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2.626 Fundamentals of Photovoltaics
Fall 2008

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Efficiency Limits and Loss Mechanisms

Lecture 16 – 2.626

Tonio Buonassisi

PV Conferences – One of the Best Ways to Disseminate Your Research

- **IEEE Photovoltaics Specialists Conference (IEEE-PVSC): Philadelphia, PA**
  - Conference Dates: June 7-12, 2009
  - Abstract deadline: January 14, 2009
  - http://www.34pvsc.org/
  - Be sure to sign up for Tutorials!
- **European Photovoltaics Solar Energy Conference (EU-PVSEC): Hamburg, Germany**
  - Conference Dates: September 21-25, 2009
  - Abstract deadline: January 30, 2009
  - http://www.photovoltaic-conference.com/

23rd EU-PVSEC at a glance

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http://www.photovoltaic-conference.com/fileadmin/template/res/pics/01_conference/23rd/programme/80410-Outline_Valencia_mit_Codes_WEB.pdf

Topics of Today's Lecture

- Optical losses, recombination losses, surface recombination velocity, series and parallel resistance (shunts).
- Evaluation of loss mechanisms, common characterization tools.
- Efficiency loss mechanisms.
- Theoretical efficiency limits.
- Specific loss mechanisms in each technology class.

Spectrally-Resolved Laser Beam Induced Current (SR-LBIC)

Image removed due to copyright restrictions. Please see http://www.isfh.de/institut_solarforschung/media/sr_lbic_messplatz_1.jpg

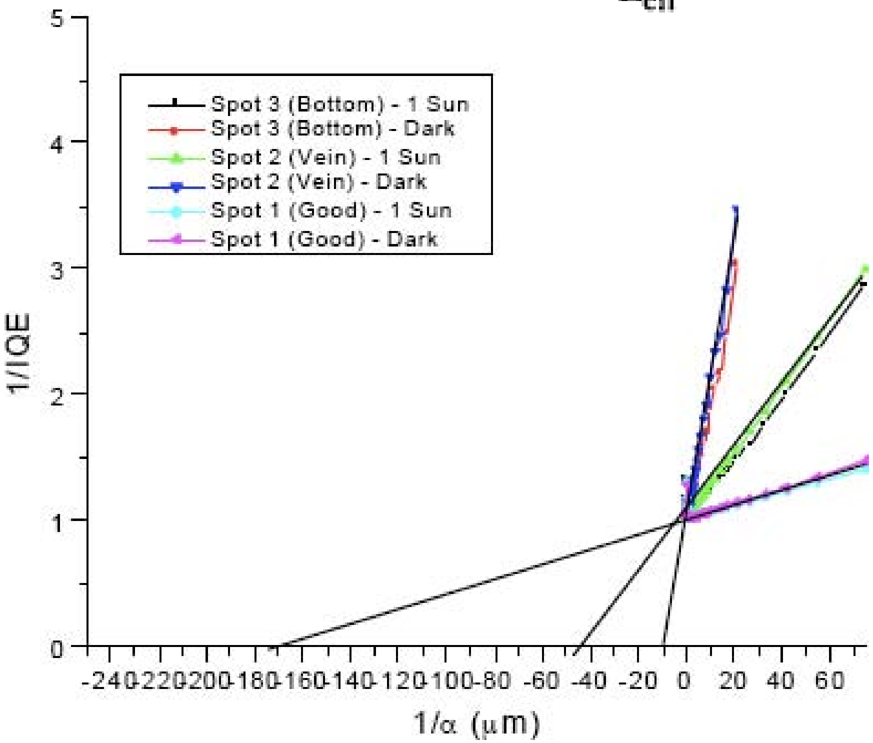
- 4 or more lasers measure IQE(λ).
- Digital processing of data extracts relevant device parameters.
- XY stage moves sample.
- A 2D map of IQE obtained!
- In advanced versions, all lasers fire simultaneously (as they are pulsed at different frequencies) into a fibre optic cable. FFT of the current signal decouples different wavelengths.

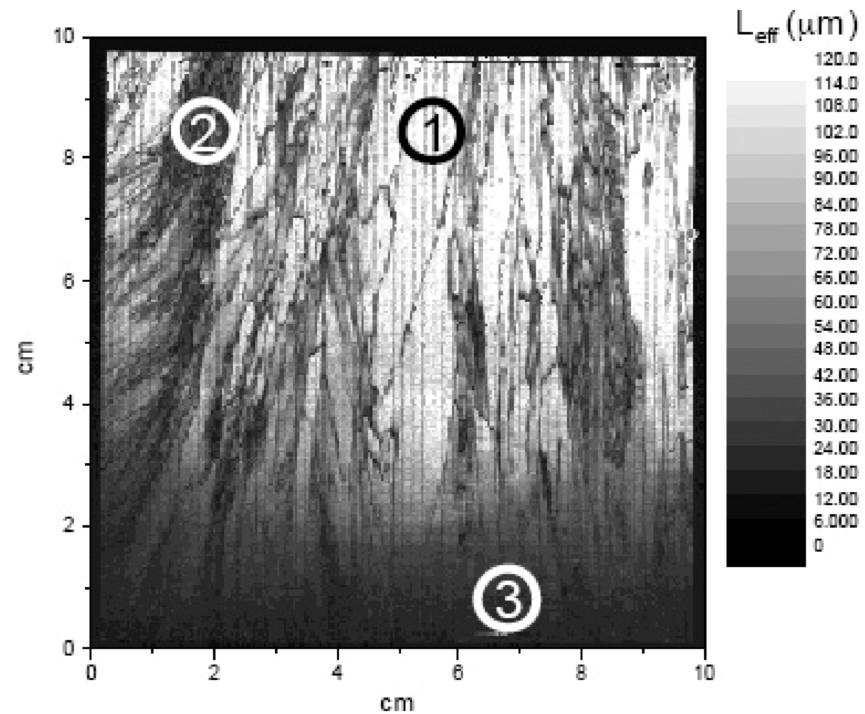
Minority Carrier Diffusion Length

At each point…

Mapped over an entire sample…

$$IQE^{-1} = 1 + \alpha^{-1}\frac{\cos\theta}{L_{eff}}$$





See: P. A. Basore, *IEEE Trans. Electron. Dev.* **37**, 337 (1990).

Lock-in Thermography

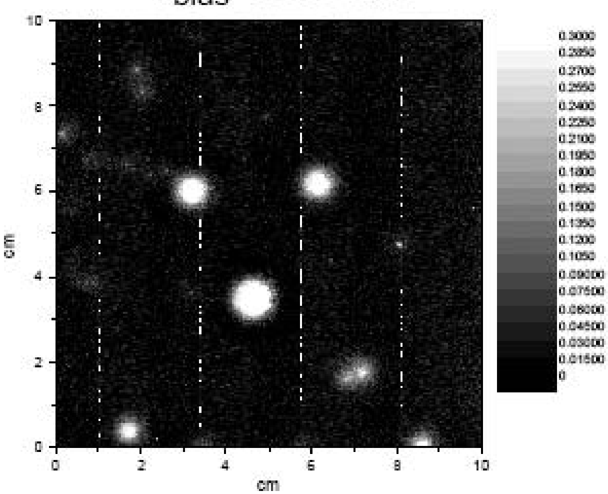
Image removed due to copyright restrictions. Please see Fig. 1 in Kaes, M., et al. "Light-modulated Lock-in Thermography for Photosensitive pn-Structures and Solar Cells." *Progress in Photovoltaics: Research and Applications* 12 (2004): 355-363.

M. Kaes et al., *Prog. Photovolt.* **12**, 355 (2004)
J. Isenberg and W. Warta, *Prog. Photovolt*. **12**, 339 (2004)
O Breitenstein et al., *Solar Energy Mater. Solar Cells* **65**, 55 (2001)

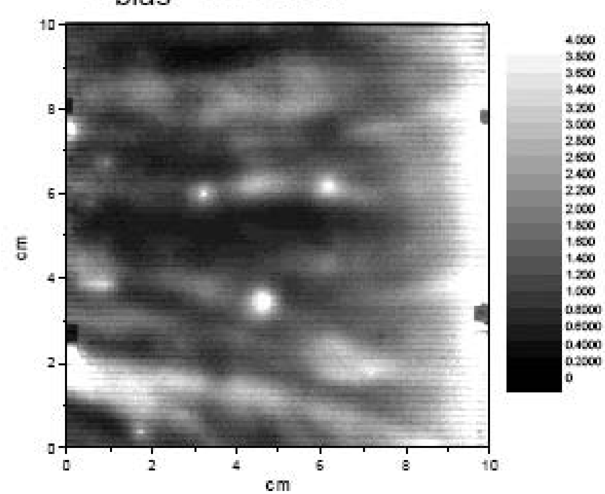
Lock-in Thermography – Imaging Losses

$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right) - \frac{V+JR_s}{R_{shunt}}$$

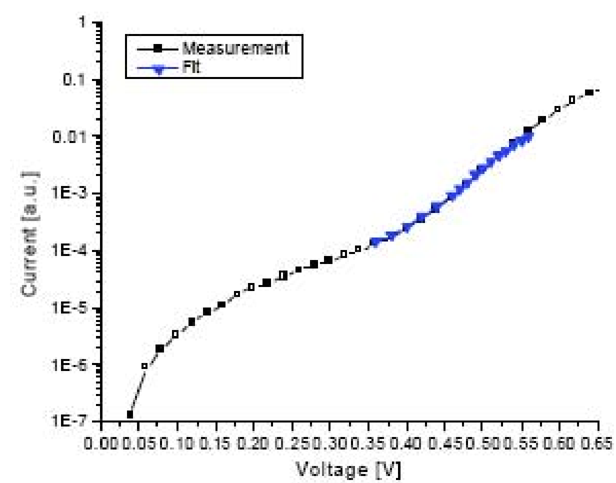
a) Lock in Thermography V_{bias}=360 mV



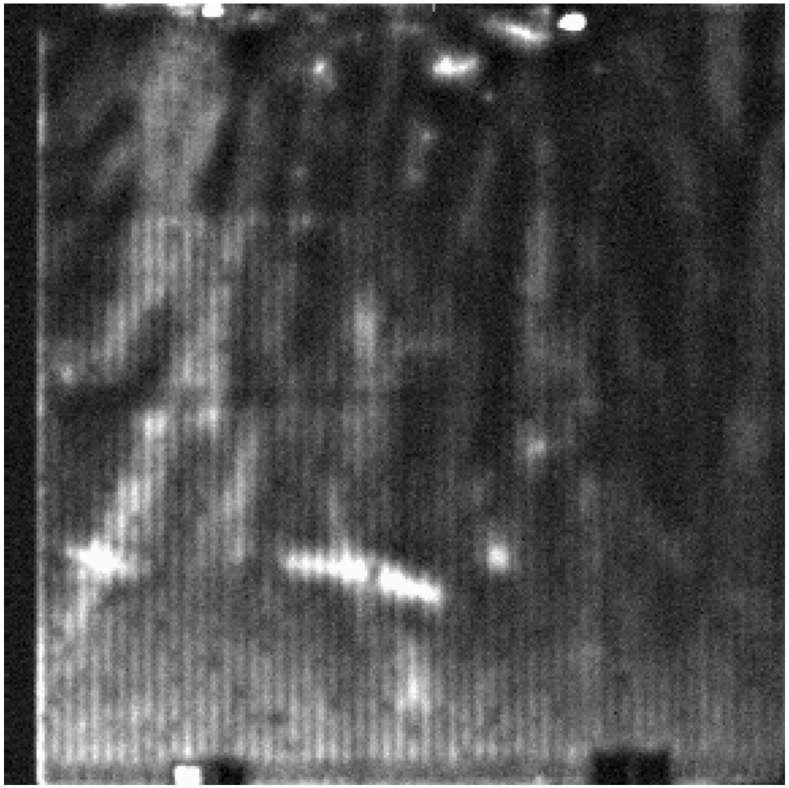
b) Lock in Thermography V_{bias}=560 mV



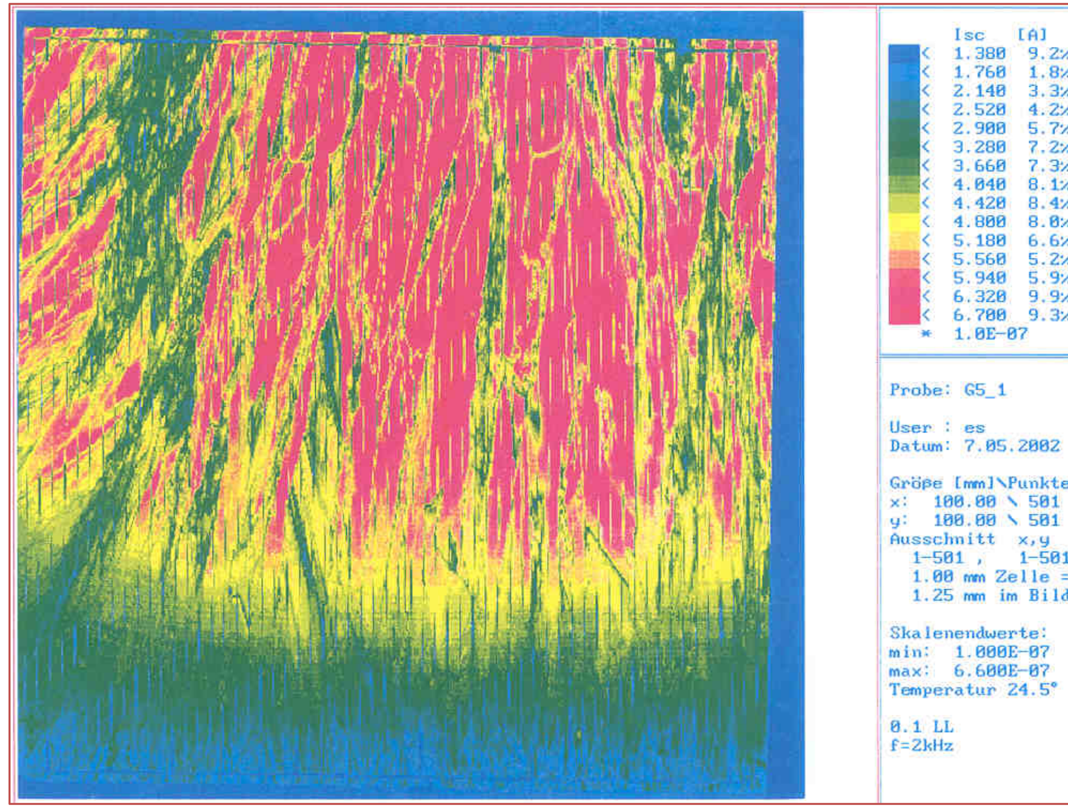
c) Dark IV Curve Fitting



Correlation between Thermography and LBIC



525mV Forward Biased
(V_{oc} = 571mV)
8Hz, 2hour scan, (30000 Frames)



White-light LBIC
(essentially probes the bulk, below the emitter)

Ideal Diode Equation Revisited

$$J = J_0\left(\exp\left(qV / nkT\right) - 1\right) - J_{sc}$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

$$I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A}\cdot\frac{S_h\cosh\left(W_N/L_h\right) + D_h/L_h\sinh\left(W_N/L_h\right)}{D_h/L_h\cosh\left(W_N/L_h\right) + S_h\sinh\left(W_N/L_h\right)} + \frac{qD_h n_i^2}{L_h N_D}\cdot\frac{S_e\cosh\left(W_P/L_e\right) + D_e/L_e\sinh\left(W_P/L_e\right)}{D_e/L_e\cosh\left(W_P/L_e\right) + S_e\sinh\left(W_P/L_e\right)}\right)$$

Note: J is current density A/cm^2, I is current.

Cheaper Methods of Shunt Detection:

Liquid Crystal Thermochromic Sheets

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http://www.tep.org.uk/FMimages/Smart%20modules/DSCN0739.jpg

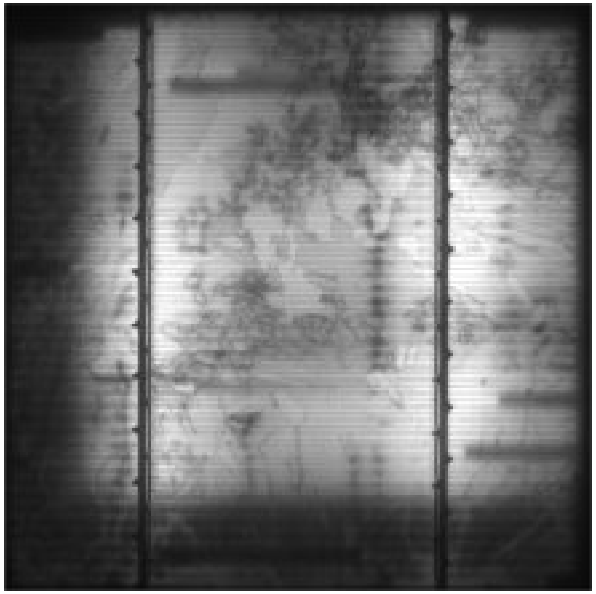
See: "Shunt imaging in solar cells using low cost commercial liquid crystal sheets" C. Ballif *et al*., *Proc. IEEE Photovoltaic Specialists Conference*, 2002, pp. 446- 449.

Electroluminescence

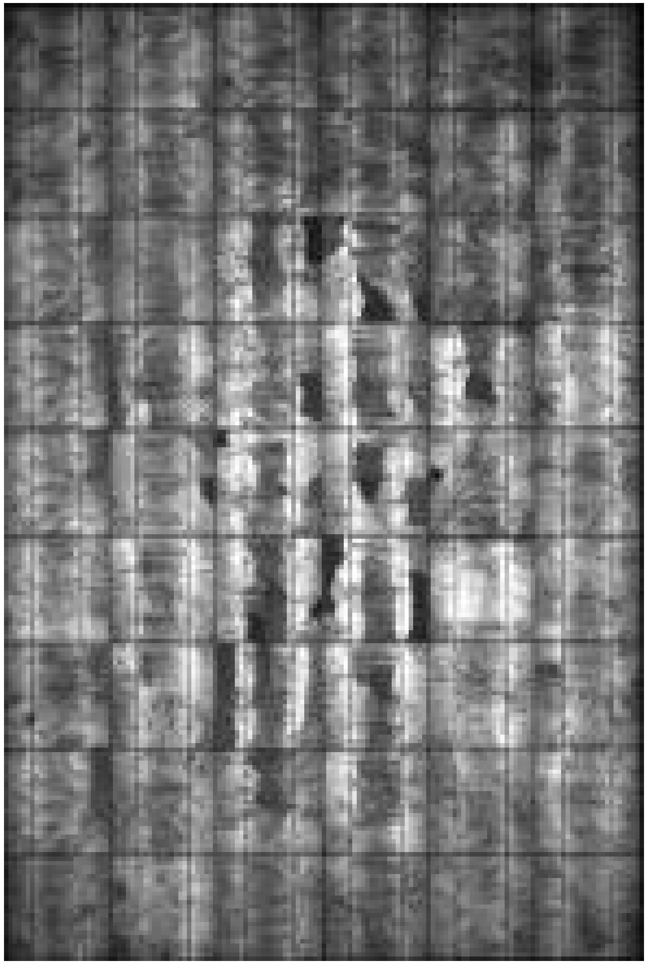
Image remove due to copyright restrictions. Please see http://ipw.naist.jp/international/siliconvalley.files/image003.jpg.

Electroluminescence

Cell



Module



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Evolution of IR Imaging Techniques

Image and text removed due to copyright restrictions. Please see Fig. 1 and Table 1 in Kasemann, M., et al. “Progress in Silicon Solar Cell Characterization with Infrared Imaging Methods.” *Proceedings of the 23rd European Photovoltaic Solar Energy Conference* (2008): 965-973.

Evolution of IR Imaging Techniques

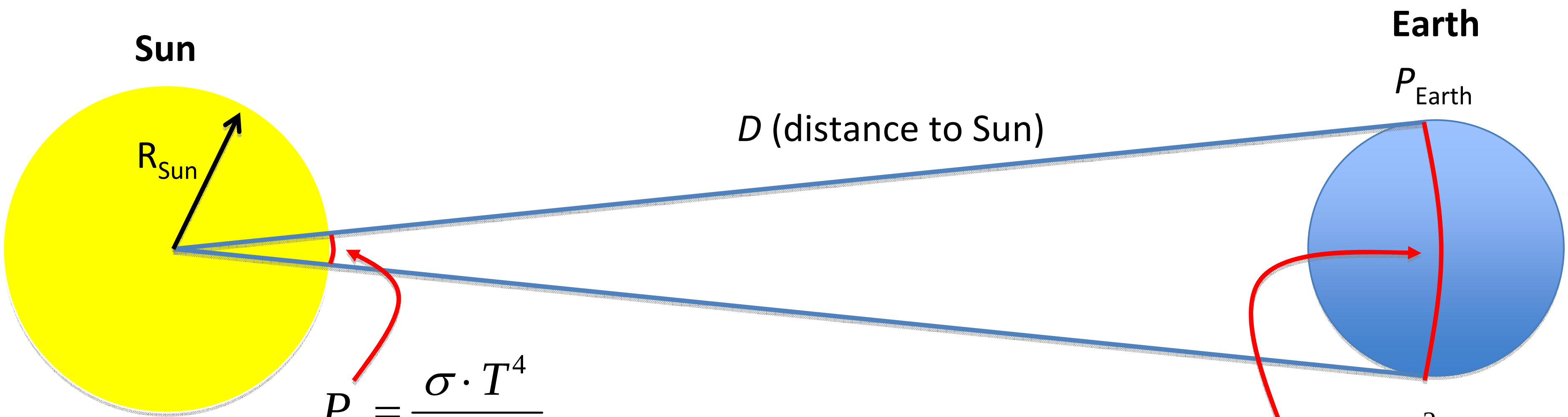
…and the kitchen sink!

Theoretical Efficiency Limits

- History of Efficiency Limit Calculations
- “Modern” Efficiency Limit Calculations

Blackbody Limit

not to scale!



$$P_o = \frac{\sigma \cdot T^4}{4\pi R_{sun}^2}$$

$$P_{\text{Earth}} = \frac{R_{Sun}^2}{D^2} P_o$$

T_{Sun} = ~6000 K

T_{Earth} = ~300 K

Light Absorption

First Paper: Prince

Key contribution: Efficiency in a single-junction device varies as a function of bandgap.

JOURNAL OF APPLIED PHYSICS VOLUME 26, NUMBER 5 MAY, 1955

Silicon Solar Energy Converters

M. B. PRINCE
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey

(Received August 12, 1954)

Theory is given for the design of silicon solar energy converters commonly known as the Bell Solar Battery. Values are given for the various parameters in the design theory. Experimental data are presented and compared with the theoretical relations based on a simple model.

It is found that with present techniques, units can be made with up to 6 percent efficiency in the conversion of solar radiant energy to electrical energy. An important factor in obtaining such high efficiencies is the reduction of the series resistance of the cell to as low a value as possible.

First Power Conversion Efficiency Calculations

Image removed due to copyright restrictions. Please see Fig. 2 in Prince, M. B. "Silicon Solar Energy Converters." *Journal of Applied Physics* 26 (1955): 534-540.

Detailed Balance

Seminal Paper: Shockley-Queisser efficiency limit

Key contribution: "Detailed balance limit": Light absorption is balanced (counteracted) by radiative recombination.

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_c of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and f_c 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 $f_c = 1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.

Detailed Balance

Image removed due to copyright restrictions. Please see Fig. 3 in Shockley, William, and Hans J. Queisser. “Detailed Balance Limit of Efficiency of p-n Junction Solar Cells.” *Journal of Applied Physics* 32 (1961): 510-519.

W. Shockley and H.J. Queisser, *J. Appl. Phys.* **32**, 510 (1961)

Detailed Balance

Image removed due to copyright restrictions. Please see Fig. 6 in Shockley, William, and Hans J. Queisser. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells." *Journal of Applied Physics* 32 (1961): 510-519.

W. Shockley and H.J. Queisser, *J. Appl. Phys.* **32**, 510 (1961)

Approaching the Limit

Image removed due to copyright restrictions. Please see Fig. 1 in Swanson, Richard M. "Approaching the 29% Limit Efficiency of Silicon Solar Cells." *Proceedings of the 31st IEEE Photovoltaic Specialists Conference* (2005): 889-894.

APPROACHING THE 29% LIMIT EFFICIENCY OF SILICON SOLAR CELLS

Richard M. Swanson, Proc. IEEE PVSC (2005).

Realistic Limit for c-Si

Image removed due to copyright restrictions. Please see Fig. 4 in Swanson, Richard M. "Approaching the 29% Limit Efficiency of Silicon Solar Cells." *Proceedings of the 31st IEEE Photovoltaic Specialists Conference* (2005): 889-894.

APPROACHING THE 29% LIMIT…
Richard M. Swanson, Proc. IEEE PVSC (2005).

Loss Mechanisms Visualized

Image removed due to copyright restrictions. Please see Fig. 5 in Swanson, Richard M. “Developments in Silicon Solar Cells.” *Proceedings of the IEEE International Electron Devices Meeting* (2007): 359-362.

Richard M. Swanson (SunPower)

Gap Between (Lab Record) Cells and (Commercial) Modules

Image removed due to copyright restrictions. Please see Fig. 6 in Swanson, Richard M. “Developments in Silicon Solar Cells.” *Proceedings of the IEEE International Electron Devices Meeting* (2007): 359-362.

Richard M. Swanson (SunPower)

Good Resource

- *Theoretical Limits of Photovoltaic Conversion*

  By Antonio Luque and Antonio Martí

  in "Handbook of Photovoltaic Science and Engineering", online at http://www.knovel.com/

Discussion about Specific Loss Mechanisms for Each Technology Class

- Crystalline Silicon
- Thin Film
- Emerging Technologies

Take-Home Examination

- ***Individual effort!***
- Due in class Thursday, November 13th.