PV characterization

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Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

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The maximum power conversion efficiency of a solar cell consisting of single semiconducting absorber material with band-gap energy Eg is described by the Shockley–Queisser

(i) the probability for the absorption of solar light by the generation of a single electron–hole pair in the photovoltaic absorber material is unity for all photon energies E >= Eg and zero for E < Eg.

ii) All photogenerated charge carriers thermalize to the band edges.

iii) The collection probability for all photo- generated electron–hole pairs at short-circuit is unity.

iv) The only loss mechanism in excess of the non absorbed photons of (i) and the thermalization losses is the spontaneous emission of photons by radiative recombination of electron–hole pairs as required by the principle of detailed balance.

The Shockley–Queisser Theory

(1) $$J_{\mathrm{sc,SQ}} = q\int_0^\infty A(E)\phi_{\mathrm{inc}}(E)dE = q\int_{E_g}^\infty \phi_{\mathrm{inc}}(E)dE$$

$\phi_{\mathrm{bb}}(E,T)$ Black body spectrum at temperature T

$$\phi_{\mathrm{em}} = A(E)\phi_{\mathrm{bb}}(E,T)$$

A(E) = 1 (for E > Eg) and A(E) = 0 (for E < Eg)

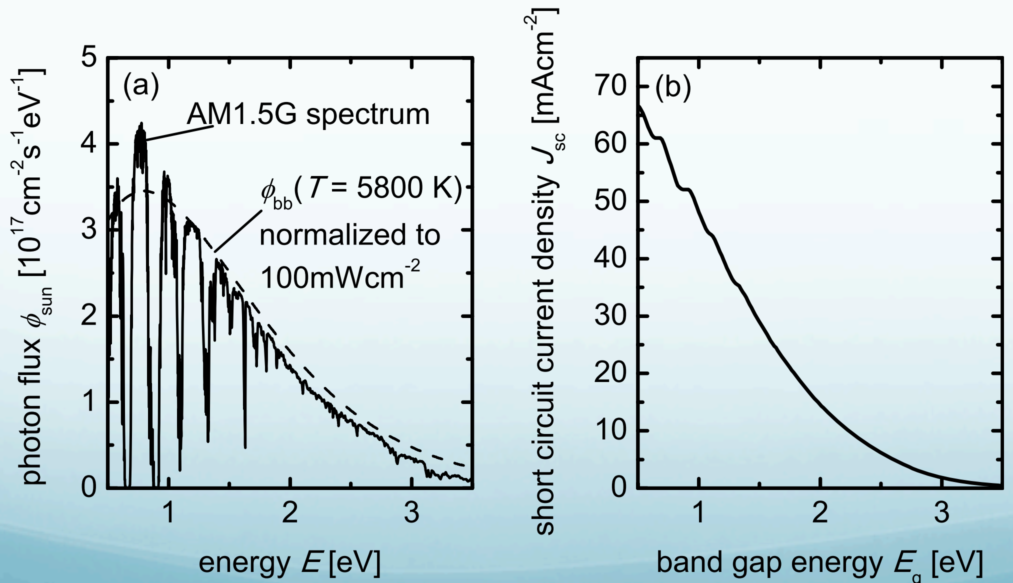
(2) $$J_{\mathrm{rec,SQ}} = q\int_0^\infty A(E)\phi_{\mathrm{bb}}(E,T)\exp\left(\frac{qV}{kT}\right)dE = q\int_{E_g}^\infty \phi_{\mathrm{bb}}(E,T)\exp\left(\frac{qV}{kT}\right)dE$$

$$J(V) = J_{\mathrm{rec,SQ}}(V) - J_{\mathrm{sc,SQ}} = q\int_{E_g}^\infty \phi_{\mathrm{bb}}(E)dE\,\exp\left(\frac{qV}{kT}\right) - q\int_{E_g}^\infty \phi_{\mathrm{inc}}(E)dE$$

There are two contributions to the incoming photon φ_{inc}, that is, the spectrum φ_{sun} of the sun and the photon φ_{bb} from the environment, which has the same temperature as the sample. When we replace the incoming photon φ_{inc} with the sum $\varphi_{sun} + \varphi_{bb}$,

$$J(V) = q \int_{E_g}^{\infty} \phi_{bb}(E)dE \left[\exp\left(\frac{qV}{kT}\right) - 1\right] - q \int_{E_g}^{\infty} \phi_{sun}(E)dE \qquad \left(J = J_0 \left[\exp\left(\frac{qV}{kT}\right) - 1\right] - J_{sc} \right)$$

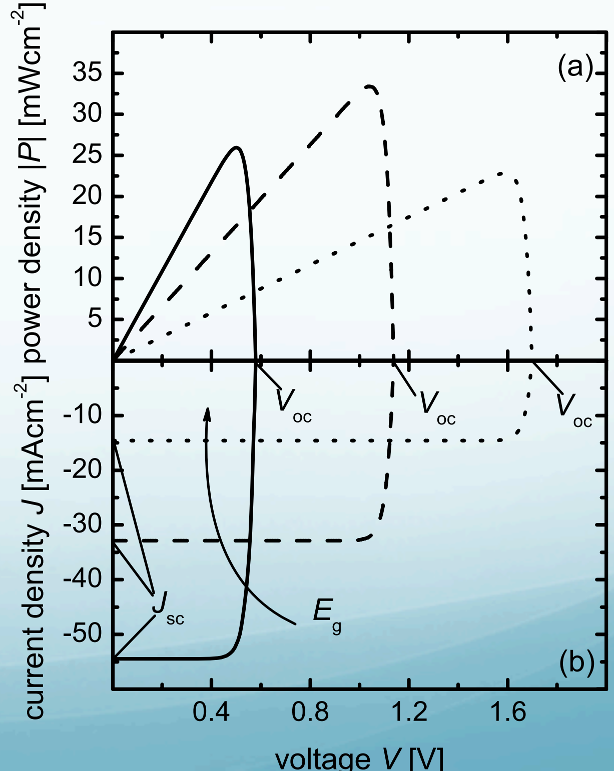
typical diode equation with an additional photocurrent only due to the extra illumination from the sun.

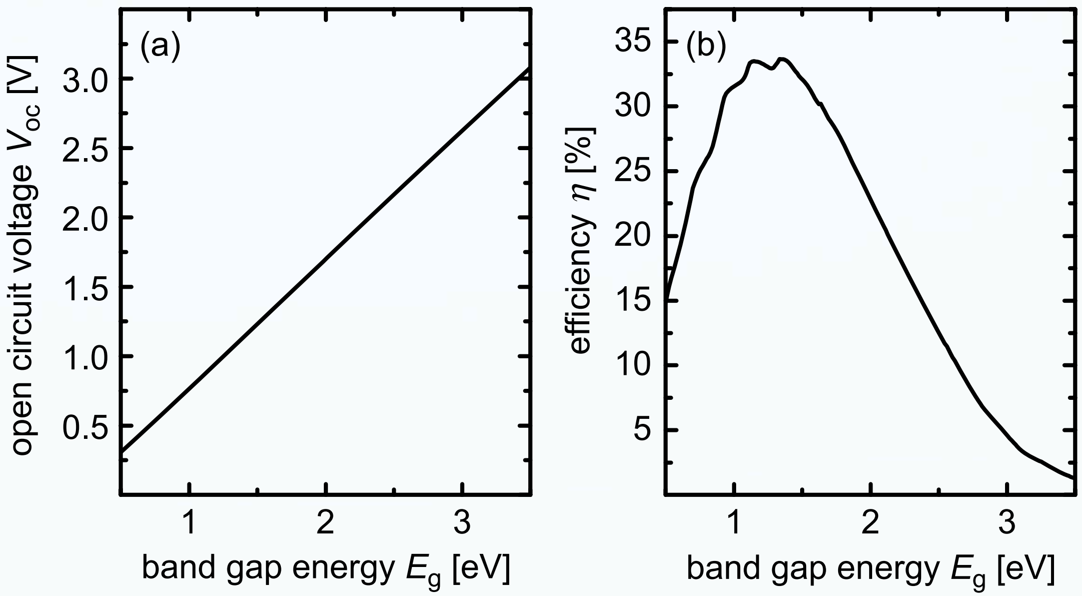


Open circuit conditions, J=0

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{\int_{E_g}^{\infty}\phi_{sun}(E)dE}{\int_{E_g}^{\infty}\phi_{bb}(E)dE} + 1\right) = \frac{kT}{q}\ln\left(\frac{J_{sc,SQ}}{J_{0,SQ}} + 1\right)$$

Here, $J_{0,SQ}$ is the saturation current density in the SQ limit, that is, the smallest possible saturation current density for a semiconductor of a given band gap. The open-circuit voltage increases nearly linearly with increasing band gap





The final result of the SQ theory: the efficiency as a function of the band-gap energy for illumination with the AM1.5G spectrum.

Shape of Current/Voltage Curves and their Description with Equivalent Circuit Models

$$J = J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - J_{sc}$$

$$\begin{aligned} J_{rec} &= J_d = q\int_0^d R\,dx = q\int_0^d B(np - n_i^2)\,dx = qBd\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \\ &= J_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \end{aligned}$$

$(R \propto np)$

J_d dark current density

- The recombination rate does not scale directly with the np-product.
- Instead, the typical recombination mechanism in thin-film solar cells is **Shockley–Read–Hall recombination** via defects in the band gap. Assuming a defect in the middle of the band gap, the recombination rate scales with:

$$R = \frac{np - n_\mathrm{i}^2}{(n+p)\tau}$$

$$R(n \ll p) = \frac{np - n_\mathrm{i}^2}{(n+p)\tau} \approx \frac{n}{\tau} \qquad R(n \ll p) \approx \frac{n}{\tau} \propto \exp\left(\frac{qV}{kT}\right)$$

Diode 1 represents the recombination current in the quasi-neutral regions (∝ eqV /kT)

In the p-type layer in the dark and for not too high voltages, the electron concentration is much smaller than the hole concentration (n << p).

$$R(n = p) = \frac{np - n_\mathrm{i}^2}{(n+p)\tau} \approx \frac{n}{2\tau} = \frac{\sqrt{np}}{2\tau} \qquad R(n = p) \propto \sqrt{\exp\left(\frac{qV}{kT}\right)'} = \exp\left(\frac{qV}{2kT}\right)$$

Diode 2 represents recombination in the depletion region (∝ eqV/2kT)

Found within the junction for n = p

Two diode model in the dark

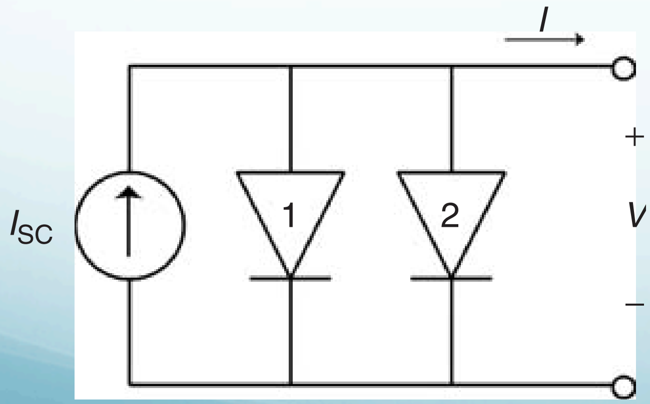
$$J = J_{01}\left[\exp\left(\frac{qV}{n_{\mathrm{id1}}kT}\right)-1\right] + J_{02}\left[\exp\left(\frac{qV}{n_{\mathrm{id2}}kT}\right)-1\right]$$

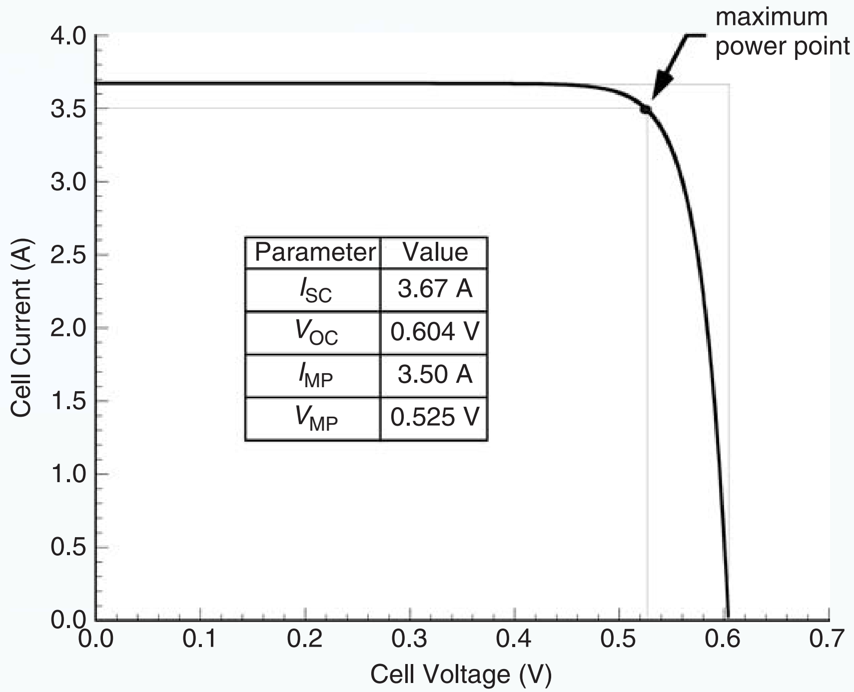
And in the light

$$J = J_{sc} - J_{01}(\exp(\frac{qV}{n_{id1}kT})-1) + J_{02}(\exp(\frac{qV}{n_{id2}kT})-1)$$

$$n_1 \cong 1.86 \quad n_2 = 2$$

It is apparent that a solar cell can be modeled by an ideal current source J_{SC} in parallel with two diodes – one with an ideality factor of 1 and the other with an ideality factor of 2.



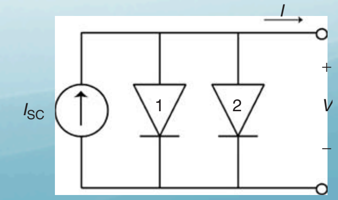


$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} = \frac{P_{MP}}{V_{OC} I_{SC}}.$$

$$\eta = \frac{P_{MP}}{P_{in}} = \frac{FF V_{OC} I_{SC}}{P_{in}}$$

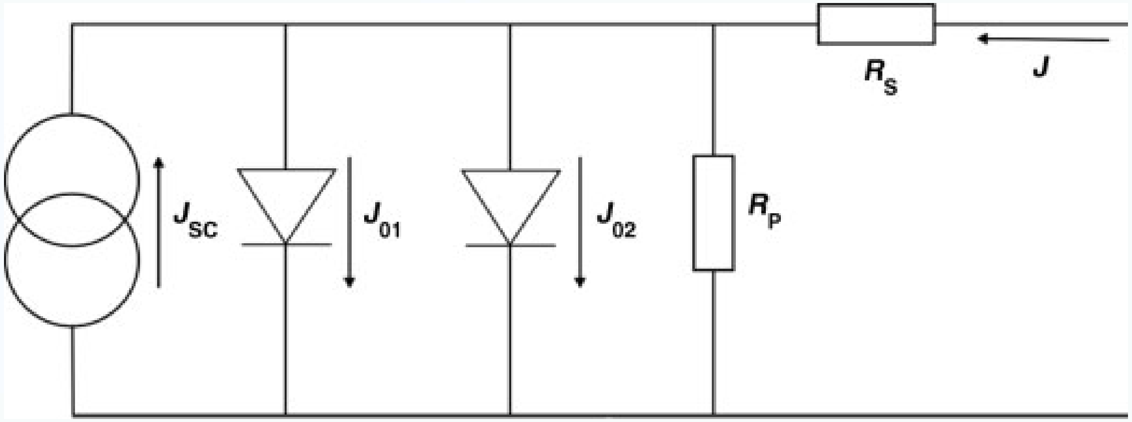
At open-circuit (J=0), all the light-generated current Jsc is flowing through diode 1 (diode ignored, as assumed above), so the open-circuit voltage can be written as

$$V_{OC} = \frac{kT}{q} \ln \frac{I_{SC} + I_{o1}}{I_{o1}} \approx \frac{kT}{q} \ln \frac{I_{SC}}{I_{o1}},$$

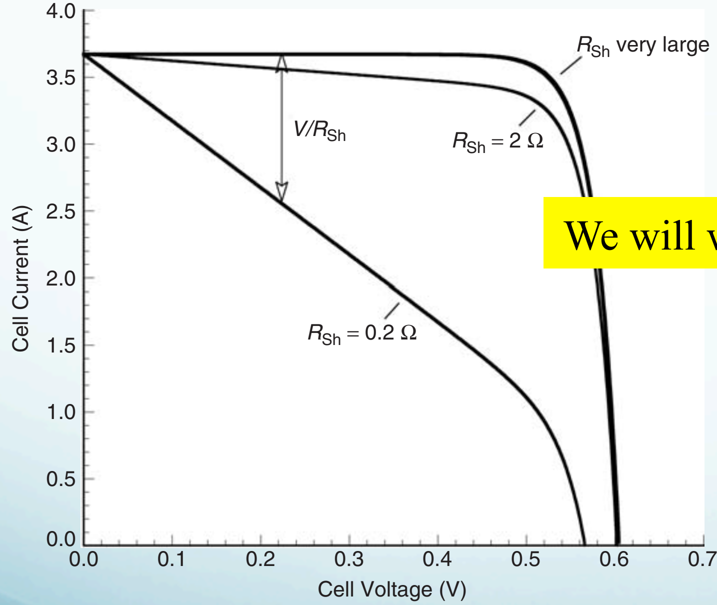


$$J = J_{01}\left[\exp\left(\frac{q(V-JR_s)}{n_{id1}kT}\right)-1\right] + J_{02}\left[\exp\left(\frac{q(V-JR_s)}{n_{id2}kT}\right)-1\right] + \frac{V-JR_s}{R_p} - J_{sc}$$

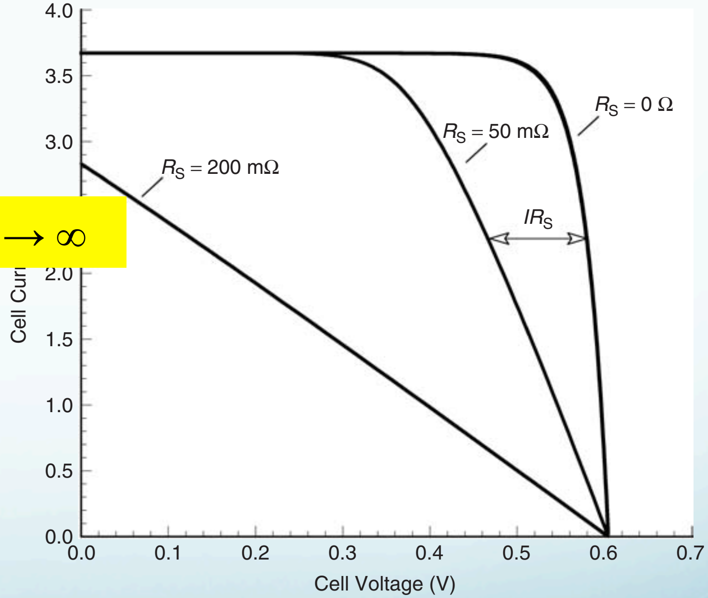
Rs - The series resistance may originate from the finite conductivity of the absorber layers themselves or from the front and back contacts.



Rp- shunt resitance (Rsh)



We will want Rs=0 and $R_{Sh} \rightarrow \infty$



Effect of shunt resistance on the current–voltage characteristic of a solar cell (RS = 0)

Effect of series resistance on the current–voltage characteristic of a solar cell (RSh → ∞)

Measurements of current voltage curves

- The biggest challenge for this measurement is to have a light source generating a spectrum that resembles the solar spectrum as much as possible. Since the terrestrial solar spectrum is close to that of a black body with a temperature of about 5800 K, any light bulb will have a black body spectrum with a much lower temperature since no element can withstand these temperatures without melting.

- The pure metal with the highest melting point is W (approximately 3700 K), which is therefore commonly used in light bulbs. Since any black body source will not reach the temperature of the sun and thus the spectrum of the sun without melting, a W halogen lamp is usually combined with a Xe-lamp to get a close match to the solar spectrum.

- Assuming that the device under test is illuminated with a spectrum resembling the standard AM1.5G spectrum, the device is contacted and the load resistance is varied such that the voltage changes. The voltage and current are usually measured during the voltage sweep with a four-point probe technique, that is, the current measurement is connected in series with the load resistance.

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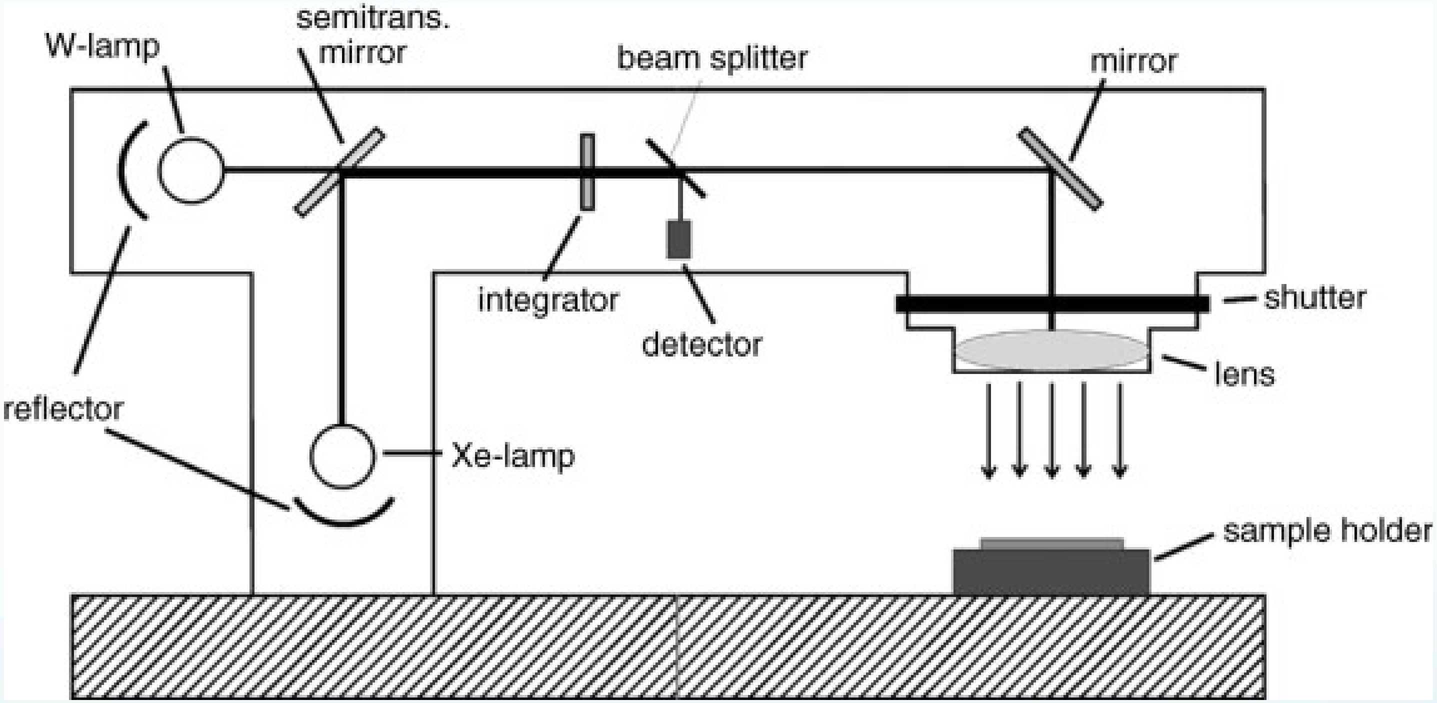
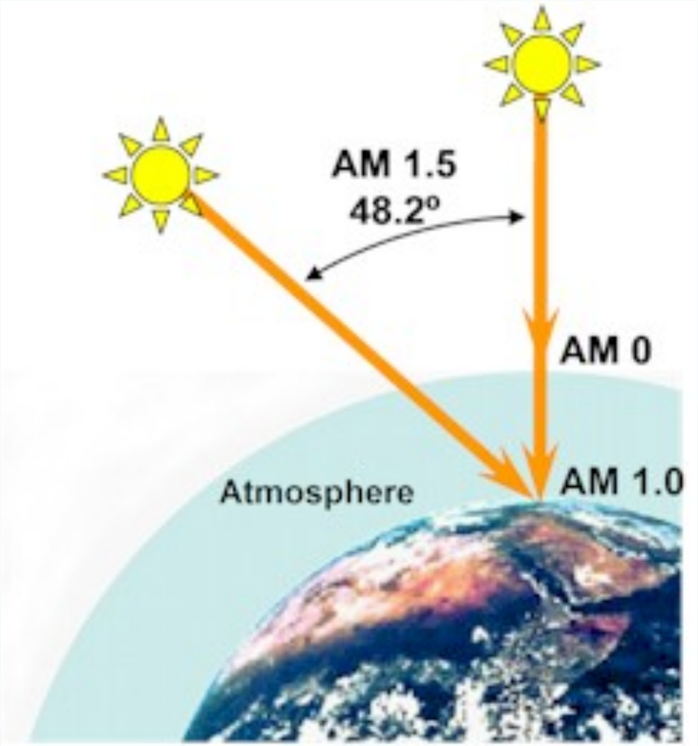


W-lamp
semitrans.
mirror
beam splitter
mirror
integrator
detector
shutter
lens
reflector
Xe-lamp
sample holder



Characterization Standard

- Power density of 1000 W/m^2
- Spectral power distribution corresponding to AM1.5

The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length

The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust.

Quantum Efficiency Measurements
(Incident photon to current efficiency)

A J-V measurement yields information on the absolute value of the short-circuit current density Jsc produced in a solar cell.

However, this simple measurement does not yield information on the origin of the **loss mechanisms** that are responsible for the fact that not every photon in the solar spectrum contributes to Jsc.

The external quantum efficiency Qe is defined as the number of electrons collected per photon incident on the solar cell according to:

$$Q_e(E) = \frac{1}{q}\frac{dJ_{sc}(E)}{d\Phi(E)} \qquad QE(\lambda) = \frac{\#\, of\ electrons\ collected}{\#\, of\ incident\ photons}.$$

where dW(E) is the incident photon Φin units of cm^{-2} s^{-1} in the (photon) energy interval dE that leads to the short-circuit current density dJsc.

In the ideal Shockley–Queisser case, we would have Qe(E)=1 for E≥Eg and Qe(E) = 0, otherwise.
In real solar cells, we have Qe(E) < 1 (even for E ≥ Eg) resulting either from
(i) optical or (ii) recombination losses.
The optical losses can be further broken down to losses due to reflection and due to parasitic absorption within the device.

For an opaque solar cell we know that all photons that are not reflected are absorbed in the device, that is, the **absorptance** A is given by A=1-R.
The **internal quantum efficiency** Qi is then defined as the number of collected electrons per number of photon absorbed in the solar cell

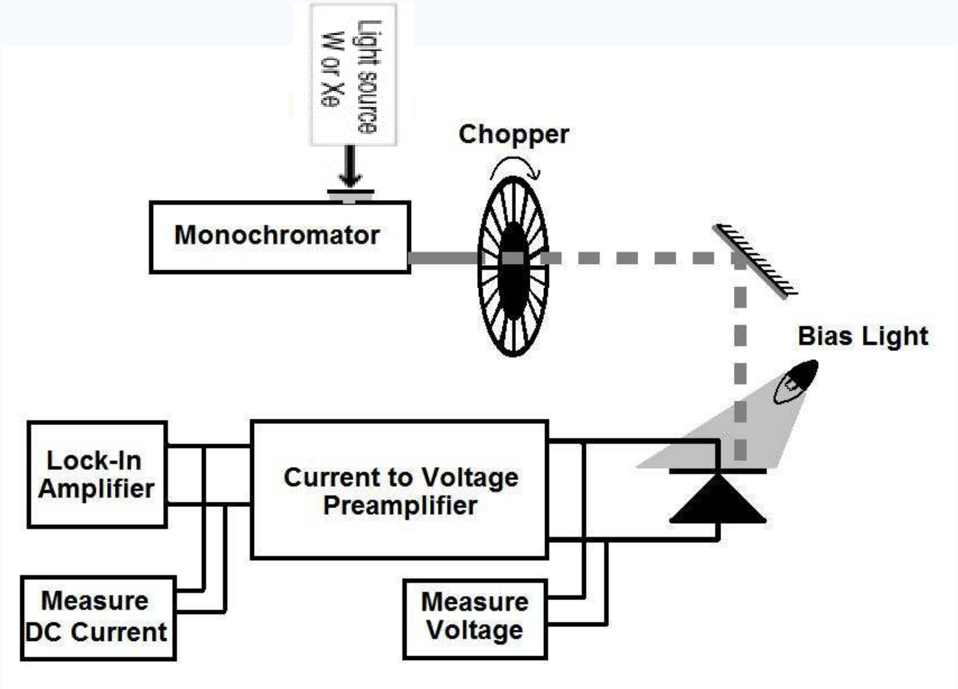
$$Q_i(E) = \frac{Q_e(E)}{1 - R(E)}$$

If QE is obtained under true J_{SC} conditions (AM1.5 illumination, V = 0), then QE measurements can be related to the photovoltaic parameter J_{SC} by

$$J_{SC} = q \int \Phi_{AM1.5}(\lambda) QE(\lambda) d\lambda,$$

Measurement principle

Monochromator based setup



- The advantage of using monochromators is the high wavelength resolution and the broad spectral range.

- In case of the setup with grating monochromator, first white light from a W-halogen lamp or a Xe-arc lamp is chopped before entering the monochromator. **The chopper is needed to obtain a periodic signal, which a lock-in amplifier can use.**

The monochromatic light is then focused on the

(i) solar cell to be measured (during the actual measurement) or

(ii) on the reference cell or detector (during the calibration).

The reference used for calibration of the setup can either

(i) be a pyroelectric radiometer for the relative calibration combined with a solar cell or photodiode for the absolute calibration at one wavelength

(ii) one reference solar cell for the whole spectral range.

The advantage of using a pyroelectric radiometer lies in its spectrally independent sensitivity over a broad wavelength range. Thus, the calibration has a high quality for all wavelengths, where the intensity of the lamp is sufficient for a high signal to noise ratio in the radiometer.

In case of the reference solar cell, not only the intensity of the lamp but also the quantum efficiency of the reference cell must be sufficiently high. Using a reference cell (without a radiometer) is particularly useful as long as the reference cell has high quantum efficiency for all wavelengths of interest of the device under test.

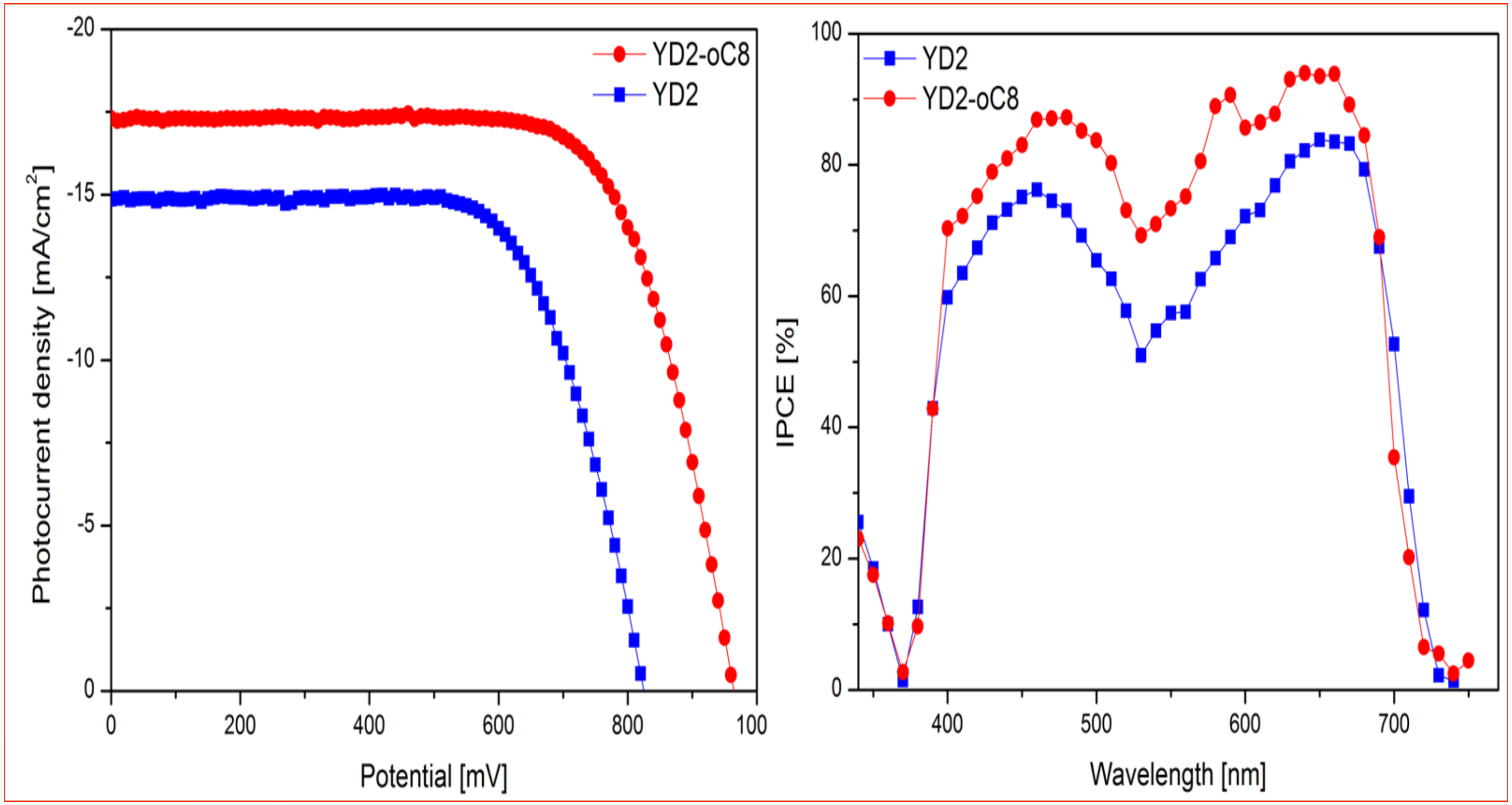
Current to voltage converter

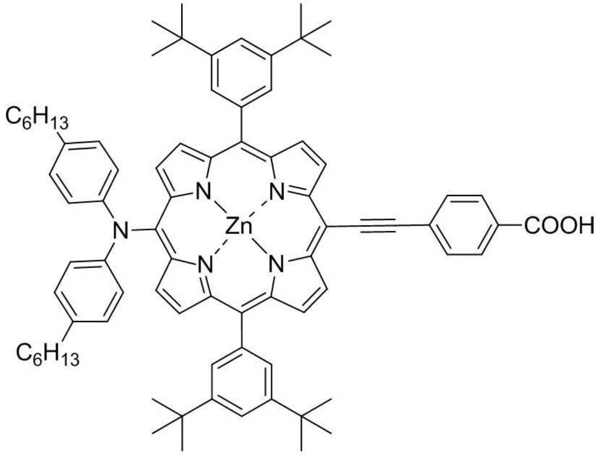
The current signal from the monitor and the test solar cell are then converted into a voltage by a current-to-voltage converter with a typical amplification ratio of 10^4–10^6 V/A. The voltage output of the converter serves as input for the lock-in amplifier that uses the synchronization output of the chopper controller as trigger input.

The lock-in reference frequency comes directly from the chopper controller

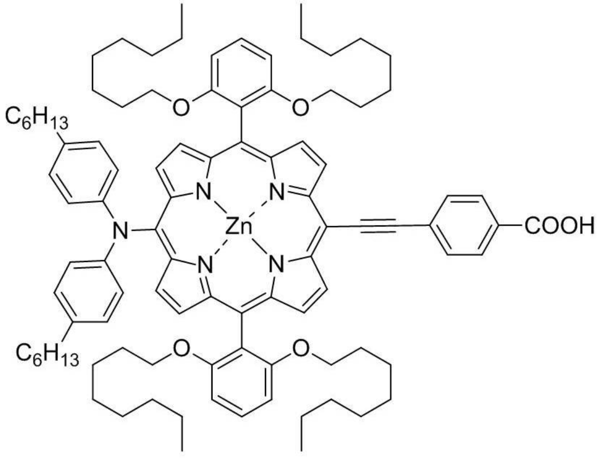
The amplified signal of the lock-in amplifier is then read and displayed by a computer.

Subtle changes in porphyrine structure produce large effect on PV performance

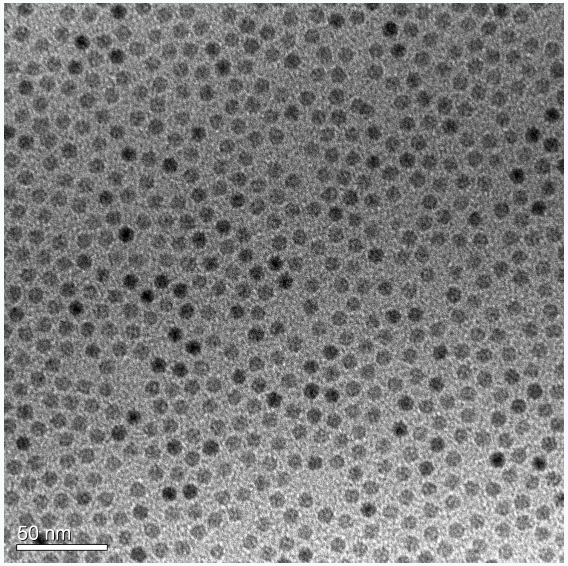


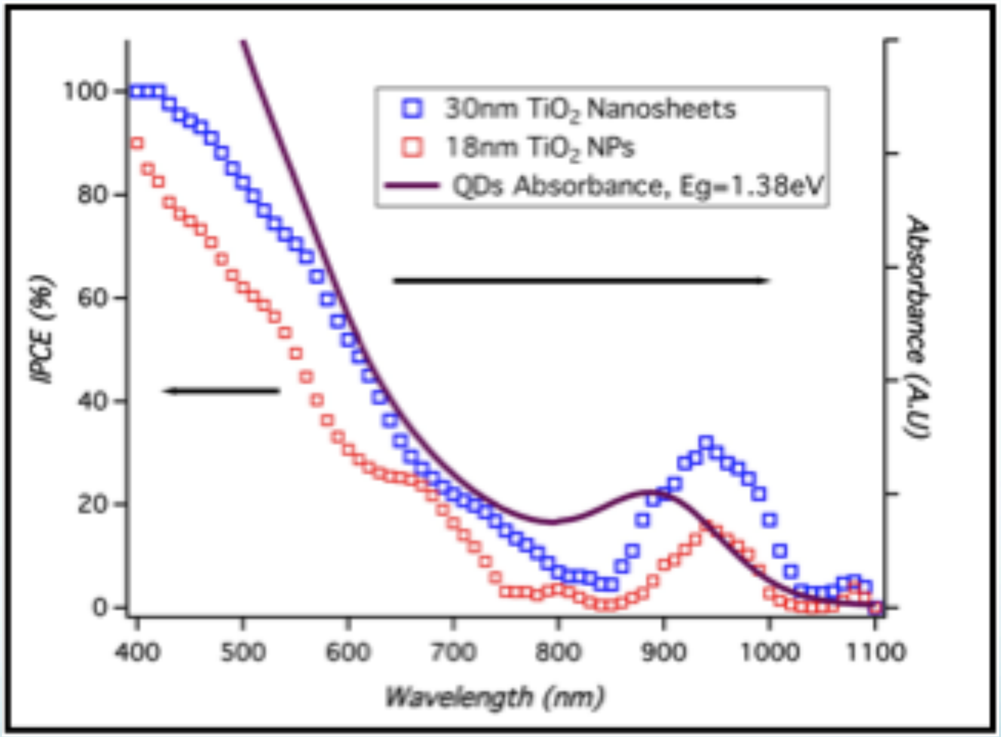


YD 2



YD2-oC8


50 nm


30nm TiO2 Nanosheets
18nm TiO2 NPs
QDs Absorbance, Eg=1.38eV
IPCE (%)
Absorbance (A.U)
Wavelength (nm)
0
20
40
60
80
100
400
500
600
700
800
900
1000
1100