Blake Weaver – 7/27/2011

Factors that Affect Current-Voltage Characteristics of Dye Solar Cells

Introduction

Current-voltage (IV) curves represent the most important and most direct characterization method for DSCs and for solar cells in general. The open circuit voltage (V_{oc}), short circuit current (I_{sc}) and the shape of the IV curve determine the efficiency η of DSCs under any given light condition. There are three additional important descriptors for IV curves of solar cells:

- V_{mpp} = voltage at the maximum power point (P_{max})
- I_{mpp} = current at the maximum power point (P_{max})
- ff = fill factor: describes how well the area under the IV curve "fills in" the maximum possible rectangle defined by $I_{s}c \times V_{oc}$ (i.e. the rectangle in light blue in Fig. 1). The fill factor can most easily be visualized by the ratio of the areas of the dark blue rectangle to the light blue one.

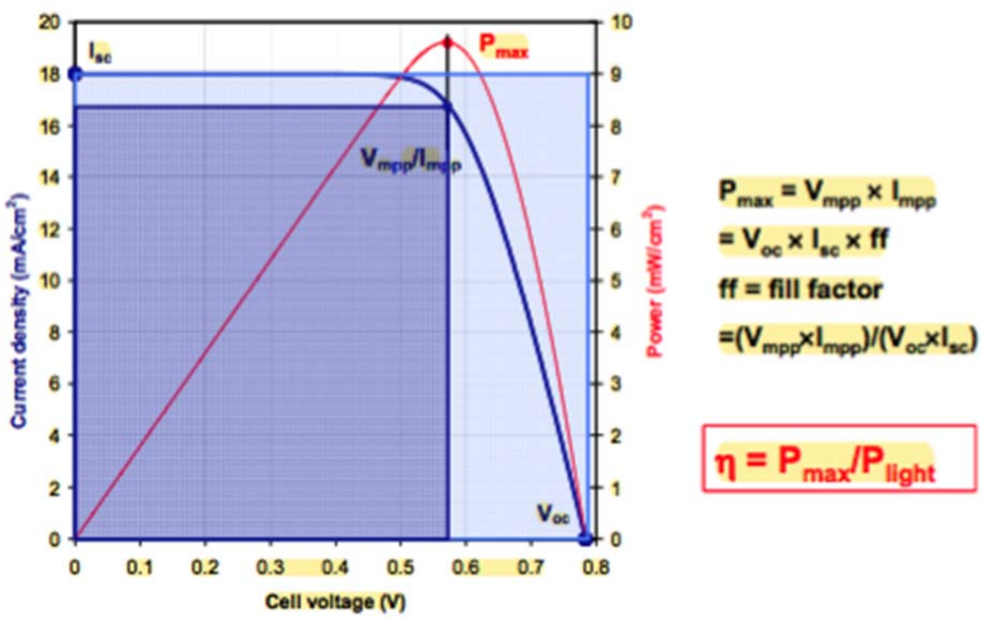

Figure 1: IV curve of a solar cell, along with the main descriptors and their relationship with efficiency η = electrical power(out)/light power(in).

The Ultimate Photodiode

Typical photodiode can be described by the following circuit:

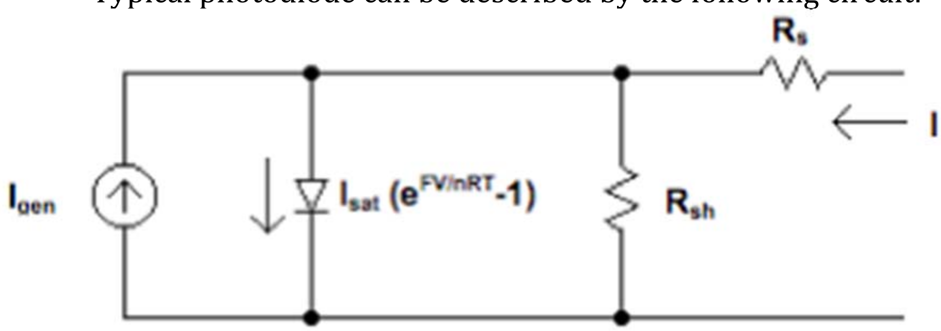

Figure 2: Equivalent circuit of a photodiode, I_{gen} = photo generated current (corresponding to I_{sc},), I_{sat} = reverse saturation current, Faraday constant = 96,485 s mol-1, n = diode ideality factor, R = universal gas constant = 8.314 J K-1 mol-1, T = absolute temperature, R_{sh} = shunt resistance, R_s = series resistance

R_s stems from a number of limiting materials and electrochemical processes within the solar cell. The total observable photocurrent I_{ph} for a photodiode with $R_{sh} \rightarrow \infty$ and $R_s = 0$ is thus given by:

$$I_{ph} = I_{gen} - I_{sat}\left(e^{\frac{FV}{nRT}} - 1\right) \qquad [1]$$

The open circuit voltage can then easily be calculated for Iph = 0:

$$V_{OC} = \frac{nRT}{F}\ln\left(\frac{I_{ph}}{I_{sat}}\right) \qquad [2]$$

Diode Ideality Factor's Influence on IV

While n is close to 1 for high-quality DSCs over many orders of magnitude of light intensity other solar cells such as commercial c-Si display n values between 1.26 and 1.5 n values of 1.4-1.45 were reported for CdS/CdTe and CdS/CuInSe2 cells by the same authors 1).

Figure 3 shows that an increase in n significantly lowers cell fill factors and efficiencies, particularly at the lower light levels because of the markedly lower open circuit voltages and hence makes those cells less effective at low light as Vmpp may fall below a useful level for conversion.

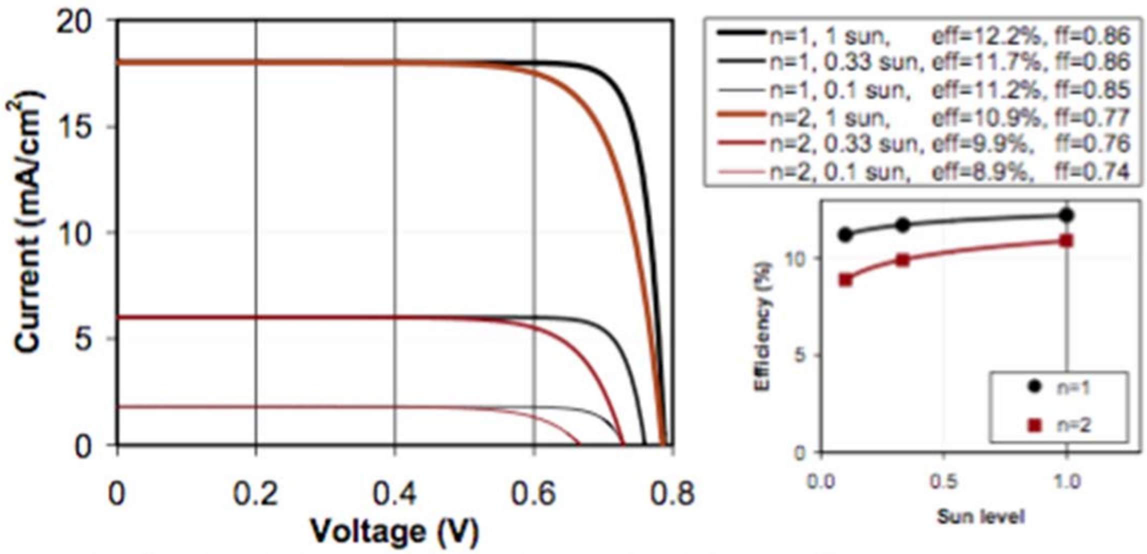

Figure 3: Calculated IV curves according to Eq. [1] and efficiency vs light level output, assuming I_{gen} (@1 sun) = 18 mA/cm^2, V_{oc} (@1 sun) = 0.79 V and I_{gen} linearity as a function of light intensity.

Temperature's Influence

Figure 4 shows IV curves for a typical commercial DSC design at temperatures varying from -10oC to 70°C. Fill factors of DSCs increase with temperature and only start to level off and then decrease above 50-60°C. The ff maximum as a function of temperature depends on the light level, on the electrolyte composition, specifically the I_{3-} concentration, the electrolyte viscosity and other cell design parameters such as anode-to-cathode distance.

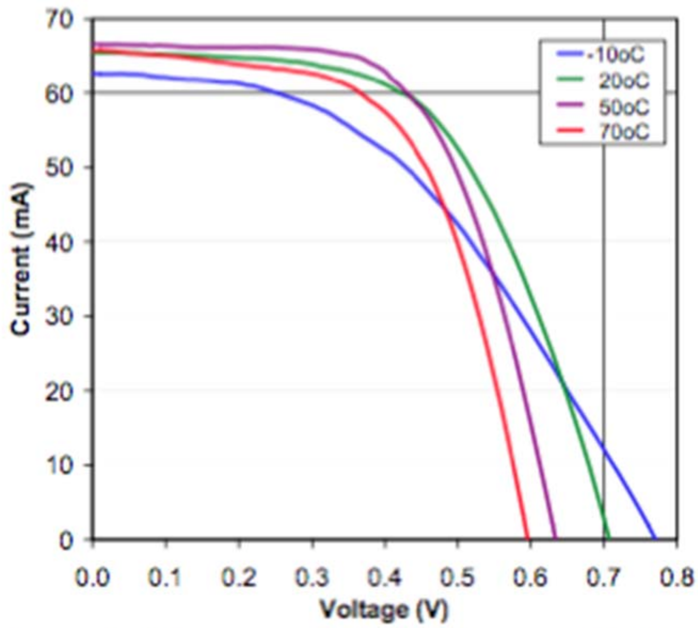

Figure 4: IV curves of metal-based flexible Dyesol DSC from -10°C to 70°C at 1 sun illumination.

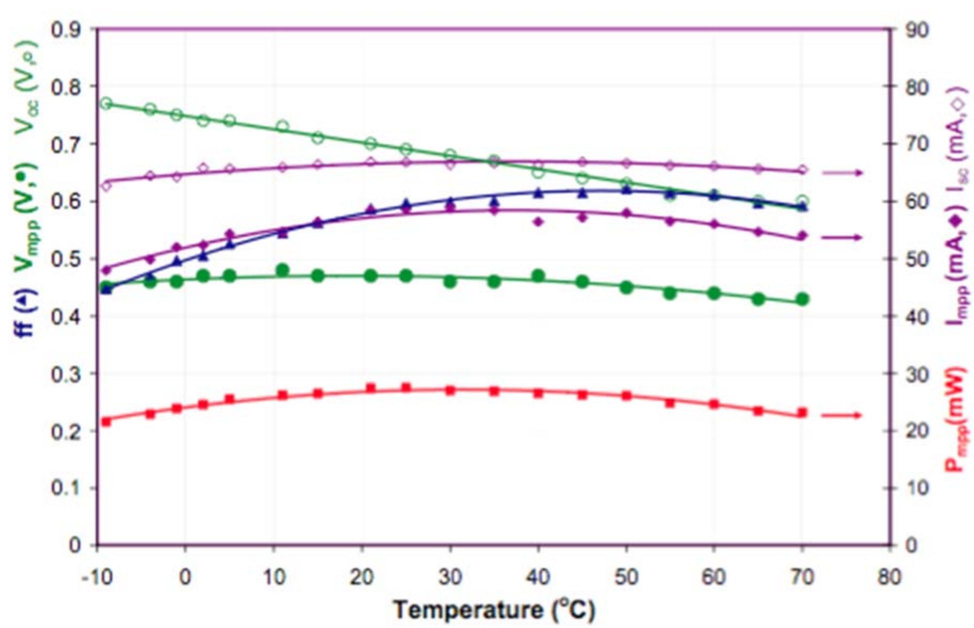

Figure 5: Influence of cell temperature on key IV characteristics of metal-based flexible Dyesol DSC at 1 sun illumination.

Influence of Electrolyte Conductivity

The electrolyte resistance R_e which represents part of the series resistance R_S depends, according to Equation [4], on the electrolyte layer thickness, i.e. the distance d between the two electrodes, the electrolyte conductivity σ and the electrode cross section A.

$$R_e = \frac{d}{\sigma A} \qquad [4]$$

Influence of Substrate Conductivity, Cell Width, and Cell Contacts

Thin-layer DSCs require at least one transparent conductive substrate. Since electronically highly conductive substrates generally display low light transmittance the substrate sheet conductivity needs to be compromised for:

-- the best performance in a given application,

-- cost

-- availability of transparent conductive oxide (TCO) on a substrate such as glass or plastic.

Typical sheet resistances γ of commercially available affordable TCO layers are in the order of 8-15 Ohm per square (Ohm/□). This means that a 1 cm x 1 cm cell contacted on both sides by a bus bar displays a series resistance of 8-15 Ohm. This value is much higher than the resistance of the typical electrolyte layer.

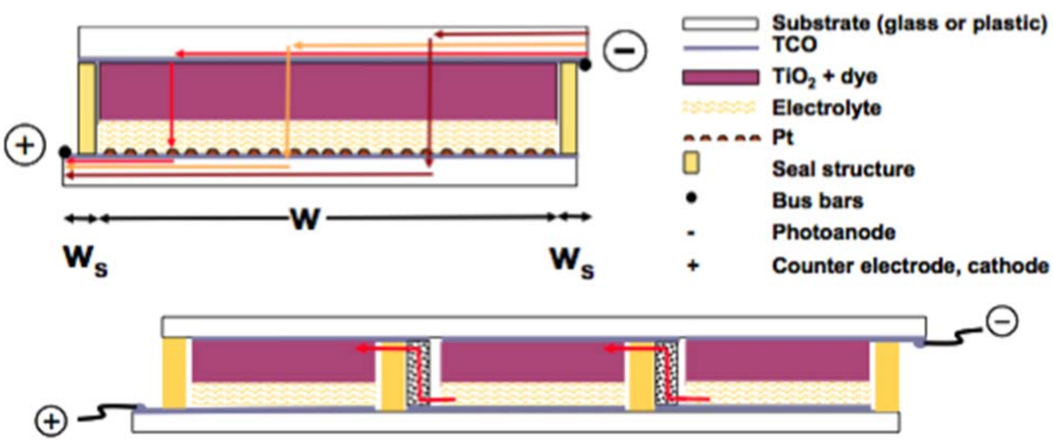

Figure 7: Top: schematic cross section through DSC along with current paths, w = width of active area (TiO_2), w_s = width of cell seal structure. Bottom: schematic for Z-interconnected cells.

For a cell of length, L, the voltage, V, at any current, I, can be expressed in relation to V_o, which is the cell voltage for zero sheet resistance [i)]:

$$V = V_0 - IR_s = V_0 - \frac{I\gamma(w + 2w_s)}{L} \qquad [5]$$

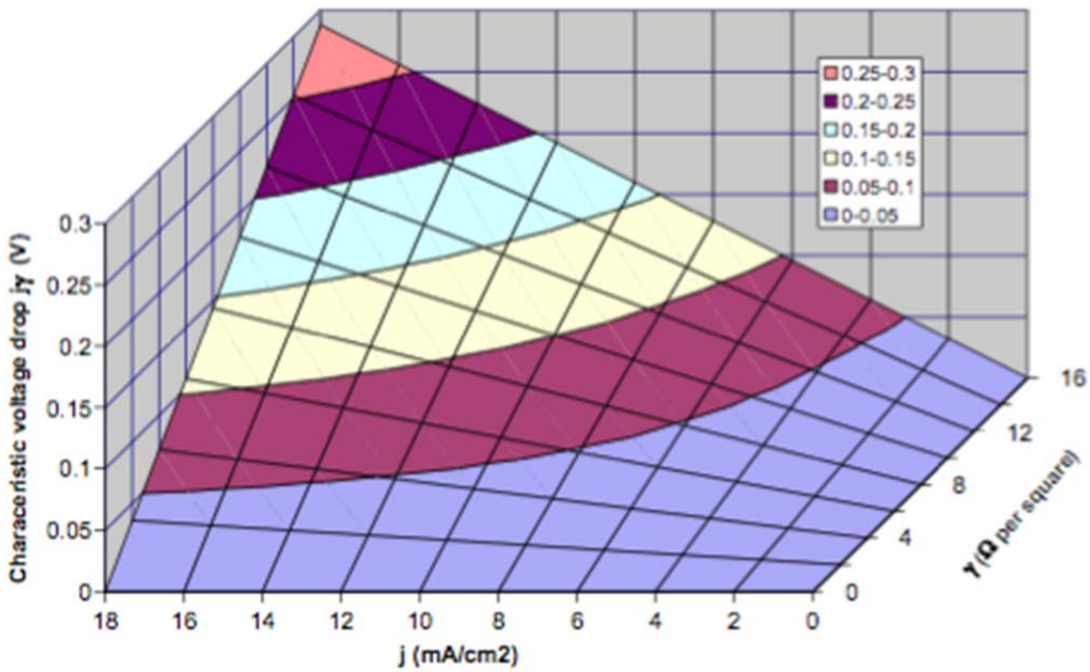

Figure 8: Characteristic voltage drop as a function of current density and sheet resistance

Figure 8 shows that for high performance cells delivering maximum power point photocurrents of 15 mA/cm2 or more in full sun and for a sheet resistance of 15 Ohm/□ the characteristic voltage drop is >0.2V, which starts to seriously limit cell efficiency. Thus lower width cells are required for maximum performance in full sun.

Figure 10 shows calculated IV curves for DSCs of different widths based on resistance-corrected V_o curves according to Eq. [5].

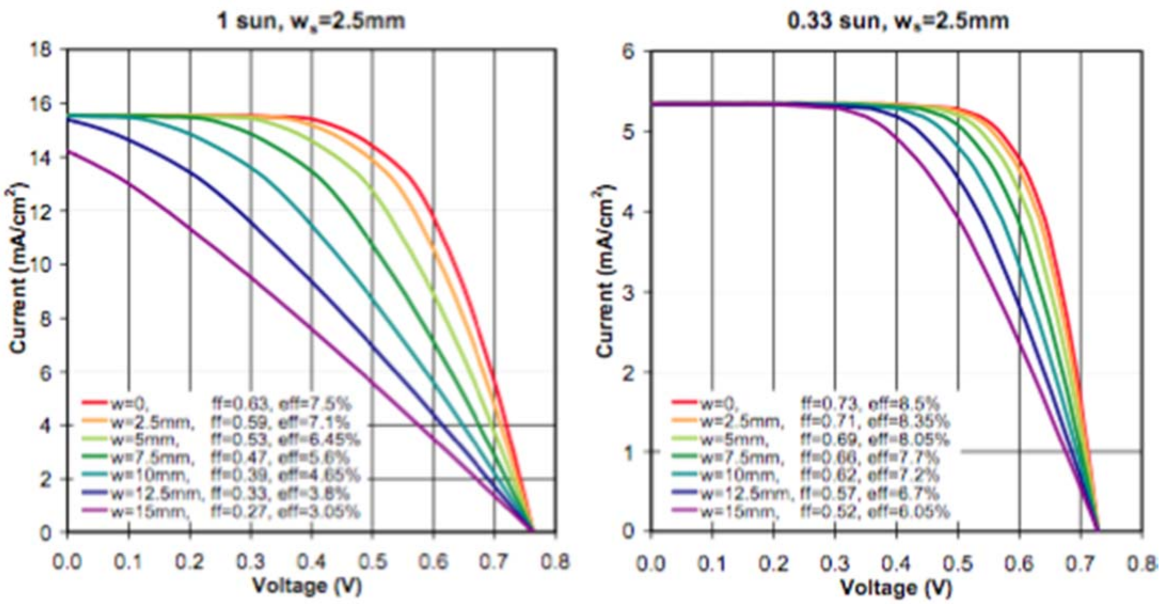

Figure 10: IV curves at full (left) and 0.33 sun (right) as a function of active area width, calculated from I vs V_o curves. γ = 12 Ohm/□, w_s = 2.5 mm. The I vs V_o curves were obtained from a typical Dyesol DSC from $V_o = V + IR_s$, where R_s was determined through electrochemical impedance spectroscopy (EIS).

Influence of Counter Electrode

Counter electrodes (CEs) of DSCs can effectively be evaluated independently in symmetrical CE-CE cells through IV curves and/or EIS. Figure 12 shows IV curves for symmetrical cells of 3 different internal cell thicknesses. In order to extract electrokinetically useful information from such curves they need to be corrected for the cell series resistance according to Eq. [8] (see the thin dark blue curve in Fig. 12).

$$V_{corr} = V - IR_s \qquad [8]$$

Figure 12 curve is very useful to estimate the influence of the counter electrode on the IV characteristics. It can be seen that the electrokinetic voltage loss at 20 mA/cm2 amounts to ~80 mV which is substantial and will significantly lower ff. Such a j_{ET} curve is an indication that the counter electrode characteristics should be improved through optimization of the P_t deposition method

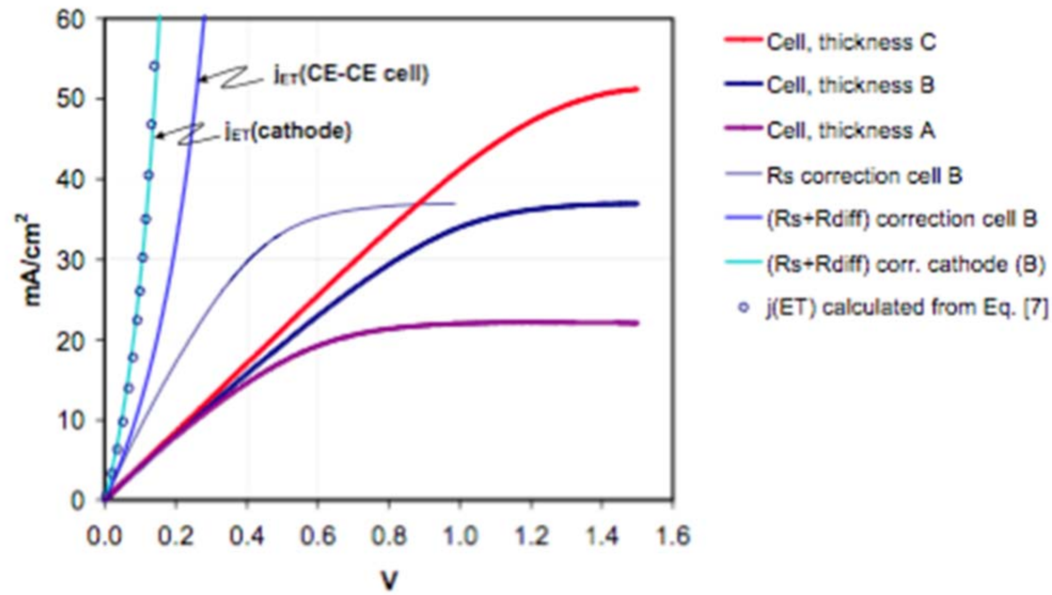

Figure 12: IV curves of symmetrical CE-CE cells for 3 different cell internal thicknesses A>B>C, adjusted by suitably chosen seal gaskets. R_S-correction of the B-cell through Eq. [8] with R_s determined from EIS. R_{diff} correction through Eq. [9]. The cathodic IV curve (light blue) is based on 55% polarisation from the (R_S+R_{diff}) corrected curve (blue). (O): calculated from Eq. [7] with n = 1 and α = 0.45.

Additional Physical Factors Influencing IV Characteristics

There are quite a number of additional factors which influence DSC output and which need to be considered in order to obtain meaningful and reliable IV data:

-- **Nature of the electrical contact:** providing a low electrical resistance contact to the measuring leads is particularly important for larger area/high current devices. Good electrical contacts can be obtained through bus bars applied by screen-printing or ultrasonic welding, followed by soldering the test leads to the bus bars.

-- **Lighting conditions:** care needs to be taken to avoid any diffuse or stray light hitting the device under test, which may artificially increase device output. IV curves are best measured in black box on a matt black background.

-- **Masking:** cell masking can be used to accurately define the illuminated cell area in the case of a well-collimated light beam. With a more diffuse light source, on the other hand, masking can be used to artificially boost measured currents due to internal light reflection and indirect illumination of the masked area. Fill factor increases through masking due to lower absolute current resulting in less resistive losses. Used correctly though, masking can provide more accurate cell performance data.