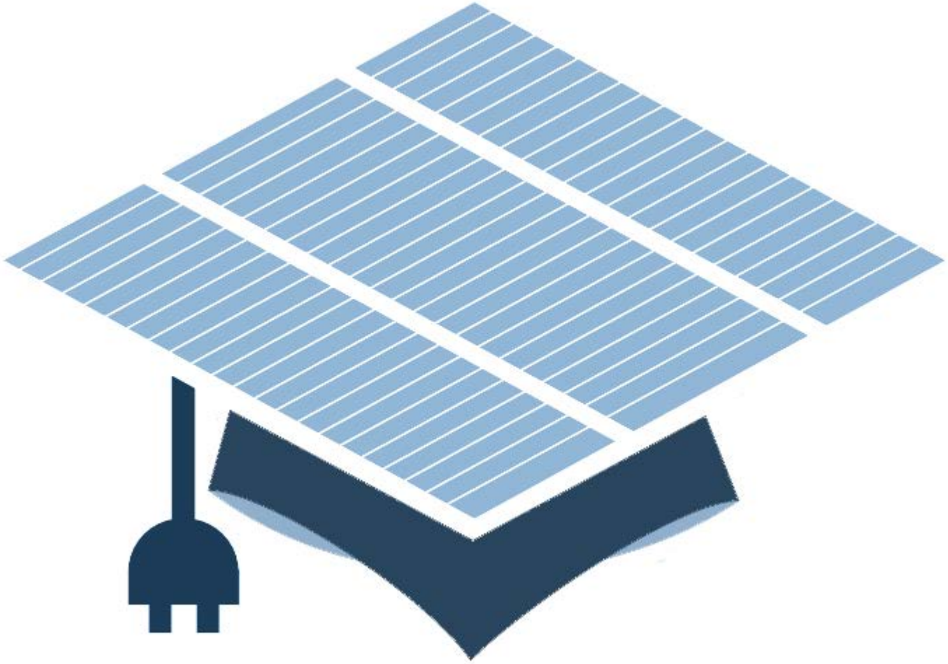


Lecture 6
Junction characterisation

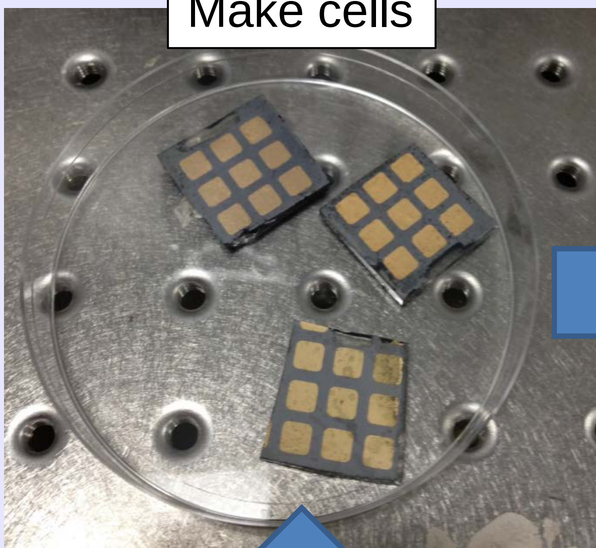
Jon Major

Nov 6th 2014

UNIVERSITY OF LIVERPOOL

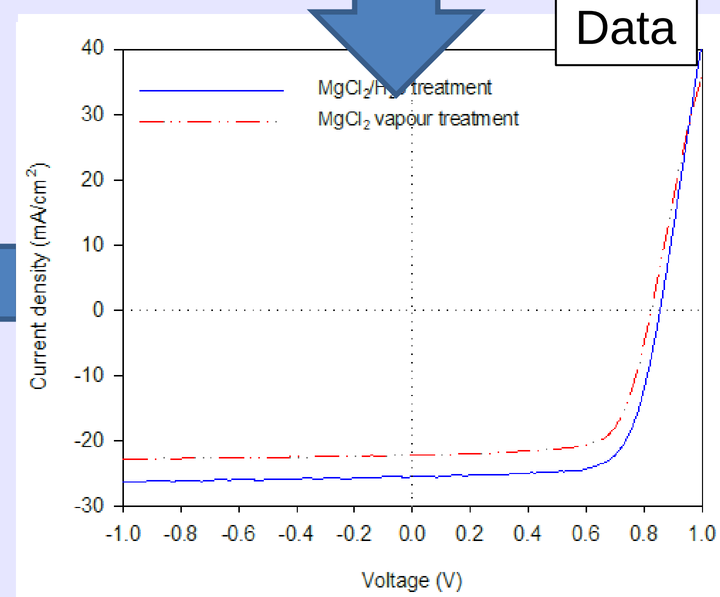
The PV research cycle

Make cells



Measure cells

Data



Repeat

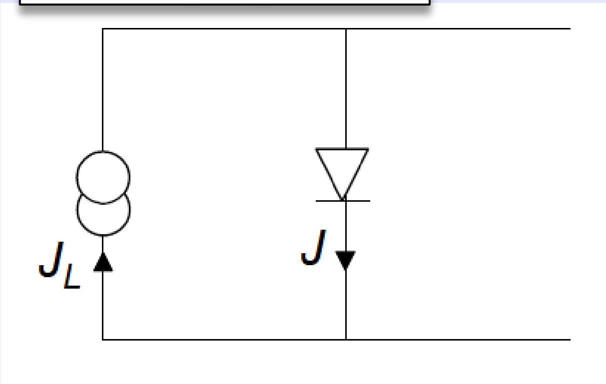
Lecture Outline

Key junction characterisation techniques

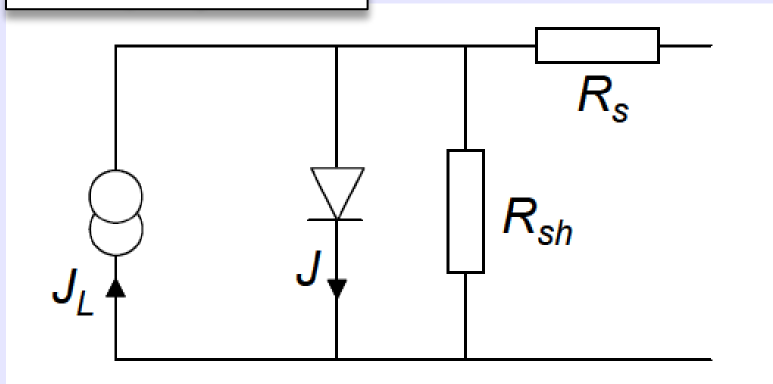
- Analysis of current voltage (J-V) curves
- External quantum efficiency (EQE) measurements
- Capacitance voltage (C-V) measurements

Parasitic resistances

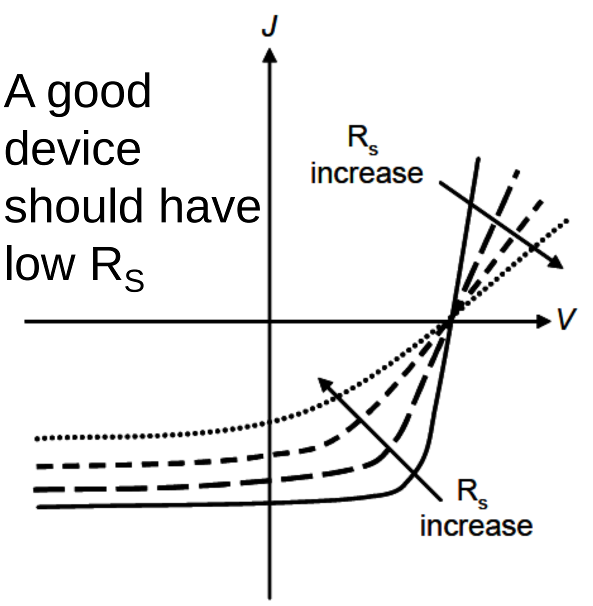
Perfect p-n junction



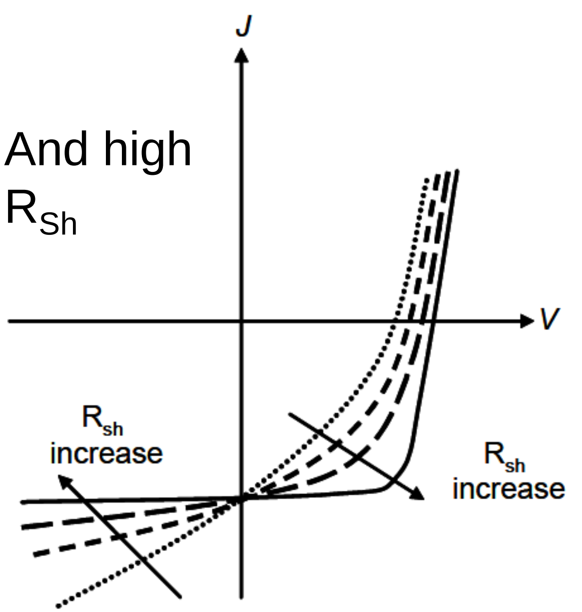
Real p-n junction



A good device should have low R_S

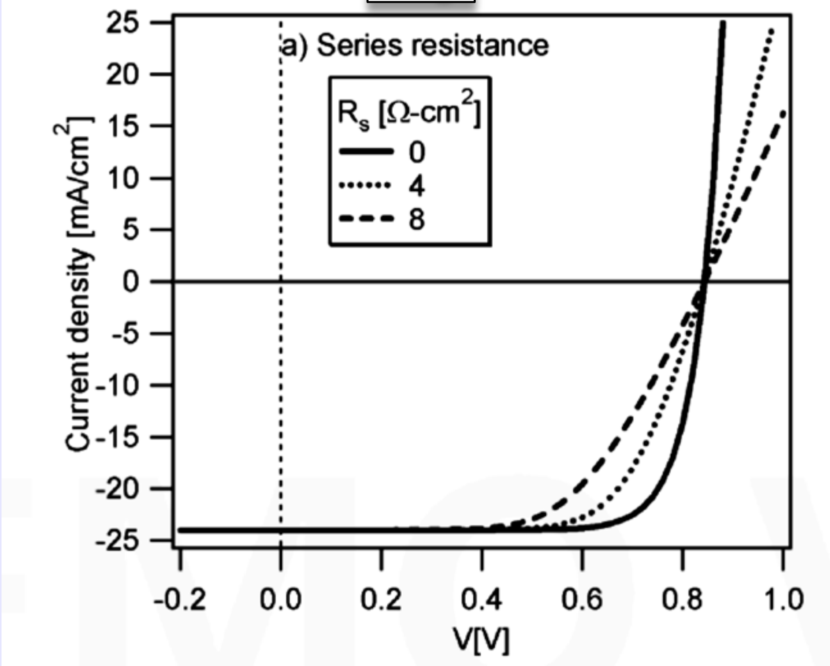


And high R_{Sh}

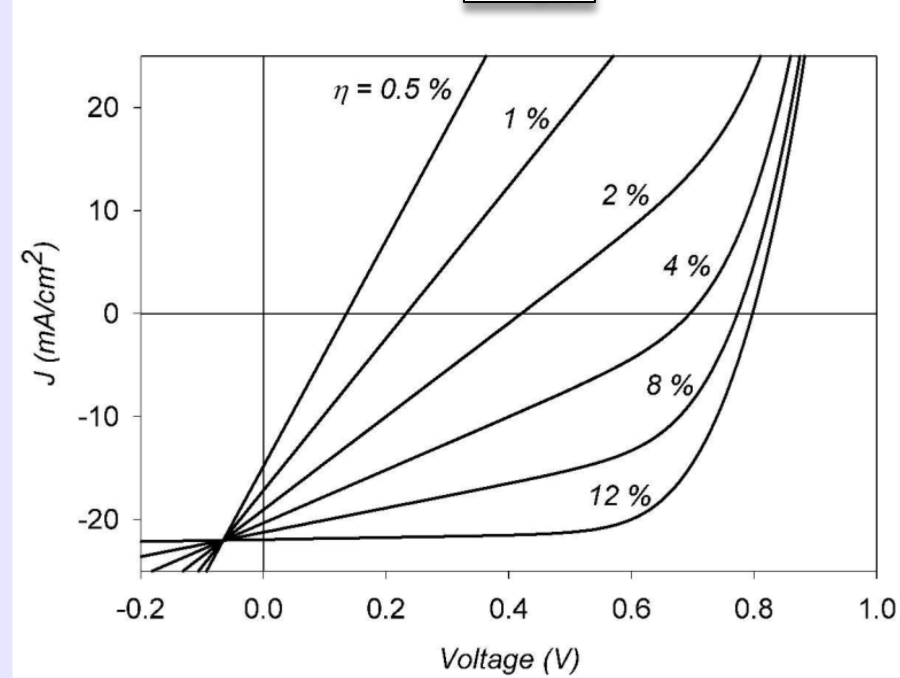


J-V analysis (J-V)

R_s



R_{sh}



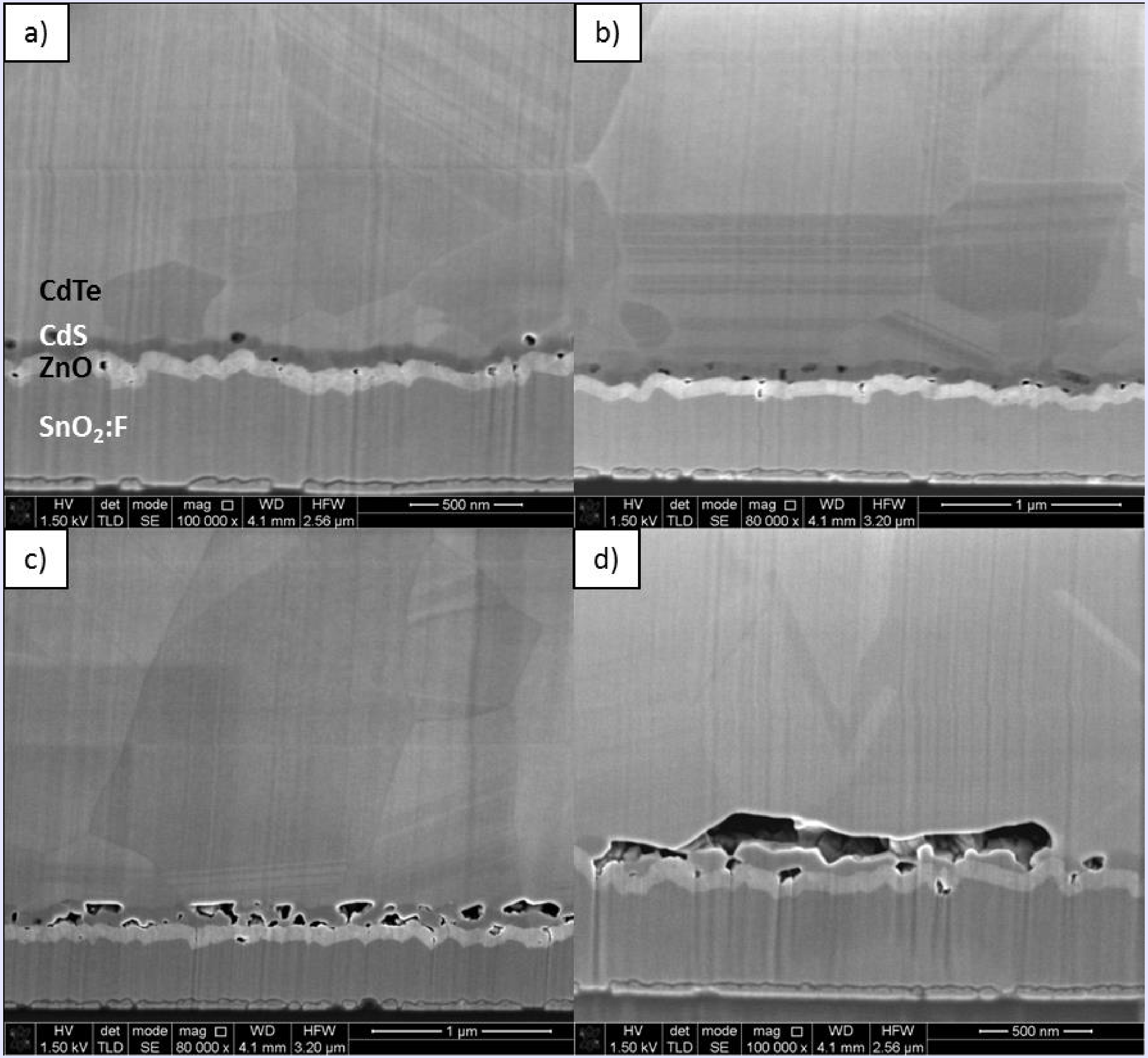
Causes of high R_S values

- Overly thick absorber layer
- Low conductivity TCO
- Low doping levels

Causes of low R_{Sh} values

- Pinholes in layers
- Weak diode regions

J-V analysis (J-V)



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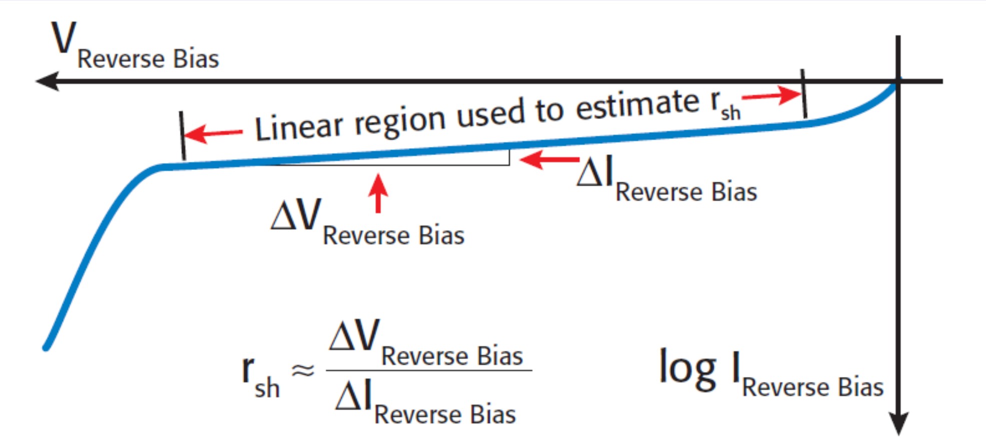
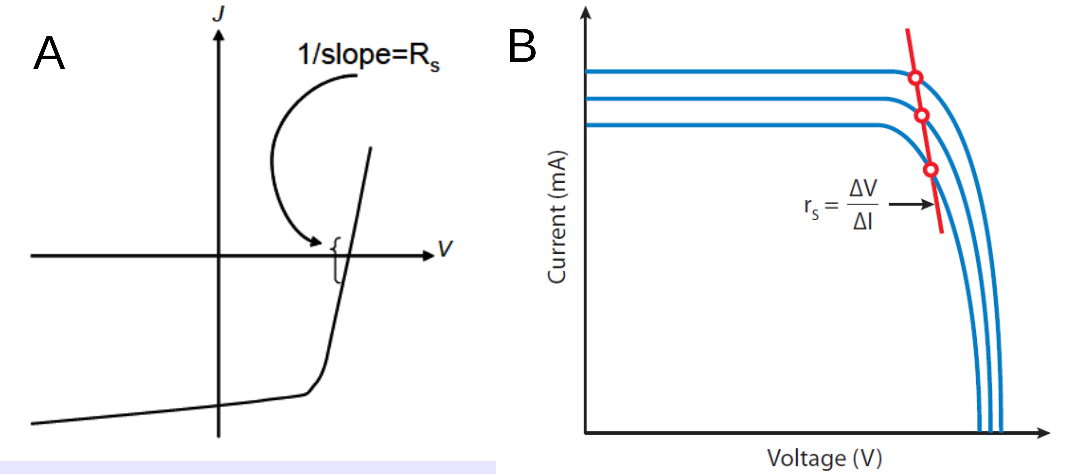
J-V analysis (J-V)

To determine R_{sh} fit to straight line portion of JV curve in reverse bias



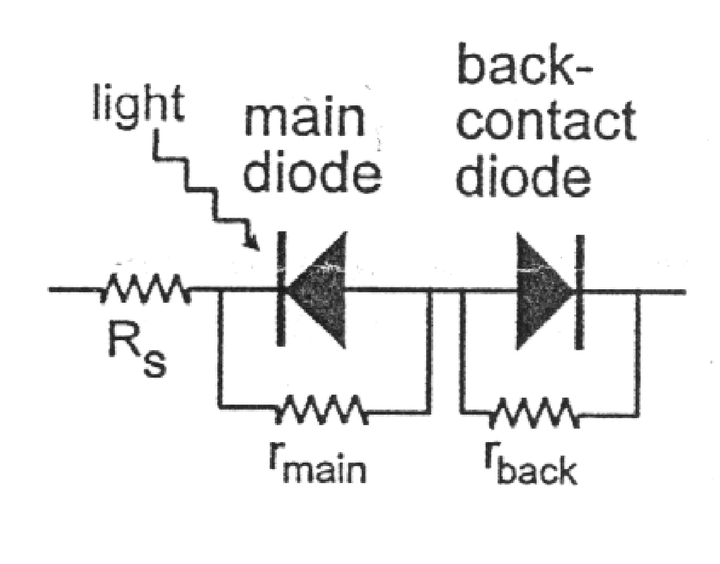
R_s can be more difficult to accurately determine. Two common methods



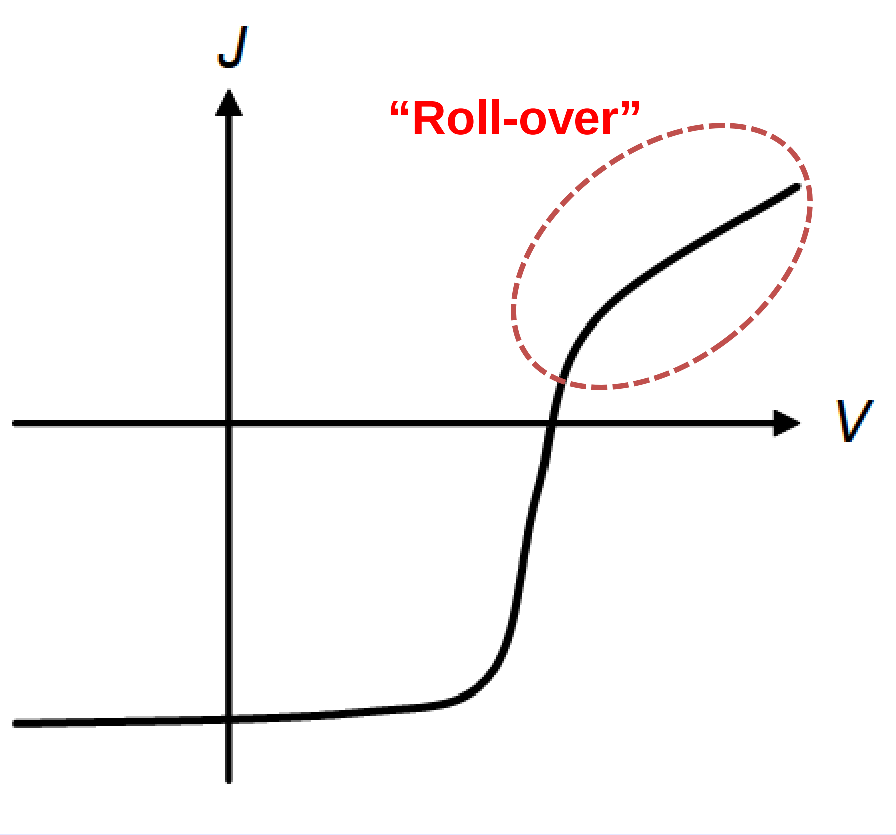
Fit to forward bias region of curve

Measure change as function of light bias

J-V analysis (J-V)



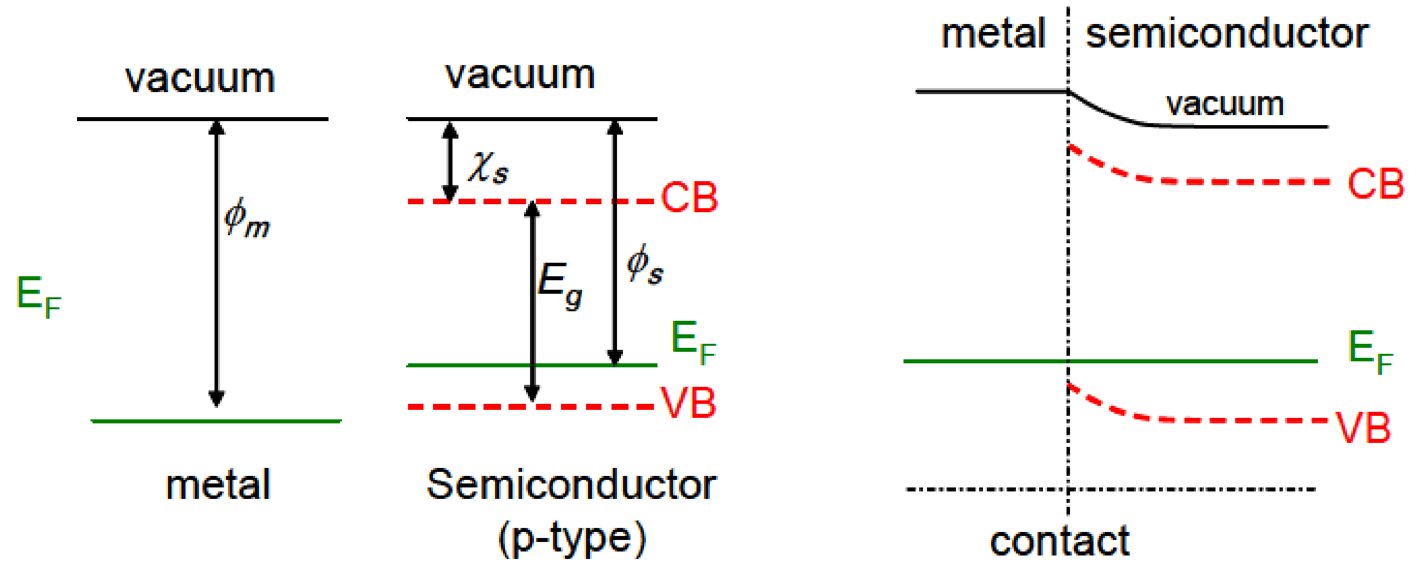
If a non-ohmic contact is formed this results in the creation of a back contact junction diode.



This back-contact diode opposes the main junction diode and leads to the phenomenon of "roll-over" at high forward bias.

J-V analysis (J-V)

Ohmic contact



For a p-type semiconductor can create an ohmic contact if;

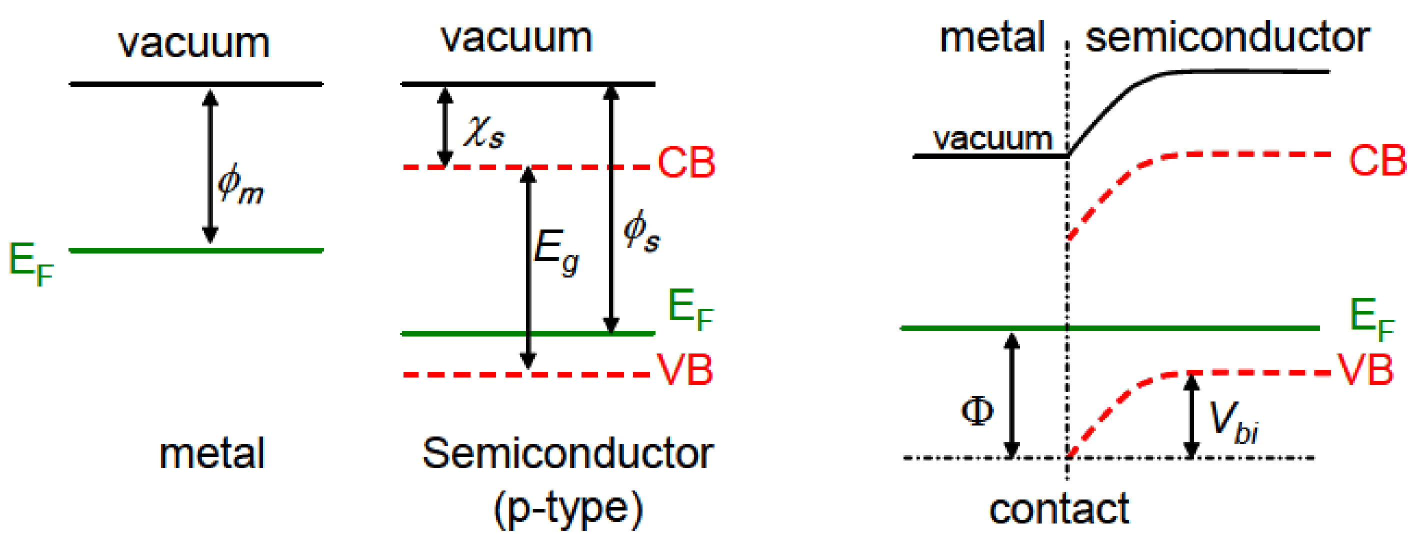
$$\phi_m \geq \chi_s + E_g$$

Metal work function

Electron affinity

Bandgap

Schottky barrier

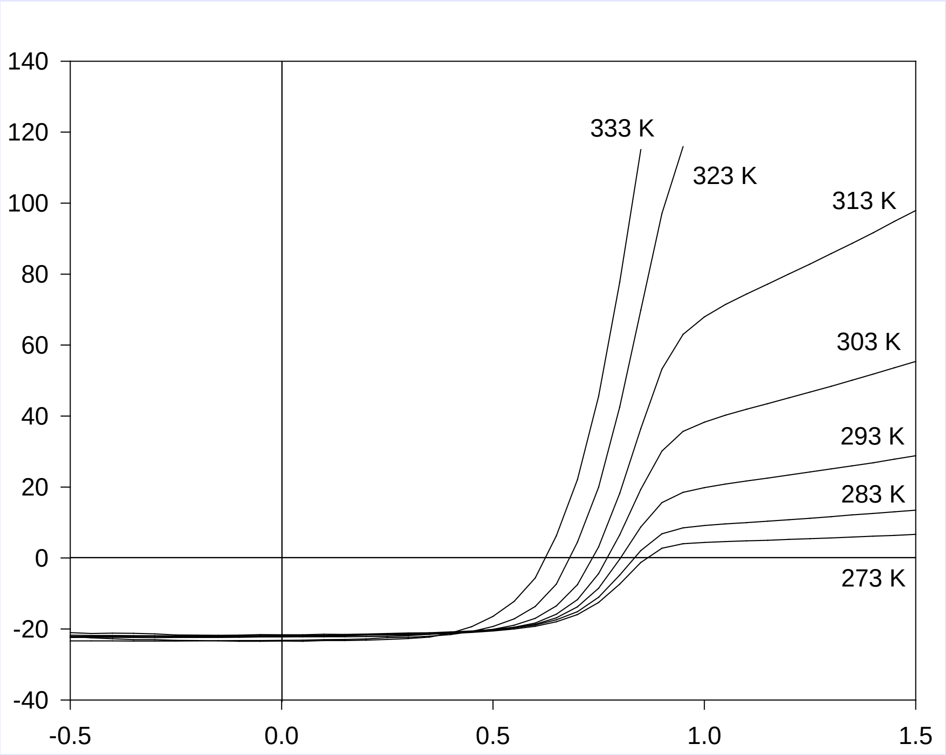


If this condition is not met we introduce a back contact Schottky barrier

$$\Phi \approx \phi_m - (\chi_s + E_g)$$

Back contact barrier height

J-V-T analysis



Influence of barrier height changes as a function of temperature

By measuring J-V curves as a function of temperature we can extract the barrier height

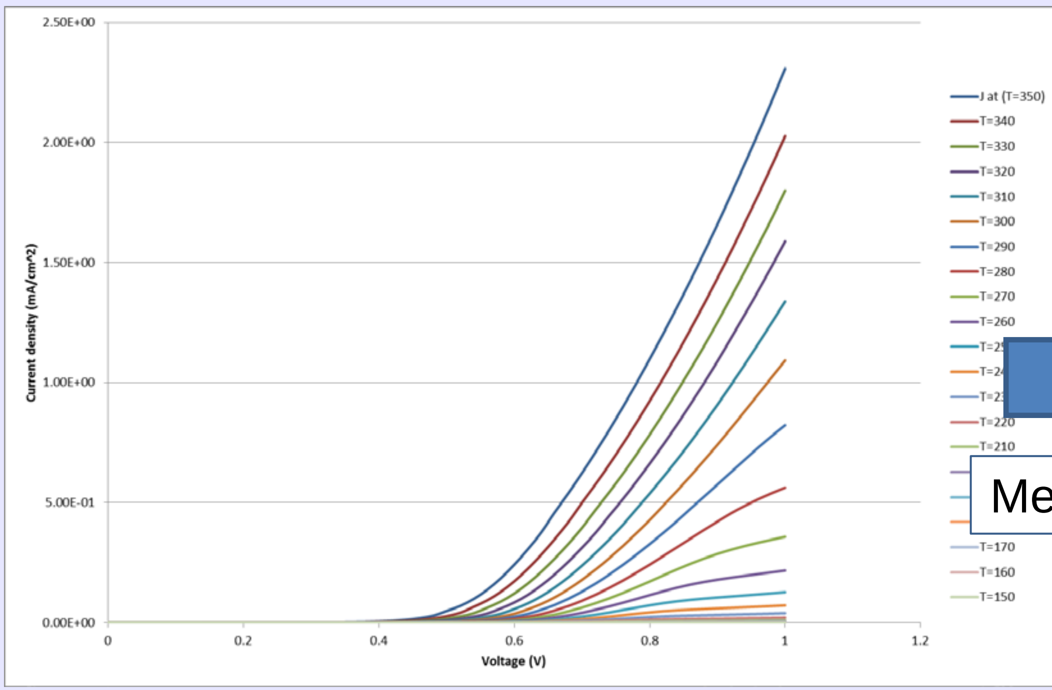
J-V-T analysis

Series resistance varies with temperature via

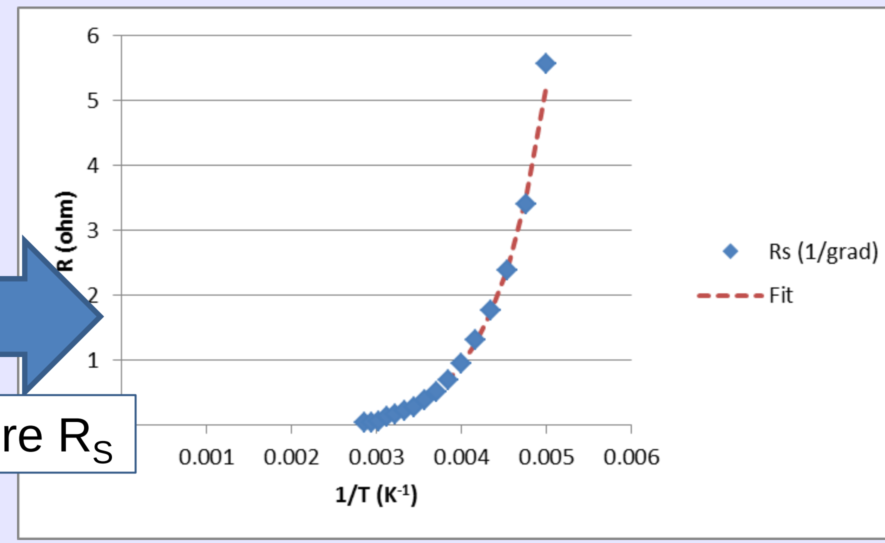
$$R_S = R_{\Omega 0} + \frac{\partial R_{\Omega 0}}{\partial T} T + \frac{C}{T^2} \exp\left(\frac{\Phi_b}{kT}\right)$$

Ohmic resistance

Ohmic temperature dependence



Measure R_S



Fitting to exponential region allows us to extract a value in eV for the barrier height. Generally anything < 0.3eV is considered a good contact

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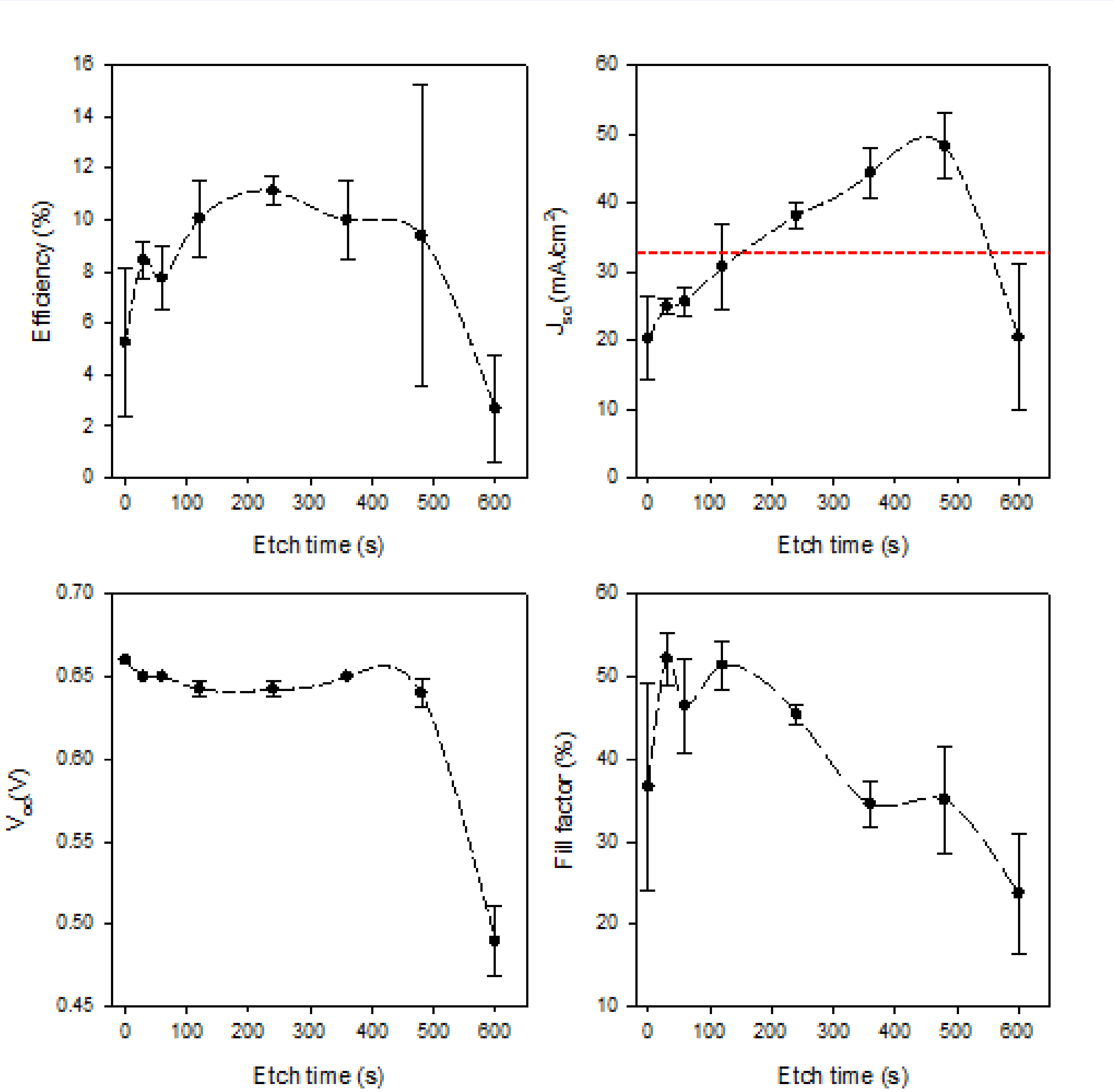
A cautionary tale



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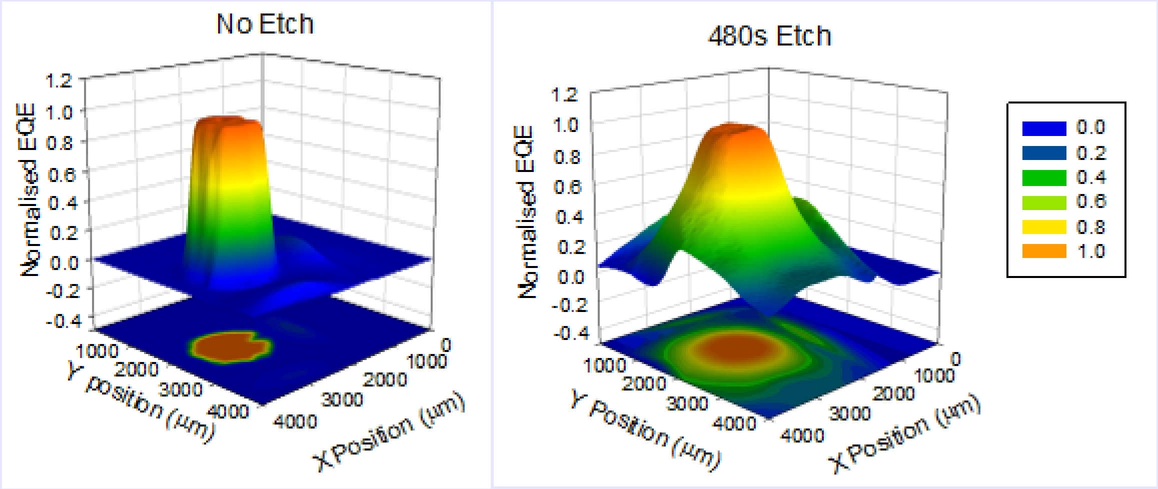
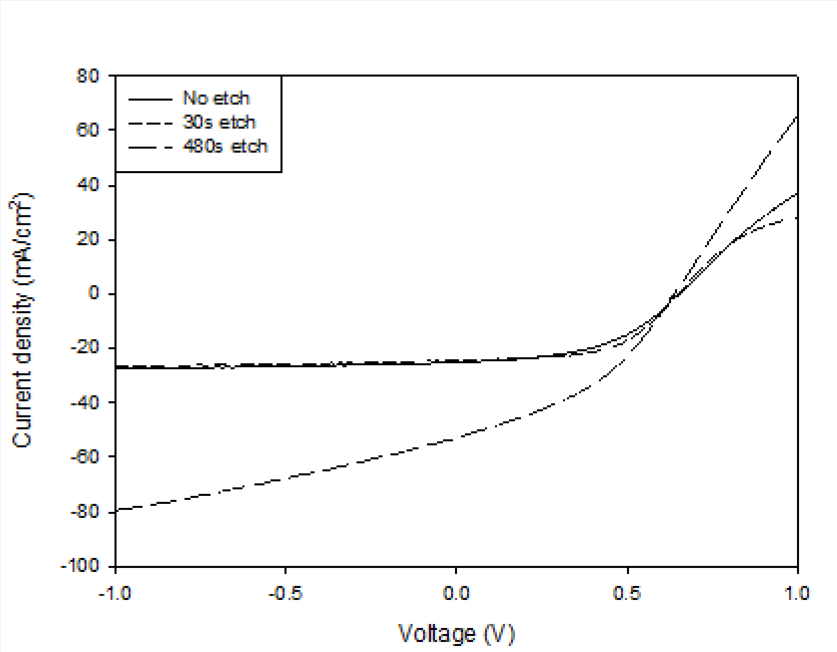
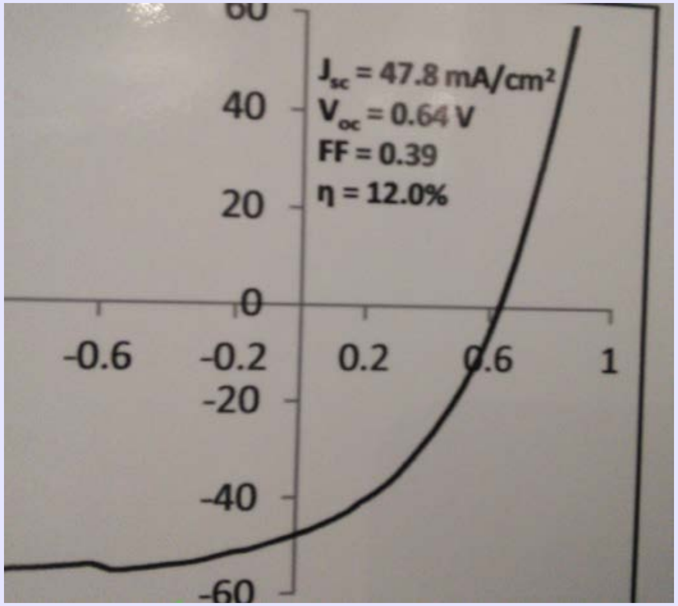
Errors in J-V analysis (J-V)

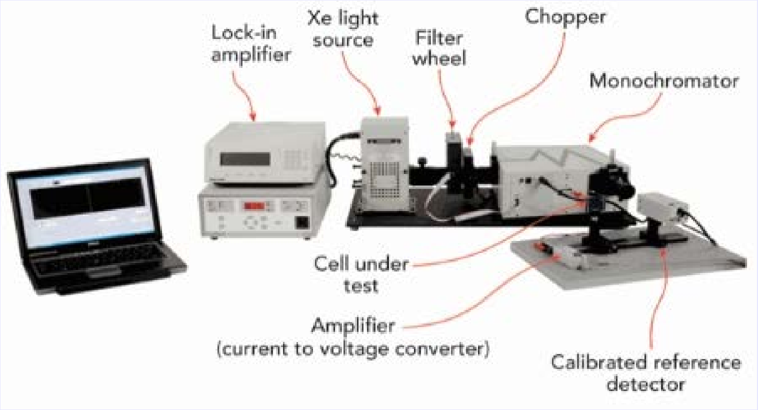


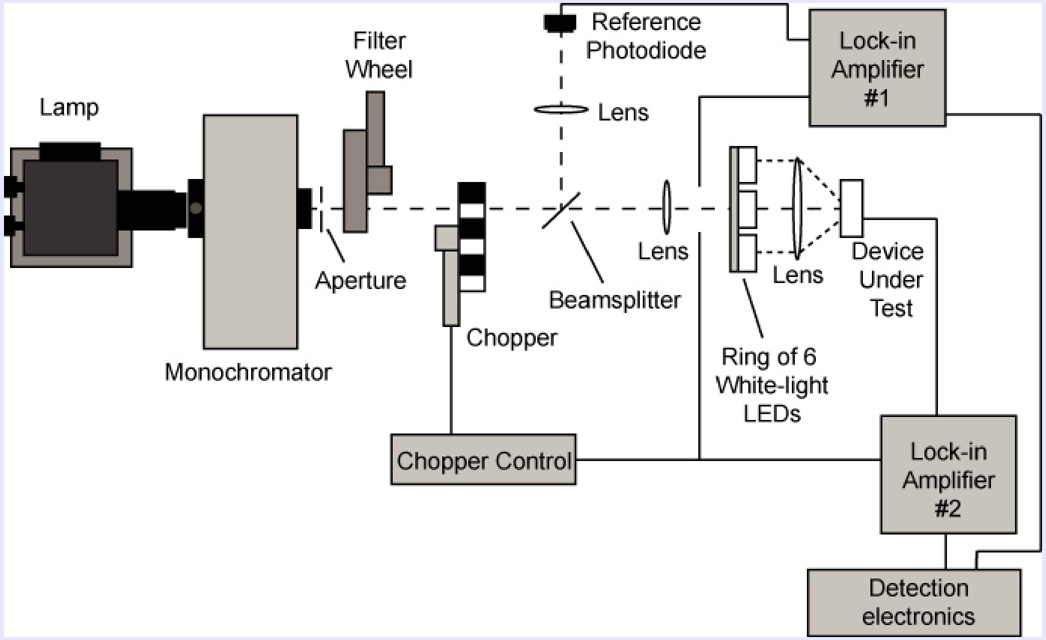




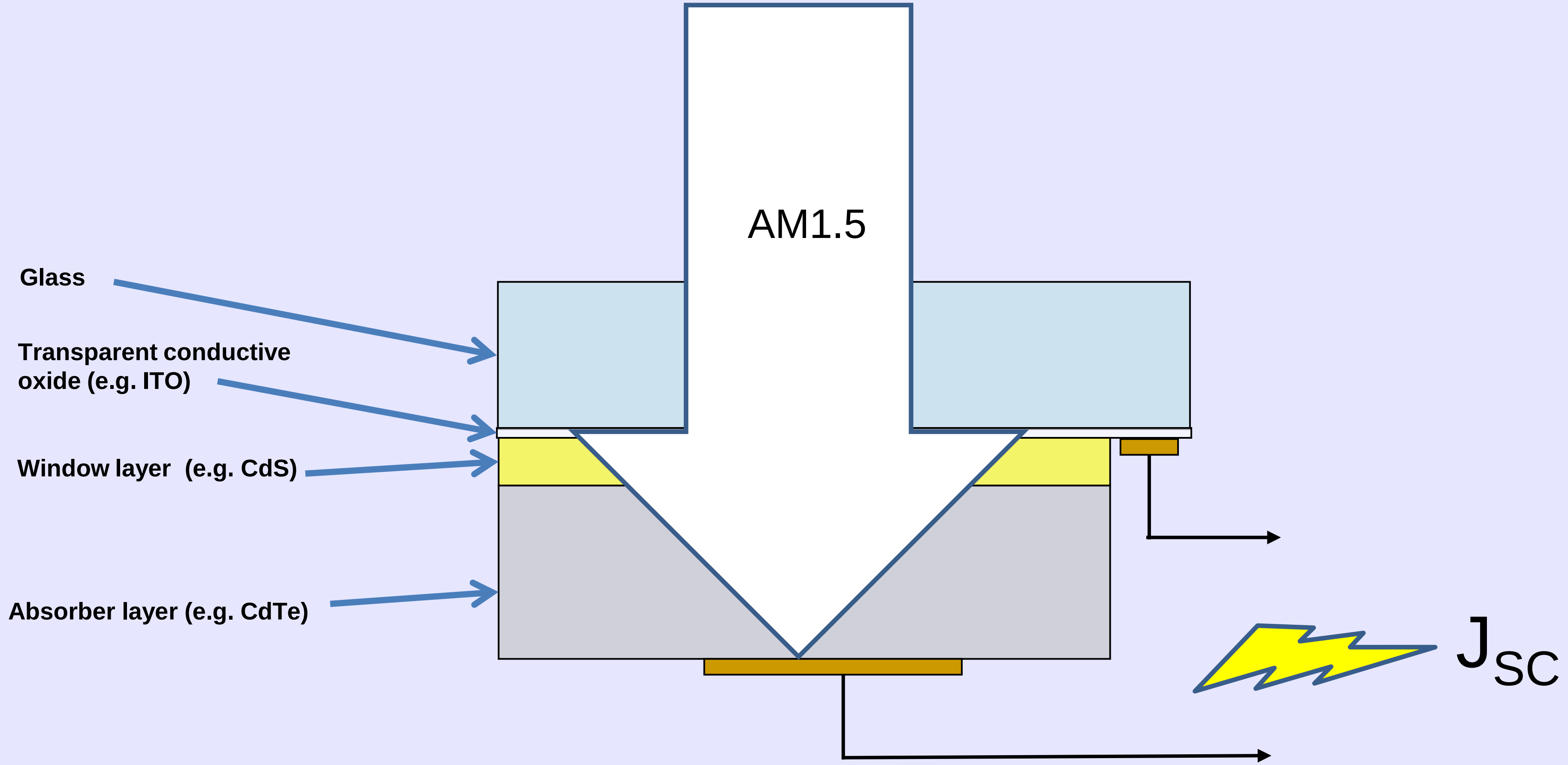
- High Voc and FF are reliable
- J_{sc} values are very sensitive to calibration or contact size errors
- Contacts should be minimum of $0.25cm^2$
- If it looks to good to be true it usually is!

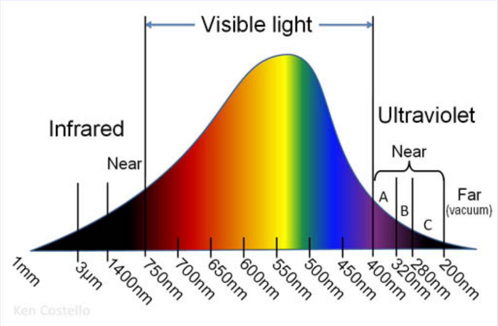
External quantum efficiency (EQE)





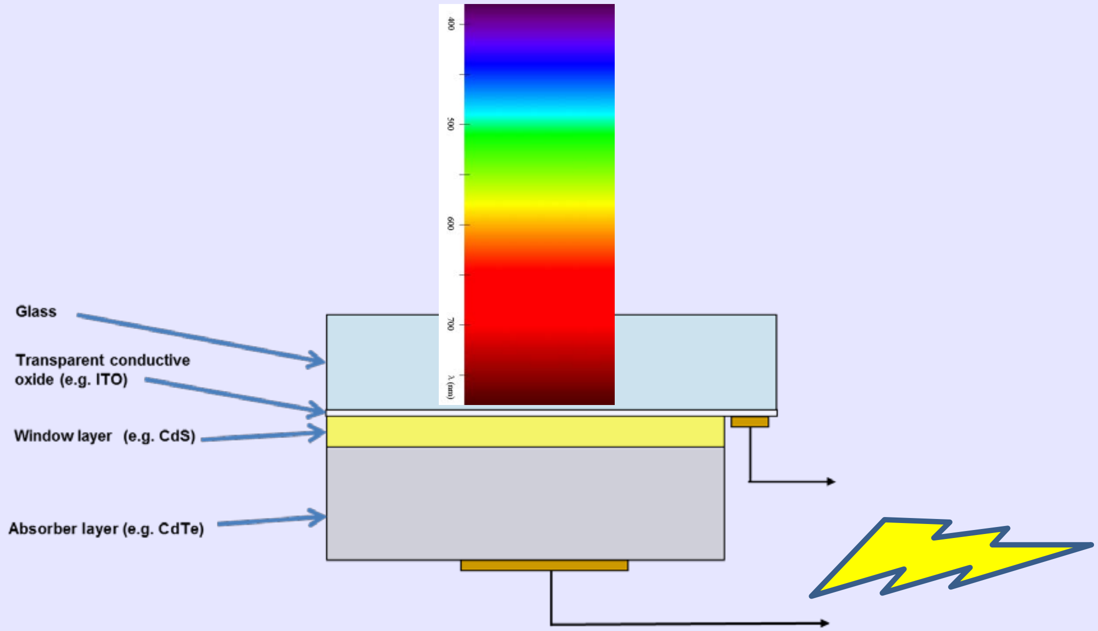
External quantum efficiency (EQE)





$$E(\lambda) = \frac{hC}{\lambda}$$

External quantum efficiency (EQE)



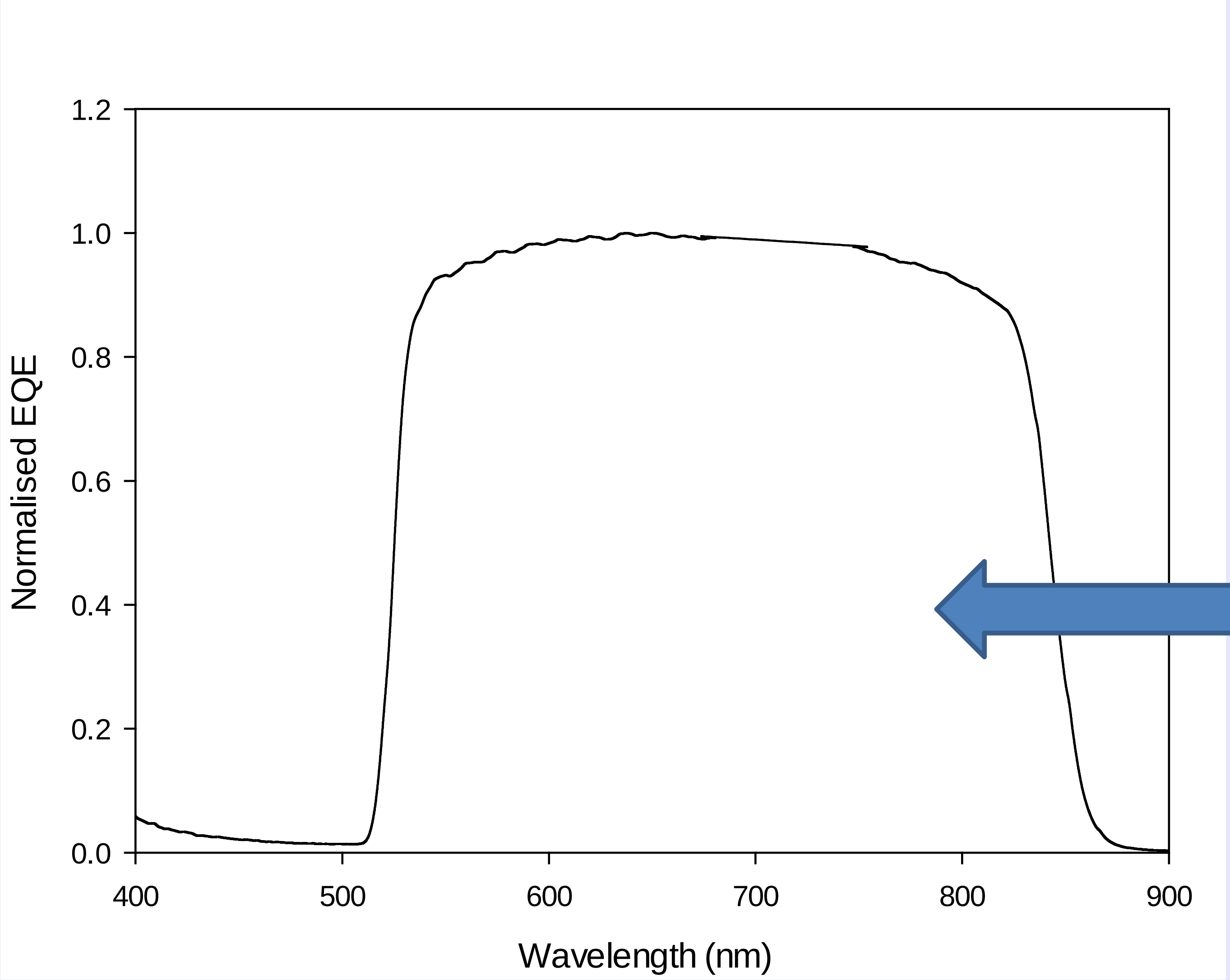
$$J(\lambda)$$

Define the EQE as the ratio of photons in to current generated

$$EQE = \frac{J_{cell}}{J_{photon}}$$

A 100% EQE means every photon that strikes the cell generates an electron hole pair which flows through the external circuit

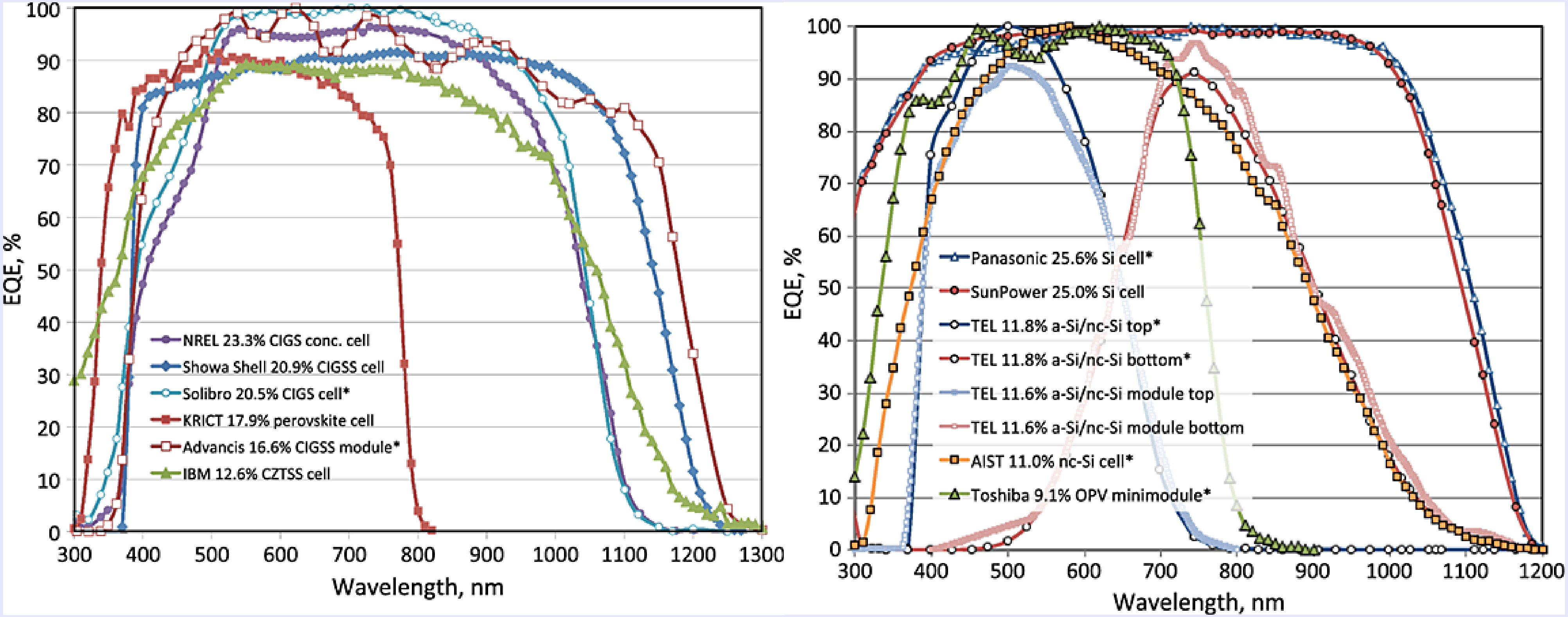
Theoretical case



Area under curve proportional to J_{SC}

External quantum efficiency (EQE)

Most solar cell technologies display same typical "top hat" EQE curve shape



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External quantum efficiency (EQE)

Progress in
PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2014; **22**:701–710
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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 44)

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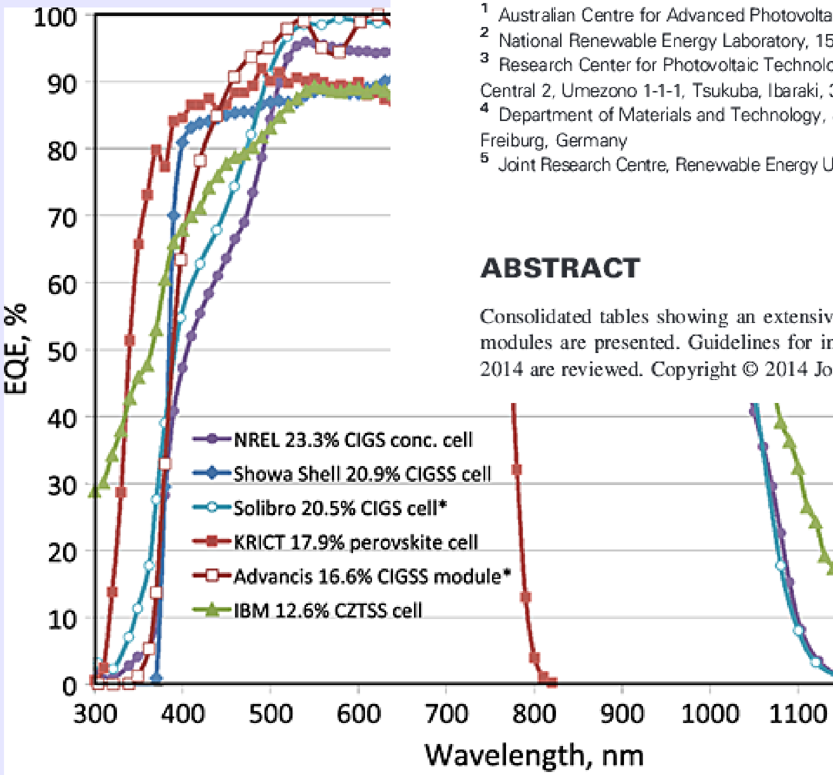
[2] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401, USA
[3] Research Center for Photovoltaic Technologies (RCPVT), National Institute of Advanced Industrial Science and Technology (AIST), Central 2, Umezono 1-1-1, Tsukuba, Ibaraki, 305-8568, JAPAN
[4] Department of Materials and Technology, Solar Cells, Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2; D-79110 Freiburg, Germany
[5] Joint Research Centre, Renewable Energy Ur

ABSTRACT

Consolidated tables showing an extensive
modules are presented. Guidelines for in
2014 are reviewed. Copyright © 2014 Joh



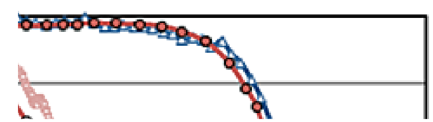


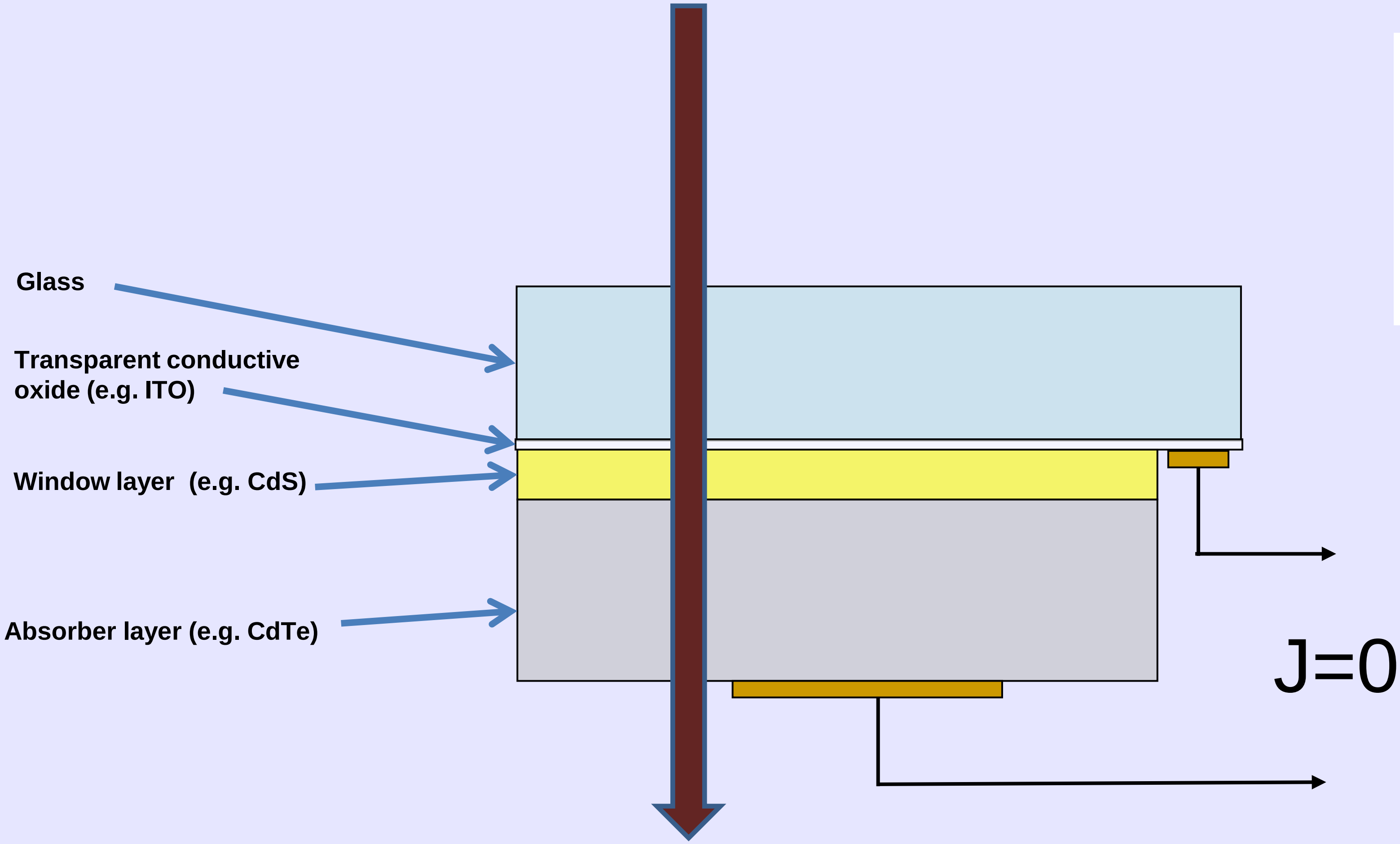
Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25 °C (IEC 60904-3: 2008, ASTM G-173-03 global).

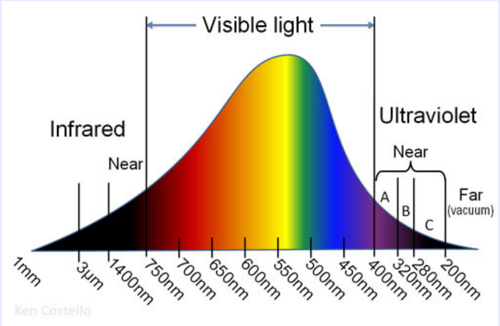
Classification[a]	Efficiency (%)	Area[b] (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	Fill factor (%)	Test centre[c] (date)	Description
Silicon							
Si (crystalline)	**25.6 ± 0.5**	**143.7 (da)**	**0.740**	**41.8[d]**	**82.7**	**AIST (2/14)**	**Panasonic HIT, rear-junction [4]**
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04)[e]	FhG-ISE [21]
Si (thin film transfer)	20.1 ± 0.4	242.6 (ap)	0.682	38.14[f]	77.4	NREL (10/12)	Solexel (43 µm thick) [22]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[g]	29.7[g]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 µm on glass; 20 cells) [23]
III–V Cells							
GaAs (thin film)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[h]	86.5	NREL (5/12)	Alta Devices [24]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)[e]	RTI, Ge substrate [25]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90)[e]	Spire, epitaxial [26]
Thin film chalcogenide							
CIGS (cell)	**20.5 ± 0.6**	**0.9882 (ap)**	**0.752**	**35.3[d]**	**77.2**	**NREL (3/14)**	**Solibro, on glass [5]**
CIGS (minimodule)	18.7 ± 0.6	15.892 (da)	0.701[g]	35.29[g,j]	75.6	FhG-ISE (9/13)	Solibro, four serial cells [27]
CdTe (cell)	19.6 ± 0.4	1.0055 (ap)	0.8573	28.59[j]	80.0	Newport (6/13)	GE Global Research [28]
Amorphous/microcrystalline Si							
Si (amorphous)	10.1 ± 0.3[k]	1.036 (ap)	0.886	16.75[l]	67.8	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [29]
Si (microcrystalline)	**11.0 ± 0.3[m]**	**1.045 (da)**	**0.542**	**27.44[d]**	**73.8**	**AIST (1/14)**	**AIST [9]**
Dye sensitised							
Dye sensitised	11.9 ± 0.4[n]	1.005 (da)	0.744	22.47[f]	71.2	AIST (9/12)	Sharp [30]
Dye sensitised (minimodule)	29.9 ± 0.4[n]	17.11 (ap)	0.719[g]	19.4[g,j]	71.4	AIST (8/10)	Sony, eight parallel cells [31]
Dye (submodule)	8.8 ± 0.3[n]	398.8 (da)	0.697[g]	18.42[g,j]	68.7	AIST (9/12)	Sharp, 26 serial cells [32]
Organic							
Organic thin film	10.7 ± 0.3[o]	1.013 (da)	0.872	17.75[f]	68.9	AIST (10/12)	Mitsubishi Chemical (4.4 × 23.0 mm) [33]
Organic (minimodule)	**9.1 ± 0.3[o]**	**25.04 (da)**	**0.794[g]**	**17.06[g,d]**	**67.5**	**AIST (2/14)**	**Toshiba (four series cells) [10]**
Organic (submodule)	6.8 ± 0.2[o]	395.9 (da)	0.798[g]	13.50[f,g]	62.8	AIST (10/12)	Toshiba (15 series cells) [10]
Multijunction devices							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[i]	86.7	AIST (2/13)	Sharp [34]
a-Si/nc-Si/nc-Si (thin film)	13.4 ± 0.4[p]	1.006 (ap)	1.963	9.52[f]	71.9	NREL (7/12)	LG Electronics [35]

Prog. Photovolt: Res. Appl. 2014; 22:701–710 © 2014 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

ces

External quantum efficiency (EQE)





$$E(\lambda) = \frac{hC}{\lambda}$$

Region 1: $E_{photon} < E_{Asorber}$

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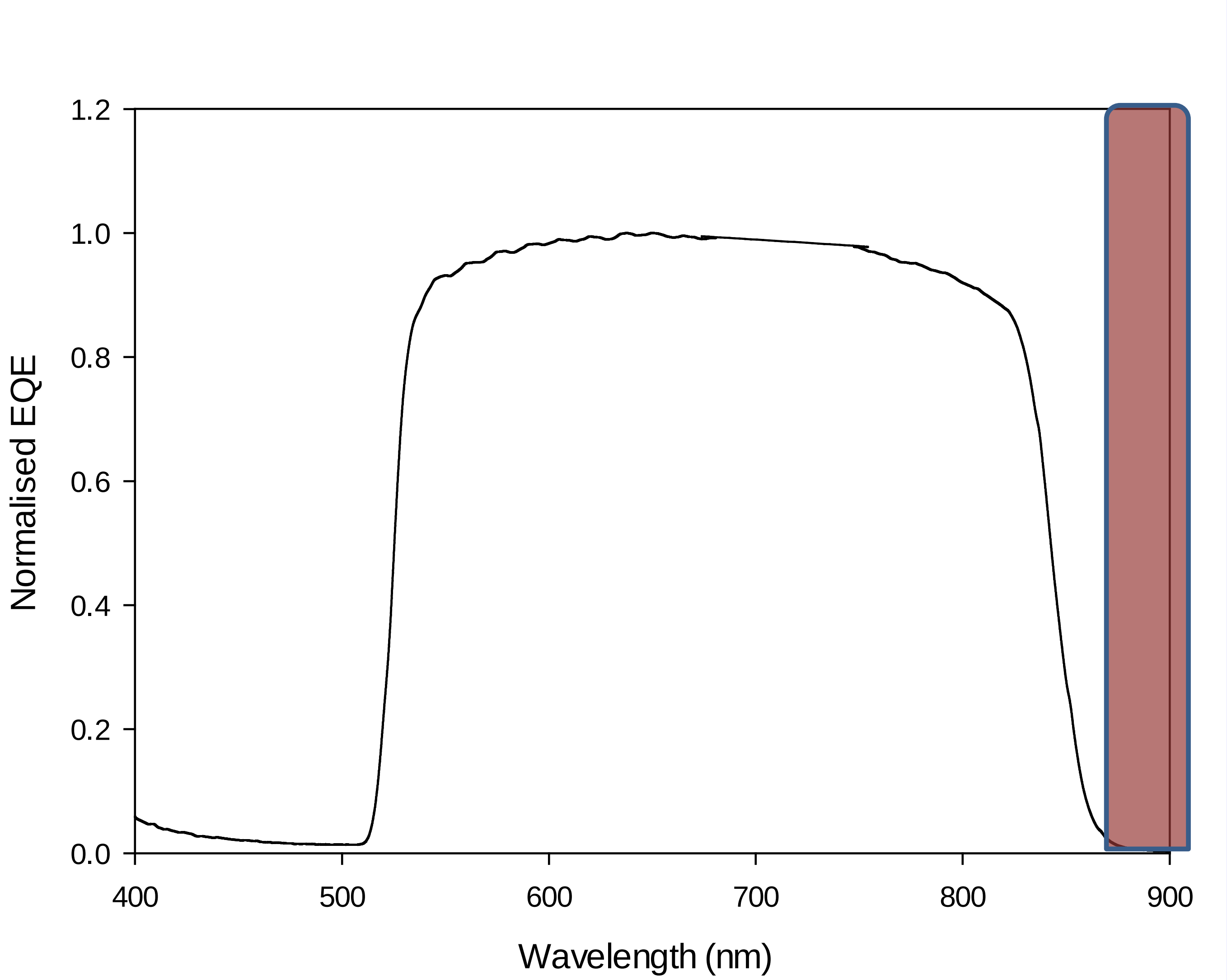
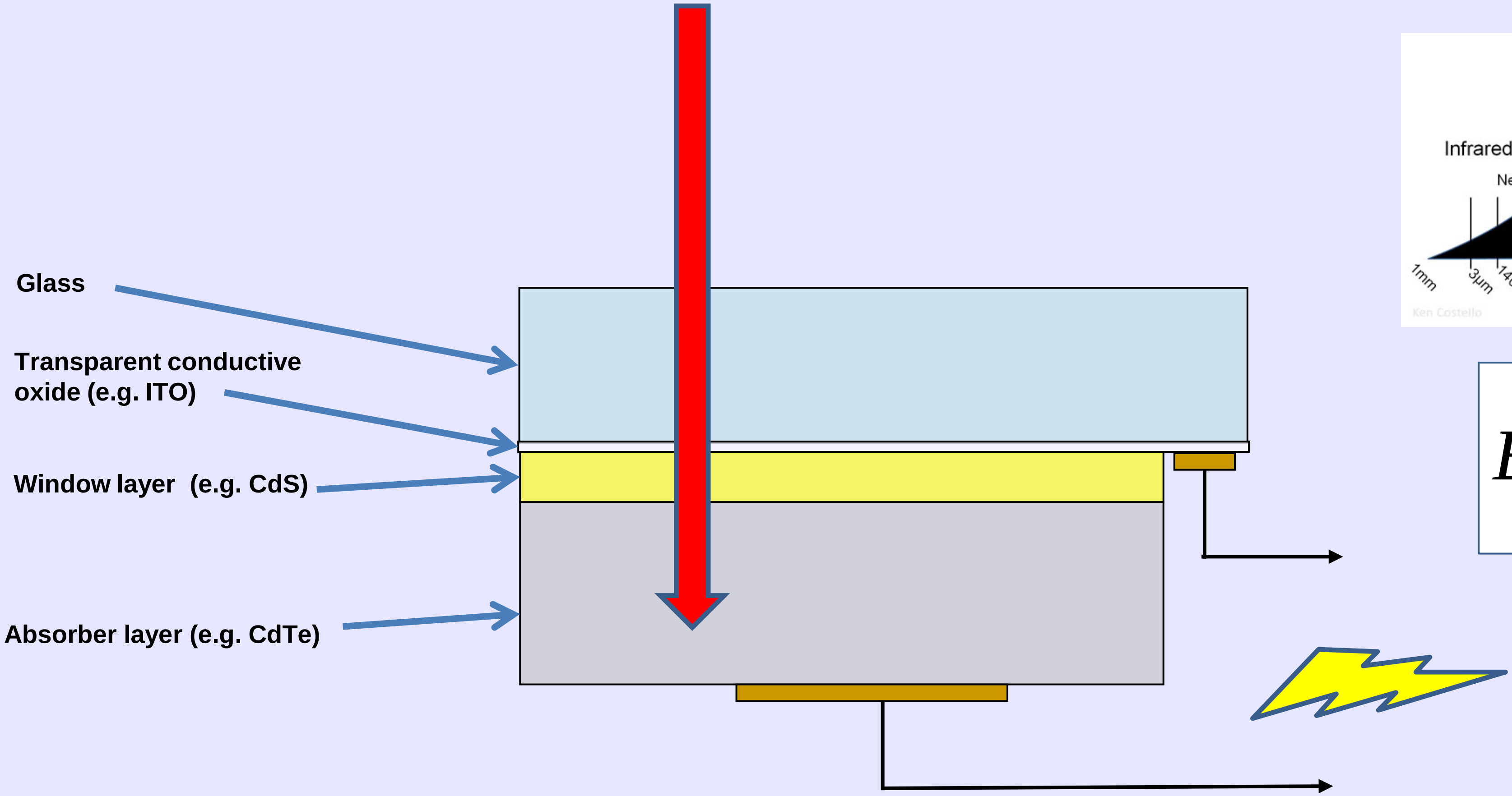
External quantum efficiency (EQE)



External quantum efficiency (EQE)



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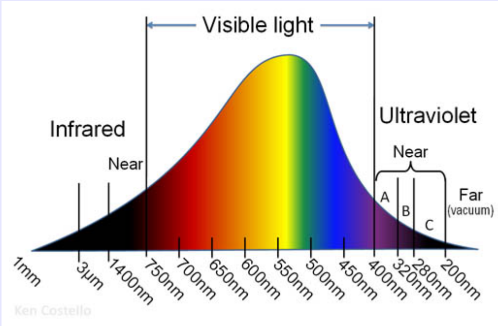
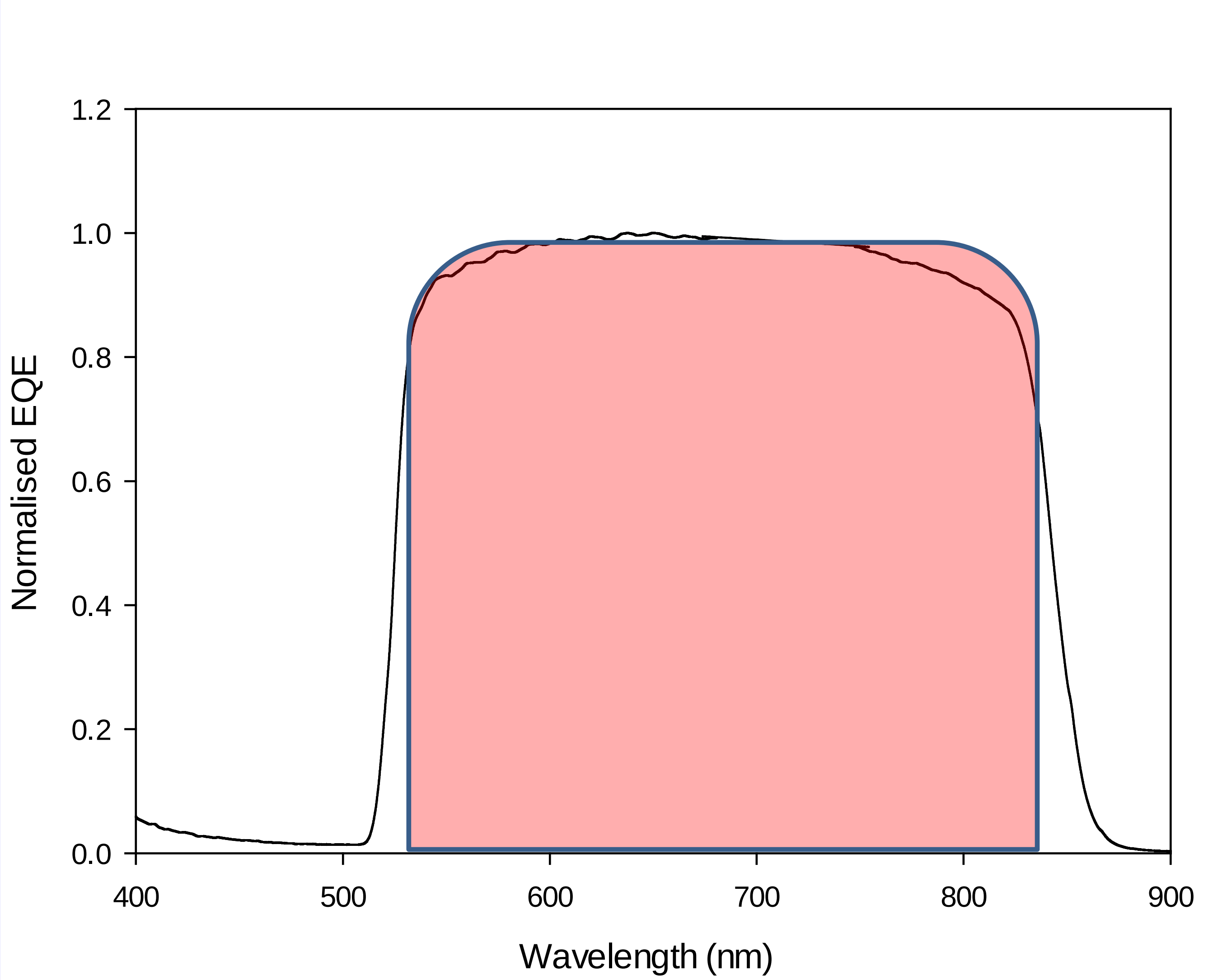


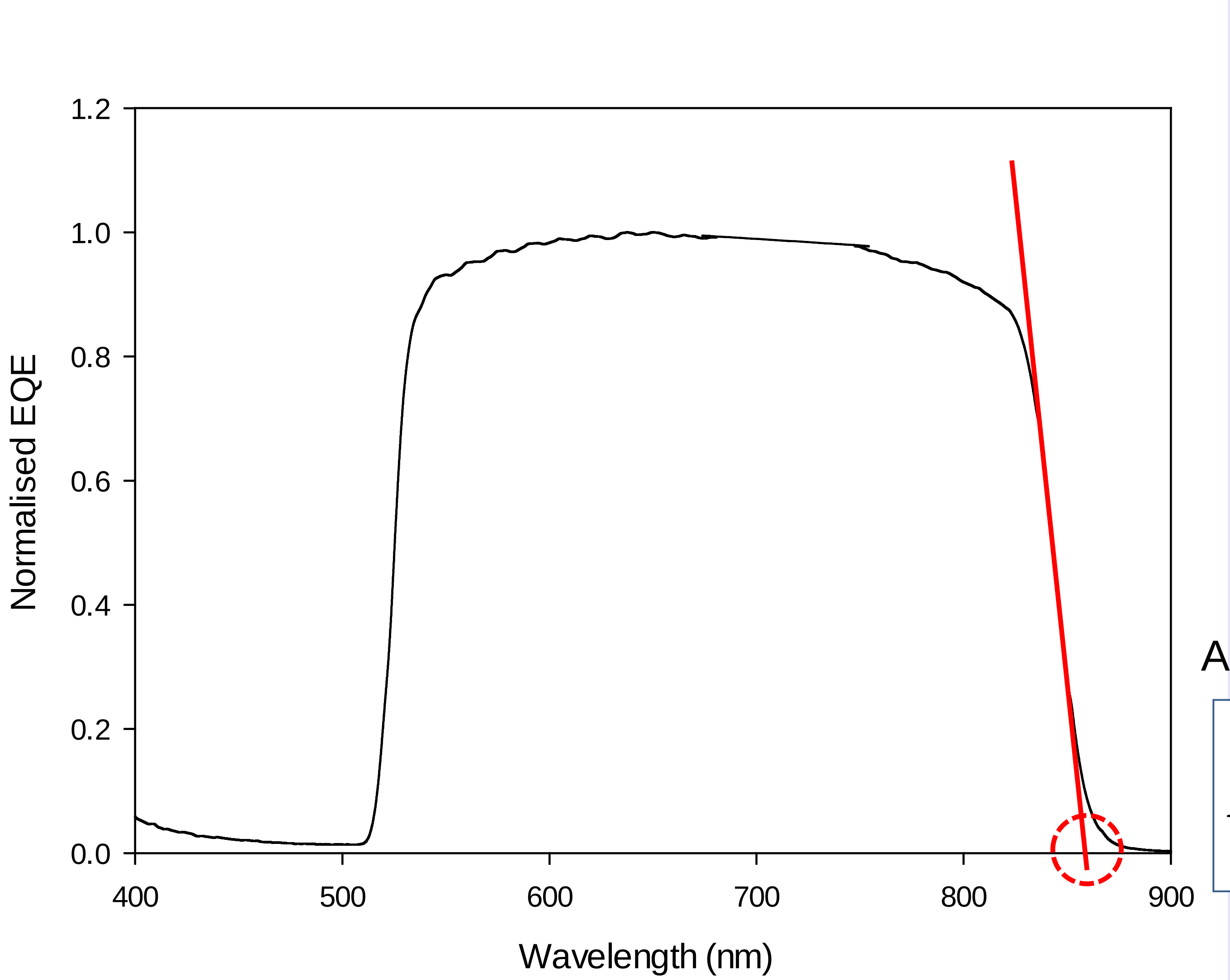
$$E(\lambda) = \frac{hC}{\lambda}$$

Region 2: $E_{photon} > E_{Asorber}$

External quantum efficiency (EQE)



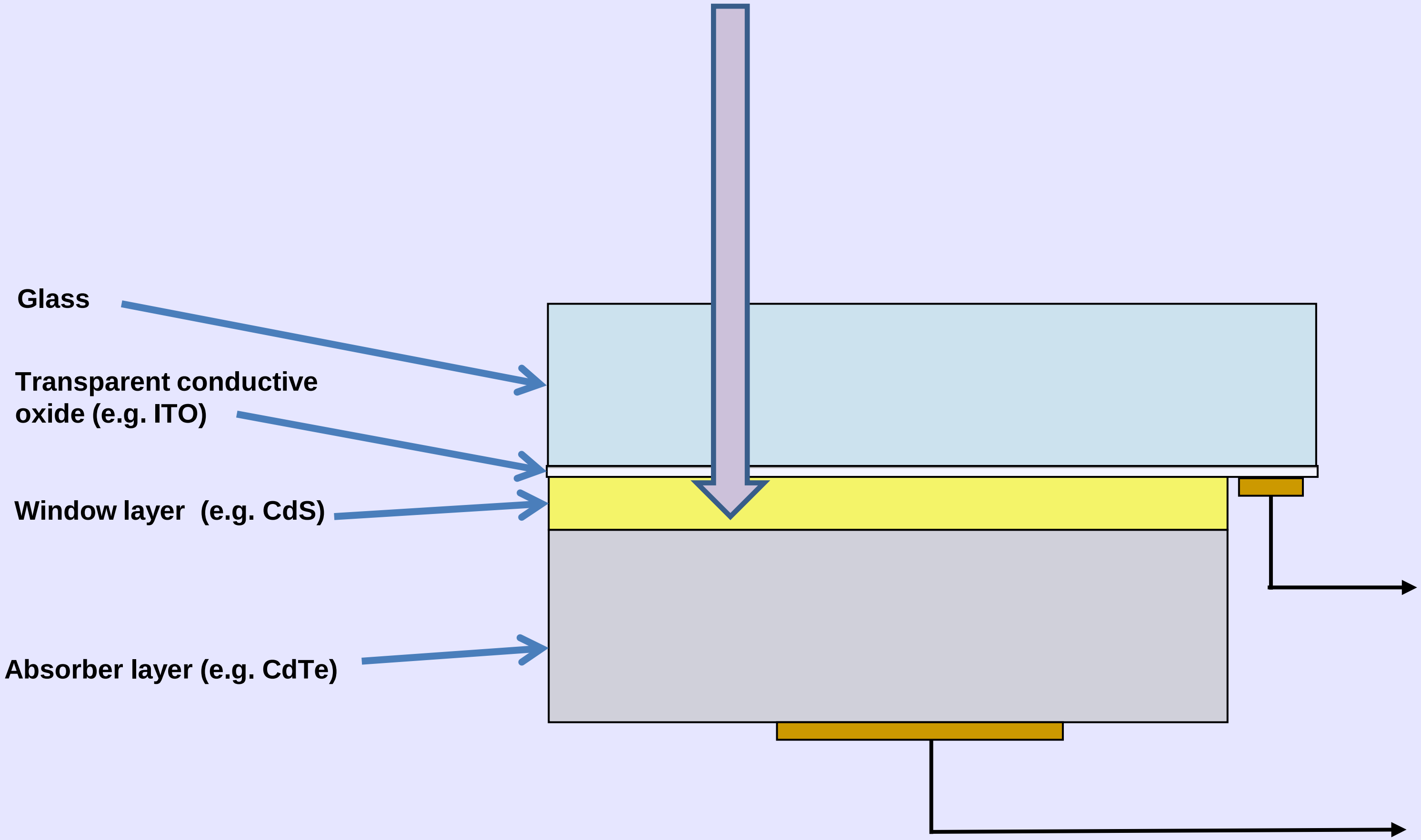
External quantum efficiency (EQE)

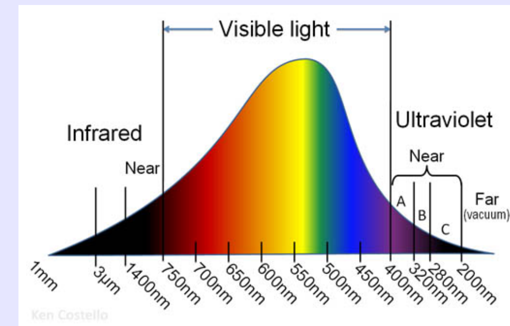


Absorber bandgap

$$E(\lambda) = \frac{hC}{\lambda}$$

External quantum efficiency (EQE)

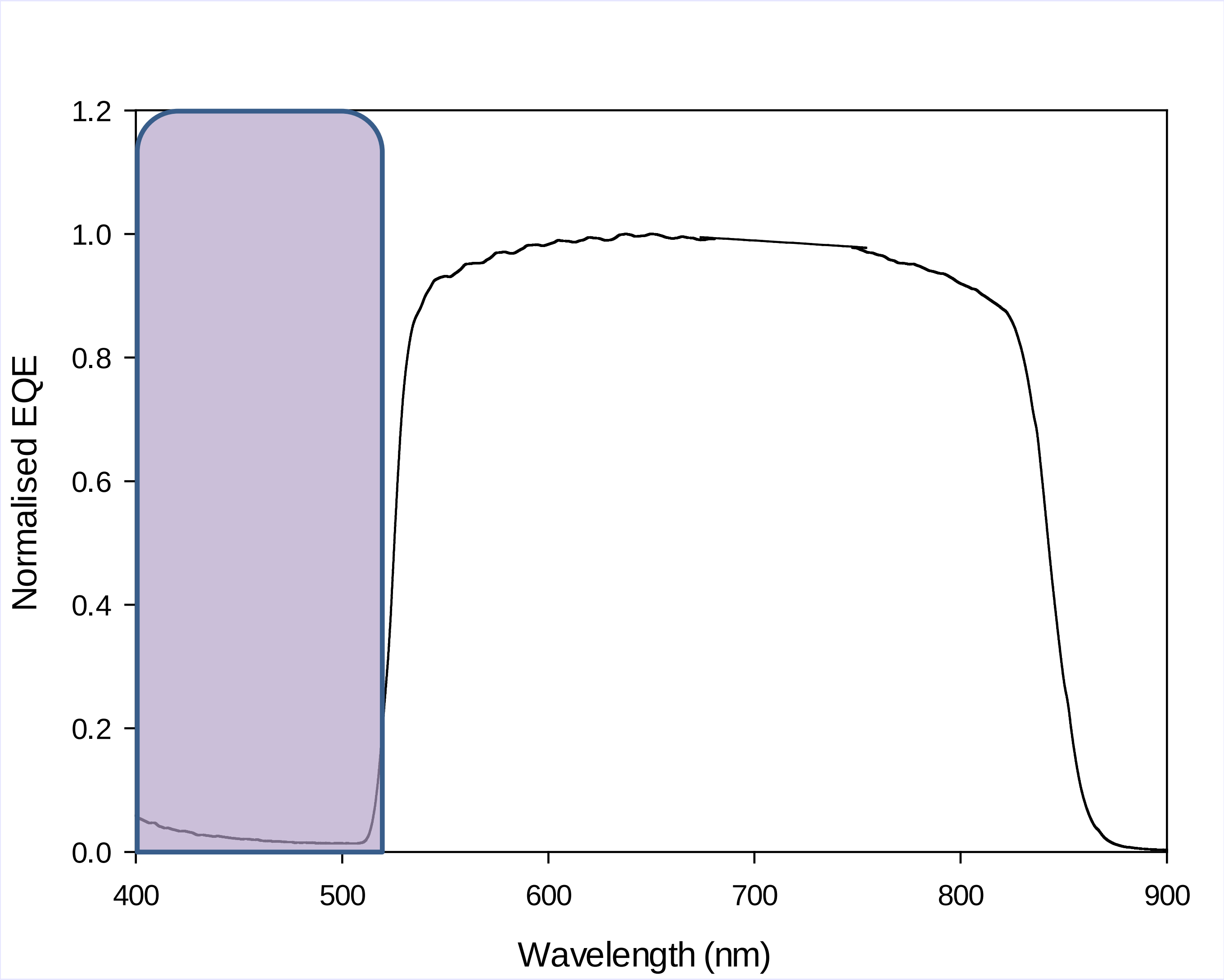




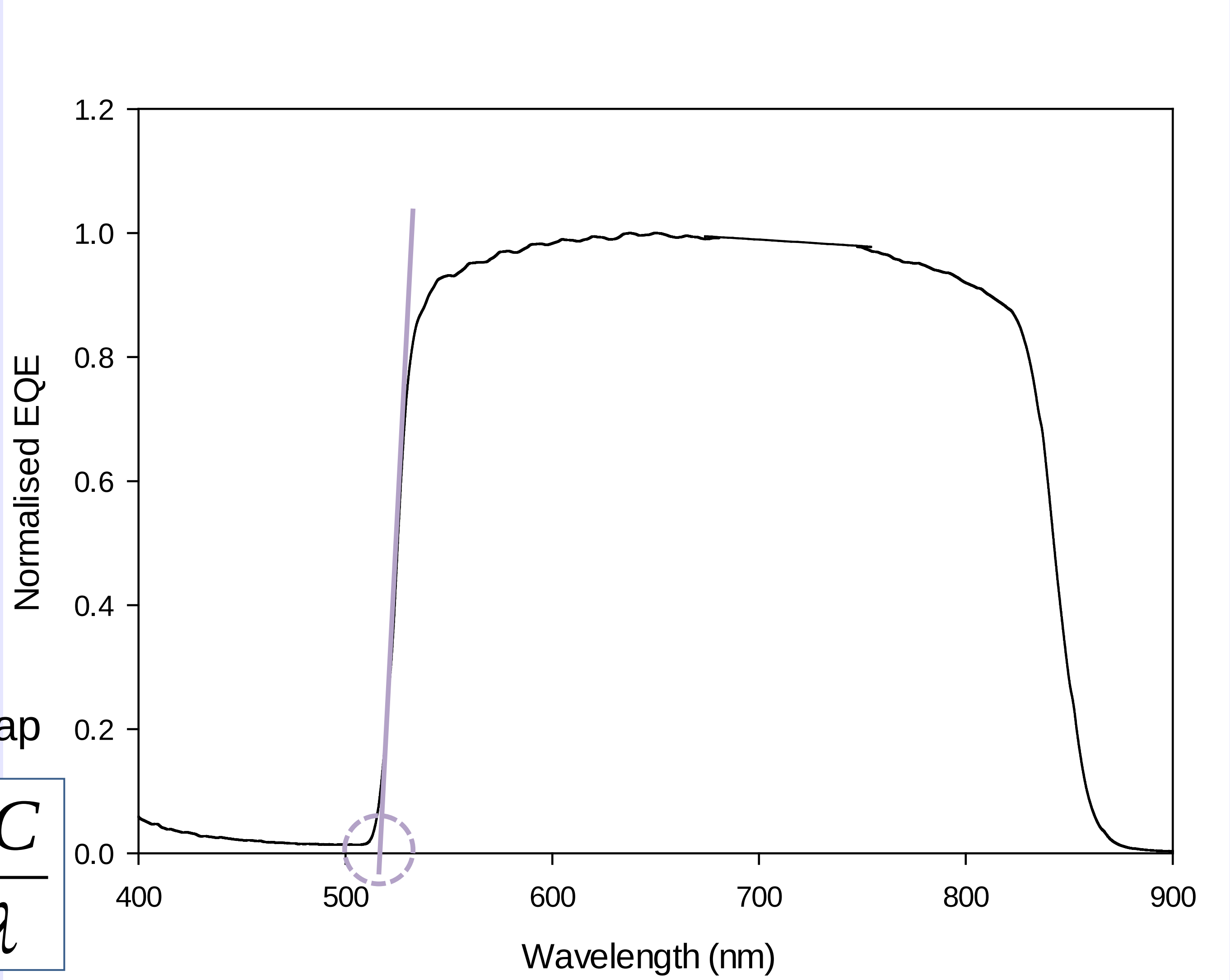
$$E(\lambda) = \frac{hC}{\lambda}$$

Region 3: $E_{photon} > E_{window}$

External quantum efficiency (EQE)



External quantum efficiency (EQE)

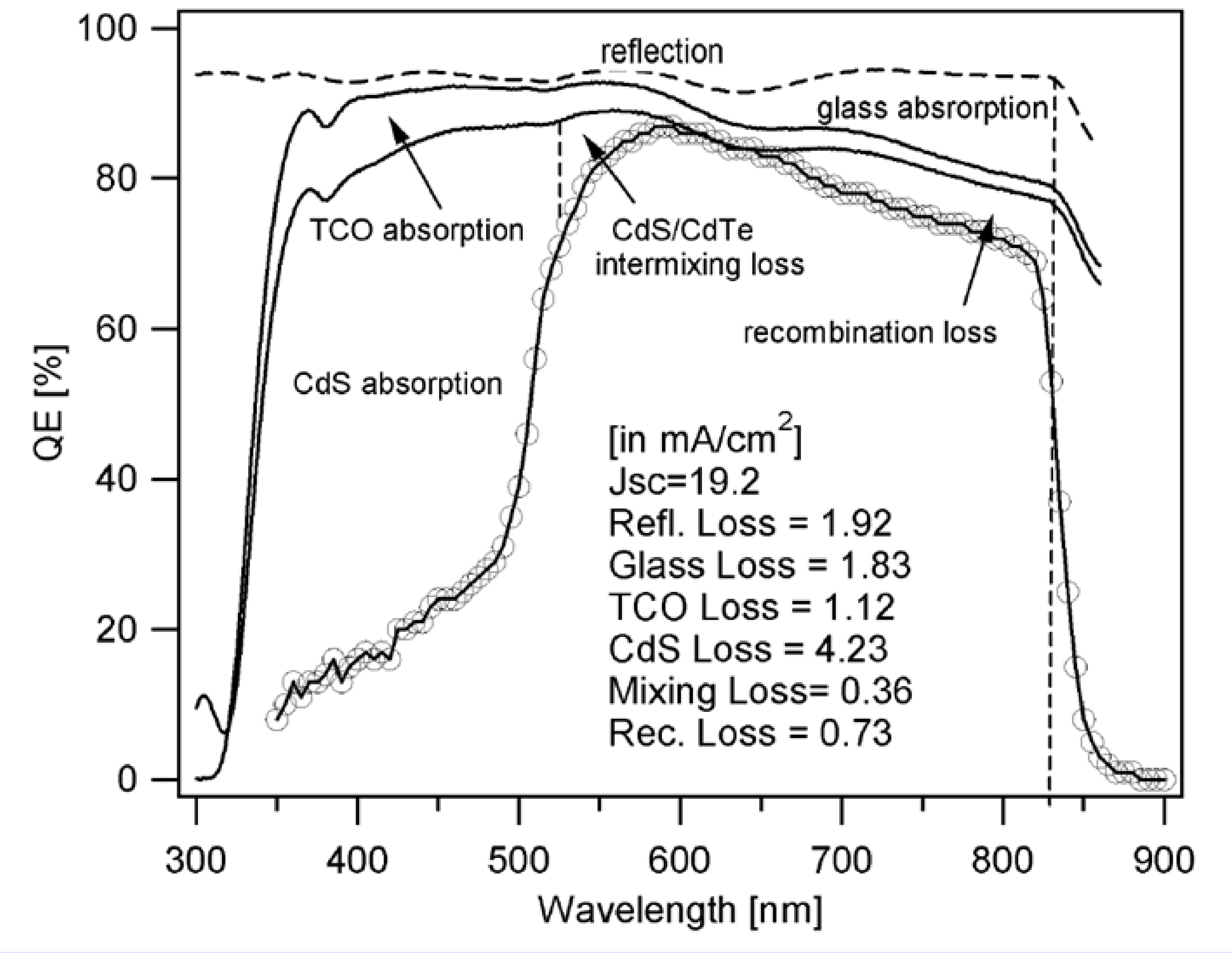


Window bandgap

$$E(\lambda) = \frac{hC}{\lambda}$$

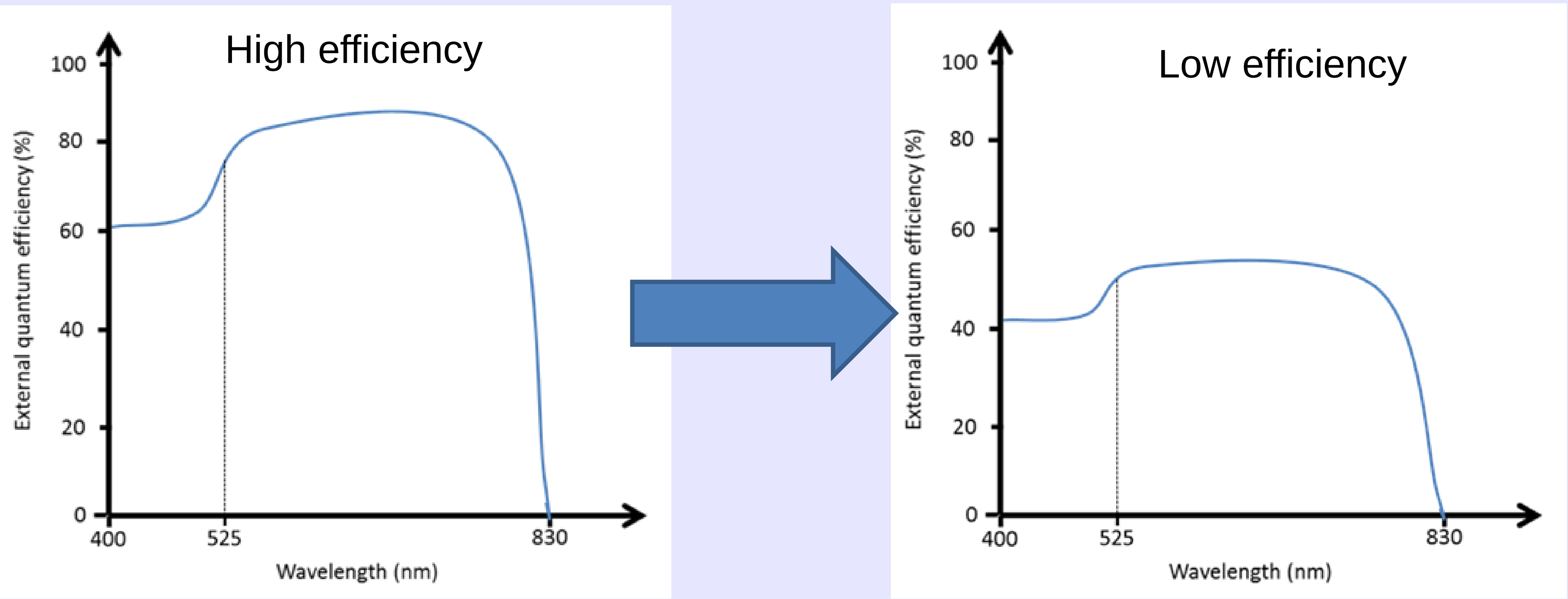
External quantum efficiency (EQE)

Real cells



External quantum efficiency (EQE)

<u>Optical losses</u>



Uniform reduction in EQE signal across wavelength range is an indication of optical losses i.e. reflection loss, optical blockages etc.

Can also be an indication of poor system calibration.

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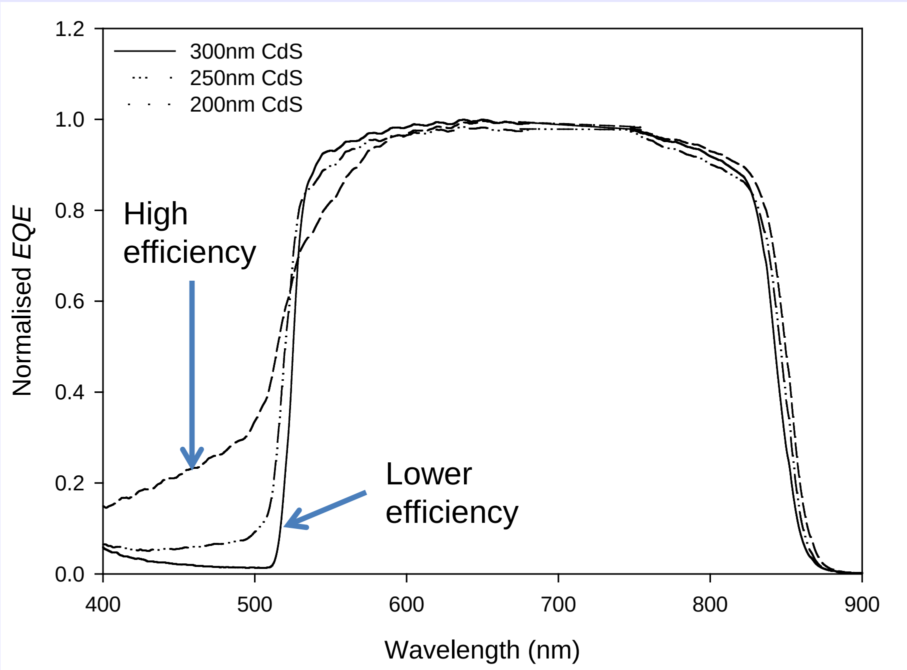
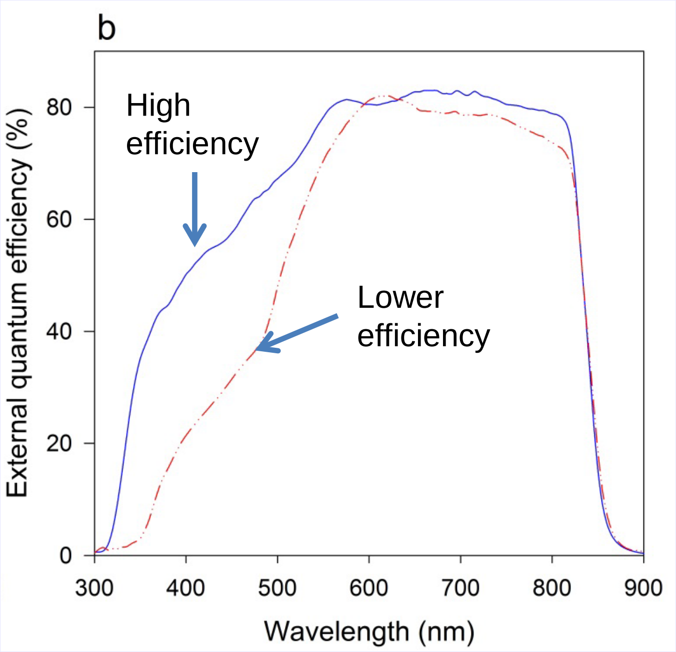
External quantum efficiency (EQE)

window/ n-type layer losses



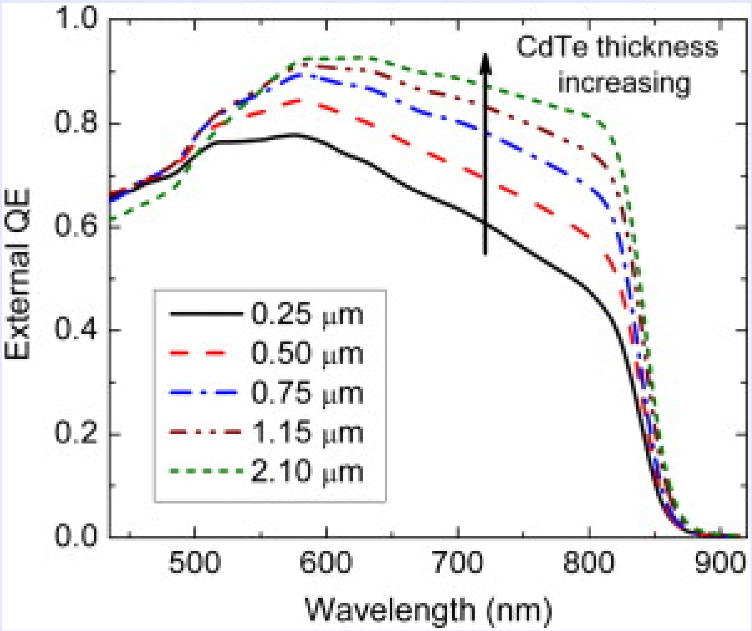


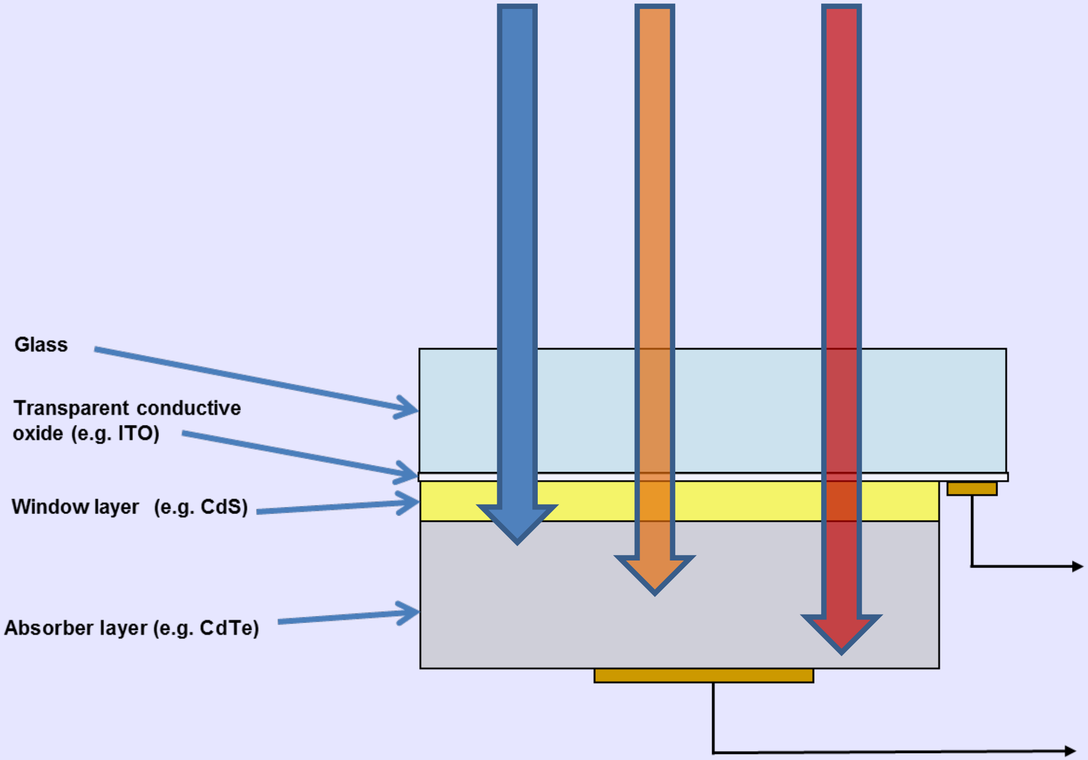
Reduced window layer thickness allows more light transmission to absorber

Higher bandgap n-type layer shifts absorption edge

External quantum efficiency (EQE)

Deep penetration losses

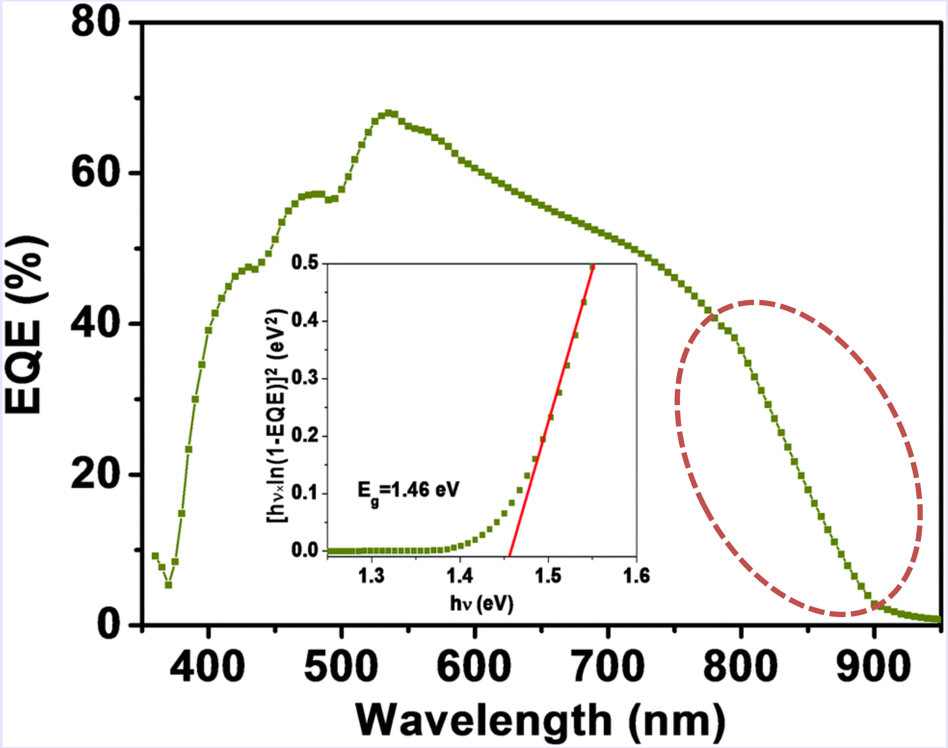




If absorber layer is thin or depletion width is narrow then longer wavelength photons have an increased probability of not contributing to photocurrent. See a decrease in EQE for longer wavelengths.

External quantum efficiency (EQE)

Graded bandgap/back surface recombination

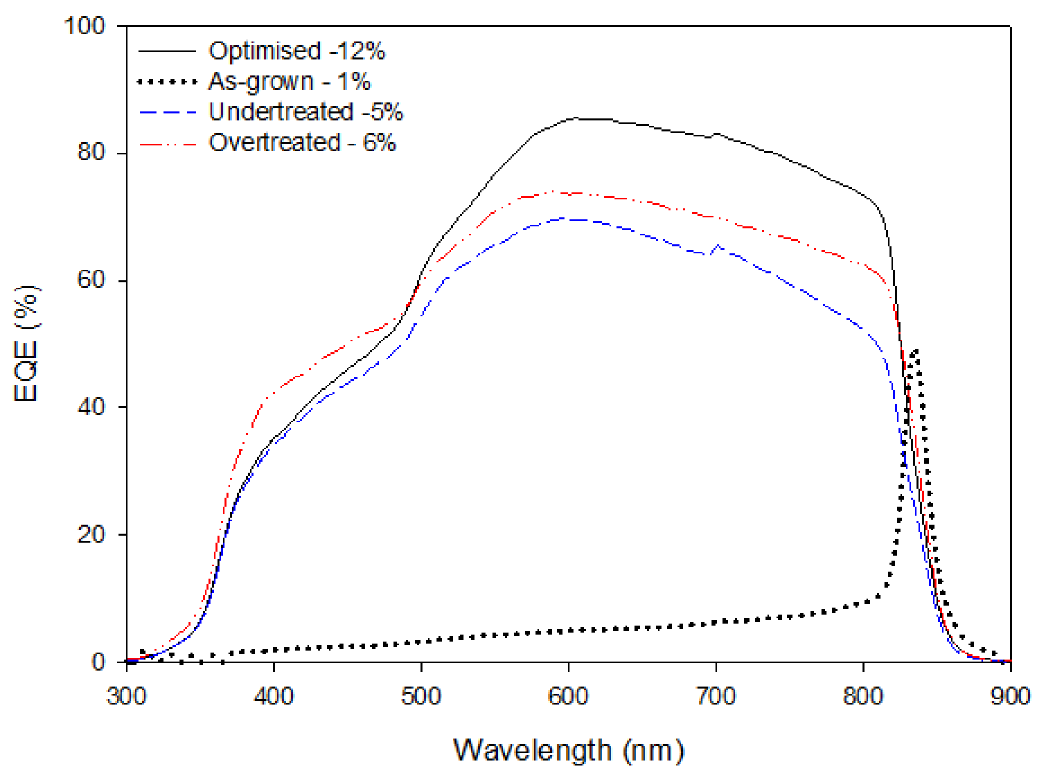


In multi component materials such as CZTS can get a broad cut-off region due to changes in the absorber bandgap.

This often signifies the material isn't single phase and reduces the efficiency.

Can also indicate enhanced recombination close to the back surface.

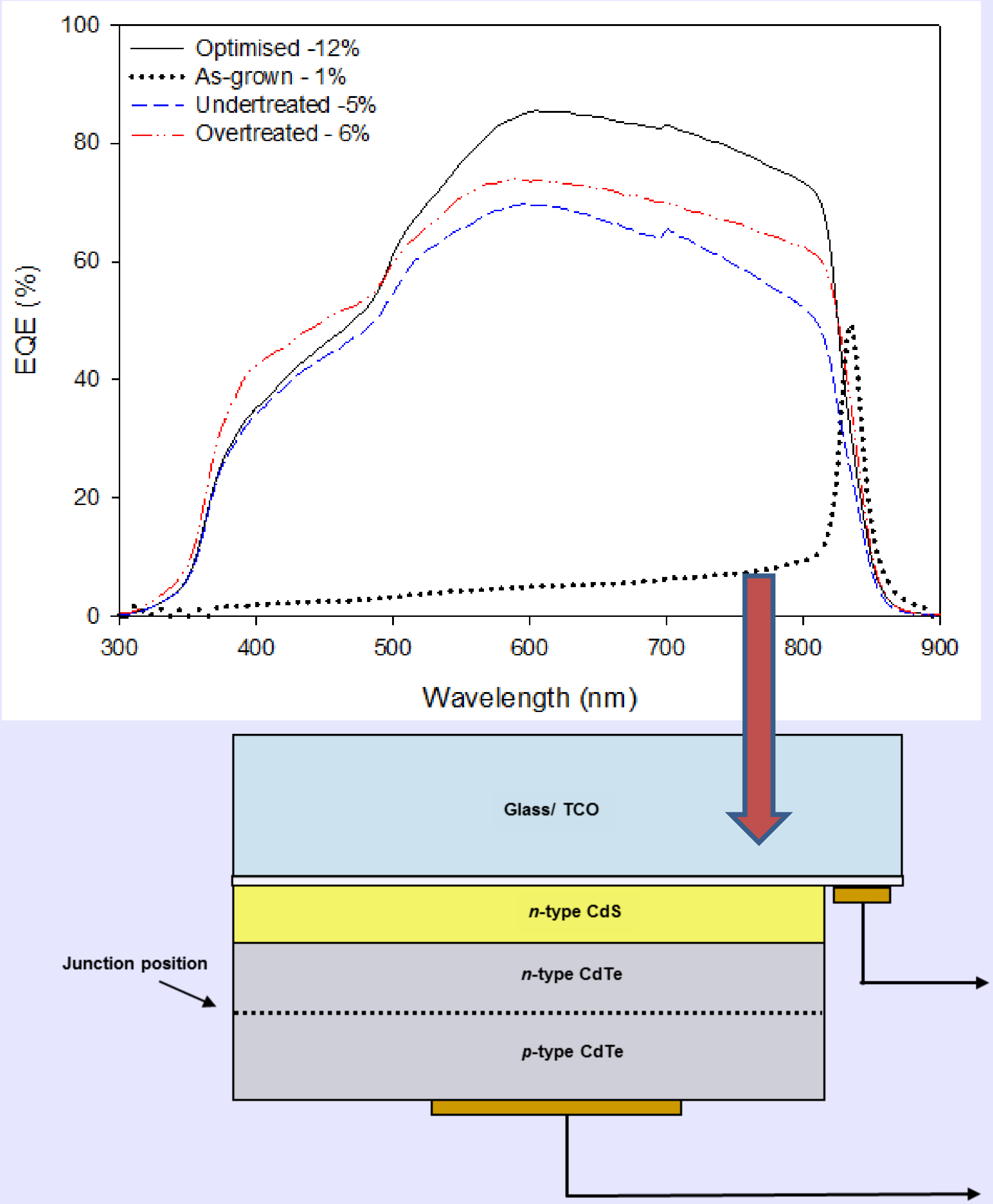
External quantum efficiency (EQE)



In certain situations see a complete change in EQE that corresponds to very low performance

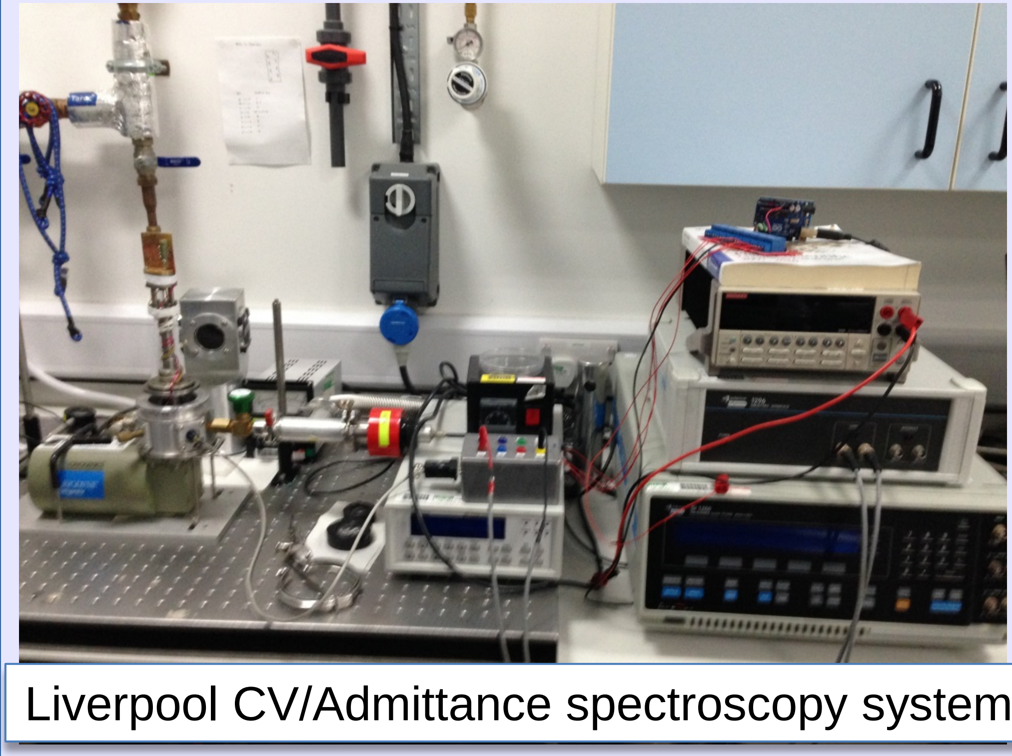
See reasonable EQE response near absorber band-edge but low response at all other wavelengths

External quantum efficiency (EQE)



This is a **buried junction response** due to both *p* and *n* type regions being present in the absorber layer

Capacitance Voltage analysis (C-V)



Liverpool CV/Admittance spectroscopy system

Capacitance-voltage measurements are useful in deriving particular parameters about PV devices.

Depending on the type of solar cell, capacitance-voltage (C-V) measurements can be used to derive parameters such as the doping concentration
and the built-in voltage of the junction.

A capacitance-frequency (C-f) sweep can be used to provide information on the existence of traps in the depletion region.

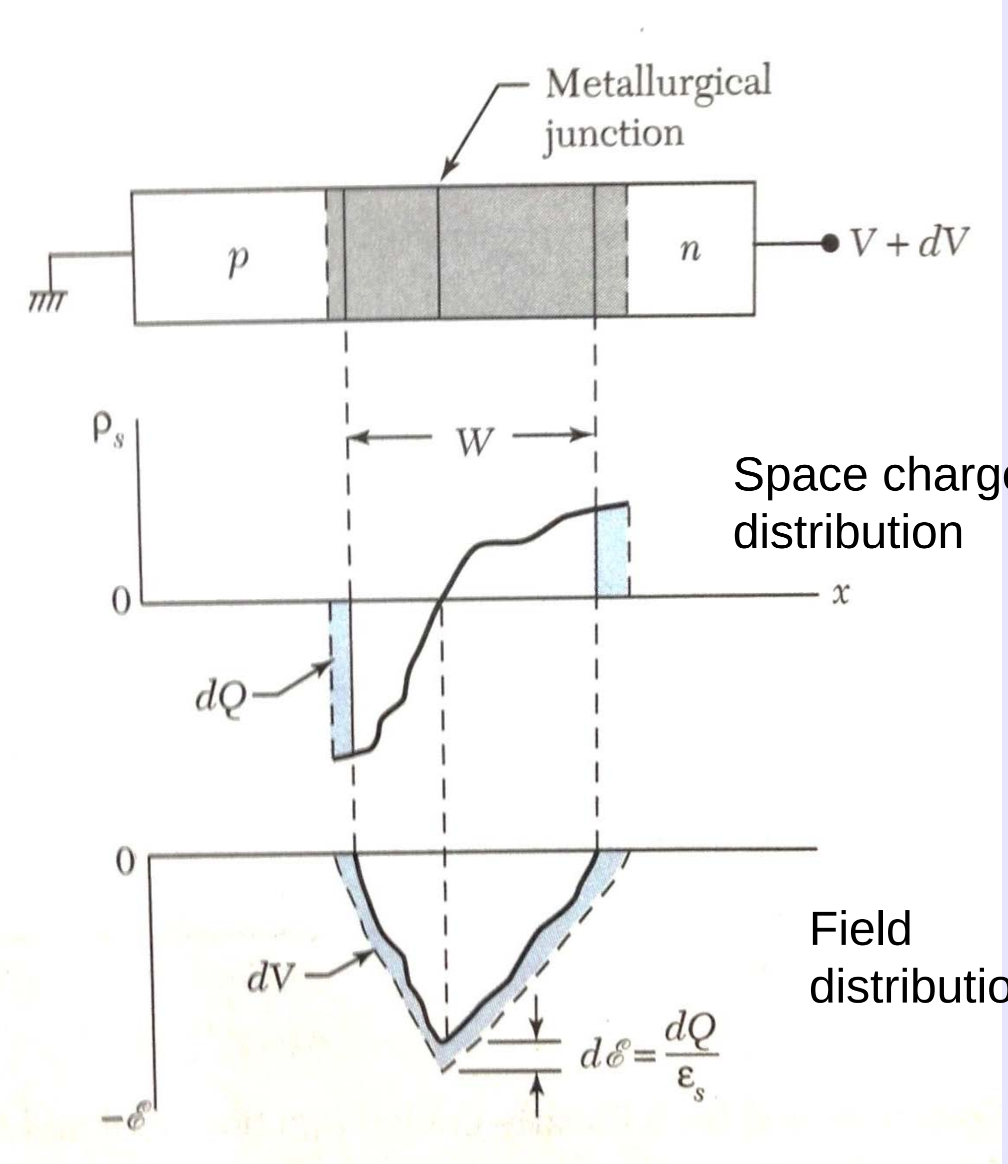
Capacitance Voltage analysis (C-V)

Can treat a p-n junction as a capacitor - depletion region sandwiched between two plates.

Can define the junction capacitance per unit area as

$$C_j \equiv \frac{dQ}{dV} = \frac{dQ}{W \frac{dQ}{d\varepsilon_s}} = \frac{\varepsilon_s}{W}$$

Where W is the width of the depletion region and ε_S is the semiconductor permittivity

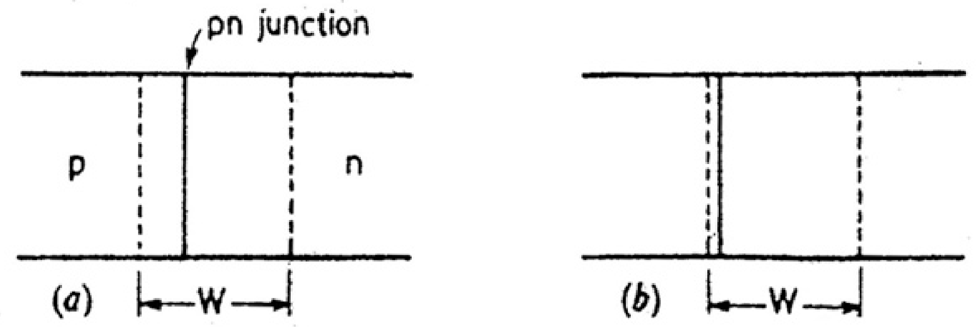


Space charge distribution

Field distribution

Capacitance Voltage analysis (C-V)

We generally assume a one sided abrupt junction for calculations. This is due to the higher doping densities in the n-type layer meaning the depletion region lies within the p-type layer



pn junction depletion region (between two dashed lines) width (*a*) general case (*b*) p^+n "one-sided" junction.

For a one sided junction we can determine the depletion width as

$$W = \sqrt{\frac{2\varepsilon_s V}{qN_a}}$$

Electron charge

Acceptor doping density

Using previous equation we get the relation

$$\frac{1}{C^2} = \frac{2V}{q\varepsilon_s N_a}$$

Hence we can get N_a from a plot of $1/C^2$ vs V

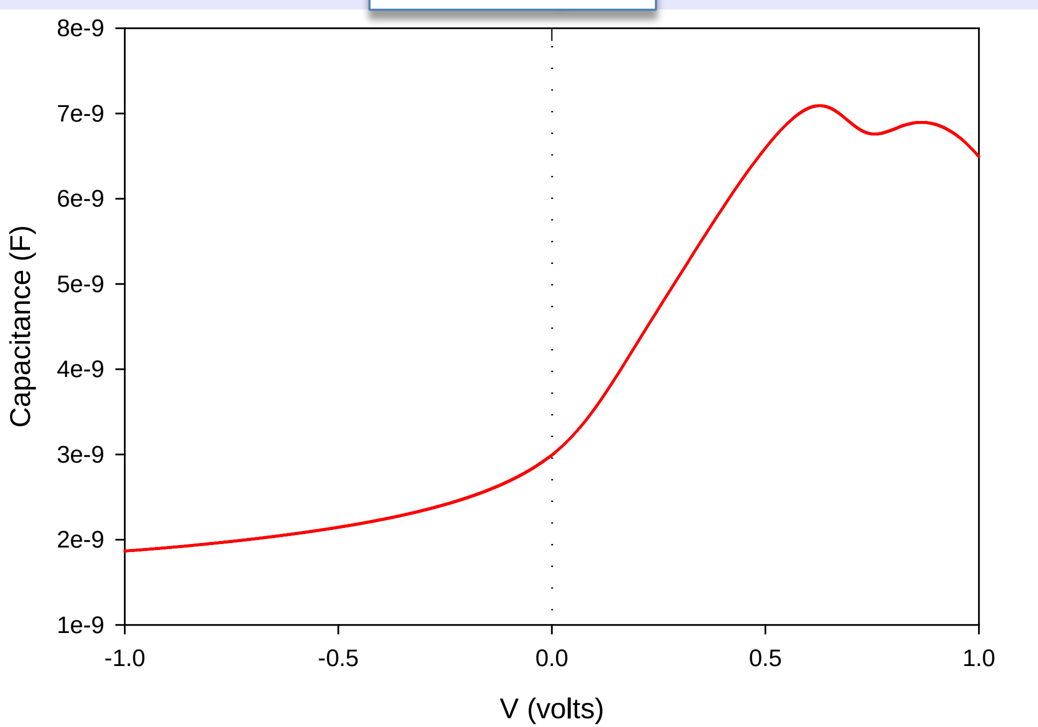
Capacitance Voltage analysis (C-V)

Worked example – CdTe solar cell

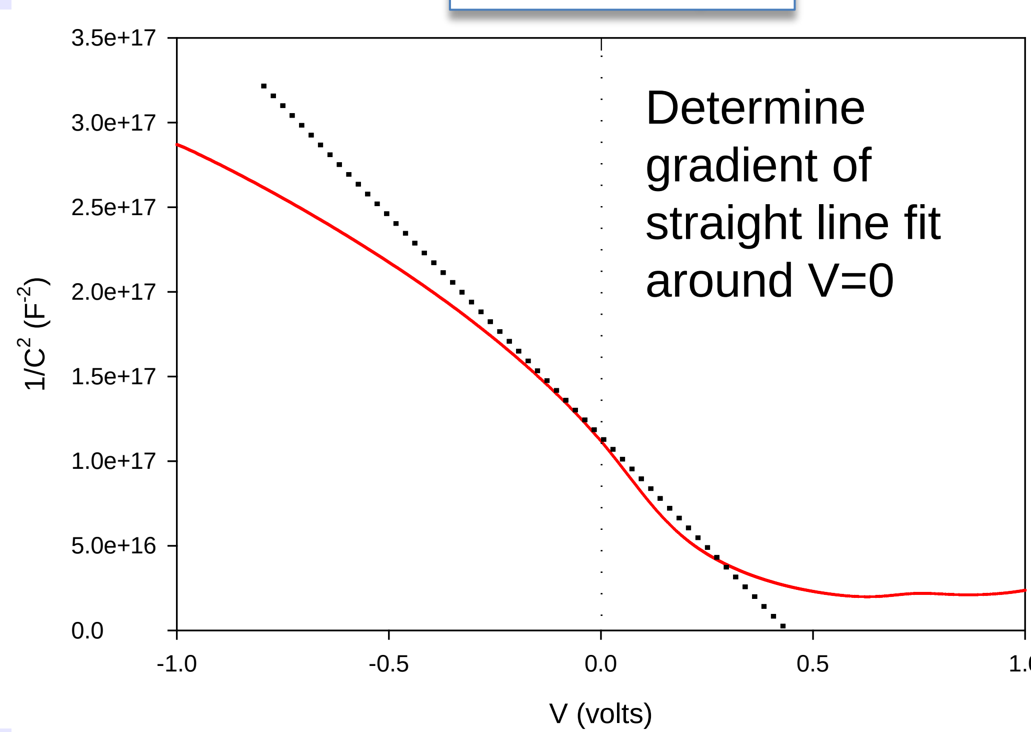
Measure the capacitance response of the cell as a function of applied bias.

C-V measurements can be made either forward-biased or reverse biased. However, when the cell is forward-biased, the applied DC voltage must be limited; otherwise non-ohmic back contacts can alter the signal.

C vs. V plot



$1/C^2$ vs. V plot



Capacitance Voltage analysis (C-V)

p-type doping density is given by

$$N_a = \frac{2}{q\varepsilon_s A^2 \frac{d(\frac{1}{C^2})}{dV}}$$

We have included a contact area term A

So for a CdTe cell with 5mm diameter square contacts we measured a the slope of the $1/C^2$ plot to be 2.7×10^{17}.

$$\frac{d(\frac{1}{C^2})}{dV} = 2.7 \times 10^{17} V^{-1} F^{-2}$$

$$A = 0.005 \times 0.005 = 0.25 \times 10^{-5} m^2$$

$$\varepsilon_s = 10.36\varepsilon_0 = 9.2 \times 10^{-11} Fm^{-1}$$

$$q = 1.6 \times 10^{-19} C$$

So CdTe doping density is

$$N_a = 8.1 \times 10^{20} m^{-3} = 8.1 \times 10^{14} cm^{-3}$$

Summary

Key junction characterisation techniques

- JV – R_S and R_{SH} → can infer the issue
- J-V-T – Back contact barrier height measurements
- EQE – Layer behaviour and optical losses
- CV - doping density of p-type layer