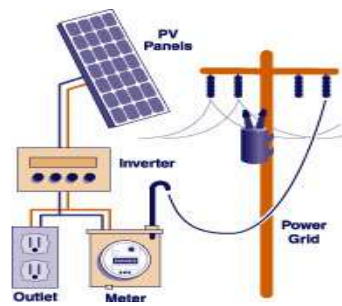
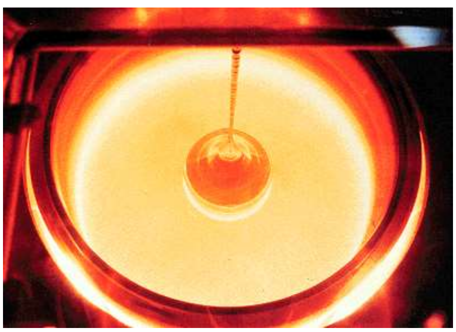
ECE Department
Birzeit University

Photovoltaic Materials and characteristics





ENEE5307 Renewable Energy & PV Energy Systems

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BZU-2017

Introduction

- A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be ***photovoltaic***.
- A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it.
- If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current.
- **The driving force to power photovoltaics comes from the sun, and it is interesting to note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.**

History

- **The history of photovoltaics (PVs) began in 1839 when a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode in a weak electrolyte solution (Becquerel, 1839).**
- Almost 40 years later, ***Adams*** and ***Day*** were the first to study the photovoltaic effect in solids (Adams and Day, 1876).
- They were able to build cells made of selenium that were 1% to 2% efficient.

اعتمدت   تكنولوجيا ناشئة / مستجدة

- **Selenium cells were quickly adopted by the emerging photography industry for photometric light meters; in fact, they are still used for that purpose today.**

History

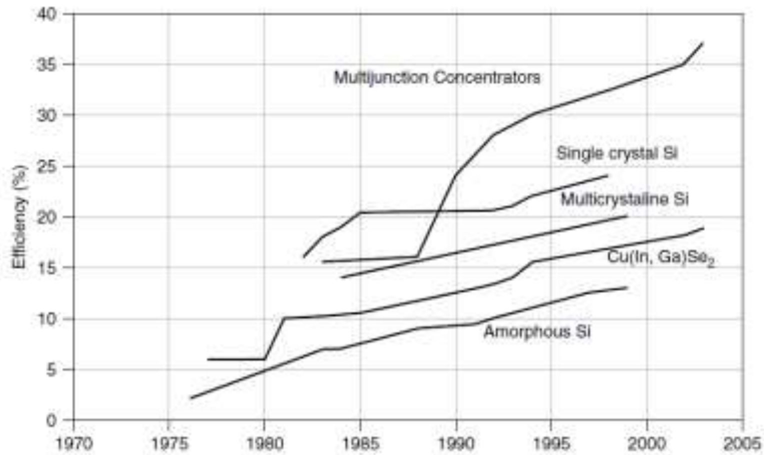
- **As part of his development of quantum theory, Albert Einstein published a theoretical explanation of the photovoltaic effect in 1904, which led to a Nobel Prize in 1923.**
- About the same time, in what would turn out to be a cornerstone of modern electronics in general, and photovoltaics in particular, a Polish scientist by the name of Czochralski began to develop a method to grow perfect crystals of silicon.
- By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single-crystal silicon photovoltaics, and that technique continues to dominate the photovoltaic (PV) industry today.

History

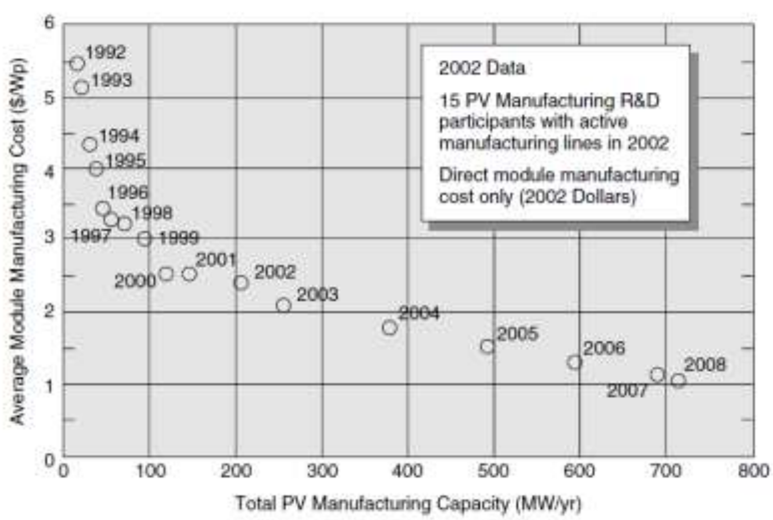
- In the 1950s there were several attempts to commercialize PVs, but their cost was prohibitive.
- The real emergence of PVs as a practical energy source came in 1958 when they were first used in space for the Vanguard I satellite.
- For space vehicles, cost is much less important than weight and reliability, and solar cells have ever since played an important role in providing onboard power for satellites and other space craft.
- Spurred on by the emerging energy crises of the 1970s, the development work supported by the space program began to pay off back on the ground

History

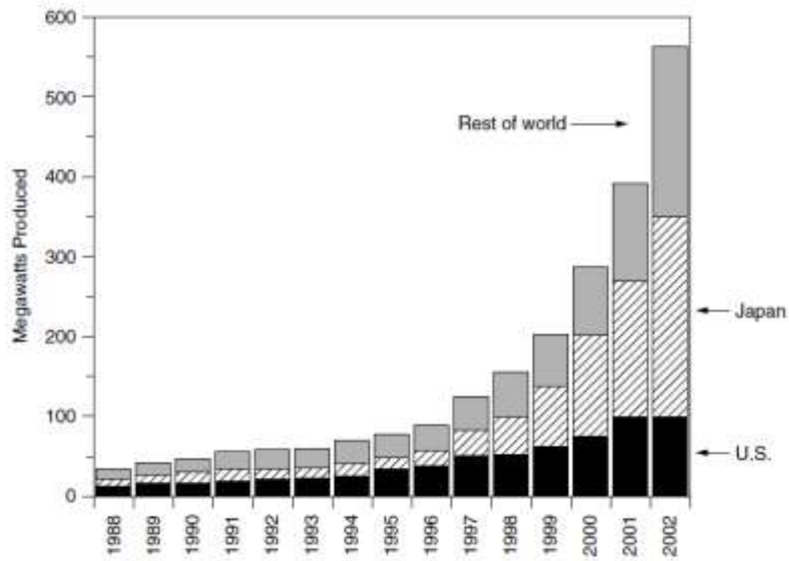
- By the late 1980s, higher efficiencies and lower costs brought PVs closer to reality, and they began to find application in many off-grid terrestrial applications such as pocket calculators, highway lights, signs and emergency call boxes, rural water pumping, and small home systems. ريف
- While the amortized cost of photovoltaic power did drop dramatically in the 1990s, a decade later it is still about double what it needs to be to compete without subsidies in more general situations.



Best laboratory PV cell efficiencies for various technologies. (From National Center for Photovoltaics, www.nrel.gov/ncpv 2003).



PV module manufacturing costs for DOE/US Industry Partners. Historical data through 2002, projections thereafter (www.nrel.gov/pvmat).



World production of photovoltaics is growing rapidly,
Based on data from Maycock (2004).

BASIC SEMICONDUCTOR PHYSICS

ال 4 صفحات التالية للمراجعة

Review

- Photovoltaics use semiconductor materials to convert sunlight into electricity.
- The technology for doing **so is very closely related** to the solid-state technologies used to make transistors, diodes, and all of the other semiconductor devices that we use so many of these days.
- The starting point for most of the world's current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon.

BASIC SEMICONDUCTOR PHYSICS

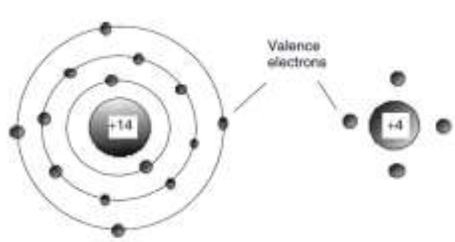
- It is in the fourth column of the periodic table, which is referred to as Group IV (Table 8.1). Germanium is another Group IV element, and it too is used as a semiconductor in some electronics.
- Other elements that play important roles in photovoltaics are boldfaced. As we will see, boron and phosphorus, from Groups III and V, are added to silicon to make most PVs.
- Gallium and arsenic are used in GaAs solar cells, while cadmium and tellurium are used in CdTe cells.

TABLE 8.1 The Portion of the Periodic Table of Greatest Importance for Photovoltaics Includes the Elements Silicon, Boron, Phosphorus, Gallium, Arsenic, Cadmium, and Tellurium

I	II	III	IV	V	VI
		5 B	6 C	7 N	8 O
		13 Al	**14 Si**	**15 P**	16 S
29 Cu	30 Zn	**31 Ga**	32 Ge	**33 As**	34 Se
47 Ag	**48 Cd**	49 In	50 Sn	51 Sb	**52 Te**

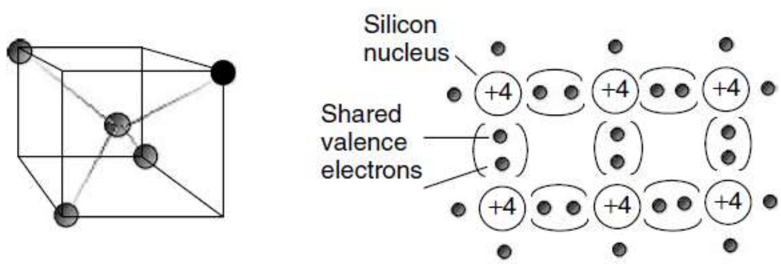
- Silicon Atom is shown

4 valence electrons



(a) Actual (b) Simplified

- In pure crystalline silicon, each atom forms covalent bonds with four adjacent atoms in the three-dimensional tetrahedral pattern shown in Fig. a.
- For convenience, that pattern is drawn as if it were all in a plane, as in Fig. b.



(a) Tetrahedral
رباعي السطوح

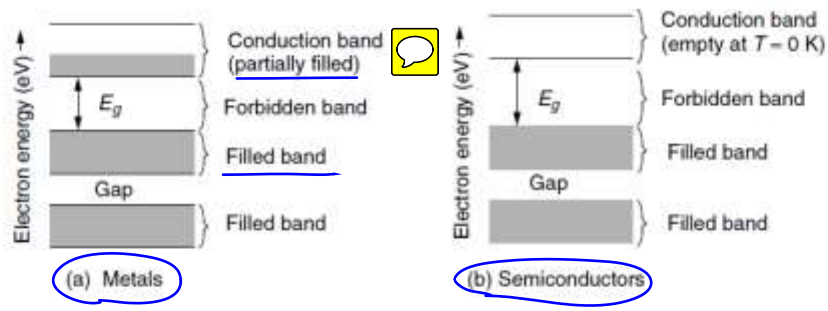
(b) Two-dimensional version

- The gaps between allowable energy bands are called forbidden bands, the most important of which is the gap separating the conduction band from the highest filled band below it.
- The energy that an electron must acquire (يكتسب) to jump across the forbidden band to the conduction band is called the band-gap energy, designated *Eg*.
- The units for band-gap energy are usually electron-volts (eV), where one electron-volt is the energy that an electron acquires when its voltage is increased by 1 V (1 eV = 1.6 × 10^−19 J).

الكترونات المدار الاخير بدها طاقة حتى تروح لل conduction band هذه الطاقة هي ال electron volt

هنا بدنا نعمل مقارنة بين ال semiconductor وال metals

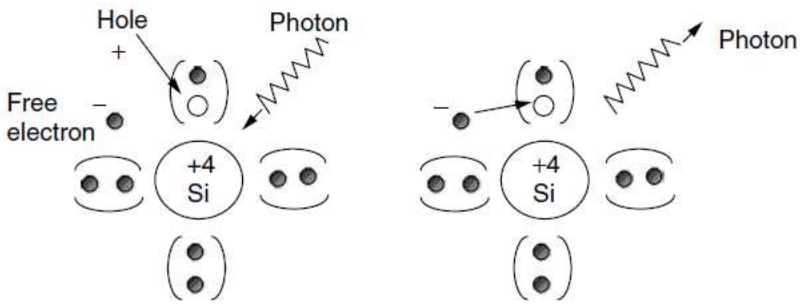
Energy Bands



- Energy bands for (a) metals and (b) semiconductors.
- Metals have partially filled conduction bands, which allows them to carry electric current easily.
- Semiconductors at absolute zero temperature have no electrons in the conduction band, which makes them insulators.

- The band-gap ***Eg* for silicon is 1.12 eV**, which means an electron needs to acquire that much energy to free itself from the electrostatic force that ties it to its own nucleus—that is, to jump into the conduction band.
- Where might that energy come from?
- We already know that a small number of electrons get that energy thermally.
- **For photovoltaics, the energy source is photons of electromagnetic energy from the sun.**
- When a photon with more than 1.12 eV of energy is absorbed by a solar cell, a single electron may jump to the conduction band.
- When it does so, it leaves behind a nucleus with a +4 charge that now has only three electrons attached to it.
- That is, there is a net positive charge, called a *hole*, associated with that nucleus as shown in Fig. 8.7a.

لازم نعرف كم عدد الفوتونات الي بتعطي 1.12 الكترون فولت تقريبا بحالة السيليكون ، الزيادة في عدد الفوتونات رح يعمل losses تتحول ل heat ويسخن السيليكون

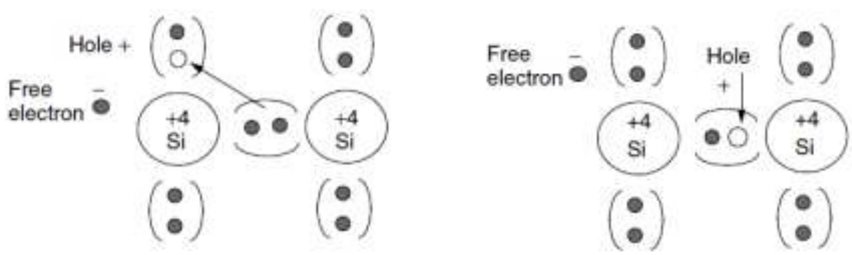


(a) Formation — energy اخذ

(b) Recombination عملية عكسية — energy اعطى

A photon with sufficient energy can create a hole–electron pair as in (a).
The electron can recombine with the hole, releasing a photon of energy (b).

ال hole electron pair هي سبب مرور التيار



(a) An electron moves to fill the hole

(b) The hole has moved

When a hole is filled by a nearby valence electron, the hole appears to move.

كل فوتون له wave length & frequency & energy

Photon Energy

- Thus, 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
- $E = hv = hc/\lambda$ — العلاقة بين ال wave length& energy عكسية
- Where E is the energy of a photon (J) and h is Planck's constant (6.626 × 10^−34 J-s).

بدنا نشوف نسبة الالكترونات التي عندها 1.12 الكترون فولت واكثر ، شو هو ال wavelength تاعهم ؟؟

- Example: photon to create hole –electron pair in Silicon

What is the maximum wavelength can a photon have to create hole-electron pairs in Silicon?

What minimum frequency is that?

Si has a band-gap of 1.12 eV (1 eV=1.6x10^-19 J)

شو قيمة lamda ال min الي فيها energyكافية

Solution. From (8.2) the wavelength must be less than

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

desired value 1.12

and from (8.1) the frequency must be at least

$$v \geq \frac{c}{\lambda} = \frac{3 \times 10^{8}\ \text{m/s}}{1.11 \times 10^{-6}\ \text{m}} = 2.7 \times 10^{14}\ \text{Hz}$$

اذا عندي بال spectrum ، من خلال ال curve
شوف عند lamda =1.11
كل الترددات التي عندها
اقل من هذا المقدار هي lamda
التي تنفعنا

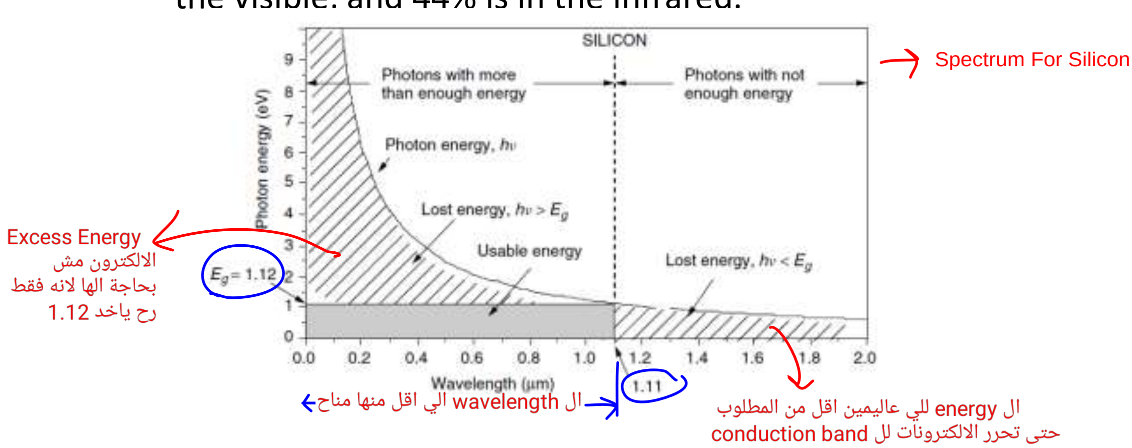
Summary

- **For a silicon photovoltaic cell, photons with wavelength greater than 1.11 μm have energy *hv* less than the 1.12 eV band-gap energy needed to excite an electron.**
- None of those photons create hole–electron pairs capable of carrying current, so all of their energy is wasted. It just heats the cell.
- On the other hand, photons with wavelengths shorter than 1.11 μm have more than enough energy to excite an electron. Since one photon can excite *only* one electron, any extra energy above the 1.12 eV needed is also dissipated as waste heat in the cell.
- The band gaps for other photovoltaic materials—gallium arsenide (GaAs), cadmium telluride (CdTe), and indium phosphide (InP), in addition to silicon—are shown in Table 8.2.
- **These two phenomena relating to photons with energies above and below the actual band gap establish a maximum theoretical efficiency for a solar cell. To explore this constraint, we need to introduce the solar spectrum.**

Solar Spectrum

يعتمد على ال air mass

- AM1- means that the sun is directly overhead. على سطح البحر
- AM0 means no atmosphere; that is, it is the extraterrestrial solar spectrum. على حافة الغلاف الجوي
- For an AM 1.5 spectrum, 2% of the incoming solar energy is in the UV portion of the spectrum, 54% is in the visible. and 44% is in the infrared.



ال usable energy بين 1.11 و 1.12

العلاقة بين ال Energy وال Wave length عكسية ، يعني ال high energy موجودة بال shorter wave length

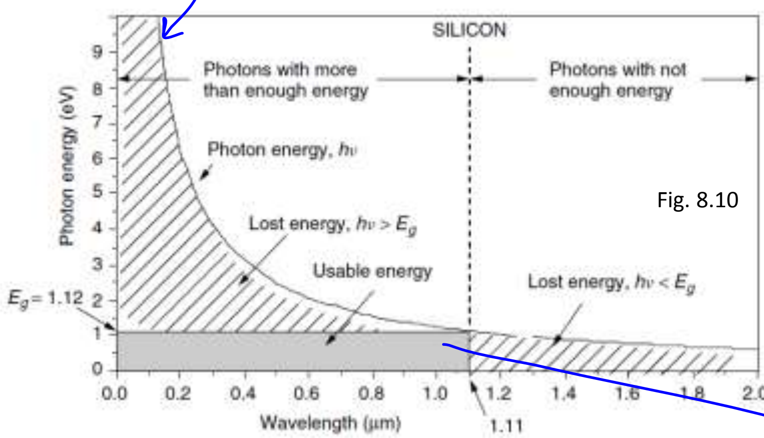


Fig. 8.10

- 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.

المستطيل السكني هو الذي يحدد كفاءة المادة وبالتالي ايضا كفاءة الخلية

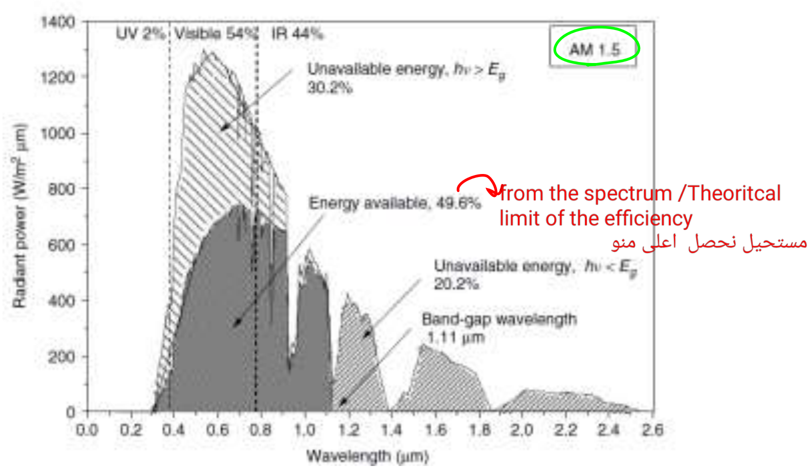
TABLE 8.2 Band Gap and Cut-off Wavelength Above Which Electron Excitation Doesn't Occur

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

باستخدام مواد اخرى قد تزداد المساحة المستفادة منها (المساحة السكنية) وبالتالي بتزيد الكفاءة، وهذا سبب اختلاف كفاءات الخلايا

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



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.

Photovoltaic Efficiency

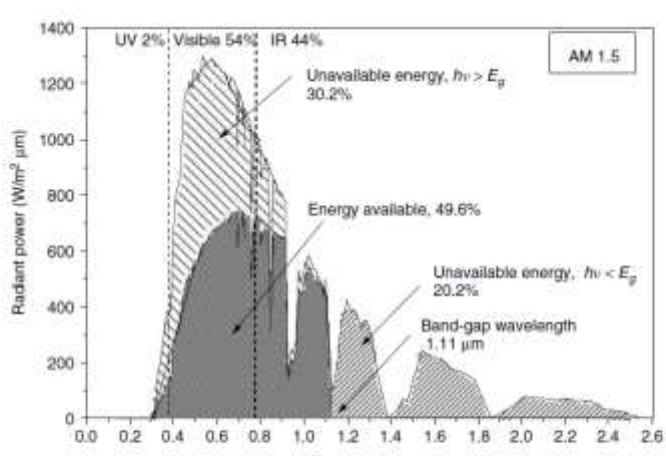
Theoritical Limit

- 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%.** (قيود)
- There are other constraints to PV efficiency, mainly black-body radiation losses and recombination.
- Cells in the sun get hot, which mean their surface radiate energy proportional to the fourth power of their temperature
- This accounts for 7% losses
- Hole saturation effects in silicon can result in another 10% losses …see hardcopy of book page 261

في قيود بتخلي الرقم 49.6% اقل
losses from radiation
losses from heat

الكفاءات التي بمتناول اليد بدون تكنولوجيا متقدمة هي بحدود ال 25%

- Notice that the efficiencies in Figure are roughly in the 20–25% range—well below the 49.6% we found when we considered only the losses caused by (a) photons with insufficient energy to push electrons into the conduction band and (b) photons with energy in excess of what is needed to do so.



بدنا نحافظ على ال electronsوال holes التي نتجت بسبب الفوتونات ونمنع تعاود تعمل recombination

ال holes رح نعملهم swept للخارج باستخدام electric field احنا بنحطو

الالكترونات رح يكونو swept للطرف الثاني، وكون ال poles بالجانب الاخر رح يتكون فرق جهد

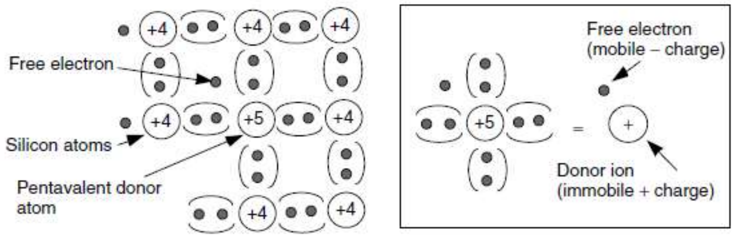
The p-n Junction

- As long as a solar cell is exposed to photons with energies above the bandgap energy, hole–electron pairs will be created.
- The problem is, of course, that those electrons can fall right back into a hole, causing both charge carriers to disappear.
- **To avoid that recombination, electrons in the conduction band must continuously be swept away from holes.**
- In PVs this is accomplished by creating a built-in electric field within the semiconductor itself that pushes electrons in one direction and holes in the other.

Electric Field

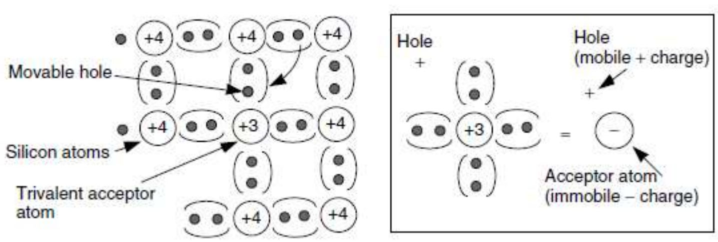
حتى نتجنب ال recombination بنعمل Electric Field بداخل ال semi conductor, ورح يودي ال poles بجهة والالكترونات بجهة اخرى

- To create the electric field, two regions are established within the crystal.
- On one side of the dividing line separating the regions, pure (intrinsic) silicon is purposely contaminated with very small amounts of a trivalent element from column III of the periodic chart;
- On the other side, pentavalent atoms from column V are added.



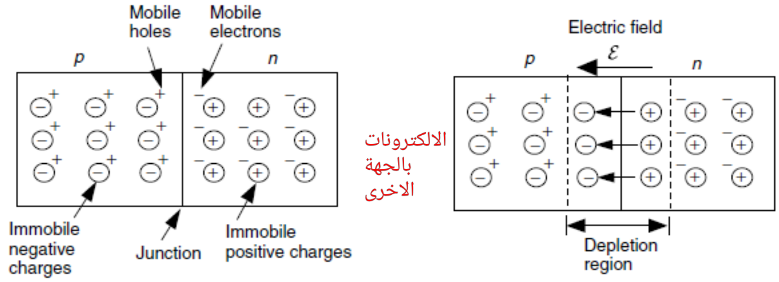
(a) The donor atom in Si crystal (b) Representation of the donor atom

An *n*-type material.
(a) The pentavalent donor.
(b) The representation of the donor as a mobile negative charge with a fixed, immobile positive charge



(a) An acceptor atom in Si crystal (b) Representation of the acceptor atom

In a *p*-type material, trivalent acceptors contribute movable, positively charged holes leaving rigid, immobile negative charges in the crystal lattice.



(a) When first brought together (b) In steady-state

الالكترونات بالجهة الاخرى

الpoles بجهة

(a) When a *p*–*n* junction is first formed, there are mobile holes in the *p*-side and mobile electrons in the *n*-side.

(b) As they migrate across the junction*, an electric field builds up that opposes, and quickly stops, diffusion.

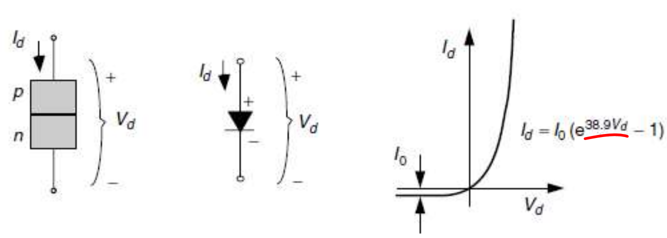
- As the diffusion process continues, the electric field countering that movement increases until eventually (actually, almost instantaneously) all further movement of charged carriers across the junction stops.
- This is a pn junction (Diode)

عملية ال conduction بتم عن طريق source external bias وهو بهذه الحالة الفوتون الي عنده طاقة اكثر من 1.12 eV

The *p*–*n* Junction Diode

- Anyone familiar with semiconductors will immediately recognize that what has been described thus far is just a common, conventional *p*–*n* junction diode.
- :

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



(a) *p*–*n* junction diode (b) Symbol for real diode (c) Diode characteristic curve

- where *Id* is the diode current in the direction of the arrow (A), *Vd* is the voltage across the diode terminals from the *p*-side to the *n*-side (V), *I*0 is the reverse saturation current (A), *q* is the electron charge (1.602 × 10^−19C), *k* is Boltzmann's constant (1.381 × 10^−23 J/K), and *T* is the junction temperature (K).

$$\frac{qV_d}{kT} = \frac{1.602 \times 10^{-19}}{1.381 \times 10^{-23}} \cdot \frac{V_d}{T(\mathrm{K})} = 11,600\frac{V_d}{T(\mathrm{K})}$$

- A junction temperature of 25◦C is often used as a standard, which results in the following diode equation:

1/ (25.69 mV) = 38.9

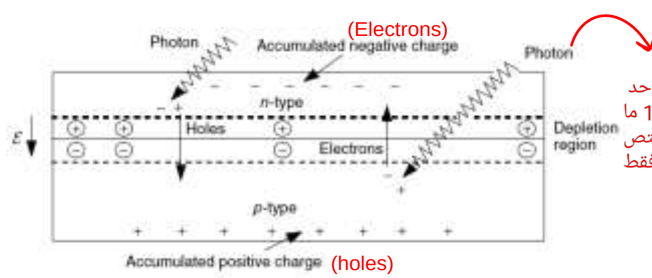
$$I_d = I_0(e^{38.9V_d} - 1) \qquad (\text{at } 25^\circ\text{C})$$

Standard Value

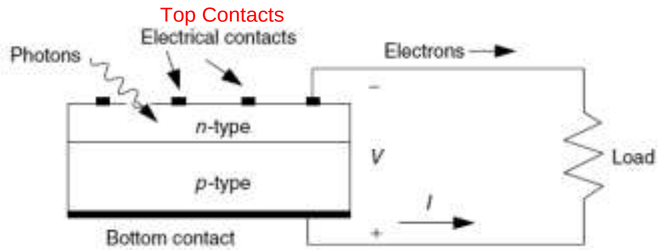
0.7 V

A GENERIC PHOTOVOLTAIC CELL

- Let us consider what happens in the vicinity of a *p*–*n* junction when it is exposed to sunlight. As photons are absorbed, hole-electron pairs may be formed.
- When photons create hole–electron pairs near the junction, the electric field in the depletion region sweeps holes into the *p*-side and sweeps electrons into the *n*-side of the cell.



كل فوتون يختص فقط بالكترون واحد
لو كان عندو الفوتون طاقة اكثر من 1.12 ما
رح يعطي الفرق لالكترون اخر لانه يختص
بالكترون واحد فقط



- If electrical contacts are attached to the top and bottom of the cell, electrons will flow out of the *n*-side into the connecting wire, through the load and back to the *p*-side as shown above.
- Since wire cannot conduct holes, it is only the electrons that actually move around the circuit. When they reach the *p*-side, they recombine with holes completing the circuit.
- Conventional current I is in the opposite direction.

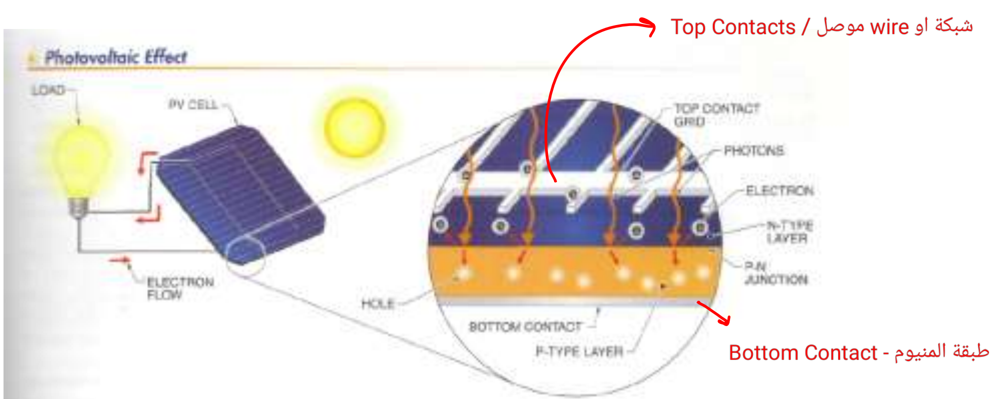
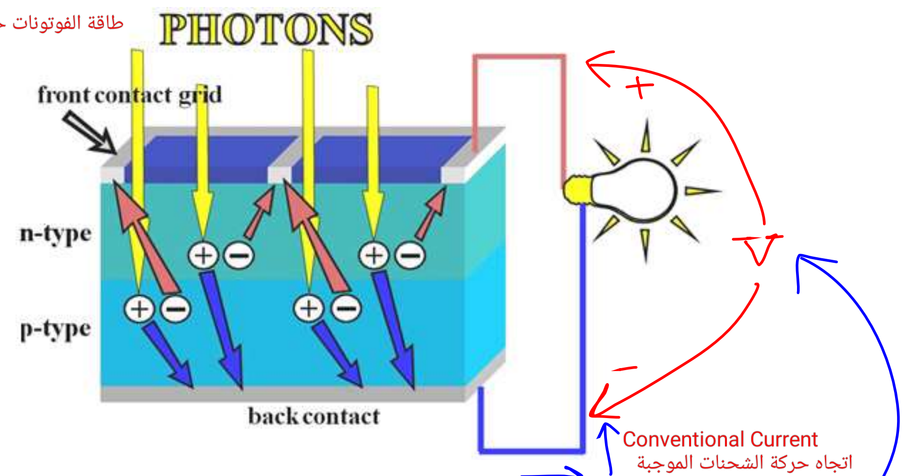


Figure 5-3. *The photovoltaic effect produces free electrons that must travel through conductors in order to recombine with electron voids, or "holes."*

Cross Section of PV Cell

طاقة الفوتونات حررت الالكترونات



يهمني اعرف قيمة التيار هذا لل pv cell الواحدة

ايضا يهمني اعرف قيمة الفولتج لل cell الواحدة

Summary

- Higher energy is associated with shorter wavelength (higher frequency)
- Photons of light transfer their energy to the electrons in the material surface
- The extra electrons with enough energy to escape from their atoms are conducted as an electric current
- Because of the electric result, the photovoltaic effect is also called ***photoelectric effect***

الي سبب العملية الفوتونات

الناتج هو التيار

Summary

- The electrons gain potential energy and are in a position to do useful work before returning to a lower energy state
- When these electrons are excited , they can move around to other atoms leaving behind voids (holes)
- The holes can act in a similar manner to the electrons; appearing to move when a neighboring electron moves to fill a hole, but they are associated with positive charge

Summary

- An electric field produced by the pn junction prevents electrons and holes from immediately recombining which would accomplish no work
- The electrons are repelled from the p-type layer toward the top surface of the cell
- The holes are repelled away from the n-type layer toward the bottom surface
- This created a difference in electrical potential (voltage) between the top and bottom

Summary

- The free electrons are collected by metal contacts on the top surface of the cell and the holes migrate toward the bottom surface
- For the electrons and holes to recombine, the electrons must travel from top surface to the bottom surface
- This is accomplished by connecting the surfaces with conductors and loads
- The electrons flow through the loads, doing electrical work, then arrive at the bottom and recombine with holes

Summary

- The process of electrons and holes being separated by photon energy, and doing work before recombining , occurs continuously while PV cells are exposed to light
- **There is no way of turning off a PV device other than completely covering the top surface with no light reaching the cells**

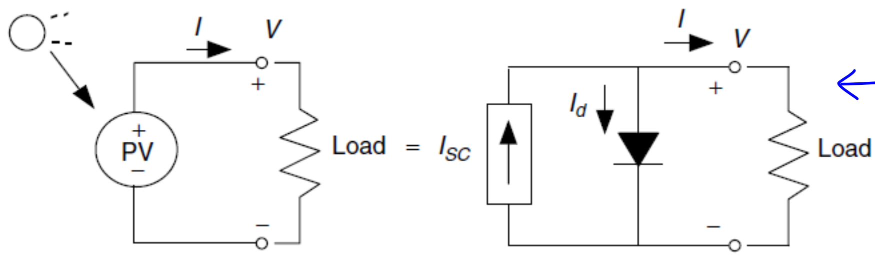
دائما هناك
فولتج من
الخلية طالما
في ضوء

ENEE5307 Renewable Energy and Photovoltaic Power Systems (Instructor Nasser Ismail) BIRZEIT UNIVERSITY

(Model)

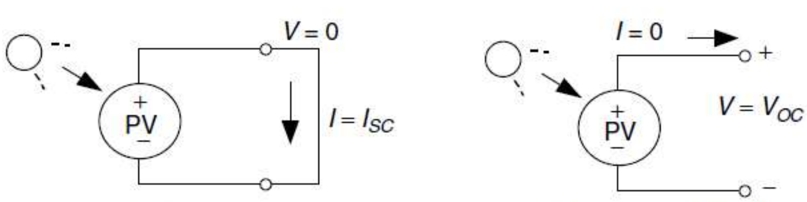
The Simplest Equivalent Circuit for a Photovoltaic Cell

DC current Source الخلية هي عبارة عن



This is the simplest Model

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



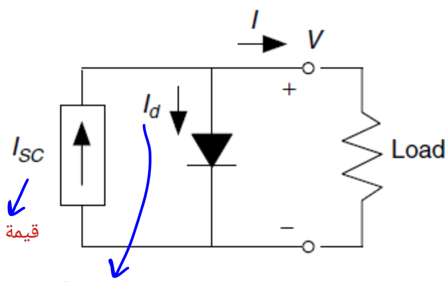
(a) Short-circuit current (b) Open-circuit voltage

There are two conditions of particular interest for the actual PV and for its equivalent circuit

(1) the current that flows when the terminals are shorted together (the short-circuit current, *Isc*) and

(2) the voltage across the terminals when the leads are left open (the open-circuit voltage, *Voc*)

- When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since *Vd* = 0, so all of the current from the ideal source flows through the shorted leads.
- Since that short-circuit current must equal *Isc*, the magnitude of the ideal current source itself must be equal to *Isc*.
- Now we can write a voltage and current equation for the equivalent circuit of the PV cell shown.
- Start with
- $I = I_{SC} - I_d$



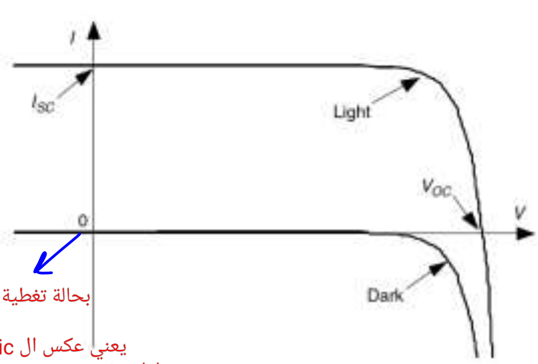
$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$

قيمة تيار تعتمد على شدة الاشعاع الشمسي / يعني فقط
يتغير بتغير الاشعاع الشمسي

قيمته تعتمد على Vd

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

- It is interesting to note that the second term above is just the diode equation with a negative sign.
- That means that a plot of I is just *Isc* added to the diode curve turned upside-down.
- Figure below shows the current–voltage relationship for a PV cell when it is dark (no illumination) and light (illuminated)



اهم Two Parameters لل PV Cell :
1- Short Circuit Current Isc
2- Open Circuit Voltage Voc

بحالة تغطية الخلية بالكامل Isc يساوي صفر
اما I = 0 - Id = -Id
يعني عكس ال characteristic تاعت ال diode
واذا Isc مش صفر يعني رح يعمل ازاحة للكيرف للاعلى

- When the leads from the PV cell are left open, *I* = 0 and we can solve for the open-circuit voltage *Voc* :

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

- And at 25◦C,

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

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

25.7 mV

عند 25 درجة مؤية

الفولتج Voc عند درجات حرارة اعلى ، مثلا 50 درجة رح يقل
عند قيمة تيار ثابتة ، ال power رح تقل لان الفولتج قل

- In both of these equations, short-circuit current, *Isc*, is directly proportional to solar insolation, which means that we can now quite easily plot sets of PV current–voltage curves for varying sunlight.
- Also, quite often laboratory specifications for the performance of photovoltaics are given per cm^2 of junction area, in which case the currents in the above equations are written as current densities.
- Both of these points are illustrated in the following example.

ECE Department
Birzeit University

احيانا بعض الشركات تعطي ال performance تاع الخلايا اي قيم التيار والفولتج تاعت الخلايا لكل سنتيمتر مربع من مساحة الخلية

Example 8.3 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.

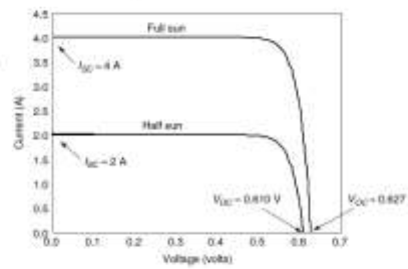
1000 watt/ m^2

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.

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

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

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

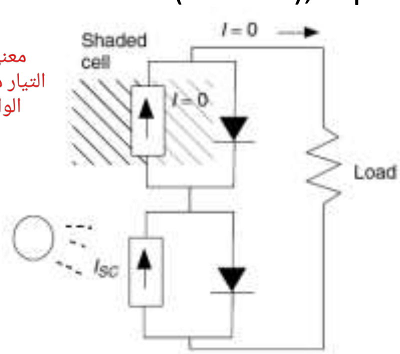


A More Accurate Equivalent Circuit for a PV Cell

هناك اشكالية بالمودل السابق

- There are times when a more complex PV equivalent circuit than the one shown in previously is needed.
- For example, consider the impact of shading on a string of cells wired in series (Figure below shows two such cells).
- If any cell in the string is in the dark (shaded), it produces no current.

معنى هذا الكلام انه لن يمر التيار من هنا، ولكن على ارض الواقع يمر تيار ، يعني لازم نعدل ال model



احنا بنشبك ال cells بشكل series حتى نحصل على فولتج اعلى

- In our simplified equivalent circuit for the shaded cell, the current through that cell's current source is zero and its diode is back biased so it doesn't pass any current either (other than a tiny amount of reverse saturation current).
- This means that the simple equivalent circuit suggests that no power will be delivered to a load if any of its cells are shaded.
- A more complex model can deal with this problem

The simple equivalent circuit of a string of cells in series suggests no current can flow to the load if any cell is in the dark (shaded).

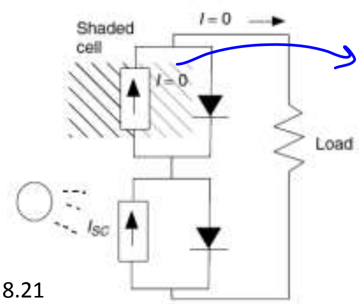


Fig. 8.21

ال shading ممكن يصير على
جزء من الخلية يعني مش شرط
يصير التيار صفر ممكن تعطي
فرضا 1 امبير والخلية الاخرى 4
امبير يعني حسب هذا ال
model بتصور الخلية المظللة
تسحب power وتسخن وممكن
تخرب ، ولكن هذا الحكي لا
يحصل على ارض الواقع يعني
لازم نعدل ال model

A More Accurate Equivalent Circuit for a PV Cell

ال model المعدل لمشكلة ال shading

- While it is true that PV modules are very sensitive to shading, the situation is not quite as bad as that.
- So, we need a more complex model if we are going to be able to deal with realities such as the shading problem.
- A PV equivalent circuit that includes some parallel leakage resistance *Rp* is shown
- The ideal current source I_{SC} in this case delivers current to the diode, the parallel resistance, and the load:

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

بال model المعدل واضح
ان قيمة التيار I بتطلع اقل من
ال model الاول

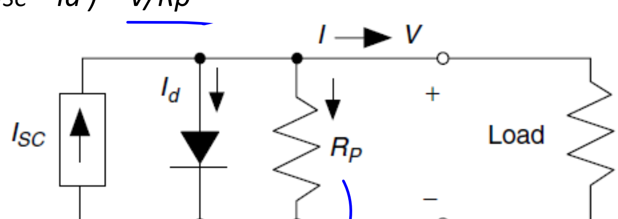
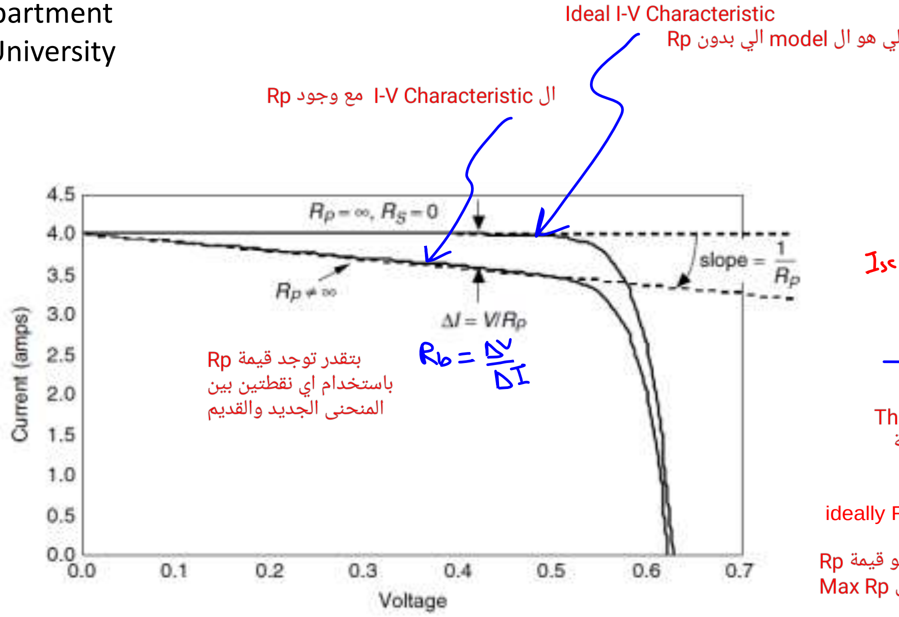
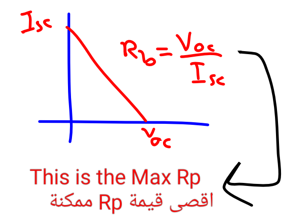


Figure 8.22

قيمتها مش صغيرة !





ideally Rp = infinity

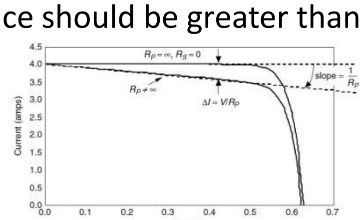
بالعادة بالتصنيع بحاولو يخلو قيمة Rp اكبر ب 100 مرة من ال Max Rp

Modifying the idealized PV equivalent circuit by adding parallel resistance causes the current at any given voltage to drop by V/R_P.

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

- The term in the parentheses is the same current that we had for the simple model.
- So, what the equation tells us is that at any given voltage, the parallel leakage resistance causes load current for the ideal model to be decreased by V/R_p as is shown I
- For a cell to have losses of less than 1% due to its parallel resistance, R_P should be greater than about

  $R_P > 100\, V_{OC} / I_{SC}$
- Consider a large cell, with I_{SC} around 7 A and V_{OC} about 0.6 V, which says its parallel resistance should be greater than about 9 .



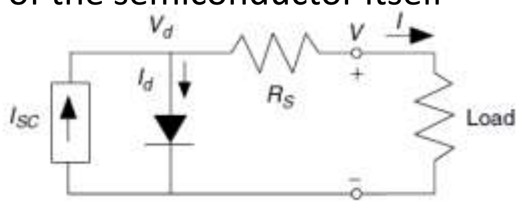
Series Resistance

التعديل الثاني على ال model

- An even better equivalent circuit will include series resistance as well as parallel resistance.
- Before we can develop that model, consider Fig. 8.24 in which the original PV equivalent circuit has been modified to just include some series resistance, *RS*.

ال Rs جاية من مقاومة ال wire او الشبكة الي بال top contacs لل cell

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



لدراسة تأثير Rs لحالها بدون Rp

Fig. 8.24

صارت ال V مش نفسها ال Vd

Effect of Rs

- To analyze effect of series resistance, start with the simple equivalent circuit

$$I = I_{SC} - I_d = I_{SC} - I_0\left(e^{qV_d/kT} - 1\right)$$

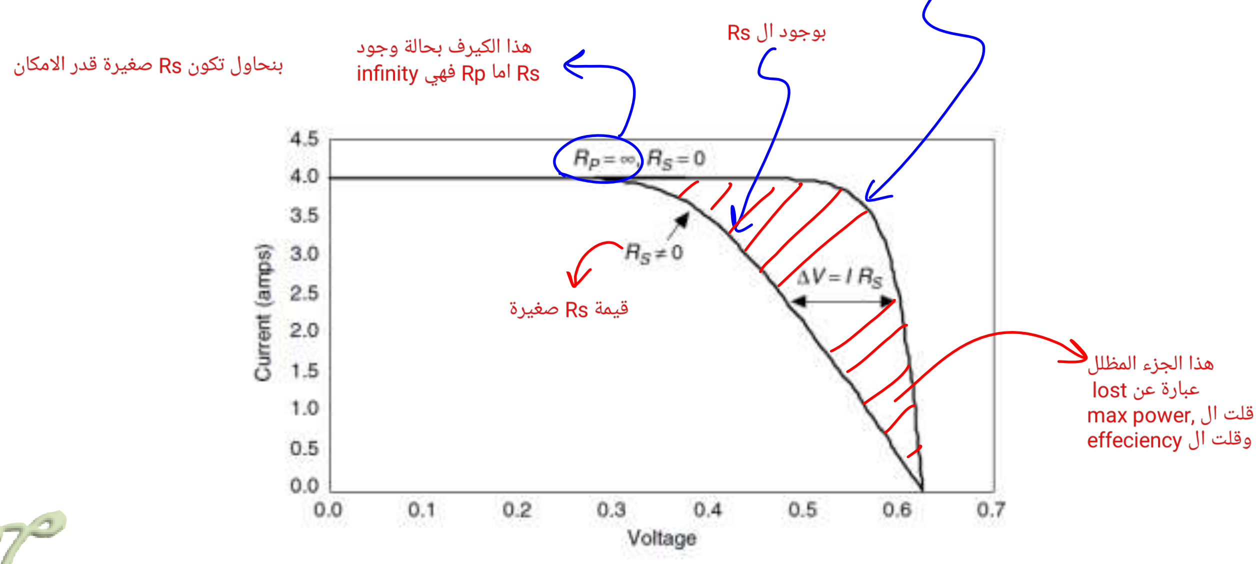
- and then add the impact of *RS*

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

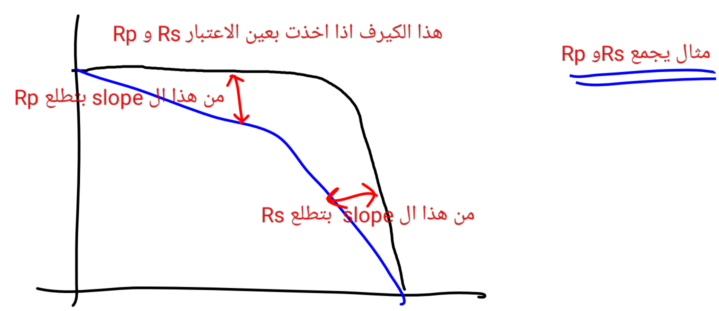
رسمة هذا الكيرف بالسلايد التالي

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

- Equation above can be interpreted as the original PV *I* –*V* curve with the voltage at any given current shifted to the left by $\Delta V = IR_S$ as shown in Fig. 8.25.



Adding series resistance to the PV equivalent circuit causes the voltage at any given current to shift to the left by $\Delta V = I R_S$.



مثال يجمع Rsو Rp

مثال

- For a cell to have less than 1% losses due to the series resistance, *RS* will need to be less than about

اقصى قيمة ل R

$$R_S < \frac{0.01 V_{OC}}{I_{SC}}$$

بالتصنيع بحاولو يخلو Rs اصغر ب 100 مرة من Voc/Isc

- which, for a large cell with *Isc* = 7 A and *Voc* = 0.6 V, would be less than 0.0009 ohm

ال model بوجود ال Rs و ال Rp

Generalized PV cell equivalent Circuit

- Finally, let us generalize the PV equivalent circuit by including both series and parallel resistances as shown in Fig. 8.26. We can write the following equation for current and voltage:

معادلة ال PV الكاملة

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

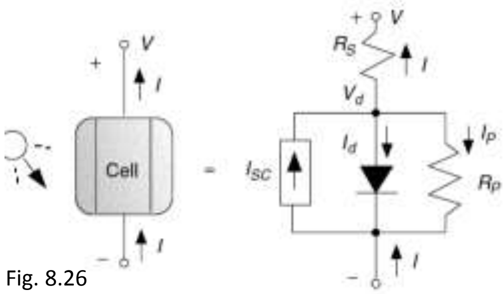


Fig. 8.26

A more complex equivalent circuit for a PV cell includes both parallel and series resistances. The shaded diode reminds us that this is a “real” diode rather than an ideal one.

بحالة عندي خليتين و صار shading على وحدة ، وباستخدام ال model الجديد :

الخلية الي صار عليها رح تطفي وتصير تعمل voltage drop = Delta V

Delta V = (Rs + Rp) I

والفولتج الكلي الي كنت استفيد منو V1 + V2 رح يصير

V1 - Delta V

بضل عندي power طالعة بس اقل من الحالة الطبيعية

- Under the standard assumption of a 25◦C cell temperature, (8.17) becomes:

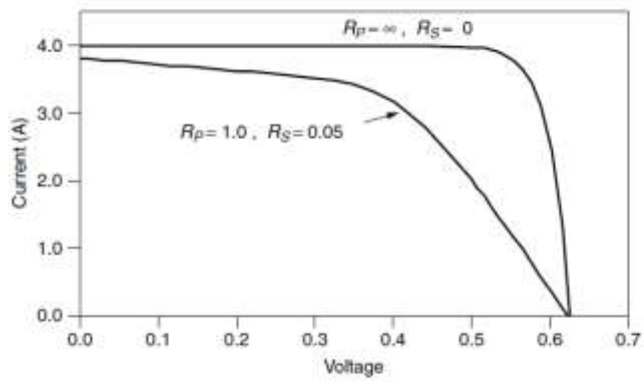
$$I = I_{SC} - I_0\left[e^{38.9(V+IR_S)} - 1\right] - \frac{1}{R_P}(V + IR_S) \qquad \text{at } 25^\circ\text{C}$$

- Unfortunately, this is a complex equation for which there is no explicit solution for either voltage *V* or current *I* .
- A spreadsheet solution, however, is fairly straightforward and has the extra advantage of enabling a graph of *I* versus *V* to be obtained easily.
- The approach is based on incrementing values of diode voltage, *Vd* , in the spreadsheet.
- For each value of *Vd* , corresponding values of current *I* and voltage *V* can easily be found.

$$I_{SC} = I + I_d + I_P$$

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

- Voltage across an individual cell then can be found from $V = V_d - I R_S$
- for an equivalent circuit with *RS* = 0.05 and *RP* = 1 is shown



PV materials

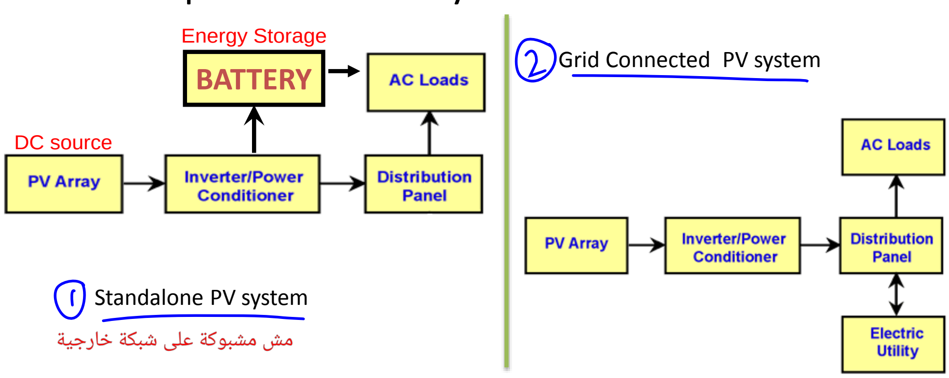
- While silicon used to dominate the PV industry, there is emerging competition from thin film made from compounds of two or more elements
- PV properties similar to silicon can be obtained by using materials from group III and V or group II and VI
- Examples Gallium (III) and Arsenic (V) are used to form gallium –arsenide (GaAs) PVs
- Also Cadmium (II) and tellurium (VI) form CdTe cells

System Components

- Photovoltaic “PV” systems are highly versatile modular electrical power generation systems
- Every PV system require components to conduct, control, convert, distribute, and store the energy produced by the array
- The specific components required depends on the type of system and functional requirements
- But ,major components such as inverters, batteries, charge controllers, as well as wiring, switchgear and overcurrent protection are typically included

يوجد نوعين من مختلفين من ال systems :

- PV Systems are broadly categorized by how they are or are not integrated with electrical systems
- Here the purposes and functions of the major components in PV systems will be described



ال cells بكونو modules وال modules بكونو arrays

PV Modules and Arrays

- The primary component common to all PV systems is the PV array which consists of individual modules that are connected to produce desired voltage, current, and power output
- Modules and arrays produce DC power ,which can be used to charge batteries, directly power DC loads, or converted to AC power by inverters to power AC loads or to interface with electric utility grid

PV Modules and Arrays

- The voltage of PV modules varies somewhat with temperature, and the current varies proportionately to solar irradiance, so power output is rarely constant
- PV systems usually require means to store or condition power so it can be used effectively by electrical loads

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Cells , Modules & Arrays

- PV systems use cells, modules, and arrays to capture sunlight and convert it into electrical energy
- Systems are modular, cells used to build modules, modules used to build arrays

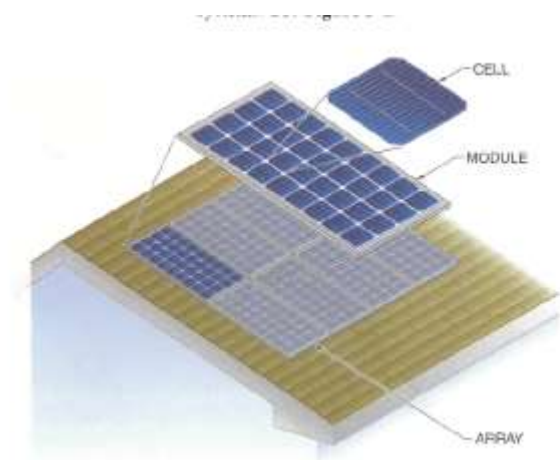

Figure 5-1. *The basic building blocks for PV systems include cells, modules, and arrays.*

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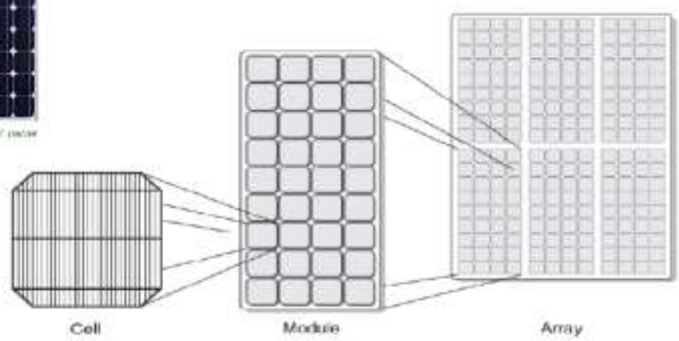
Cells, Modules, Arrays



Source: [ABS Energy Research, 2009 or [Dr. Harald Schutzeeichel, 2009]

Cell Materials

اكثر نوع من المواد المستخدم في صناعة ال pv

(1)
- **Crystalline Silicon** is most common base raw material for silicon cell production is at least 99.9% pure polysilicon, a product refined from quartz and silica sands

مصادره

يوجد درجات مختلفة من مادة السيليكون وهذه الدرجات تؤثر في كفاءة الخلية

- Various grades of polysilicon can be used in PV cell production and affect the quality and efficiency of cells

حتى الان عندهم افضل ratio performance to cost

- Crystalline silicon (C-Si) cells currently offer the **best ratio of performance to cost** and utilize many of the raw materials and process used by semiconductor industry

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Cell Materials

2 • Gallium Arsenide (GaAs) cells are more efficient than C-Si cells , but the high cost and toxicity have limited their use to space applications so far

كفاءة افضل ولكن سعر اكبر ومادة مسممة

3 • Multi-junction cell: a cell that maximizes efficiency by using layers of individual cells that each respond to different wavelengths of solar energy; the top layer captures the short wave while longer wave lengths is absorbed by the lower layer

هون بعمل اكثر من layer وكل layer لها reaction لل wave length
مختلف حتى نستفيد من wavelengths اكثر من الحالة العادية

Cell Materials

4 • Thin-Film PV devices: module based approach to cell design

هون بصنعو module قطعة صبة وحدة وبستخدمو الليزر حتى يحددو ال cells ويوصلو بينهم

• A thin film module is a module –like PV device with its entire substrate coated in thin layers of semiconductor material using chemical vapor deposition techniques and then laser-scribed to delineate individual cells and make electrical connection between them

سهولة في التصنيع ولكن كفاءة اقل

5 • Amorphous Silicon (a-Si) ; copper indium, gallium selenide (CIGS) and cadmium telluride (CdTe) are among competing thin film technologies

انواع اخرى ولكن كفاءة اقل

- Thin-Film modules are less costly to produce and use less raw materials than C-Si and may not be as durable in the field

6 Photo-Electrochemical Cell

تصنع من مواد مثل البلاستيك

- A cell that relies on chemical process to produce electricity from light, rather than using semiconductors
- Photo-Electrochemical cells include dye-sensitized cells ,and polymer (plastic) cells and are sometimes called organic cells
- Engineering challenges in developing these cells are considerable, some are expected to impact commercial markets in the next decade

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Solar Cell Construction

خطوات التصنيع :

1 - purification of the Silicon
تنقية السيليكون

- Materials
  - Crystalline Silicon رح نركز عليه
  - Gallium Arsenide (more expensive)

  المواد الاساسية
- (2) Grown into large single-crystal ingots — بعملو منو سبائك من single crystal
- (3) Sawed into thin wafers — القوالب الناتجة بتكون على شكل اسطواني او متوازي مستطيلات بقصوها الى رقائق صغيرة
- (4) 2 wafers are bonded together (p-n junction) — بجيبو رقاقة p type ورقاقة n type بعملو pn junction
- (5) Wafers grouped into panels or arrays — ومنهم بصنعو الخلايا وال modules وال arrays

http://en.wikipedia.org/wiki/Solar_panel

Wafer Manufacturing

- The manufacture of commercial silicon modules involves fabricating silicon wafers, transforming the wafers into cells, and assembling cells into modules.
- A *wafer* is a thin, flat disk or rectangle of base semiconductor material.
- Wafers are 180 μm to 350 μm thick and are made from p-type silicon. بالعادة بعملو للرقائق doping بحيث تصير p type
- Crystalline silicon cell wafers are produced in three basic types:

انواع ال Crystalline Silicon

1) Monocrystalline , 2) polycrystalline, and 3) ribbon silicon.

- Each type has advantages and disadvantages in terms of efficiency, manufacturing , and costs. من حيث

جدول يبين كفاءة الخلايا حسب المادة المستخدمة في التصنيع

PV Materials Efficiencies

PV Material Efficiencies*

MATERIAL	TYPICAL EFFICIENCIES	BEST LABORATORY EFFICIENCY
Multijunction gallium arsenide (GaAs)	33 to 38[†]	40.7[†]
Monocrystalline silicon	14 to 17	24.7
Polycrystalline silicon	11.5 to 14	20.3
Copper indium gallium selenide (CIGS)	9 to 11.5	19.9
Cadmium telluride (CdTe)	8 to 10	16.5
Amorphous silicon (a-Si)	5 to 9.5	12.1
Dye-sensitized (Grätzel)	4 to 5	11.1
Polymer (Organic)	1 to 2.5	5

* In %
† In concentrating applications

Source: NREL

Various PV materials and technologies produce different efficiencies.

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عبارة عن waffer مصنوع من single silicon crystal ومصنع بشكل سبيكة cylindrical

Mono-crystalline Silicon

- A *mono-crystalline wafer is* a silicon wafer made from a single silicon crystal grown in the form of a cylindrical ingot. See **Figure** next slide.
- Chunks of highly pure polysilicon are melted in a crucible, along with boron.
- A small seed crystal is dipped into the molten bath and slowly rotated and withdrawn.
- Over a period of many hours, the seed crystal grows into a large cylindrical crystal up to 40" in length and 8" in diameter

طريقة تصنيعها :

1) بجيبو pure silicon وبذوبوها وبضيفو عليها البورون حتى تصير P type

2) بعدين بجيبو قطعة كرستالة صلبة seed وبصيرو يلفو فيها جوا وعاء السيليكون المذاب ، وبالتالي السيليكون بصير يتجمع على ال seed ومع الوقت بعمل سبيكة cylindrical

3) بنتج عندي سبيكة تقريبا طولها 40 inch وقطرها 8 inch

wafer (رقاقة) ingot (سبيكة)

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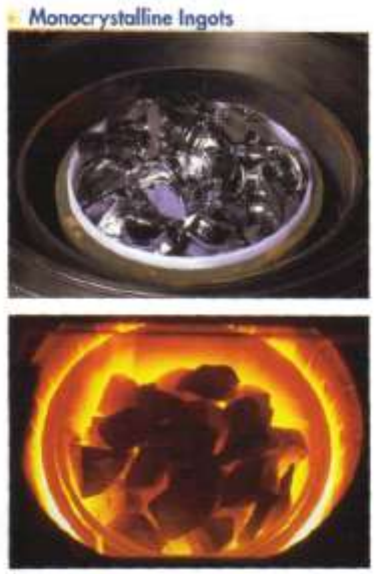


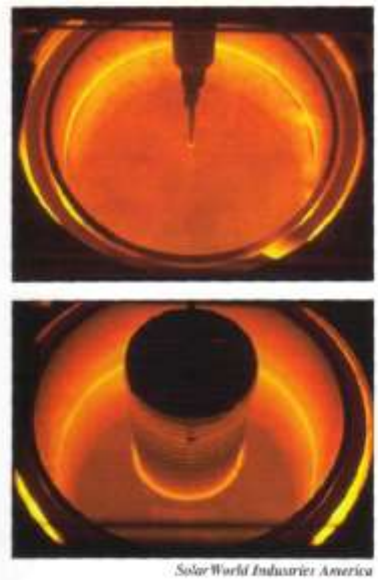
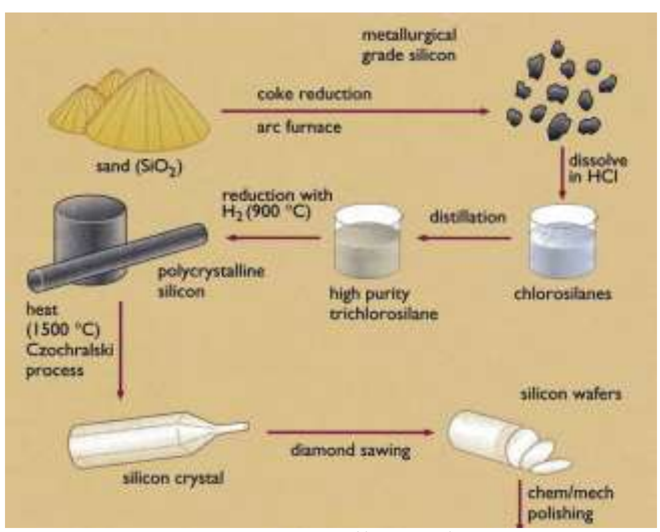


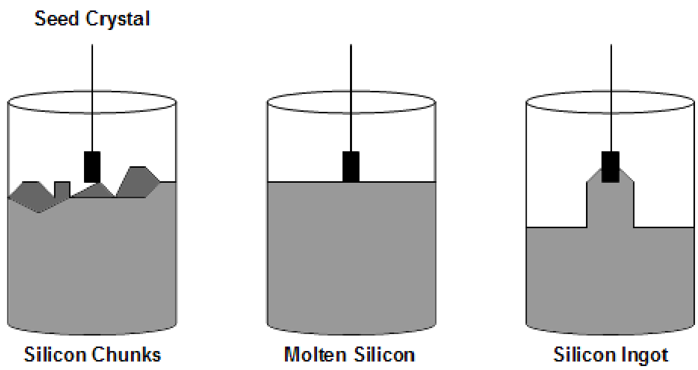
Figure 5-5. *Monocrystalline silicon wafers are sawn from grown cylindrical ingots.*

Creating Silicon Wafers



Growing Silicon Ingots

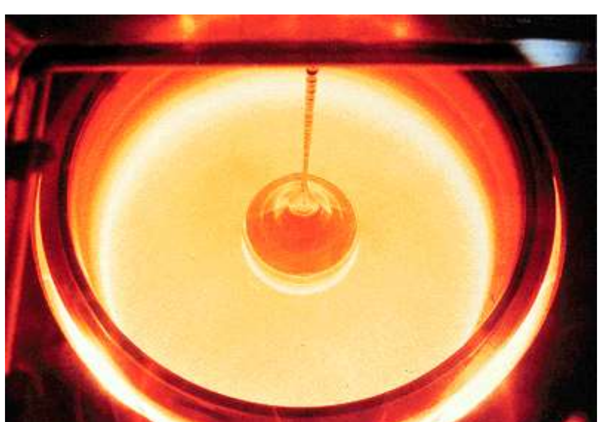
اسم عملية تصنيع ال mono crystalline السابقة هو



Czochralski Process

http://en.wikipedia.org/wiki/Czochralski_process

Drawing a Silicon Ingot



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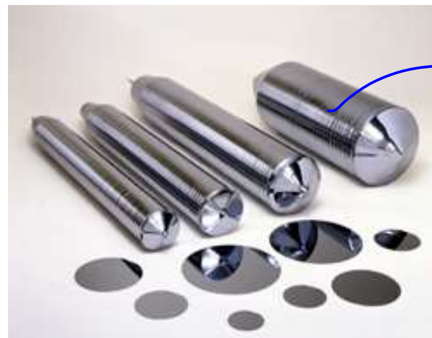
http://www.answers.com/topic/silicon

Silicon Ingots & Wafers



http://www.sumcosi.com/english/products/products2.html

Monocrystalline Silicon

السبيكة اسطوانية والقطع رح يكون
لمربعات مش دوائر لان الدوائر رح
تضيع مساحة اكبر على اللوح حتى
تكون افضل كفاءة

- Because the ingot is round, the edges are often cropped to a more rectangular or square shape, which allows cells to be packed more closely in a module.
- Individual wafers are then cut from the ingot using diamond wire saws.
- Commercial monocrystalline cells have efficiencies on the order of 14% to 17%, with some laboratory samples having efficiencies as high as about 25%.

كفائتهم

هو عبارة عن رقائق سيليكون لكن طريقة تصنيعو مختلفة ، هنا بعملو csting ، يعني بعملو قوالب بشكل معين وبصبوا فيه السليكون المذاب

Polycrystalline Silicon

النوع الثاني من السيليكون

- *A polycrystalline wafer (رقاقة)* is a silicon wafer made from a cast silicon ingot (سبيكة)that is composed of many silicon crystals.
- Molten silicon is poured into a crucible to form an ingot, which is slowly and carefully cooled over several hours.
- During cooling, many silicon crystals form and grow as the molten material solidifies.
- The cast ingot is then sectioned with wire saws to form square or rectangular wafers. يتميز بأن شكله منتظم ، مربع او مستطيل وهذا افضل

Polycrystalline Silicon

ال polycrystalline بالامكان نميزهم من ان عندهم square corners

- Polycrystalline wafers can sometimes be distinguished from monocrystalline wafers by their square corners and the grain boundaries appearing on the wafer surface.
- While polycrystalline cells have slightly lower efficiencies (11.5% to 14%) than monocrystalline cells, their lower manufacturing costs and denser packing in modules makes them competitive with monocrystalline modules.

هنا الكفاءة اقل ، ولكن تكلفة التصنيع هنا اقل من السابقة

DOE/NREL, John Wohlgemuth—Solarex

Figure 5-6. *Polycrystalline silicon wafers are sawn from cast rectangular ingots.*

شريط سيليكون، هنا بعد تذويب السيليكون بمرروه من خلال rolls بطلع شريط مثل الورق يعني لا داعي لقص قوالب هنا

Ribbon Silicon

النوع الثالث

- A *ribbon wafer* is a silicon wafer made by drawing a thin strip from a molten silicon mixture.
- The melted material is pulled between parallel dies where it cools and solidifies to form a continuous multicrystalline ribbon.

بتركها حتى تبرد

- The ribbon is then cut at specific intervals to form rectangular-shaped wafers.

بقطعها للاشكال الي بدو اياها

- While cells produced from ribbon silicon wafers have slightly lower efficiencies (11% to 13%) than other silicon cells, this process is less expensive because there is less material waste and it does not require ingot sawing.

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تكملة عملية التصنيع

Cell Fabrication

- Once a crystalline silicon wafer is produced, it must go through additional processing to become a functional PV cell.
- **Etching:** first the wafers are dipped in a sodium hydroxide solution to etch the surface and remove imperfections introduced during the sawing process.

المرحلة الثانية هي ال Etching
بغطسو ال waffers المقطعة بمحلول
هيدروكسيد الصوديوم
حتى يعملو Erching يعني
smoothing لل surface

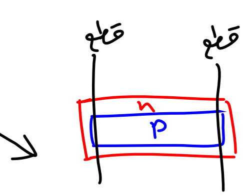
- The textured surface increases surface area, allows subsequent coatings to adhere better, and minimizes reflected sunlight.

بنعمل smoothing حتى يمتص
اشعاع اكثر وتقليل الضوء
المنعكس وايضا لما نغطيه لانه
هذا اسا p type

العملية التالية من التصنيع هي :

- **Phosphorous Diffusion**: After the wafers are cleaned they are placed on racks and into a diffusion furnace, where phosphorous gas penetrates the outer surfaces *of the cell, creating a thin n-type semiconductor* layer surrounding the original p-type semiconductor material. See **Figure** 5-8.

الطبقات الناتجة من العمليات
السابقة هي p type , بجيبوا
الطبقات وبعرضوهاولغاز الفسفور
في افران وبتتكون عليها طبقة n
type



Solar World Industries America
Figure 5-8. *Diffusion of phosphorous gas creates a thin n-type semiconductor layer over the entire surface of a p-type wafer.*

قص الاطراف حتى تشيل ال n type من الاطراف

اضافة طبقة ضد الانعكاس لل top surface لزيادة الكفاءة

- **Edge Abrasion**: the edge of the wafer is then abraded to remove the n-type material.
- **Coating**: Antireflective coatings are then applied to the top surface of the cell to further reduce reflected sunlight and improve cell efficiency.
- **Electrical Contacts:** After the coatings dry, grid patterns are screen printed on the top surface of the cell with silver paste to provide a point for electron collection and the electrical connection to other cells.
- These grid lines generally include two or more main strips across the cell, with finer lines emanating from the main strips across the cell surface.
- The configuration of these grid patterns is a critical part of cell design,

بقصد فيها ادخال مقاومتهم في الحسبان اثناء التصميم لانها تؤثر على Rs

Electrical Contacts

- The configuration of these grid patterns is a critical part of cell design, because they must be of sufficient size and distribution to be able to efficiently collect and conduct current away from the cell, but must be minimized to avoid covering much of the cell surface, which lowers the effective cell surface area exposed to sunlight.
- Finally, the entire back surface of the cell is coated with a thin layer of metal, typically aluminum, which alloys with the silicon and neutralizes the n-type semiconductor layer on the back surface.
- This results in the bottom surface of the cell being the positive connection, while the top surface is negative

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اخر خطوة بالتصنيع

Testing

بعملو اختبار حتى يتأكدو انها شغالة او لا

- After cells are produced, each is electrically tested under simulated sunlight and sorted according to its current output.
- This sorting *process largely eliminates problems with* current mismatch among series-connected cells and allows manufacturers to produce modules that are of the same physical size but have different power ratings.

ايضا بعملوه حتى يعملو sorting لل cells حسب ال Voc and Isc

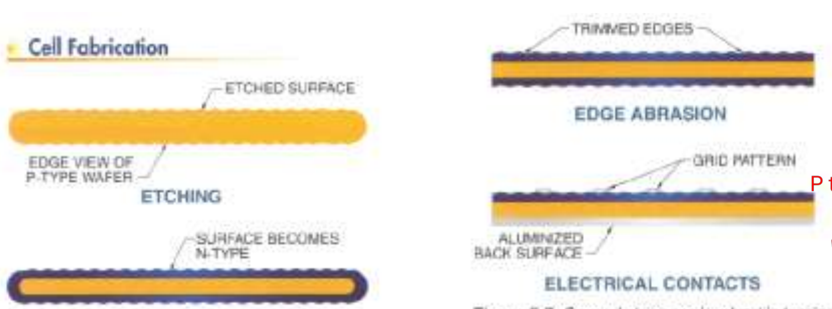

Figure 5-7. *Several steps are involved in turning silicon wafers into PV cells.*

الطبقة فوق عليها الشبكة .. P type

المنيوم

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Creating PV Cells

How Solar Cells are Made
see movie

For Reference

Thin film versus crystalline silicon

- Due to cost decreases, PV has begun to attract significant interestment. Which begs the question for developers of which PV technology is most appropriate for the region?
- Due to competitive per-watt module costs and lower BOS costs due to higher module efficiencies, crystalline silicon (c-Si) PV technology has enjoyed a resurgence in the last year over thin-film options.
- c-Si also enjoys the benefits of wider familiarity.
- However, thin-film technologies offer distinct advantages for deployment in the region, including lower temperature coefficients than crystalline silicon, meaning better performance in the region's hot climate.
- Multiple pilot projects by thin film market leaders are currently in progress to evaluate this potential.

Thin film versus crystalline silicon

- In June 2012, First Solar announced that it has joined the King Abdullah University of Science and Technology in a program to explore PV technology in the region.
- This includes building a 3.2 kW pilot plant using its PV modules on the coast of the Red Sea, which will test any performance of the company's cadmium telluride PV technology under very high temperatures.
- Solar Frontier has also provided thin film modules for a 36.4 kW pilot PV project with oil refiner Takreer in Abu Dhabi, UAE, which will measure output over a one-year period to evaluate its copper indium gallium diselenide (CIS or CIGS) technology.

Recent Developments

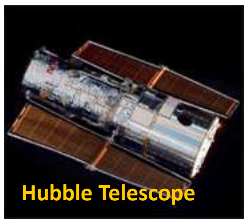
- Photovoltaic panels based on crystalline silicon modules are encountering competition in the market by panels that employ thin-film solar cells (CdTe CIGS, amorphous Si, microcrystalline Si), which had been rapidly evolving and are expected to account for 31% of the global installed power by 2013.
- However, precipitous drops in prices for poly-silicon and their panels in late 2011 have caused some thin-film makers to exit the market and others to experience severely squeezed profits.
- Other developments include casting wafers instead of sawing, concentrator modules, 'Sliver' cells, and continuous printing processes.

Recent Developments

- The San Jose-based company Sunpower produces cells that have an energy conversion ratio of 19.5%, well above the market average of 12–18%.
- The most efficient solar cell so far is a multi-junction concentrator solar cell with an efficiency of 43.5%[produced by Solar Junction in April 2011.
- The highest efficiencies achieved without concentration include Sharp Corporation at 35.8% using a proprietary triplejunction manufacturing technology in 2009,
- and Boeing Spectrolab (40.7% also using a triple-layer design).
- A March 2010 experimental demonstration of a design by a Caltech group led by Harry Atwater which has an absorption efficiency of 85% in sunlight and 95% at certain wavelengths is claimed to have near perfect quantum efficiency.
- However, absorption efficiency should not be confused with the sunlight-to- electricity conversion efficiency.

Solar PV Applications

① Spacecraft



② Recreational Use (Sailboat)

③ Remote Areas (Mexico)

A solar panel in Marla, Cirque de Mafate, Réunion

http://en.wikipedia.org/wiki/Solar_panel

④ Residential

http://www.californiasolarco.com/photos_html/grid_tied/rootop_system/nevada-city-2-4.html

5 Commercial

Solar Centre at Baglan Energy Park in South Wales

http://www.c-a-b.org.uk/projects/tech1.htm