The Physics of Solar Cells

Energy Sources and Conversion

Week 12

Supplemental Reading
How do solar cells work?

- Solar cell operation is based on the ability of semiconductors (SC) to convert sunlight directly into electricity via the photovoltaic effect.

- Electrical (metal) contacts are made to the front and the back of the p-n junction. The back side can be completely covered by metal, but the front only has a grid pattern or thin lines of metal so as not to block the sun from the silicon (no sunlight, no output).

- Incident sunlight creates mobile charged particles in the SC which are then separated by the device structure and produce electrical current.

A pure semiconductor (or an intrinsic semiconductor) contains just the right number of electrons to fill the valence band (VB) and the conduction band (CB) is therefore empty. Semiconductors can only conduct electricity if carriers are introduced into the CB or removed from the VB. One way of doing this is doping – introducing atomic impurities.
Doping of Silicon

- Si has 4 valence e⁻ s shared in bonds to neighboring atoms (intrinsic).
- B has 3 valence e⁻ s, which leaves one e⁻ vacancy or (mobile) hole (h⁺) => p-type Si
- P has 5 valence e⁻ s, which leaves one extra (mobile) e⁻ => n-type Si

http://www.see.murdoch.edu.au/resources/info/Tech/pv/
Photovoltaic energy conversion is based on **asymmetry in the electronic structure at the p-n junction** when different, or differently doped, semiconductors are brought together.

The asymmetry is caused by the presence of a strong electric field ($E$) at the p-n interface.
**Semiconductor p-n junction**

What happens when you bring an n-type and p-type semiconductor together?

- An internally generated potential difference, $V_0$, known as the **contact potential**, occurs across the $p-n$ junction. It is NOT an externally imposed potential but rather an internal potential; a property of the junction itself.

- The internal potential $V_0$ is what brings the Fermi energies to the same level: $E_f(n) - E_f(p) = eV_0$, where $E_f(n)$ and $E_f(p)$ are the Fermi energies in the n-type and p-type semiconductors, before the semiconductors are brought into contact.

From Fishbane, Gasiorowicz, Thornton. Physics for Scientists and Engineers; Fig. 44-12, p. 1199.
Semiconductor p-n junction in the dark

What happens when you bring an n-type and p-type semiconductor together?

- p-side, high concentration of holes, very few electrons. n-side, excess mobile electrons very few holes, so the mobile holes will want to diffuse from p-side to n-side and vice versa.

- When a hole leaves, it leaves behind an ionized dopant center (negatively charged)—they walk over to interface because there is an electric field. Eventually these are fixed charges that sit at the interface, negative charge is on the p-side and and they want to attract the holes back that left.

- As more charges go across you have more and more of these dopant centers and they call back the holes. Eventually you reach an equilibrium in which the drift that is associated with the electric field balances the diffusion that is associated with the concentration gradient (~instantaneous).

Fishbane, Gasiorowicz, Thornton. Physics for Scientists and Engineers; pp. 1196-1200; Fig. 44-13 (p. 1198)
Diode behavior of a p-n junction in dark

- The p-n junction behaves as a diode under an external potential $V_{ext}$ => current flows easily from the p-side to the n-side, but not in reverse.

- Reverse bias...asks holes on this side to come over to this side...but there aren’t any holes. Well there are a few, and that’s the first component of $I_0$—the minority carriers. **That’s really why a diode is one way (rectifier).** (Note: $I_0$ does not exist without an applied bias, otherwise you’d violate conservation of energy.)

- However, there is also the part of $I_0$ which most people don’t associate with $I_0$, “generated” or “thermal” current—this is much more current at room temperature—and goes in direction of $I_0$. **This thermally generated current exists at RT without a bias.**
p-n junction diode in the dark

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

Ex. p-n junction diode at 25°C with a reverse saturation current \( I_0 = 10^{-9} \text{ A.} \) **What is the voltage drop across the diode when it is carrying:**

a) **No current.**
   \( I_d = 0 \Rightarrow V_D = 0 \)

b) **\( I_d = 1 \text{ A} \)**
   \[ V_d = \frac{1}{38.9} \ln \left( \frac{I_d}{I_0} + 1 \right) = \frac{1}{38.9} \ln \left( \frac{1}{10^{-9}} + 1 \right) = 0.532 \text{ V} \]

\[ DV = \text{only 0.06 for } 10\text{x’s } I! \]

c) **\( I_d = 10 \text{ A} \)**
   \[ V_d = \frac{1}{38.9} \ln \left( \frac{I_d}{I_0} + 1 \right) = \frac{1}{38.9} \ln \left( \frac{10}{10^{-9}} + 1 \right) = 0.592 \text{ V} \]

\( V_d \) is nominally \( \sim 0.6 \text{ V} \) when conducting.

Note: A more realistic equation includes ideality factor, resistances and shading...
Semiconductor p-n junctions under illumination

Generation of $e^-h^+$ pairs by light.

Separation of charges by built-in $E$-field.

- **Solar cells are current generators under illumination.**
- Photogenerated $e^-h^+$ pairs diffuse to the depletion region, where they are separated and swept to opposite sides of the PV device by the strong $E$-field.
- 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.

Markvart, Fig. 3.8

Modified from Fishbane, Fig. 44-13.

Simplest equivalent circuit for a solar cell

PV cells are current generators under illumination.

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

Net current: \( I = I_{sc} - I_d \)
Solar cell I-V curve under illumination

Dark: \( I = I_D = I_0(e^{qV_d/kT} - 1) \) (diode equation)

Light: \( I = (I_L - I_D) = I_{sc} - I_0(e^{qV_d/kT} - 1) \)

Standard test conditions (STC): AM 1.5, 25\(^\circ\) C, 100 W/m\(^2\)
PV equivalent circuit and I-V curve under illumination

Load connected

Short circuit ($I_{sc}$)

Open circuit ($V_{oc}$)

Dark

Light
Equivalent circuit & I-V curve for PV cell under sunlight

Short circuit current \( (I_{sc}) \) \(<- P=0 ->\)  Open circuit voltage \( (V_{oc}) \)

\[
V = 0 \quad \Rightarrow \quad I = I_{sc} = I_L
\]

\[
I = I_{sc} - I_0 \left( e^{\frac{qV}{kT}} - 1 \right)
\]

At \( V_{oc} \), \( I=0 \)

\[
V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{I_0} + 1 \right)
\]

At 25°C (STC) : \( (q/kT) = 38.9 \text{ V}^1 \); \( (kT/q) = 0.0257 \text{ J/C (=V)} \)
PV cell under illumination

The I-V curve is just the diode curve upside down.
The light curve is the dark curve plus $I_L (I_{sc})$.
Since the cell is generating power the convention is to invert the current axis.
PV I-V curve and device performance

\[ P = IV = I_{MP}V_{MP} = FF \times I_{SC}V_{OC} \]

\[ \eta = \frac{P_{\text{max}}}{P_{\text{in}}} \]

\[ FF = \frac{I_{MP}V_{MP}}{I_{SC}V_{OC}} \]

70-75% for Si<sub>c</sub>,
50-60% for a-Si(-H)
Temperature and irradiance dependence of the I-V curve of a solar cell

Voltage is dependent on cell temperature.

Current is proportional to irradiance.

\[ \frac{dV_{oc}}{dT} = -2.3 \text{ (mV/°C)} \text{ per cell} \]

Figures from Markvart (2000), Fig. 3.21 (left) and Fig. 3.22 (right)
At the 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.
Connecting PV cells in series

- Individual cells will not provide sufficient voltage/power to drive circuits – connect cells in series into modules for relevant amounts of voltage output.
- Modules can be connected in series/parallel to get desired values
- Common module arrangements
  - 36 cells in series (~18V output)
  - 72 cells in series (~36V output)
- These values are implemented due to their ability to charge batteries.
Relationship between $I_0$, $V_{oc}$, $E_g$ and power

Both $I_L$ and $I_0$ depend on the device structure. However, it is $I_0$ (which can vary by orders of magnitude depending on the material) that determines $V_{oc}$ in practical devices.

$I_0$ has a complex quantum physical origin based on carrier densities ($n_i^2$) but for practical purposes can be estimated from the band gap (e.g. see table: $E_g$ at 25ºC and corresponding $I_0$).

### Table: $E_g$ and $I_0$

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (eV)</th>
<th>$I_0$ (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>$2.5 \times 10^{-14}$</td>
</tr>
<tr>
<td>a-Si(-H)</td>
<td>1.75</td>
<td>$3.1 \times 10^{-25}$</td>
</tr>
<tr>
<td>CuInSe₂</td>
<td>1.05</td>
<td>$2.3 \times 10^{-13}$</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.45</td>
<td>$3.8 \times 10^{-20}$</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.4</td>
<td>$2.7 \times 10^{-19}$</td>
</tr>
</tbody>
</table>

$V_{oc} = \frac{kT}{q} \ln \left( \frac{I_L}{I_0} + 1 \right)$

$I_0 = A \left( \frac{qD_n n_i^2}{L_e N_A} + \frac{qD_h n_i^2}{L_h N_D} \right)$

$I_0 = 1.5 \times 10^5 (e^{-E_g/kT})$ (A/cm²)
Band Gap and Absorption of Solar Spectrum

Generation of $e^-\text{h}^+$ pairs by light.

Markvart, Fig. 3.8

Photon flux utilized by a silicon solar cell.

Markvart, Fig. 3.9

$$V_{\text{max}} = \frac{E_g}{q} \Rightarrow \text{higher } E_g \Rightarrow \text{higher } V. \quad \text{Small } E_g \Rightarrow \text{higher } I.$$  

Since $P = VI$, this means there is an optimal $E_g$ (1.4 eV, GaAs).
PV conversion of solar energy to electricity

Solar spectrum and utilization by a Si<sub>c</sub> solar cell.

E<sub>ph</sub> = hc/λ

Masters (p.454), Fig. 8.10
Maximum PV efficiency as a function of band gap 
(from Hersel and Zweibel (1982))
Utilization of solar energy by Si solar cells

- $E_{ph} < E_g$: Photons with wavelengths (l) longer than 1.11 mm don’t have enough energy to excite electrons (20.2% of incoming solar energy for Si).
- $E_{ph} > E_g$: generate current but $E_{ph} \gg E_g$ wasted (30.2% for Si).
Power losses in Si solar cell

The figures are per cm² for production cells and in () for laboratory cells

Voltage available 1.1 V
Recombination
Open-circuit voltage 0.6 V (0.7 V)

Current available 44 mA
Collection efficiency:
- Incomplete absorption
- Top-surface reflection
- Top contact shading

Short-circuit current 28 mA (41 mA)

Series resistance losses
Fill factor 0.75 (0.8)

Cell output 14 mW (23 mW)

From Markvart, “Solar Cells”, p. 43, Fig. 3.20
# Power losses in solar cells

<table>
<thead>
<tr>
<th>Loss Phenomena</th>
<th>Fix / workaround</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fundamental Losses</strong></td>
<td></td>
</tr>
<tr>
<td>• Dissipation of generated carriers into heat</td>
<td>Tandem Cells</td>
</tr>
<tr>
<td>• $h v &lt; E_g$ not utilized ($\sim 20%$ of solar spectrum for $Si_c$)</td>
<td>• Stack of several cells with increasing $E_g$ (high to low)</td>
</tr>
<tr>
<td>• $h v \gg E_g$ wasted ($30.2%$ for $Si_c$)</td>
<td>• $h \sim 48%$ (2013)</td>
</tr>
<tr>
<td><strong>Recombination (defects, impurities at contacts)</strong></td>
<td></td>
</tr>
<tr>
<td>• Reduces both $V$, $I$ output from cell</td>
<td>Materials development</td>
</tr>
<tr>
<td>• $V$ losses reduce max. value ($=E_g/q$) to $V_{oc}$, which is restricted</td>
<td>• Low-$l_0$ $p-n$ junctions.</td>
</tr>
<tr>
<td>primarily by $l_0$.</td>
<td></td>
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<tr>
<td><strong>Current losses</strong></td>
<td></td>
</tr>
<tr>
<td>• Collection efficiency ($#$ carriers generated/$#$ collected)</td>
<td>Materials development</td>
</tr>
<tr>
<td></td>
<td>• Improve charge transport and collection efficiency.</td>
</tr>
<tr>
<td><strong>Light reflection from top surface</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• ARC, light trapping ($Si$)</td>
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<tr>
<td><strong>Shading</strong></td>
<td></td>
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<td></td>
<td>Bypass and blocking diodes</td>
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<tr>
<td><strong>Parasitic resistance</strong></td>
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<td></td>
<td>Bypass and blocking diodes</td>
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</table>
PV Equivalent Circuits including Parasitic Resistance

- In real cells, power is dissipated through the resistance of the contacts and through leakage current around the sides of the device.

- These effects are equivalent electrically to two parasitic resistances in series ($R_s$) and in parallel ($R_p$ or $R_{SH}$ (shunt)) with the cell.

\[ I = \text{current} = I_{sc} - I_L \]
\[ V_d = \text{diode voltage} \]
\[ R_s = \text{series resistance} \]
\[ R_p = \text{parallel resistance} \]
\[ I_{sc} = \text{ideal current source} \]
\[ I_d = \text{diode current} \]
Series Resistance in a Solar Cell

- The transmission of current produced by the solar cell involves ohmic losses, which can be grouped together and included as a resistance in the equivalent circuit.

- Some of this might be contact resistance associated with the bond between the cell and the wire leads, and some might be due to the resistance of the semiconductor itself.

- Series resistance, $R_s$, arises from the resistance of the cell material to current flow, particularly through the front surface to the contacts, and from resistive contacts.

- $R_s$ is a particular problem at high current densities, for instance under concentrated light.
A more realistic PV equivalent circuit: series resistance

Include some series resistance $R_s$ to original circuit (e.g. contact resistance, resistance of the semiconductor itself).

![Circuit Diagram]

$I_d = \text{diode current}$  
$V_d = \text{diode voltage}$  
$V = \text{external bias}$  
$I_{sc} = \text{short circuit current}$  
$I = \text{current} = I_{sc} - I_L$  
$R_s = \text{series resistance}$

To analyze the equivalent circuit, begin with the simple equivalent circuit:

$$I = I_{sc} - I_0 \left( e^{qV/kT} - 1 \right)$$

and then add the impact of $R_s$:

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

to give:

$$I = I_{sc} - I_0 \left\{ \exp \left[ \frac{q(V + I \cdot R_s)}{kT} \right] - 1 \right\}$$

*This is the original PV I-V curve with the voltage at any given positive current to shift to the left by $DV = IR_s$. Masters, p. 466-467*
A more realistic PV equivalent circuit: series resistance

This is the original PV I-V curve with the voltage at any given positive current to shift to the left by $DV = I R_s$.

Masters (p. 466)
Fig. 8.25

\[ I = I_{SC} - I_0 \left\{ \exp \left[ \frac{q(V + I \cdot R_s)}{kT} \right] - 1 \right\} \]

For a cell to have less than 1% losses, due series resistance, $R_s$ should be less than $\sim R_s < \frac{0.01 V_{oc}}{I_{SC}}$.

which, for a large cell with $I_{SC} = 7 \text{ A}$ and $V_{oc} = 0.6 \text{ V}$, is less than $0.0009 \text{ W}$.

The main impact of series resistance is to reduce the fill factor (FF), although excessively high values may also reduce the short circuit current. DFF is linearly proportional to DP.
Parallel (Shunt) Resistance

Now, include some parallel resistance, $R_p$, to the original circuit. $R_p$ arises from leaking of current through the cell, around edges of the device and between contacts of different polarity.

In this case, the ideal current source $I_{SC}$ delivers current to the diode, the parallel resistance, $R_p$, and the load:

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

- The higher the shunt resistance, the better the diode performance (higher resistance against reverse current), since $I$ is inversely proportional to $R_p$.
- Low $R_p$ results in poorly rectifying devices.
- Thus, to improve cell performance, you want high $R_p$ and low $R_s$. 

Note: $R_p \gg R_s$

Masters (p. 464), Fig. 8.22.
Parallel (Shunt) Resistance

- Parallel resistance ($R_P$), also known as shunt resistance ($R_{SH}$) causes the current at any given voltage to drop by an amount:
  \[ DI = \frac{V}{R_P} \]  
  (see I-V curve)

- For a cell to have losses of less than 1% due to its parallel resistance, $R_P$ should be greater than about: \( R_P > \frac{100V_{OC}}{I_{SC}} \approx 9 \, \text{W} \) (based on a large cell with $I_{SC} \approx 7 \, \text{A}, \, V_{OC} \approx 0.6 \, \text{V}$).
  \[ \frac{V}{I_{SC}} \]

- For same cell, to have < 1% losses due to series resistance, $R_S \approx 0.0009 \, \text{W}$!
Effect of $R_S$ and $R_P$ on PV performance

Nelson (p. 14) Fig. 1.11.

- Effect of (a) increasing $R_S$ and (b) decreasing $R_P$. In each case the effect of the resistances is to reduce the area of the maximum power rectangle compared to $J_{SC} \times V_{oc}$.

- Series and parallel resistances in the PV equivalent circuit decrease both the voltage and current delivered. To improve cell performance, **high $R_P$** and **low $R_S$** are needed.
Every solar cell has losses due to both $R_s$ and $R_{sh} (R_p)$

$$I = I_{SC} - I_0 \left\{ \exp \left[ \frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left( \frac{V + I \cdot R_S}{R_P} \right)$$

$$I = I_{SC} - I_0 \left[ e^{38.9(V + I R_S)} - 1 \right] - \frac{1}{R_P} (V + IR_s) \quad \text{at 25°C}$$

- $V_d = \text{diode bias}$
- $I_d = \text{diode current}$
- $I_{SC} = \text{ideal current source}$
- $V = \text{applied bias}$
- $R_s = \text{series resistance}$
- $R_p = \text{parallel resistance}$
Effect of $R_s$ and $R_p$ on PV performance

Series and parallel resistances in the PV equivalent circuit decrease both the voltage and current delivered. To improve cell performance, high $R_p$ and low $R_s$ are needed.

$$V_d = \text{diode bias}$$
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$$R_p = \text{parallel resistance}$$

$$I = I_{SC} - I_0 \left\{ \exp \left[ \frac{q(V + I \cdot R_s)}{kT} \right] - 1 \right\} - \left( \frac{V + I \cdot R_s}{R_p} \right)$$

$$I = I_{SC} - I_0 \left[ e^{38.9(V + IR_s)} - 1 \right] \frac{1}{R_p} (V + IR_s) \quad \text{at } 25^\circ C$$

Masters (p. 468) Fig. 8.27
The output of a PV module can be reduced dramatically when even when a small portion of it is shaded.

- For example, when one solar cell is shaded while the remainder in the module are not, some of the power being generated by the “sunny” solar cells can be dissipated by the “shaded” cell rather than powering the load.

- This in turn can lead to highly localized power dissipation and the resultant local heat may cause irreversible damage to the module.
The effect of shading

- The same current flows through cells connected in series.
- If any cell in a string is in the dark (shaded) it produces no current.

- Since $I = I_{SC} - I_D$, the shading of one cell ($I_{SC} = 0$) converts it into a diode under reverse bias so the diode current is also (essentially zero).
- The entire module current must travel through both $R_p$ and $R_s$ in the shaded cell on its way to the load.
- **Instead of contributing to the output voltage, the top shaded cell actually reduces it!**
The effect of shading

Consider the case when the bottom n-1 cells still have full sun and still somehow carry their original current I so they will still produce their original voltage $V_{n-1}$.

Output voltage of entire module $V_{SH}$ with 1 cell shaded will drop to:

$$V_{SH} = V_{n-1} - I(R_p + R_s)$$

Original output voltage (with all n cells in the sun and carrying I) was $V$, so the voltage of the bottom (n-1) cells will be:

$$V_{n-1} = ((n-1)/n)V$$

$$\Rightarrow V_{SH} = ((n-1)/n)V - I(R_p + R_s).$$

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

$$DV = V - V_{SH} = V - (1 - 1/n)V + I(R_p + R_s)$$

$$DV = V/n + I(R_p + R_s)$$

Since $R_p \gg R_s$, this simplifies to:

$$DV \equiv V/n + IR_p$$

Masters (p.478), Fig. 8.37
The effect of shading in an n-cell module

Masters (p.479), Fig. 8.38

- At any given current, with one cell shaded, module voltage drops from V to (V – DV) where 
  \[ DV = \frac{V}{n} + IR_p \]
- This has a huge impact on the I-V characteristics (performance) of a PV system.
Impact of shading on a PV module

Ex. 36 cell PV module with \( R_p = 6.6 \, \text{W} \), full sun, \( I = 2.14 \, \text{A} \), \( V = 19.41 \, \text{V} \).
If 1 cell is shaded and the current \( (I) \) somehow stays the same:

a) What is the new module output voltage and power?

\[
DV = V/n + IR_p = 19.41/36 + 2.14(6.6) = 14.66 \, \text{V}
\]
\[
V_{SH} = V - DV = 19.41 - 14.66 \, \text{V} = 4.75 \, \text{V}
\]
\[
P_{SH} = VI = (4.75 \, \text{V})(2.14 \, \text{A}) = 10.1 \, \text{W}, \text{ compare with} \ 41.5 \, \text{W in full sun!}
\]

b) What is the voltage drop across the shaded cell?

All of that 2.14 A of current goes through the parallel and series resistance (0.005 W) so the voltage drop across the shaded cell is:

\[
V_c = I(R_p + R_s) = 2.14 \, \text{A}(6.6 \, \text{W} + 0.005 \, \text{W}) = 14.14 \, \text{V},
\]

compare with adding 0.5 V to the module under full sun.

c) What is the power dissipated in the cell?

\[
P = V_cI = (14.14 \, \text{V})(2.14 \, \text{A}) = 30.2 \, \text{W}.
\]

All this power is converted to heat, which can cause a local hot spot that may permanently damage the cell (plastic laminate enclosure).

Masters, Example 8.6, p. 480
A solar cell in full sun normally contributes about 0.5 V to the voltage output of the module, but a shaded cell experiences a drop in voltage as current is diverted through the parallel and series resistances.

The shaded cell will dissipate all the power produced by the illuminated cells into heat and may cause a hot spot which damages the module.

Therefore, the shaded cell, instead of adding to the voltage, actually reduces the voltage.
The effect of shading on PV module I-V curves

Masters (p.481), Fig. 8.39

- The dashed line shows a typical voltage that the module would operate at when charging a 12 V battery (typical operating voltage is 13 V).

- The impact of shading on charging current is obviously severe: with just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about 2/3's!
The shade problem can be mitigated 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 \( \approx 0.6 \) V to occur. So the bypass diode controls the voltage drop across the shaded cell, limiting it to a rather small value.
Impact of Bypass Diodes

Masters (p. 482), Fig. 8.42

- 5 modules in series deliver 65 V to a battery bank.
- With 1 module having 2 shaded cells, **charging current drops by almost 1/3** (from 3.3 A to 2.2 A) **when there are no bypass diodes**.
- With the module bypass diodes there is little drop.
Impact of Bypass Diodes

- Bypass diodes 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 (c).
Bypass diodes help current go around a shaded or malfunctioning module within a string. This improves string performance and also prevents hot spots from developing.

When strings of modules are wired in parallel, a similar problem may arise when one of the strings is not performing well. Instead of supplying current to the array, a malfunctioning or shaded string can withdraw current from the rest of the array.

By placing blocking diodes (isolation diodes) at the top of each string, the reverse current is prevented from flowing down malfunctioning or shaded strings.
• Therefore, in addition to PV modules, the photovoltaic generator contains bypass and blocking diodes.

• These diodes protect the modules and prevent the generator acting as a load in the dark.
Power losses in Si solar cell

The figures are per cm² for production cells and in ( ) for laboratory cells

From Markvart, p. 43, Fig. 3.20

100 mW

- 21 mW: No below-bandgap absorption
- 31 mW: Excess photon energy lost as heat

Voltage available 1.1 V
- Recombination
  - Open-circuit voltage 0.8 V (0.7 V)

Current available 44 mA
- Collection efficiency
- Incomplete absorption
- Top-surface reflection
- Top-contact shading
  - Short-circuit current 26 mA (41 mA)

Series resistance losses
- Fill factor 0.75 (0.8)

Cell output 14 mW (23 mW)
The structure and spectral contributions of the tandem cell

Ref: Markvart, “Solar Cells”, p. 40, Fig. 3.17
Tandem Cells

**Multi-junction Cells**

Highly Efficient: ~40% in production; ~42+% in lab

- Three (today) coupled cells, each tuned to a different part of the solar spectrum
- Theoretical max efficiencies in low 70%

![Graph showing quantum efficiency vs wavelength for GaInP₂, GaAs, and Ge]

- GaInP₂
- GaAs
- Ge

Theoretical max efficiencies in low 70%