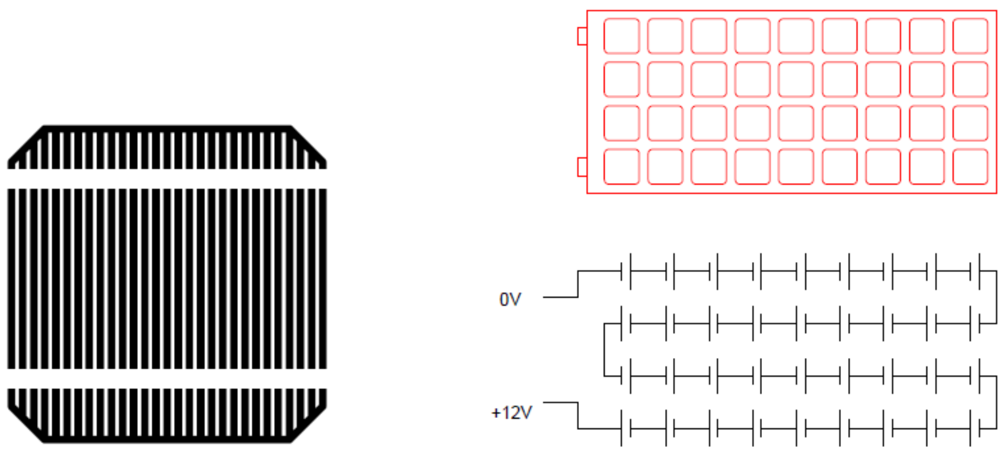
In a normal material, electrons absorb photon and get excited. After a certain while, they relax back to the ground state. In a photovoltaic device, there is some built-in asymmetry which pulls the electrons and feeds them to the external circuit before they can relax back to the ground state. The extra energy of the excited electrons generate the emf which drives the electrons through the load. The effectiveness of photovoltaics depends upon what material is being used as an absorber and how efficiently the electrons are transferred to the external circuit.

Solar cell can be considered as a two-terminal device that conducts like a diode in the dark and produces photo-voltage when charged by the sun. It is electrically equivalent to a current generator in parallel with an asymmetric, non-linear resistive element (diode). Typically the basic unit consists of thin slice of semiconducting material of 100 cm^2 in area. When charged by sun, this basic unit causes V_{OC} (dc photo-voltage) of 0.5V to 1V, a short circuit photocurrent~10mA per cm^2. The voltage being too small, 28 to 36 cells are connected in series and they come in modules. A module generates 12V photo-voltage.



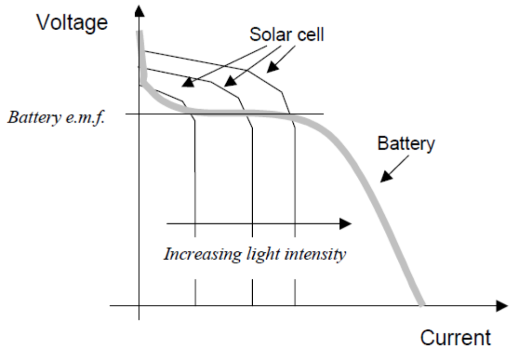
(a) (b)

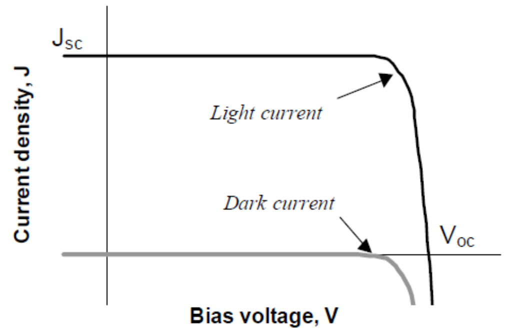
Two important parameters are V_{OC} and I_{SC}. Generated photo-voltage V is in between 0 and V_{OC}. Thus I and V are determined by illumination and load. Since current is directly proportional to the illuminated area, J_{SC} is more relevant quantity.

Difference with battery: e.m.f of the battery is due to a permanent difference of electrochemical potential between two phases of the cell, while e.m.f. of the solar cell is due to a temporary change of the electrochemical potential caused by the light.

$$J_{\mathrm{sc}} = q \int b_{\mathrm{s}}(E) QE(E) dE$$

QE (E) is the quantum efficiency of the solar cell, it is the probability that an incident photon of energy E will deliver one electron to the external circuit. It depends on three factors: absorption coefficient of the solar cell material, charge separation efficiency and charge collection efficiency of the device. It does not depend upon light flux. $b_s(E)$ = incident spectral photon flux density.

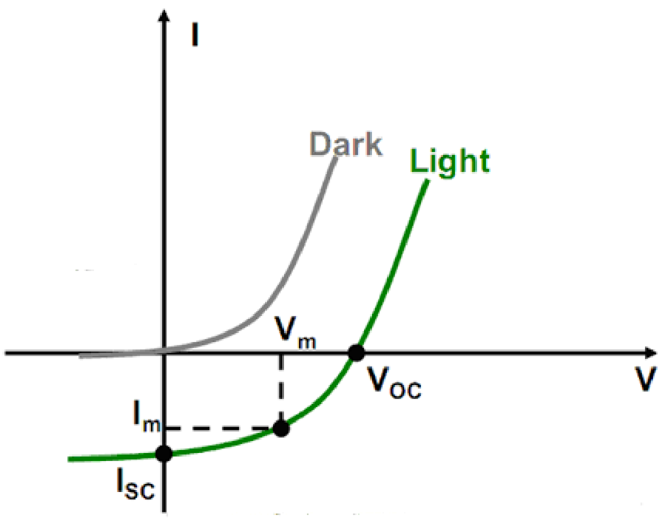




Battery has constant emf, except very low resistance loads, where potential starts to drop.

Figure on the right is I-V characteristics of an ideal diode. In case of an ideal diode, large current flows under forward bias and small current flows under reverse bias. Under illumination, the reverse saturation current that flows under reverse bias increases. The current values under zero illumination is called dark current and it varies with V as follows: $J_{\mathrm{dark}}(V) = J_{\mathrm{o}}(e^{\mathrm{qV/k_BT}} - 1)$

In case of a solar cell, when load is connected across the junction, a potential difference develops across the terminals of the cell. This causes a current in the opposite direction of the photocurrent. This current is called dark current. As a result of this dark current, the net current density $J(V) = J_{\mathrm{sc}} - J_{\mathrm{dark}}(V)$ is reduced, and falls from the short circuit current density. This current is called dark current in analogy with the current we will get in the absence of the illumination, under applied bias V, as a solar cell is nothing but a pn diode. Forward current can be obtained only in the dark, and it flows opposite to the photocurrent. For a good solar cell, dark current must be small. This reverse current and dark current are not equal always, but in most photovoltaic materials, they are equal.



This is for a diode. For a solar cell, V_{OC} is the max possible voltage and forward current is not possible ($0<V<V_{OC}$). That is why, dark current primarily means forward current. Smaller the dark current, higher the fill factor and higher the efficiency.

V<0: this acts as a photo-detector. Consumes power to generate light dependent, bias independent photocurrent.

0<V<V_{OC}: acts as a solar cell. Generates power to convert light energy into electrical energy.

V>V_{OC}: acts as LED. Consumes power to convert electrical energy into light energy.

Why dark current study is necessary? Because it will give us the Junction quality factor or ideality factor (its between 1 and 2), and the value of Reverse saturation current as well as forward current. For a good performance of solar cell, reverse saturation current must be small so that open circuit voltage is high.. The reverse saturation current depends on the material properties because, diffusion coefficients depend on mobility of the carriers through the semiconductor material. The diffusion lengths must be long enough so that the generated carriers reach the contact areas of the solar cell before they recombine. Maximum voltage or open circuit voltage condition is the condition at which photocurrent and dark current exactly cancels out. V_{OC} increases logarithmically with light intensity and decreases logarithmically with reverse saturation current or leakage current.

$$V_{\mathrm{oc}} = \frac{kT}{q} \ln\left(\frac{J_{\mathrm{sc}}}{J_0} + 1\right)$$

with increase in temperature, reverse saturation current increases, which is a measure of the leakage of carriers across the pn junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction. With increase of T, V_{OC} is reduce.

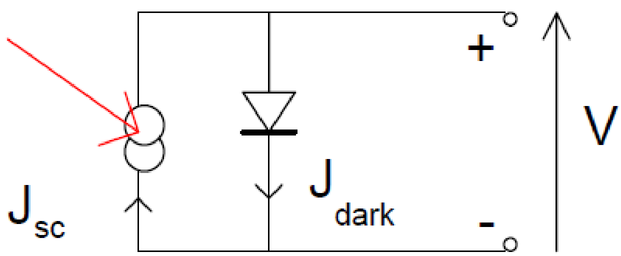
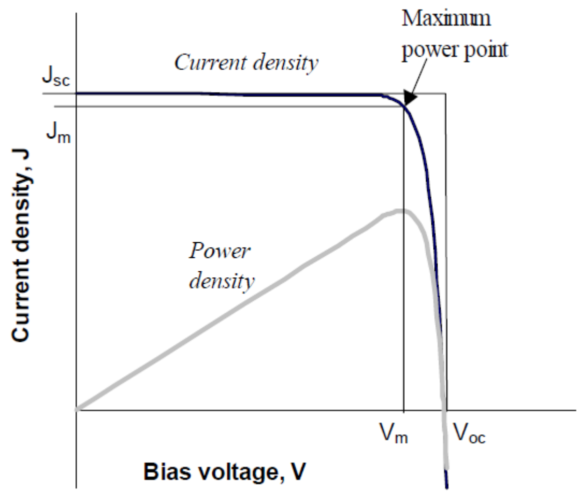


Fig. 1.7. Equivalent circuit of ideal solar cell.

Power density P=JV. The point where P is maximum is the solar cell operating point.



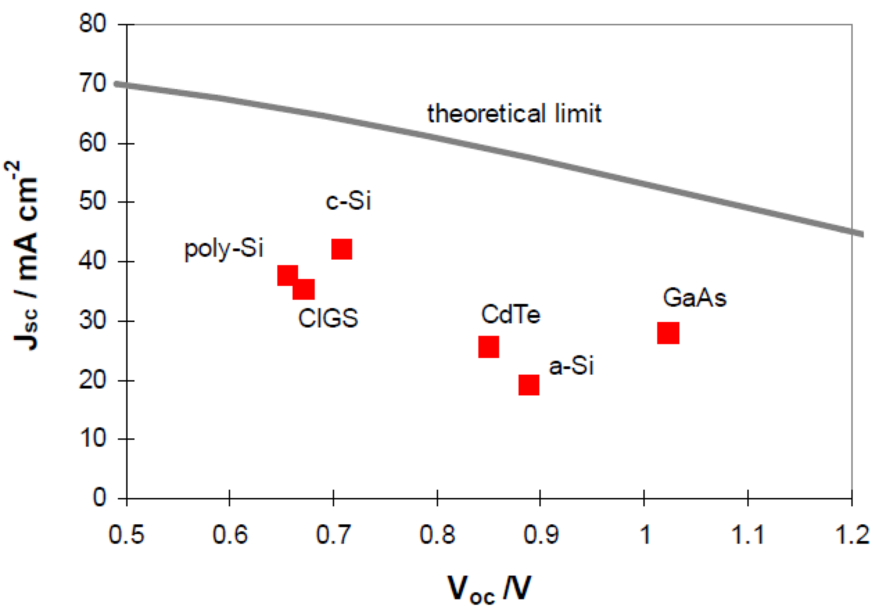
the sheet resistance is defined as V_m/J_m. The fill factor (FF) is defined as $J_mV_m/J_{sc}V_{oc}$ and describes the squareness of the I-V curve. The efficiency η is defined as the ration of power density delivered per unit incident light power density:

$$\eta = \frac{J_{\mathrm{m}}V_{\mathrm{m}}}{P_{\mathrm{s}}} = \frac{J_{\mathrm{sc}}V_{\mathrm{oc}}FF}{P_{\mathrm{s}}}.$$

These four key factors: η, FF, J_{SC}, V_{OC} determine performance of a solar cell.

Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

Cell Type	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
crystalline Si	4.0	0.706	42.2	82.8	24.7
crystalline GaAs	3.9	1.022	28.2	87.1	25.1
poly-Si	1.1	0.654	38.1	79.5	19.8
a-Si	1.0	0.887	19.4	74.1	12.7
$CuInGaSe_2$	1.0	0.669	35.7	77.0	18.4
CdTe	1.1	0.848	25.9	74.5	16.4



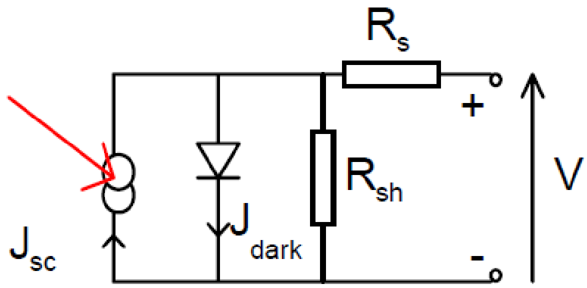
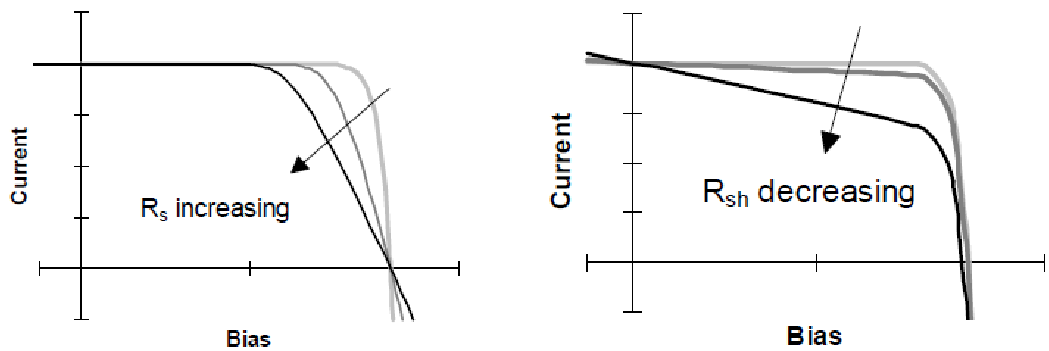


Fig. 1.10. Equivalent circuit including series and shunt resistances.



(a) (b)

The contact resistance must be small. This appears in series. Sometimes there is leakage current through the cell and around the edges of the cell. This is equivalent to a parallel resistance. This must be large for good performance.

	a-Si/SiGe	c-Si *
Grain Size (μm)	Amorphous	Single Crystal
Sub. Temp. (•C)	< 300	1000-1400
Typical Growth Methods	CVD	epitaxy + "epi-lift," "smart-cut"
Rates (μm/m)	0.01-0.1	1-10
Efficiencies (%)	8-13	~18
Cell Thk. (μm)	0.3-0.7	5-50
Cell Type	drift, stacked	diffusion
Pros	very high absorption, E_g tailoring	infrastructure, synergy with IC industry
Cons	instable (SWE), poor red collection	3-step processes, large area difficult