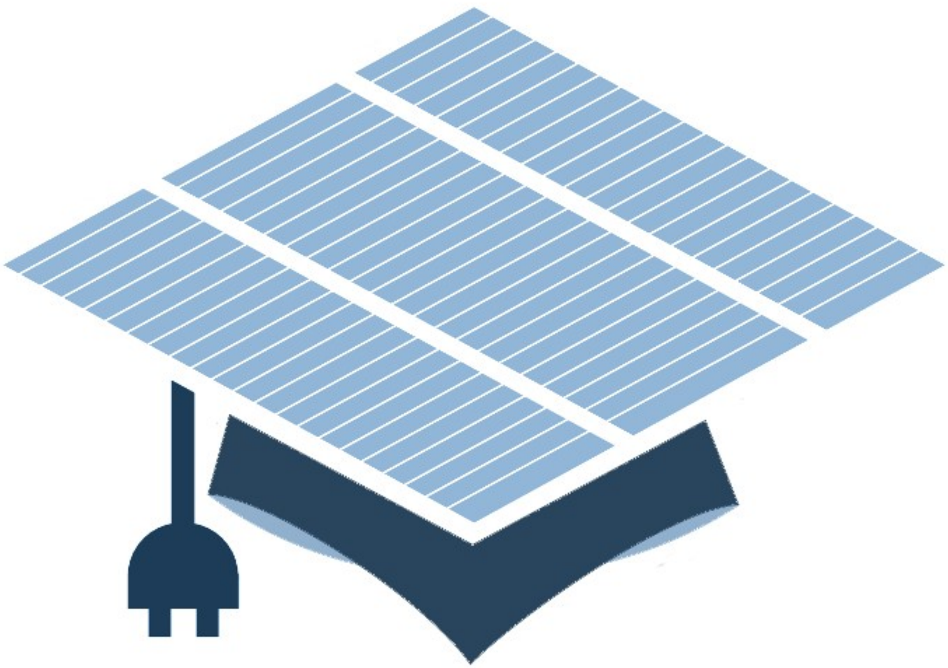


Fundamentals of Photovoltaics

Nov 5th – 7th 2014

UNIVERSITY OF LIVERPOOL

Course Overview

Wed Nov 5

1. **The Sun –** Mauritzio 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

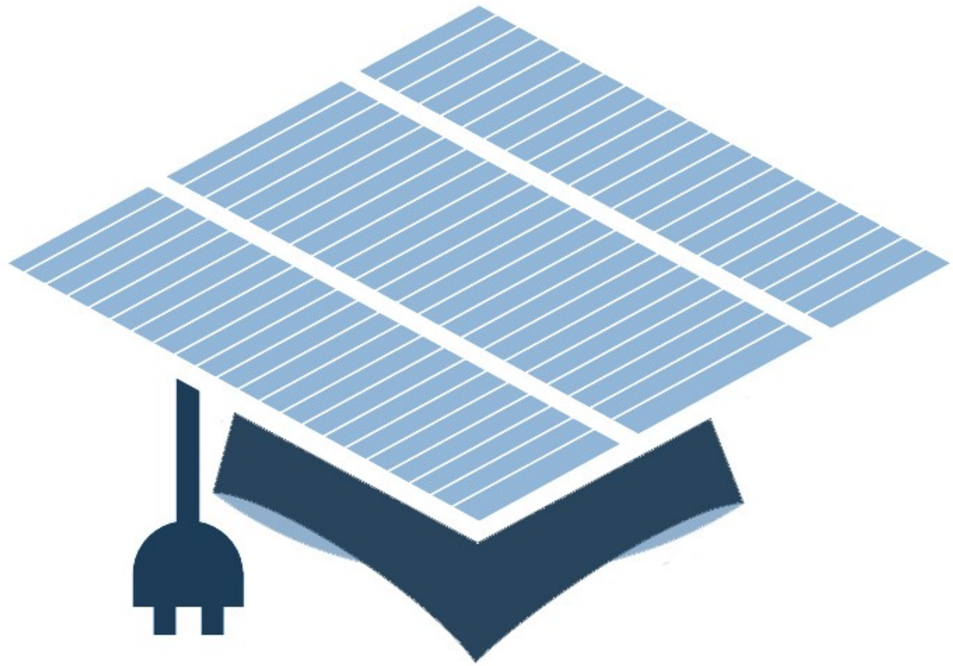
Mon Nov 10

EXAM

Download Lectures Overview here!

Questions?

#cdtpvC1



Lecture 1
Solar spectrum and basic device response

R. Treharne

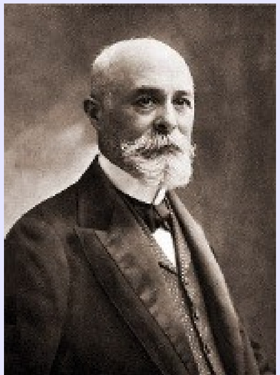
Nov 5th 2014

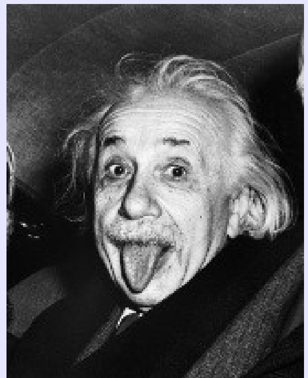
UNIVERSITY OF LIVERPOOL

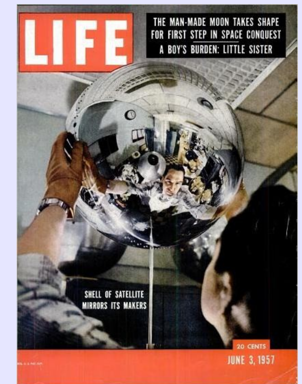
Lecture Outline

- 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/

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PHOTOVOLTAICS

L2

SS History of PV

1977:
U.S. DOE launches Solar Energy Research Institute. Now NREL.
Total PV manufacturing capacity exceeds 500 kW

1982:
First MW capacity solar plant goes online.
Hisperia, California

1992:
CdTe solar cell 15.9% efficient
Univ. South Florida.

1994:
GaAs solar cells > 30%
NREL

First Solar®

2000:
First Solar starts production

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

2010:
Global installed PV capacity reaches 40GW

2012:
Emergence of high-efficiency perovskite cells.


REVIEW ARTICLE
PUBLISHED ONLINE: XX JULY 2014 | DOI: 10.1038/NPHOTON.2014.134
nature photonics

The emergence of perovskite solar cells

Martin A. Green[1]*, Anita Ho-Baillie[1] and Henry J. Snaith[2]

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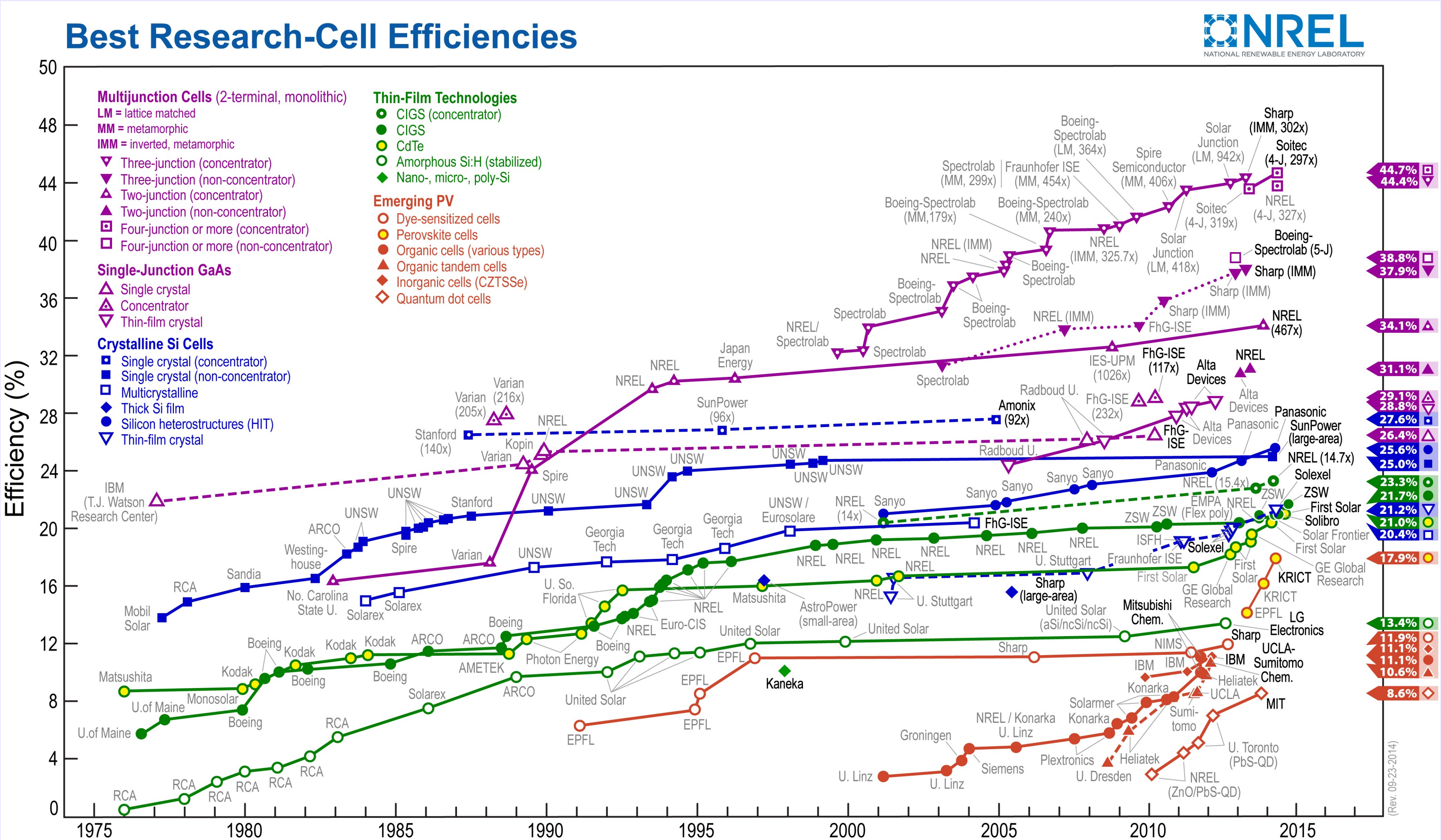
L2

SS History of PV



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

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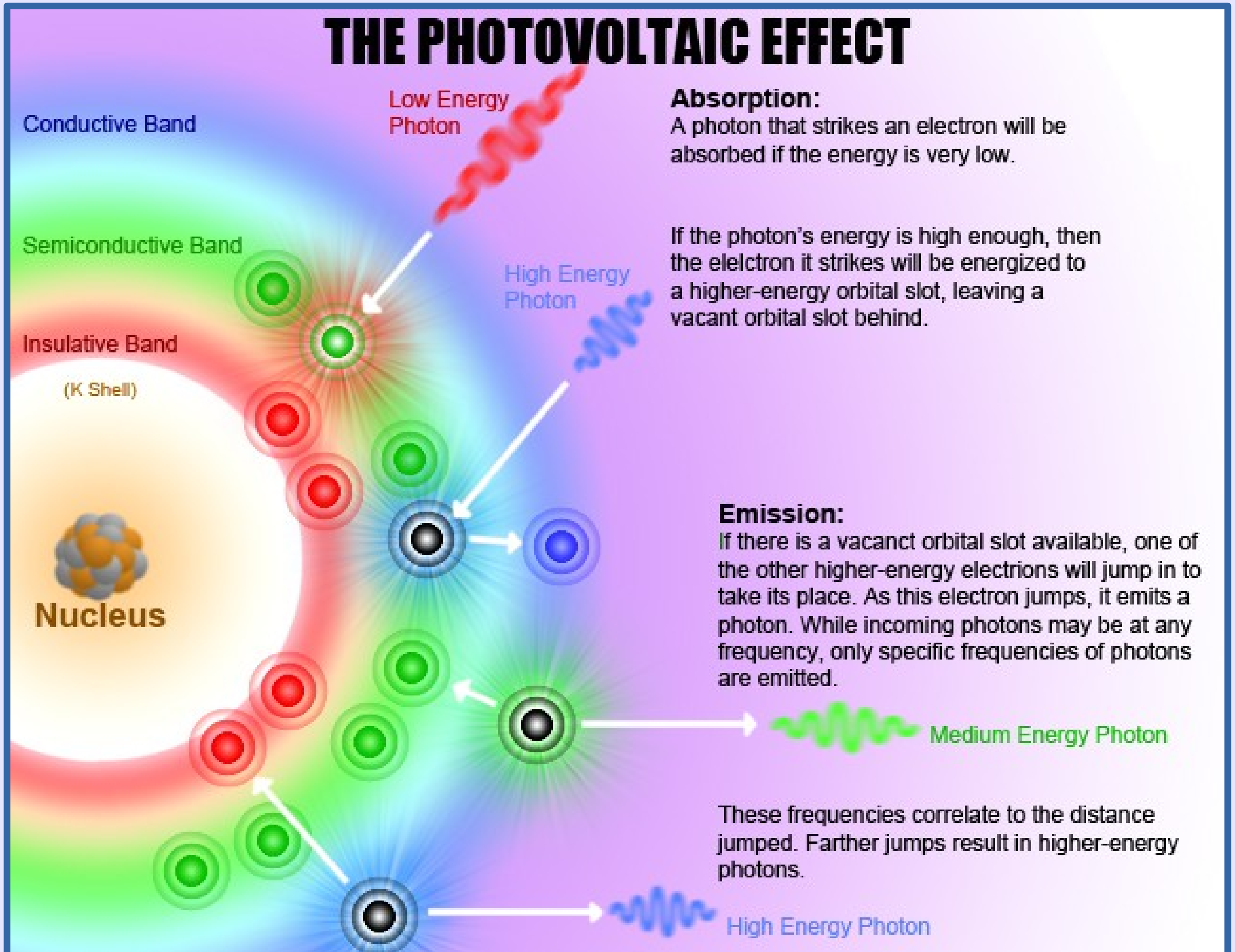
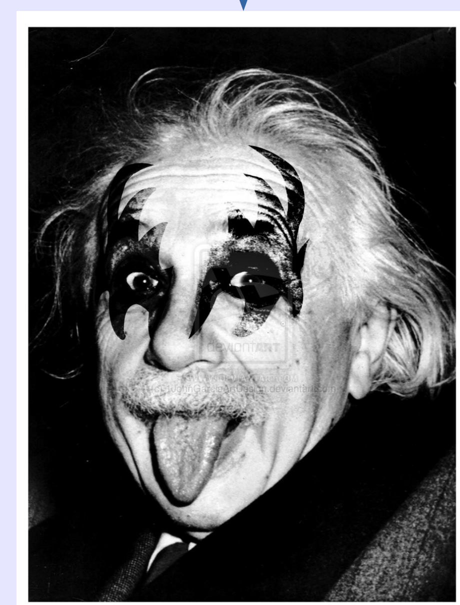
Research Council

Photovoltaic Effect



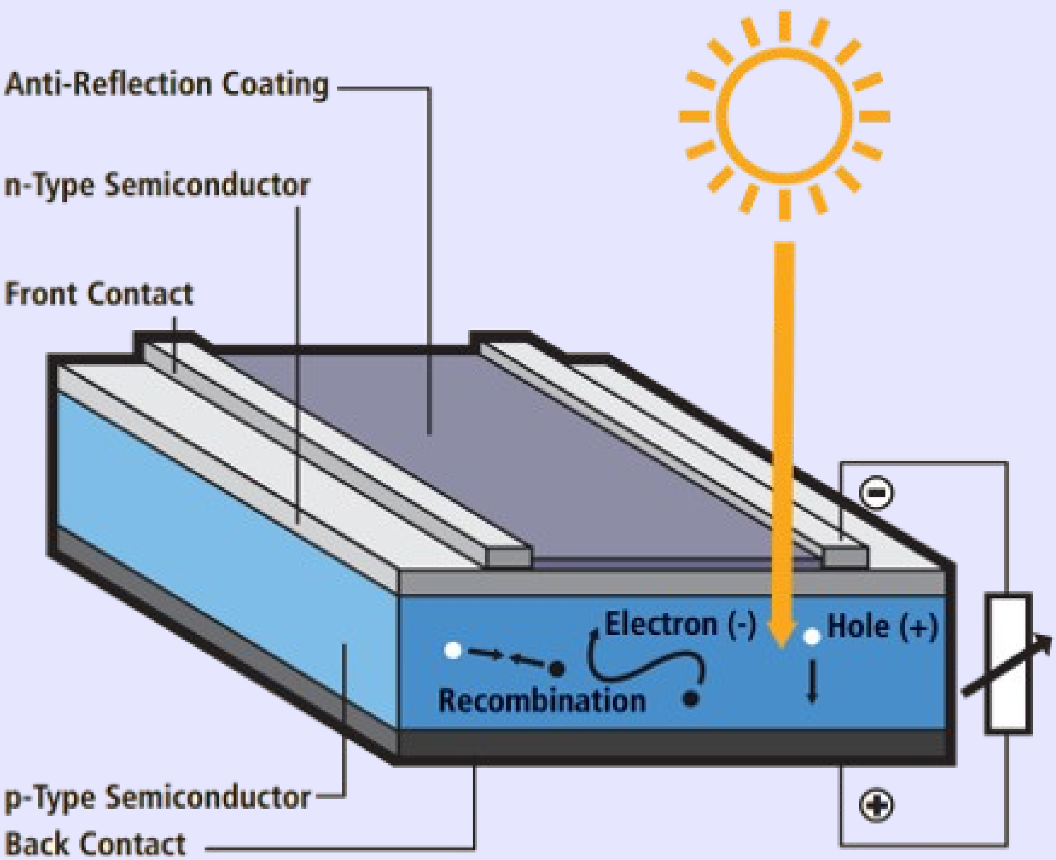
Do you know the difference between the **photoelectric** and **photovoltaic** effects?



http://sargosis.com/articles/science/how-pv-modules-work/the-photoelectric-and-photovoltaic-effects/

Photovoltaic Effect

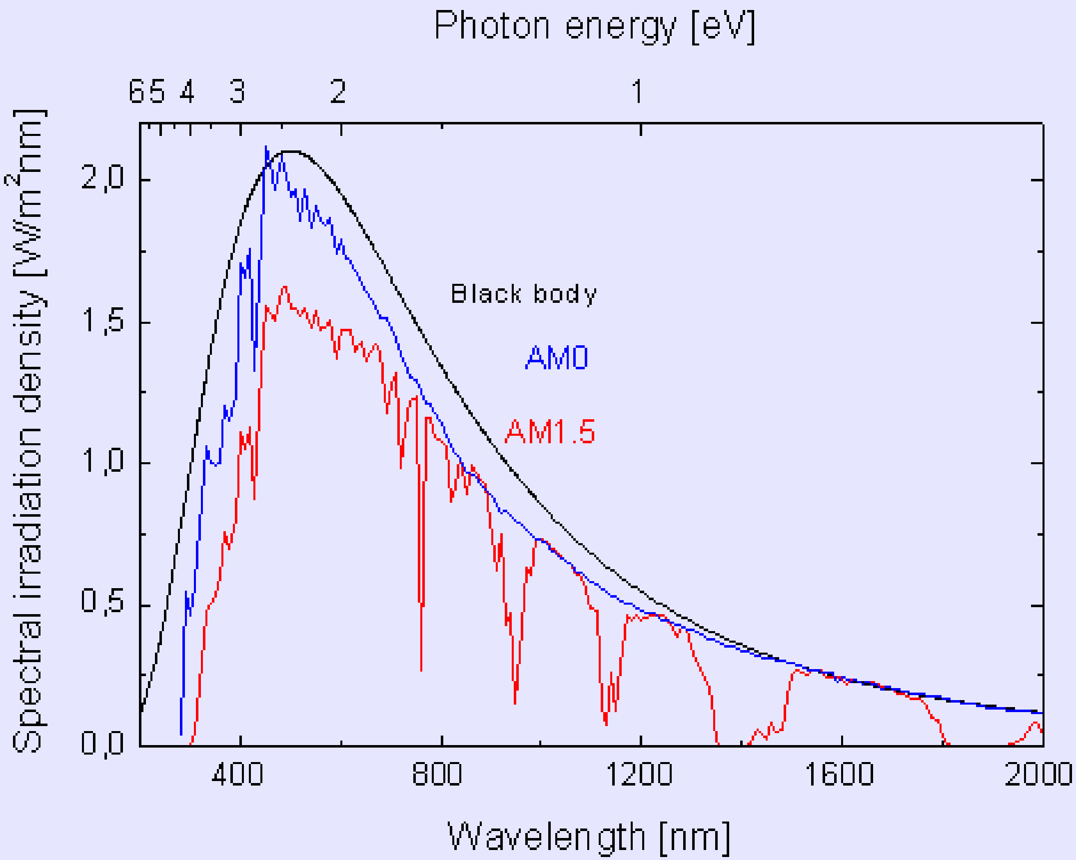
How do we use the **PV** effect to do work?



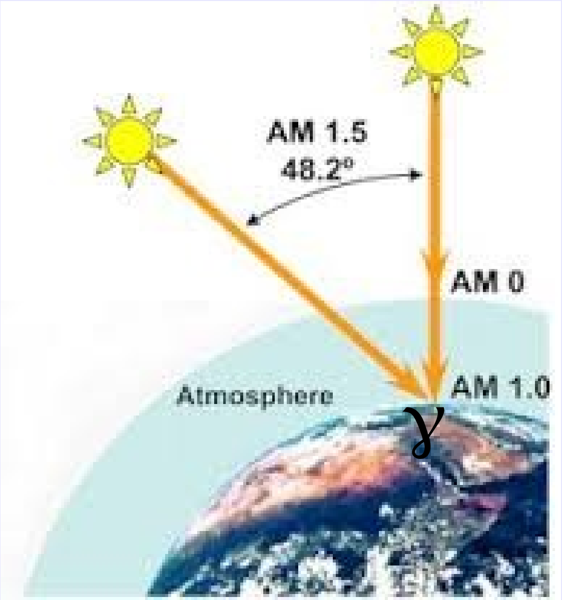
- Must separate generated electron-hole pair
- Prevent recombination
- Need internal field
- How? JUNCTION!
- Hold in your excitement until **L5**

AM1.5 Spectrum

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



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



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

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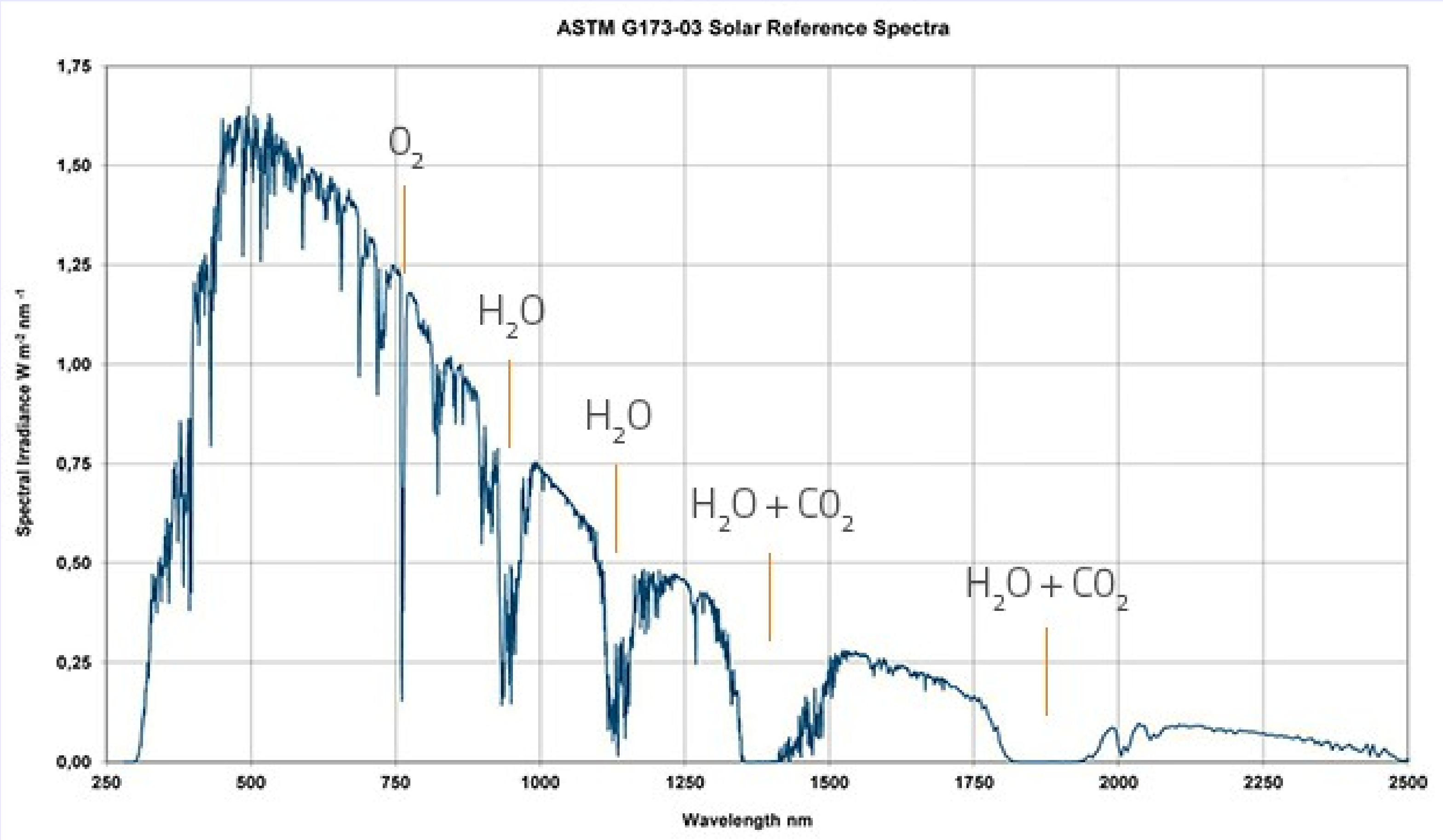
L2

AM1.5 Spectrum



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

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

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Solar Simulators

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

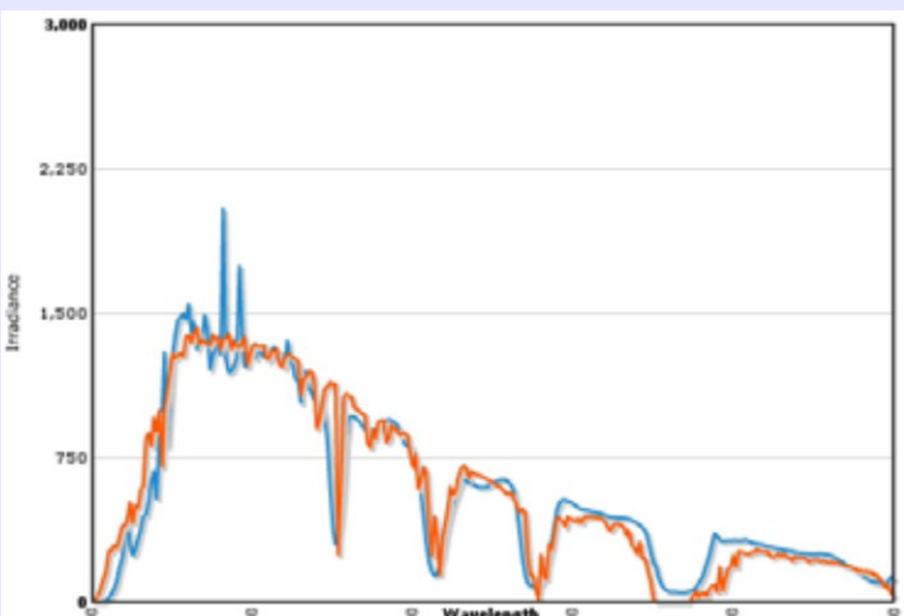
1) Spectral content
2) Spatial uniformity
3) Temporal stability

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

TS-SPACESYSTEMS



You will get to use this! Be excited.

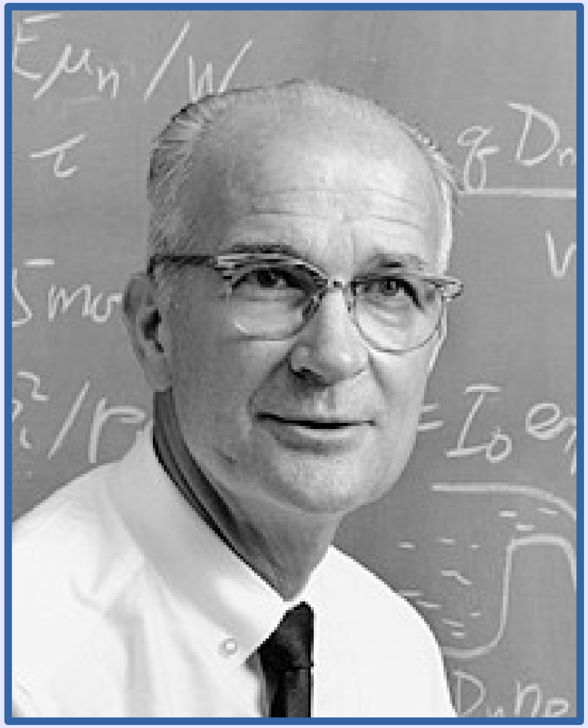
Ideal Diode Equation

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)



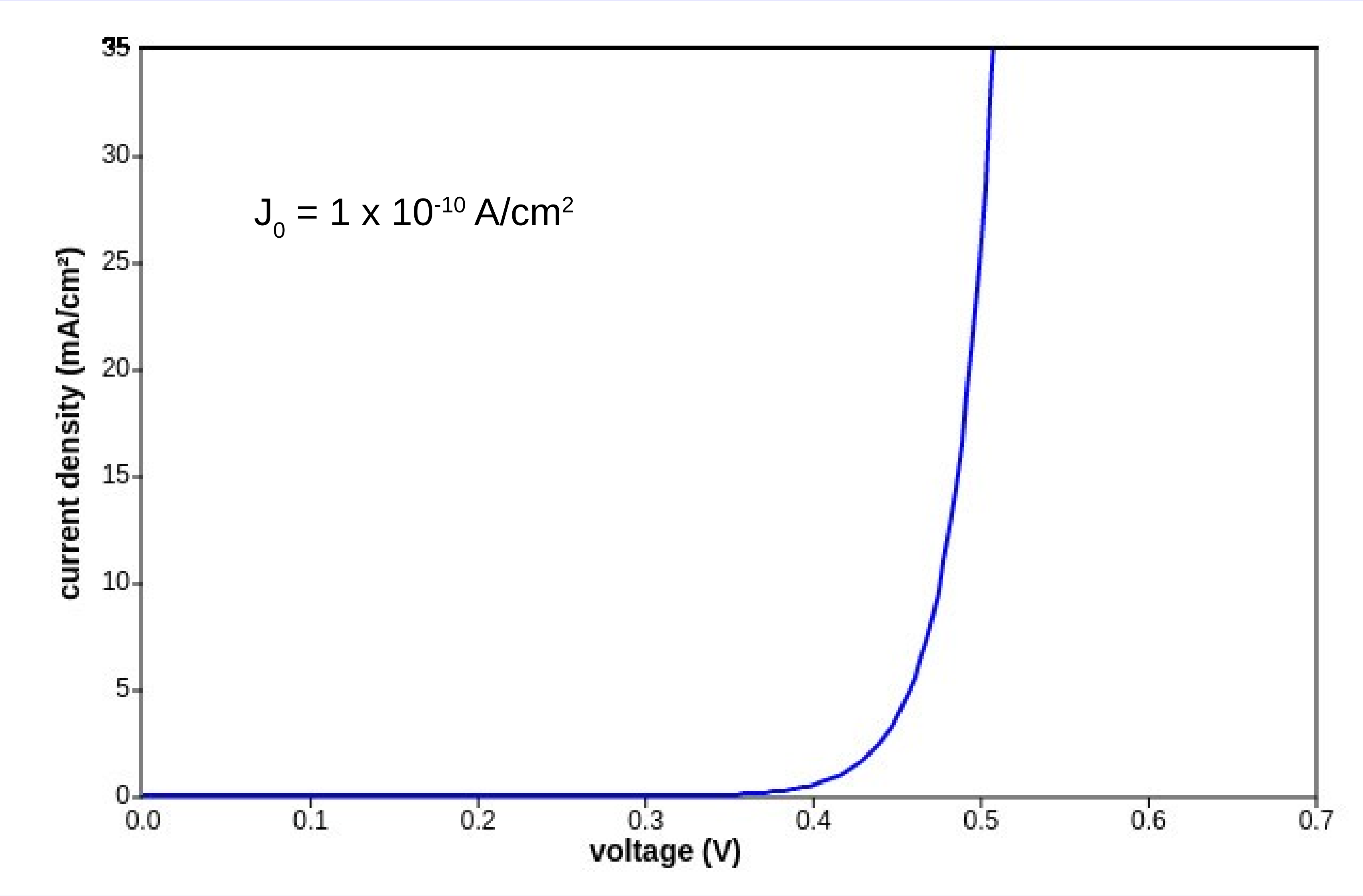
William Shockley:
Co-inventor of the transistor
with Bardeen and Brattain 1948

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



http://pveducation.org/pvcdrom/pn-junction/diode-equation

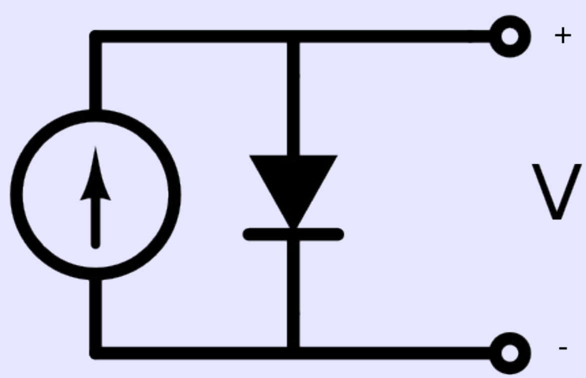
Ideal diode for solar cell

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}

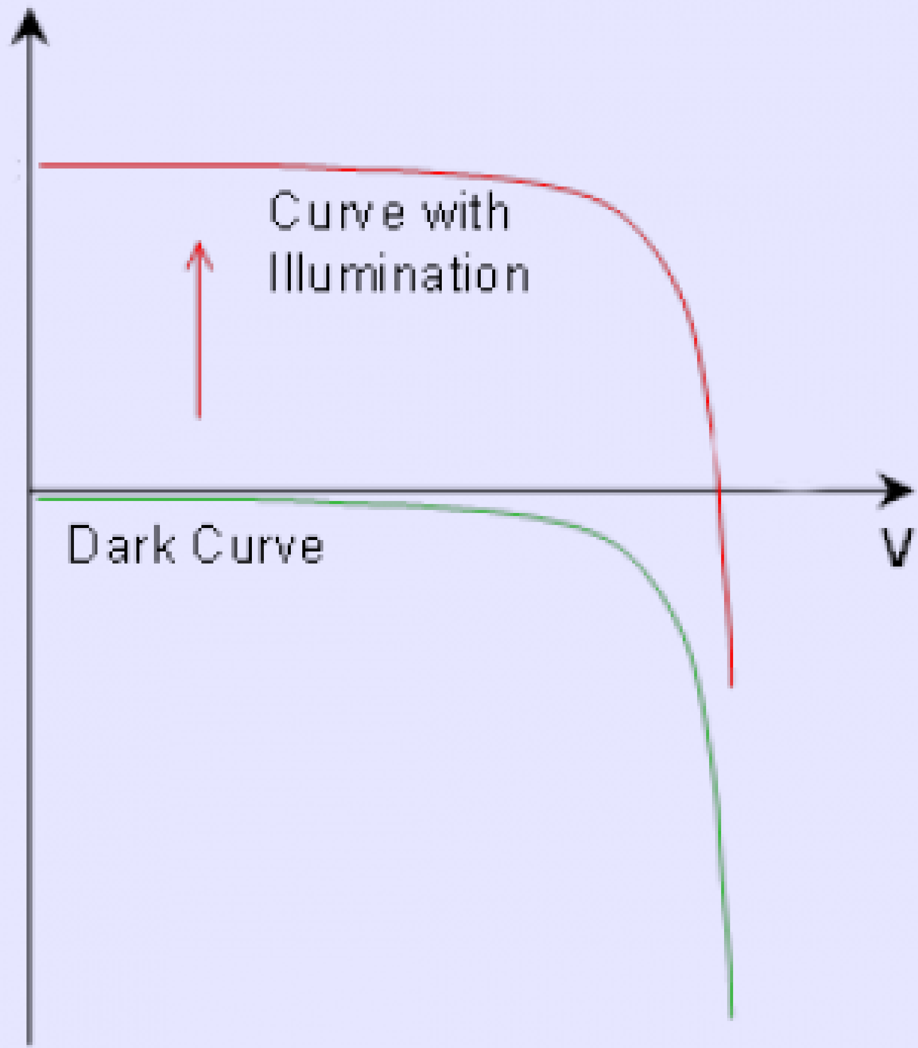
$$J = J_L - J_{dark}$$

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

Equivalent Circuit:
Ideal solar cell



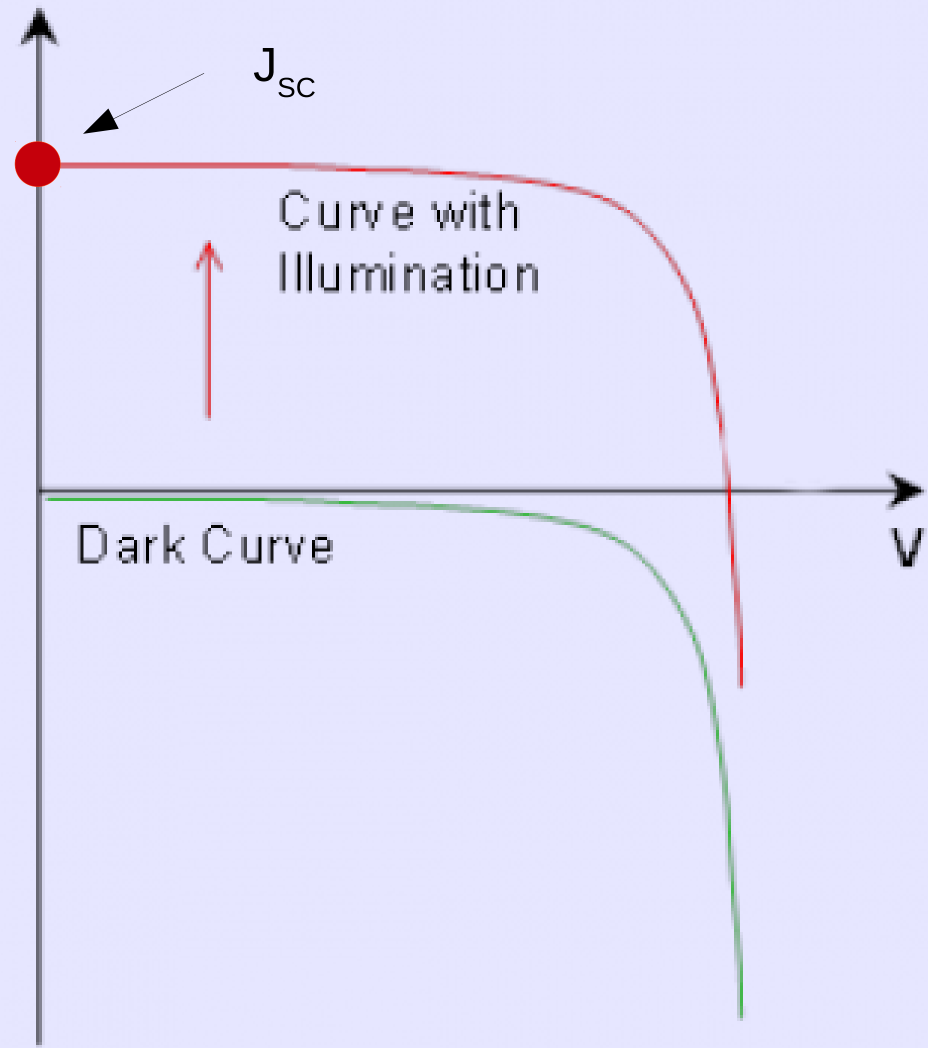
Light JV response



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?

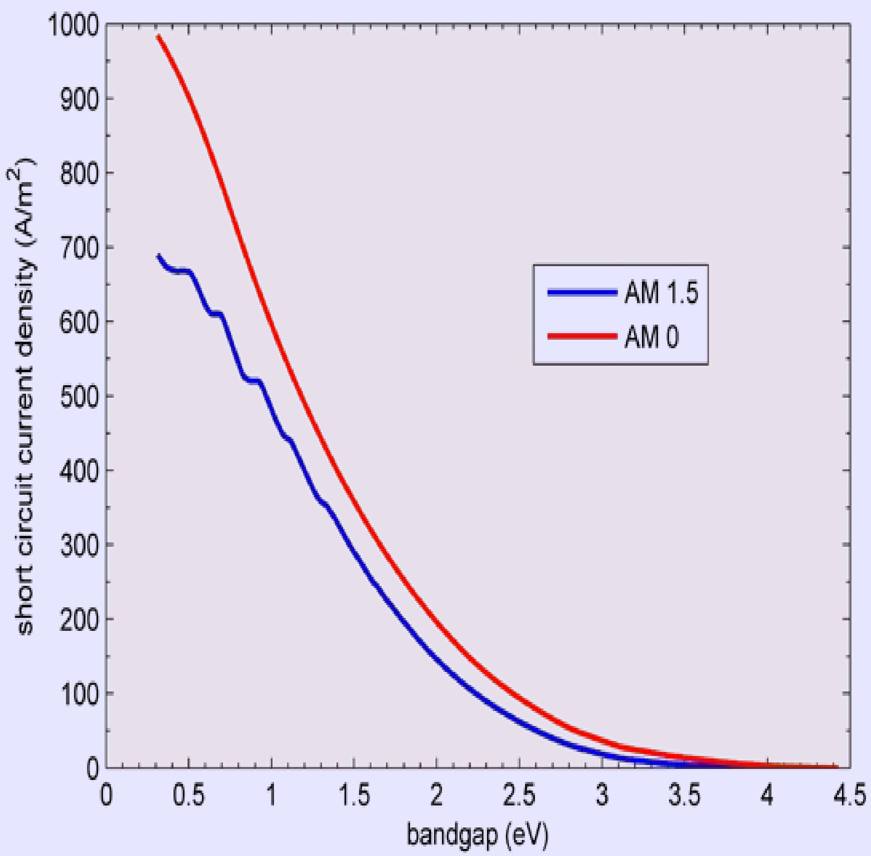
- **Intensity**
- **Optical properties** – REFLECTION!
- **Lifetime (L5)**
- **Band gap**

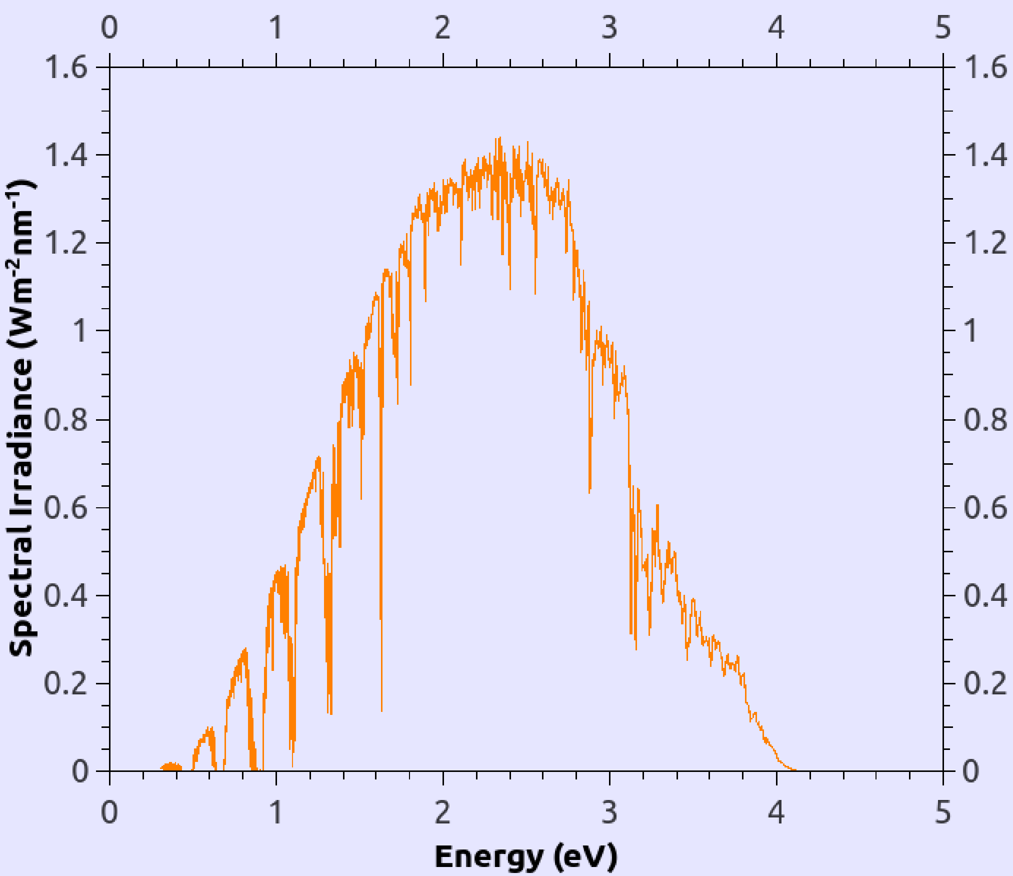
For ideal case:

$$J_L = J_{sc}$$

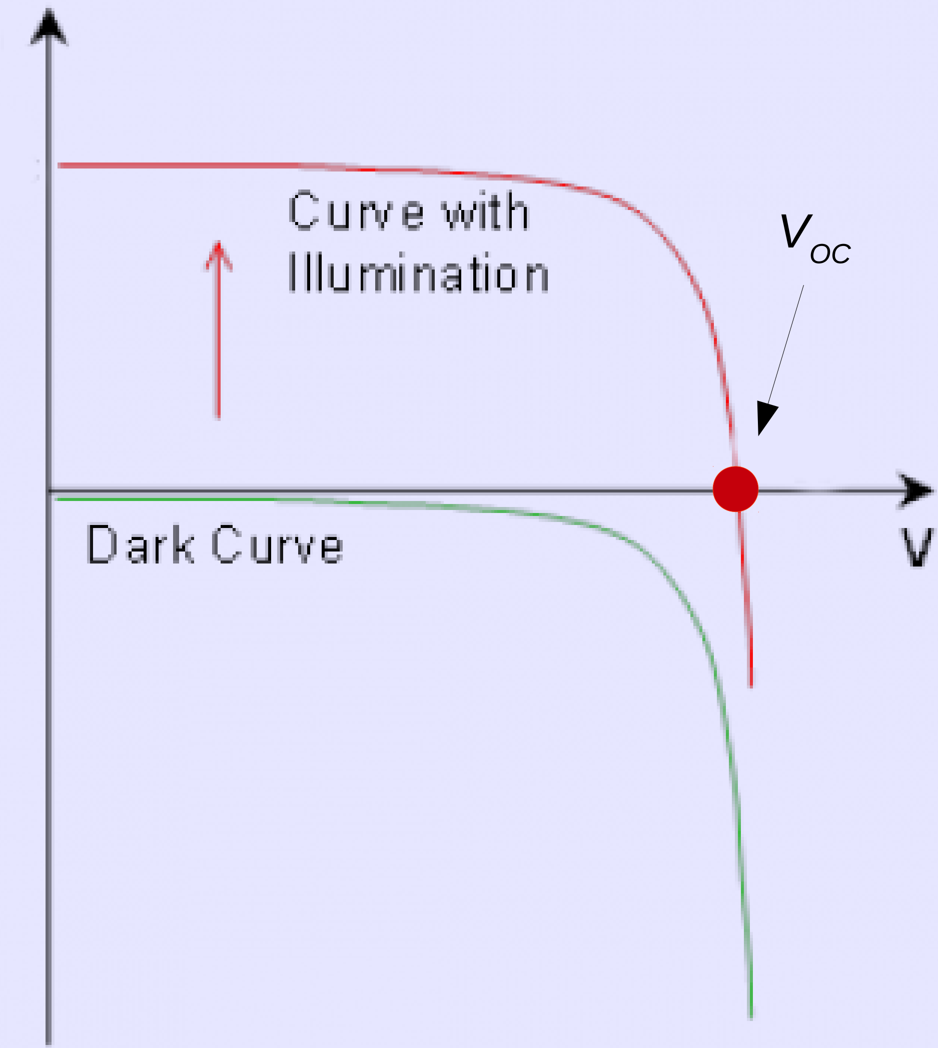
(but not true in reality)

Short Circuit Current - J_{SC}





Fill Factor - *FF*



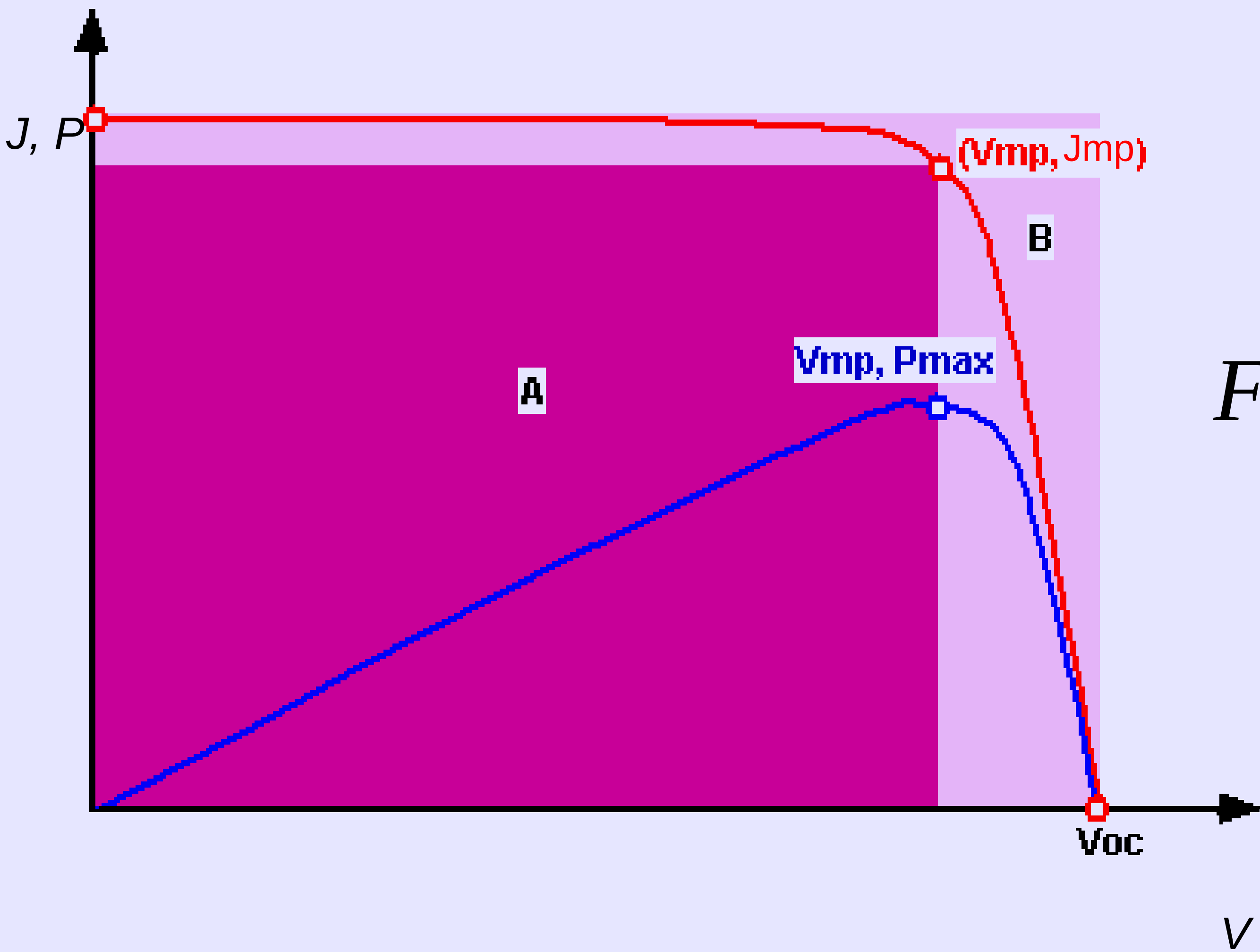
Estimating V_{oc}

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

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

Fill Factor - *FF*

Fill factor defines the "squareness" of the J-V curve



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

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

Efficiency, η

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

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

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

AM1.5!

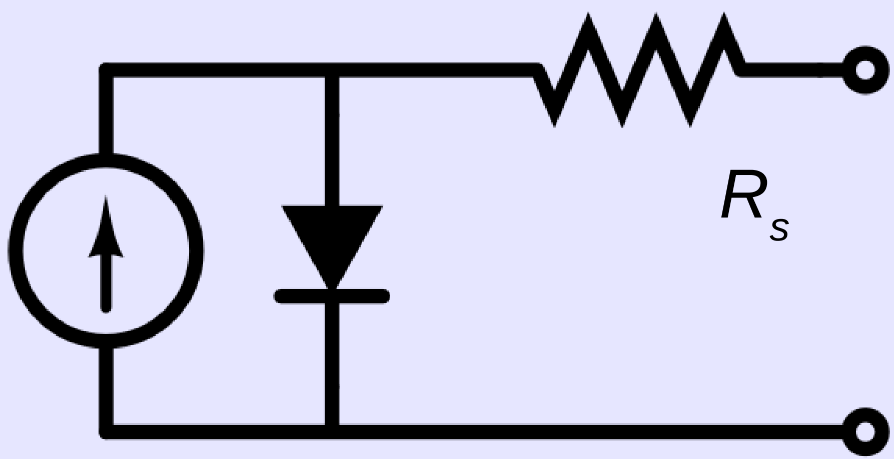
Note: Units OK because *J* measured in Am^{-2}.
i.e. m^{-2} cancel (Be careful)

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**:



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

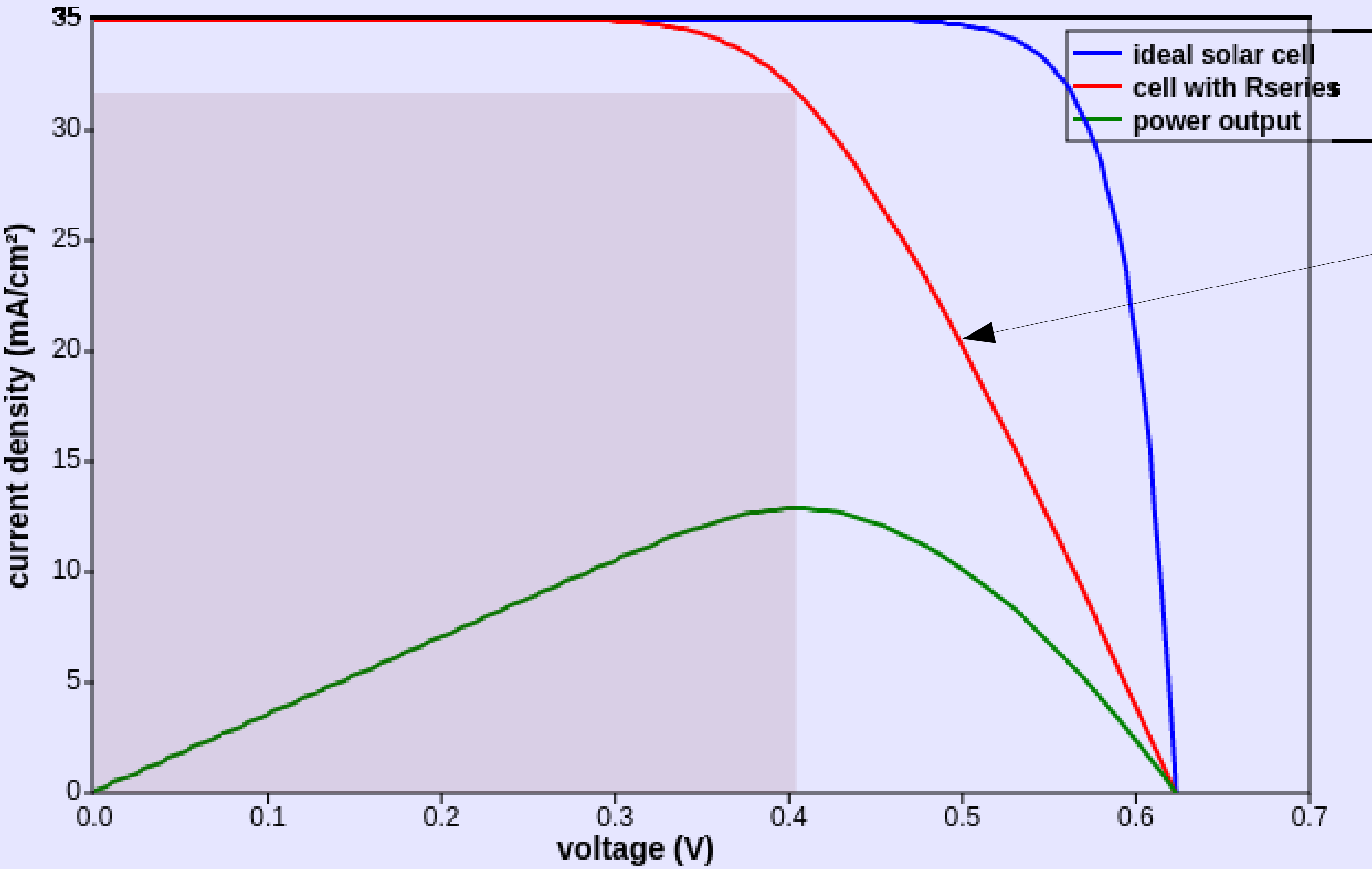
Uh oh!
Recursive Equation!

Series Resistance

Effect of R_s on shape of *JV* curve:

- V_{OC} reduced
- *FF* reduced

η decreases!



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

For moderate R_s

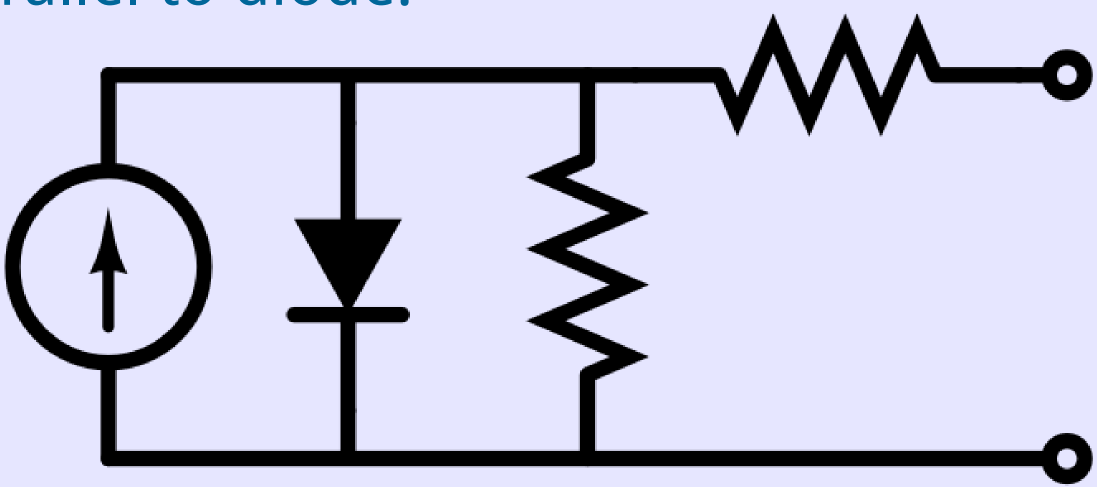
http://pveducation.org/pvcdrom/solar-cell-operation/series-resistance

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:



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

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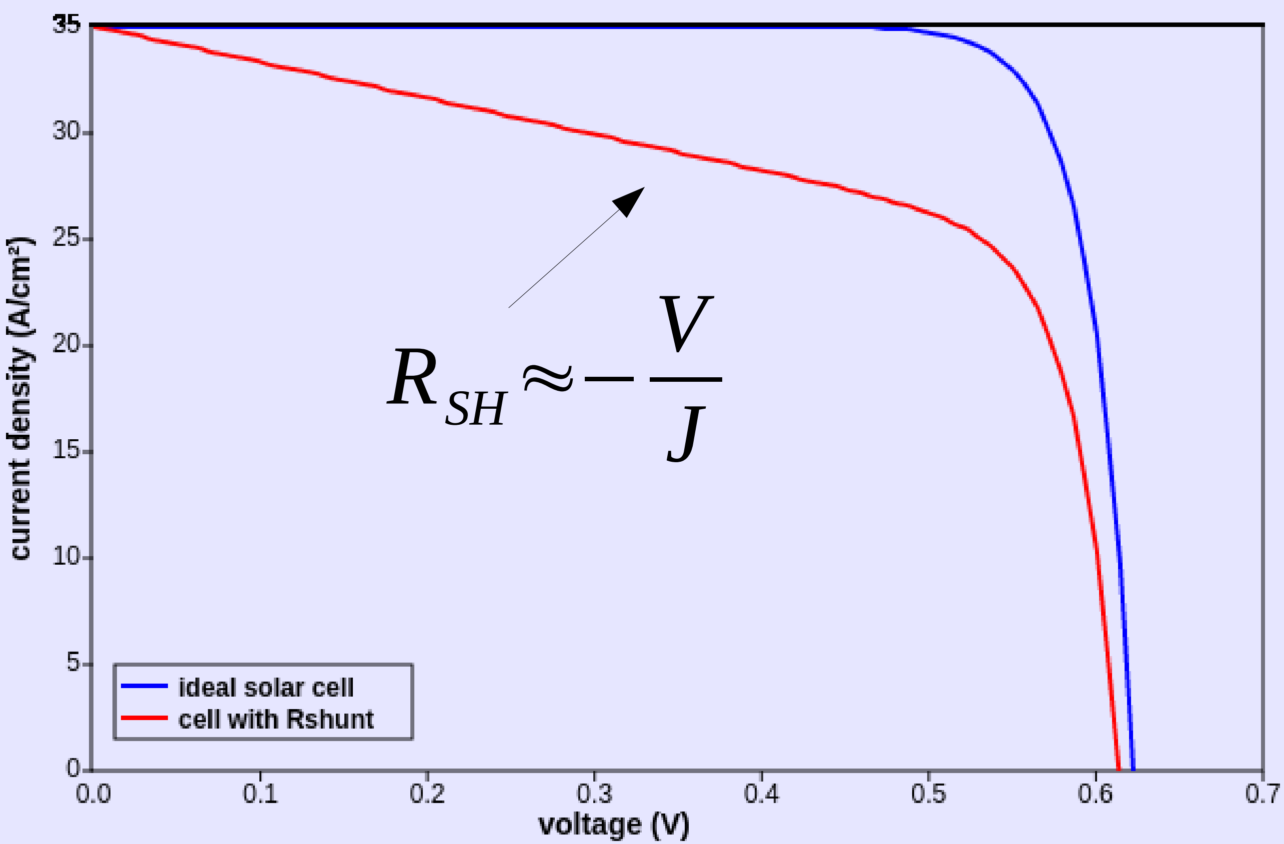
Shunt Resistance, R_{SH}

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

- *FF* decreases
- V_{OC} decreases for very low R_{SH} (<50 Ω cm²)



$$R_{SH} \approx -\frac{V}{J}$$

http://pveducation.org/pvcdrom/solar-cell-operation/impact-of-both-resistances

Ideality Factor

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

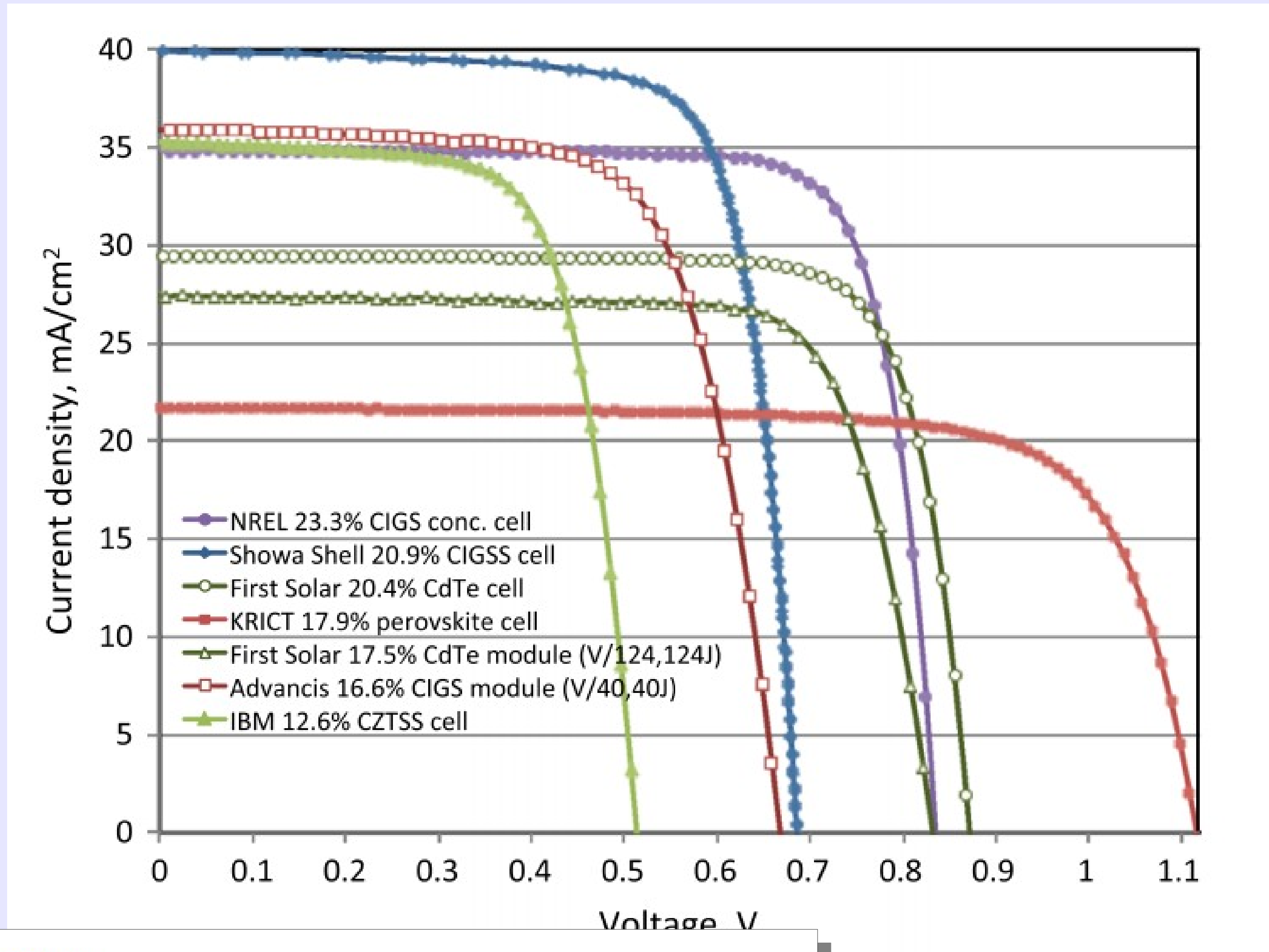
Nice Try

- ***n*** and J_0 inextricably linked
- Increase $n \longrightarrow$ increase in J_0
- Net effect: **decrease** in V_{OC}

(not increase, D'oh!)

http://pveducation.org/pvcdrom/pn-junction/diode-equation

JV Examples



ACCELERATED PUBLICATION

Solar cell efficiency tables (version 44)

Martin A. Green[1]*, Keith Emery[2], Yoshihiro Hishikawa[3], Wilhelm Warta[4] and Ewan D. Dunlop[5]

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:

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

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:

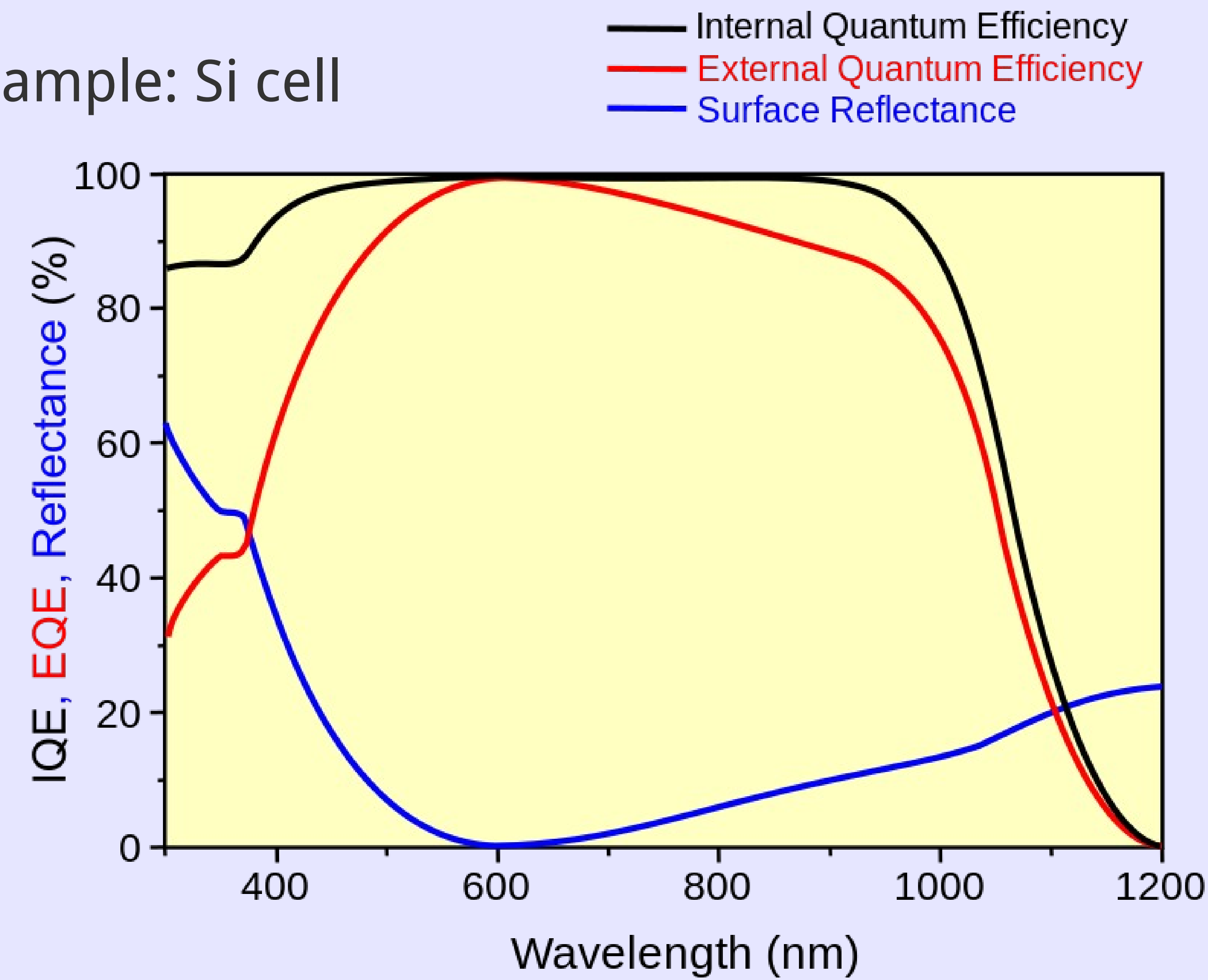
$$IQE = \frac{EQE}{1 - R - T}$$

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

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

IQE and EQE

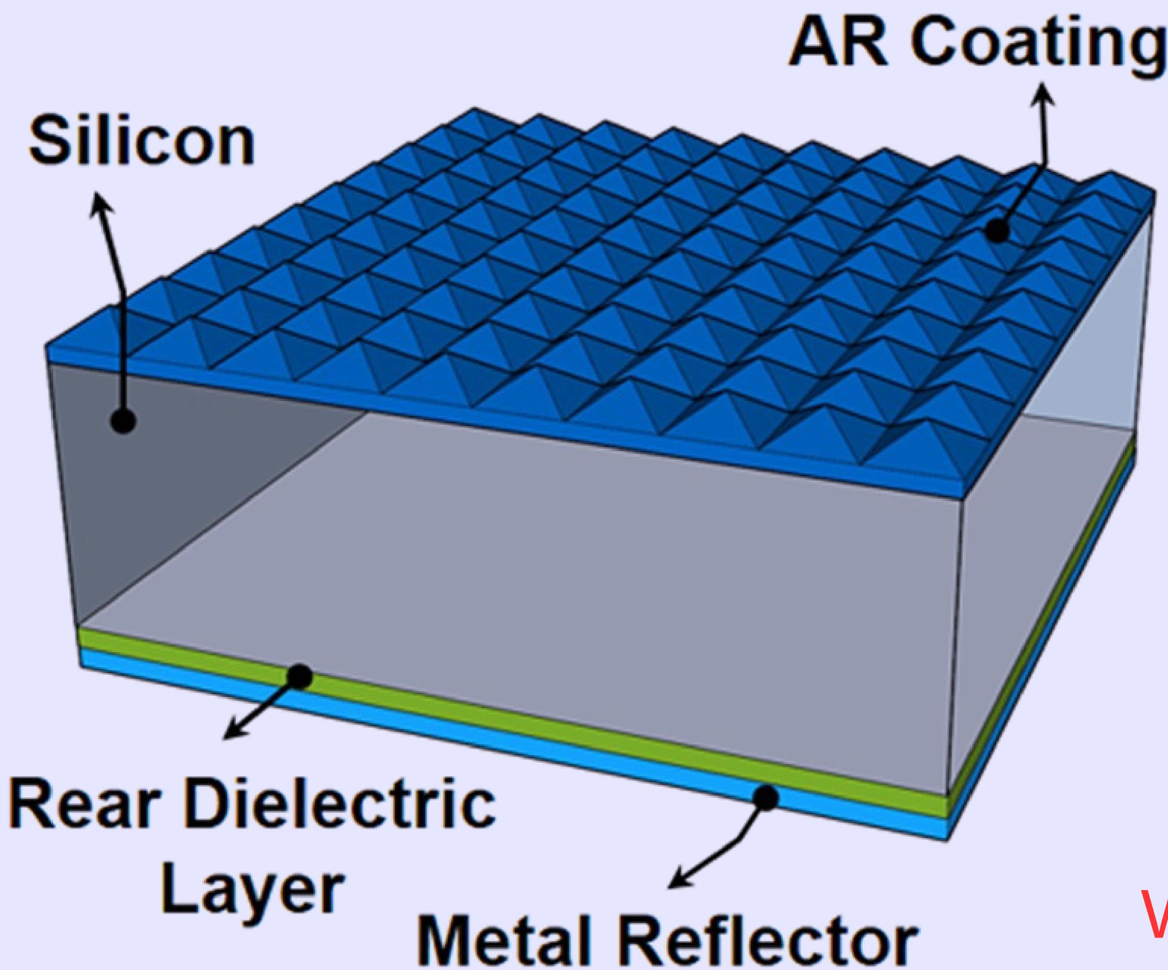
Example: Si cell

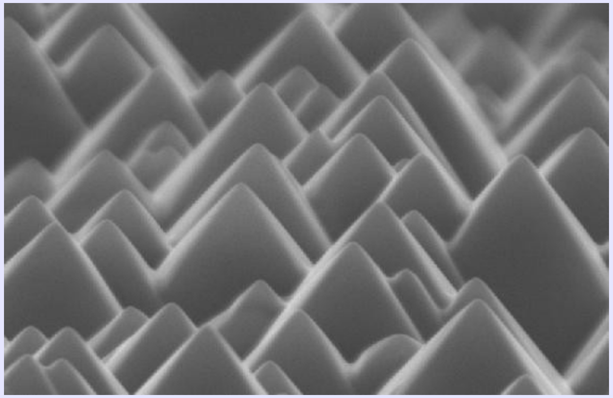


http://en.wikipedia.org/wiki/Quantum_efficiency

Increasing EQE

Classic crystalline Si cell design - "pyramids"

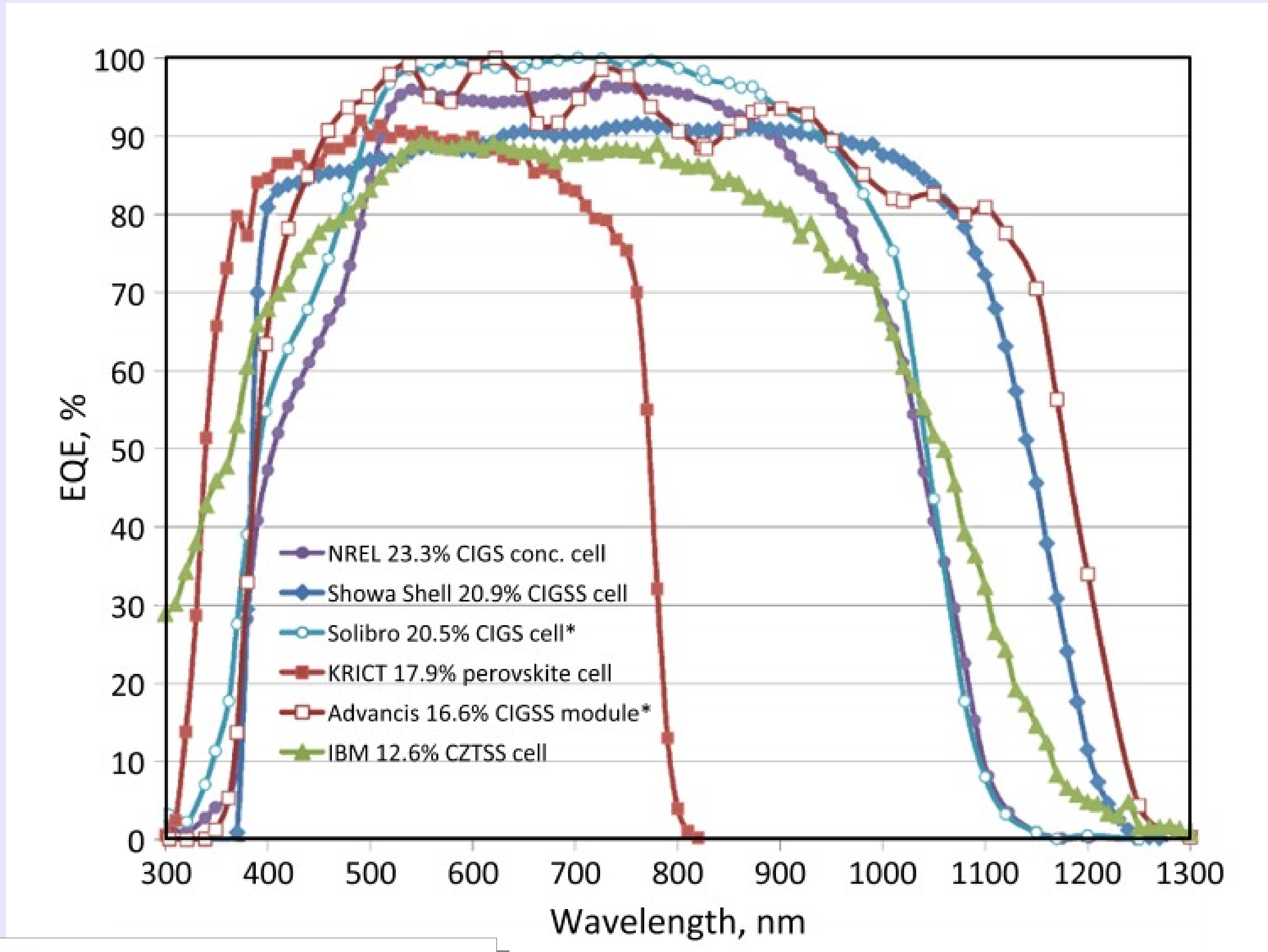




SEM micrograph of Si surface

What about thin-film PV?

Example EQE



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