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EMTEU Education and Culture DG Lifelong Learning Programme

Photovoltaic Solar Power 1

Professor John I B Wilson

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Course Content

1. **Fundamentals**
    - Solar radiation
    - PV effect & semiconductors
    - Solar cell losses
    - *Semiconductor science (extra material)*
2. **PV cells & arrays**
    - Series & Parallel connection
    - Light intensity and temperature effects
    - PV parameters
    - Types of PV cell
    - PV efficiency
    - Modules / Panels
3. **Energy output**
    - Cost of PV panels & electricity
    - PV Performance Estimation
    - PV installation examples
    - Degradation
    - Maintenance
    - Balance of System Components

4. PV Connections

- Standards & Warranties
- Grid connection
- FiTs
- MCS
- The MCS Guide to Installation …
- Health & Safety Legislation
- RECC

5. Balance of system components

- Types of inverters
- Inverter operating principle
- Inverter sizing and lifetime
- Battery storage and charge controllers
- Battery science and parameters
- Battery system design

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Solar Radiation

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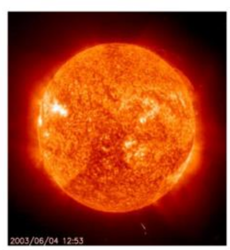
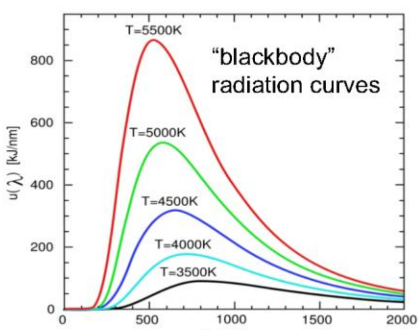
Our Nuclear Fusion Reactor:



NASA



Wikipedia

Equation for each curve:
Energy depends on temperature of surface:

$$I(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda KT}-1}$$

Peak Wavelength x Temperature = Constant:

$$\lambda_{max}T = 2900\ \mu m\ K$$

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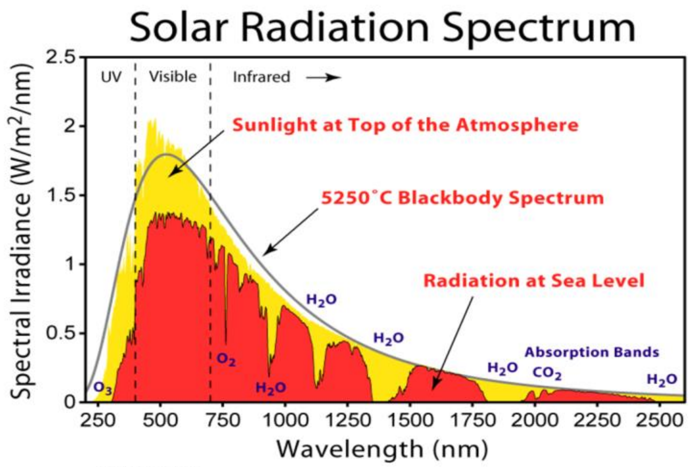

Wikipedia

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Diffuse & Direct Solar Radiation

- "Direct Solar Radiation" arrives directly from the sun and is measured by a *pyrheliometer* mounted on a solar tracker
- "Diffuse Solar Radiation" is scattered by molecules, dust, clouds
- "Global Solar Radiation" is the sum of these falling on a horizontal surface and is measured by a *pyranometer*
- Diffuse solar radiation is blue-shifted

- *How is the diffuse component obtained?*

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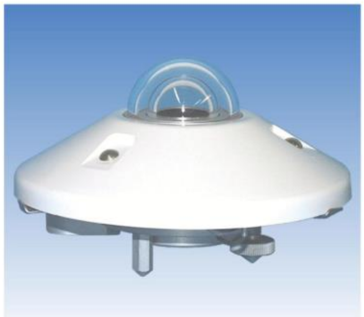

Kipp & Zonen Pyranometer

OSC pyrheliometer

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Air Mass Number

- The angle ϕ between the zenith (vertically above Earth's surface) and the direct solar beam determines the maximum radiation anywhere on the Earth's surface:

  $$\text{Air Mass} = 1 / \cos \phi$$

- AM0 is the value of the solar radiation outside the Earth's atmosphere [1.350 kW m^{-2}]
- AM1 is the value on the Earth's surface when the Sun is directly overhead, in the tropics [~1kW m^{-2}]
- Higher latitudes (e.g. Northern Europe) see only ~ AM1.5
- *E.g. What is the air mass number when the sun is at an altitude of 30^o to the horizontal?*

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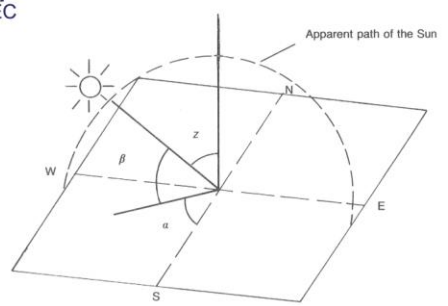
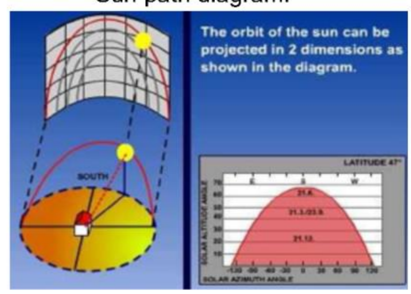


Figure 2.6. Definition of solar altitude, β, azimuth, α, and zenith, z.
β = angle between line from Sun to Earth's centre, and tangent to Earth's surface.
α = angle between south meridian, measured in horizontal plane westwards, and the direction of the Sun.
z = angle between the line from the Sun to the Earth's centre, and the normal to the Earth's surface.

Sun path diagram:



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Seasonal Variations

How much solar radiation falls on a surface over any day of the year?

- Find the angle of the Sun in the sky: *"solar declination" is tabulated for latitudes throughout the year*
- Calculate hours of daylight: *3-D geometry problem*
- Find *AM* number for that day
- Include small seasonal change in solar constant: *Earth's orbit is eccentric*
- Allow for any tilt (and azimuth) in the collector surface
- Allow for diffuse component: ~$I_H \cos^2$ (tilt angle/2)
- *Both intensity and spectrum vary with Sun's position.*

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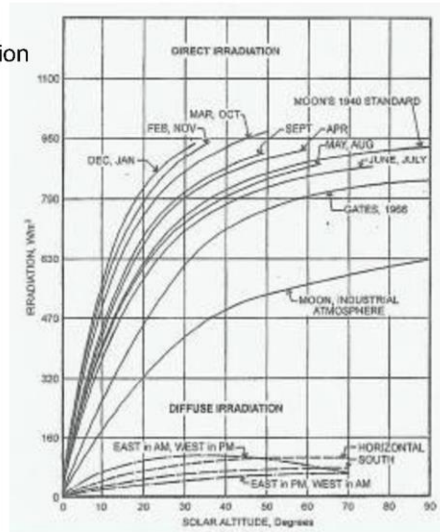
Showing wide variation in seasonal direct and diffuse solar irradiance



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Reflection Effects

- Reflectivity of any surface depends on material and its smoothness, and on spectrum, polarization, and incident angle of illumination.
- Solar cells do have antireflection (A/R) coatings or a textured surface, but the module cover glass should also be treated (giving ~3% boost).
- Antireflection (A/R) coatings or texturing may be applied to cover plates to reduce this loss in radiation, but roughened surfaces may trap dirt unless they have a "closed surface" and inner porosity. Present day mass produced A/R coatings have a lifetime of ~15 years.
- Textured A/R is being combined with an anti-soiling coating and durability is improving. (*e.g. functionalised silica nanoparticles*).
- N.B. The adjacent surfaces to a solar collector of any type may usefully reflect radiation on to the collector (either specular or diffuse paths).

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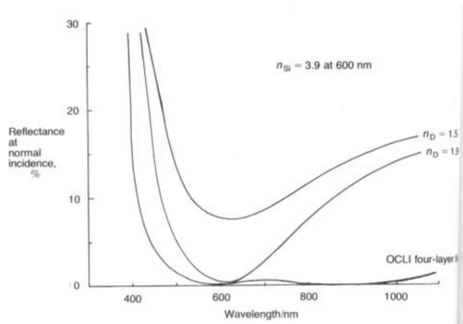

Figure 11.6. Anti-reflection coatings on silicon (n_D is the refractive index of the coating). (Based on data from OCLI, California, USA.)

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Photovoltaic Effect

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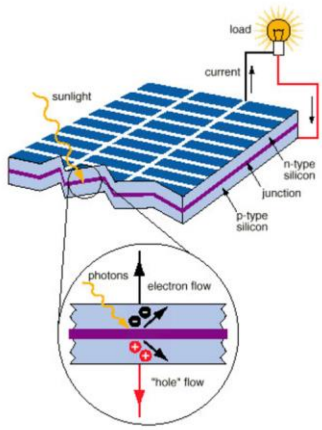
Sunlight to Electricity



(Murdoch University)

- Absorbed light generates pairs of charges
  –> current
- Charges separated by junction field
  –> voltage
- Contacts pass charges to load
  –> power

Power = Volts x Amps

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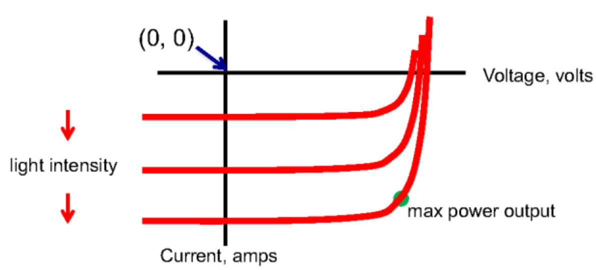
Solar cell output

Current depends on illumination and area [~60 A m^{-2}]

Voltage depends on built-in field [~ 0.6V]

Efficiency depends on illumination, semiconductor material and cell structure [~5 - 20 %]

Power available depends on load resistance and on cell's current ~ voltage characteristic [??? W m^{-2}]



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Semiconductors

Photovoltaic solar cells convert quanta of light (photons) to quanta of electrical energy (electrons, holes) without a thermal, chemical or mechanical process.

- The active material is a *semiconductor* which conducts electricity better than insulators but worse than metals.
- The atoms making up the semiconductor (e.g. Si) are held together by chemical bonds: essentially the forces between the outer "valence" electrons of each atom bind them together into a symmetrical lattice.
- The valence electrons may be released by energising them (e.g. light or heat): these become free to move through the lattice of ions/atoms.

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The minimum energy to free a valence electron is the *binding energy* or *bandgap energy*, E_g. At room temperature it is 1.11 eV for Si and 1.43 eV for GaAs. (The value decreases slightly with increasing temperature.)

A note on photon Energy units:

$E = h\nu$ and $c = \lambda \nu$ — $\lambda \uparrow$ implies $E \downarrow$

where: h is Planck's constant = 6.63×10^{-34} J s
c is speed of light = 3.00×10^{8} m s^{-1}
ν is frequency, s^{-1}
λ is wavelength, m

As Joules are too big to describe a photon's energy we use eV (electron volts) where 1 eV = 1.60×10^{-19} J

The 1.11 eV bandgap energy of Si may therefore be provided by a single photon of wavelength <1.1 μm (near infrared)

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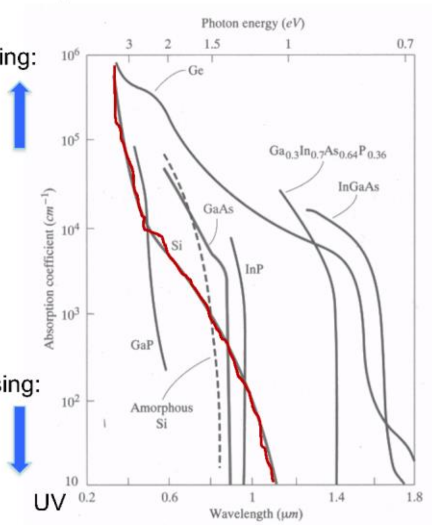
Optical absorption of semiconductors: spectral dependence

Absorption increasing: thinner material required

Absorption decreasing: thicker material required



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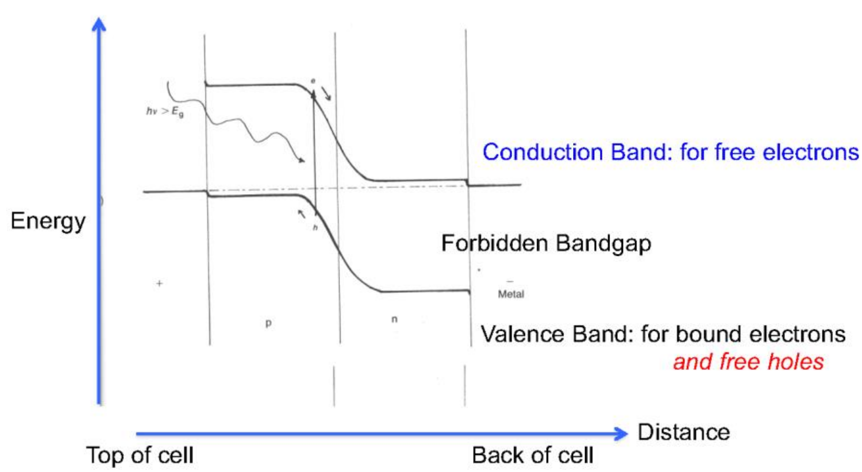
Operation of a PN junction photovoltaic cell can be shown on an *energy diagram*:



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Photovoltaic Losses: optical & electrical

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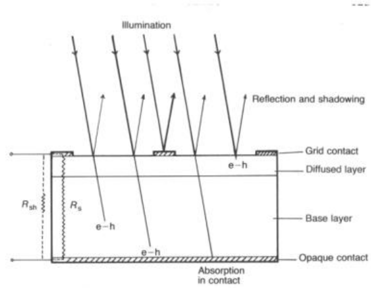

Figure 11.1. Losses in photovoltaic cells. e–h signifies production of free electron–hole pairs and subsequent recombination.

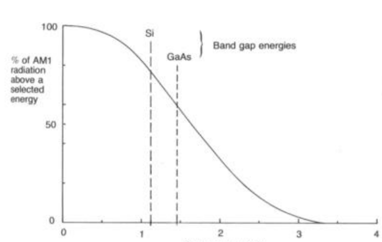

Figure 11.2. Percentage of AM1 insolation capable of producing electron-hole pairs in a chosen semiconductor.

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Note that each incoming photon will only be absorbed if it has energy higher than E_g
Low energy photons (long wavelengths) will pass through the semiconductor
High energy photons (short wavelengths) will each only produce one electron-hole pair.

Where does the remainder of the photon energy go?

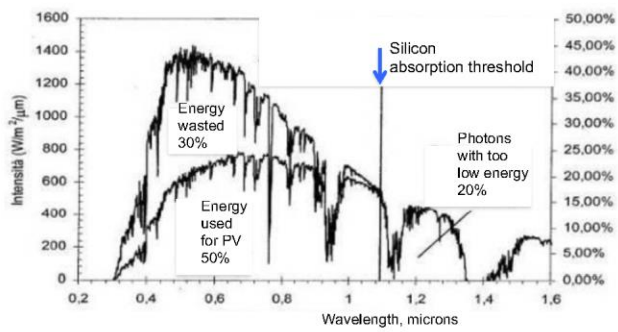

Figure shows the energy used from the AM1.5 solar spectrum by a Si cell.

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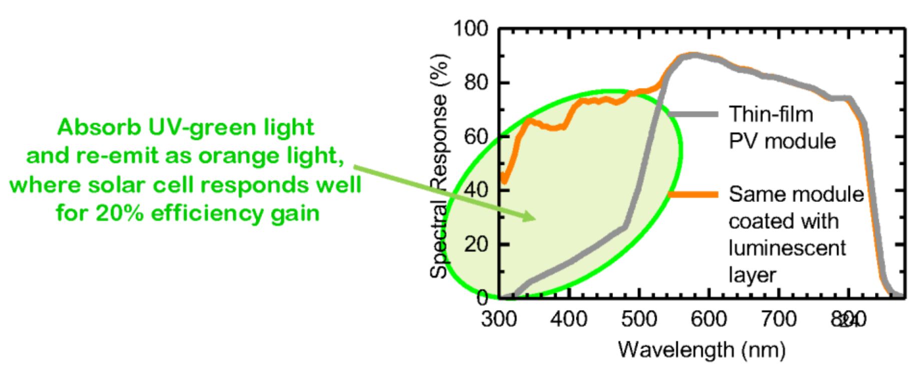
Improving PV Performance by Converting the Solar Spectrum

Some PV modules respond poorly to UV-blue light
Use luminescent materials to absorb these wavelengths and re-emit at longer wavelengths



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"Photovoltaic Windows"

B.S. Richards, Karlsruhe Institute of Technology

Large sheets of cheap material (e.g. plastic) incorporate luminescent materials to absorb sunlight; emitted light is trapped within the sheet, leaving at the edge where solar cells are placed

even concentrates light when cloudy

But still inefficient!

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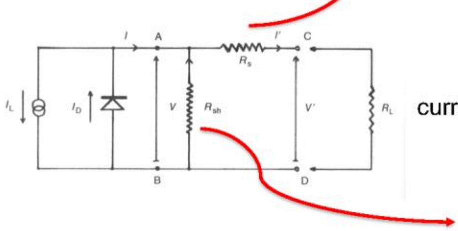
Electrical equivalent circuit of a photovoltaic cell; resistance losses



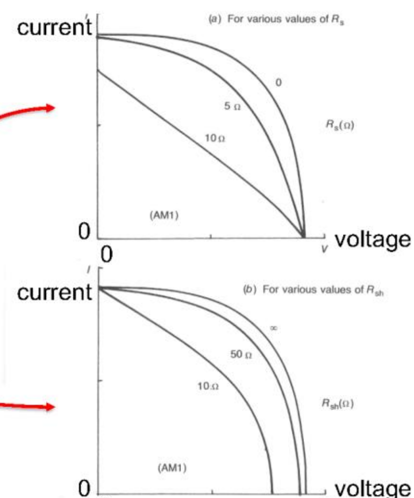


Figure 7.12. The effect of resistance losses on p–n Si solar cell characteristics (cell area 2 cm^2).

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Semiconductor Science

material additional to course

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Silicon has very few free electrons at room temperature, so is insulating: pure Si has only ~ 2 x 10^{16} m^{-3} electrons at room temperature but metals have ~ 2 x 10^{28} m^{-3} at room temperature.

{The number of free electrons actually depends on: $1/exp\ (E_g\ /\ 2KT)$ }

So we can introduce electrons by heating (but causes other problems), or by illumination (at the correct wavelength), or we can *dope* the lattice by adding particular impurities:

Donors, such as phosphorus, readily provide extra electrons (making Si *n-type*) and *acceptors, such as boron,* provide extra holes (making Si *p-type*).

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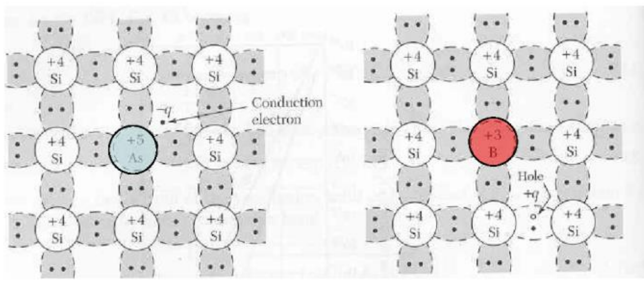
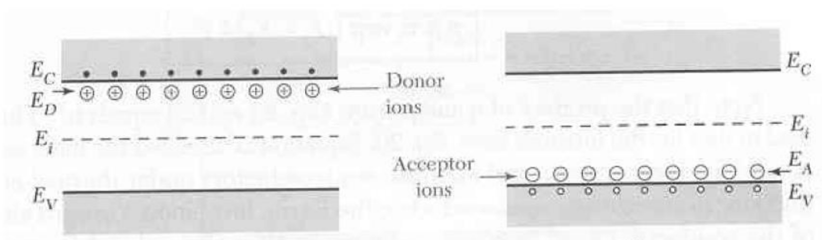


These various binding energies can be shown on an energy diagram:



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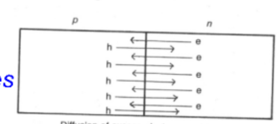
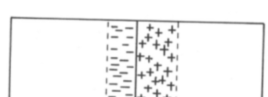
A PN junction will contain a built-in electric field caused by diffusion of mobile charges leaving behind the fixed, charged, dopant ions:

Free charges, electrons and holes



Diffusion of excess electrons and holes sets up a depletion region.

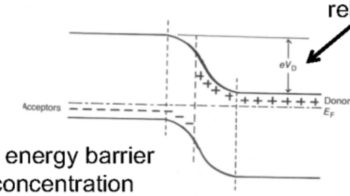
Fixed charges, ionised dopants



Fixed ionic charges, uncompensated locally by free charges, give a built-in electric field.

Height of energy barrier is related to built-in voltage

Energy band diagram



Width and height of energy barrier depend on doping concentration

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Summary - part 1

1. **Fundamentals**
   - Solar radiation
   - PV effect & semiconductors
   - Solar cell losses
   - *Semiconductor science (extra material)*

Questions?

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