Energia Fotovoltaica

Parte I - Materiais Fotovoltaicos e Características Elétricas

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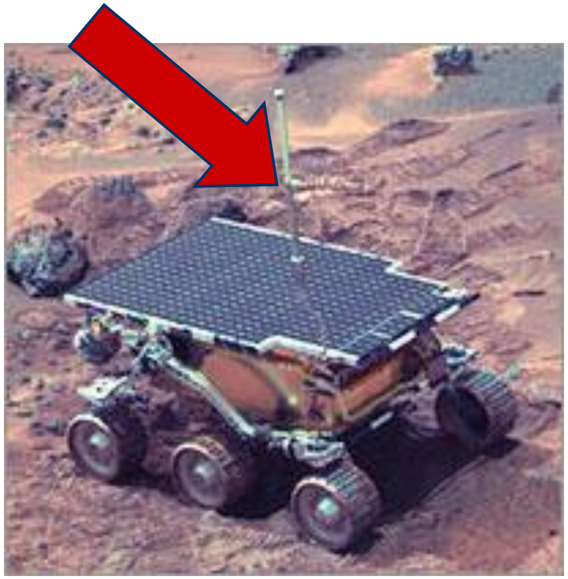
Photovoltaics (PV)

Photovoltaic definition- a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current

- **Photon:** is the *quantum* of electro-magnetic radiation, such as light;
- The mass of the photon is zero;
- It always moves at the speed of light in vacuum;
- A photon with short enough wavelength and high enough energy can cause an electron in a PV material to break free;
- If a nearby electric field exists, those electrons can cause an electric current.

"Sojourner" exploring Mars, 1997



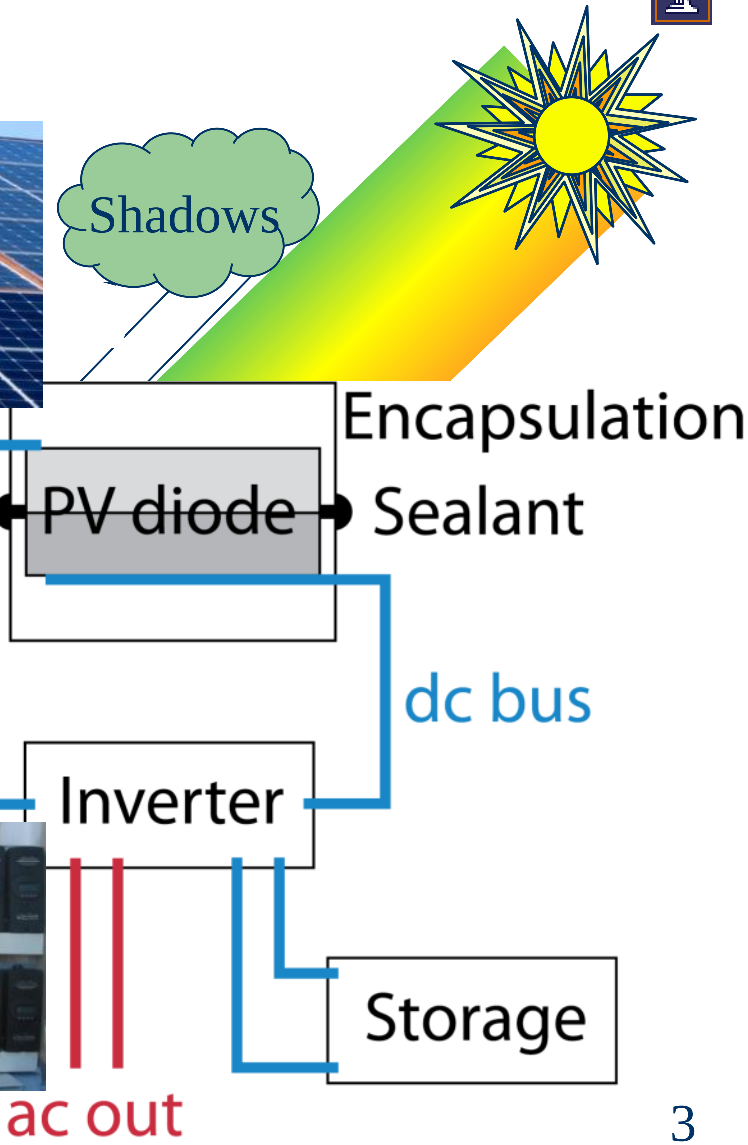
PV History

- Edmund Becquerel (1839): discovered PV effect;
- Adams and Day (1876): studied PV effect in solids;
- Albert Einstein (1904): Theoretical explanation
  (Nobel Prize 1923);
- Czochralski (1940s): method to grow perf. silicon crystals;
- Vanguard I satellite (1958): first practical application;

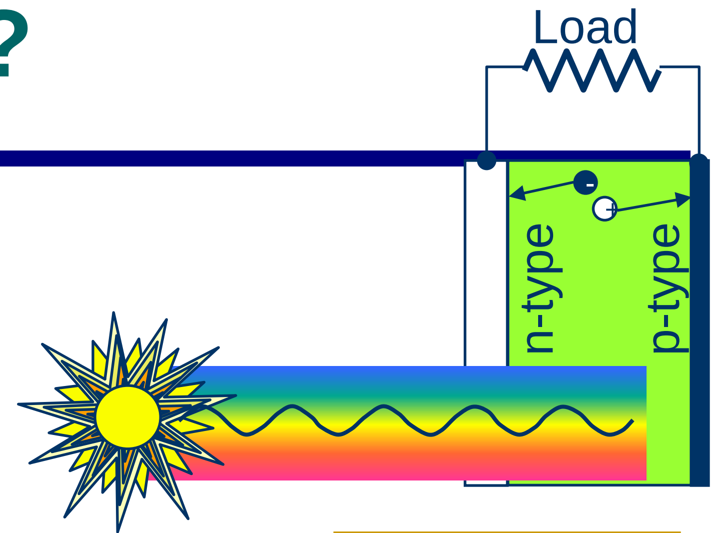
- Costs have recently dropped quite substantially.

PV System Overview

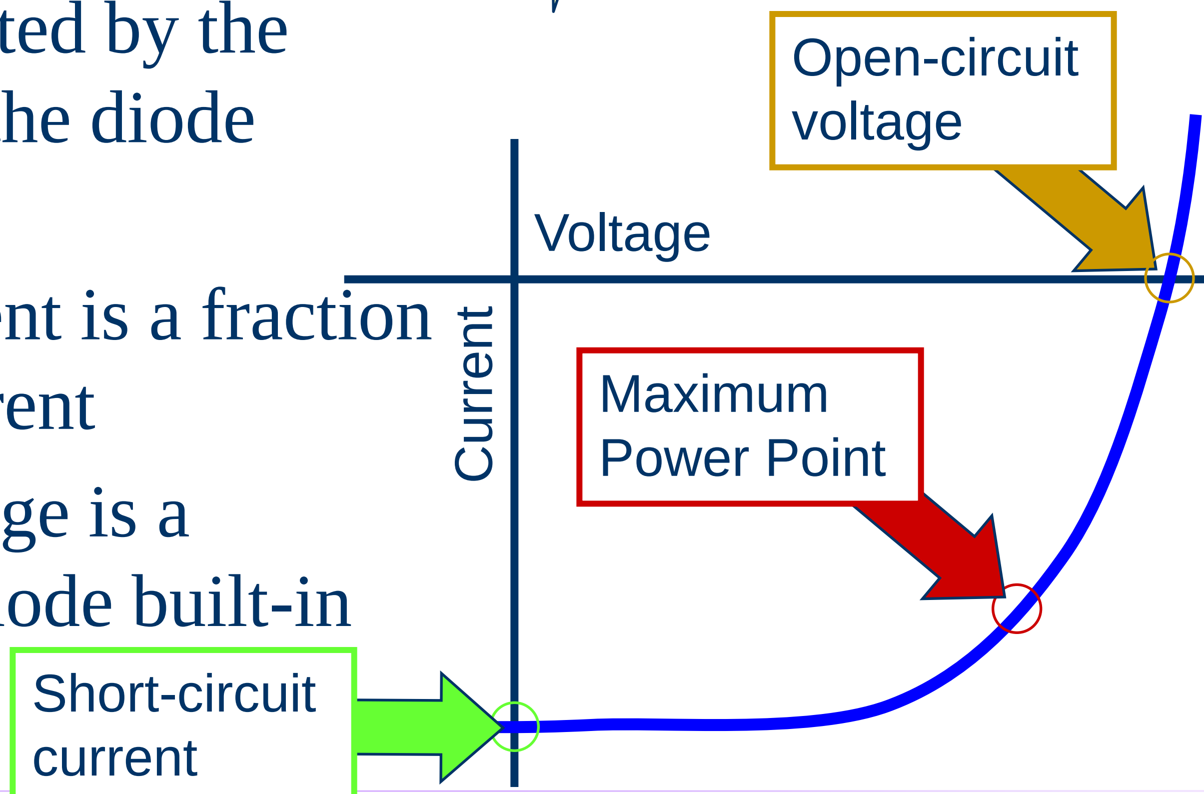
- Solar cell is a diode;
- Photopower converted to DC;
- Shadows & defects convert generating areas to loads;
- DC is converted to AC by an inverter;
- Loads are unpredictable;
- Storage helps match generation to load.



What are Solar Cells?



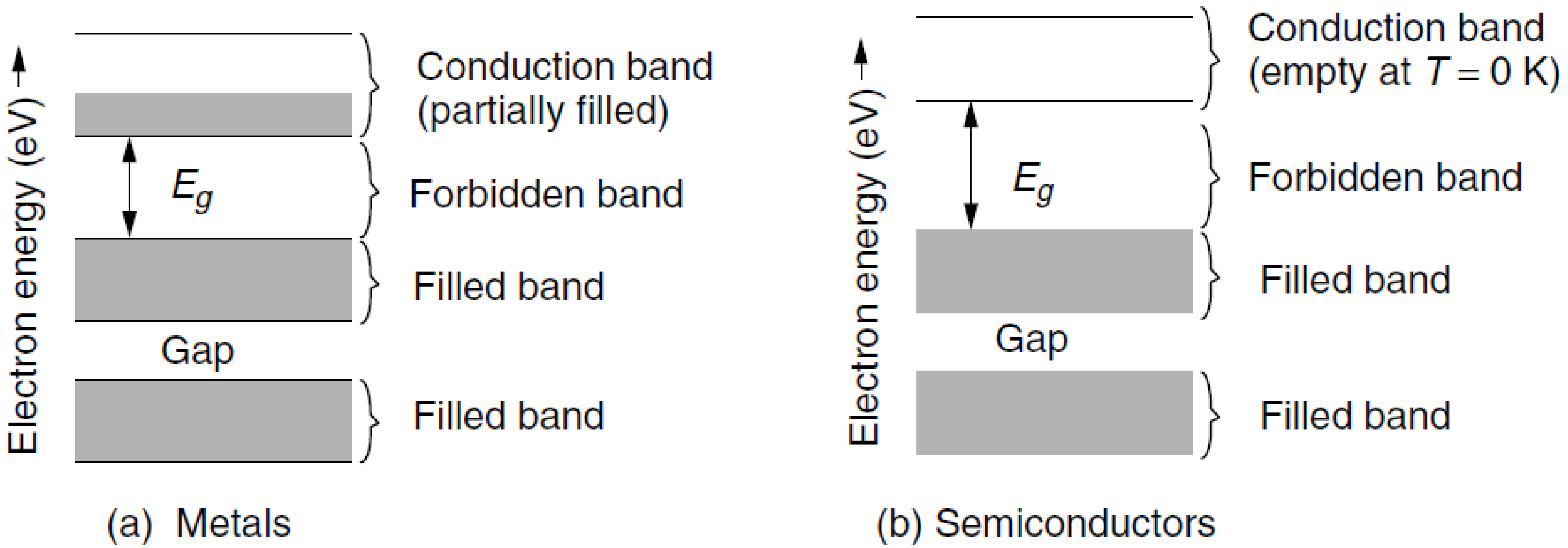
- Solar cells are diodes
- Light (photons) generate free carriers (electrons and holes) which are collected by the electric field of the diode junction
- The output current is a fraction of this photocurrent
- The output voltage is a fraction of the diode built-in voltage



Band-Gap Energy

- Electrical conduction is caused by free electrons (electrons in conduction band);
- At absolute zero temperature metals have free electrons available and hence are good conductors;
  - Metal conductivity decreases with increasing temperature
- Semi-conductors, such as silicon, have no free electrons at absolute zero and hence are good insulators;
  - As temperature increases, some electrons will be given enough energy to free themselves from their nuclei.

Energy bands for metals and semiconductors



- At room temperature, only about 1 in 10^{10} electrons in silicon exists in the conduction band;
- Band-gap energy, E_g: energy that an electron must acquire to jump across the forbidden band;
- E_g for silicon is 1.12 eV;
- For PV, E_g comes from photons of solar energy.

Band-gap energy and holes

- When a photon with energy > 1.12 eV is absorbed by a solar cell:
  - A single (negatively charged) electron jumps to the conduction band;
  - This also creates a (positively charged) *hole*, which also helps to carry the electrical current.
- Conclusion: photons with enough energy create hole-electron pairs in a semiconductor;
- Also, one photon can excite only one electron, so that any energy above 1.12 eV is dissipated as waste heat.

Photons

- Photons are characterized by their wavelength (or their frequency) and their energy:

$$c = \lambda v$$

$$E = hv = \frac{hc}{\lambda}$$

Planck's constant *h* is 6.626×10^{-34} J-s
Velocity of light *c* is 3×10^{8} m/s
v: frequency, Hz

- In this context energy is often expressed in electron-volts (eV), which is defined as 1.6×10^{-19} J
  - This is the amount of energy gained by a single electron moving across a voltage difference of one volt

Above equation for E can be rewritten with E in eV and λ in μm

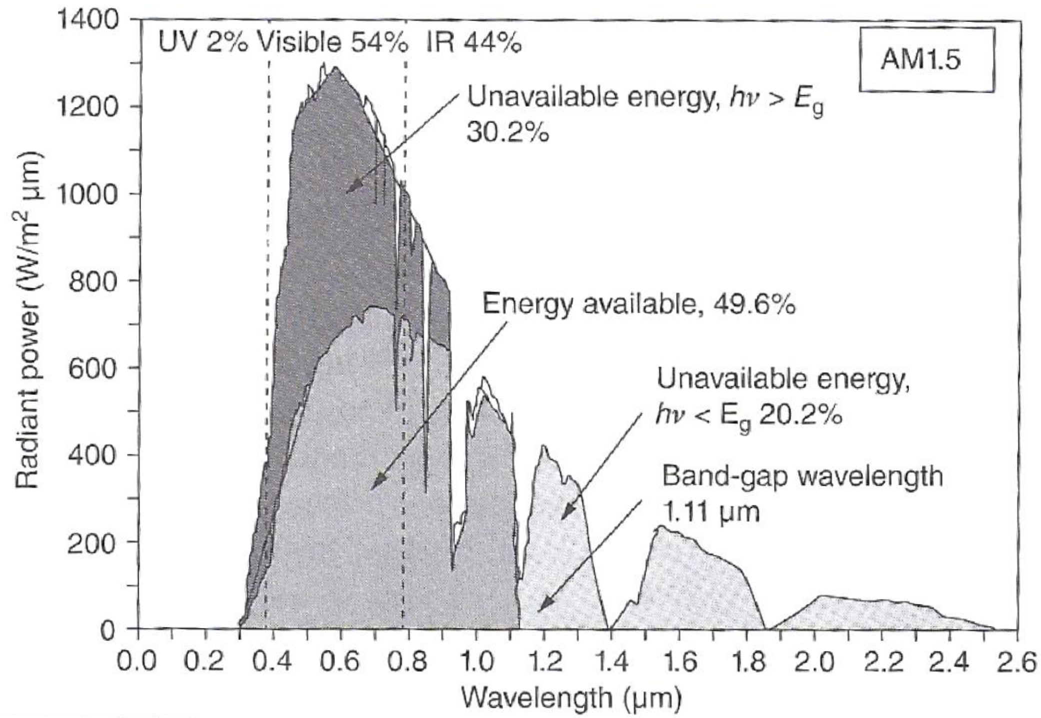
$$E = \frac{hc}{\lambda}, E_{EV} = \frac{1.242}{\lambda_{\mu m}}$$

Photon wavelength x Cell efficiency

- The maximum wavelength a photon can have to create hole-electron pairs in silicon is 1.11 μm;
- Photons with $\lambda > 1.11\ \mu m$ have less energy than needed to excite an electron $\Rightarrow$ their energy is wasted;
- Photons with $\lambda < 1.11\ \mu m$ have more than enough energy to excite na electron, but any energy above *1.12 eV* is also dissipated as waste heat;
- These two phenomena relating photons with band-gap energy establish a maximum theoretical efficiency for a solar cell.

Silicon Solar Cell Max Efficiency

- For an Air Mass Ratio of 1.5, 49.6% is the maximum possible fraction of the sun's energy that can be collected with a silicon solar cell
- Efficiencies of real cells are in the ~20-25% range



Air mass ratio: (length of path taken by sun's rays to reach the ground)/(path length corresponding to sun directly overhead). AM 1.5 ↔ 42° above horizon

Solar Cell Efficiency

- Factors that add to losses
  - Recombination of electrons/holes
  - Internal resistance
  - Photons might not get absorbed, or they may get reflected
  - Heating
- Smaller band gap - easier to excite electrons, but more photons have extra, surplus energy
  - Results in higher current, lower voltage
- High band gap – opposite problem
- There must be some middle ground since P=VI (DC), this is usually between 1.2 and 1.8 eV

Maximum Efficiency for Cells

- The maximum efficiency of single-junction PV cells for different materials was derived in 1961 by Shockley and Queisser

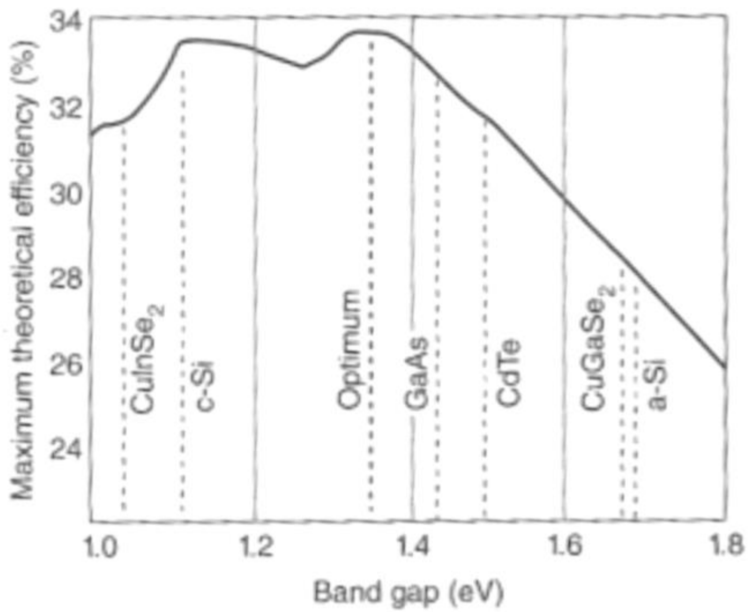
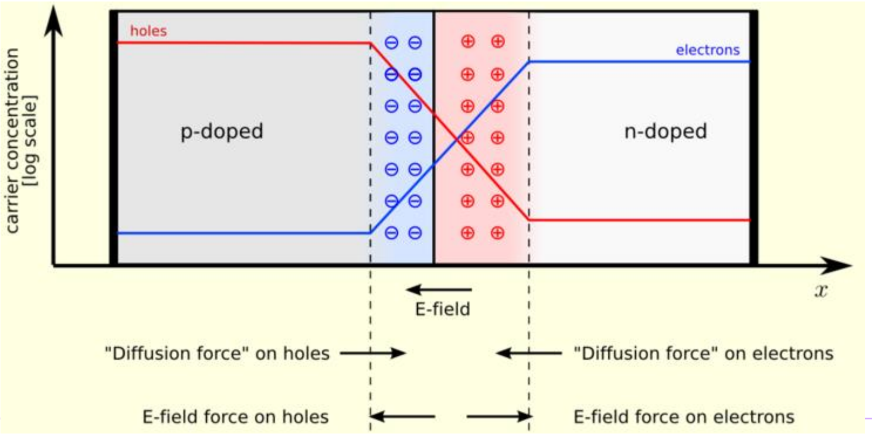
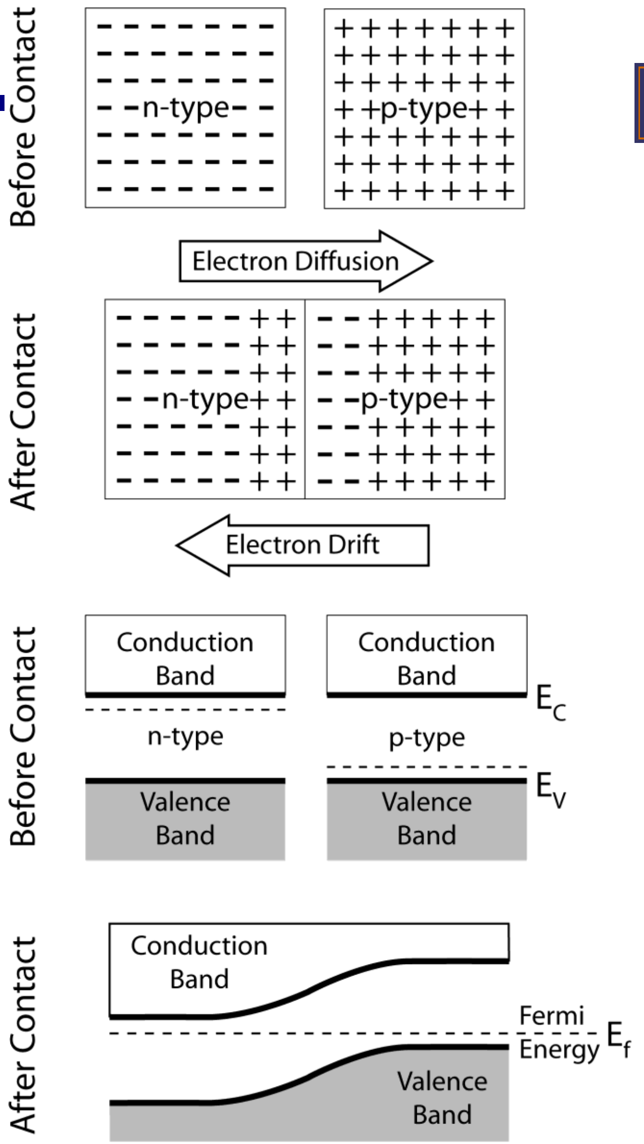


FIGURE 5.8 The Shockley–Queisser limit for the maximum possible solar cell efficiency (single-junction, unenhanced insolation) as a function of band-gap.

Review of Diodes

- Two regions: “n-type” which donate electrons and “p-type” which accept electrons
- p-n junction- diffusion of electrons and holes, current will flow readily in one direction (forward biased) but not in the other (reverse biased). This is the diode.

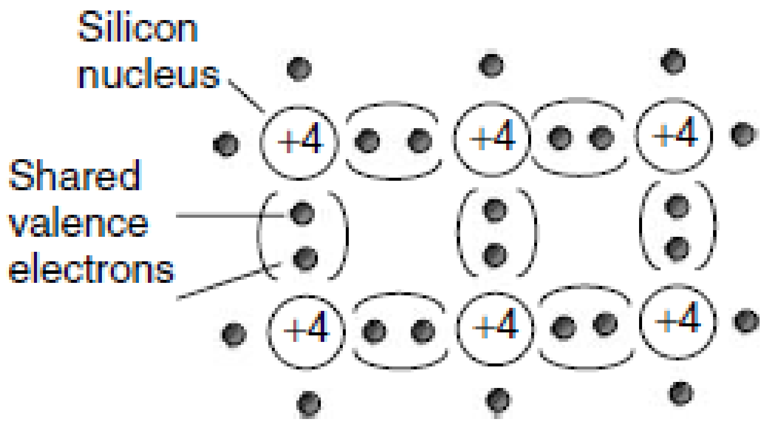




http://en.wikipedia.org/wiki/File:Pn-junction-equilibrium.png

p-n Junction (I)

- Silicon is tetravalent (4 electrons in outer orbit);
- Each atom forms covalent bonds with 4 adjacent atoms ⇒ crystalline pattern;

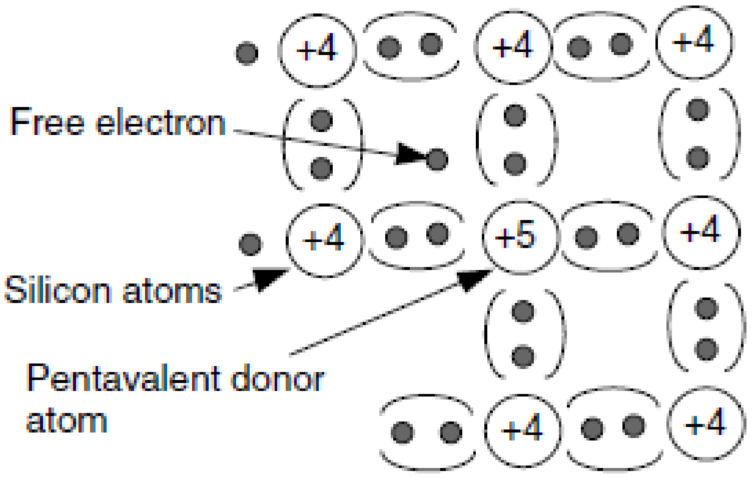


- As already seen, photons with enough energy create hole-electron pairs in a semiconductor;
- However, electrons may fall right back into a hole ⇒ both carriers desappear;
- Thus, an electric field must be created within the semiconductor to push electrons in one direction and holes in the other;
- This is accomplished by contaminating silicon with very small amounts of other elements.

p-n Junction (II)

- Silicon is doped with a *pentavalent* element like phosphorus (1 **P** atom for 1000 **Si** atoms);
- Since **P** has 5 "free" electrons, one of those does not connect with **Si** and is left on its own to roam around the crystal;

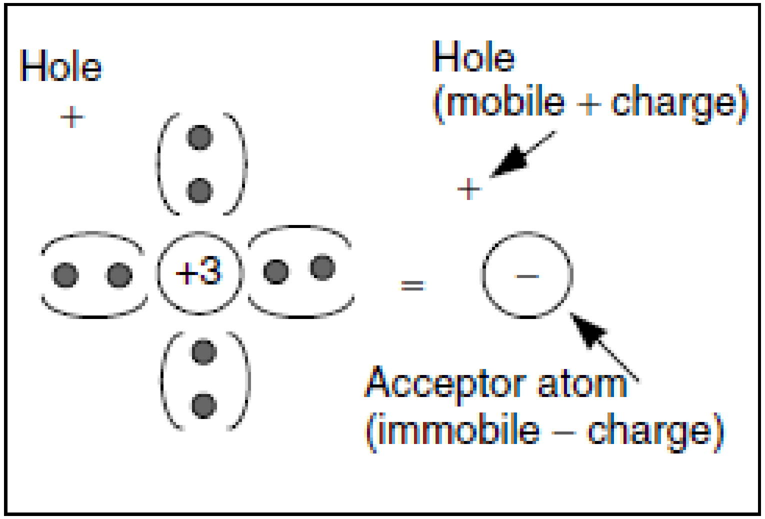
- Also, a +5 donor ion is left behind ⇒ each donor atom represented by a fixed positive charge + a free negative charge;
- Thus, **P** is a *donor doping atom* & we have a *n-type* material.



p-n Junction (III)

- On the other side of the semiconductor, **Si** is doped with a *trivalent* element like boron (**B**): 1 **B** atom for 10^6 **Si** atoms);
- Since each **B** atom has only 3 electrons, one electron is missing to establish a covalent bond ⇒ a positively charged hole appear next to its nucleus;

- A **Si** can easily move into the hole ⇒ **B** is called *acceptor;*
- Since **B** creates a *positively charged* hole free to move around the crystal, this side of the semicond. is called a *p-type* material.

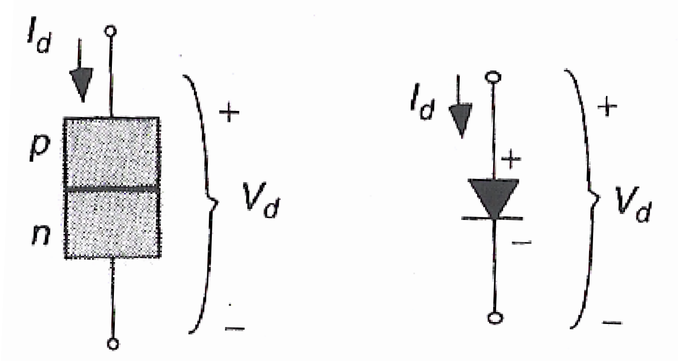


p-n Junction (IV)

- If we put a n-type material on one side of a **Si** semiconductor and a p-type material on the other, we have a *p-n junction;*
- Mobile electrons drift by diffusion across the junction, and mobile holes drift do the same, but in the opposite direction;
- The net effect is the creation of an electric field across the junction;
- The PV effect occurs when the p-n junction is exposed to photons from solar radiation, generating a electric current and inducing a voltage across the material;
- Since the electric field "pushes" a positive charge and attracts a negative charge, the resulting electric current is unidirectional.

The p-n Junction Diode

- Can apply a voltage V_d and get a current I_d in one direction, but if you try to reverse the voltage polarity, you'll get only a very small reverse saturation current, I_0



(a) p–n junction diode

(b) Symbol for real diode

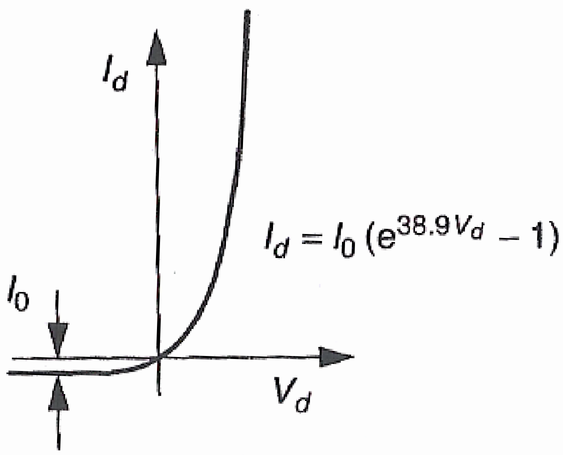
- Diode voltage drop is about 0.6 V when conducting

The p-n Junction Diode

Voltage-Current (VI) characteristics for a diode

$$I_d = I_0(e^{qV_d/kT} - 1)$$

$$I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at 25°C)}$$



(c) Diode characteristic curve

k = Boltzmann's constant 1.381×10^{-23} [J/K]

T = junction temperature [K]

V_d = diode voltage

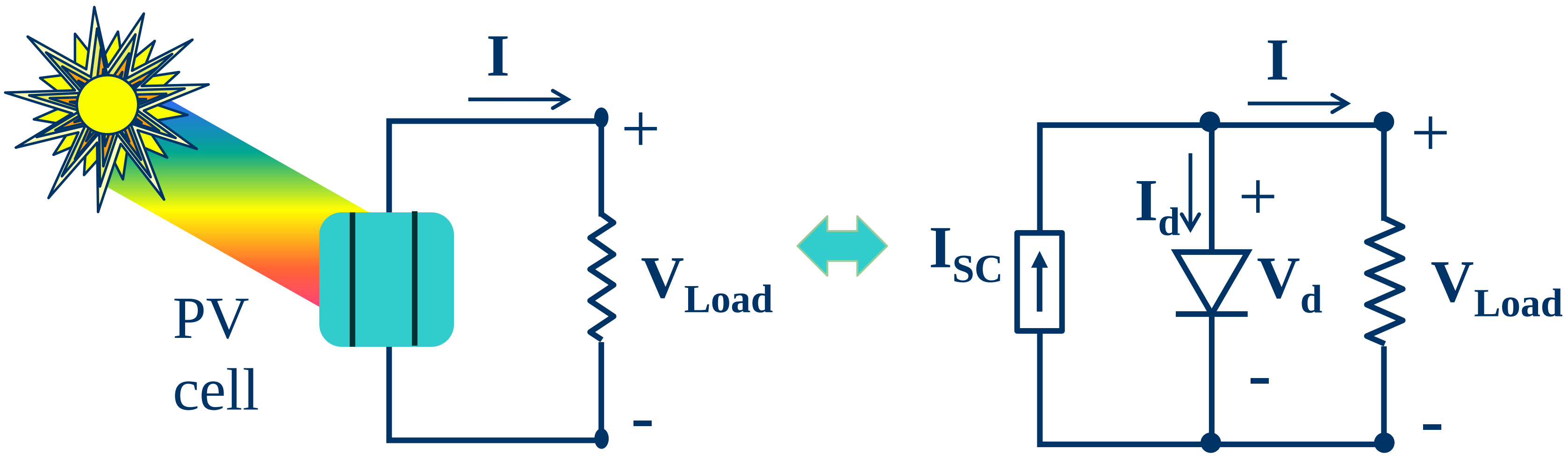
I_d = diode current

q = electron charge 1.602×10^{-19} C

I_0 = *reverse saturation current*

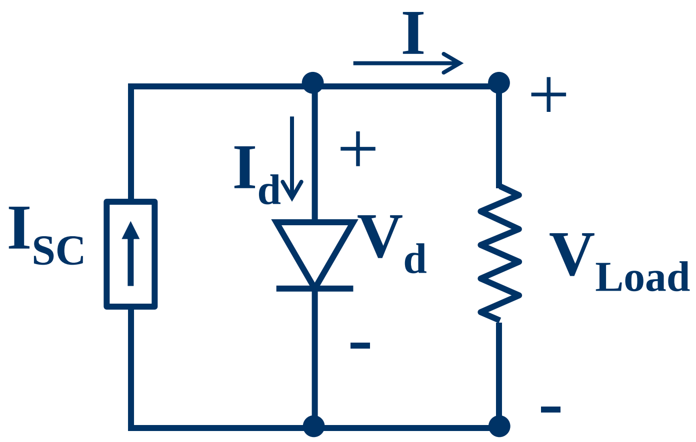
Circuit Models of PV Cells

- The simplest model of PV cell is an ideal current source in parallel with a diode



- The current provided by the ideal source I_{SC} is proportional to insolation received
- If insolation drops by 50%, I_{SC} drops by 50%

Circuit Models of PV Cells



The subscript SC is for short circuit

- From KCL, $I_{SC} = I_d + I$, and the current going to the load is the short-circuit current minus diode current

$$I = I_{SC} - I_0(e^{qV/kT} - 1)$$

- Setting *I* to zero, the open circuit voltage is

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0}+1\right)$$

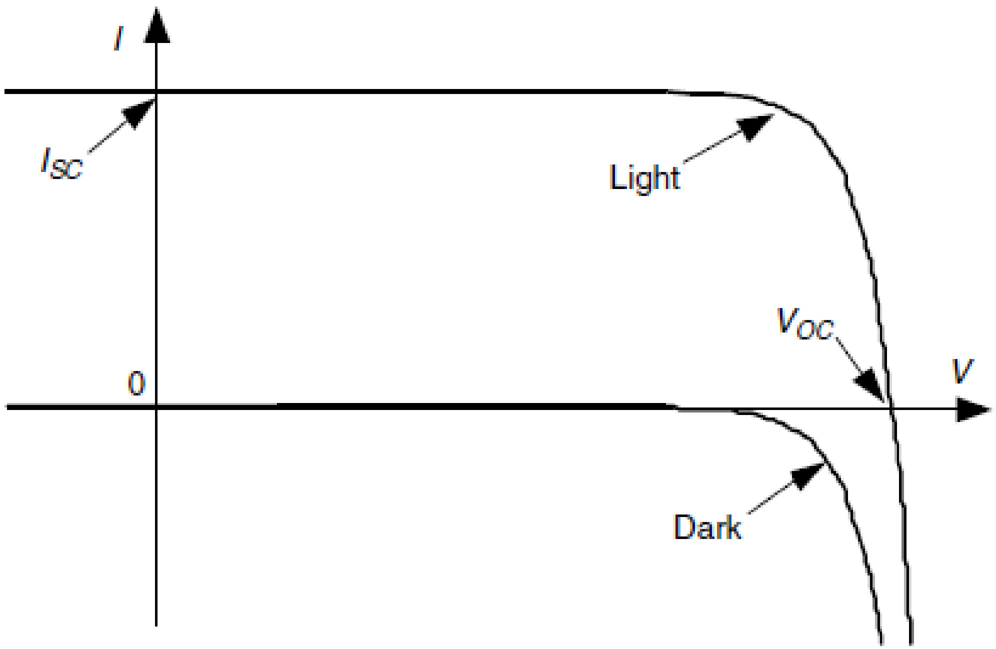
PV Cell I-V Characteristic

- For any value of I_{SC} , we can calculate the relationship between cell terminal voltage and current (the I-V characteristics)

$$I = I_{SC} - I_0(e^{qV/kT} - 1) = f(I_{SC}, V)$$

- Thus, the I-V characteristic for a PV cell is the diode I-V characteristic turned upside-down and shifted by I_{SC} (because $I = I_{SC} - I_d$)
- The curve intersects the x-axis at V_{OC} and the y-axis is I_{SC} .

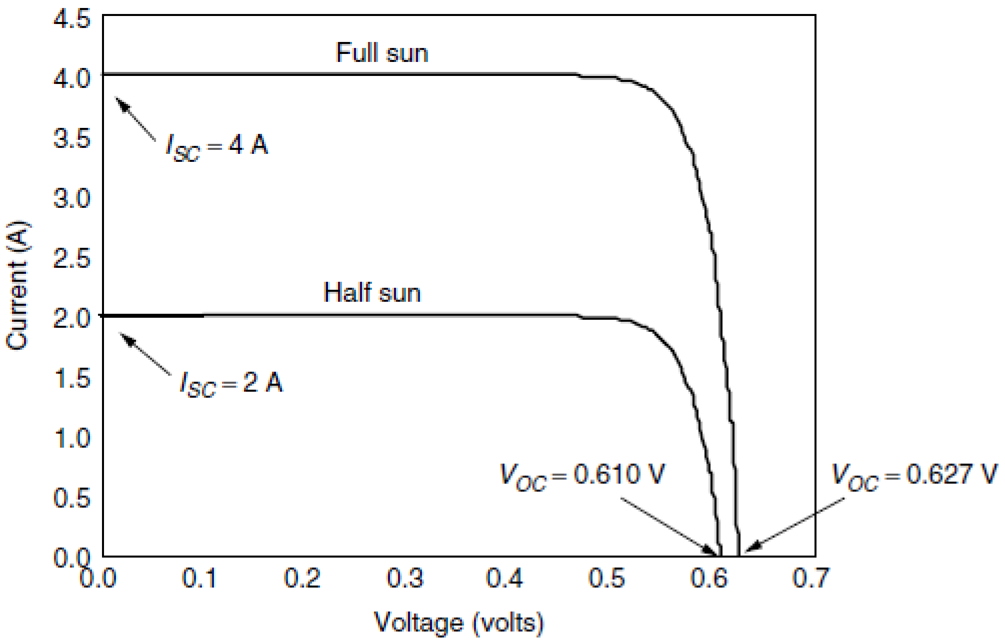
PV Cell I-V Curves



- I-V curve for an illuminated cell = "dark" curve + I_{SC}

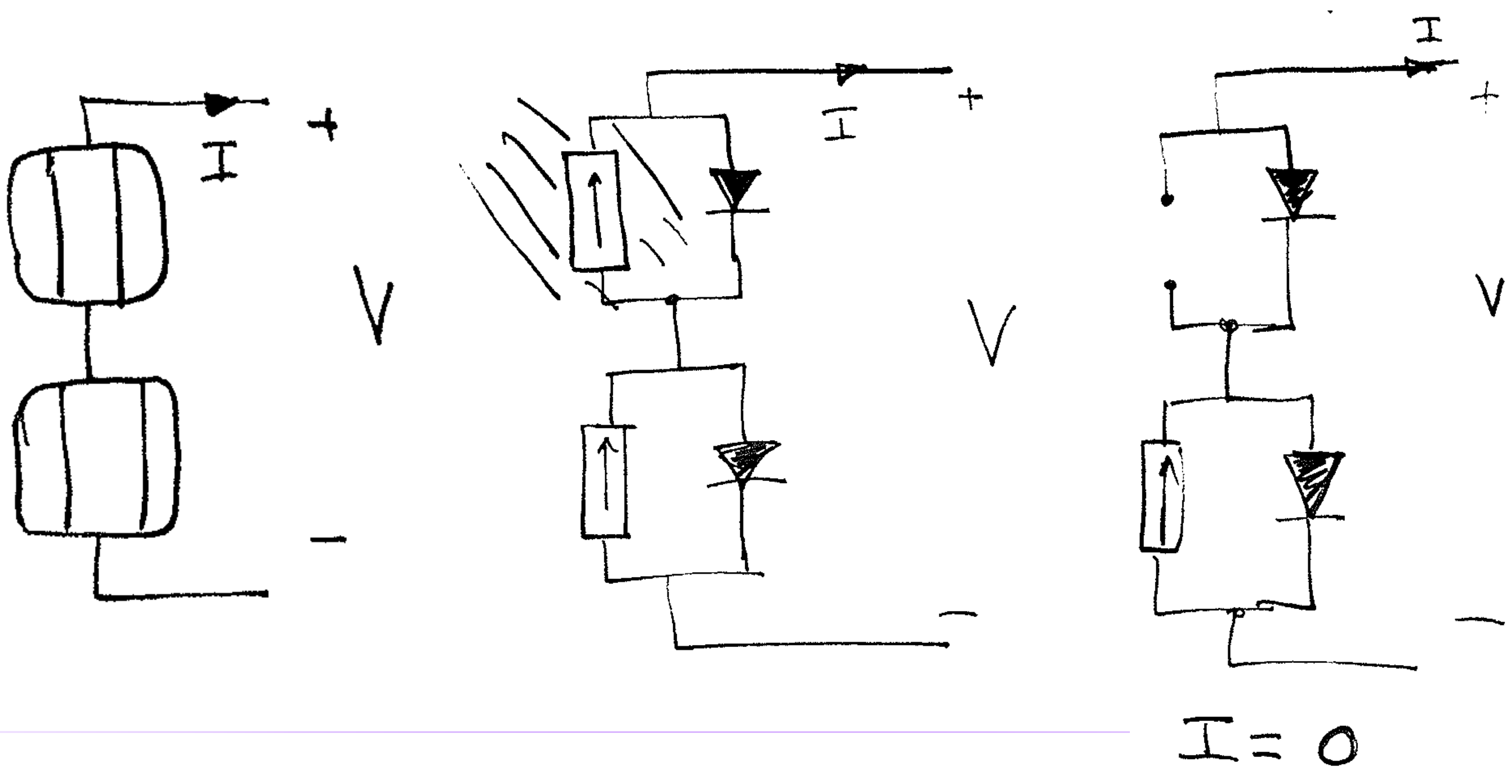
PV Cell I-V Curves

- More light effectively shifts the curve up in I, but V_{OC} does not change much
- By varying the insolation, we obtain not a single I-V curve, but a collection of them



Need for a More Accurate Model

- The previous circuit is not realistic for analyzing shading effects (we’ll talk more about shading later)
- Using this model, absolutely NO current can pass when one cell is shaded (I = 0)



PV Equivalent Circuit

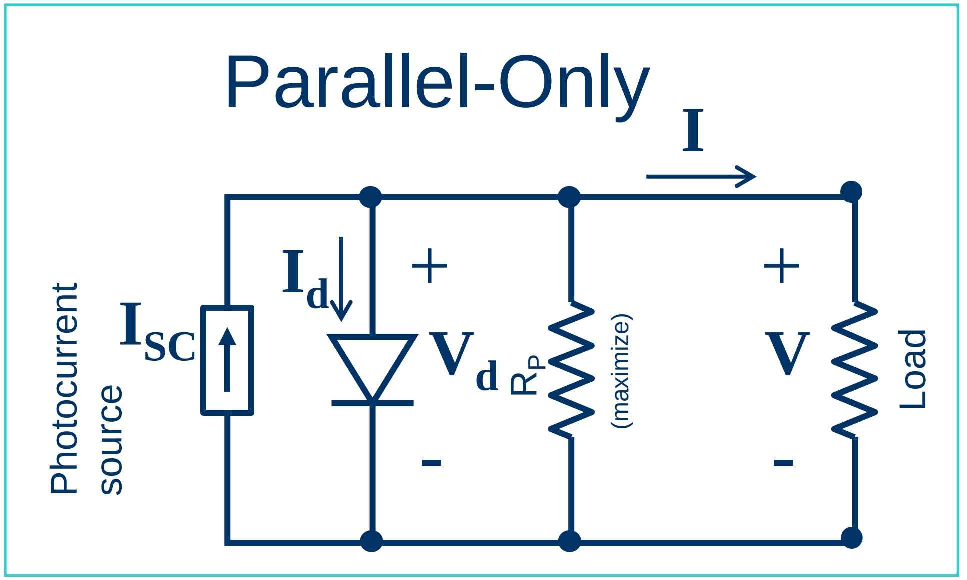
- It is true that shading has a big impact on solar cell power output, but it is not as dramatic as this suggests! Otherwise, a single shaded cell would make the entire module’s output zero.
- A more accurate model includes a leakage resistance R_P in ***parallel*** with the current source and the diode
- R_P is large, $\sim R_P > 100 V_{OC}/I_{SC}$
- A resistance R_S in ***series*** accounts for the fact that the output voltage V is not exactly the diode voltage
- R_S is small, $\sim R_S < 0.01 V_{OC}/I_{SC}$

PV Equivalent with Parallel Resistor

- From KCL, $I = I_{SC} - I_d - I_{RP}$

$$I = (I_{SC} - I_d) - \frac{V}{R_P}$$

Shunt resistance drops some current (reduces output current)



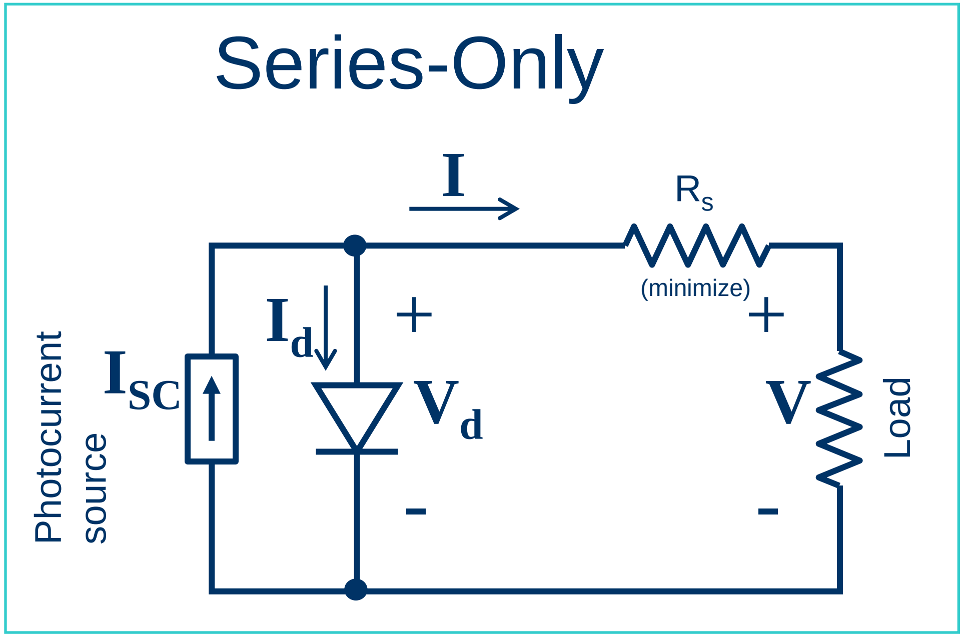
- For any given voltage, the parallel leakage resistance causes load current for the ideal model to be decreased by V/R_P

PV Equivalent with Series Resistor

- Add impact of ***series*** resistance R_S (we want R_S to be small) due to contact between cell and wires and from some resistance of the semiconductor
- From KVL

$$V_d = V + I \cdot R_S$$

Series resistance drops some voltage (reduces output voltage)



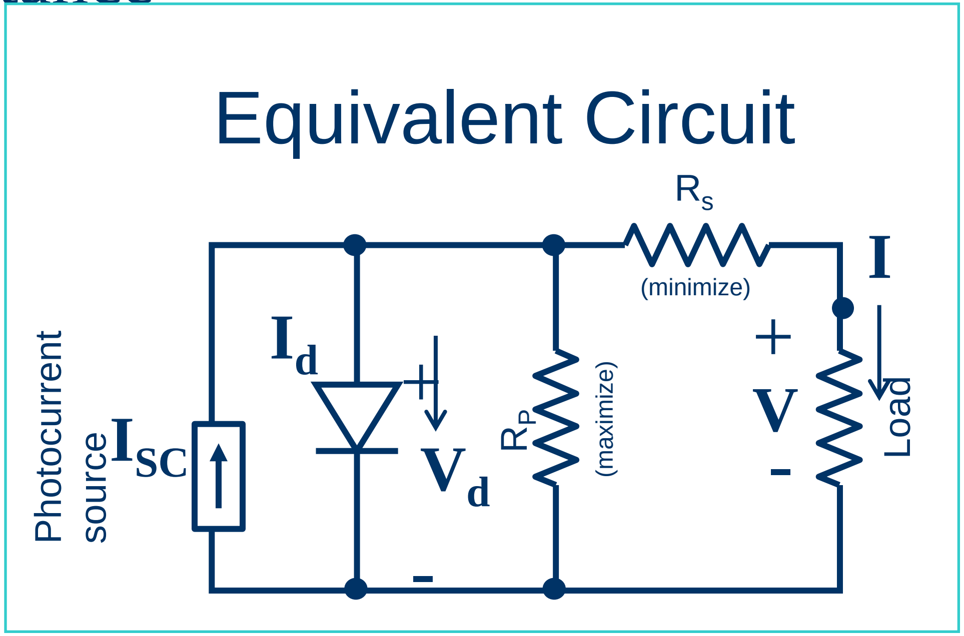
- The output voltage V drops by IR_S

General PV Cell Equivalent Circuit

- The general equivalent circuit model considers both parallel and series resistance

$$I = (I_{SC} - I_d) - \frac{V_d}{R_P}$$

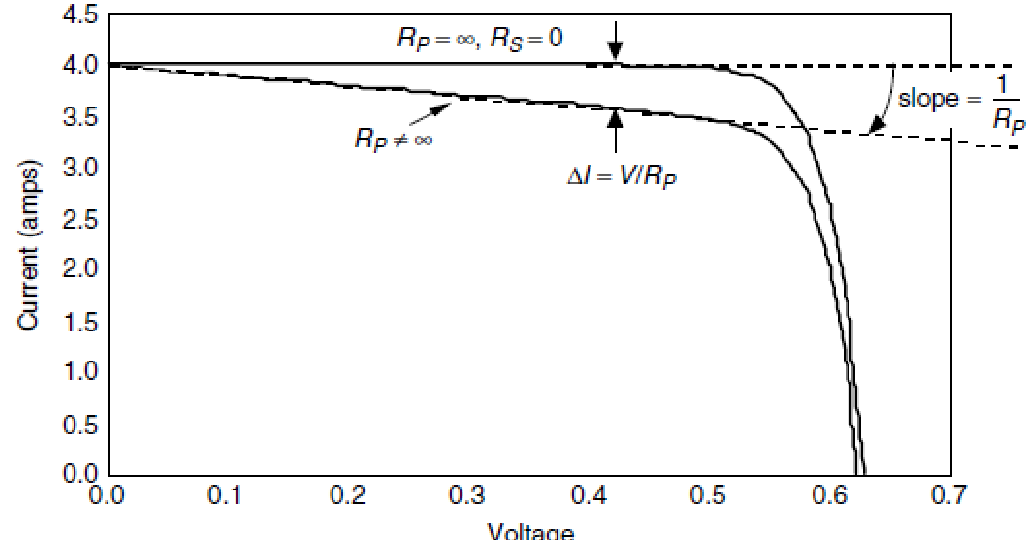
$$V = V_d - I \cdot R_S$$



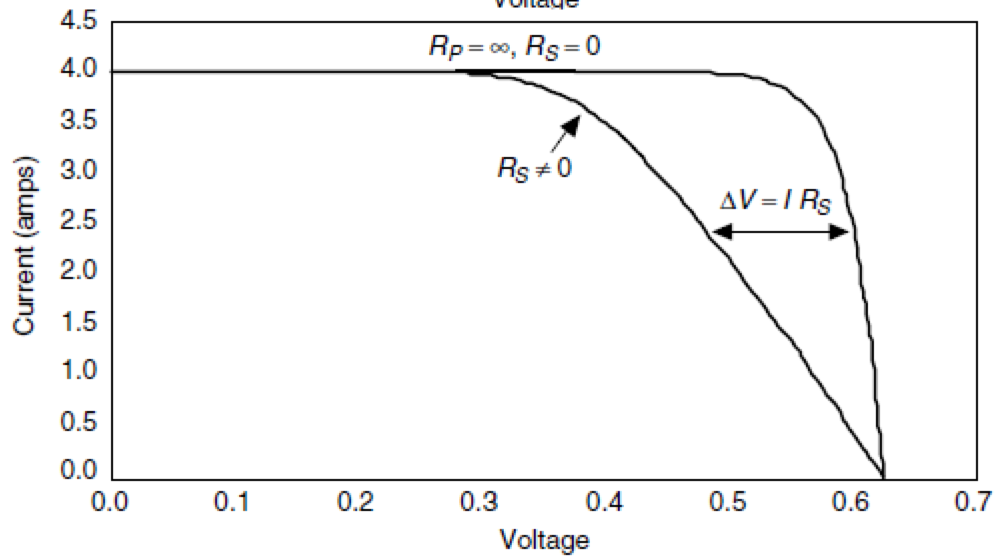
$$I = (I_{SC} - I_0(e^{q/kT(V+R_S I)} \text{-}1)) - \frac{V + R_S I}{R_P}$$

Series and Shunt Resistance Effects

- Parallel (R_P) – current drops by $\Delta I = V/R_P$

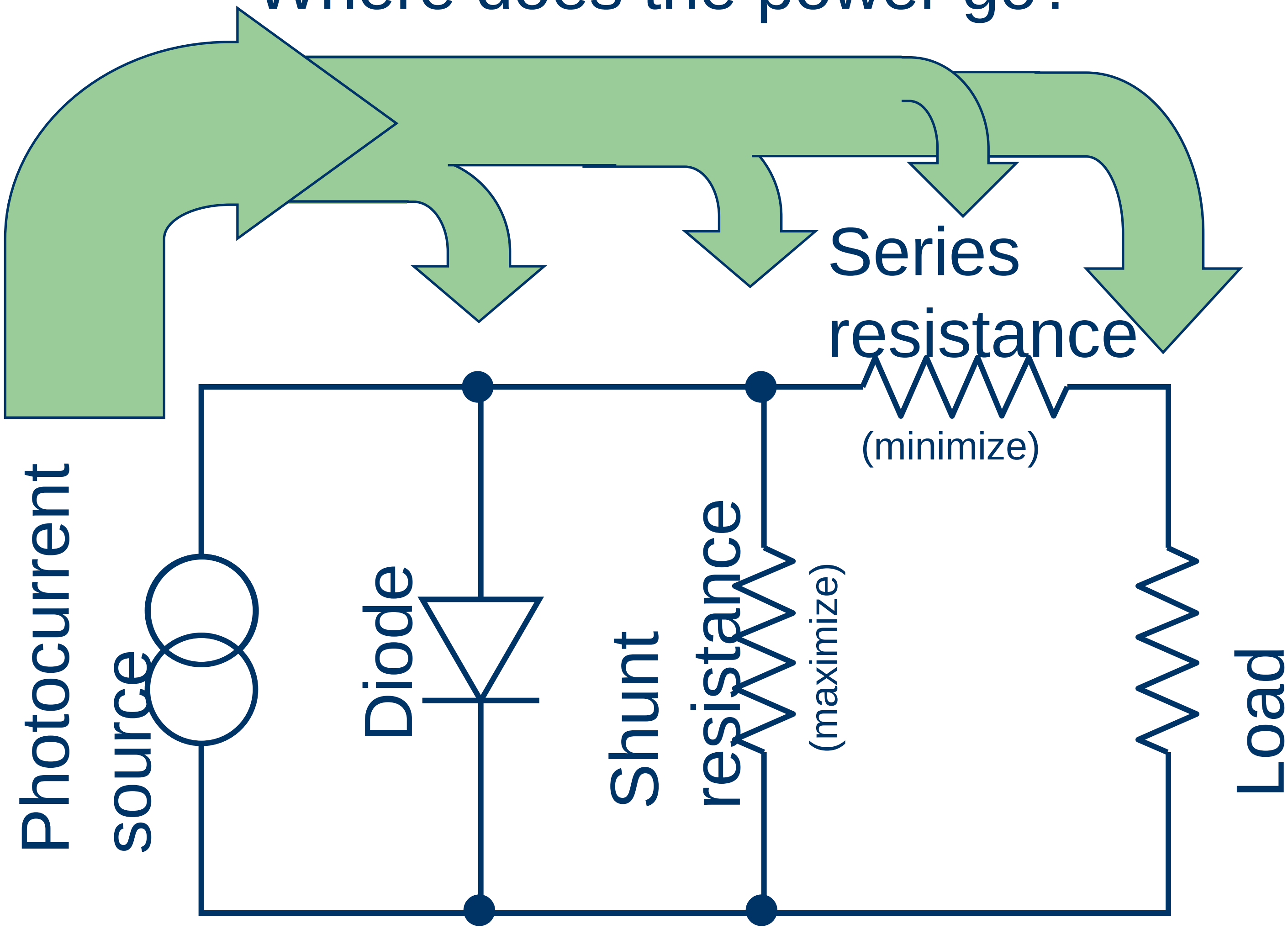


- Series (R_S) – voltage drops by $\Delta V = IR_S$



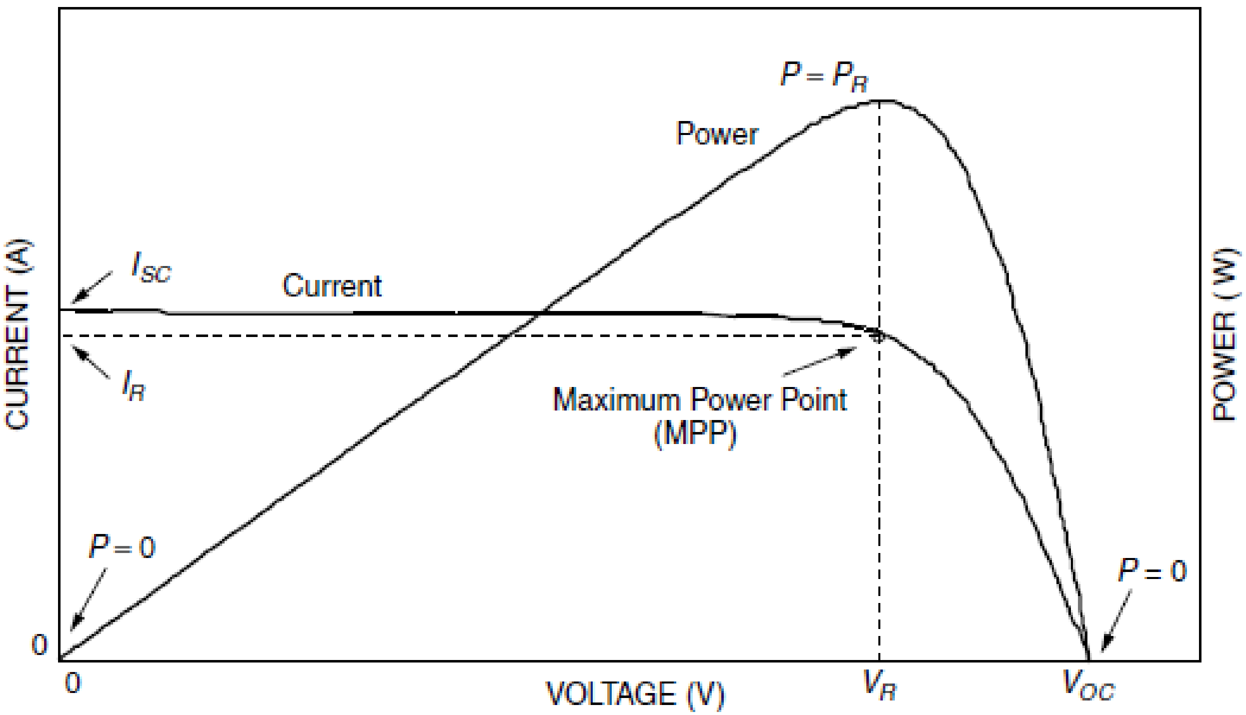
Standard Equivalent Circuit Model

Where does the power go?



I-V Curve and Power Output

- Power delivered by a PV module is the product of voltage and current;
- Curve maximum indicates the maximum power point (MPP).

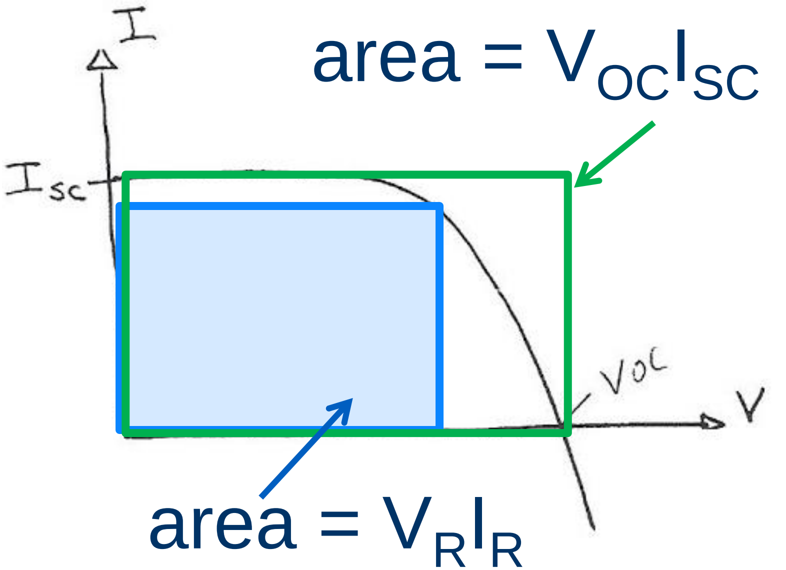


Fill Factor and Cell Efficiency

- Another way to visualize the location of MPP;

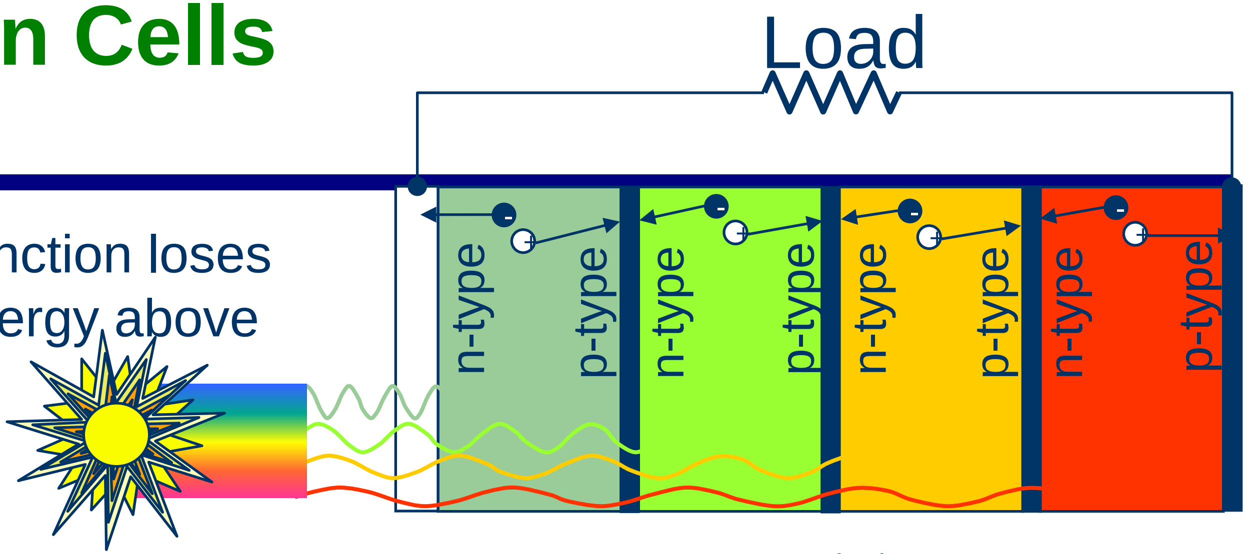
$$\text{Fill Factor (FF)} = \frac{V_R \bullet I_R}{I_{sc} \bullet V_{oc}}$$

Fill factor is ratio value at the maximum power point



$$\text{Cell Efficiency } (\eta) = \frac{I_{sc} \bullet V_{oc} \bullet FF}{\text{Incident Power}} = \frac{I_{max} \bullet V_{max}}{\text{Incident Power}}$$

Multijunction Cells



Problem: Single junction loses all of the photon energy above the gap energy.

Solution: Use a series of cells of different gaps.

Each cell captures the light transmitted from above.