بسم الله الرحمن الرحيم

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Undergraduate Course

Solar Cells Fundamental

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Lecture (4)

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Solar Energy

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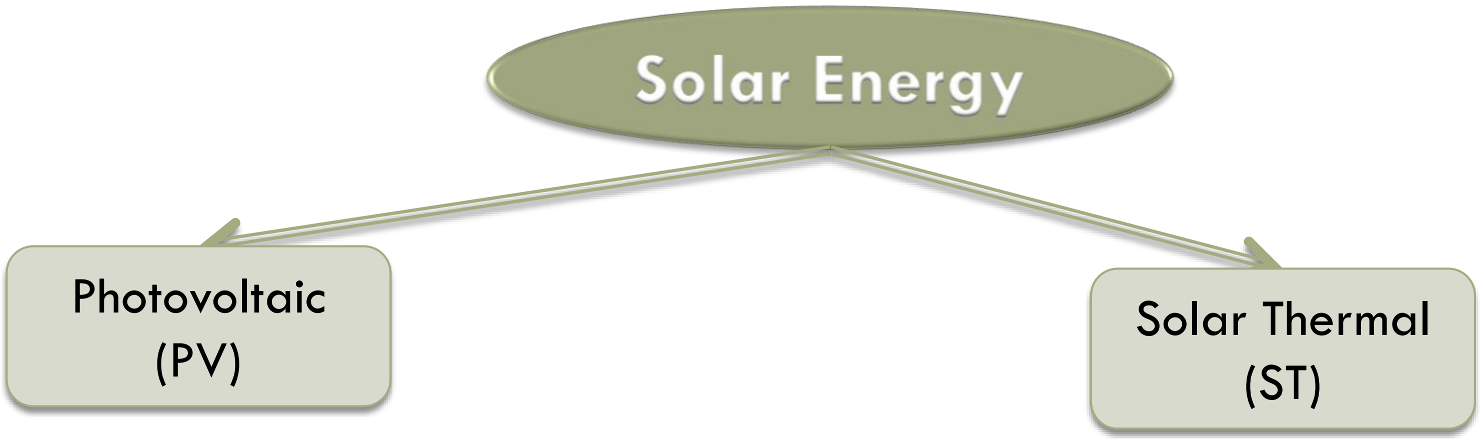
What is the solar energy?

- Most renewable energy comes either directly or indirectly from the sun.
- Sunlight, or solar energy, can be used directly for heating and lighting homes and other buildings, for generating electricity, and for hot water heating, solar cooling, and a variety of commercial and industrial uses.

Types

- **There are two basic technologies of solar energy**



1. Photovoltaic (PV)

- These are the most common form and have always been, and now increasingly common on top of our homes, Each cell converts the light of the sun into electrical energy, which can then be used to power electrical devices.
- Solar Cell often made from semiconductors material such as silicon materials.

2. Solar Thermal

- This type of technology is known as Concentrated Solar Power (CSP).
- May look similar to PV, but they work differently in that they draw in a concentrated beam of sunlight, reflecting it through a system of mirrors.
- The resulting heat generated by the process activates a turbine that produces electricity through a conventional generator. Where PV produces energy from light, this produces energy from heat.

First

Solar Photovoltaic's

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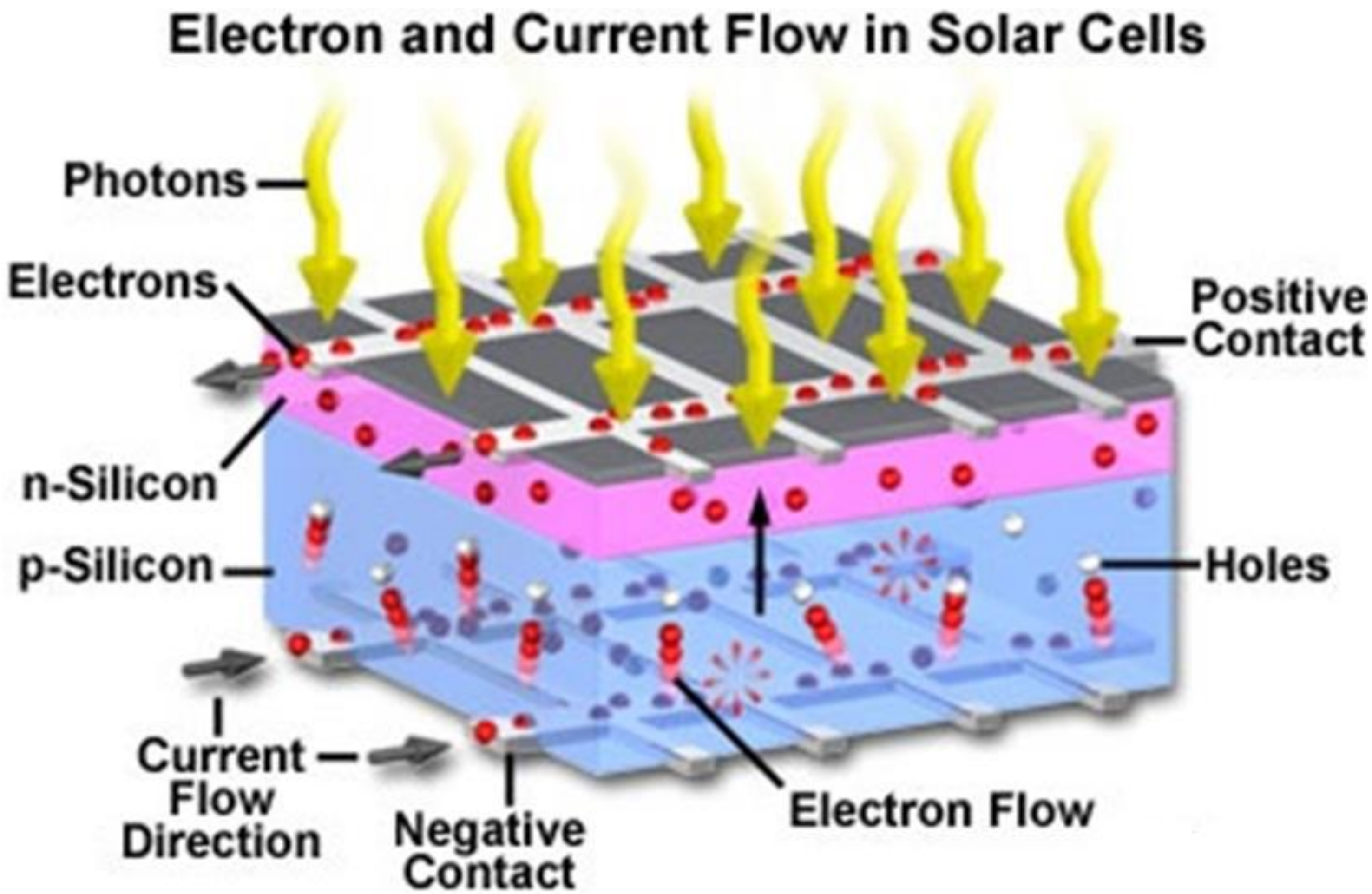
1. PV General overview

- PV was recognized as an important source of space power in the 1950s.
- Terrestrial PV development began in response to the 1970s oil crises.
- Concern for the environment, as well as global efforts to seek indigenous sources of energy, drives the investment in PV research and deployment.
- Today, PV is a several-billion-dollar industry worldwide, with more than 520 MW of PV modules shipped in 2002.

- These include large, multi-megawatt installations feeding into the utility grid, kilowatt rooftop systems supplying power to a home or business, and single 50- or 100-W PV modules on homes in developing countries.

2. Solar cells are semiconductor devices

- That produce electricity from sunlight via the photovoltaic effect.
- Sunlight strikes the cell, photons with energy above the semiconductor band gap impart enough energy to create electron-hole pairs.
- A junction between dissimilarly doped semiconductor layers sets up a potential barrier in the cell, which separates the light-generated charge carriers.
- This separation induces a fixed electric current and voltage in the device. The electricity is collected and transported by metallic contacts on the top and bottom surfaces of the cell.


Electron and Current Flow in Solar Cells
Photons
Electrons
Positive Contact
n-Silicon
p-Silicon
Holes
Current Flow Direction
Negative Contact
Electron Flow

Band Gap Energy

- Photons with enough energy create hole–electron pairs in a semiconductor.
- Photons can be characterized by their wavelengths or their frequency as well as by their energy; the three are related by the following:

$$c = \lambda v$$

where c is the speed of light (3×10^8 m/s), v is the frequency (hertz), λ is the wavelength (m), and

$$E = hv = hc/\lambda$$

where E is the energy of a photon (J) and h is Planck's constant (6.626×10^{-34} J-s).

Example

Photons to Create Hole–Electron Pairs in Silicon

What maximum wavelength can a photon have to create hole–electron pairs in silicon?

What minimum frequency is that?

Silicon has a band gap of 1.12 eV and 1 eV = 1.6×10^{-19} J.

Solution.

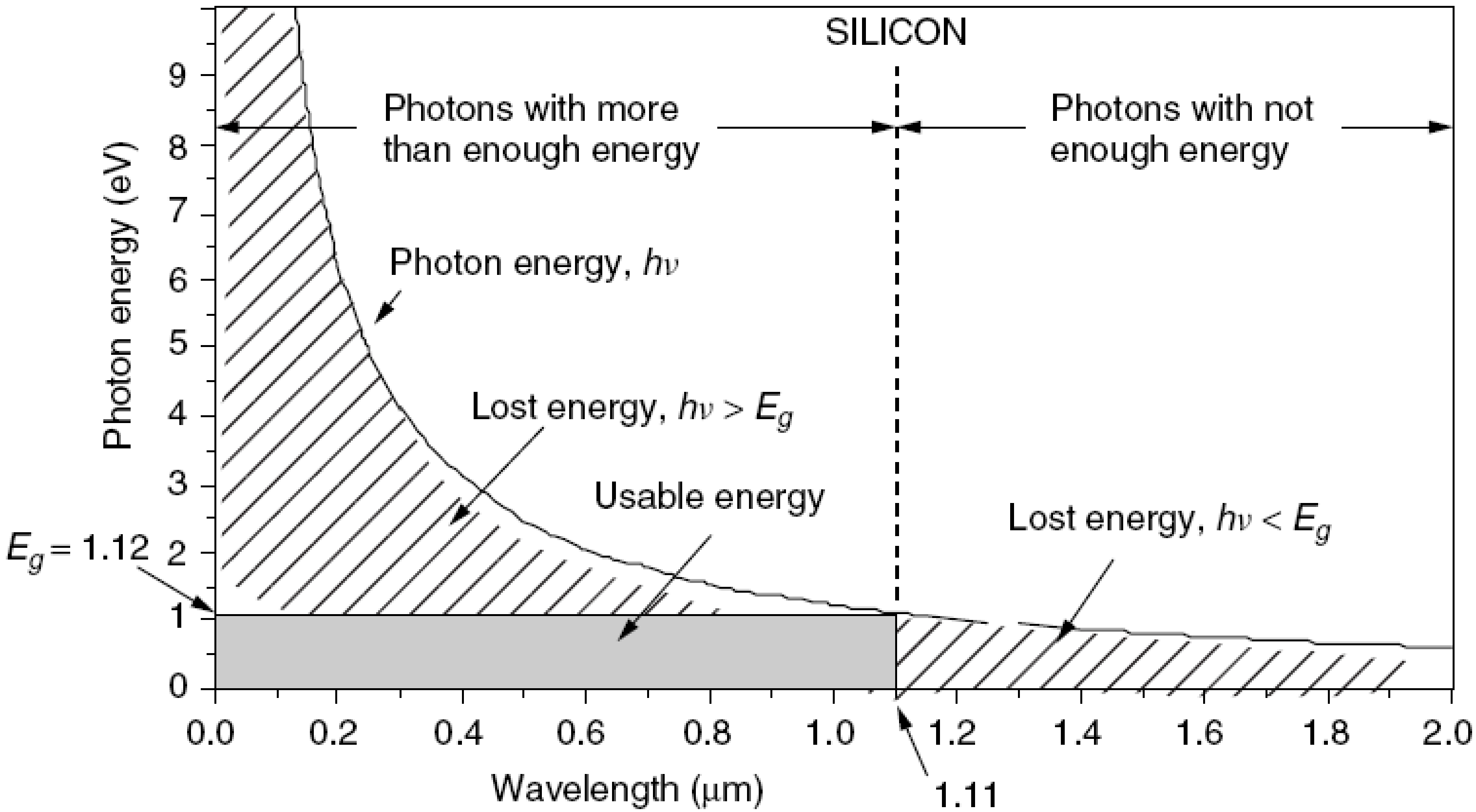
The wavelength must be less than

$\lambda \leq hc/E = (6.626 \times 10^{-34}\ \text{J} \cdot \text{s} \times 3 \times 10^{8}\ \text{m/s}) / (1.12\ \text{eV} \times 1.6 \times 10^{-19}\ \text{J/eV}) = 1.11 \times 10^{-6}\ \text{m} = 1.11\ \mu\text{m}$

The frequency must be at least

$v \geq c / \lambda = 3 \times 10^{8}\ \text{m/s} / 1.11 \times 10^{-6}\ \text{m} = 2.7 \times 10\ \text{Hz}$

The Solar Spectrum



Photons with wavelengths above 1.11 μm don't have the 1.12 eV needed to excite an electron, and this energy is lost. Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted as well.

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Band Gap and Cut-off Wavelength Above Which Electron Excitation Doesn't Occur

Quantity	Si	GaAs	CdTe	InP
Band gap (eV)	1.12	1.42	1.5	1.35
Cut-off wavelength (μm)	1.11	0.87	0.83	0.92

Band-Gap Impact on Photovoltaic Efficiency

We can now make a simple estimate of the upper bound on the efficiency of a silicon solar cell.

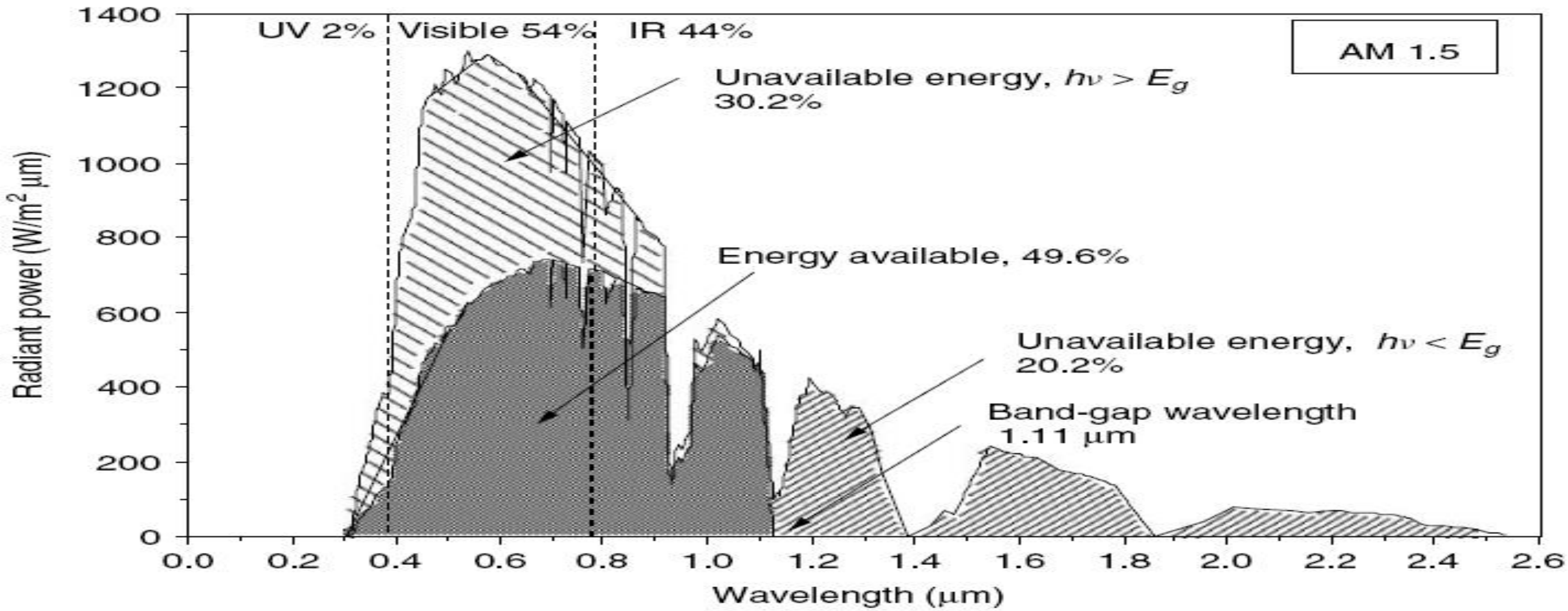
- We know the band gap for silicon is 1.12 eV, corresponding to a wavelength of 1.11 μm
- which means that any energy in the solar spectrum with wavelengths longer than 1.11 μm cannot send an electron into the conduction band. And, any photons with wavelength less than 1.11 μm waste their extra energy.
- If we know the solar spectrum, we can calculate the energy loss due to these two fundamental constraints.

Band-Gap Impact on Photovoltaic Efficiency

The following figure shows the results of this analysis, assuming a standard air mass ratio AM 1.5.

- As is presented there, 20.2% of the energy in the spectrum is lost due to photons having less energy than the band gap of silicon ($h\nu < E_g$).
- And another 30.2% is lost due to photons with $h\nu > E_g$.
- The remaining 49.6% represents the maximum possible fraction of the sun's energy that could be collected with a silicon solar cell.
- That is, the constraints imposed by silicon's band gap limit the efficiency of silicon to just under 50%.

Band-Gap Impact on Photovoltaic Efficiency



Solar spectrum at AM 1.5. Photons with wavelengths longer than 1.11 µm don't have enough energy to excite electrons (20.2% of the incoming solar energy); those with shorter wavelengths can't use all of their energy, which accounts for another 30.2% unavailable to a silicon photovoltaic cell. Spectrum is based on ERDA/NASA (1977).

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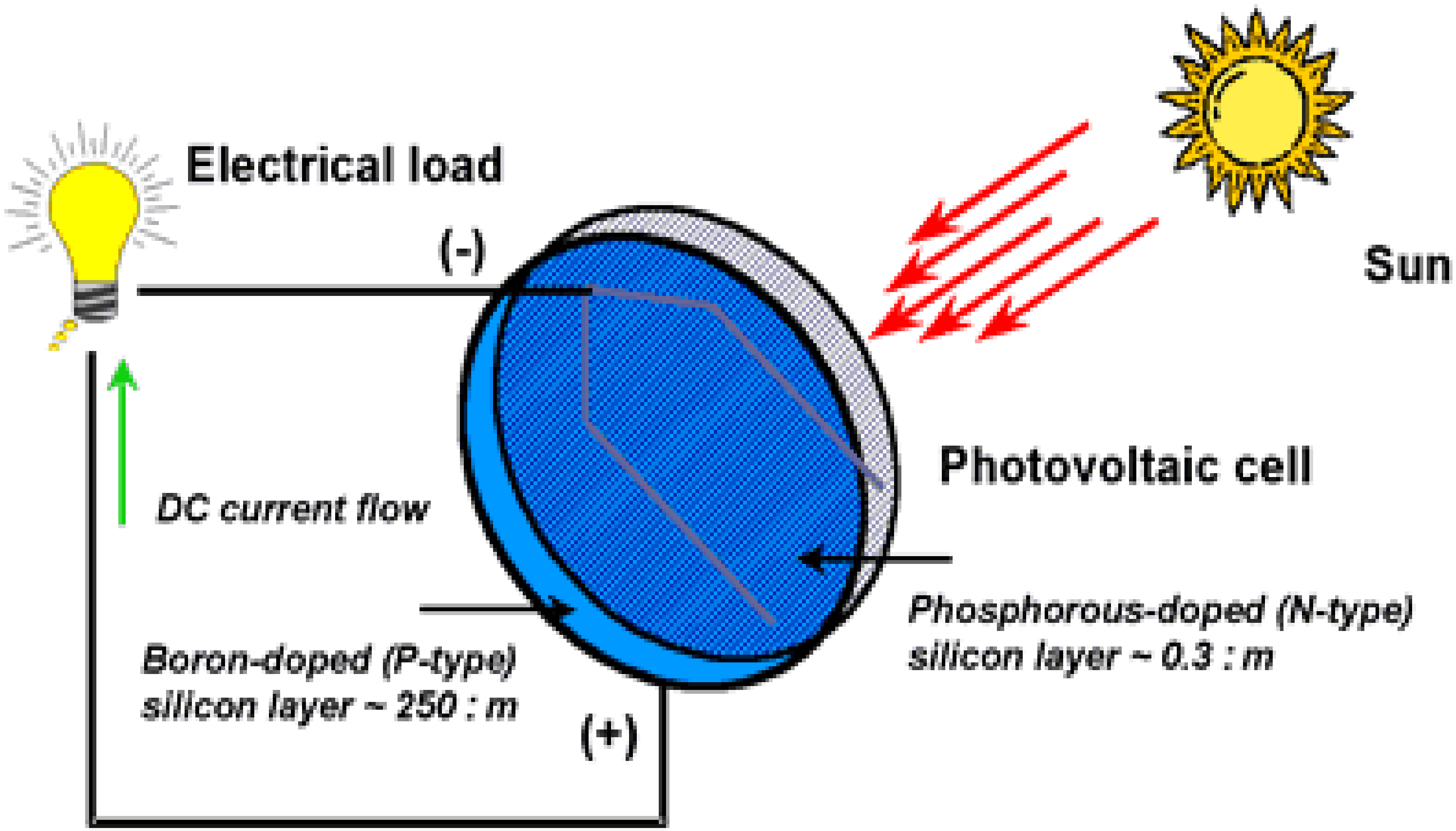
How PV Cells Work ?

- A typical silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon.
- An electrical field is created near the top surface of the cell where these two materials are in contact, called the P-N junction.
- When sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the solar cell is connected to an electrical load.

How PV Cells Work ?



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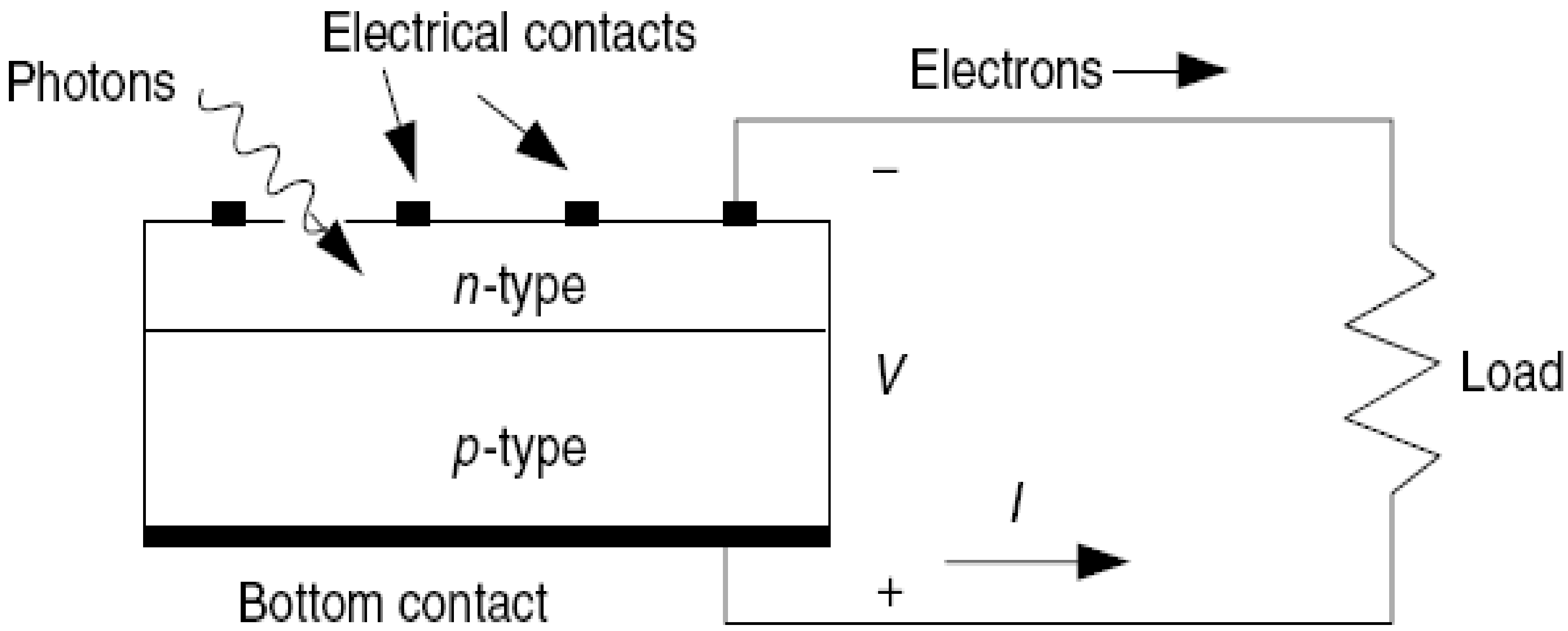
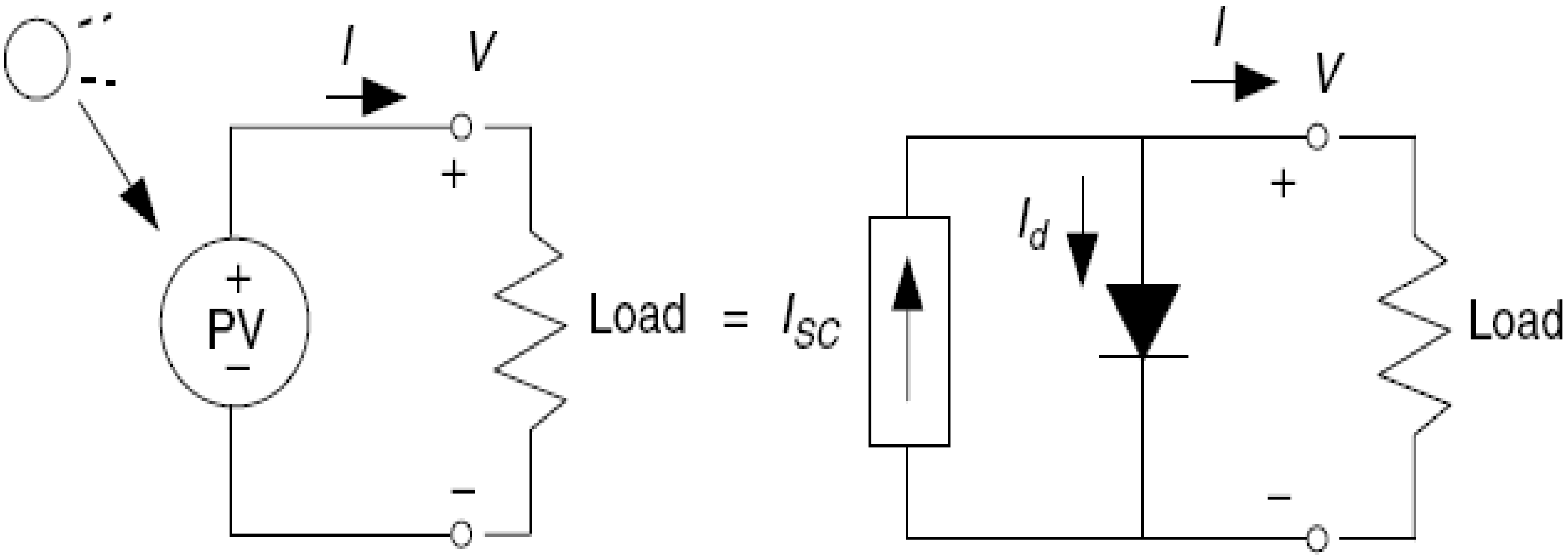
Equivalent Circuit for a Photovoltaic Cell "Ideal Circuit"



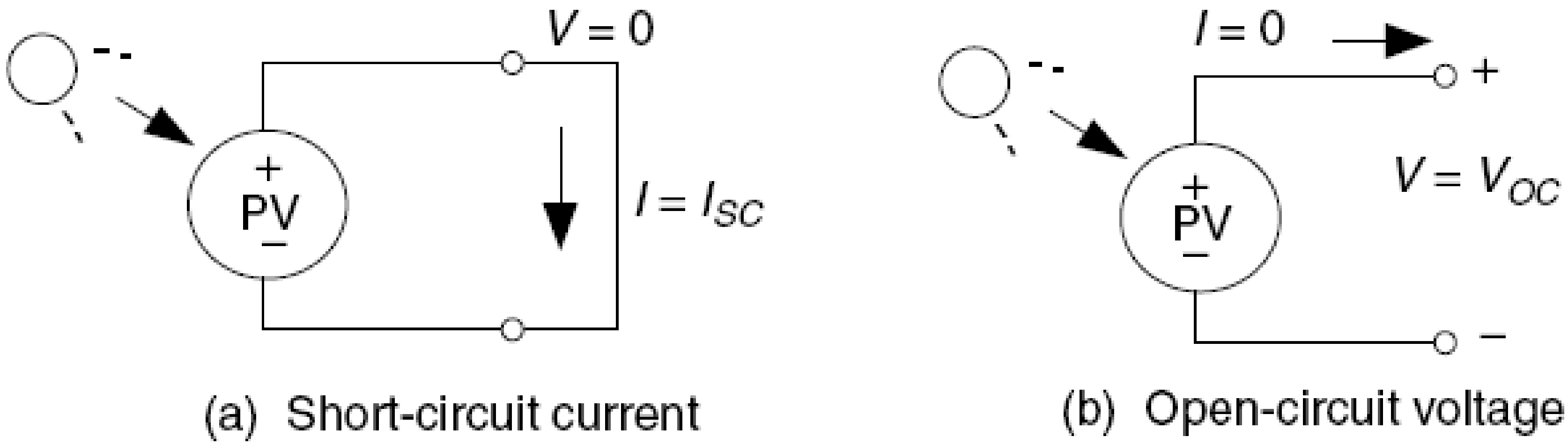
Electrons flow from the *n*-side contact, through the load, and back to the *p*-side where they recombine with holes. Conventional current *I* is in the opposite direction

Equivalent Circuit for a Photovoltaic Cell "Ideal Circuit"



A simple equivalent circuit for a photovoltaic cell consists of a current source driven by sunlight in parallel with a real diode.

Equivalent Circuit for a Photovoltaic Cell "Ideal Circuit"



Two important parameters for photovoltaics are the short-circuit current I_{SC} and the open-circuit voltage V_{OC}.

Equivalent Circuit for a Photovoltaic Cell "Ideal Circuit"

Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown in the previous figure. Start with

$I = I_{SC} - I_d$

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

When the leads from the PV cell are left open, I = 0 and we can solve the current equation for the open-circuit voltage V_{OC} :

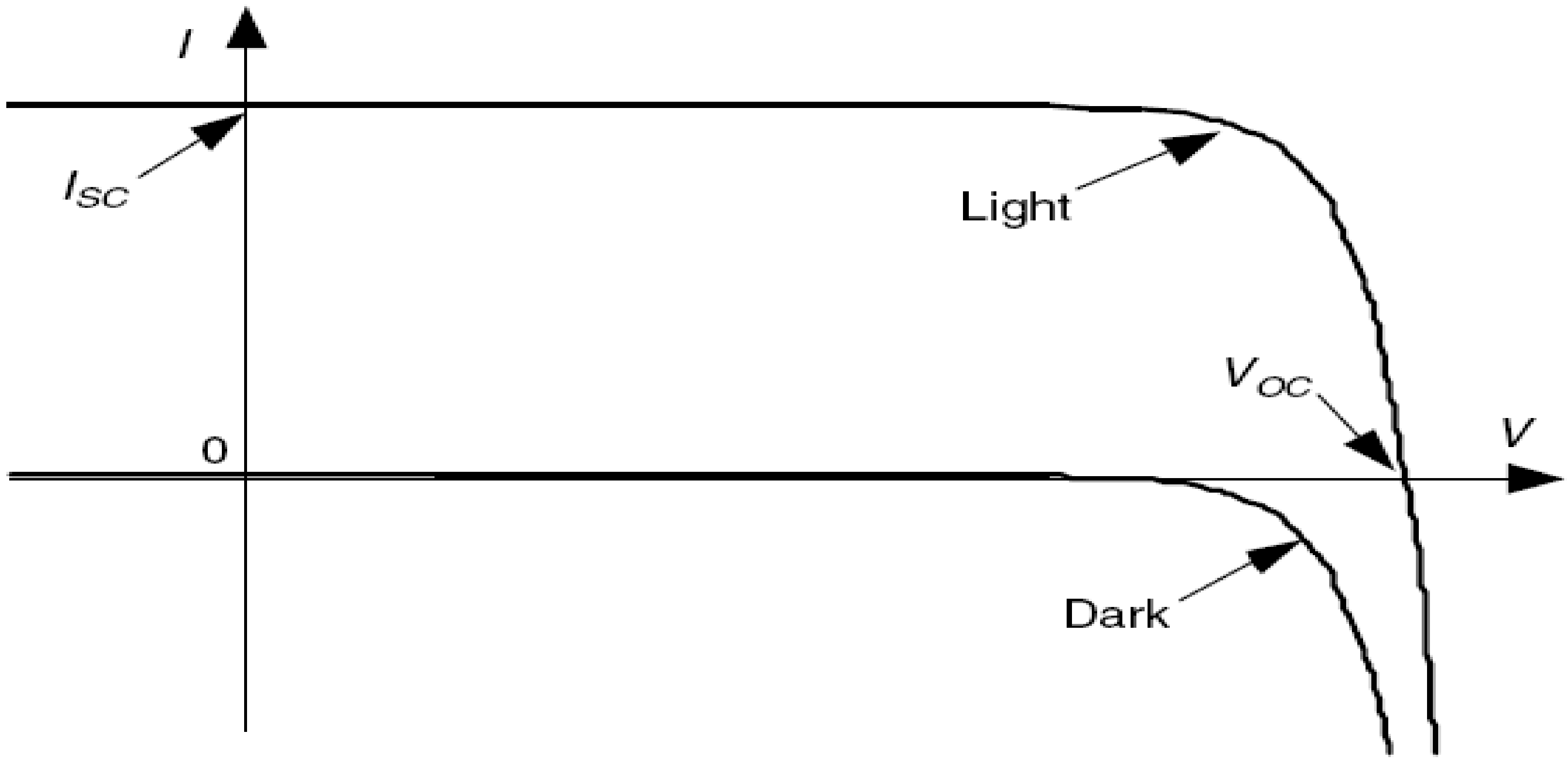
$V_{OC} = (kT / q) * \ln ((I_{SC} / I_0) + 1)$

And at 25°C, the current and voltage equations become

$I = I_{SC} - I_0\ (e^{38.9\ V} - 1)$

$V_{OC} = 0.0257 \ln ((I_{SC} / I_0) + 1)$

Current – Voltage Ch/s for Photovoltaic Cell "Ideal Circuit"



Photovoltaic current–voltage relationship for "dark" (no sunlight) and "light" (an illuminated cell). The dark curve is just the diode curve turned upside-down. The light curve is the dark curve plus I_{SC}

Example

The *I* –*V* Curve for a Photovoltaic Cell. Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12}$ A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

Solution.

The reverse saturation current I_0 is 10^{-12} A/cm^2 × 100 cm^2 = 1 × 10^{-10} A.

At full sun I_{SC} is 0.040 A/cm^2 × 100 cm^2 = 4.0 A.

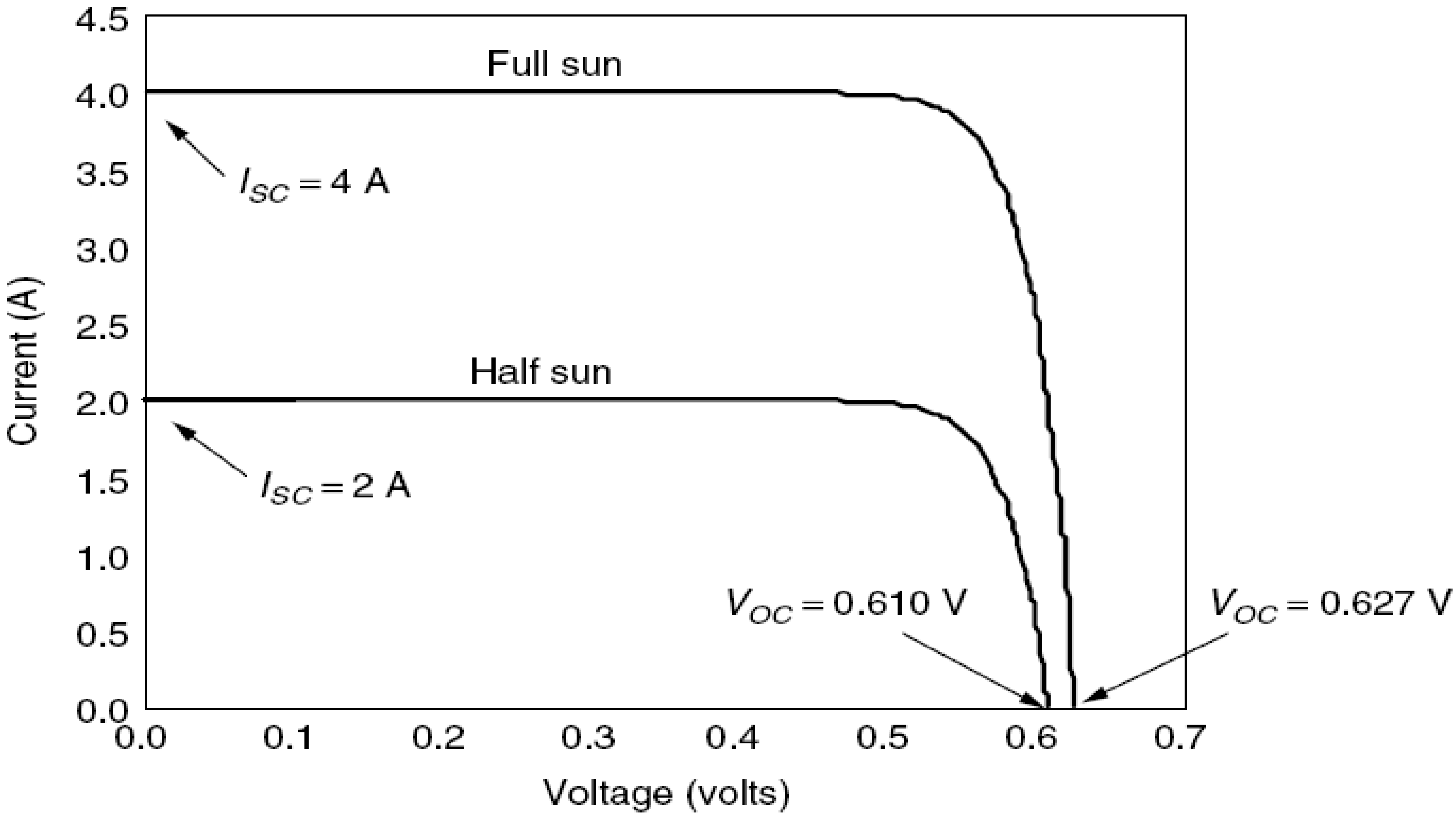
From the open-circuit voltage equation

$V_{OC} = 0.0257 \ln((I_{SC}/I_0) + 1 = 0.0257 \ln((4/10^{-10}) + 1) = 0.627$ V

Since short-circuit current is proportional to solar intensity, at half sun I_{SC} = 2 A and the open-circuit voltage is

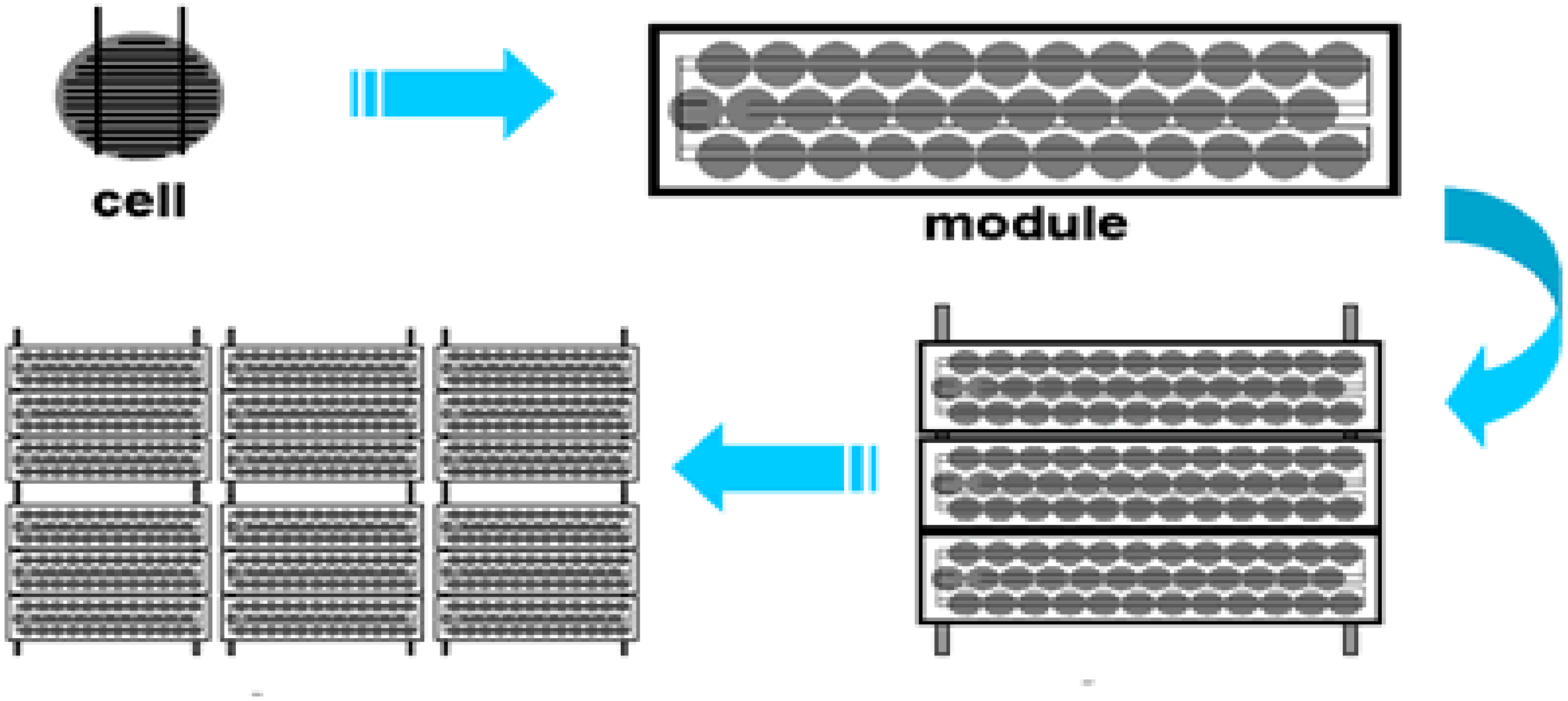
$V_{OC} = 0.0257 \ln((2/10^{-10}) + 1) = 0.610$ V

Results Plotting



4. Photovoltaic Hierarchy (Components)

Cell < Module < Array

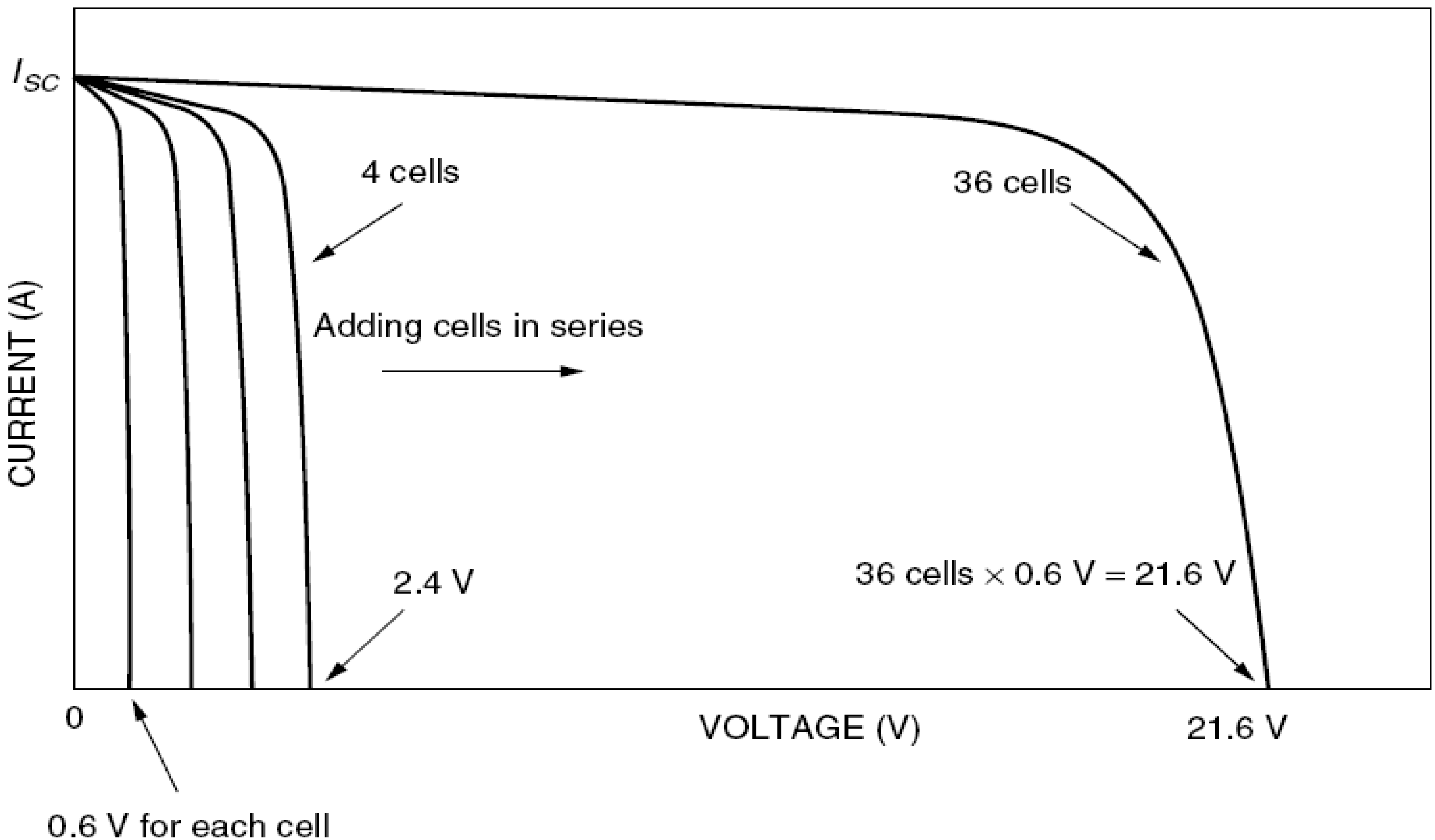


- Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels.

- Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building block of PV systems.

- Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.

From Cells to a Module



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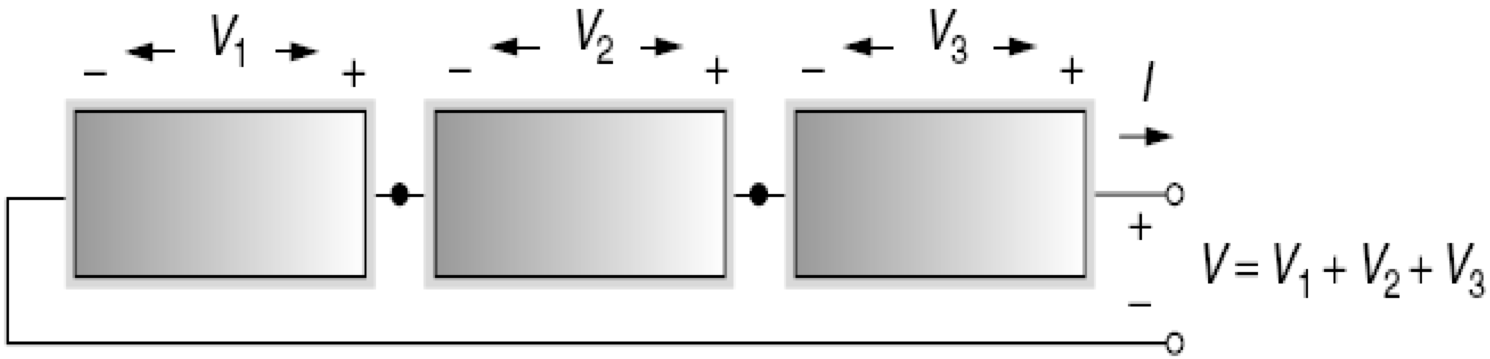
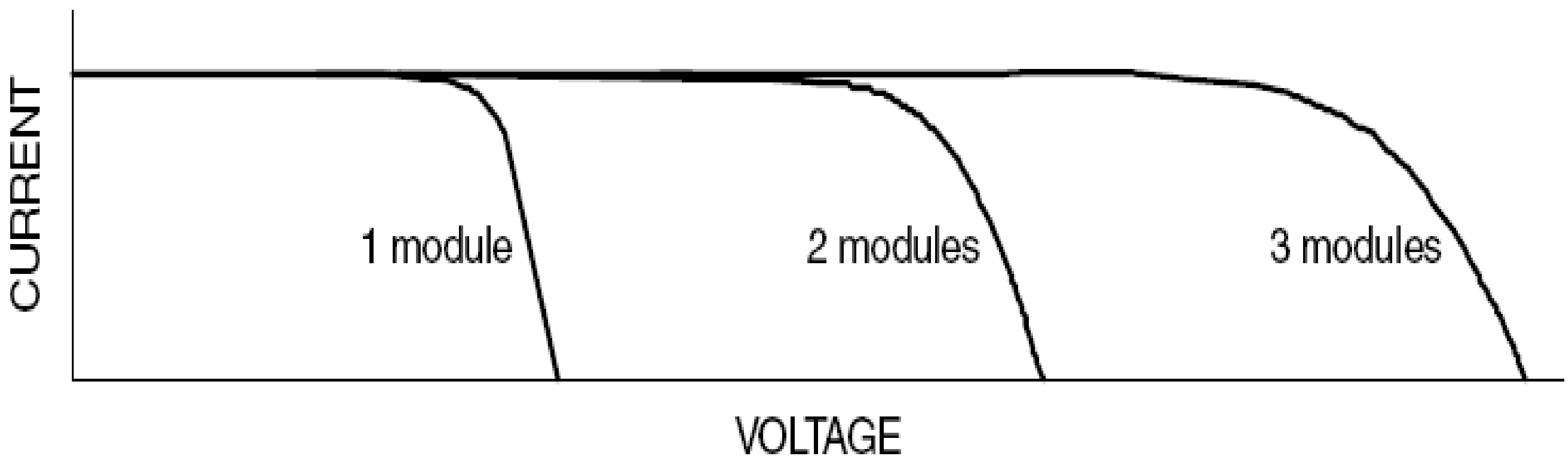
From Module to Array
Series Connection





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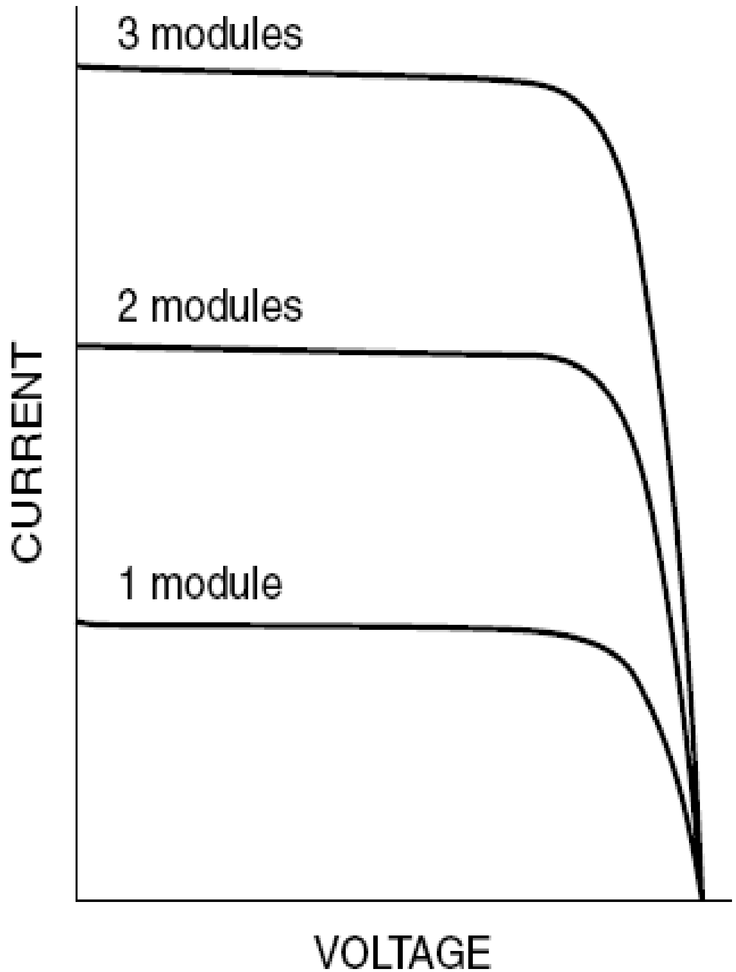
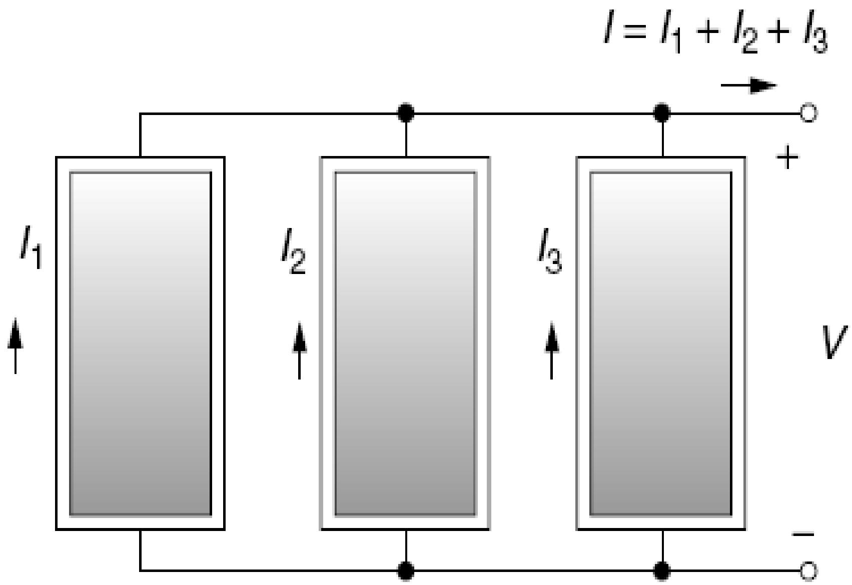
From Module to Array
Parallel Connection





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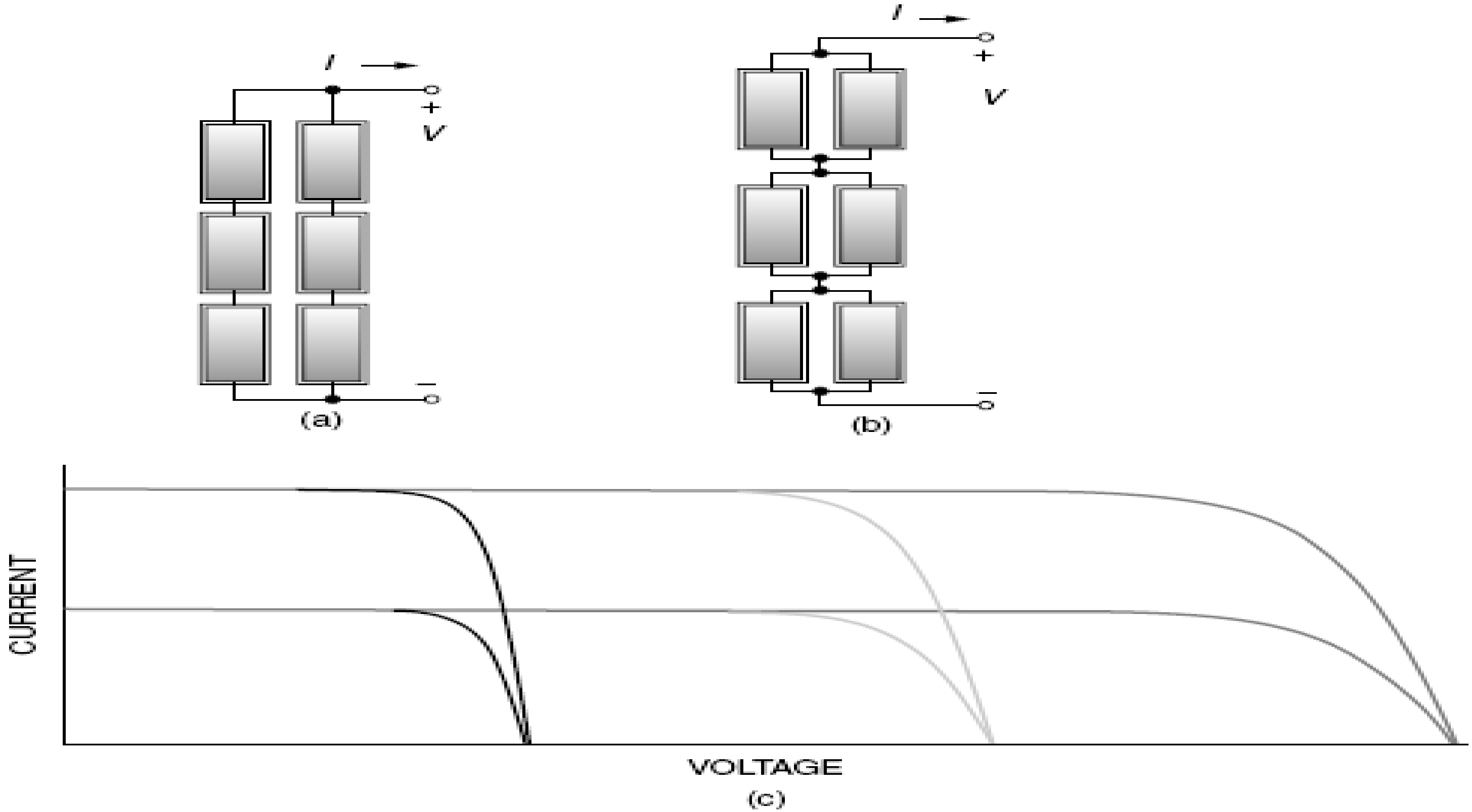
From Module to Array
Which one is the best??!!!!!!!



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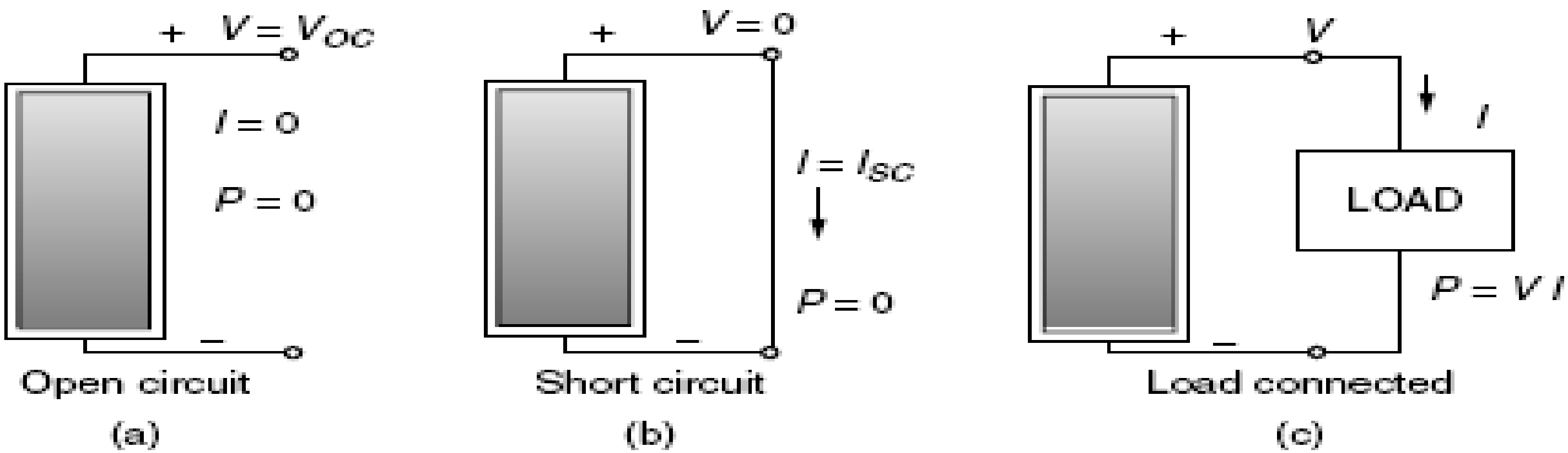
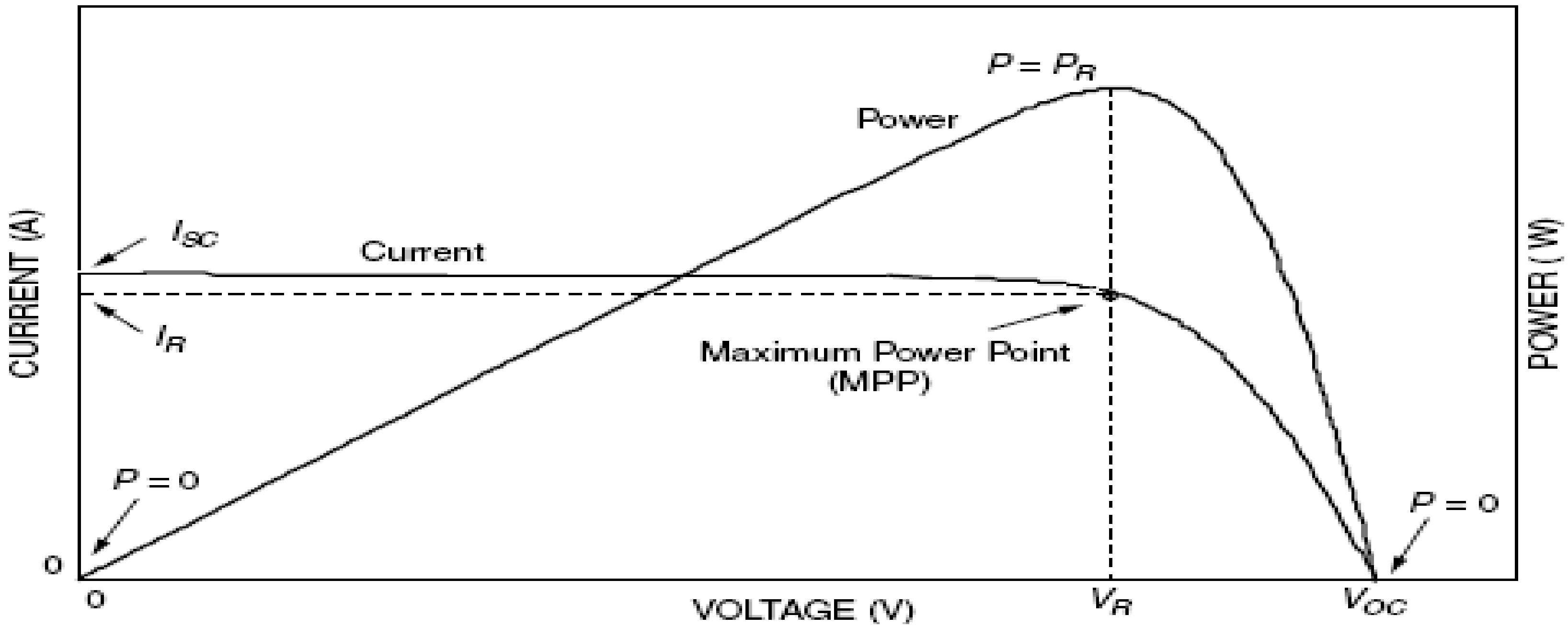
PV I – V Ch/s Understanding



No power is delivered when the circuit is open (a) or shorted (b). When the load is connected (c), the same current flows through the load and module and the same voltage appears across them.

PV I – V Ch/s Understanding



The *I* –*V* curve and power output for a PV module. At the maximum power point (MPP) the module delivers the most power that it can under the conditions of sunlight and temperature for which the *I* – *V* curve has been drawn.

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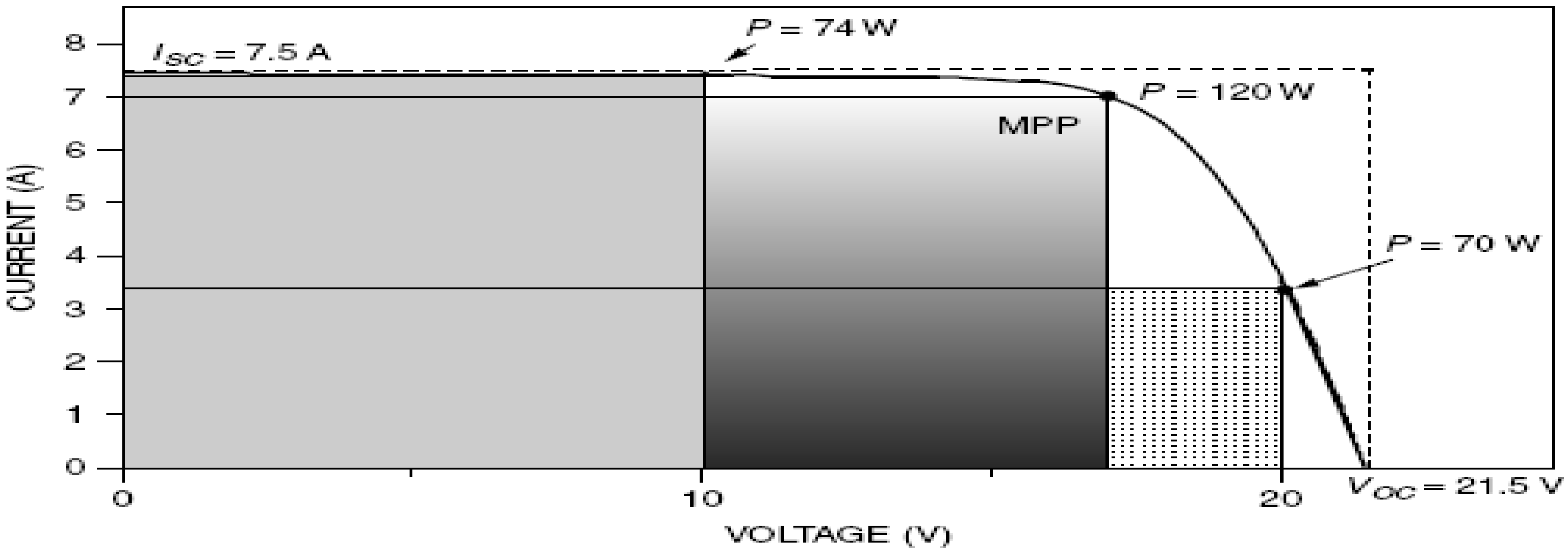
PV I – V Ch/s Understanding



The maximum power point (MPP) corresponds to the biggest rectangle that can fit beneath the *I* –*V* curve. The fill factor (FF) is the ratio of the area (power) at MPP to the area formed by a rectangle with sides V_{OC} and I_{SC}.

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Fill Factor

Fill factors around 70–75% for crystalline silicon solar modules are typical, while for multijunction amorphous-Si modules, it is closer to 50–60%.

$$\text{Fill factor (FF)} = \frac{\text{Power at the maximum power point}}{V_{OC}\ I_{SC}} = \frac{V_R I_R}{V_{OC} I_{SC}}$$

Examples of PV Module Performance Data Under STC ($1\ kW/m^2$, AM 1.5, 25°C Cell Temperature)

Manufacturer	Kyocera	Sharp	BP	Uni-Solar	Shell
Model	KC-120-1	NE-Q5E2U	2150S	US-64	ST40
Material	Multicrystal	Polycrystal	Monocrystal	Triple junction a-Si	CIS-thin film
Number of cells n	36	72	72		42
Rated Power $P_{DC,STC}$ (W)	120	165	150	64	40
Voltage at max power (V)	16.9	34.6	34	16.5	16.6
Current at rated power (A)	7.1	4.77	4.45	3.88	2.41
Open-circuit voltage V_{OC} (V)	21.5	43.1	42.8	23.8	23.3
Short-circuit current I_{SC} (A)	7.45	5.46	4.75	4.80	2.68
Length (mm/in.)	1425/56.1	1575/62.05	1587/62.5	1366/53.78	1293/50.9
Width (mm/in.)	652/25.7	826/32.44	790/31.1	741/29.18	329/12.9
Depth (mm/in.)	52/2.0	46/1.81	50/1.97	31.8/1.25	54/2.1
Weight (kg/lb)	11.9/26.3	17/37.5	15.4/34	9.2/20.2	14.8/32.6
Module efficiency	12.9%	12.7%	12.0%	6.3%	9.4%

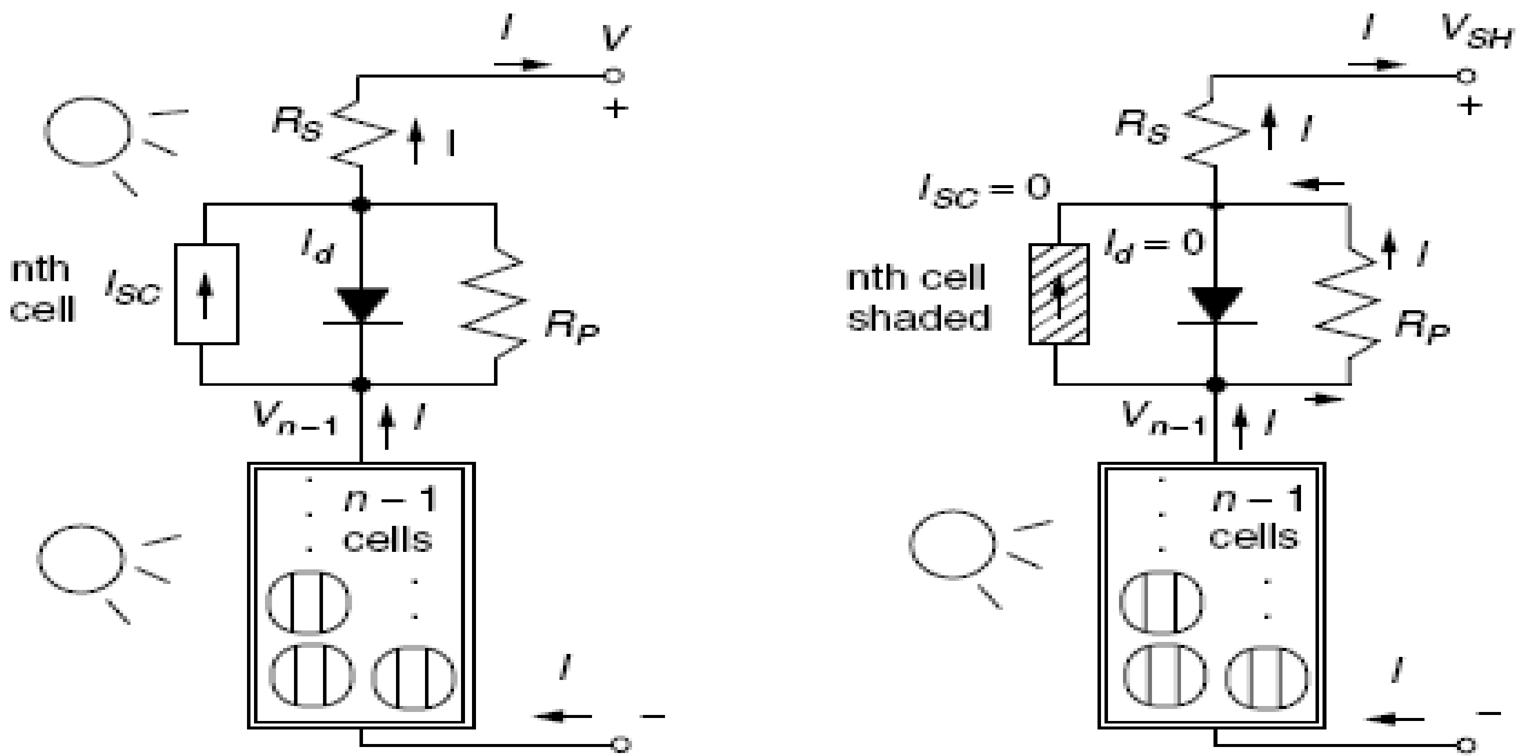
SHADING IMPACTS ON I –V CURVES

- The output of a PV module can be reduced dramatically when even a small portion of it is shaded.
- Unless special efforts are made to compensate for shade problems, even a single shaded cell in a long string of cells can easily cut output power by more than half.
- External diodes, purposely added by the PV manufacturer or by the system designer, can help preserve the performance of PV modules.
- The main purpose for such diodes is to mitigate the impacts of shading on PV *I –V* curves. Such diodes are usually added in parallel with modules or blocks of cells within a module.

Physics of Shading

To help understand this important shading phenomenon, consider the following figure in which an n-cell module with current I and output voltage V shows one cell separated from the others (shown as the top cell, though it can be any cell in the string). The equivalent circuit of the top cell has been drawn using the exact PV model, while the other $(n - 1)$ cells in the string are shown as just a module with current I and output voltage V_{n-1}.

Physics of Shading



(a) All cells in the sun

(b) Top cell shaded

A module with *n* cells in which the top cell is in the sun (a) or in the shade (b).

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Physics of Shading

- In figure a, all of the cells are in the sun and since they are in series, the same current I flows through each of them.

- In figure b, however, the top cell is shaded and its current source I_{SC} has been reduced to zero. The voltage drop across R_P as current flows through it causes the diode to be reverse biased, so the diode current is also (essentially) zero. That means the entire current flowing through the module must travel through both R_P and R_S in the shaded cell on its way to the load. That means the top cell, instead of adding to the output voltage, actually reduces it.
- Consider the case when the bottom $n - 1$ cells still have full sun and still some how carry their original current I so they will still produce their original voltage V_{n-1}. This means that the output voltage of the entire module V_{SH} with one cell shaded will drop to

Physics of Shading

- Consider the case when the bottom $n - 1$ cells still have full sun and still some how carry their original current I so they will still produce their original voltage V_{n-1}. This means that the output voltage of the entire module V_{SH} with one cell shaded will drop to

$$V_{SH} = V_{n-1} - I\,(R_P + R_S)$$

With all n cells in the sun and carrying I , the output voltage was V so the voltage of the bottom $n - 1$ cells will be

$$V_{n-1} = \left(\frac{n-1}{n}\right) V$$

Combining both equations

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I\,(R_P + R_S)$$

Physics of Shading

The drop in voltage ΔV at any given current I , caused by the shaded cell, is given by

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$

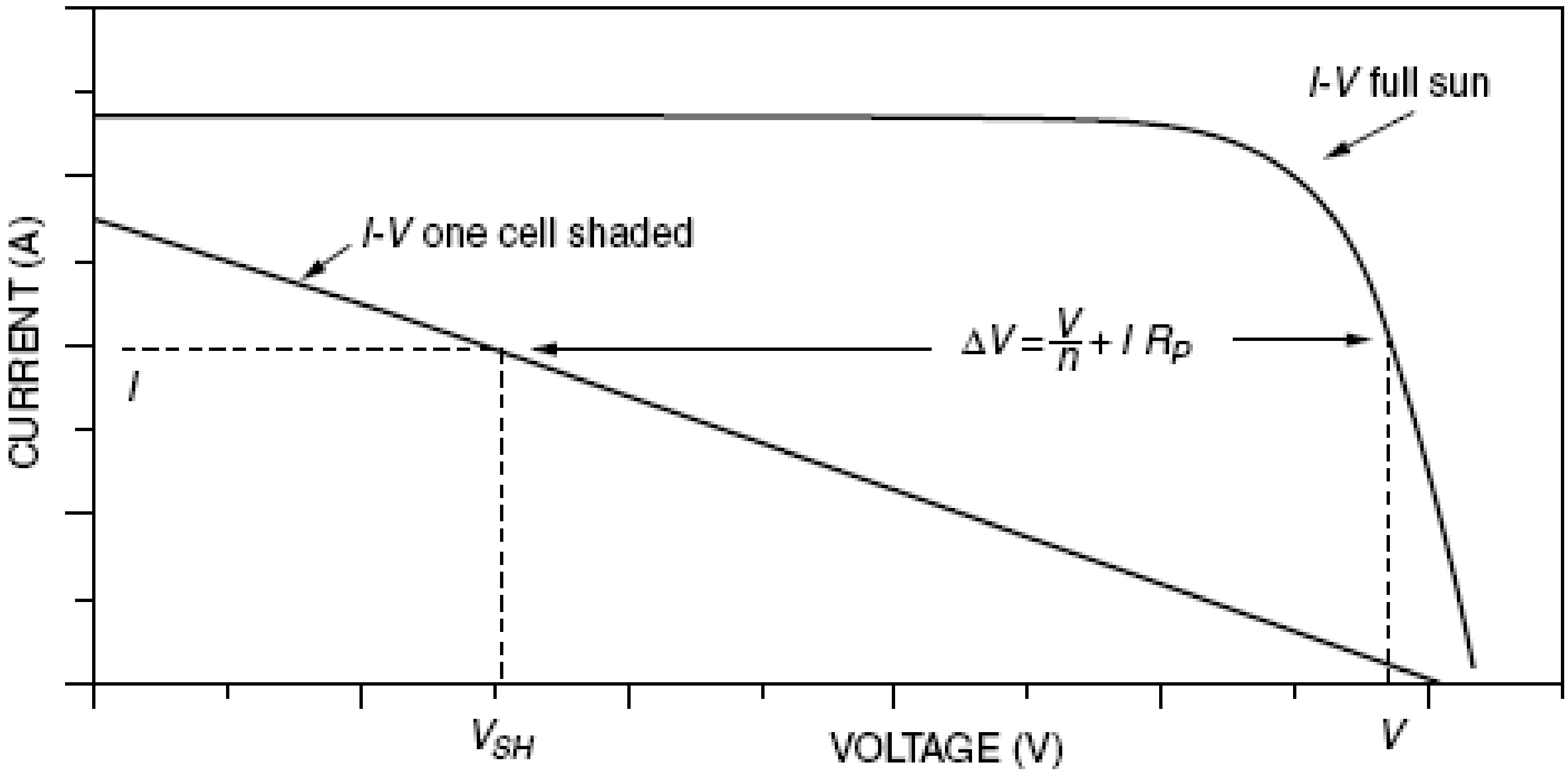
$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

Since the parallel resistance R_P is so much greater than the series resistance R_S , The ΔV equation can be simplified to

$$\Delta V \cong \frac{V}{n} + I R_P$$

At any given current, the I –V curve for the module with one shaded cell drops by ΔV. The huge impact this can have is illustrated in the following figure.

Physics of Shading



Effect of shading one cell in an *n*-cell module. At any given current, module voltage drops from V to $V - \Delta V$.

Example

Impacts of Shading on a PV Module. The 36-cell PV module described in Example 8.4 had a parallel resistance per cell of *RP* = 6.6 . In full sun and at current *I* = 2.14 A the output voltage was found there to be *V* = 19.41 V. If one cell is shaded and this current somehow stays the same, then:

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?

Solution.

a. The drop in module voltage will be

$$\Delta V = \frac{V}{n} + I R_P = \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

Example

The new output voltage will be 19.41 − 14.66 = 4.75 V.
Power delivered by the module with one cell shaded would be
$P_{module} = V\,I$ = 4.75 V × 2.14 A = 10.1 W
For comparison, in full sun the module was producing 41.5 W.

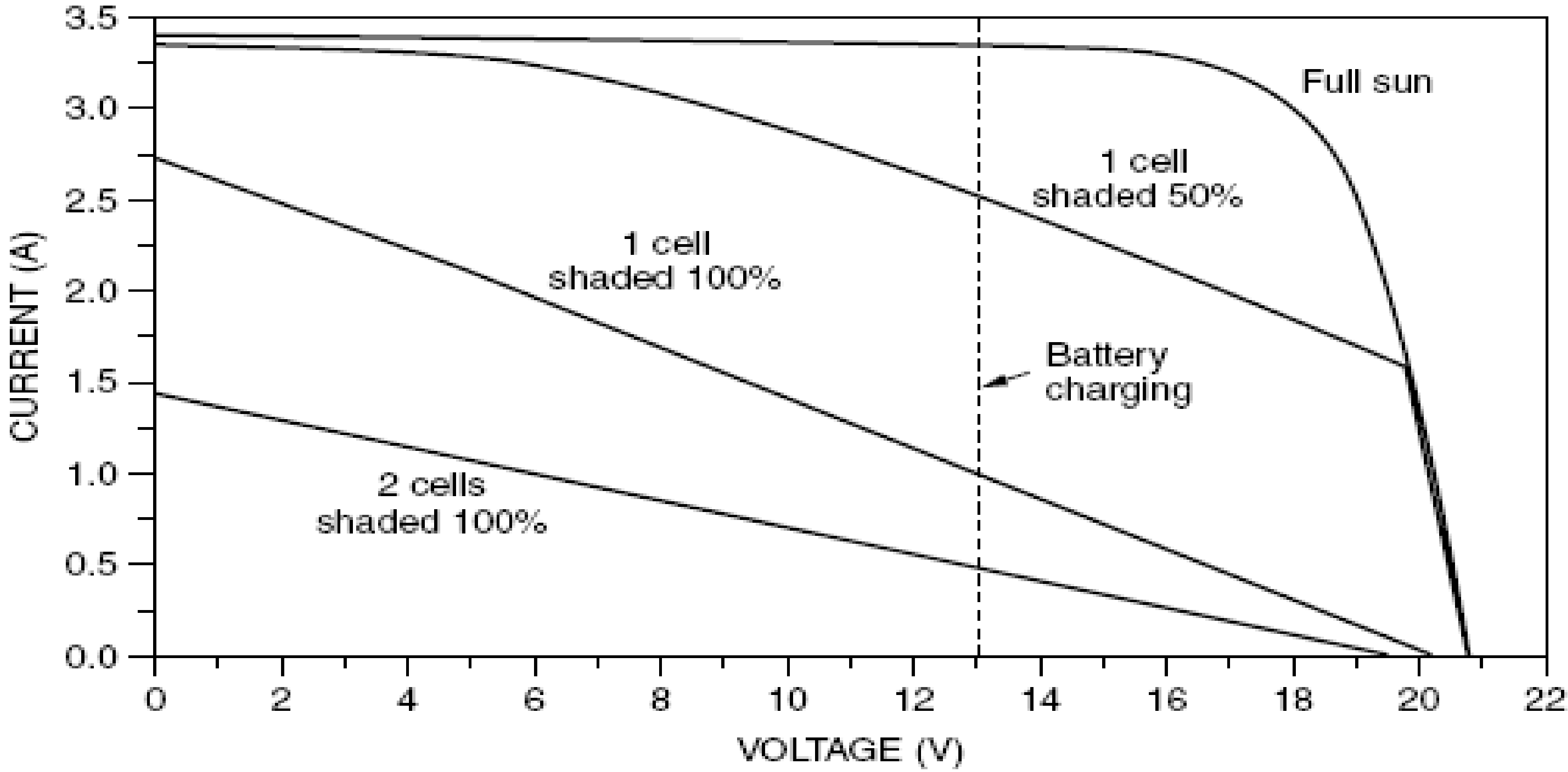
b. All of that 2.14 A of current goes through the parallel plus series resistance (0.005) of the shaded cell, so the drop across the shaded cell will be
$Vc = I\,(RP + RS) = 2.14(6.6 + 0.005) = 14.14\ V$
(normally a cell in the sun will add about 0.5 V to the module; this shaded cell subtracts over 14 V from the module).

c. The power dissipated in the shaded cell is voltage drop times current, which is $P = V_c I$ = 14.14 V × 2.14 A = 30.2 W
All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing the cell.

Example

The following figure shows I – V curves for the example module under full-sun conditions and with one cell 50% shaded, one cell completely shaded, and two cells completely shaded. Also shown on the graph is a dashed vertical line at 13 V, which is a typical operating voltage for a module charging a 12-V battery. The reduction in charging current for even modest amounts of shading is severe. With just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about two-thirds!

Example



Effects of shading on the *I* –*V* curves for a PV module. The dashed line shows a typical voltage that the module would operate at when charging a 12-V battery; the impact on charging current is obviously severe.

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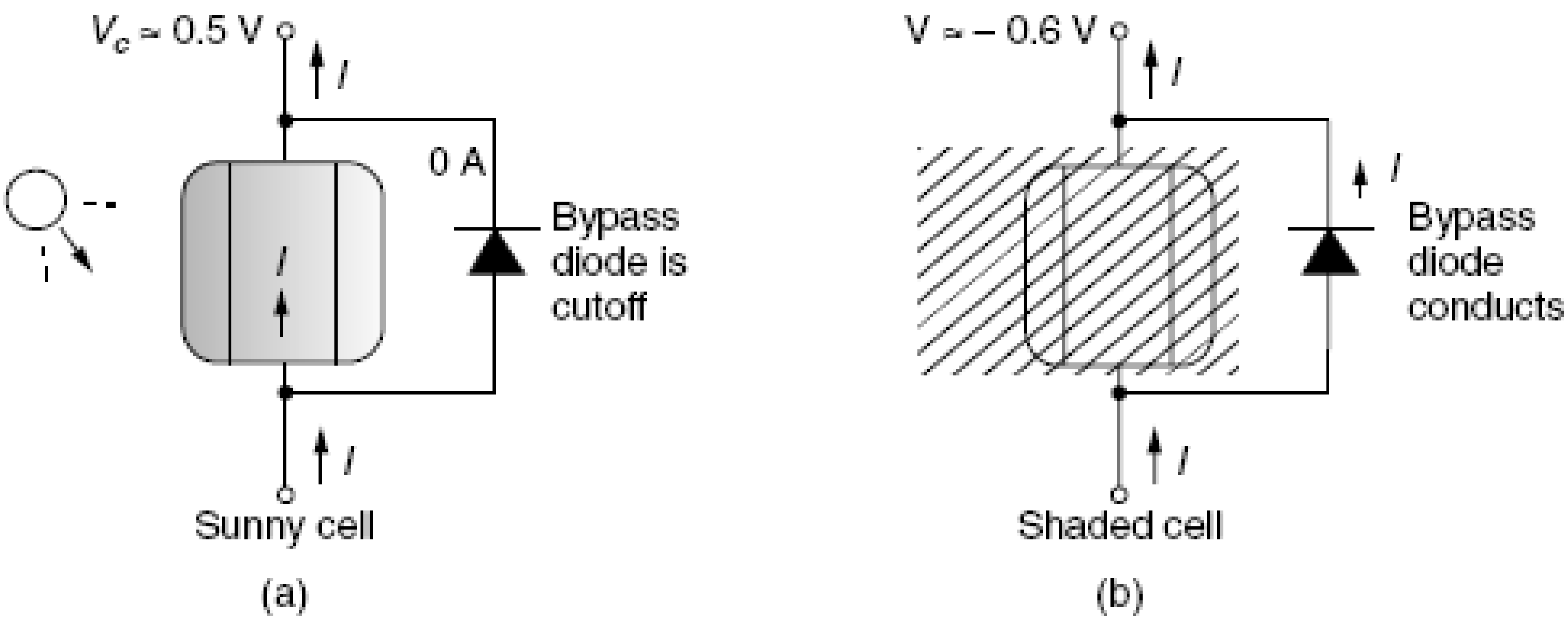
Bypass Diodes for Shade Mitigation



Mitigating the shade problem with a bypass diode. In the sun (a), the bypass diode is cut off and all the normal current goes through the solar cell. In shade (b), the bypass diode conducts current around the shaded cell, allowing just the diode drop of about 0.6 V to occur.

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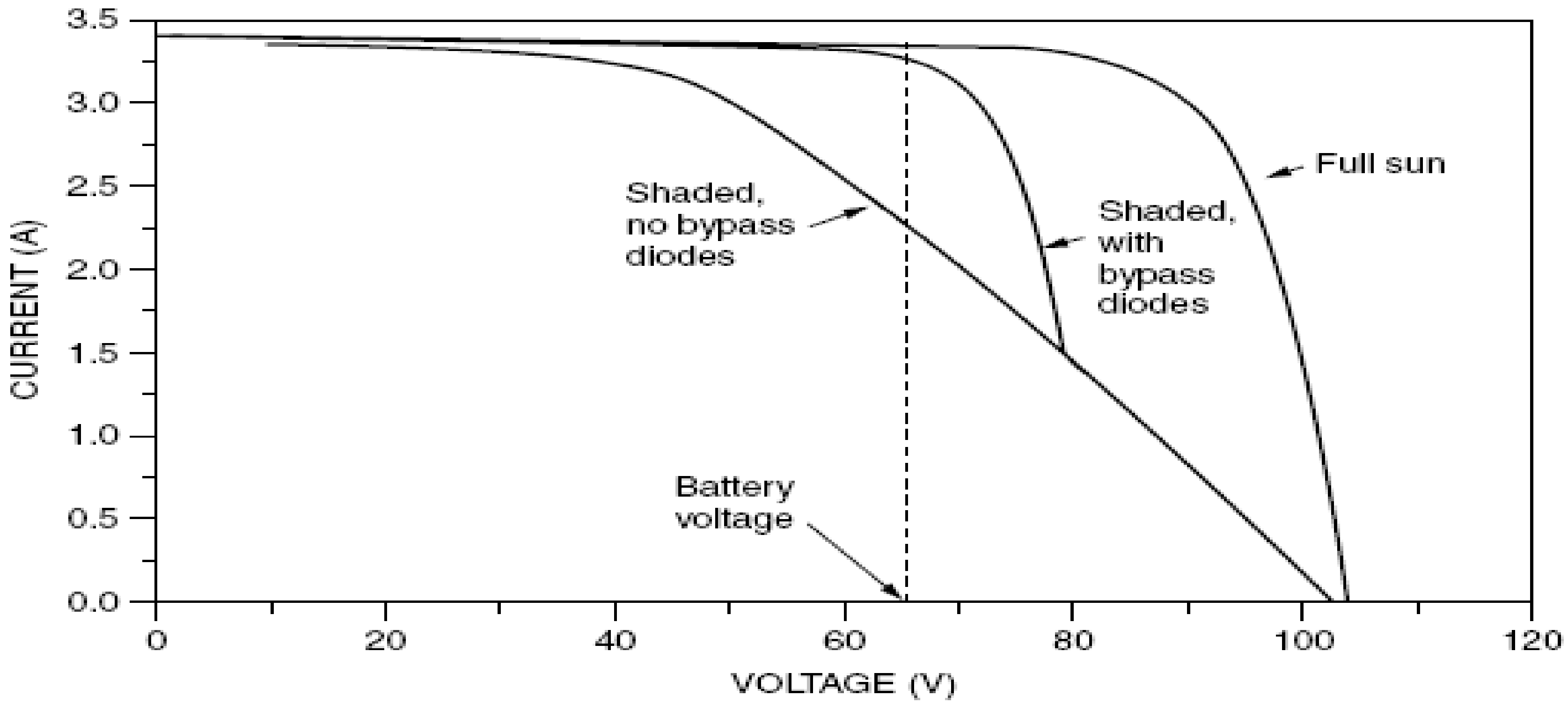
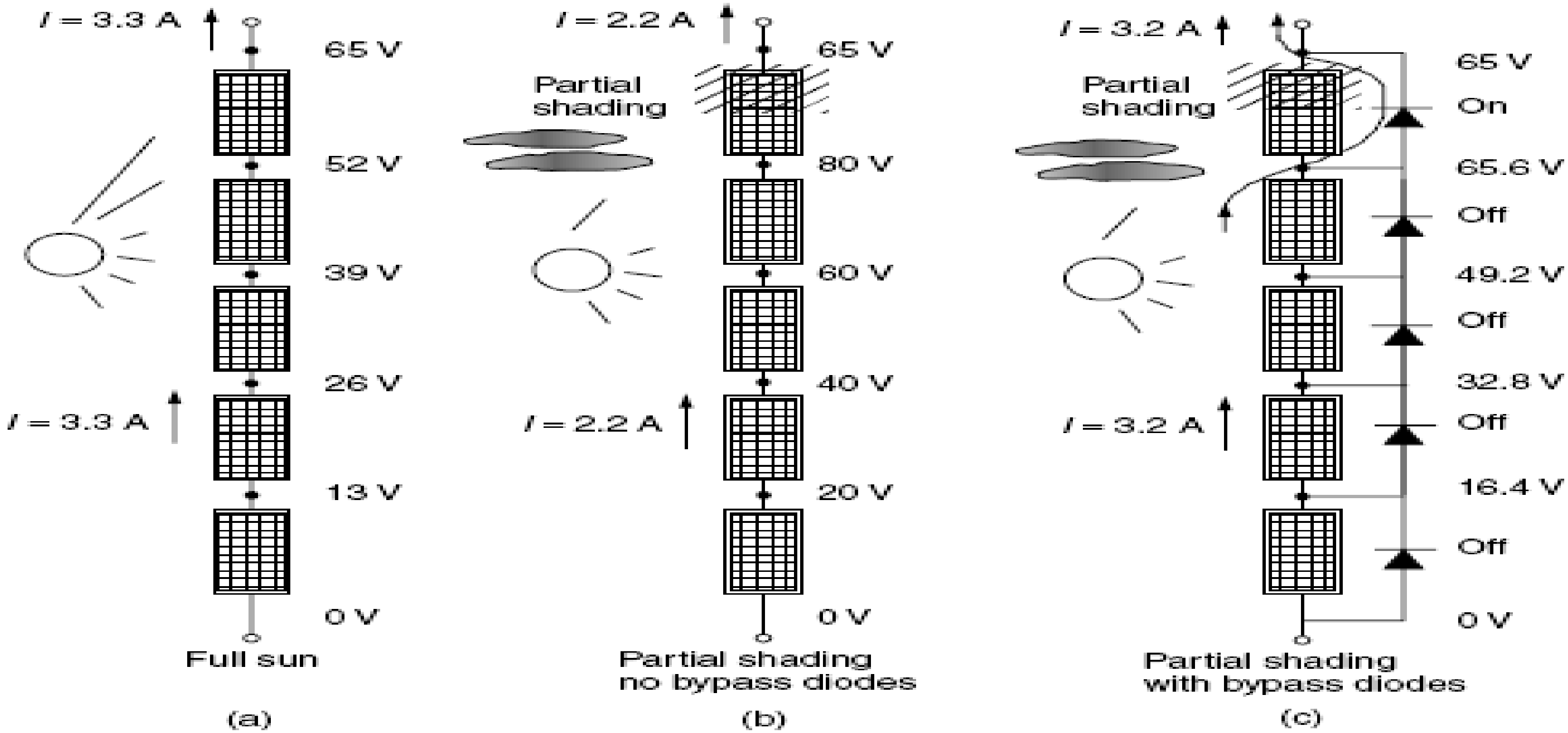
Bypass Diodes for Shade Mitigation



Impact of bypass diodes. Drawn for five modules in series delivering 65 V to a battery bank. With one module having two shaded cells, charging current drops by almost one-third when there are no bypass diodes. With the module bypass diodes there is very little drop.

Bypass Diodes for Shade Mitigation



Showing the ability of bypass diodes to mitigate shading when modules are charging a 65 V battery. Without bypass diodes, a partially shaded module constricts the current delivered to the load (b). With bypass diodes, current is diverted around the shaded module.

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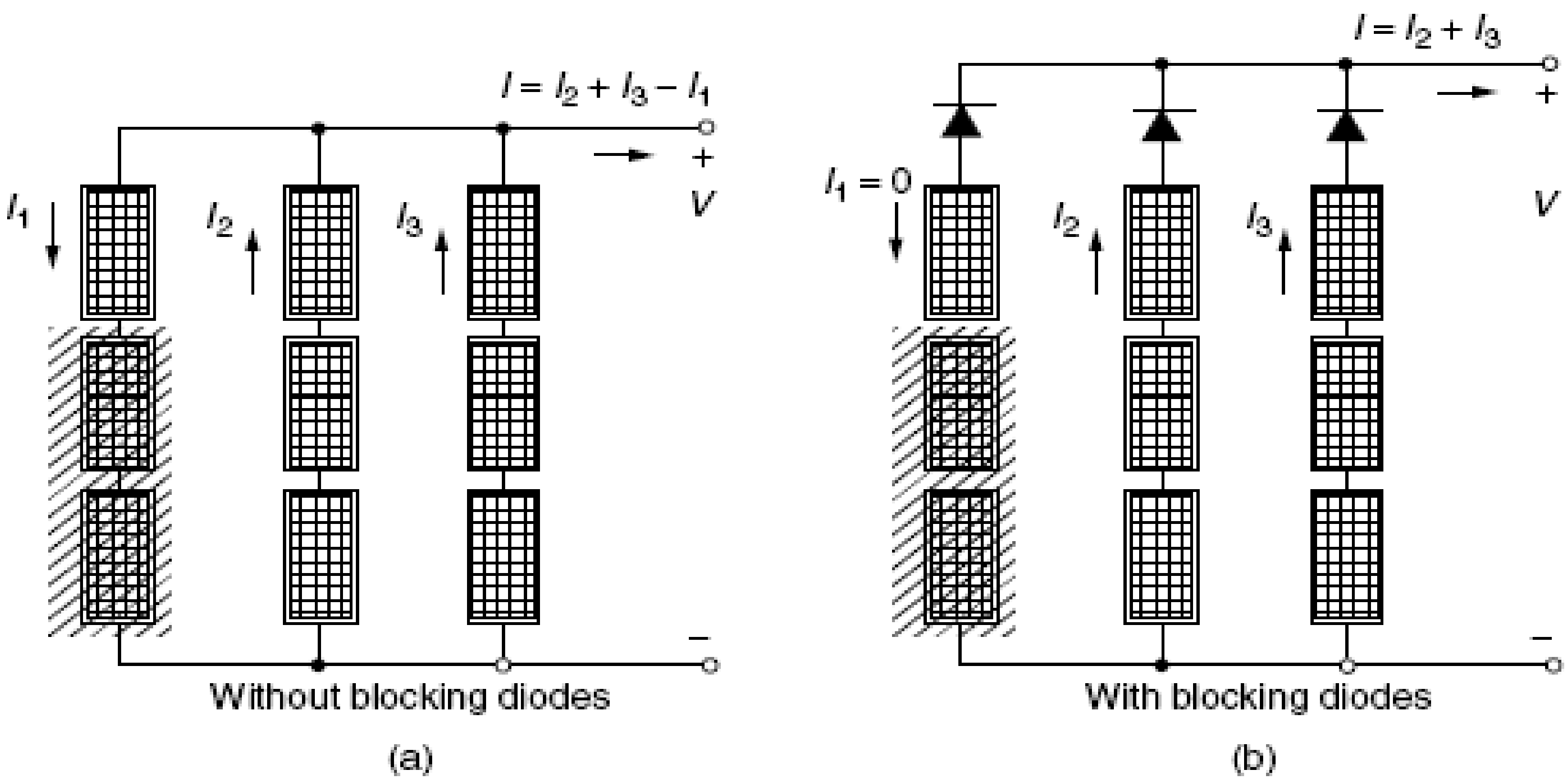
Bypass Diodes for Shade Mitigation



Blocking diodes prevent reverse current from flowing down malfunctioning or shaded strings.

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