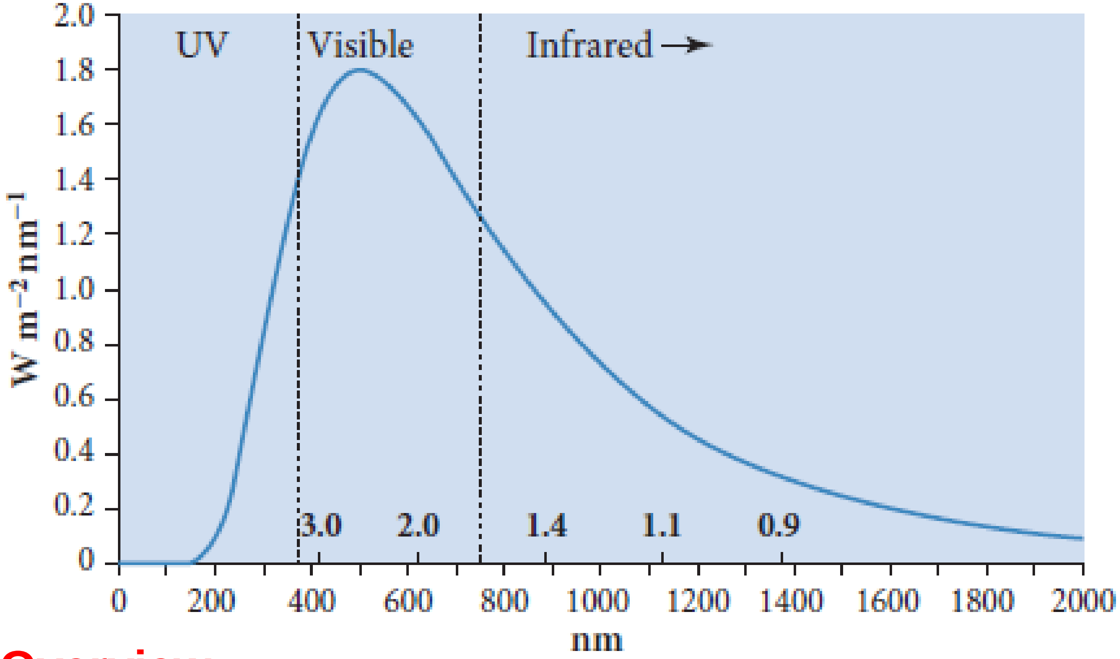
John Andrews & Nick Jelley

Lecture 8:

Photovoltaics

Incident solar radiation

Total incident power ≈ 150 000 TW (c.f. global power consumption in 2014 ≈ 19 $\mathrm{TW_{th}}$)



Solar spectrum is approximately that of a **black body at 5800 K**.

Average solar flux on the Earth ≈ **1 kW $\mathrm{m^{-2}}$** (the atmosphere reduces the flux from 1.37 kW $\mathrm{m^{-2}}$ to 1.0 kW $\mathrm{m^{-2}}$)

Overview:

- Silicon photovoltaic (PV) cells have ~20% conversion efficiency
- In 2015 installed capacity 242 GWp (output when1 kW $\mathrm{m^{-2}}$)
- Current growth ~ 25% per annum
- Cost of PV now competitive in several sunny regions with fossil fuel generation
- Could provide a very significant fraction of world electricity demand

Semiconductors

Photovoltaic cells are made from **semiconductors**, which are intermediate materials between **metals** and **insulators**.

Unlike metals, their **conductivity rises with increasing temperature**..

Their electrical properties can be altered by inserting impurities into the crystal structure, known as **doping**.

The effect of doping is to change the number of charge carriers in the material.

Materials with an excess of free electrons are called **n-type**, and those with an excess of positive holes are call **p-type**.

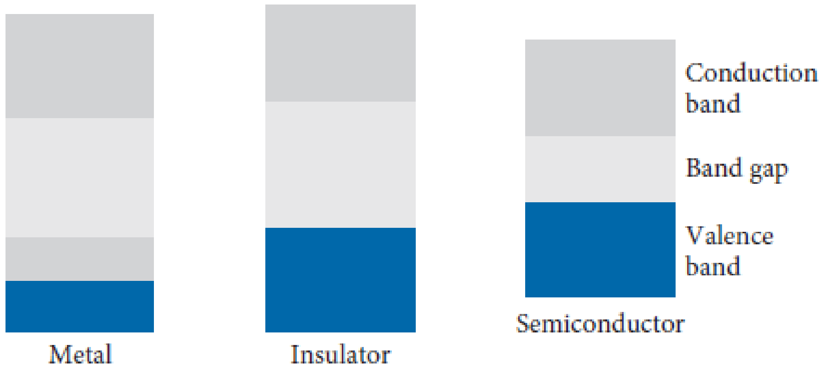
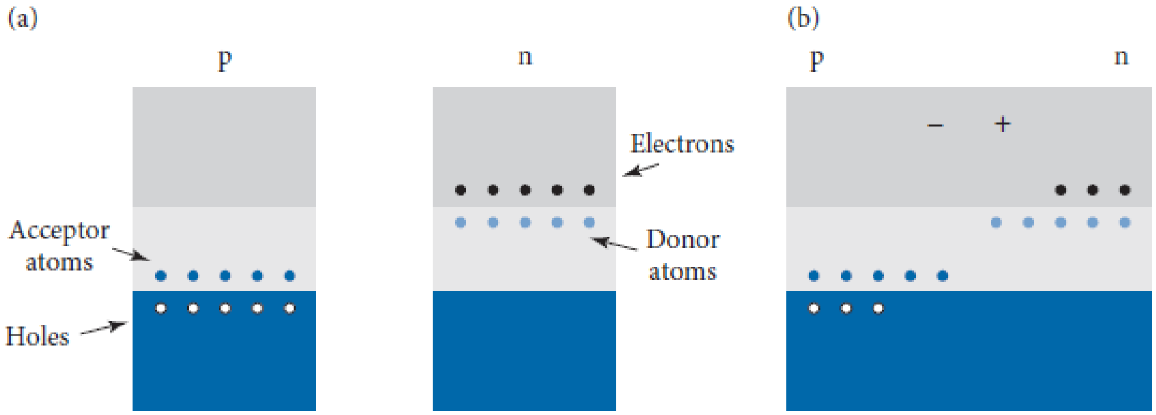


Fig. 8.3 Occupancy and band structure of a metal, an insulator, and a semiconductor.



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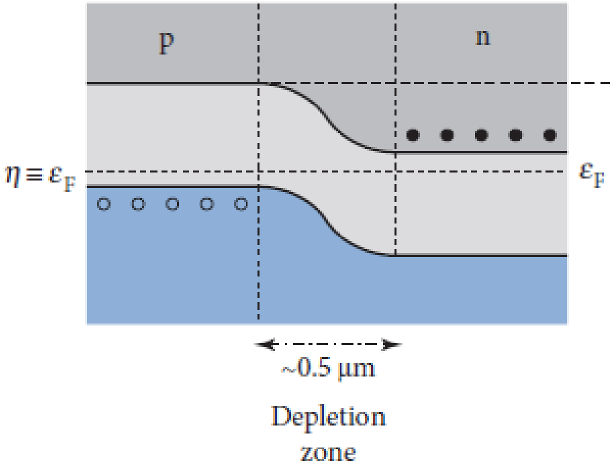
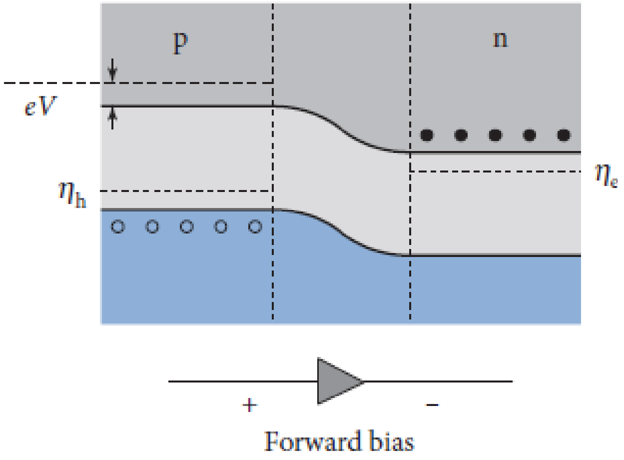
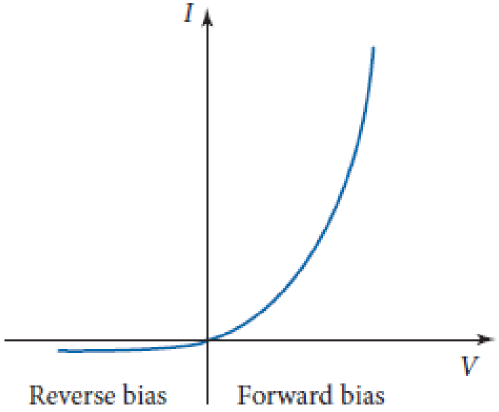
Energy levels at a p-n junction and effect of bias

At a junction between p-type and n-type semiconductors, electrons from the p-type materials diffuse across the junction and set up a **concentration gradient**, which creates an electric field that causes a drift of electrons to flow in the opposite direction.





Equilibrium is reached when there is **no net flow of current**.



The energy of electrons on the n-side is lowered compared with electrons on the p-side. When there is a **forward bias**, this difference in energy is reduced and a **forward current** is created, given by

$$I_F = I_S \left[\exp\left(\frac{V}{V_T} \right) - 1 \right]$$

where $V_T = kT/|e| \approx 0.026$ volts at room temperature and I_S is the **saturation current** (dependent on doping and area of junction).

Photocell

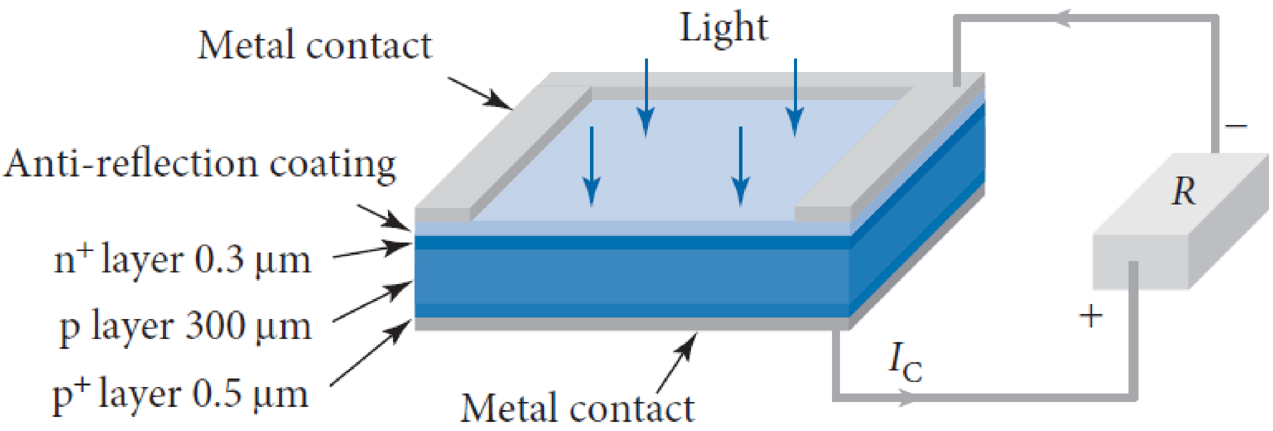


Fig. 8.7 Operation of a solar photocell.

Light impinging on a p-n junction creates electron-hole pairs, which diffuse and electrons are collected at top and holes at bottom junction, producing a light induced reverse current I_L.

The **minimum photon energy** required is equal to the band gap, E_{gap}.

In a **closed circuit**, a reverse current I_C flows within the cell from the n to the p region, given by

$$I_C = I_L - I_F = I_L - I_S\left[\exp\left(\frac{V}{V_T}\right) - 1\right]$$

, where $V_T = kT/|e| \approx 0.026$ volts

For a **silicon photocell**, $I_S \approx 10^{-9}$ A m^{-2} (saturation current), $I_L \approx 400$ A m^{-2} (light-induced current), and the open-circuit voltage ($I_C = 0$)

$$V_{OC} = V_T \ln\left(1 + \frac{I_L}{I_S}\right) \approx V_T \ln\left(\frac{I_L}{I_S}\right) \approx 0.7 \text{ volts}$$

Current-Voltage characteristic and Fill Factor

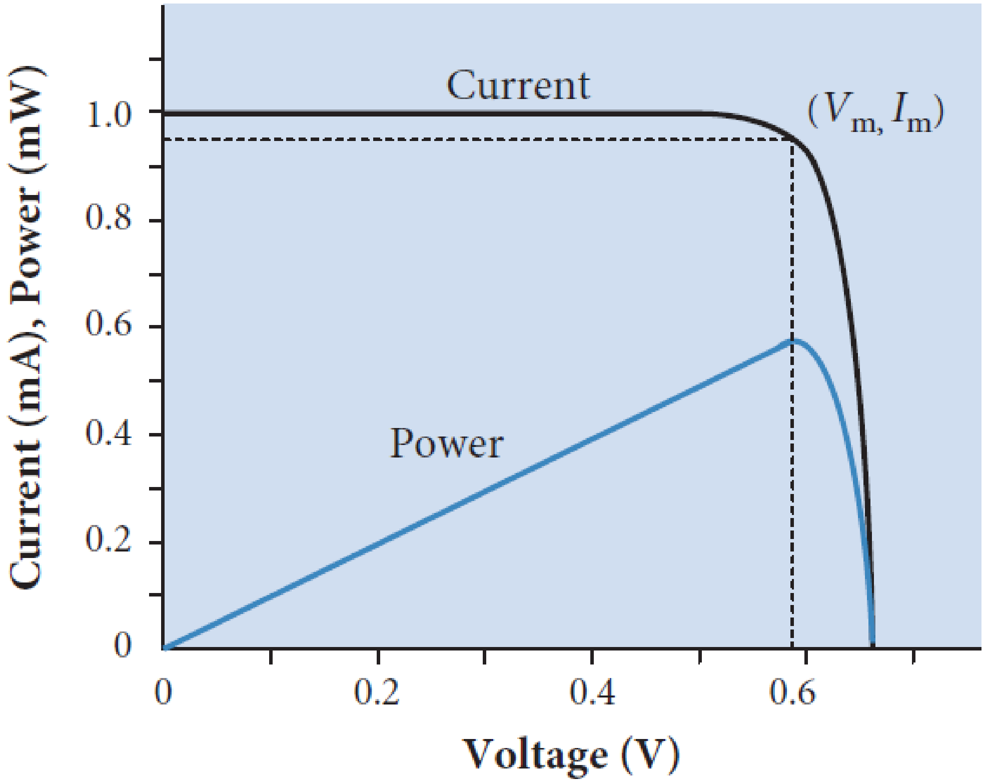


Fig. 8.8 Characteristics of a photocell.

A typical **Current-Voltage (I-V) characteristic** of a silicon PV cell is shown opposite.

Good PV cells have an I-V characteristic which is close to a **rectangle** (dotted line).

A useful measure of goodness is given by the **Fill Factor**, defined as the ratio

$$FF = \frac{P_m}{I_{SC} V_{OC}}$$

Good solar cells have $FF > 0.7$. Typically, $FF \approx 0.75 - 0.85$

For $V \ll V_{OC}$ then $I_F \ll I_L$, $I_C \approx I_L$, and the power $P = I_C V$ increases with rising V, until the increase in I_F and consequent decrease in I_C offsets the rise in V at V_m when $I_C = I_m$

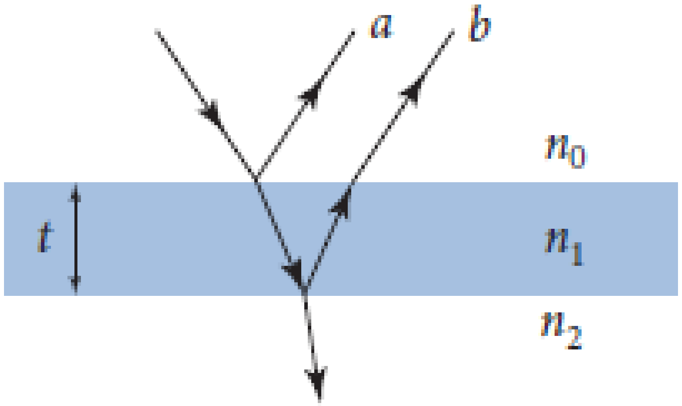
Efficiency of a photocell

The **efficiency of a photocell** is limited by a number of factors:

1 **Reflection from top surface**

Can be reduced from ~40% to ~6% using **quarter-wavelength** thick anti-reflection coating. Reflectance r between two media with refractive indexes n_1 and n_2 is given by

$$r = (n_1 - n_2)^2 / (n_1 + n_2)^2$$



For reflected components *a* and *b* to be out of phase, we put $t = \lambda/4n_1$ and the reflectance at each surface must be equal so $(n_1)^2 = n_0 n_2$

Using the quarter-wavelength effect over the range of solar wavelengths reduces *r* to ~6%

Multiple reflection coatings can reduce it still further to ~1%

Efficiency of a photocell (continued)

2 **Photons are too low in energy** (~23%) - energy wasted as heat

3 **Photons too energetic** (~30%) - excess photon energy ($h\nu - E_g$) lost as heat

4 **Voltage Factor** (~0.65) Voltage factor = eV_m/E_g ~ 0.7/1.1 (V_m = voltage at max power). Dependent on recombination rate

5 **Contact losses** front surface

6 **Charge collection efficiency**(~0.9) - some electron-hole pairs recombine

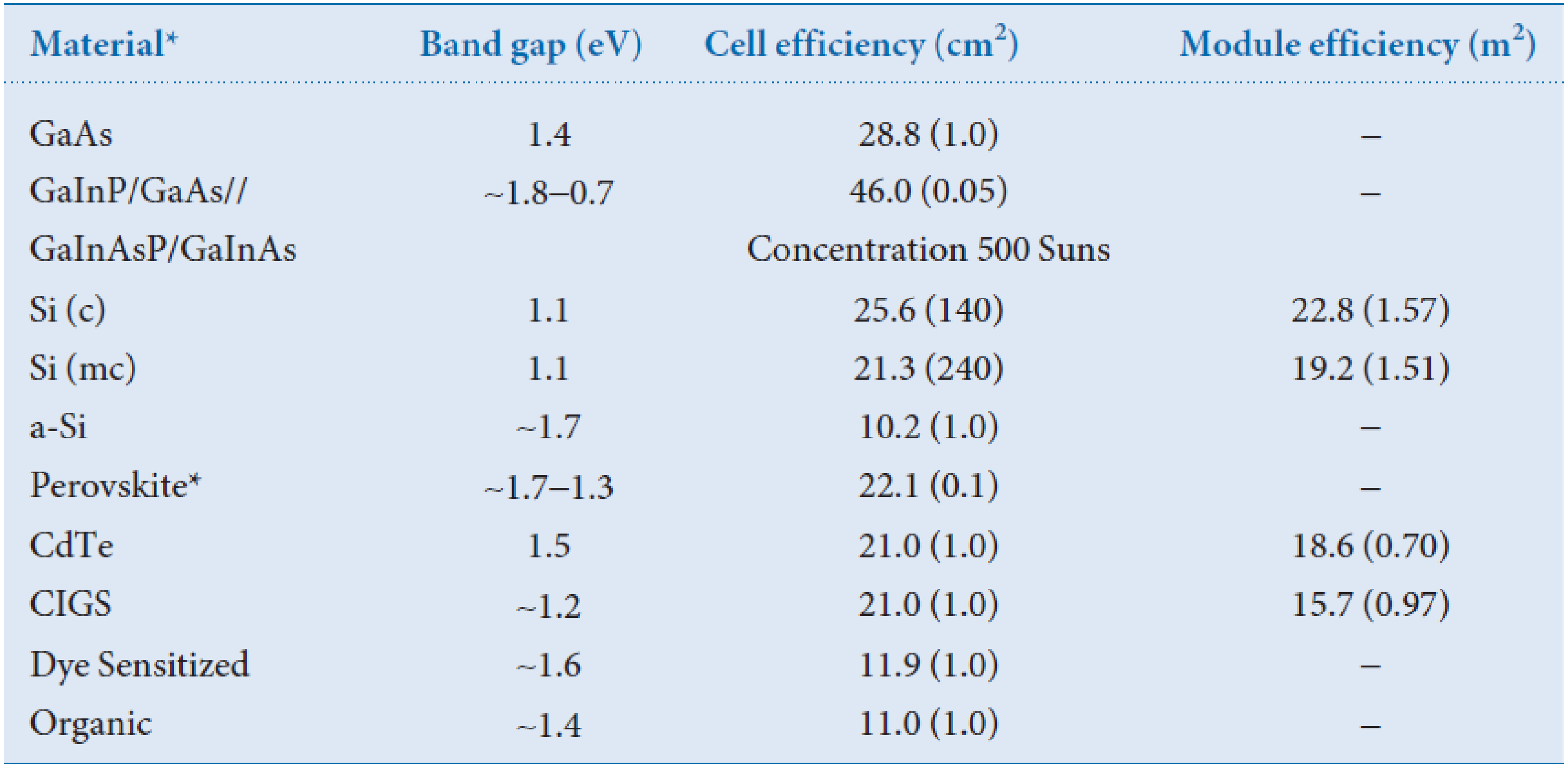
Overall efficiency ~ (0.96)(0.47)(0.65)(0.9) ~ 26%

(In 2015, state-of-the-art efficiency for standard mass-produced silicon PV modules ≈19%)

Commercial solar cells

There are 2 main types of solar cells in production today: **silicon cells** and **thin film cells**.

Silicon cells had **93%** share of the market in 2015. Production costs have fallen significantly in recent years through mass production and dedicated silicon purification plants.

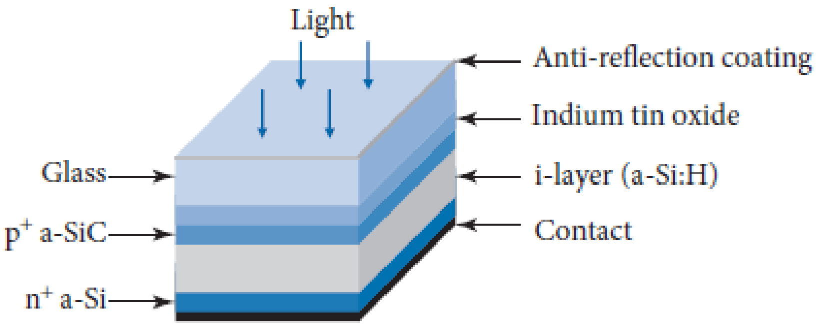


Material*	Band gap (eV)	Cell efficiency (cm^2)	Module efficiency (m^2)
GaAs	1.4	28.8 (1.0)	–
GaInP/GaAs// GaInAsP/GaInAs	~1.8–0.7	46.0 (0.05) Concentration 500 Suns	–
Si (c)	1.1	25.6 (140)	22.8 (1.57)
Si (mc)	1.1	21.3 (240)	19.2 (1.51)
a-Si	~1.7	10.2 (1.0)	–
Perovskite*	~1.7–1.3	22.1 (0.1)	–
CdTe	1.5	21.0 (1.0)	18.6 (0.70)
CIGS	~1.2	21.0 (1.0)	15.7 (0.97)
Dye Sensitized	~1.6	11.9 (1.0)	–
Organic	~1.4	11.0 (1.0)	–

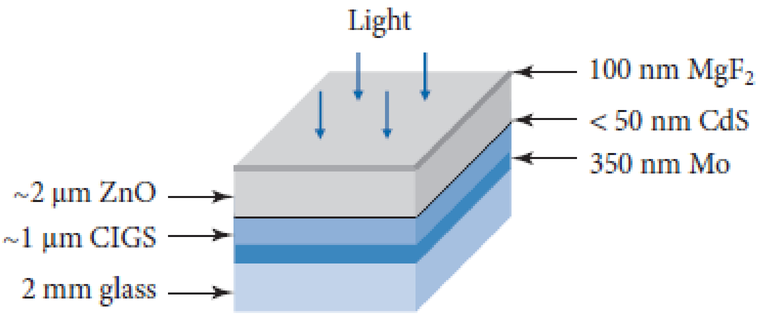
Thin film and multilayer cells

Amorphous Si: $E_g \sim 1.7$ eV; CdTe heterojunction $E_g \sim 1.5$ eV; CIGS $E_g \sim 1.2$ eV. All high optical absorption so thickness of order 1 μ.

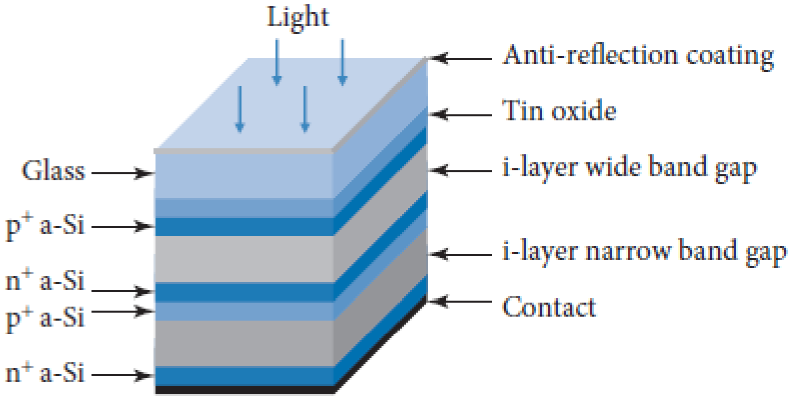
amorphous Si cell



CIGS cell

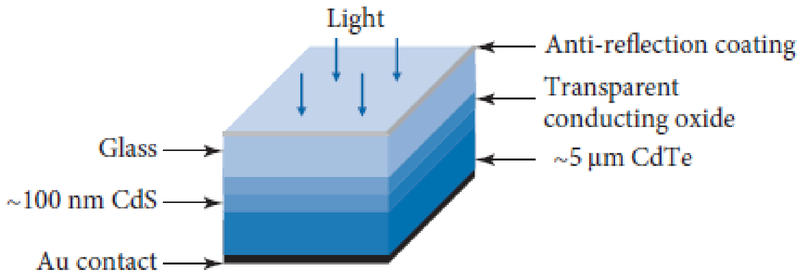


Two layers with upper wide and lower narrow band gap improves efficiency as more of solar spectrum absorbed.



2-layer amorphous Si cell

CdTe cell



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Concentrated Photovoltaics (CPV)

Solar energy reaches surface by **direct radiation** (focusable by mirrors) and as **diffuse radiation** (unfocusable). By concentrating sunlight onto PV cells, the area of cells needed per watt of output might be sufficiently reduced that the total cost of the cells plus optics plus trackers is less than that of a simple PV system.

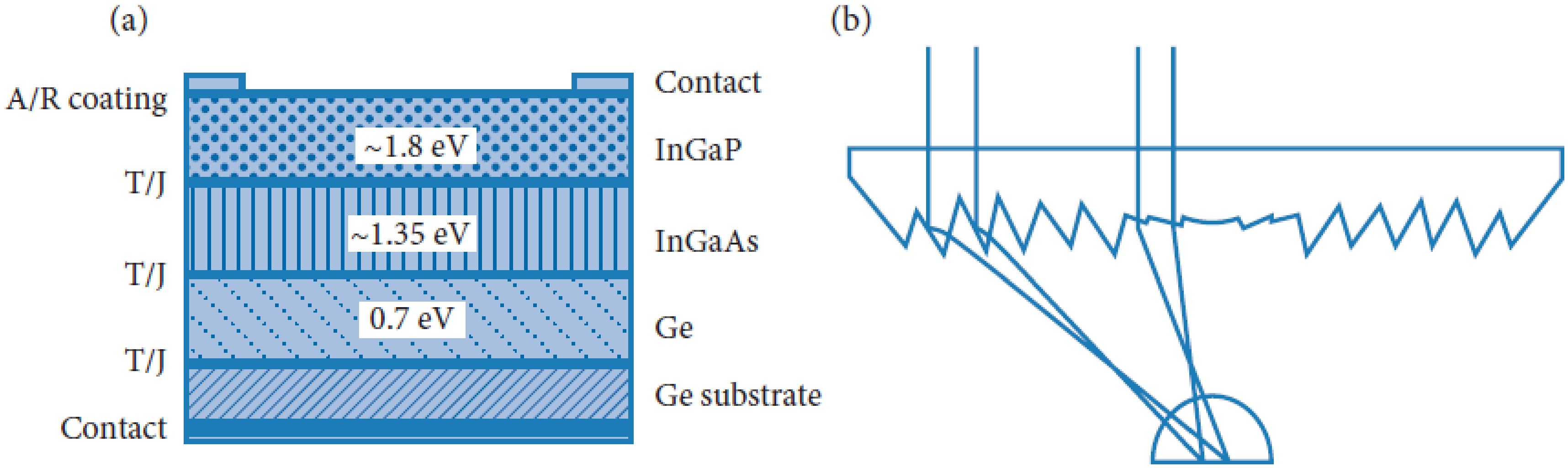
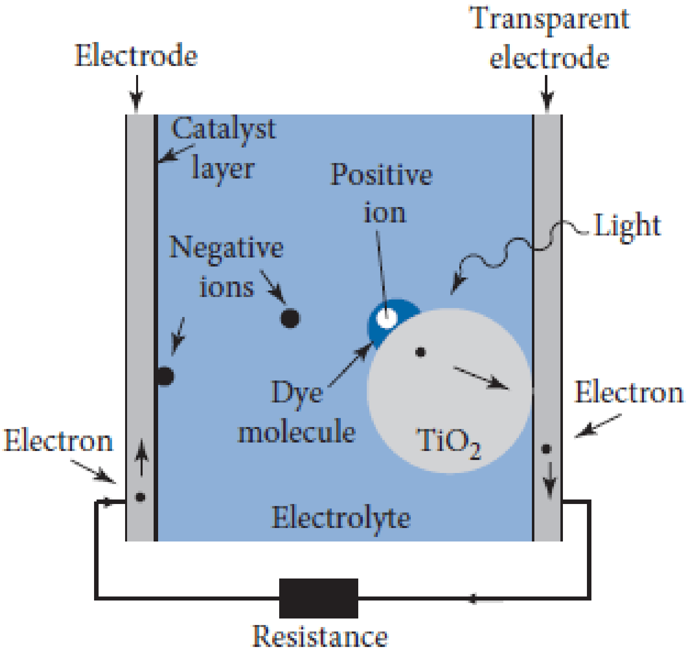


Fig. 8.15 (a) Multijunction solar cell. (b) Fresnel and domed lens concentrator.

Recent sharp fall in silicon PV has made CPV look uncompetitive, but CPV can operate at higher temperatures and waste heat is available for process heat or for CHP

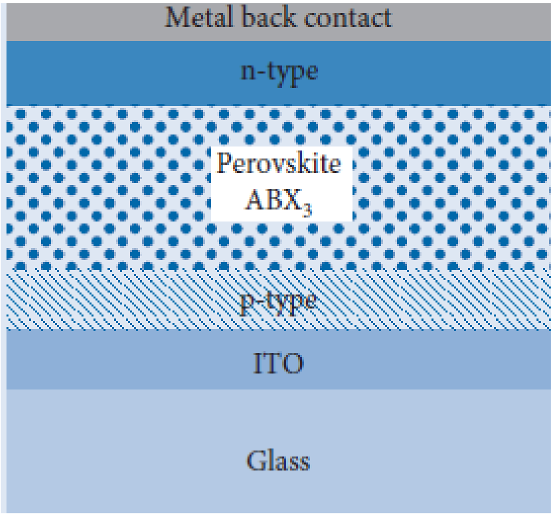
Developing technologies

Dye-Sensitized Solar Cell



(Gratzel and O'Regan, 1991) TiO_2 nanoparticles coated with dye molecules, which absorb light and produce electron-hole pairs. Efficiency ~ 12%.

Perovskite Solar Cell



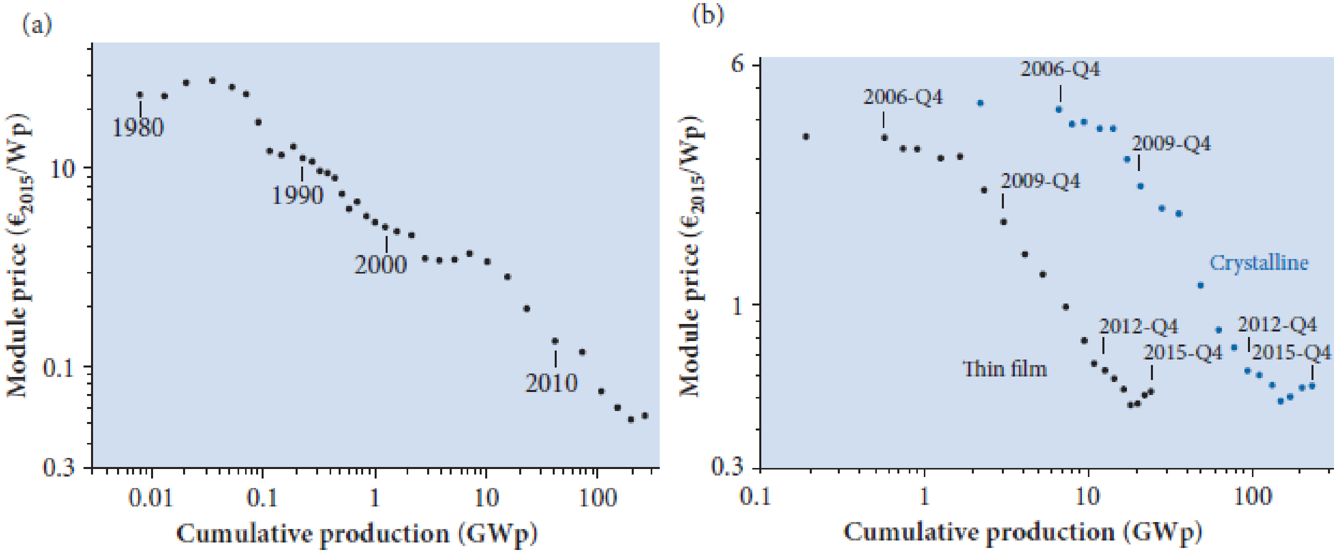
22% efficient has been achieved. As a top layer on Si, 30% possible. Cheap to manufacture but long-term stability needs to be established.

Organic Solar Cell: Considerable R&D on organic thin-film solar cells. If they could be printed on to flexible plastic sheet then large areas cheaply. These cells can have a coloured appearance, which is attractive in building integrated photovoltaic applications. Currently their competitiveness is affected by their relatively low efficiencies of ∼11%.

Learning effect and applications

Price of PV devices has fallen dramatically in last 35 years.

During 2010-2015, **learning rate** = 27% for crystalline silicon, 23.5% for thin film technologies.



Applications

- Large scale power generation: Large (> 50 MWp) PV farms in operation, but variable (as with wind), and not at night, so some backup electricity generation necessary.
- Distributed generation e.g. in Africa; avoids need for large grid.
- Remote locations/hot climates: Telecommunications, satellites, lighthouses, TVs, water pumping, air conditioning; refrigeration (food preservation, medicines)
- Low power devices: calculators, watches, radios, etc (ideal)

Solar farms and solar panels

Rapid growth in global number of **large PV solar farms** (> 50 MWp), e.g. California Valley solar farm =250 MW, capacity factor = 25%, uses 20% efficient silicon solar cells on single-axis tracking system, area = 796 ha. Over 120 solar farms of over 50 MW at start of 2016.

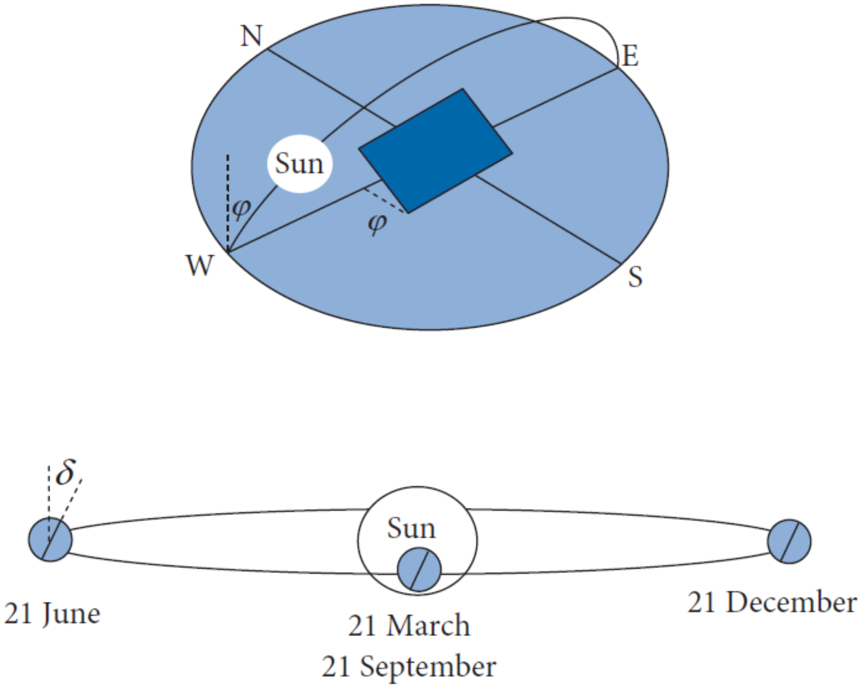
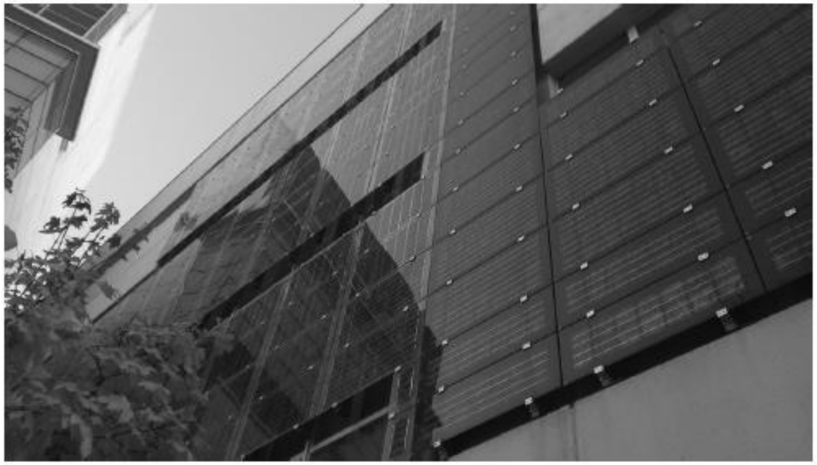


Fig. 8.20 Optimum orientation of a fixed solar panel.



Building-integrated **PV solar panels** can be used to replace tiles and windows.

Global trends

Global capacity has grown from 41 GWp in 2010 to 242 GWp in 2015.

Average **capacity factors** (CF): Middle East 26%, USA 20%, China 17%, Europe 17%, Global = 15%

Global output : 36 GWe in 2015 (~1.4% of global electricity)

Increasing fraction of electricity generation e.g. Italy 7.8%, Greece 6.5%, Germany 6.4% (2015)

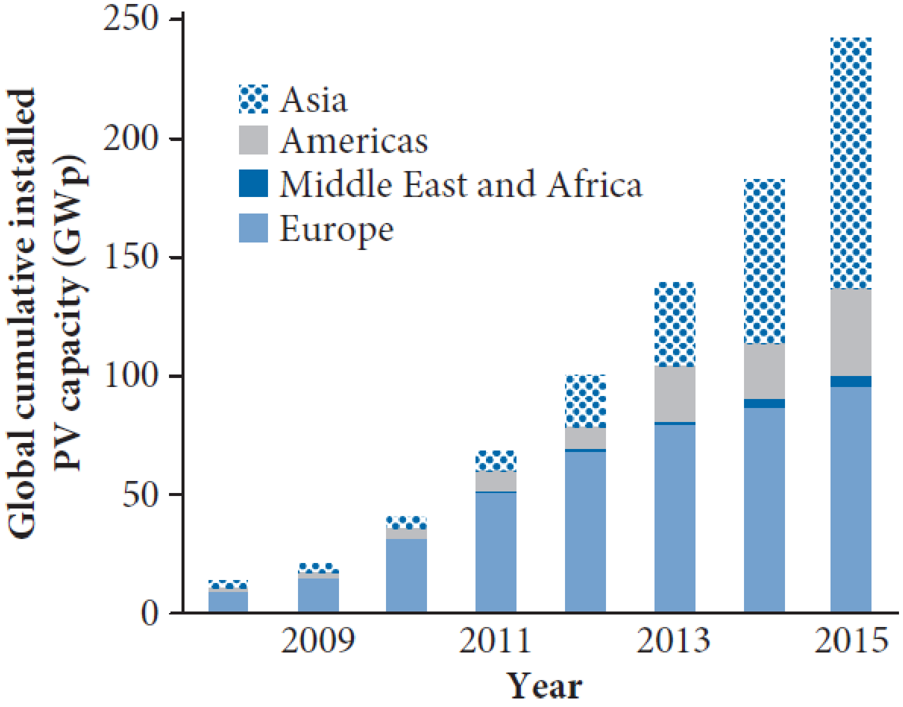


Fig. 8.22 Global installed PV capacity 2008–2015.

CO_2 emissions ~ 44 g CO_2 kWh^{-1}

Environmental impact: low

Potential: Estimate by 2050 ~ 2000 - 5000 GW_e ≡ 60 – 150 EJ (mainly developing/hot countries). IEA more conservative at 750 GWe.

Key Points

- Solar radiation is a **huge resource** offering more than 5000 times current world power consumption, but only a tiny fraction is currently exploited.

- **Solar intensity** (sunny day) is ~1000 W m^{-2}; PV power density is 5-10 MWe km^{-2}

- Silicon solar cells have conversion efficiencies of around **20%**
  Addition of a **perovskite** layer could raise efficiency to **~30%**

- The **manufacturing cost** of solar cells **is dropping significantly** and is likely to drop further through 'learning'

- The cost of generating electricity by photocells has dropped very significantly over the last 6 years and has now reached **grid parity** in many sunny regions with a LCOE ~$60/MWh.

- **Variability** of solar power means that for high penetration, extra capacity, storage, and demand side management will be required. Smoothing with super grids and using smart grids will help.

- Solar PV has great potential as a **low-carbon** source of electricity and could provide over **40% of global electricity by 2050**.