

Fundamentals of Photovoltaics

Nov 5th – 7th 2014



UNIVERSITY OF
LIVERPOOL



Course Overview

Wed Nov 5

1. The Sun – Maurizio Salaris, JMU
2. Solar spectrum and basic device response – R. Treharne
3. Detailed Balance – R. Treharne

Thu Nov 6

4. Semiconductors 101 – R. Treharne
5. Junctions – R. Treharne
6. Junction Characterisation – R. Treharne

Fri Nov 7

7. Materials Stability – K. Durose
8. Optical properties of semiconductors – T. Veal
9. Advanced characterisation of band phenomena – V. Dhanak
10. Photovoltaics – Current and future PV technologies – K. Durose

Mon Nov 10

EXAM

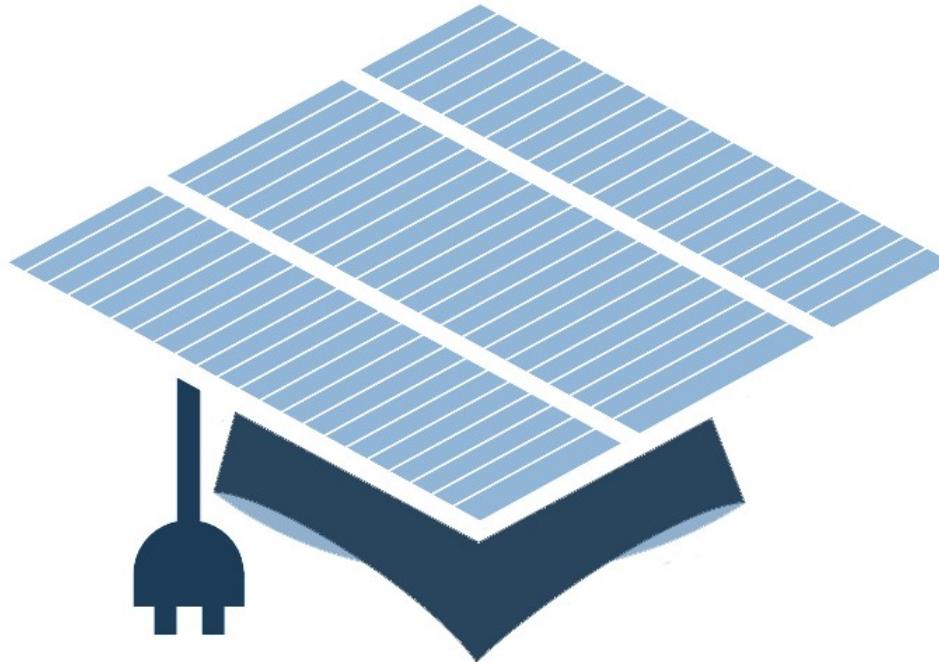
Download Lectures Overview here!



Questions?



#cdtpvC1



Lecture 1

Solar spectrum and basic device response

R. Treharne

Nov 5th 2014

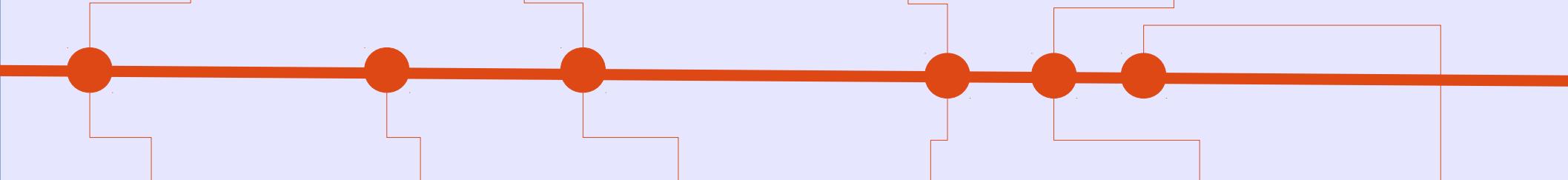
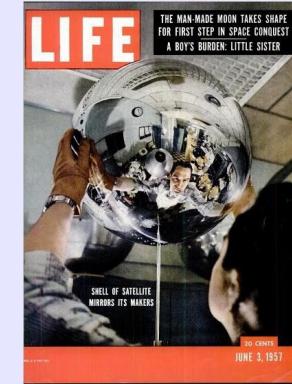
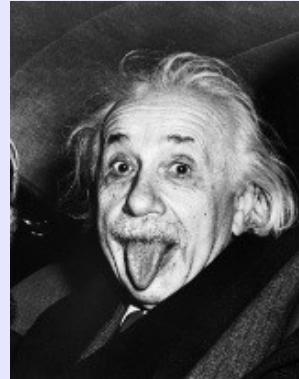
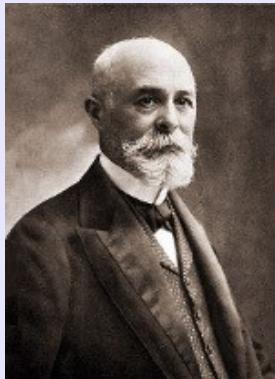




- Super speedy history of PV
- The photovoltaic effect
- AM1.5 spectrum
- Solar simulators and ratings
- The ideal diode equation + equivalent circuits
- J-V curves and important device parameters
- Parasitic resistances
- External quantum efficiency (EQE)



SS History of PV



1839:
Edmund Bequerel
discovers
photovoltaic effect
in electrolytic cell

1873:
Willoughby Smith
observes
photoconductivity
in Selenium

1905:
Einstein
publishes paper
on photoelectric
effect (not
photovoltaic
effect!)

1954:
First PV cell made
at Bell Labs, USA.
Used to power
telephone
repeaters – 4%
efficient.
Daryl Chapin, Calvin
Fuller, Gerald Pearson.

1958:
First PV cell in
space. Vanguard
Satellite. Max
power 1W!
Followed Explorer VI
and VII satellites
(1959)

1960:
Hoffman
Electronics
achieves **14%** PV
cells!

https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf
<http://jongertner.net/idea-factory/>



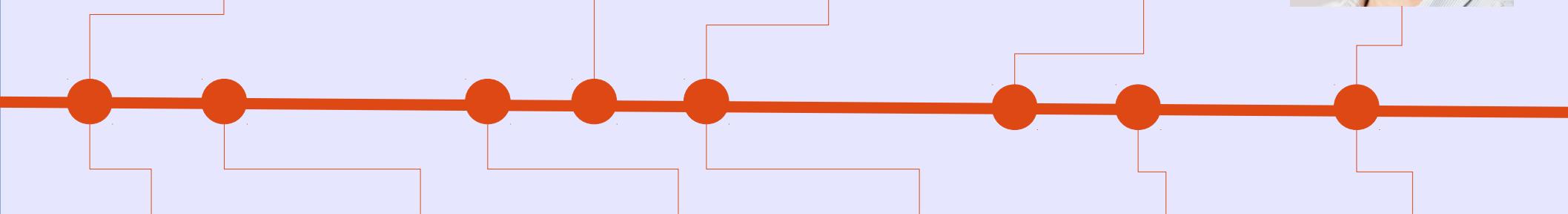
SS History of PV



1994:
GaAs solar cells
> 30%
NREL



2008:
Peak in Si cost as
production of SC
grade Si slows.
**Thin film gets
excited**



REVIEW ARTICLE

PUBLISHED ONLINE: XX JULY 2014 | DOI: 10.1038/NPHOTON.2014.134

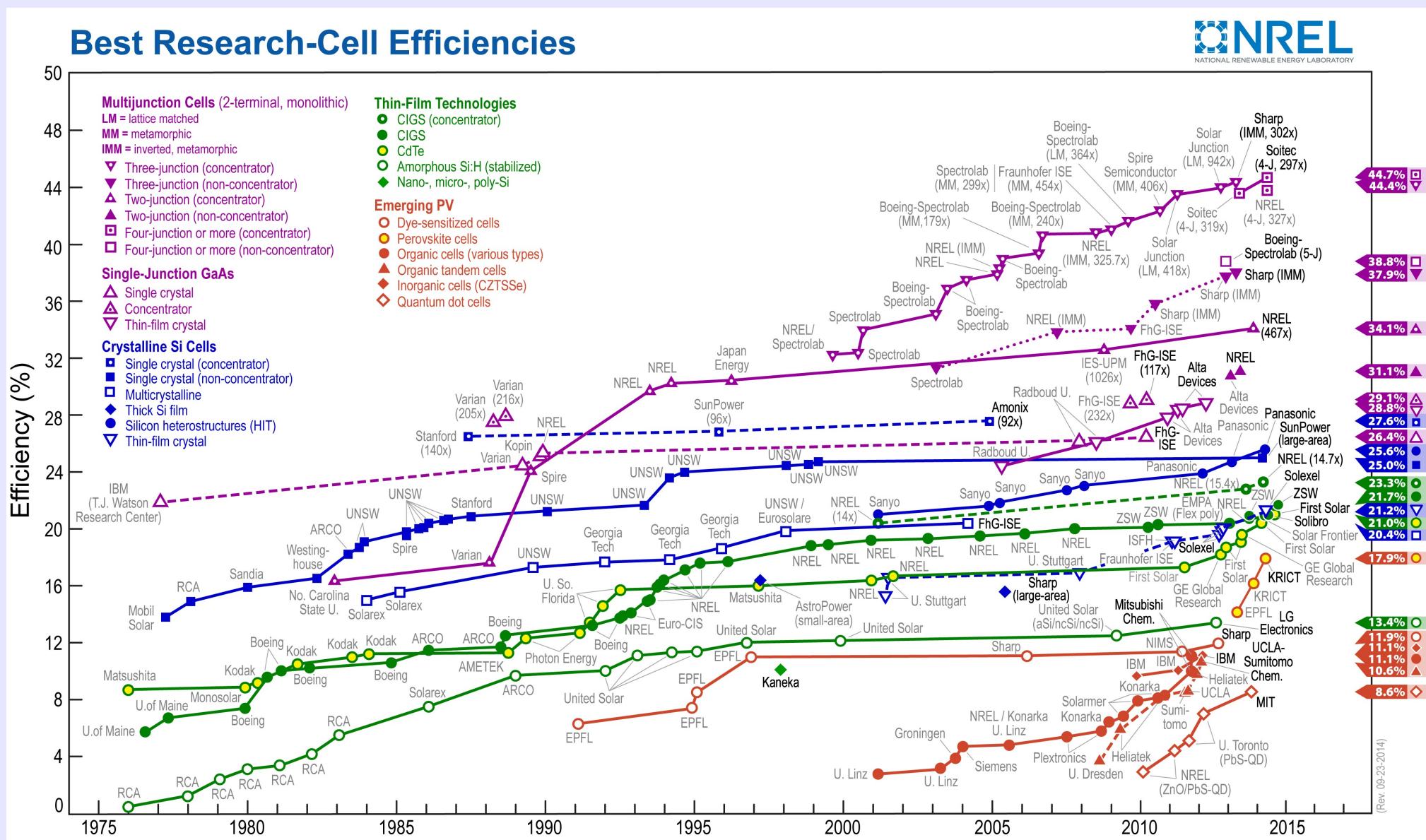
nature
photronics

The emergence of perovskite solar cells

Martin A. Green^{1*}, Anita Ho-Baillie¹ and Henry J. Snaith²

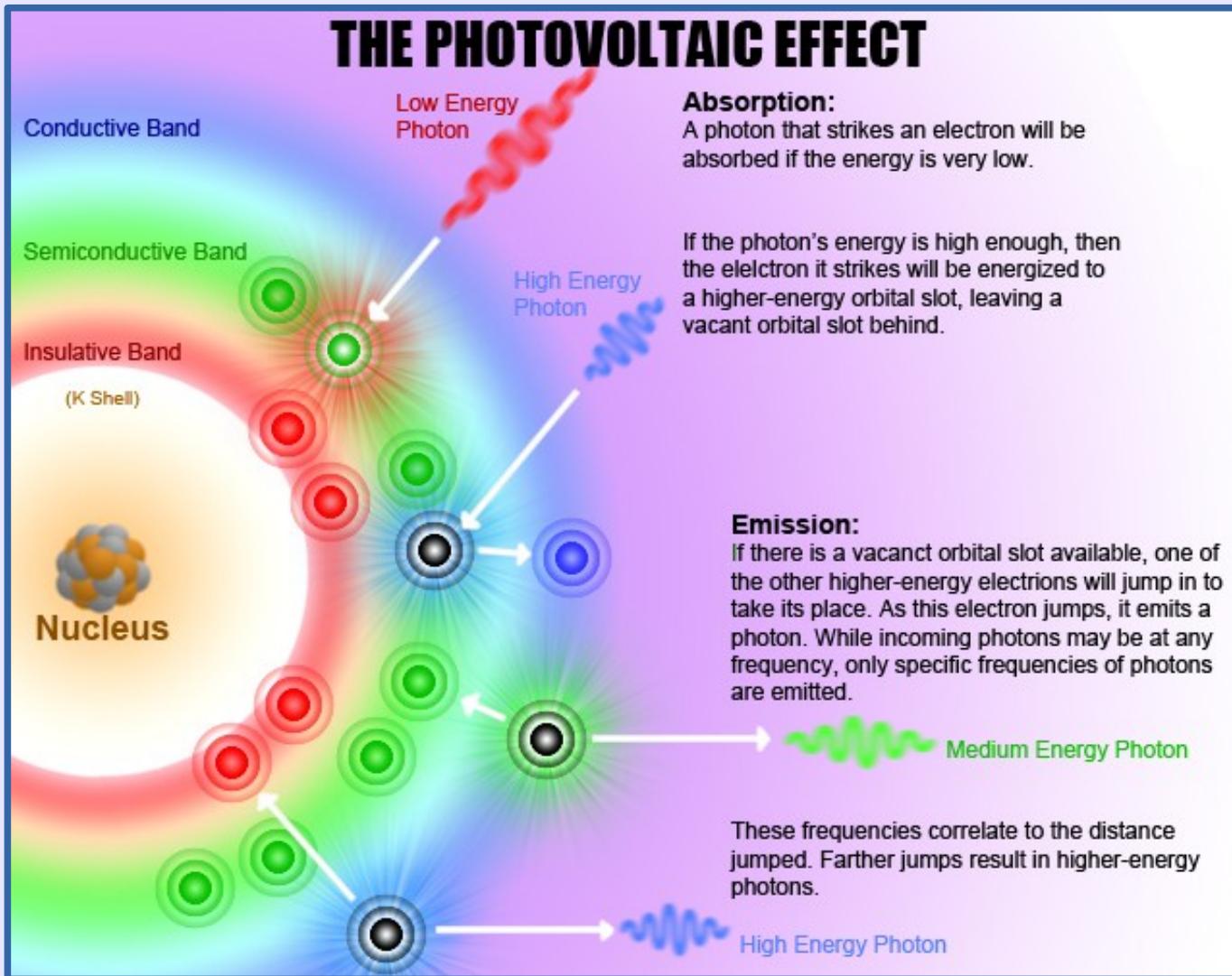
EPSRC

Engineering and Physical Sciences
Research Council

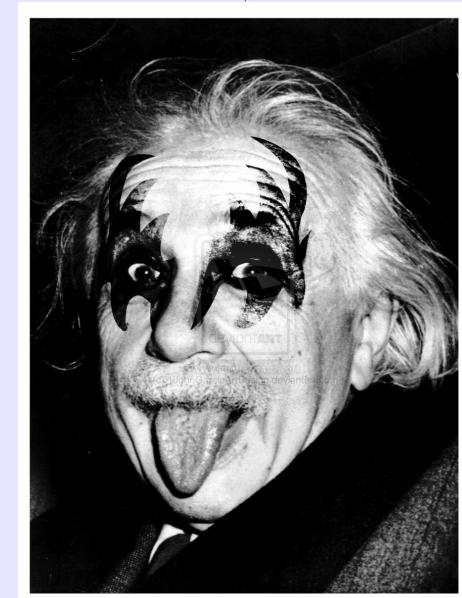




Photovoltaic Effect



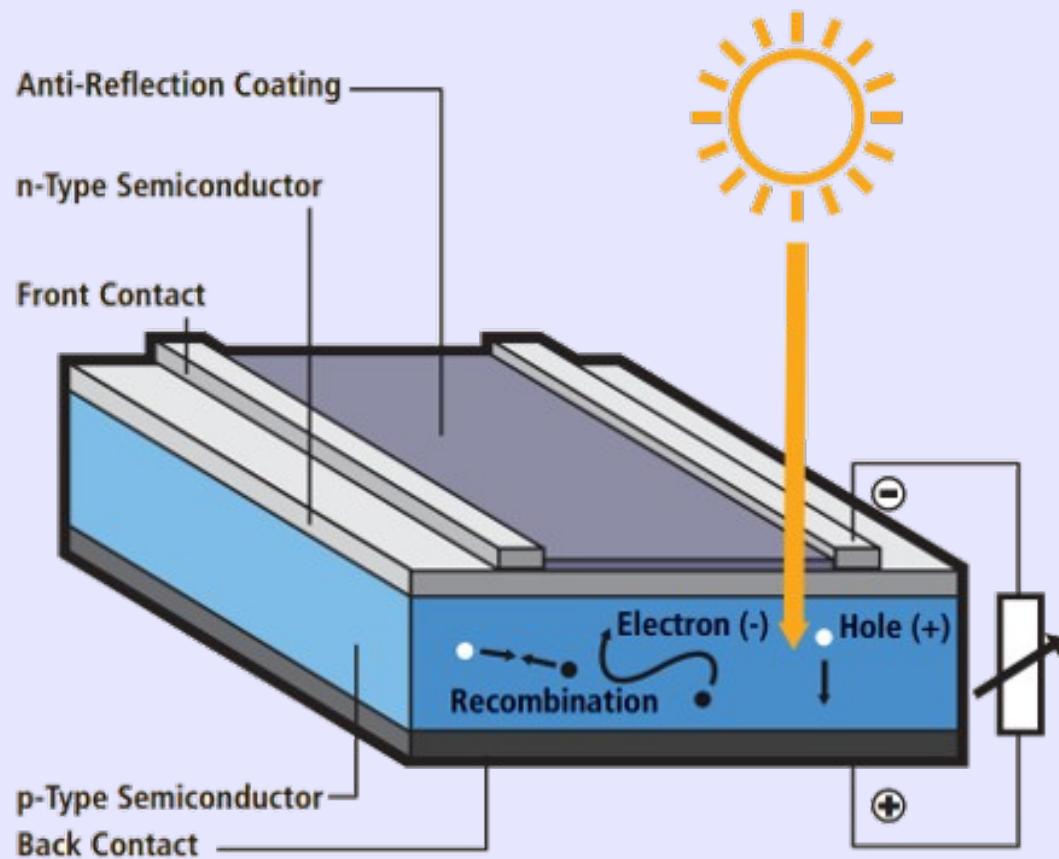
Do you know the difference between the photovoltaic and photoelectric effects?





Photovoltaic Effect

How do we use the PV effect to do work?

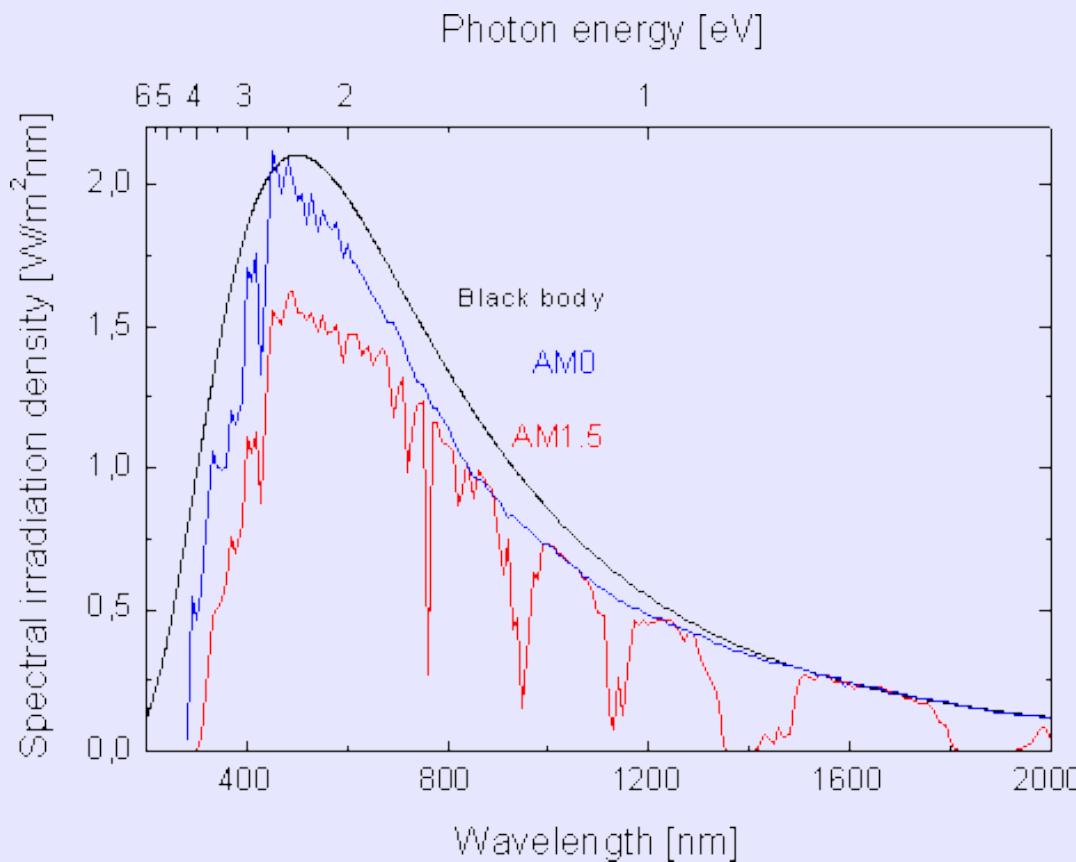


- Must separate generated electron-hole pair
- Prevent recombination
- Need internal field
- How? **JUNCTION!**
- Hold in your excitement until **L5**

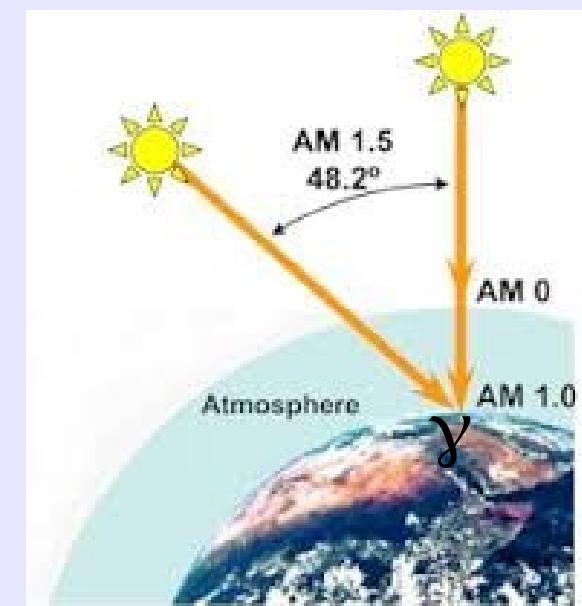


AM1.5 Spectrum

$$n_{\text{AirMass}} = \frac{\text{optical path length at angle } \gamma}{\text{optical path length at } \gamma=0}$$



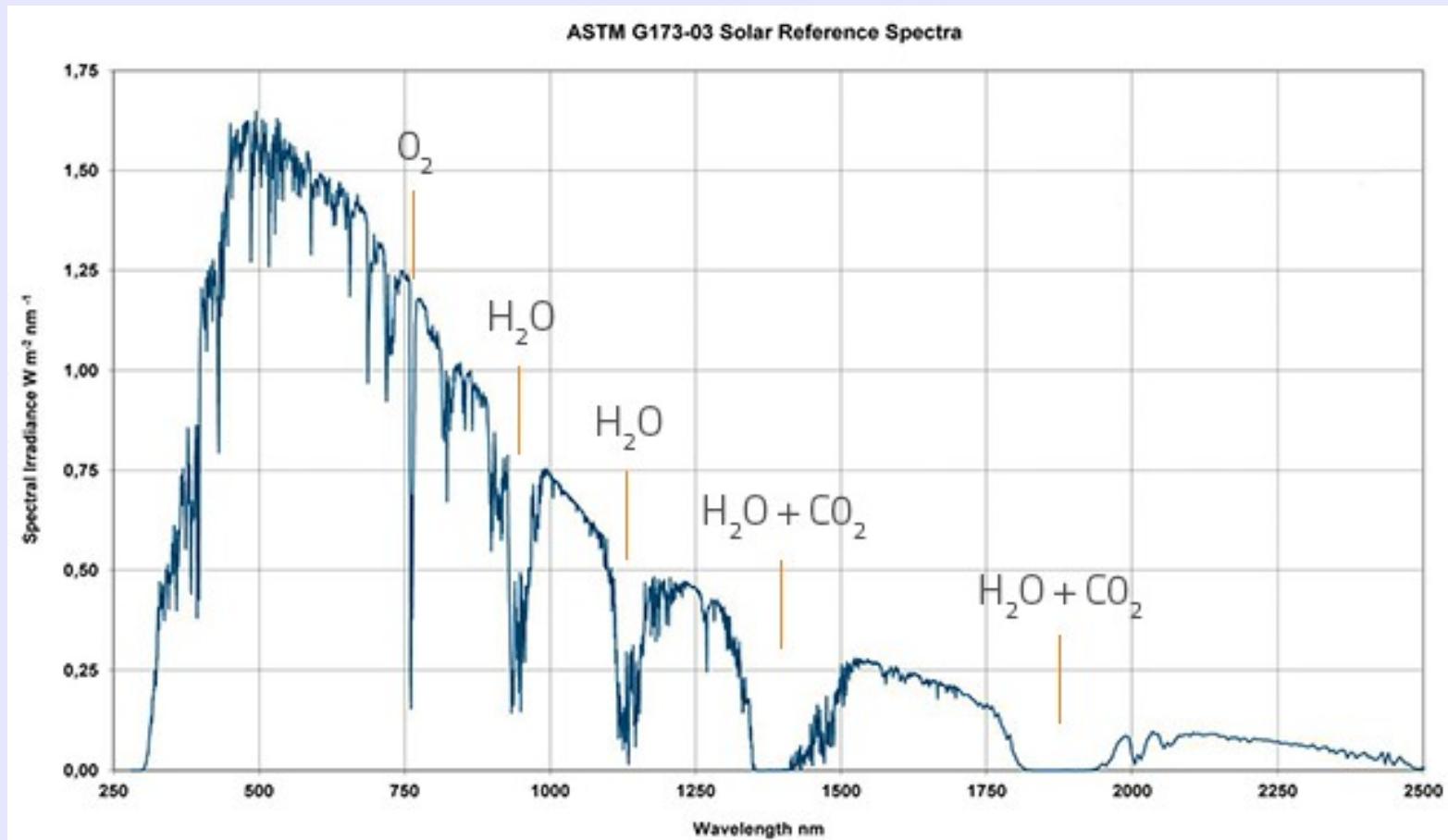
$$n_{\text{AirMass}} = \cosec \gamma$$



[http://en.wikipedia.org/wiki/Air_mass_\(solar_energy\)](http://en.wikipedia.org/wiki/Air_mass_(solar_energy))



AM1.5 Spectrum



<http://rredc.nrel.gov/solar/spectra/am1.5/>

Integrated Irradiance = **1000 Wm²** for AM1.5



Solar Simulators

The light from a solar simulator is controlled in 3 dimensions:

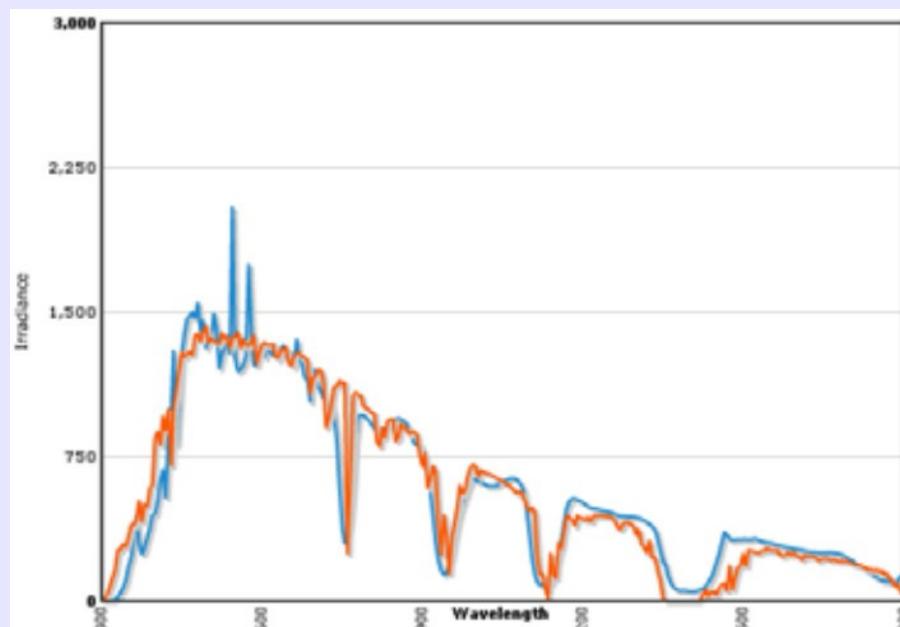
- 1) Spectral content
- 2) Spatial uniformity
- 3) Temporal stability

Classification	Spectral Match (each interval)	Irradiance Spacial Non-Uniformity	Temperal Instability
A	0.75-1.25	2%	2%
B	0.6-1.4	5%	5%
C	0.4-2.0	10%	10%

http://en.wikipedia.org/wiki/Solar_simulator



Solar Simulators



You will get to use
this! Be excited.



Ideal Diode Equation

Often called the Shockley equation:

$$J = J_0 \left[\exp \left(\frac{eV}{k_B T} \right) - 1 \right]$$

J_0 – Dark saturation current.

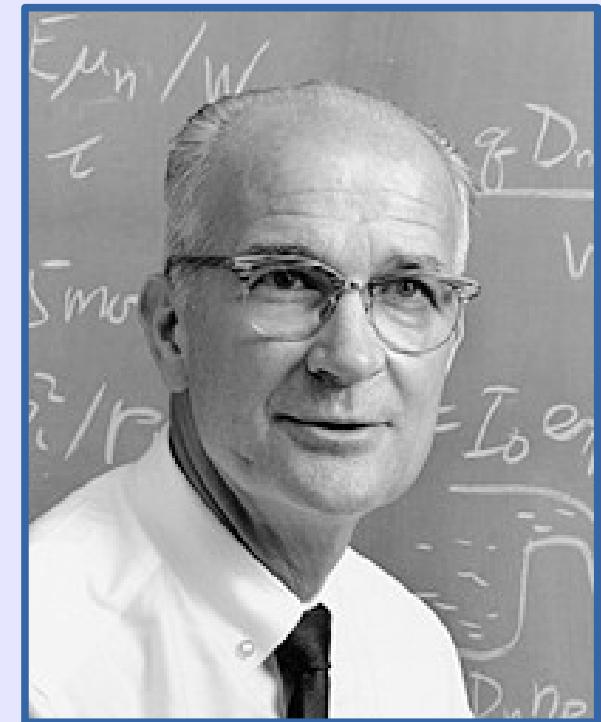
V – applied voltage across the terminals of the diode

e – Electronic charge

k_B – Boltzmann's constant

T – Absolute temperature (K)

Might derive this later for fun! (L5)



William Shockley:

Co-inventor of the transistor
with Bardeen and Brattain 1948

Nobel Prize: **1956**

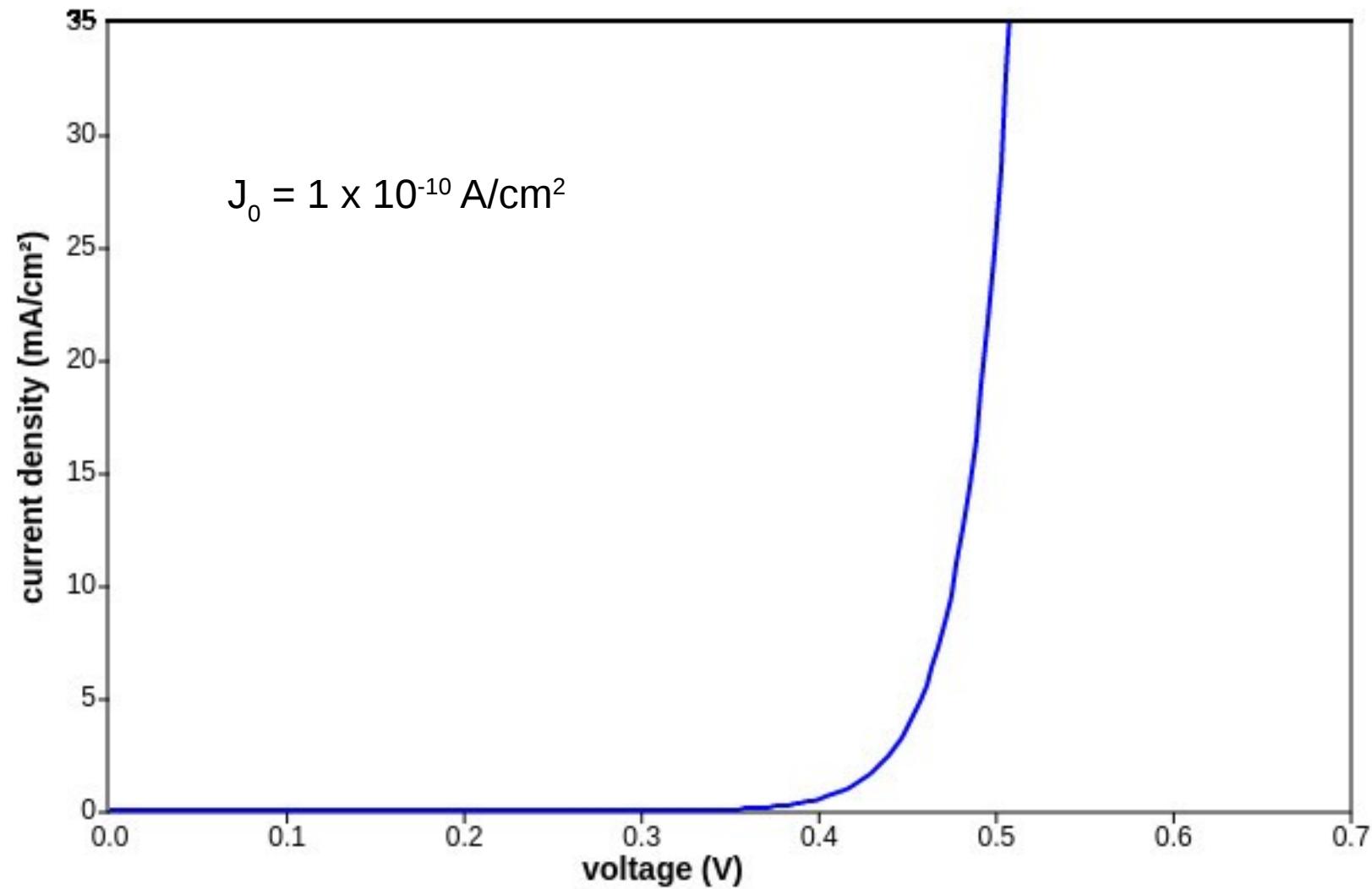
(Also a eugenicist)

If every you need some inspiration: Read this!

http://books.google.co.uk/books/about/The_Idea_Factory.html?id=uOMt_XCo81QC&redir_esc=y



Ideal dark JV curve





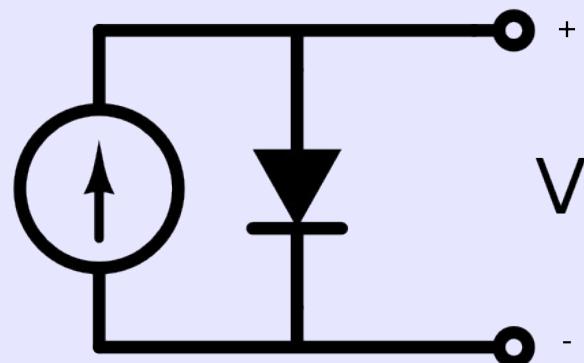
Ideal diode for solar cell

Sign convention: Lets say that the direction of a generated photo-current J_L is positive with respect to a negative dark current J_{dark}

$$J = J_L - J_{dark}$$

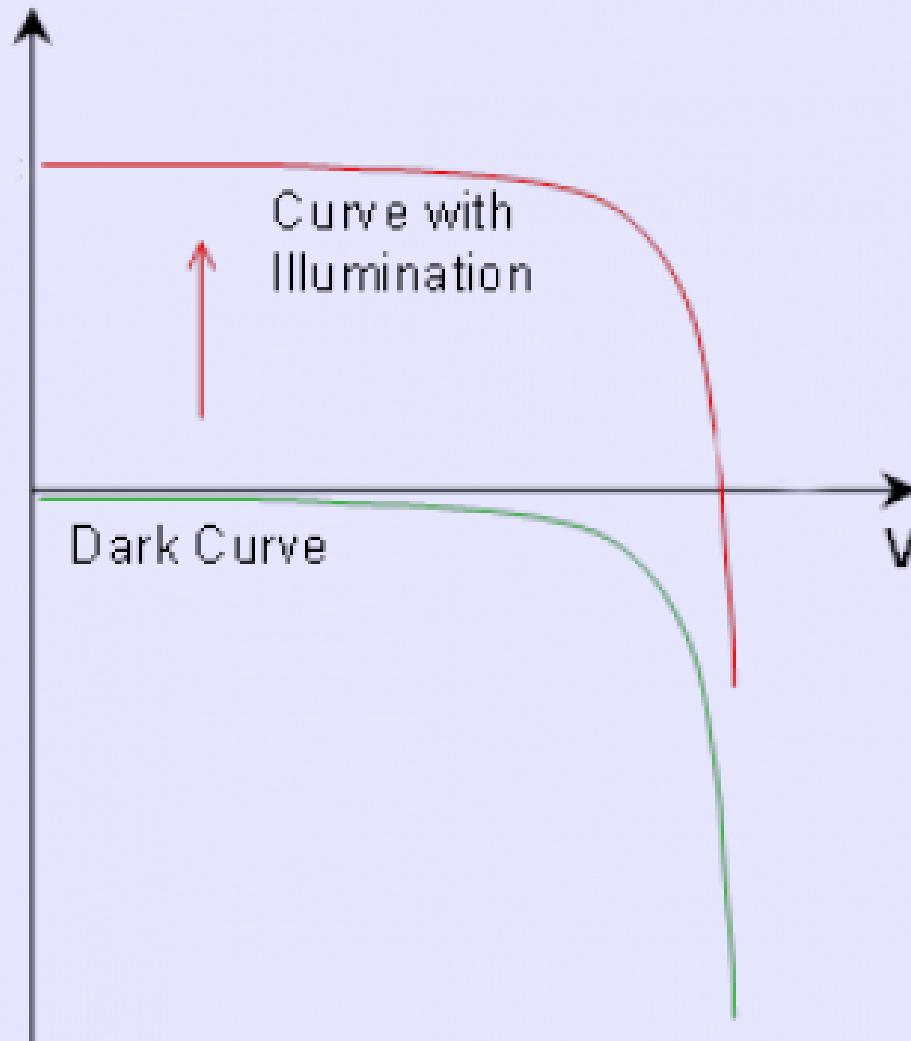
$$J = J_L - J_0 \left[\exp\left(\frac{eV}{k_B T}\right) - 1 \right]$$

Equivalent Circuit:
Ideal solar cell





Light JV response

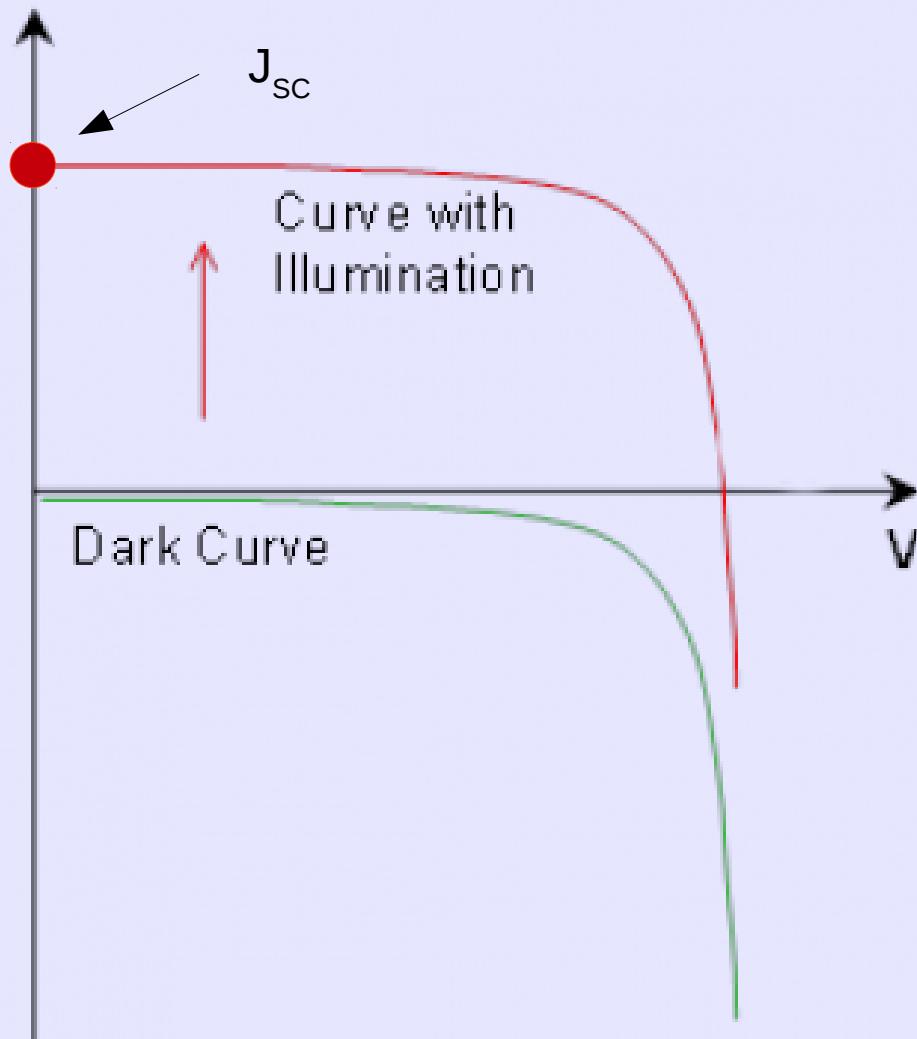


Performance of cell can be described by **three** important parameters

- Short circuit current - J_{SC}
- Open circuit voltage - V_{OC}
- Fill factor = FF



Short Circuit Current - J_{SC}



What is J_{SC} dependent on?

- Intensity
- Optical properties – REFLECTION!
- Lifetime (L5)
- Band gap

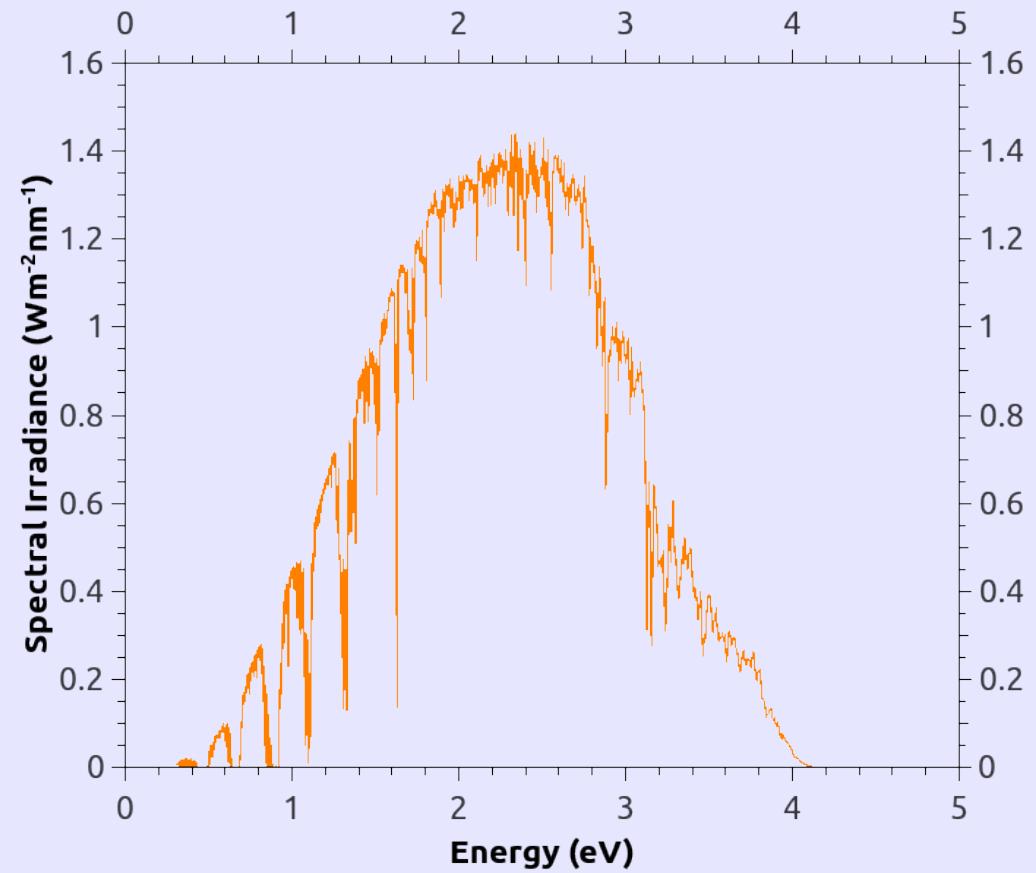
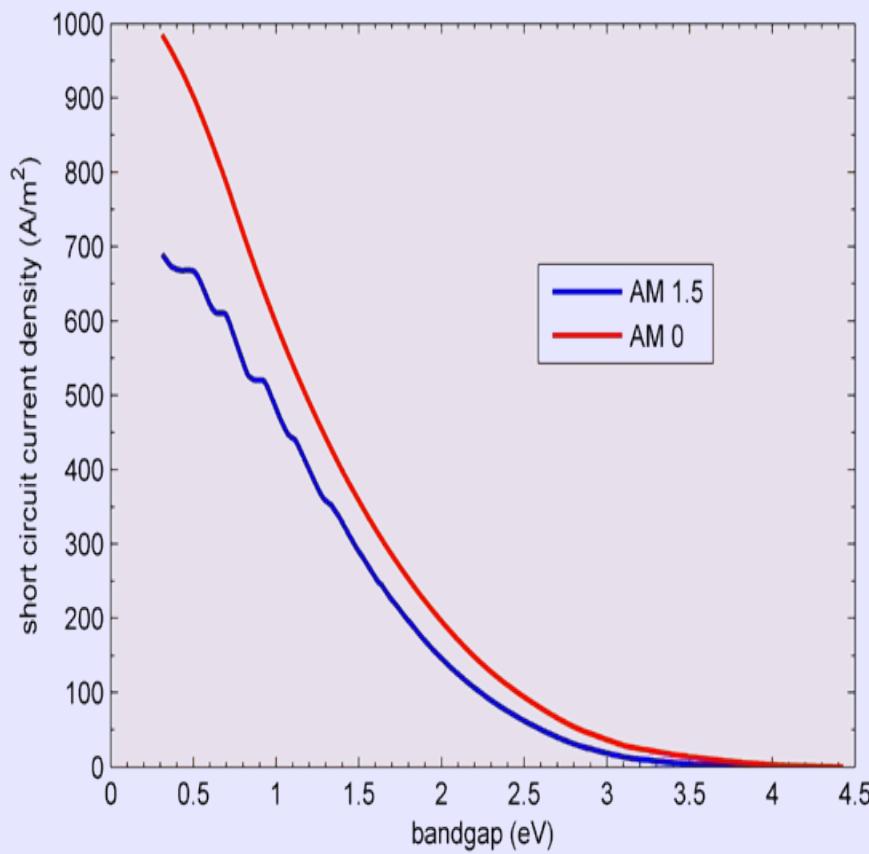
For ideal case:

$$J_L = J_{SC}$$

(but not true in reality)

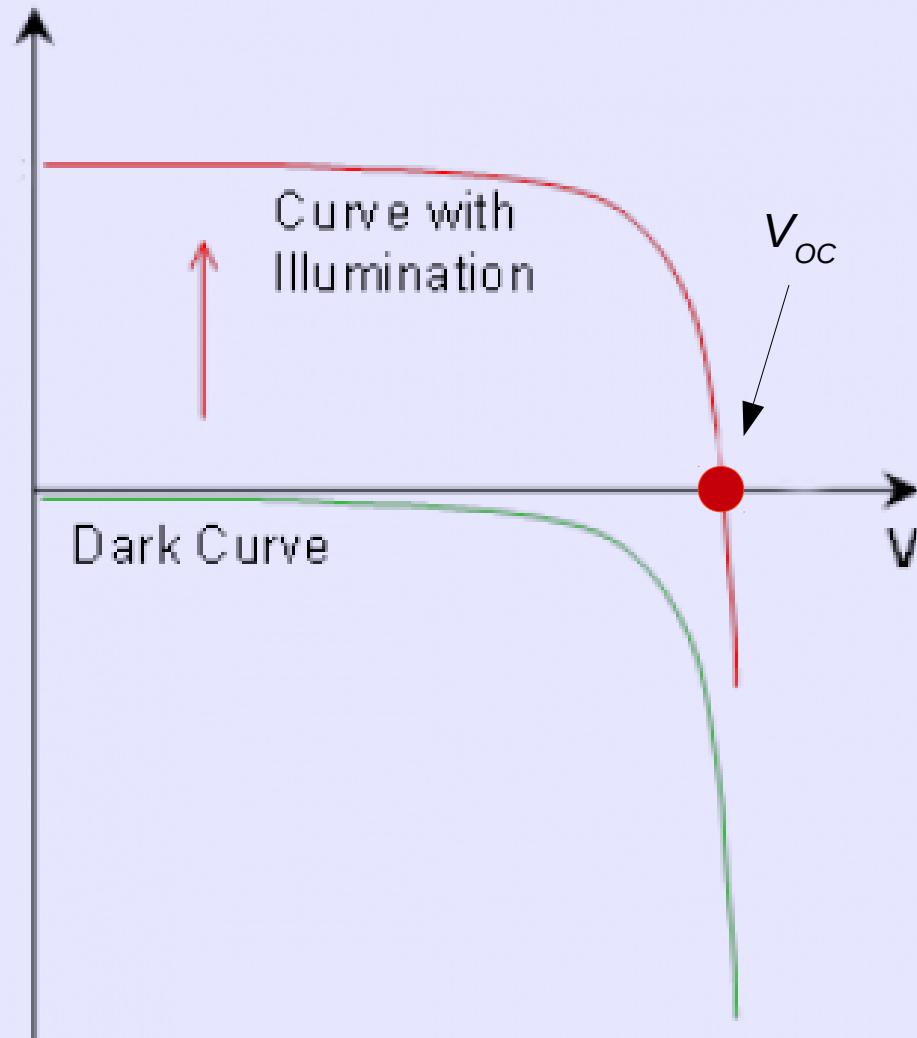


Short Circuit Current - J_{SC}





Fill Factor - FF



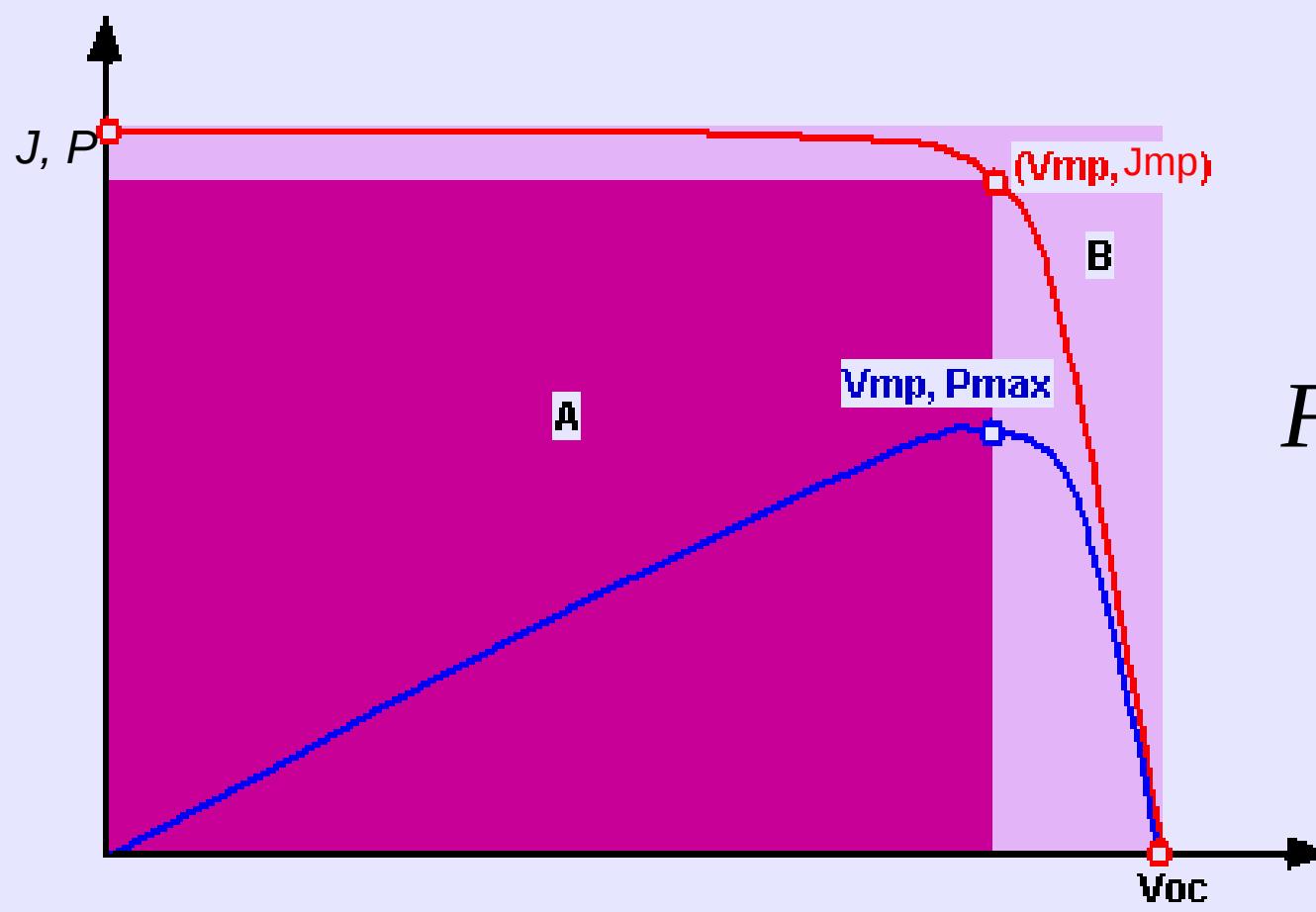
Estimating V_{oc}

$$V_{OC} = \frac{k_B T}{e} \ln \left(\frac{J_L}{J_O} - 1 \right)$$

Most significant parameter that affects the size of V_{oc}



Fill factor defines the “squareness” of the J-V curve



$$FF = \frac{\text{area } A}{\text{area } B}$$

$$FF = \frac{J_{mp} \times V_{mp}}{J_{SC} \times V_{OC}}$$



$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mp}}{P_{in}}$$

$$\eta = \frac{J_{mp} \times V_{mp}}{P_{in}} = \frac{FF \times J_{SC} \times V_{OC}}{P_{in}}$$

$$\eta = \frac{FF \times J_{SC} \times V_{OC}}{1000 W m^{-2}}$$

AM1.5!

Note: Units OK because J measured in Am^{-2} .
i.e. m^{-2} cancel (Be careful)

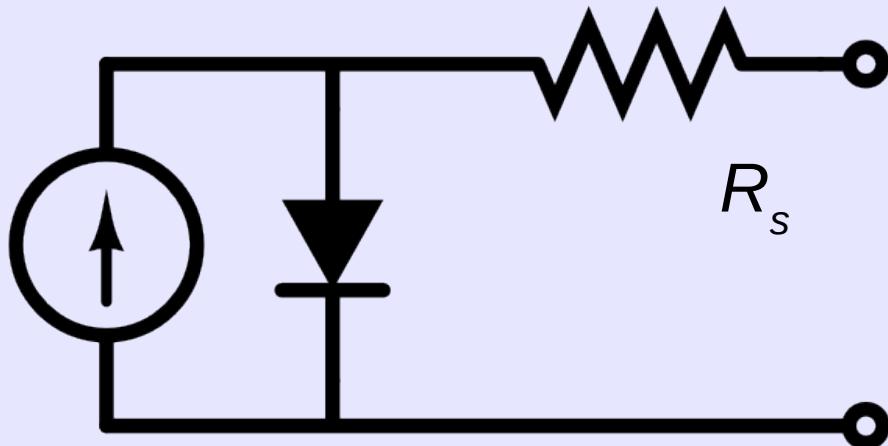


Series Resistance, R_s

Origin of **series resistance** in solar cell:

- Simply a property of real materials – i.e. non infinite mobility
- Resistances associated with back and front contacts to cell

Can represent sum of series resistance effects in equivalent circuit using a single resistor in series:



$$J = J_L - J_0 \left[\exp\left(\frac{e(V + JR_s)}{k_B T}\right) - 1 \right]$$

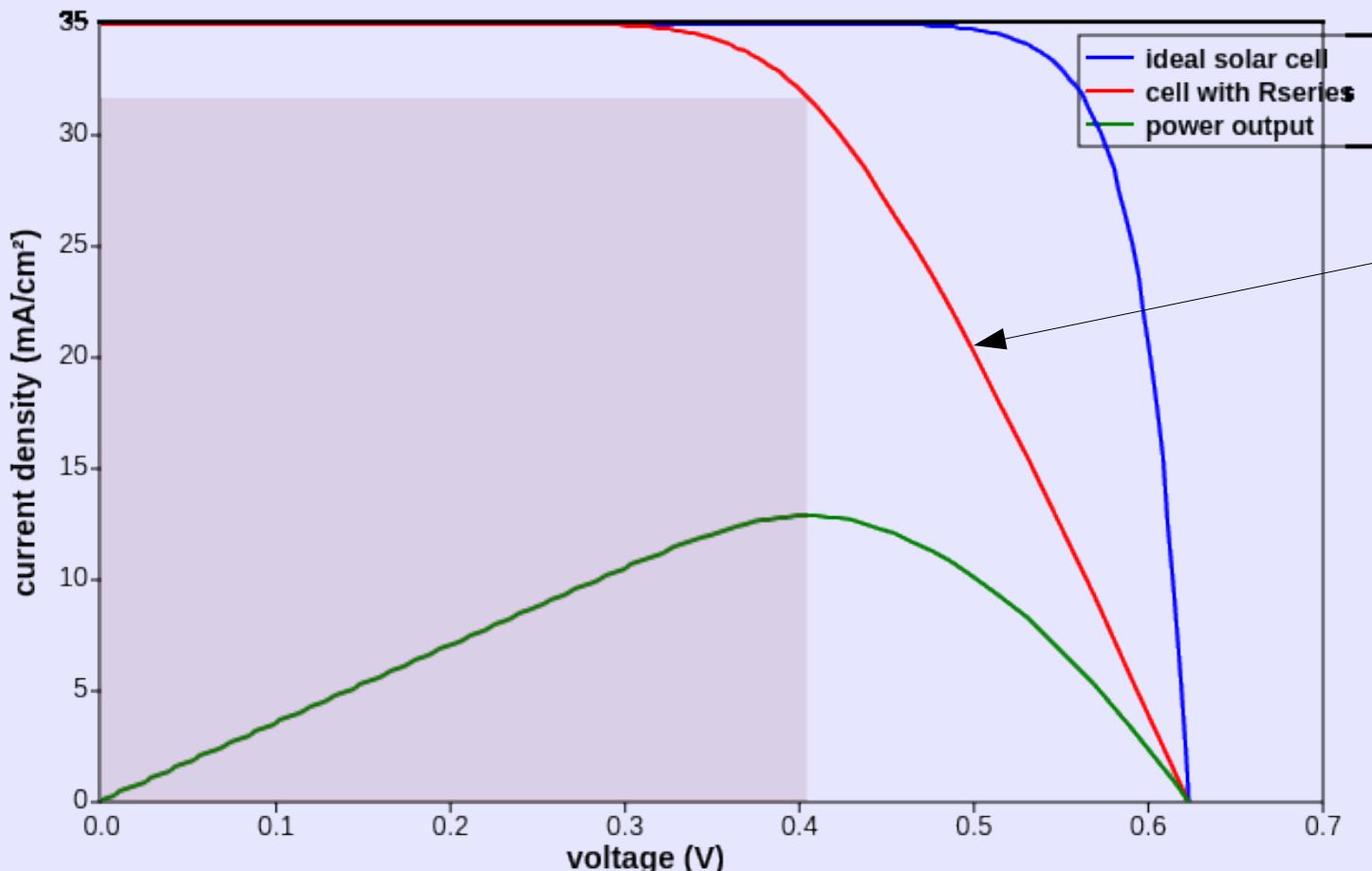
Uh oh!
Recursive Equation!



Series Resistance

Effect of R_s on shape of J/V curve:

- V_{oc} reduced
 - FF reduced
- $\longrightarrow \eta \text{ decreases!}$



$$R_s \approx -\frac{V}{J}$$

For moderate R_s

<http://pveducation.org/pvcdrum/solar-cell-operation/series-resistance>

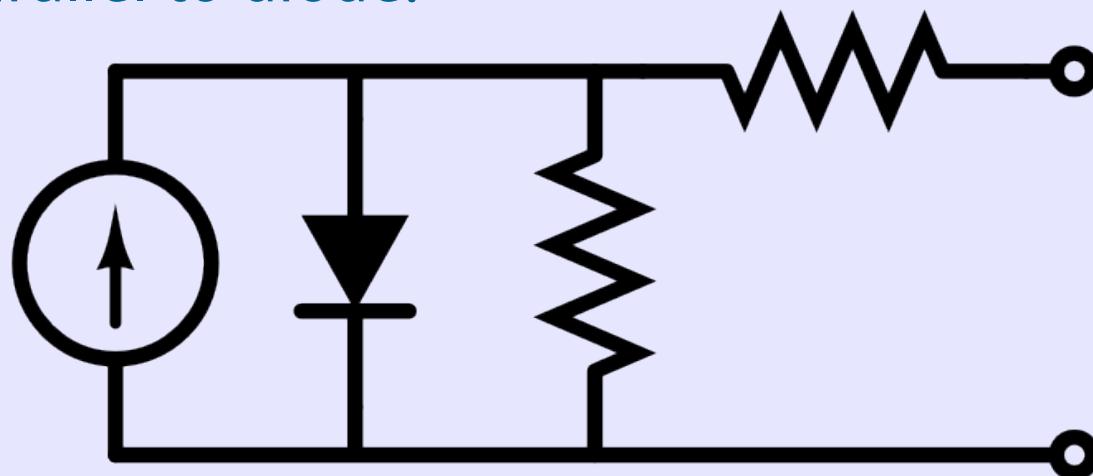


Shunt Resistance, R_{SH}

Origin of shunt resistance in solar cell:

- Usually the result of poor fabrication methods
- Short circuit paths between electrodes of cell

Can represent sum of shunts in equivalent circuit using a single resistor in parallel to diode:



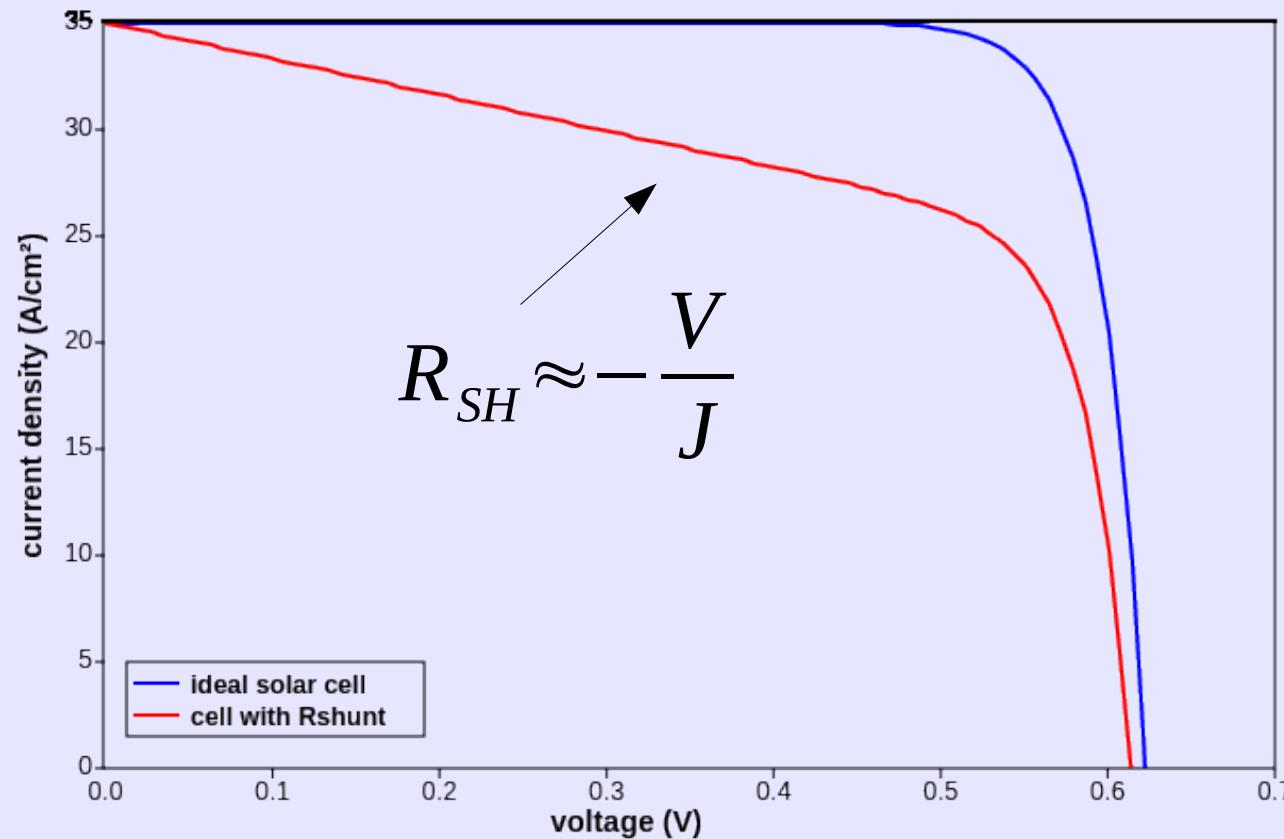
$$J = J_L - J_0 \left[\exp\left(\frac{e(V + JR_s)}{k_B T}\right) - 1 \right] - \frac{V + JR_s}{R_{SH}}$$



Shunt Resistance, R_{SH}

Effect of R_{SH} on shape of JV curve:

- FF decreases
- V_{OC} decreases for very low R_{SH} ($< 50 \Omega \text{ cm}^2$)





No such thing as an **ideal** diode

$$J = J_0 \left[\exp\left(\frac{eV}{nk_B T}\right) - 1 \right]$$

- n – typically takes values of between 1 and 2 (but can be higher)
- Originally used as a fudge factor for empirical data
- Now understood to be related to quality of SC material
- Related to carrier recombination (L4)



Diode Ideality Factor



IDEA:

Increase n to increase V_{oc}
(and efficiency)!

Hooray! You've just solved all
our problems. And we'll be home in time
for tea.

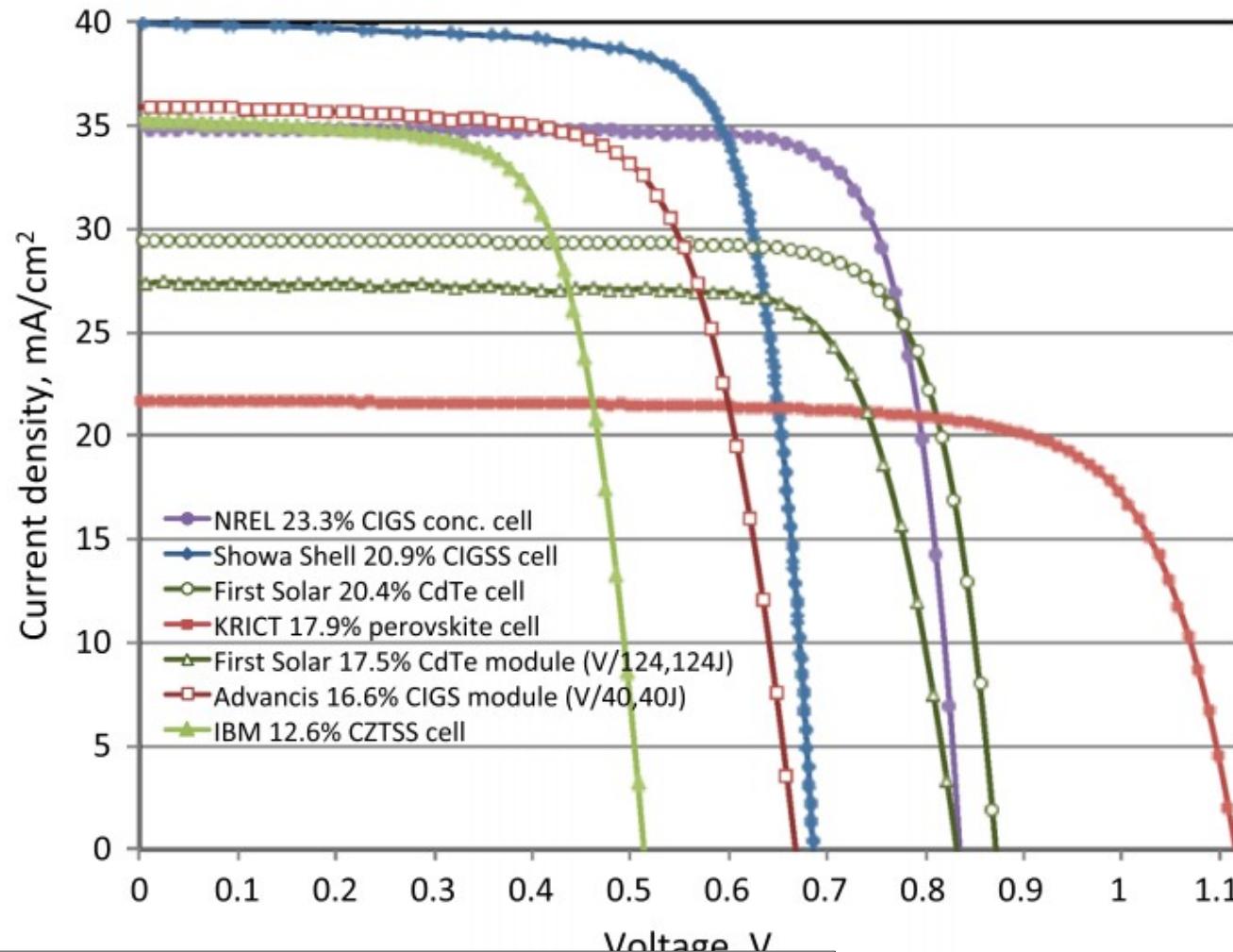


Diode Ideality Factor



Nice Try

- n and J_o inextricably linked
- Increase $n \rightarrow$ increase in J_o
- Net effect: **decrease** in V_{oc}
(not increase, D'oh!)



ACCELERATED PUBLICATION

Solar cell efficiency tables (version 44)

Martin A. Green^{1*}, Keith Emery², Yoshihiro Hishikawa³, Wilhelm Warta⁴ and Ewan D. Dunlop⁵

GO READ THIS!



External Quantum Efficiency (EQE)

The ratio of charge carriers collected to the number of incident photons (of a given energy)

For a given photon energy:

$$EQE = \frac{\text{electrons} \cdot s^{-1}}{\text{photons} \cdot s^{-1}} = \frac{\text{current}/e}{\text{total photon power}/h\nu}$$

Shape of EQE curve (i.e. plot over energy range) depends on:

- The material's absorption coefficient
- The recombination rate of free carriers (lifetime!)



Internal Quantum Efficiency (EQE)

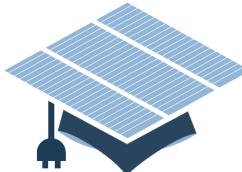
Only accounts for photons that make it into the absorber. i.e. accounts for reflection and transmission

For a given photon energy:

$$IQE = \frac{EQE}{1 - R - T}$$

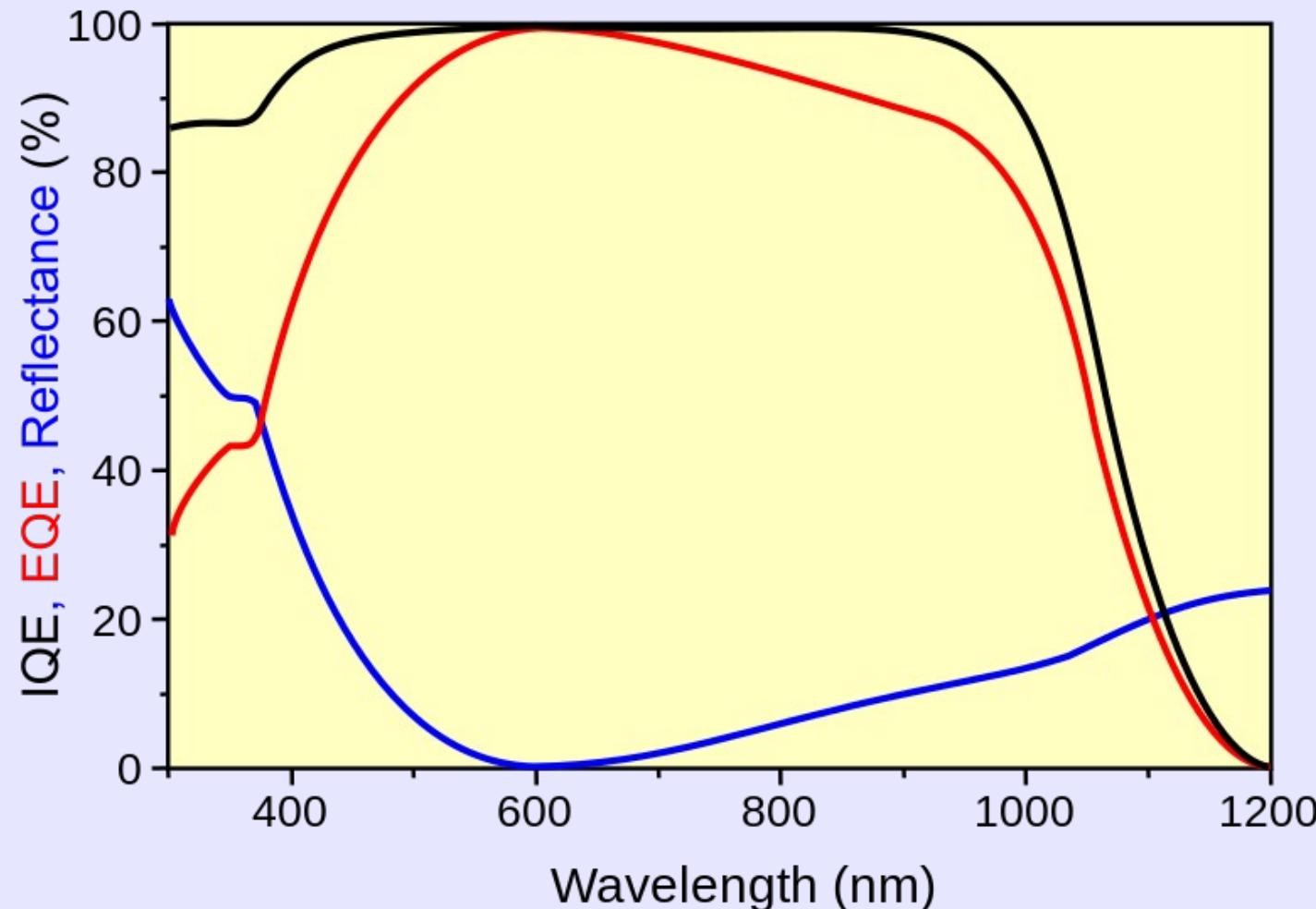
i.e. to maximise EQE need to minimise R and T. How?

- Anti-reflection coatings
- Increasing optical path lengths through absorbers
- Back reflectors



Example: Si cell

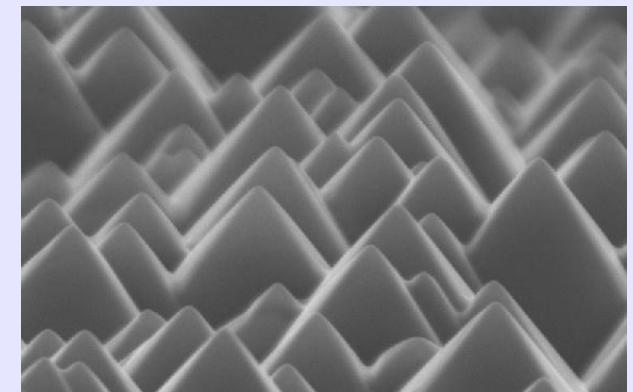
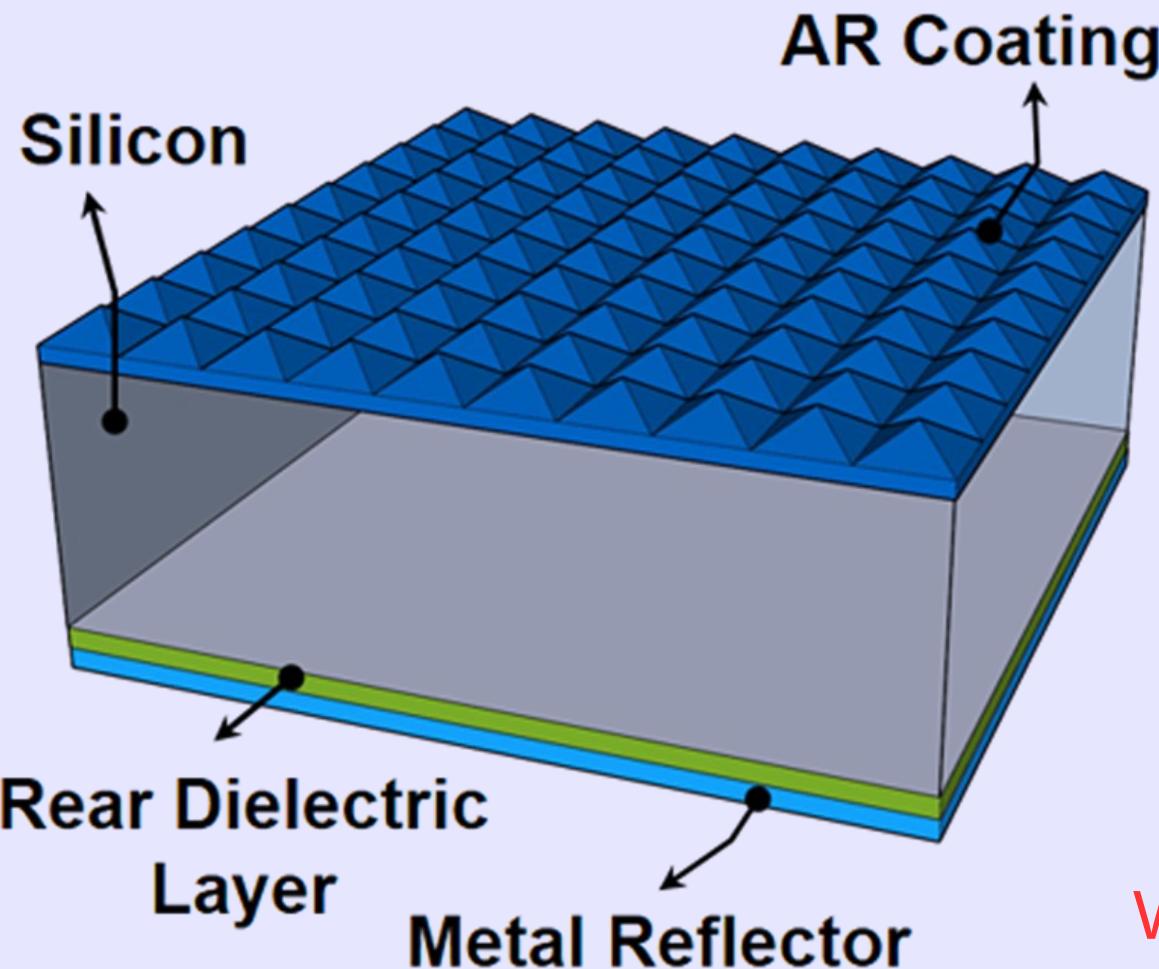
— Internal Quantum Efficiency
— External Quantum Efficiency
— Surface Reflectance



http://en.wikipedia.org/wiki/Quantum_efficiency

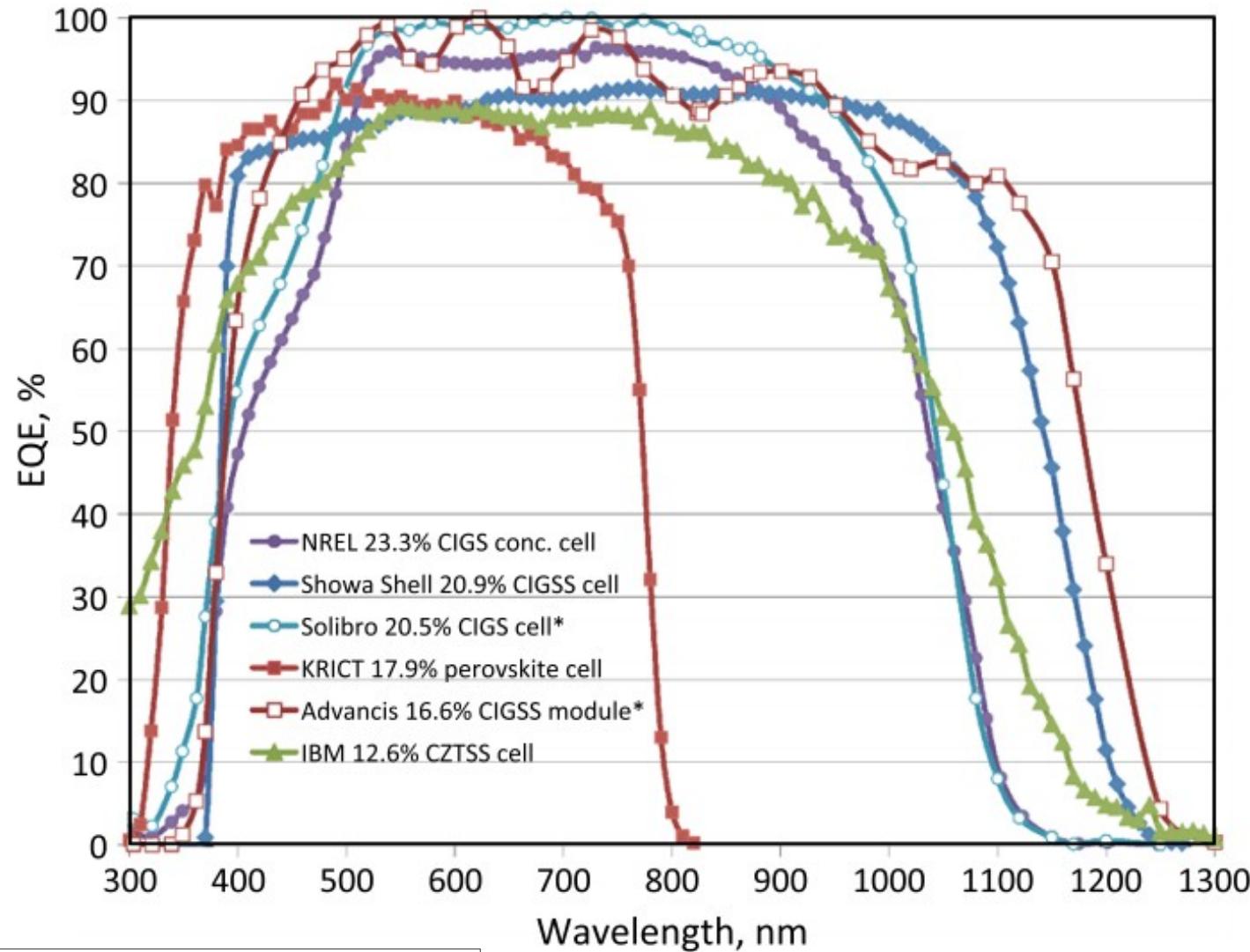


Classic crystalline Si cell design - “pyramids”



SEM micrograph of Si surface

What about thin-film PV?





- Super speedy history of PV
- The photovoltaic effect
- AM1.5 spectrum
- Solar simulators and ratings
- The ideal diode equation + equivalent circuits
- J-V curves and important device parameters
- Parasitic resistances
- External quantum efficiency (EQE)