scale solar power plants

➢ The company:
  ▪ Headquarters in Oakland, Calif.
  ▪ R&D/Engineering in Jerusalem
  ▪ 2,610 MW in signed PPAs in California

➢ The team:
  ▪ Key managers of Luz who designed and built more than 350 MW of solar thermal plants in the 1980s
  ▪ World class project development team with over 20GW of power projects developed, constructed, and managed
How do we characterize central tower systems?
Receiver working fluid

Steam

Molten salts

commercial ↑

experimental ↓

Particle

Air

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Receiver/tower configuration

- Receiver at top of tower
- “Beam-down” to ground-level receiver
Tower and solar field size

Big

Small

Tiny
Heat cycle

Rankine cycle

Brayton cycle

Combined cycle
Also...

- Solar concentration ratio
- Temperature
- Efficiencies
- Heliostat size
- Thermal storage / Dumping ("solar multiplier")

Distribution of DNI by hours of the year

The lower the line (more heliostats added), the more hours at full capacity...
(capacity factor increases)
How do we know which is “best”?

Highest optical efficiency?
Highest thermodynamic efficiency?
Lowest capital cost per MW?
Lowest cost per kWh electricity?

It’s the one that can be financed

- Plant cost / PPA
- Technology risk – is it proven?
- Permitting risk – environmental impacts + politics + transmission
- Performance risk – reliability of equipment and insolation
- Balance sheet strength of developer and partners
Direct-Steam Towers
Solar One (1985-88)

- 10MWe direct-steam tower funded by the US DOE and built at Barstow, California
- Once-through boiler with superheater to 510°C @ 60 bar
- 90m tower, 1,818 heliostats each 40m² (total 72,650 m²)
- Turbine efficiency 30-35%
- Some low-temp thermal storage in rock/sand tanks
PS10

- 11MWe tower built by Abengoa near Seville, Spain in 2006
- Saturated steam to 250°C @ 40 bar
- Forced-circulation boiler in cavity (to reduce heat losses)
- 100m tower, 624 heliostats each 120m² (total 74,880 m²)
- Gross turbine efficiency 27%
- Some low-temp thermal storage in steam
PS20

- 20MWe tower built by Abengoa near Seville, Spain in 2009
- 160m tower, 1,255 heliostats each 120m$^2$ (total 150,600 m$^2$)
- Natural circulation drum-type boiler
- Other parameters the same as PS10
**eSolar**

- 2 X 2.5MWe (equivalent) towers at Lancaster, California
- Superheated steam to 440°C @ 40 bar
- 50m towers, 24,000 heliostats each 1.2m²
- Gross turbine efficiency ~30%
- For commercial projects, eSolar proposes a plant of 46MWe comprising 16 towers
BrightSource’s Solar Energy Development Center

- Sited on 20 acres at Rotem Industrial Park
- The largest solar energy facility in the Middle East
- Inaugurated June 2008 and operating continuously in 2009/10
BrightSource’s Solar Energy Development Center

- 6 MW thermal power – utility-quality steam at 540°C, 140 bar
- 15m forced-recirculation drum boiler + superheater atop 60m tower
- 12,000 m² total reflecting area: 1,640 heliostats, each 7.3m²
Project Scale-up

Solar Energy Development Center
2008
(6 MWth)

Solar Thermal Chevron EOR Demo Plant
2010
(29 MWth)

Ivanpah Solar Power Complex
2012
(400 MWe)
2nd-generation heliostat
## Ivanpah Solar Energy Generating System

**Ivanpah Milestones**

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>400MW PG&amp;E and SCE PPAs in place</td>
<td></td>
</tr>
<tr>
<td>Received conditional approval for $1.37B US DOE Loan Guarantee</td>
<td></td>
</tr>
<tr>
<td>Bechtel Selected as EPC contractor; equity owner in all three projects</td>
<td></td>
</tr>
<tr>
<td>123MW Siemens turbine purchased</td>
<td></td>
</tr>
<tr>
<td>CEC and BLM permitting scheduled approval for mid-2010</td>
<td></td>
</tr>
<tr>
<td>1st Plant COD scheduled for late 2012</td>
<td></td>
</tr>
<tr>
<td>Dry air-cooling system</td>
<td></td>
</tr>
</tbody>
</table>

**Ivanpah Partners**

- **Bechtel**
- **Siemens**
Efficiency Evolution – the Future of Steam

Source: Alstom
Molten Salt Towers
Solar Two

- In 1995 Solar One was converted into Solar Two
  - Molten salt receiver developed by Rocketdyne
    - Mix of 60% sodium nitrate and 40% potassium nitrate
    - Molten salt thermal energy storage loop
  - An outer ring of 108 larger 95 m² heliostats was added; altogether 1,926 heliostats with a total area of 82,750 m².
  - Produced power for SCE until decommissioning in 1999
Solar Tres

- A planned 17 MW molten salt tower in Andalusia, Spain by Torresol Energy, a joint venture between Sener and Masdar
- 2,500-2,600 heliostats, each with a reflective surface of 96 m² or 115 m²
- 115m or 130m high tower
- Salt storage of 600 MWht is supposed to allow the plant to run 24/7 during the summer months

developer's impression
SolarReserve

- Licensee of the Solar Two technology
- Filed AFC for 150MW project at Rice, California
- Up to 17,500 heliostats, or mirrors, each 64 m²
- 160m high tower + 30m high molten salt receiver
- Molten salt circulation and storage system with hot (565°C) and “cold” (290°C) salt storage tanks
- Capacity: 32,000 tons (16.7 million liters) of molten salt
Masdar/Tokyo Beam-Down Project

- UAE energy firm, Japanese oil company and Tokyo Univ. professors teaming up to build and test a 100kW beam-down system in Abu Dhabi
- 48-faceted secondary reflector
- Ground-level receiver with molten salts (?)
Air Receivers
Experimental High-Temperature Tower Systems

← Europe – CESA1

↓

Israel – Weizmann

↓

US - Sandia
Juelich

- 1.5MWe ‘commercial’ university project – solar-heated air produces steam in HRSG to run small steam turbine
- Receiver made of porous ceramic elements through which incoming ambient air flows and is heated up to 680°C.
- 2,153 heliostats each 8 m² (total 18,000 m²)
My Prognosis

- Large direct-steam towers will dominate through this decade with increasing efficiencies and lower costs.
- Molten salt towers will not be able to compete in the long run unless higher-temperature salt mixes are developed.
- Companies will migrate solar field technology (helisotats) from best optics to most cost-effective.
- Small and very small towers will have very limited market acceptance.
- High-temperature air technologies may become commercial from 2020 in order to reach higher efficiencies and compete with natural gas after solar subsidies are reduced/eliminated. Hybridization a likely option.
thank you!
TRIPLE JUNCTION PV CELL SEMI
EMPIRICAL MODEL
CPV SYSTEMS

- Multi junction cells
- Flux Concentration:
  - From tens to thousands of suns (10-1000X)
- Cell Temperature:
  - Dependent on the flux
  - Dependent on the cooling system

Required: A multi-junction cell model valid at a wide range of operating conditions
Double Diode Model

\[ J = J_{ph} - J_{0,1} \left( e^{\frac{q(V+JAR_s)}{NK}} - 1 \right) - J_{0,2} \left( e^{\frac{q(V+JAR_s)}{2NK}} - 1 \right) - \frac{V + JAR_s}{AR_{sh}} \]

- **Photo current**: Weak temperature dependency,
  \[ J_{ph} \propto C \]
- **Neutral regions diffusion currents**:
  \[ J_{01} = \kappa_1 T^3 e^{\left( \frac{E_g}{NK} \right)} \]
- **Space charge region diffusion currents**:
  \[ J_{02} = \kappa_2 T^2 e^{\left( \frac{E_g}{2NK} \right)} \]
SINGLE DIODE MODEL

\[ J = J_{ph} - J_0 \left( e^{\frac{V + JAR_s}{nKT}} - 1 \right) - \frac{V + JAR_s}{AR_{sh}} \]

Diffusion currents:
\[ J_0 = \kappa T^{(3+\gamma/2)} e^{\left( -\frac{E_g}{nKT} \right)} \]

Parasitic resistances

Leakage currents

Photo-current
MULTI-JUNCTION PV CELLS

- All Junctions are electrically connected with tunnel diodes.
- All Junctions share the same current.
- The total cell Voltage is the sum of junction voltages.

The cell can be modeled by 3 junctions connected in series.
SINGLE DIODE MODEL

Model parameters:
\( \kappa_1, \kappa_2, \kappa_3, n_1, n_2, n_3, R_s \)

\[
J = J_{ph,i} - J_{0,i} \left( e^{\frac{V_i + JAR_{s,i}}{n_iKT}} - 1 \right) - \frac{V_i + JAR_{s,i}}{AR_{sh,i}}
\]

\[
J_{0,i} = \kappa T^{(3+\gamma_i/2)} e^{-\frac{E_{g,i}}{n_iKT}}
\]

\[
V = \sum_{i=1}^{3} V_i
\]

\( J_{ph,i} \)
**DOUBLE DIODE MODEL**

\[ J = J_{ph} - J_{0,1} \left( e^\frac{V + JAR_s}{KT} - 1 \right) - J_{0,2} \left( e^\frac{V + JAR_s}{2KT} - 1 \right) - \frac{V + JAR_s}{AR_{sh}} \]

The models’ parameters were calibrated according to published data.

\[ V = \sum_{i=1}^{3} V_i \]

Model parameters:
\[ \kappa_{1,1}, \kappa_{1,2}, \kappa_{2,1}, \kappa_{2,2}, \kappa_{3,1}, \kappa_{3,2}, R_s \]
RESULTS-SHARP SINGLE DIODE MODEL

Offset → Error in dark currents

Error in gradient → Error in temperature dependency

---

**Graphs:**
- **Left Graph:**
  - Title: Temperature [°C] vs. $V_{oc}$ [V]
  - Legend:
    - Exp, C=1
    - Exp, C=17
    - Exp, C=200
    - Model, C=1
    - Model, C=17
    - Model, C=200
- **Right Graph:**
  - Title: Temperature [°C] vs. Efficiency [%]
  - Legend:
    - Exp, C=1
    - Exp, C=17
    - Exp, C=200
    - Model, C=1
    - Model, C=17
    - Model, C=200
RESULTS-C1MJ SINGLE DIODE MODEL

![Graph showing temperature vs. Voc and concentration vs. Efficiency]

Offset $\rightarrow$ Error in dark currents
RESULTS- SHARP 2 DIODE MODEL

No offset → accurate dark currents

Reduced temperature dependency error
RESULTS - C1MJ 2 DIODE MODEL

Offset→ One set of parameters can’t describe dark currents under a wide range of concentrations.
## DISCUSSION

### Model RMS Errors:

<table>
<thead>
<tr>
<th></th>
<th>Sharp $V_{oc}$</th>
<th>C1MJ $V_{oc}$</th>
<th>$\eta$ Sharp</th>
<th>$\eta$ C1MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Diode Model</strong></td>
<td>88mV</td>
<td>90mV</td>
<td>0.8%</td>
<td>0.64%</td>
</tr>
<tr>
<td><strong>Two Diodes model</strong></td>
<td>13mV</td>
<td>54mV</td>
<td>0.36%</td>
<td>0.44%</td>
</tr>
</tbody>
</table>

- There is an error in the dark currents when the same parameters are used for a wide range of concentrations.
- The error at the efficiency’s temperature dependency increases at high concentration.

$n(C)$ - account for various recombination mechanisms

$R_s(T)$ - account for temperature variance of metal resistivity and mobility
CONCLUSIONS

- The two diodes model has shown superior performance for all measurements (at the price of increased calculation complexity).
- Dark currents are accurately calculated only under a restricted range of flux concentrations.
- An adjustment should be made in order to better model the efficiency’s temperature dependency.
THANK YOU!
Kaleidoscope Homogenizers in Partly Shaded Parabolic Dishes

Yosef Meller

Jasmine Florentine

Abraham Kribus

Tel Aviv University, School of Mechanical Engineering
Solar Energy Lab
A Girl With Kaleidoscope Eye

No Homogenizer

- Ungood for thermal receivers
- Doubleplus ungood for PV

Two folds

One fold
The A- and B-Planes

- 3D View of the folds
- Farther tile - more reflections

Top view of dish, with reflection zones

Chen et al. 1963
Ray Tracing Simulation

• Iteratively track rays by the laws of reflection

• Perfect optics: no absorption, specular reflection

• 100,000 x 100 rays

Homogeniety measures:

Normalized standard deviation

\[
\text{std} = \frac{1000\sigma}{I}
\]

Normalized greatest difference

\[
\frac{\text{max} - \text{min}}{\text{average}}
\]
- Circular aperture more homogenous,

- Except when it's not...

- Optima change with dish aperture.

Kreske, K. 2002
PV Array Resolution (Bins)

- Little effect on normed standard deviation
- Large effect on normed greatest difference
Shadow

- In short homogenizers, less shading always better.
- As relative length increases, multimodal curves.
- Optima move with shade.
- At offset $<0.4D$, all bets are off.
Rotation Matters
Shadow Shape

Shadow area – poor predictor of homogeniety
• Shadow area insufficient for predicting performance in CPV
• Less cells in array is better (less bins)

With 3J cells, mismatch/bypass will happen:
• Even for relatively low shading
• Even for relatively long homogenizers
Tracer

- Python package for ray tracing
- Produce flux maps or whatever you can program
- Several models already in
“Free" as in:
• Free beer
• Free speech (Copyleft)

That's just science:
• Peer review
• “Shoulders of giants"

Python:
• Science capabilities much like Matlab
• General programming tasks so much easier
• Easy to learn
• Very popular outside scientific world

Check it out, Join the effort:
http://tracer.berlios.de