PV Efficiency: Measurement & Theoretical Limits

Lecture 14 – 10/27/2011

MIT Fundamentals of Photovoltaics 2.626/2.627

Prof. Tonio Buonassisi

Motivation

1. Efficiency is a strong determining factor of cost.
2. Efficiency is tricky to measure accurately.
3. Several new technologies attempt to overcome fundamental efficiency limits of solar cells.

Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.

Key Concepts:

Updated record cell and module efficiency tables are published every six months, in the journal "Progress in Photovoltaics."
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-159X

Ref to latest version of "Efficiency Tables":

M.A. Green *et al.*, "Solar cell efficiency tables (version 38)," *Progress in Photovoltaics* **19**, 565-572 (2011)

Sample Solar Cell Efficiency Tables

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification[a]	Effic.[b] (%)	Area[c] (cm2)	V_{oc} (V)	J_{sc} (mA/cm2)	FF[d] (%)	Test Centre[e] (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[f]	82.8	Sandia (3/99)[g]	UNSW PERL [13]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[g]	FhG-ISE [14]
Si (thin film transfer)	**19.1 ± 0.4**	**3.983 (ap)**	**0.650**	**37.8**[h]	**77.6**	**FhG-ISE (2/11)**	**ISFH (43 μm thick)** [4]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492[i]	29.7[i]	72.1	FhG-ISE (8/07)[g]	CSG Solar (1–2 μm on glass; 20 cells) [15]
III–V cells							
GaAs (thin film)	**28.1 ± 0.8**	**0.998 (ap)**	**1.111**	**29.4**[h]	**85.9**	**NREL (3/11)**	**Alta Devices** [5]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[g]	RTI, Ge substrate [16]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[g]	Spire, epitaxial [17]
Thin film chalcogenide							
CIGS (cell)	19.6 ± 0.6[j]	0.996 (ap)	0.713	34.8[k]	79.2	NREL (4/09)	NREL, CIGS on glass [18]
CIGS (submodule)	16.7 ± 0.4	16.0 (ap)	0.661[i]	33.6[i]	75.1	FhG-ISE (3/00)[g]	U. Uppsala, 4 serial cells [19]
CdTe (cell)	16.7 ± 0.5[j]	1.032 (ap)	0.845	26.1	75.5	NREL (9/01)[g]	NREL, mesa on glass [20]
Amorphous/nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3[j]	1.036 (ap)	0.886	16.75[f]	67.0	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [21]
Si (nanocrystalline)	10.1 ± 0.2[m]	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [22]
Photochemical							
Dye-sensitized	**10.9 ± 0.3**[n]	**1.008(da)**	**0.736**	**21.7**[h]	**68.0**	**AIST (1/11)**	**Sharp** [6]
Dye-sensitized (submodule)	9.9 ± 0.4[n]	17.11 (ap)	0.719[i]	19.4[i,k]	71.4	AIST (8/10)	Sony, eight parallel cells [23]
Organic							
Organic polymer	8.3 ± 0.3[n]	1.031 (ap)	0.816	14.46[k]	70.2	NREL (11/10)	Konarka [24]
Organic (submodule)	3.5 ± 0.3[n]	208.4 (ap)	8.620	0.847	48.3	NREL (7/09)	Solarmer [25]
Multijunction devices							
GaInP/GaAs/Ge	32.0 ± 1.5[m]	3.989(t)	2.622	14.37	85.0	NREL (1/03)	Spectrolab (monolithic)
GaAs/CIS (thin film)	25.8 ± 1.3[m]	4.00 (t)	–	–	–	NREL (11/89)	Kopin/Boeing (four terminal) [26]
a-Si/nc-Si/nc-Si (thin film)	**12.4 ± 0.7**[o]	**1.050 (ap)**	**1.936**	**8.96**	**71.5**	**NREL (3/11)**	**United Solar** [7]
a-Si/nc-Si (thin film cell)	11.9 ± 0.8[p]	1.227(ap)	1.346	12.92[k]	68.5	NREL (8/10)	Oerlikon Solar Lab, Neuchatel [27]
a-Si/nc-Si (thin film submodule)	11.7 ± 0.4[m,q]	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka (thin film) [28]
Organic (two-cell tandem)	8.3 ± 0.3[n]	1.087 (ap)	1.733	8.03[k]	59.5	FhG-ISE (10/10)	Heliatek [29]

[a] CIGS, CuInGaSe2; a-Si, amorphous silicon/hydrogen alloy.
[b] Effic., efficiency.
[c] (ap), aperture area; (t), total area; (da), designated illumination area.
[d] FF, fill factor.
[e] FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; JQA, Japan Quality Assurance; AIST, Japanese National Institute of Advanced Industrial Science and Technology.
[f] Spectral response reported in Version 36 of these Tables.
[g] Recalibrated from original measurement.
[h] Spectral response and current-voltage curve reported in present version of these Tables.
[i] Reported on a "per cell" basis.
[j] Not measured at an external laboratory.
[k] Spectral response reported in Version 37 of these Tables.

Source: Green, M., K. Emery, et al. "Solar Cell Efficiency Tables (Version 38)." *Progress in Photovoltaics: Research and Applications* 19 (2011): 565-72.

M.A. Green, *Prog. Photovolt: Res. Appl*. **19** (2011) 565

Module Efficiency Tables

Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification[a]	Effic.[b] (%)	Area[c] (cm2)	V_{oc} (V)	I_{sc} (A)	FF[d] (%)	Test Centre (and date)	Description
Si (crystalline)	22.9 ± 0.6	778 (da)	5.60	3.97	80.3	Sandia (9/96)[e]	UNSW/Gochermann [32]
Si (large crystalline)	21.4 ± 0.6	15780 (ap)	68.6	6.293	78.4	NREL (10/09)	SunPower [33]
Si (multicrystalline)	**17.8 ± 0.4**	**14920 (ap)**	**38.86**	**9.04**[f]	**75.7**	**ESTI (2/11)**	**Q-Cells (60 serial cells)** [8]
Si (thin-film polycrystalline)	8.2 ± 0.2	661(ap)	25.0	0.320	68.0	Sandia (7/02)[e]	Pacific Solar (1–2 μm on glass) [34]
GaAs (crystalline)	**21.1 ± 0.6**	**921 (ap)**	**12.69**	**1.98**[f]	**77.1**	**NREL (4/11)**	**Alta Devices** [5]
CIGS	15.7 ± 0.5	9703 (ap)	28.24	7.254[g]	72.5	NREL (11/10)	Miasole [35]
CIGSS (Cd free)	13.5 ± 0.7	3459 (ap)	31.2	2.18	68.9	NREL (8/02)[e]	Showa Shell [36]
CdTe	**12.8 ± 0.4**	**6687 (ap)**	**94.1**	**1.27**	**71.4**	**NREL (1/11)**	**PrimeStar monolithic** [9]
a-Si/a-SiGe/a-SiGe (tandem)	10.4 ± 0.5[h,i]	905 (ap)	4.353	3.285	66.0	NREL (10/98)[e]	USSC [37]

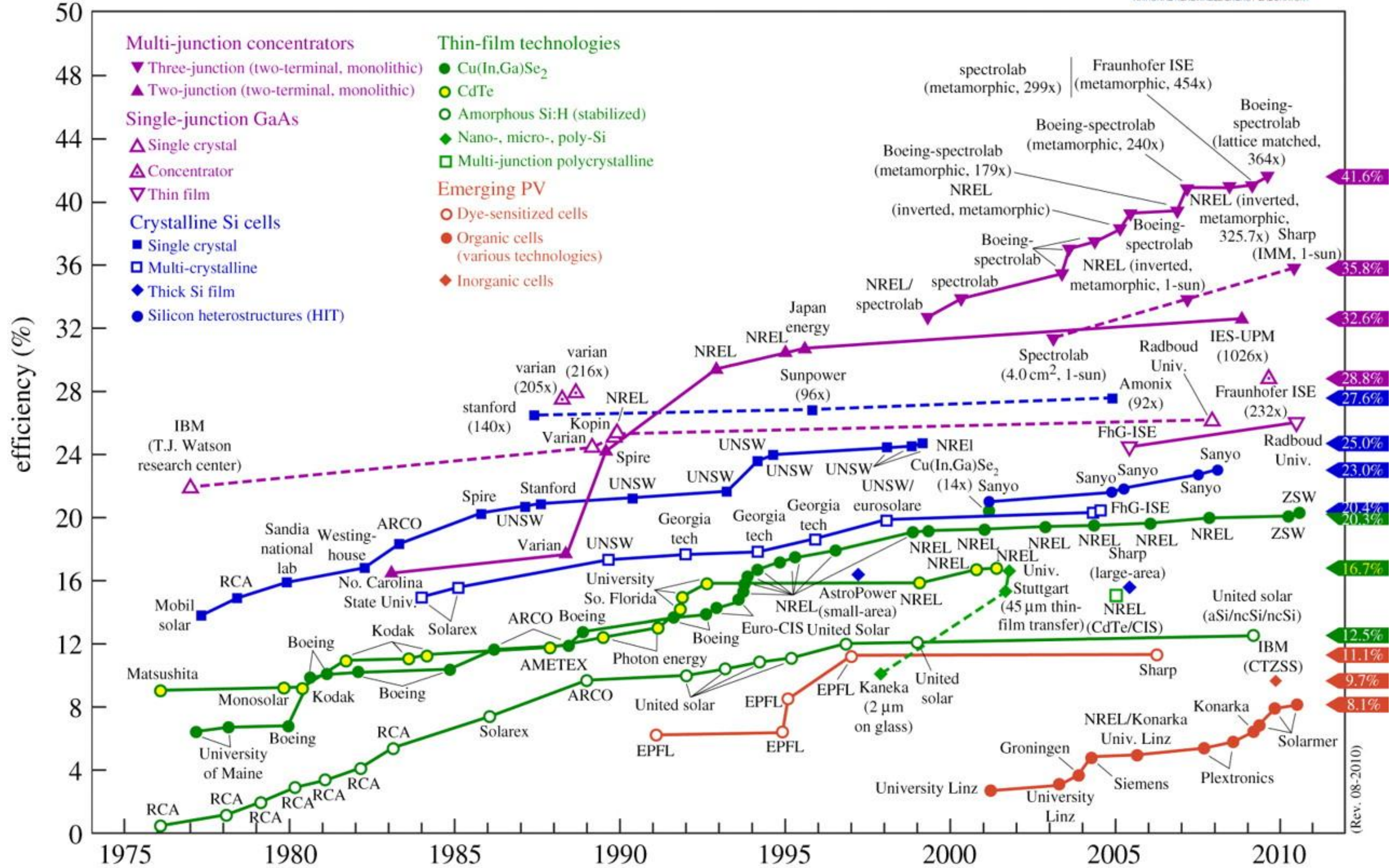
[a] CIGSS, CuInGaSSe; a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy.
[b] Effic., efficiency.
[c] (ap), aperture area; (da), designated illumination area.
[d] FF, fill factor.
[e] Recalibrated from original measurement.
[f] Spectral response and current–voltage curve reported in present version of these Tables.
[g] Spectral response reported in Version 37 of these Tables.
[h] Light soaked at NREL for 1000 h at 50°C, nominally 1-sun illumination.
[i] Measured under IEC 60904-3 Ed. 1: 1989 reference spectrum.

Source: Green, M., K. Emery, et al. "Solar Cell Efficiency Tables (Version 38)." *Progress in Photovoltaics: Research and Applications* 19 (2011): 565-72.

Record module efficiencies typically 2–7% lower than record cell

M.A. Green, *Prog. Photovolt: Res. Appl*. **19** (2011) 565

Record laboratory efficiencies of various materials



Old version referenced at: L.L. Kazmerski, Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

NOTE: These are <u>record cell efficiencies</u> under <u>ideal conditions</u> (25° C, ~1000 W/m^2)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.

Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
    - Blackbody (heat engine) limit
    - Detailed balance model
    - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.

Where to find it?

Please see the lecture 14 video to see Prof. Buonassisi explaining how to use NREL's Solar Spectra website (linked to below).

http://rredc.nrel.gov/solar/spectra/

ASTM G173-03

The receiving surface is defined in the standards as an inclined plane at 37° tilt toward the equator, facing the sun (i.e., the surface normal points to the sun, at an elevation of 41.81° above the horizon)

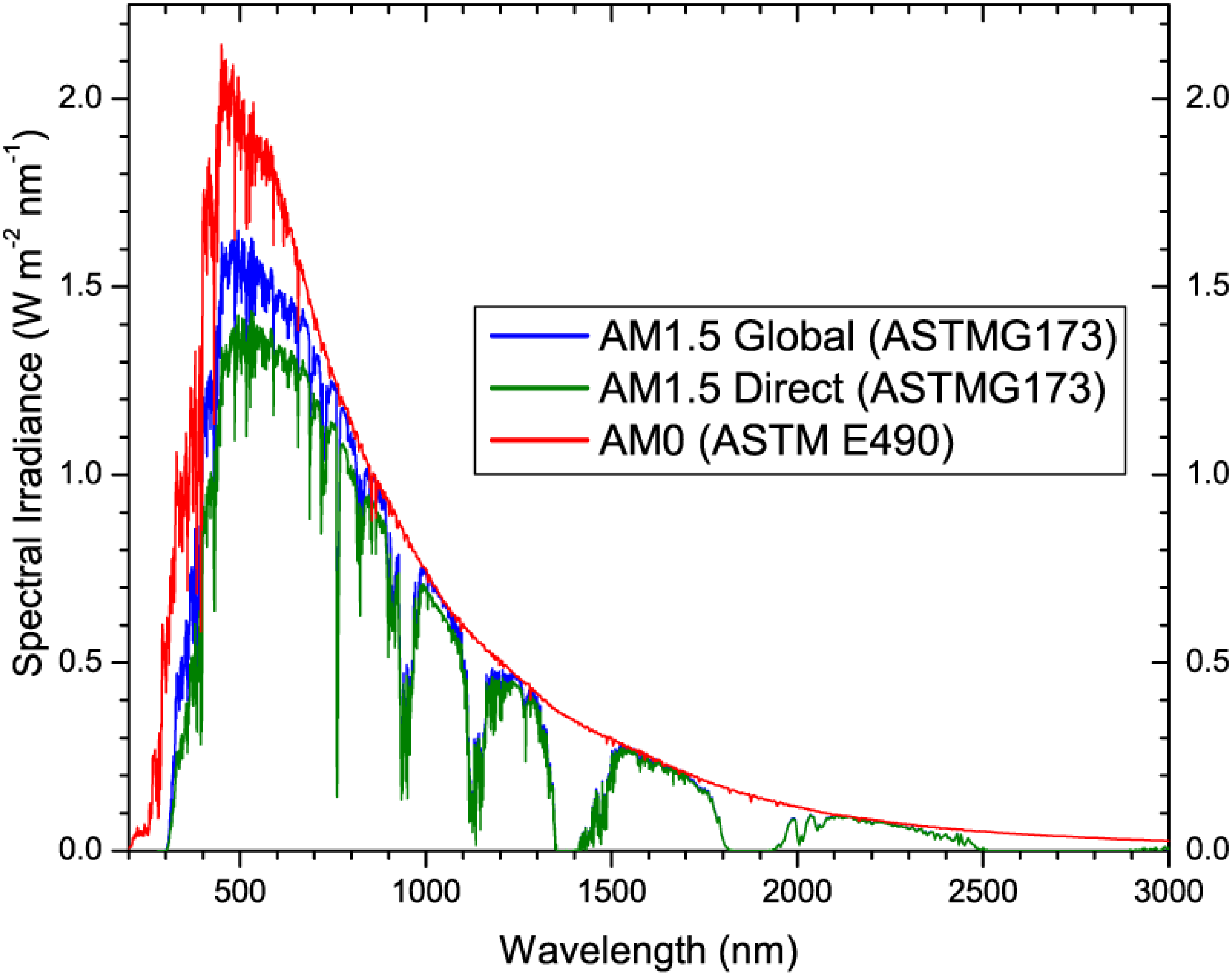
The specified atmospheric conditions are:

a) the 1976 U.S. Standard Atmosphere b with temperature, pressure, aerosol density (rural aerosol loading), air density, molecular species density specified in 33 layers

b) an absolute air mass of 1.5 (solar zenith angle 48.19° s)
c) Angstrom turbidity (base e) at 500 nm of 0.084 c
d) total column water vapor equivalent of 1.42 cm
e) total column ozone equivalent of 0.34 cm
f) surface spectral albedo (reflectivity) of Light Soil as documented in the Jet Propulaion Laboratory ASTER Spectral Reflectance Database (http://speclib.jpl.nasa.gov.)

Source: http://rredc.nrel.gov/solar/spectra/am1.5/

Standard Solar Spectra



Courtesy of PVCDROM. Used with permission.

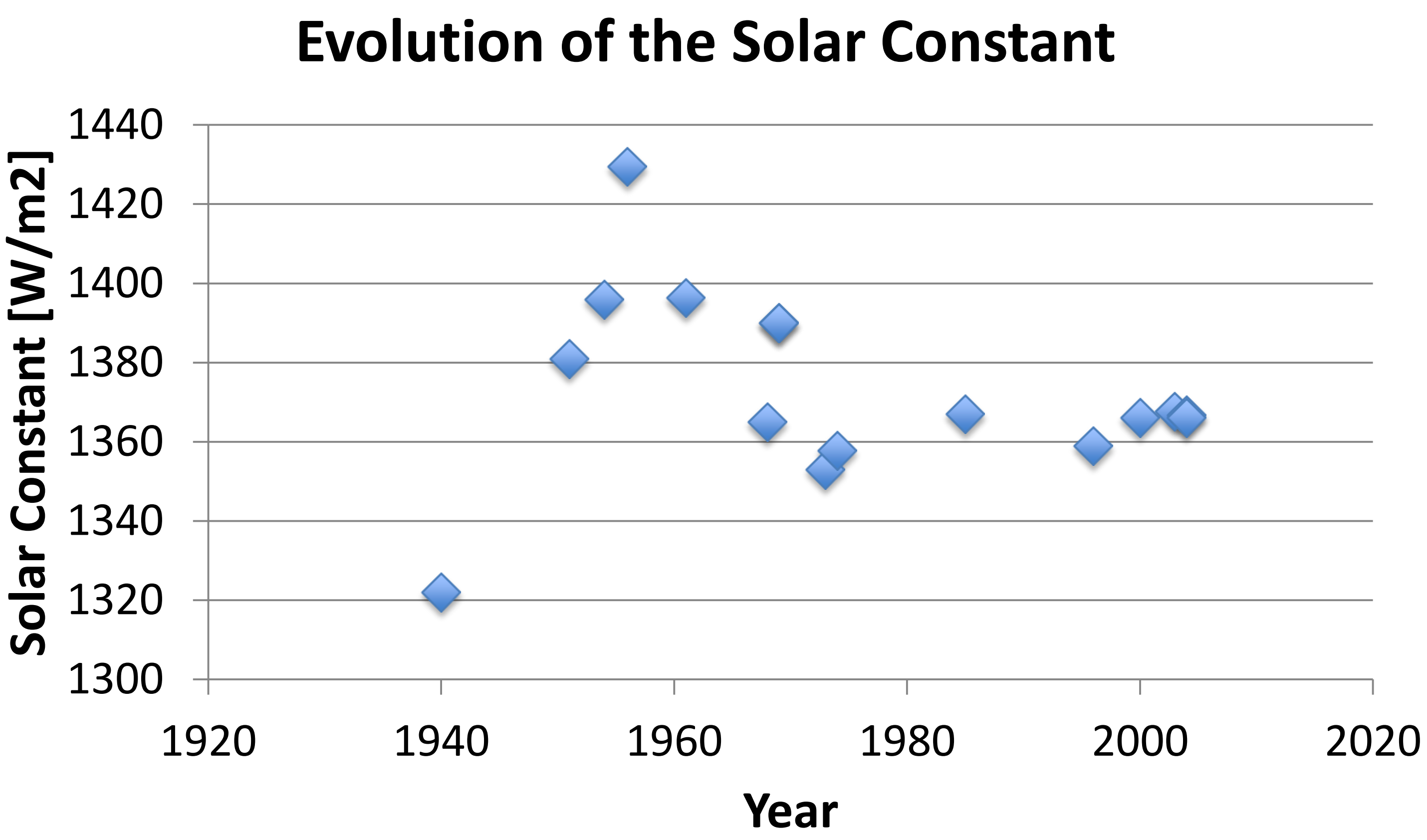
Source: http://pveducation.org/pvcdrom/appendicies/standard-solar-spectra

Measuring Global/Direct Insolation

Please see the lecture 14 video, or follow the link below to see solar irradiance measurement equipment.

Equipment for solar irradiance measurements http://www.nrel.gov/data/pix/searchpix_visual.html

Change is the Only Constant…



From data included in C.A. Gueymard, *Advances in Space Research* **37** (2006) 323–340

Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of "standard" solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.

Simulating Solar Spectra in the Lab (Solar Simulator)

Diagram removed due to copyright restrictions.
See the video for lecture 14, or Fig. 2 at the link referenced below.

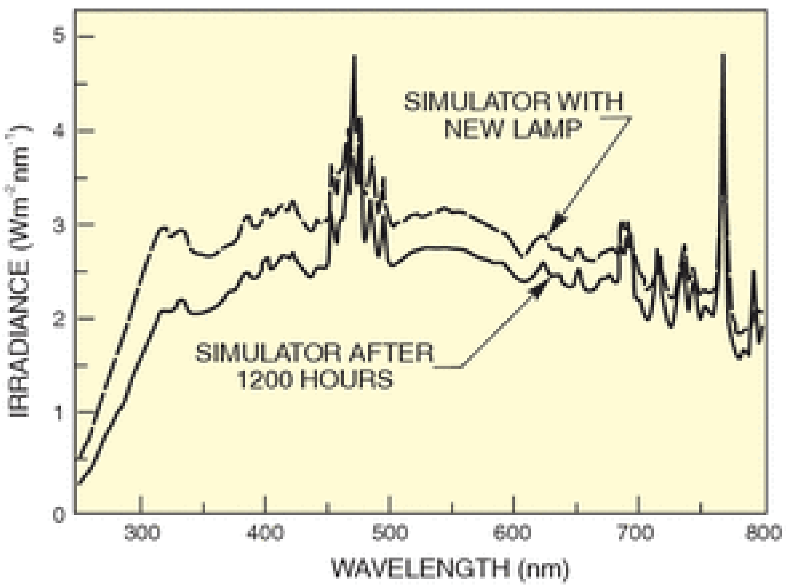
http://assets.newport.com/webDocuments-EN/images/12298.pdf

Solar Simulator Properties

Uniformity

Spectral Fidelity

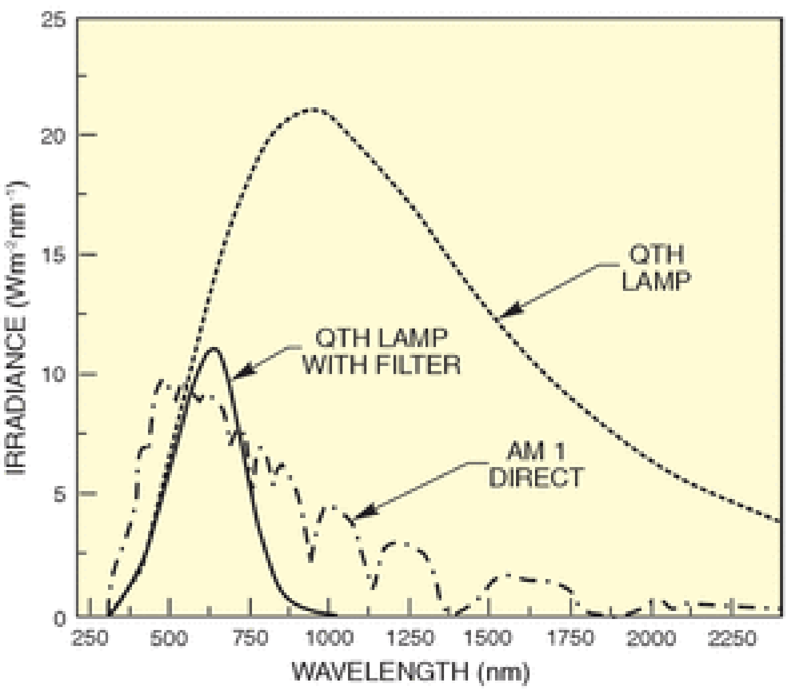
Temporal Stability

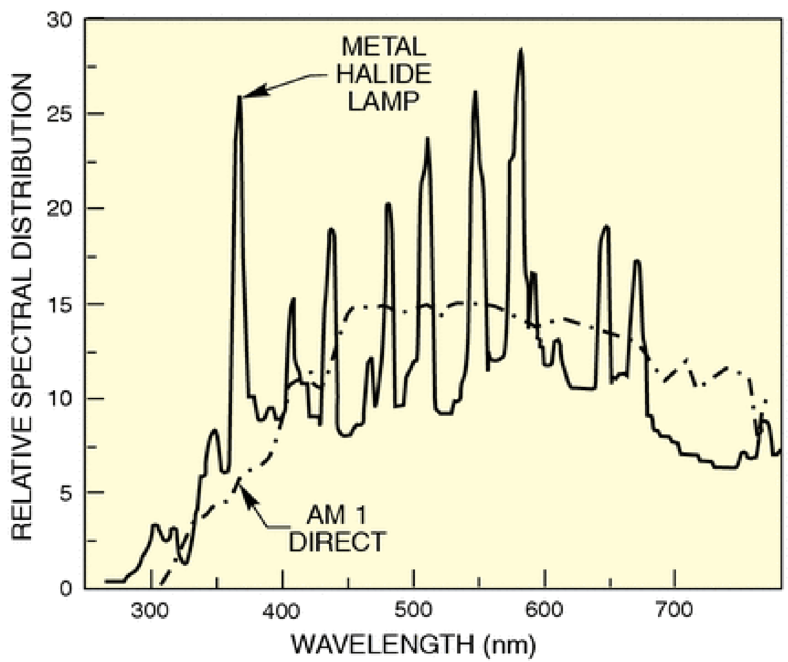


http://www.newport.com/Simulation-of-Solar-Irradiation/411986/1033/catalog.aspx

Attempts to Simulate Solar Spectra: Light Sources

Non-ideal matches: QTH, Hg, M-Halide…





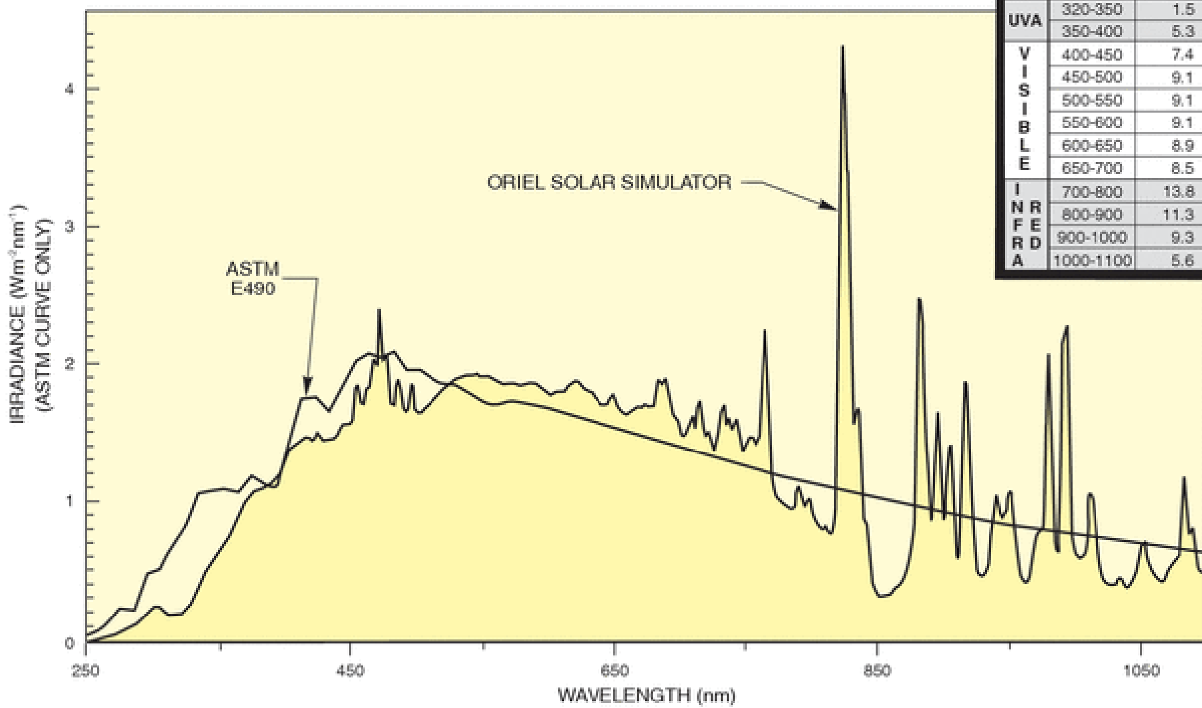
http://www.newport.com/Simulation-of-Solar-Irradiation/411986/1033/catalog.aspx

Attempts to Simulate Solar Spectra: Light Sources

Better matches: Xe lamps with air mass filters

DESCRIPTION	ASTM E490	300W 2X2 (51X51)	1000W 2X2 (51X51)	1000W 4X4 (102X102)	1000W 6X6 (152X152)	1000W 8X8 (203X203)
MODEL NO.	-	91160	91191	91192	91193	91194
TOTAL OUTPUT POWER DENSITY OVER 250 TO 1100nm (Wm^{-2})	1004	2050	9800	2640	1680	715

	RANGE (nm)	% OF 250-1100nm	
		Newport	ASTM E490 A.M.O.
UVC	<280	0.15	0.8
UVB	280-320	0.8	2.3
UVA	320-350	1.5	3.2
	350-400	5.3	5.9
VISIBLE	400-450	7.4	8.9
	450-500	9.1	10.4
	500-550	9.1	9.4
	550-600	9.1	8.8
	600-650	8.9	8.4
	650-700	8.5	7.4
INFRARED	700-800	13.8	12.8
	800-900	11.3	10.2
	900-1000	9.3	8.5
	1000-1100	5.6	6.9



Solar Simulator Standards

Standard IEC 904-9: Requirements for solar simulators for crystalline Si single-junction devices

	Class A	**Class B**	**Class C**
Spectral match (ratio of the actual percentage of total irradiance to the required percentage specified for each wavelength range)	0.75-1.25	0.6-1.4	0.4-2.0
Non-uniformity of irradiance	$< \pm 2\%$	$< \pm 5\%$	$< \pm 10\%$
Temporal Instability*	$< \pm 2\%$	$< \pm 5\%$	$< \pm 10\%$

For more info on PV testing standards, see:
http://photovoltaics.sandia.gov/docs/pvstndrds.htm

Other common standards:
- ASTM E927-05: http://www.astm.org/Standards/E927.htm
- JIS C 8912-1989

**requires temporal instability of $\leq \pm 1\%$ for Class A*

Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.

Practical Considerations when Measuring Efficiency

Obtain & use an NREL-certified calibration (reference) cell.

Avoid extraneous light. *(A light-tight curtain works well.)*

Please see the lecture 14 video for a visual of example efficiency measurement equipment.

Ensure 25° C measurement conditions.

Remember: V_{oc} can change by up to 0.25–1% / ° C. Ideal chucks contain active heating/cooling, and independent temperature verification at the site of measurement (*i.e.*, not under the chuck).

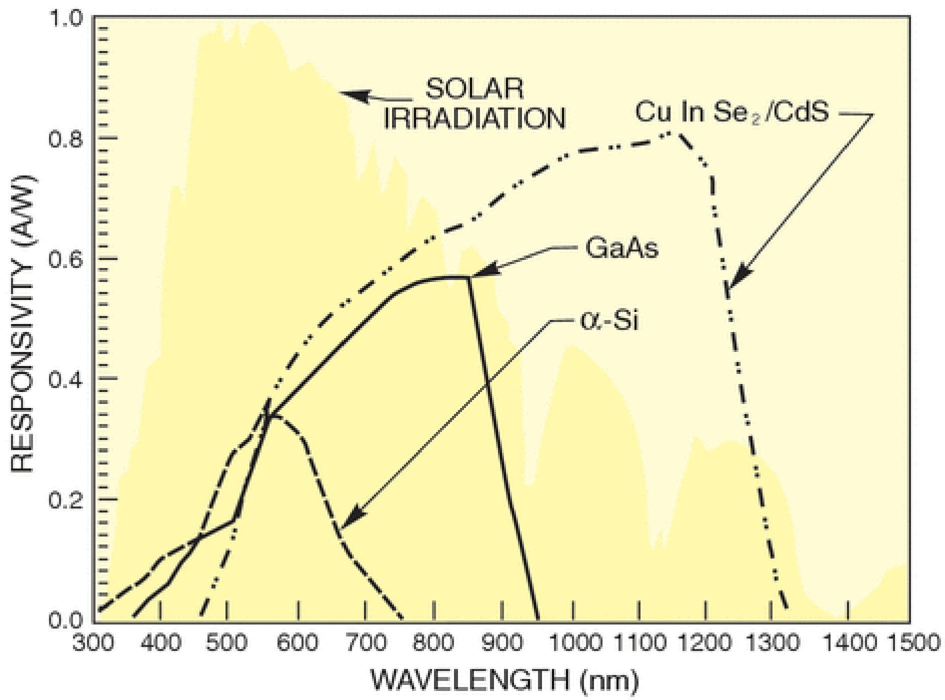
Choose probe location judiciously to avoid series resistance losses.

ASTM E948 - 09 Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight http://www.astm.org/Standards/E948.htm

Account for spectral mismatch between calibration cell and your solar cell.

NB: Spectral response mismatch

Warning: Different PV materials are sensitive to different parts of the solar spectrum. You may be over/under estimating your performance, if the solar simulator calibration cell is made of a different material to the cells you are testing.



http://www.newport.com/Energy-Conversion/412147/1033/catalog.aspx

ASTM E973 - 10 Standard Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
http://www.astm.org/Standards/E973.htm

Best Practices

When making a record efficiency claim, get the cell certified by NREL (FhISE, or other certified testing facility). This avoids controversies. This is challenging, however, for materials that degrade quickly.

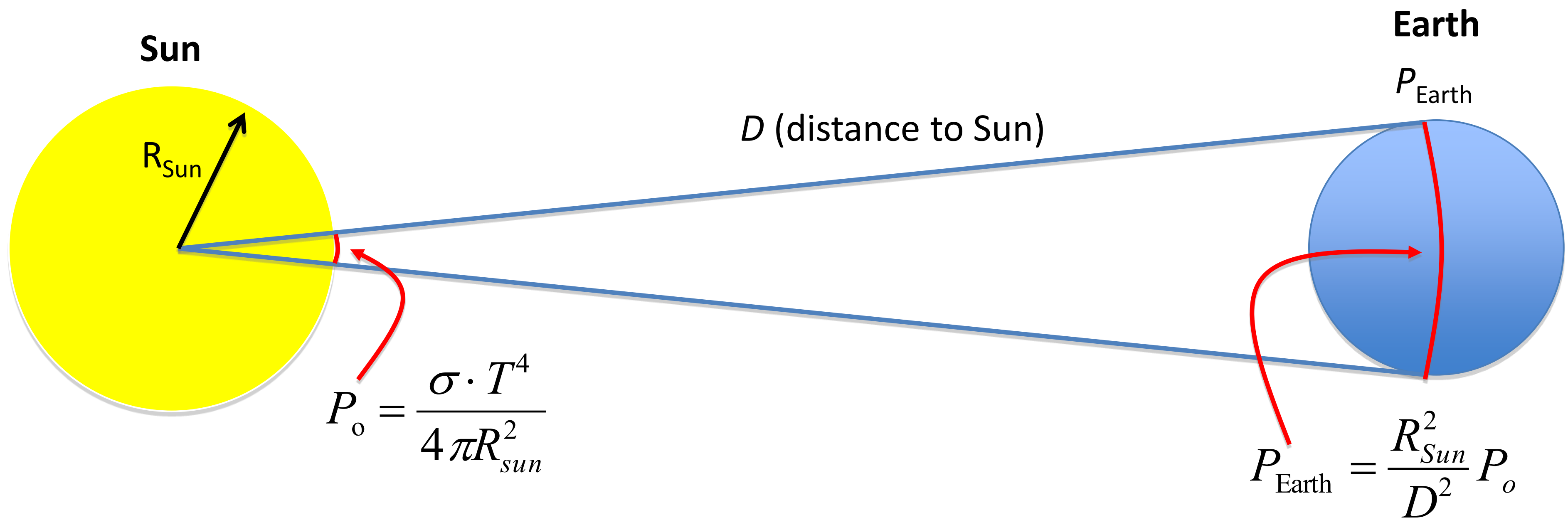
Please see the lecture 14 video for paper extracts.

Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.

Max Solar Heat Engine (Blackbody) Efficiency: 86%

not to scale!



T_{Sun} = ~6000 K

T_{Earth} = ~300 K

See: Peter Würfel, Physics of Solar Cells, p. 33–37

Jenny Nelson, The Physics of Solar Cells, p. 291

Theoretical Efficiency Calculations

First Paper: Prince

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

Prince, M. B. "Silicon Solar Energy Converters." *J. Appl. Phys*. 26, no. 5 (1955).

First Power Conversion Efficiency Calculations

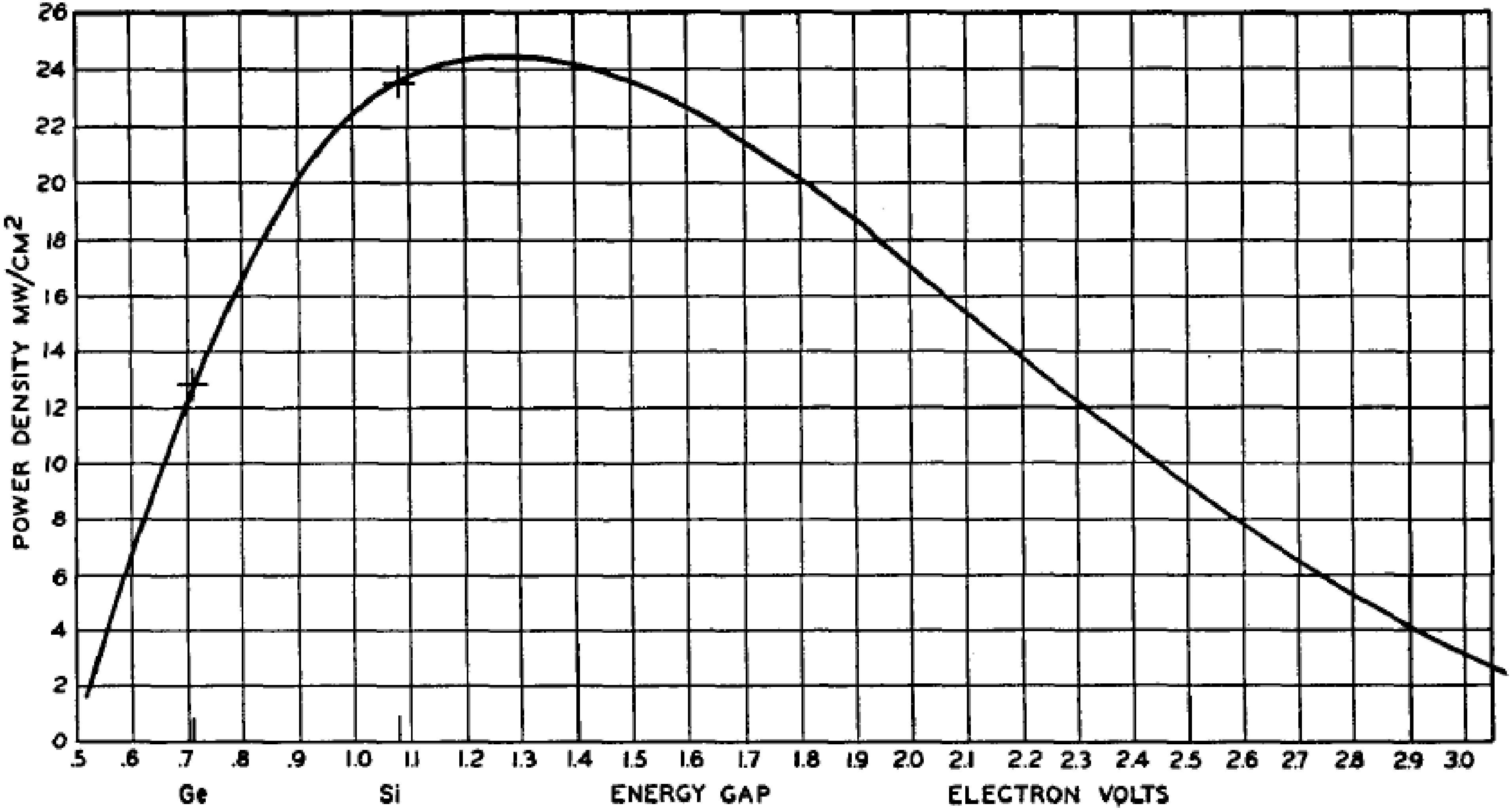


Fig. 2. Maximum converted power density in bright sunlight as a function of energy gap of semiconductor.

"Detailed Balance" Limit

Seminal Paper: Shockley-Queisser efficiency limit

Key contribution: "Detailed balance limit": Light absorption is balanced (counteracted) by radiative recombination. Works for materials with large minority carrier lifetimes.

Shockley, W., and H.J. Queisser. "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells." *J. Appl. Phys. 32, no. 3 (1961): 510.*

"Detailed Balance" Limit

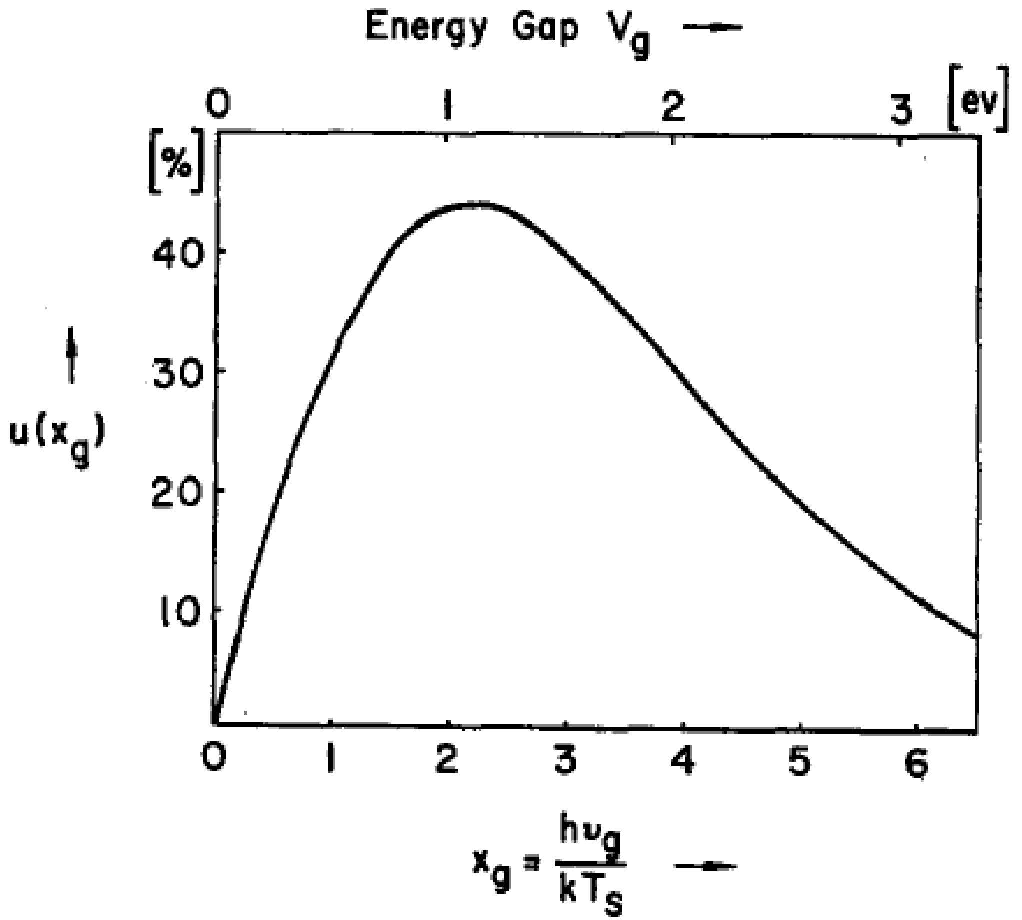


FIG. 3. Dependence of the ultimate efficiency $u(x_g)$ upon the energy gap V_g of the semiconductor.

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

"Detailed Balance" Limit

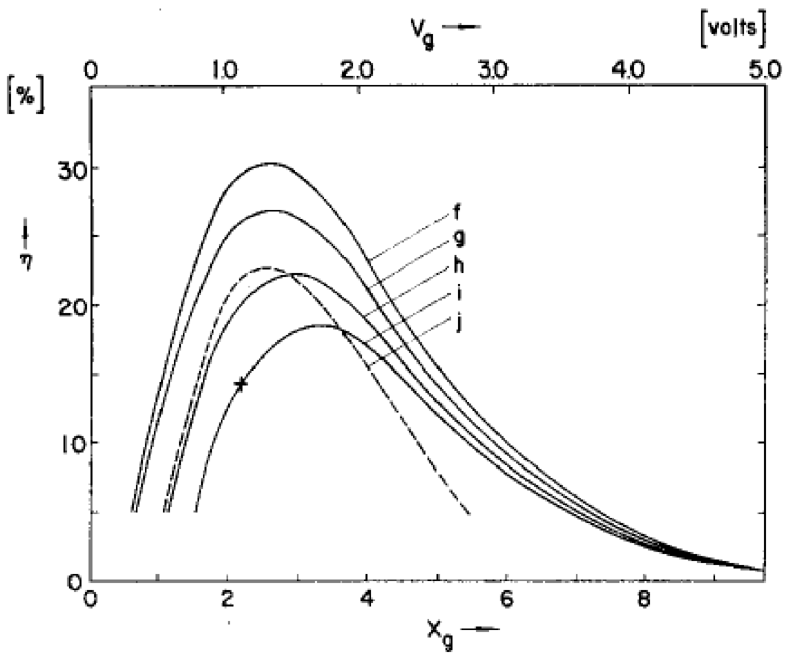


FIG. 6. Efficiency η for a solar cell at temperature $T_c=300°K$ exposed to a blackbody sun at temperature $T_s=6000°K$. Curve (f) is the detailed balance limit of efficiency, assuming the cell is a blackbody (i.e., $t_s=t_c=1$). Curve (j) is the semiempirical limit, or limit conversion efficiency of Prince (see footnote 3). + represents the "best experimental efficiency obtained to date" for Si (see footnote 6). Curves (g), (h), and (i) are modified to correspond to 90% absorption of radiation (i.e., $t_s=t_c=0.9$) and 100-mw incident solar energy. The values for the f quantities discussed in Sec. 6 are: (f) $f=1.09\times10^{-5}$ ($f_\omega=2.18\times10^{-5}$, $f_c=1$) $t_s=t_c=1$; (g) $f=0.68\times10^{-5}$ ($f_\omega=1.36\times10^{-5}$, $f_c=1$) $t_s=t_c=0.9$; (h) $f=0.68\times10^{-8}$ ($f_\omega=1.36\times10^{-5}$, $f_c=10^{-3}$) $t_s=t_c=0.9$; (i) $f=0.68\times10^{-11}$ ($f_\omega=1.36\times10^{-5}$, $f_c=10^{-6}$) $t_s=t_c=0.9$.

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

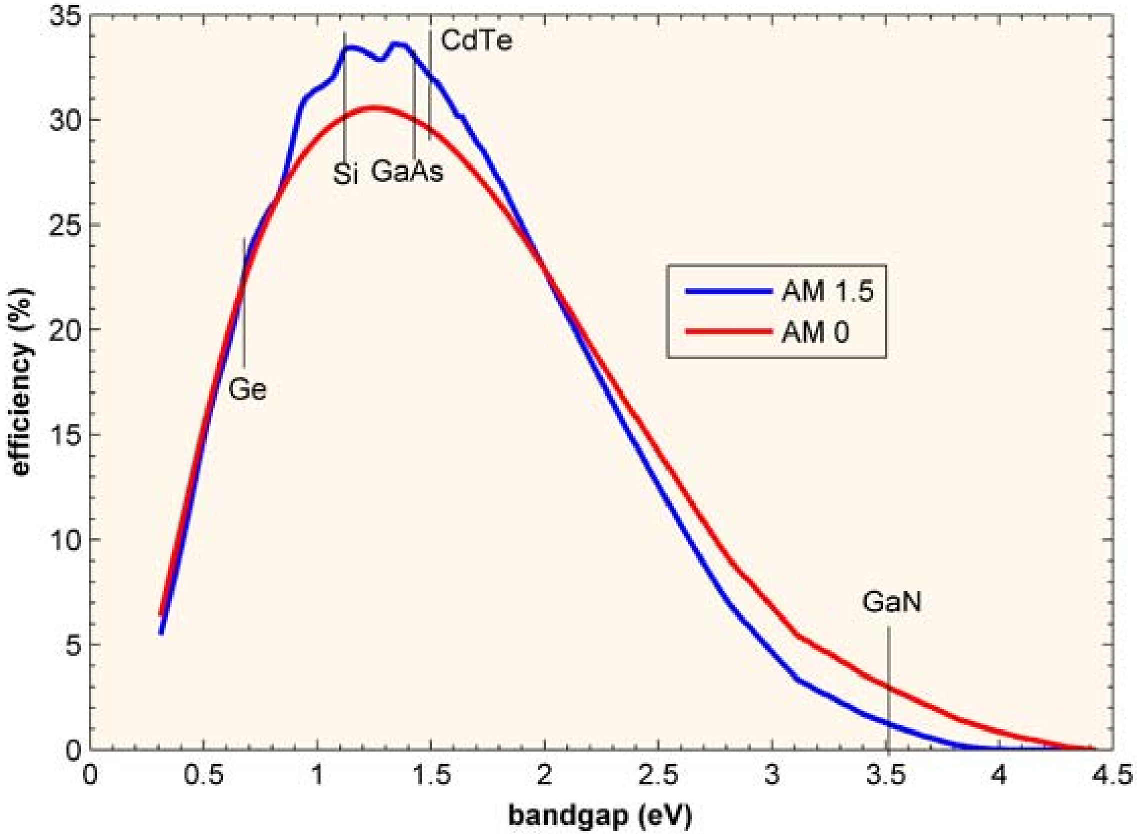
Key Assumptions of the "Detailed Balance" Limit

- All photons with $E > E_g$ are absorbed, and create one electron-hole pair.
- Electron and hole populations relax to band edges to create separate distributions in quasi thermal equilibrium with the lattice temperature, resulting in quasi Fermi levels separated by $\Delta\mu$.
- Each electron is extracted with a chemical potential energy μ, such that $qV = \Delta\mu$. Requires constant quasi Fermi levels throughout, i.e., carriers have infinite mobility.
- The only loss mechanism is radiative recombination (a.k.a., spontaneous emission).

"Detailed Balance" Limit

- Home discovery: Walk through the derivation of "detailed balance limit" yourself:
- http://www.pveducation.org/pvcdrom/solar-cell-operation/detailed-balance
- Download and read: W. Shockley and H.J. Queisser, *J. Appl. Phys.* **32**, 510 (1961)

Theoretical Maximum Efficiency as a Function of Bandgap Energy



Courtesy of PVCDROM. Used with permission.

http://www.pveducation.org/pvcdrom/solar-cell-operation/detailed-balance

Modifications to Detailed Balance Calculations: Realistic Effects

- Bulk recombination (*e.g.*, Auger).
- Absorption losses (free-carrier absorption, continuously-varying absorption coefficient).

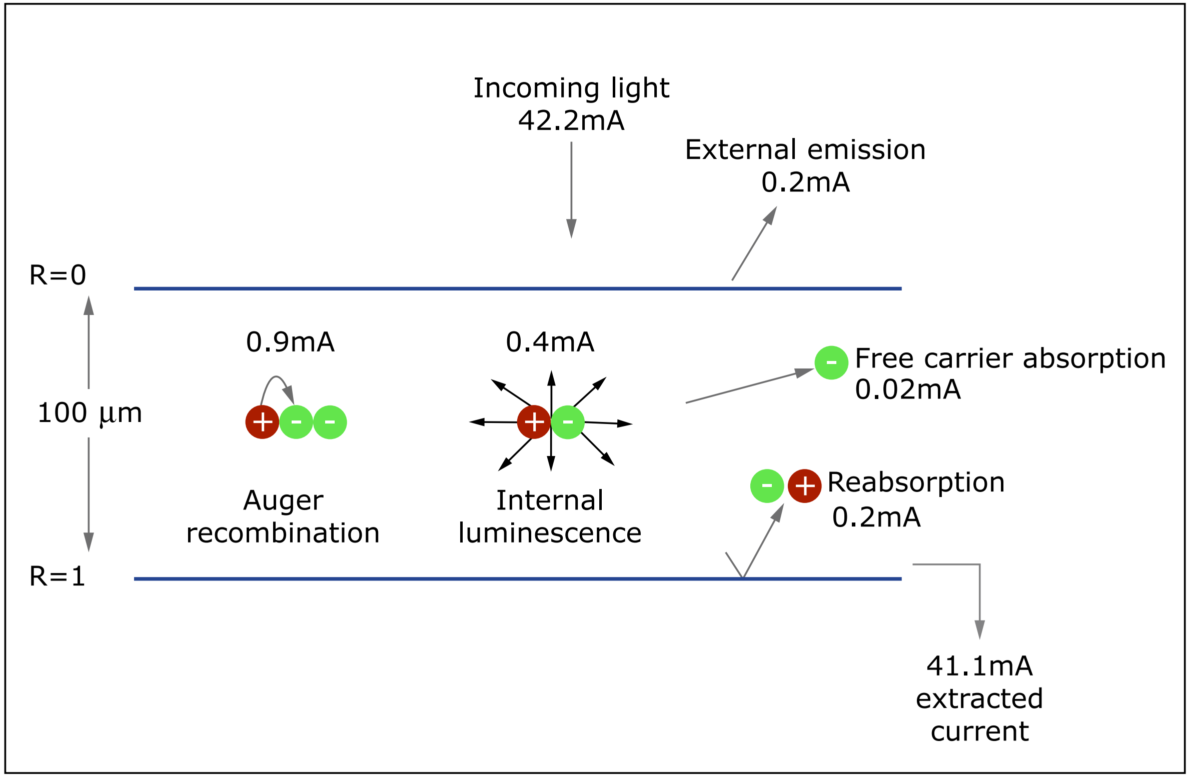


Image by MIT OpenCourseWare.

T. Teidje *et al.*, *IEEE Trans. Electron Dev.* **31**, 711 (1984)

Modifications to Detailed Balance Calculations: Finite Carrier Transport

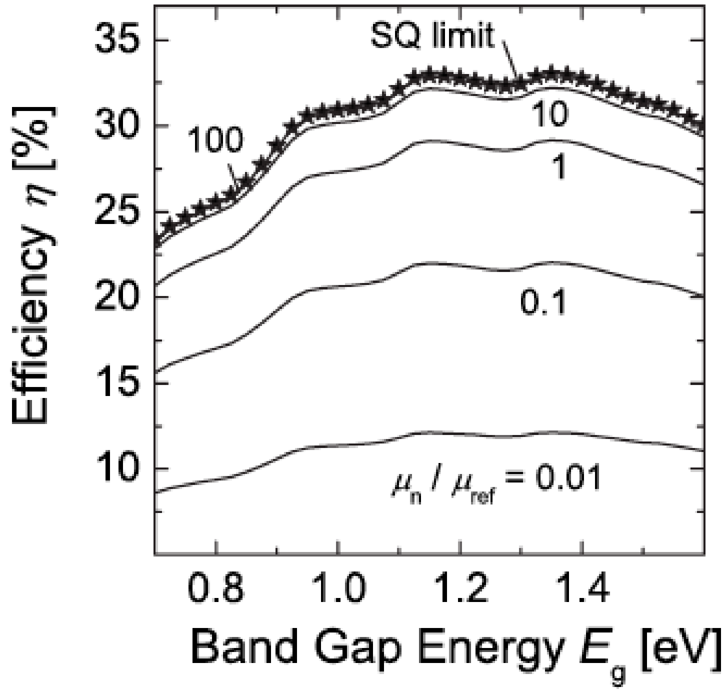
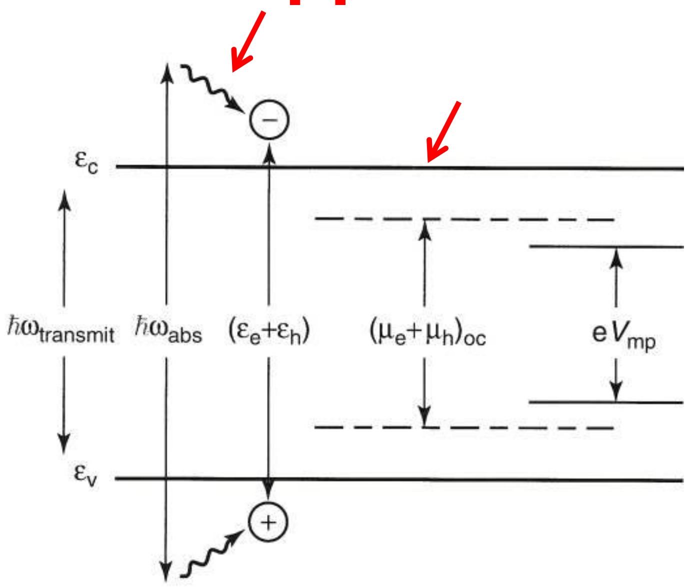


FIG. 2. Radiative efficiency (no nonradiative recombination) vs band gap energy E_g. The absorption coefficient is $\alpha = \alpha_0$, the normalized thickness is $\alpha_0 d = 10$, and the front surface is textured. All

Lower carrier *mobility* = Lower *efficiency* limit!

J. Mattheis et al., *Phys. Rev. B* **77**, 085203 (2008)

Another Approach



Peter Würfel, Physics of Solar Cells, p. 183–185

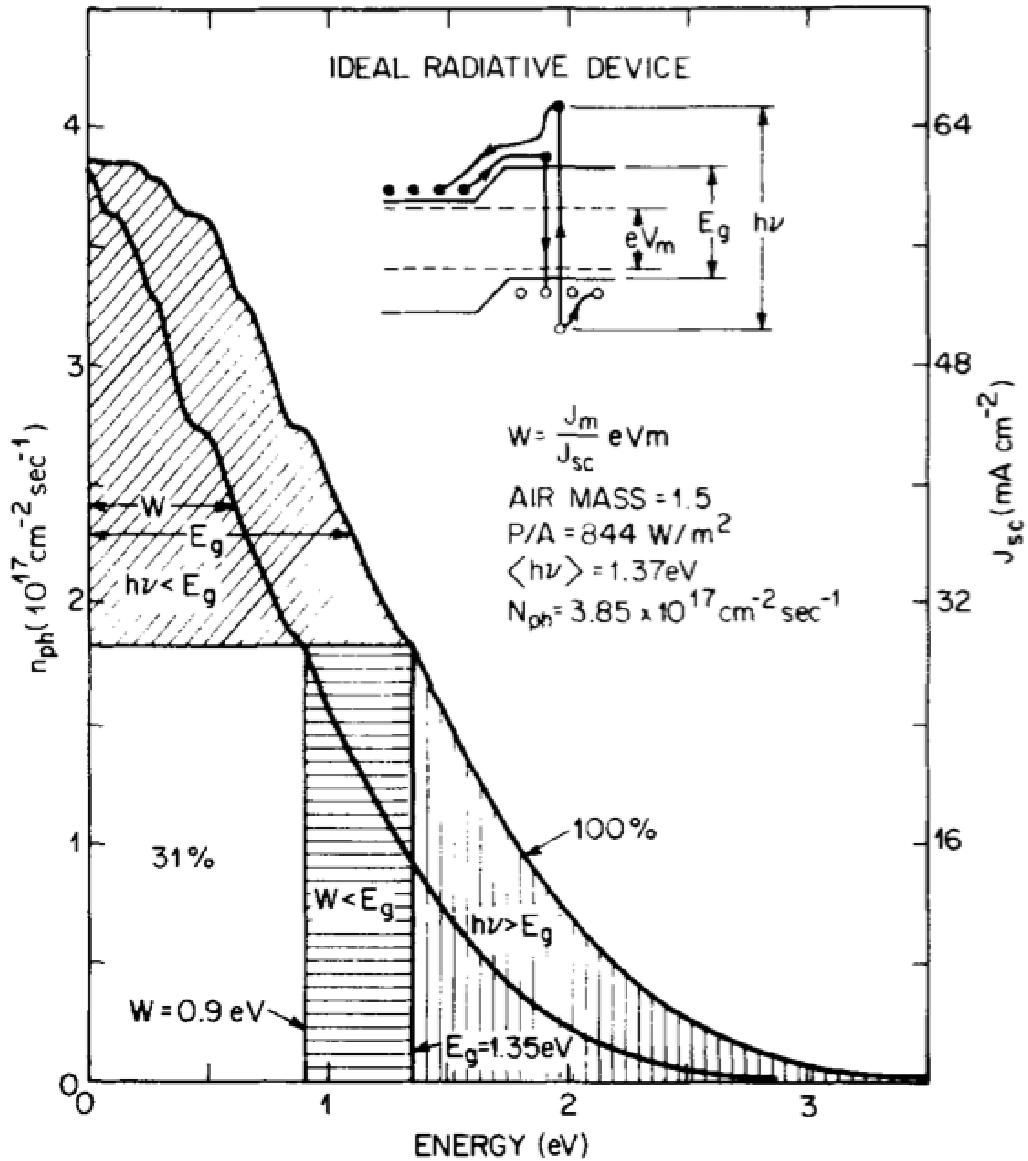
Following analysis in P. Würfel's Physics of Solar Cells, p. 183–185:

Assume all efficiency losses derive from:

- Non-absorption of light ($E_{ph} < E_g$): 0.74
- Thermalization of charge carriers ($E_{ph} > E_g$): 0.67
- Thermodynamic losses: 0.64
- Fill factor losses (practical solar cell operation): 0.89

Resulting Efficiency Limit: (0.74) x (0.67) x (0.64) x (0.89) = 0.28

Representation of Maximum Power: Single Junction



C.H. Henry, *J. Appl. Phys.* **51**, 4494 (1980)

Evolution of Efficiency Limit Calculations

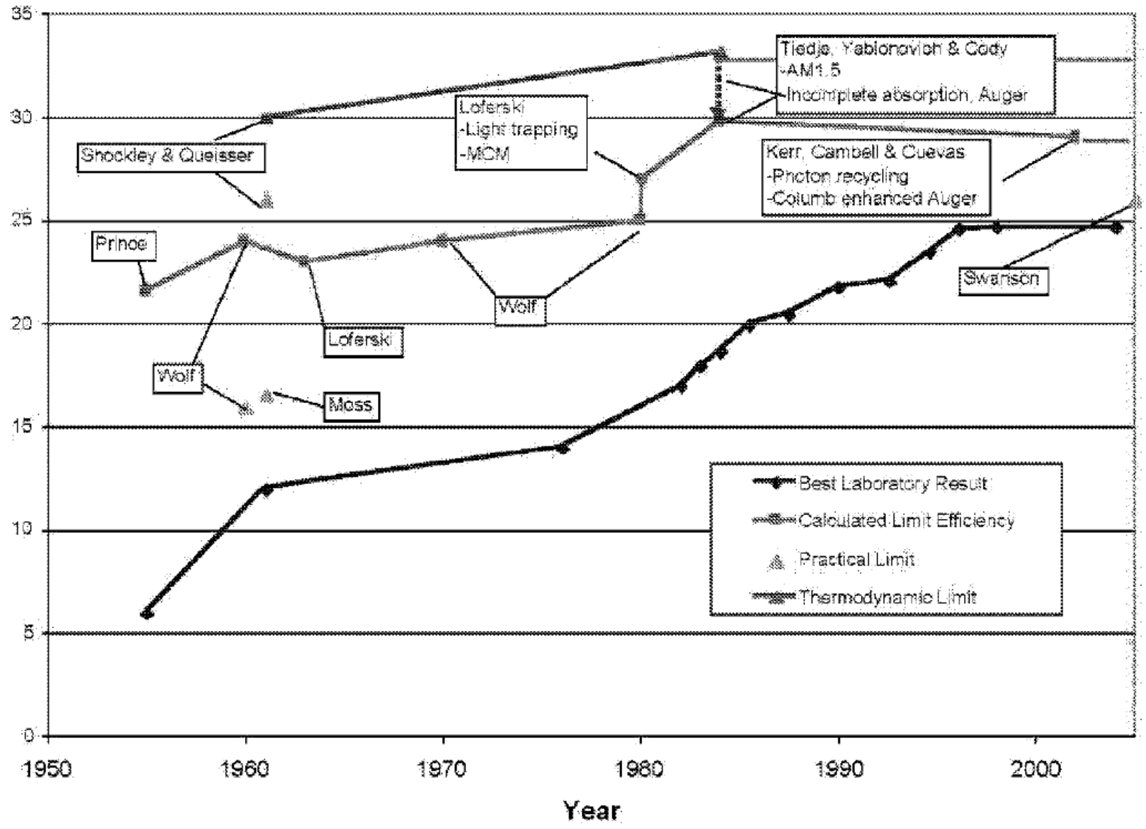
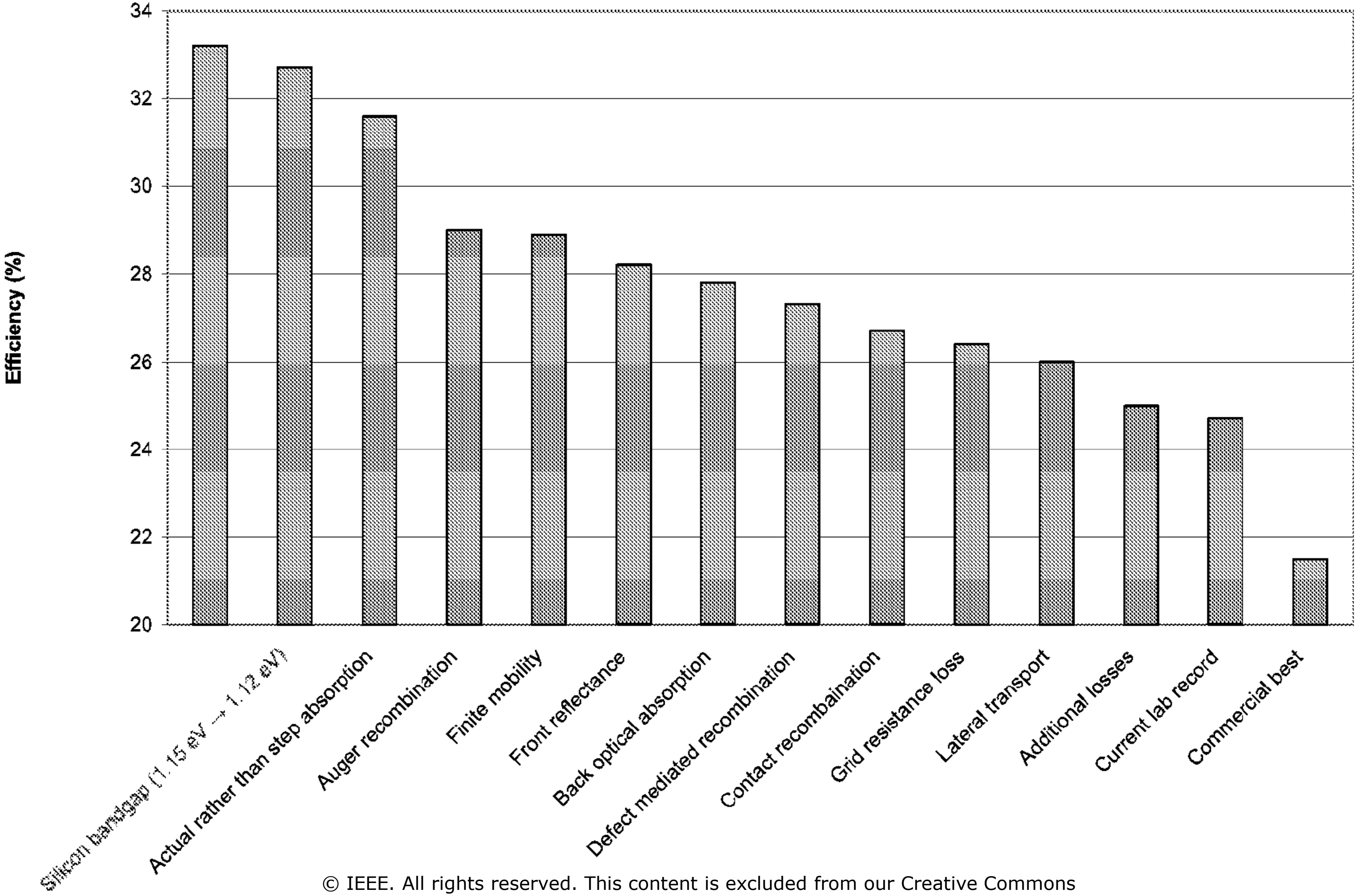


Figure 1. Progress in calculated limit efficiencies. AM0 efficiencies have been adjusted to AM1 by adding 10% relative.

From "APPROACHING THE 29% LIMIT EFFICIENCY OF SILICON SOLAR CELLS
Richard M. Swanson, Proc. IEEE PVSC (2005).

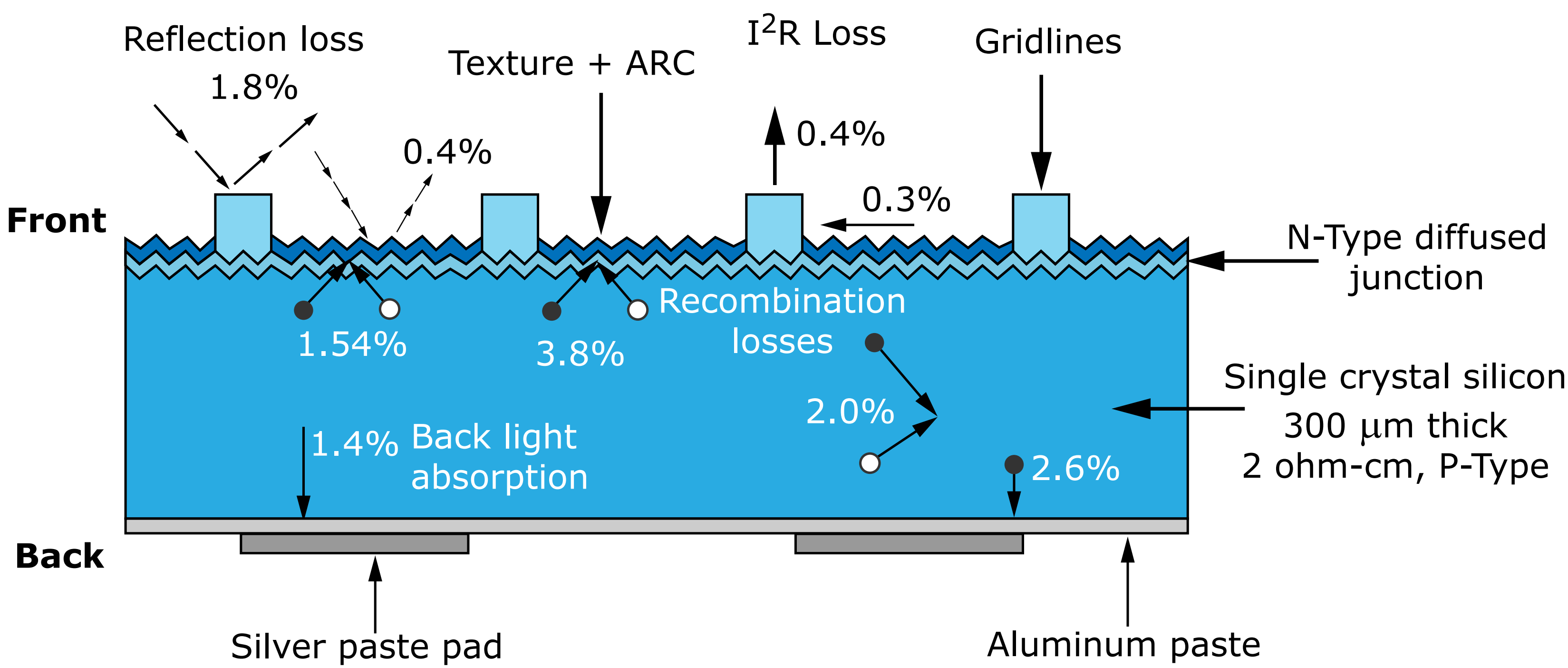
Realistic Limit of Crystalline Si



APPROACHING THE 29% LIMIT…

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

Loss Mechanisms Visualized



Generic silicon solar cell with its loss mechanisms. The losses subtract from the 29% limit efficiency, and are expressed as percentages of incident power (100 mW/cm², standard test conditions).

Image by MIT OpenCourseWare.

Richard M. Swanson (SunPower)

Good Readings on Efficiency Limits

- *Theoretical Limits of Photovoltaic Conversion*

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

- *Physics of Solar Cells*

  By Peter Würfel, in Library Reserve.

- *The Physics of Solar Cells*

  By Jenny Nelson, in Library Reserve.

- *Solar Cells*

  By Martin Green, Chapters 5 and 8.