ES427: The Natural Environment and Engineering

Global warming and renewable energy

Lecture 3: Photovoltaic cells

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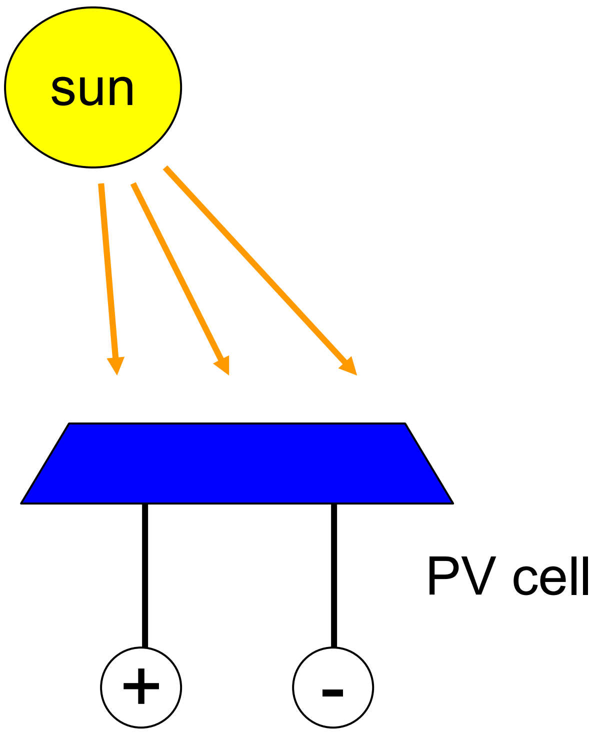
Overview of lecture

- Photovoltaics: fundamental attractions and drawbacks
- How does a photovoltaic cell work?
  - Review of semiconductors, electrons and holes
  - Absorption of light in semiconductors
  - The p-n junction
- Anatomy of solar cells and modules

Photovoltaics (PV): attractions

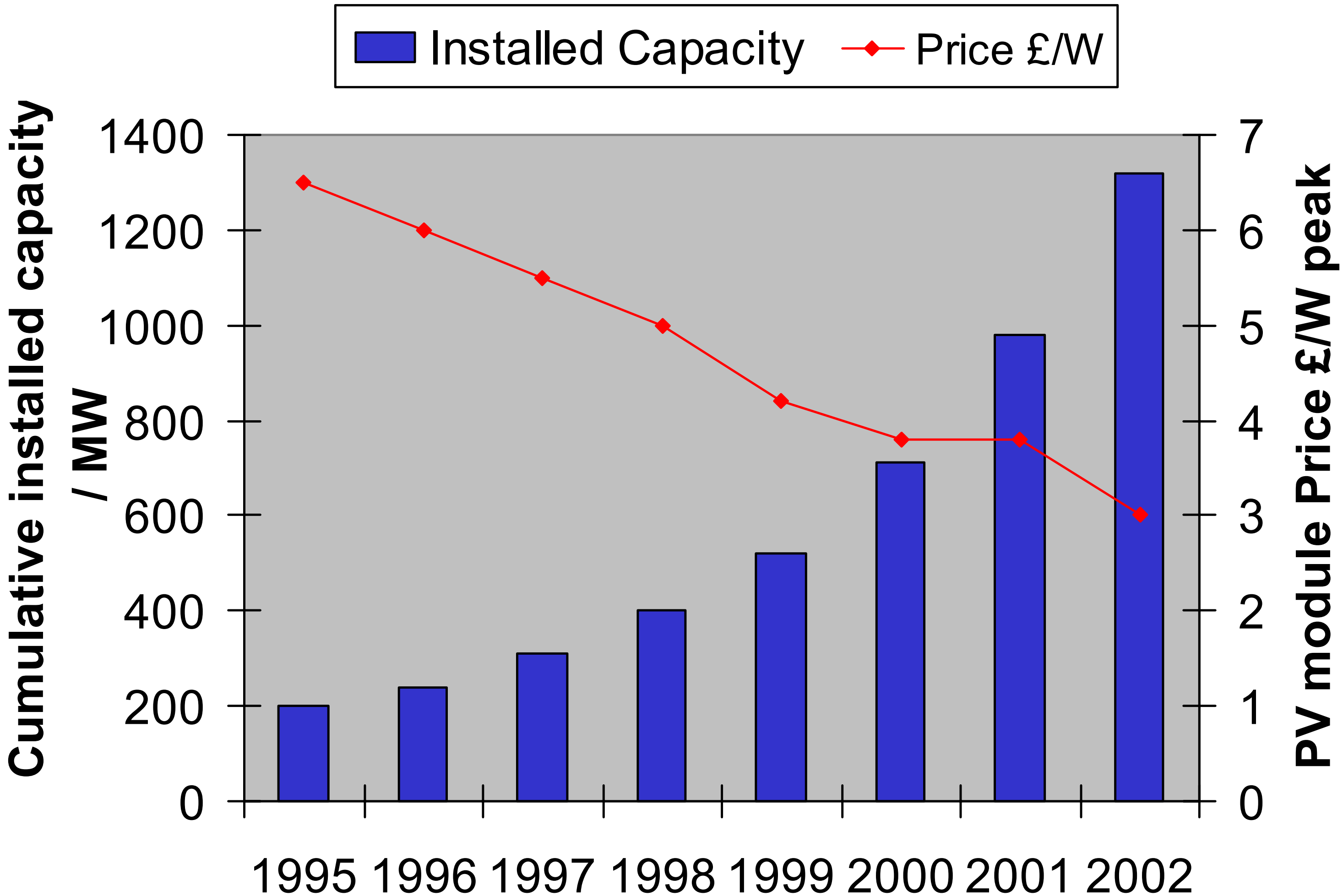
- Converts sunlight directly to electricity
- Sunlight is the most abundant renewable resource (175 PW)
- Electricity is a very versatile form of energy
- No moving parts, long lifetime (>20 years)



Photovoltaics: drawbacks

- Sunlight is very spread out (<1 kW/m^2)
- It is irregular and somewhat unpredictable
- Electricity is difficult to store
- So far PV cells are expensive compared to other means of power generation

Growth in PV market



Timeline of PV applications

1950's	First modern PV cells
1960's	Satellites
1970's	Remote industrial applications
1980's	Rural electrification, water pumping. First grid-connected systems.
1990's	Building integrated systems
2000's	Market continues to grow …

Building integration: Grid-connected house, Devon

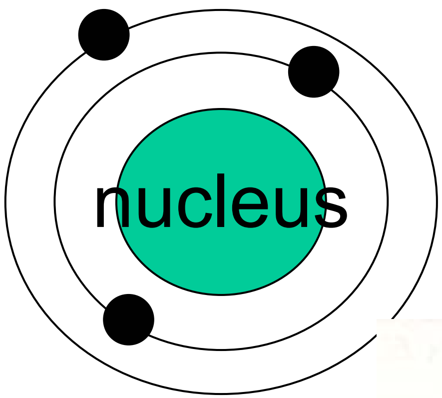
Solar Cell Materials

We focus on crystalline silicon solar cells because:

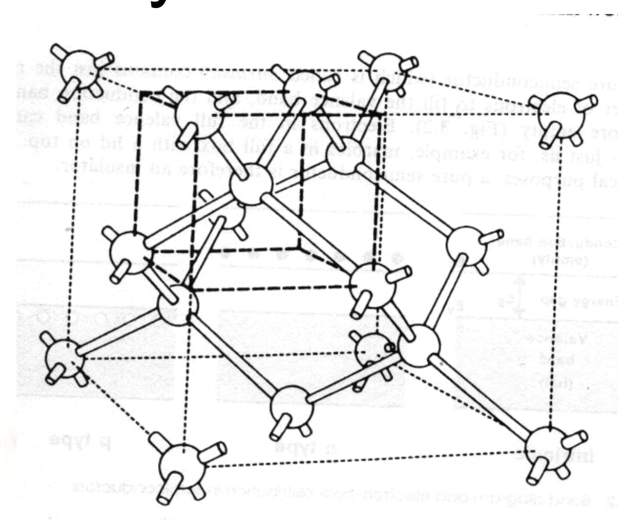
- They account for over 95% of the world market
- Mostly of this is either multi- or mono-crystalline silicon (as opposed to amorphous)
- Silicon is a semiconductor, as are the other materials that are sometimes used

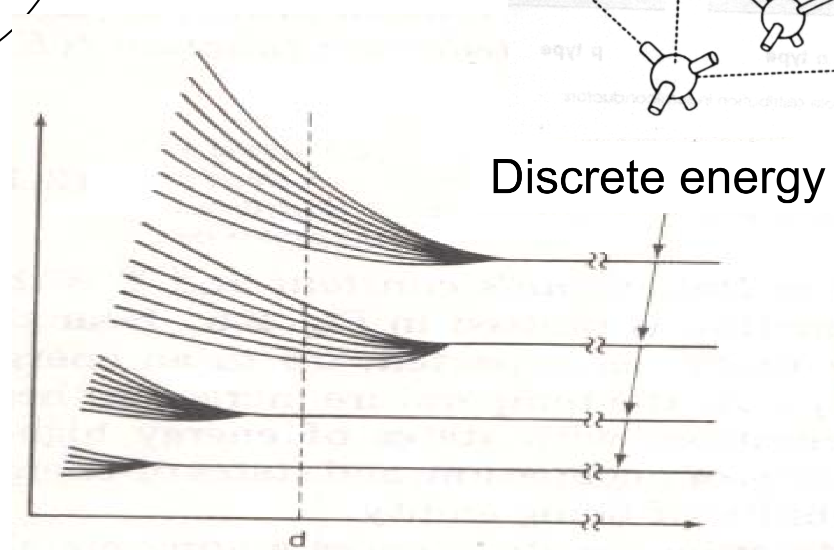
Energy states of electrons

Individual atom

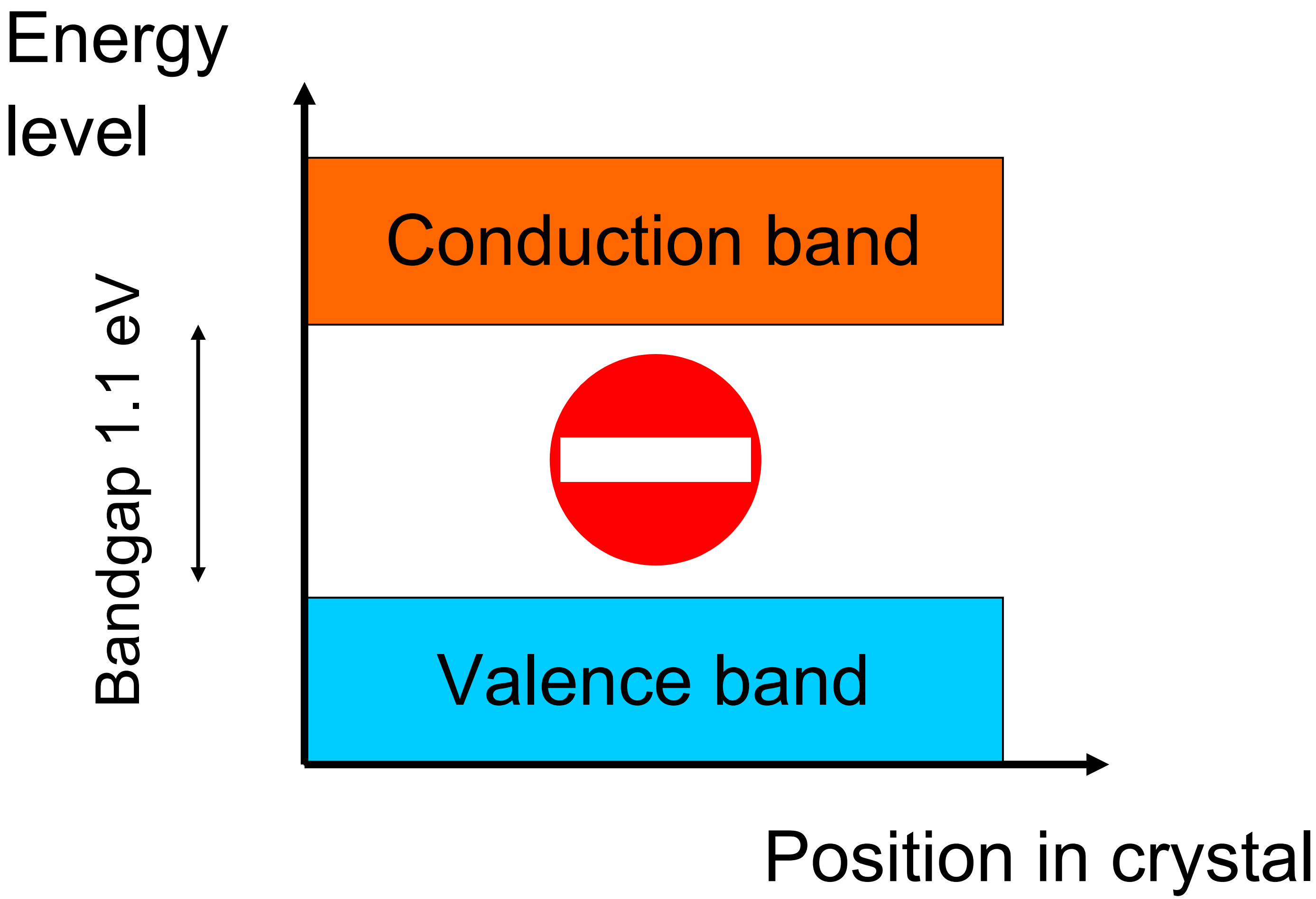


Crystal lattice

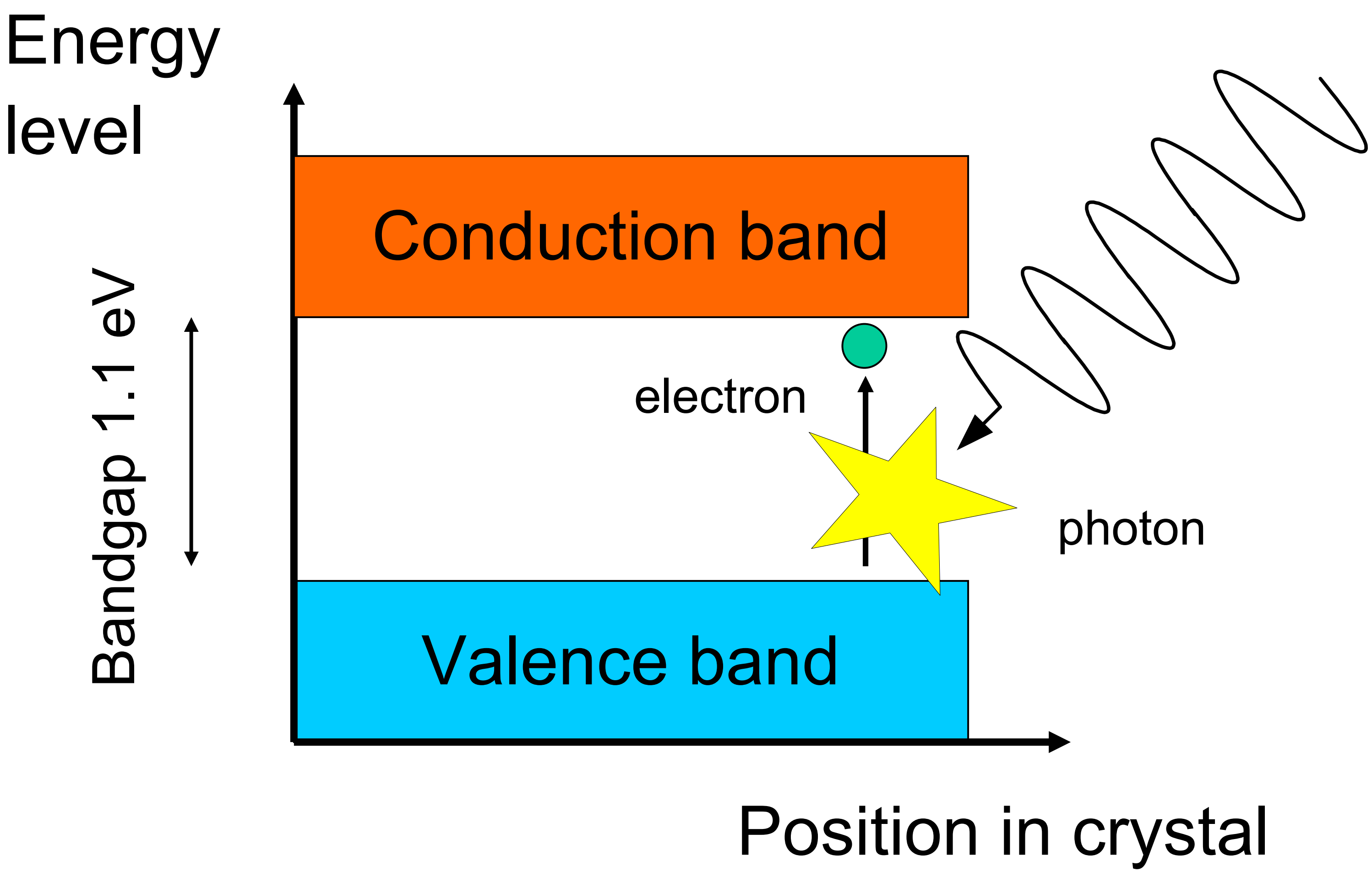




Forbidden zone

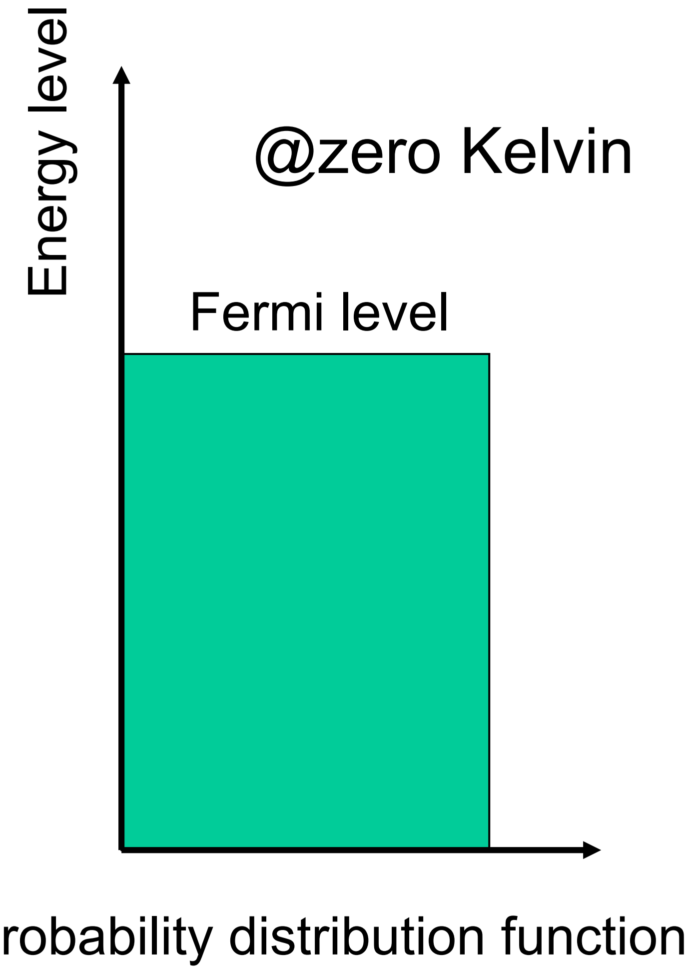


Photogeneration



Fermi level

- Pauli exclusion principle: no more than two electrons in a system can occupy exactly the same energy level
- This means that, even at zero K, electrons will have energy levels above zero
- Energy levels are filled up to a maximum, called the **Fermi level**

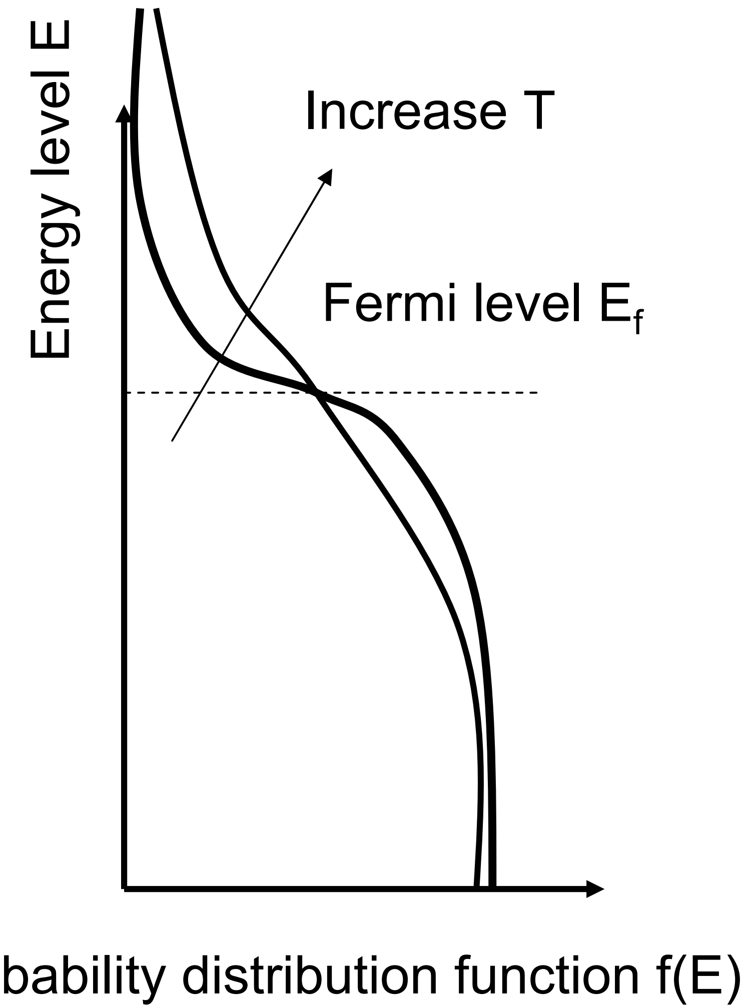


Fermi-Dirac distribution

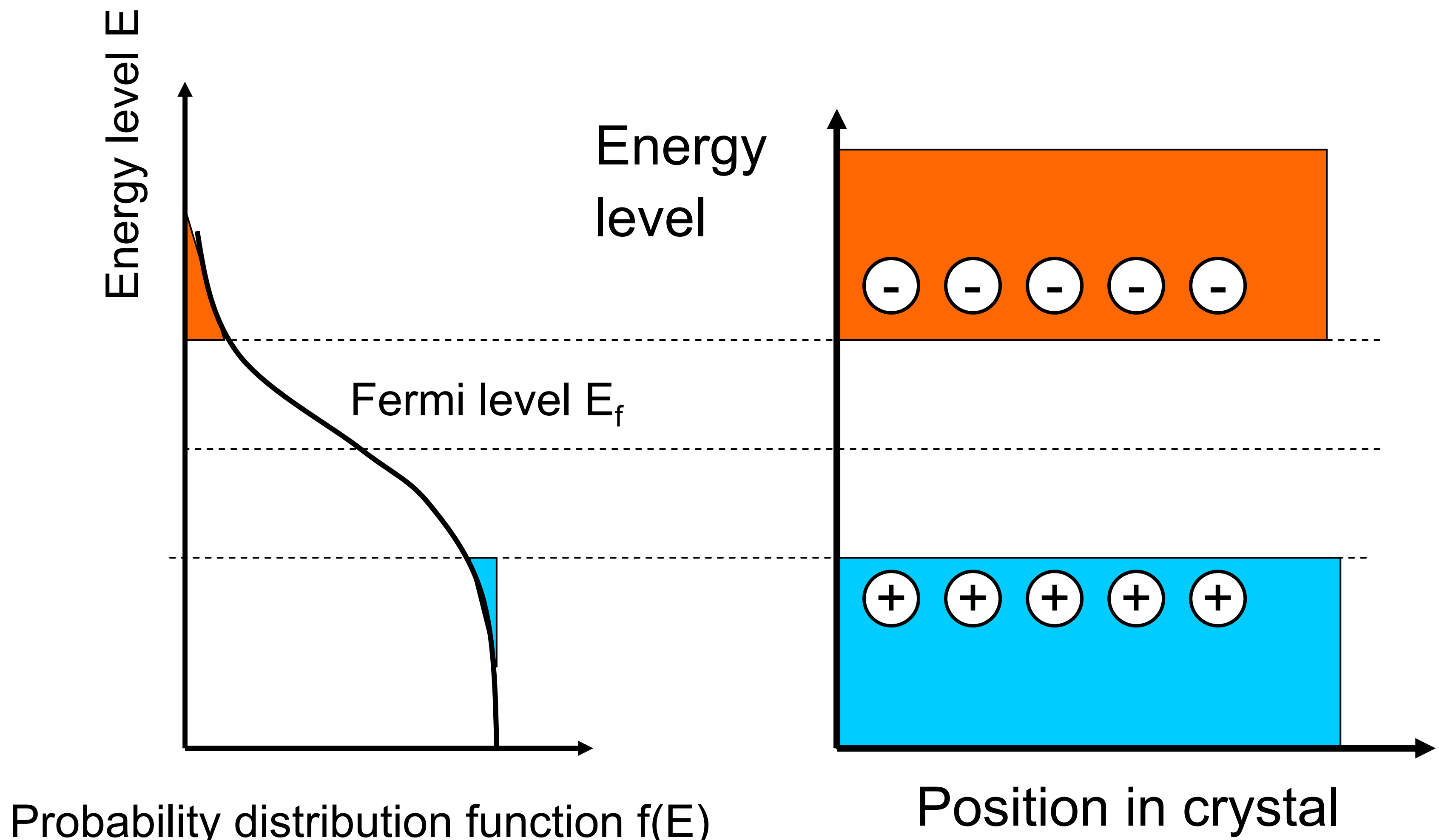
- As temperature T increases, some electrons start to occupy states above the Fermi level. This is represented by the Fermi-Dirac distribution function:

$$f(E) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

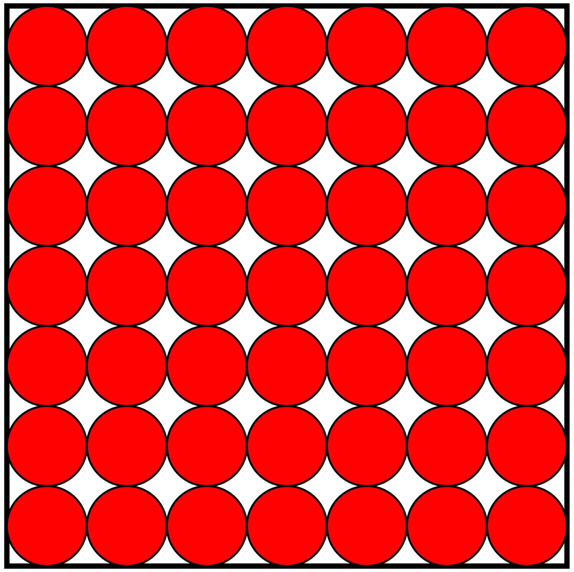
k is Boltzmann's constant



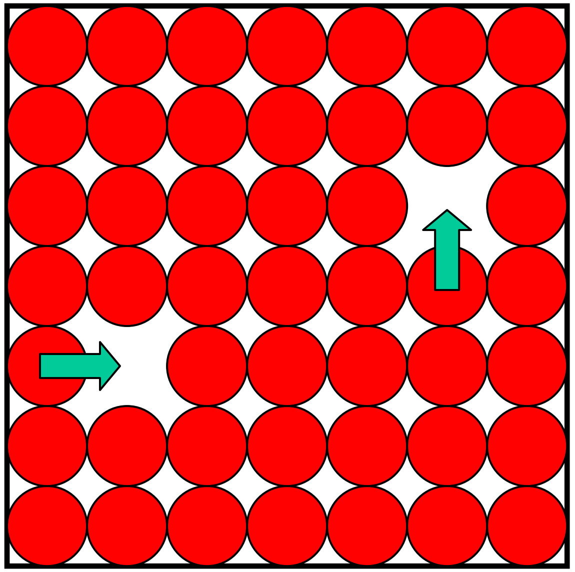
Fermi-Dirac distribution and forbidden zone



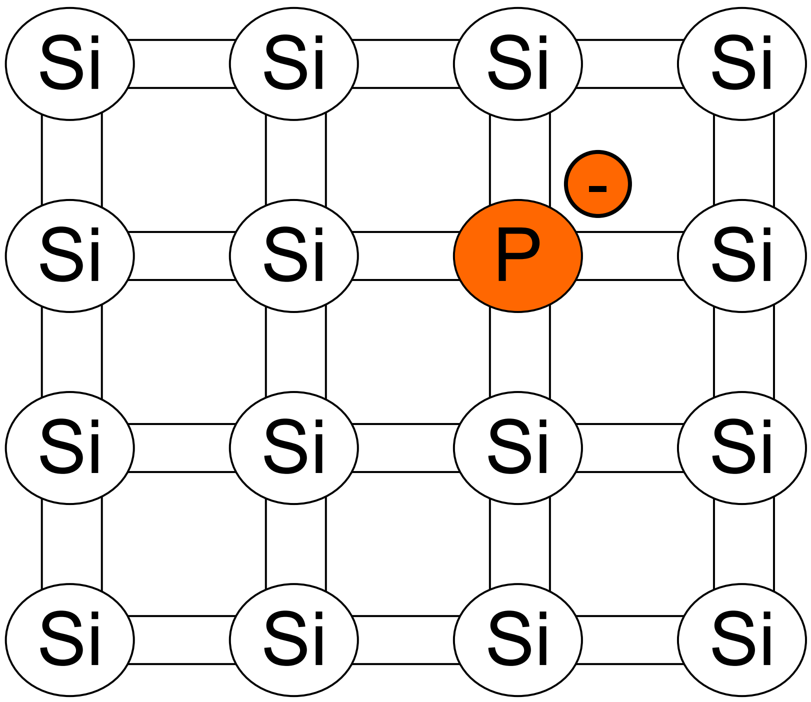
Holes

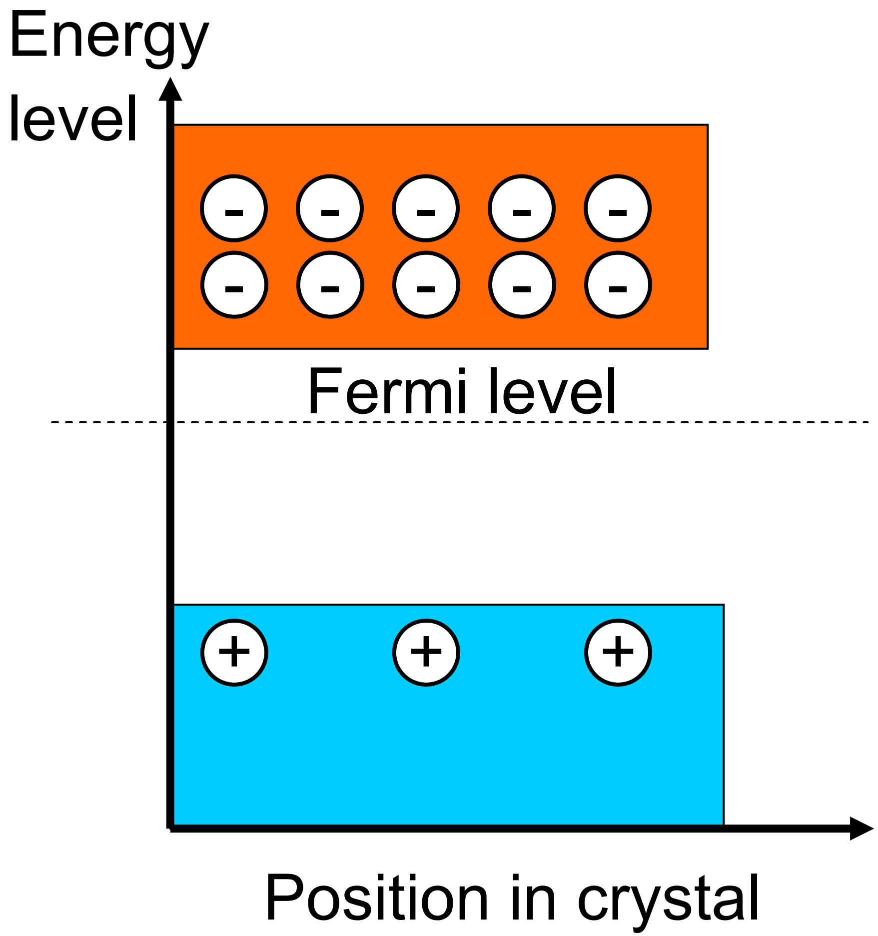


Grid lock

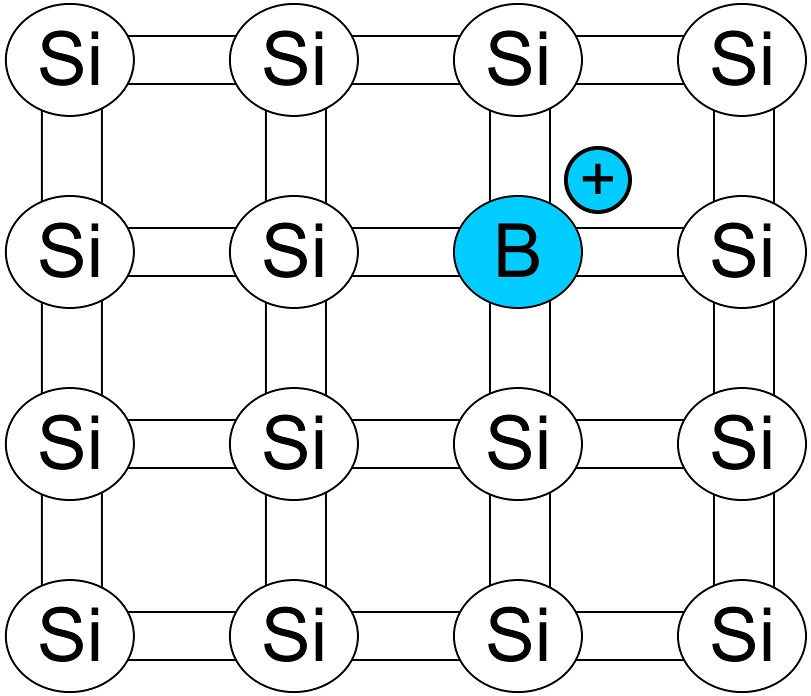


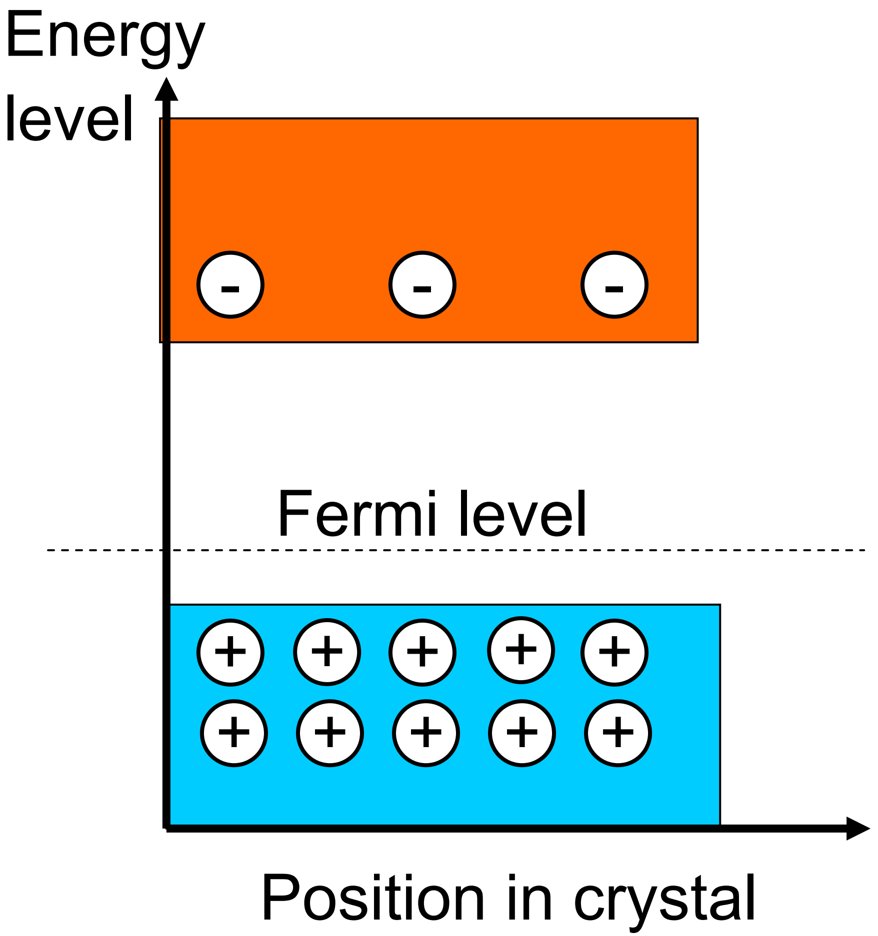
Doping: n-type



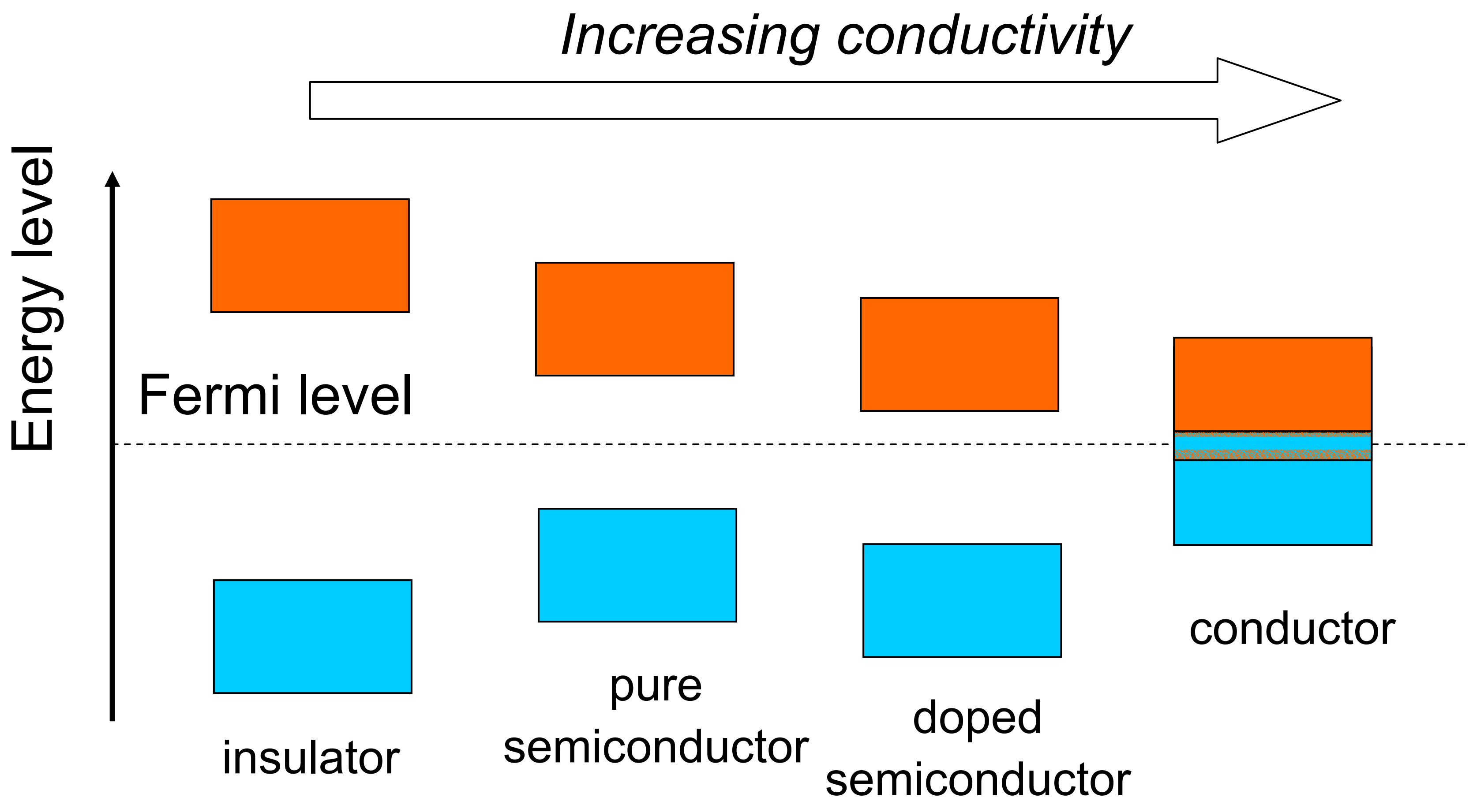


Doping: p-type



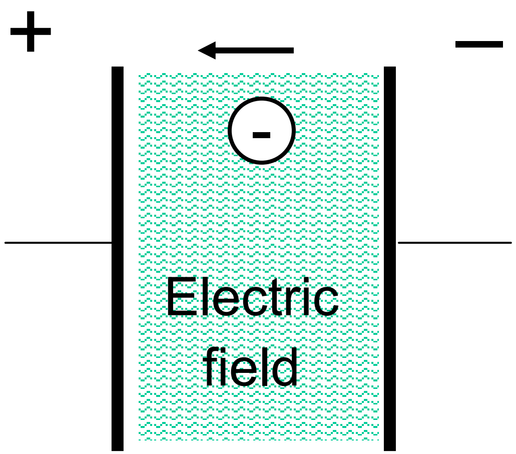


Insulators, semiconductors, conductors

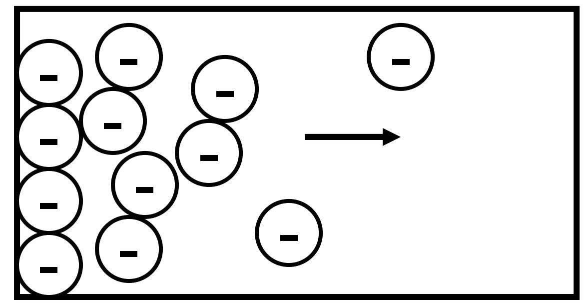


Conduction processes

Drift



Diffusion



Field strength

Current density: $J_e = q\mu_e n\xi + qD_e \frac{dn}{dx}$

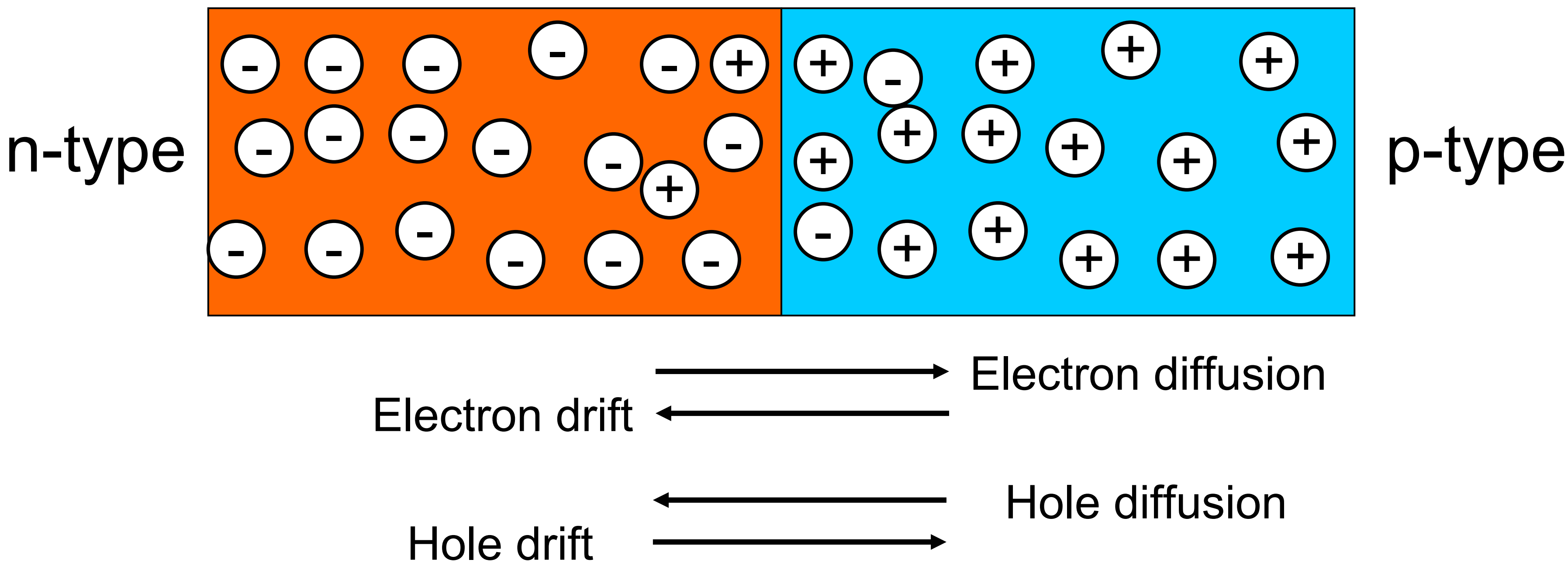
Unit charge

mobility

Concentration of electrons

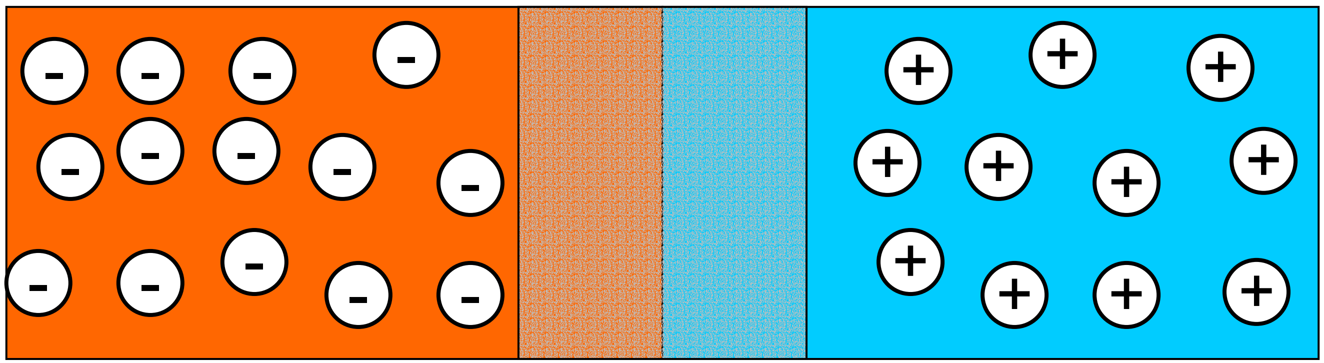
diffusion coefficient

p-n junction


n-type
p-type
Electron diffusion
Electron drift
Hole diffusion
Hole drift

p-n junction

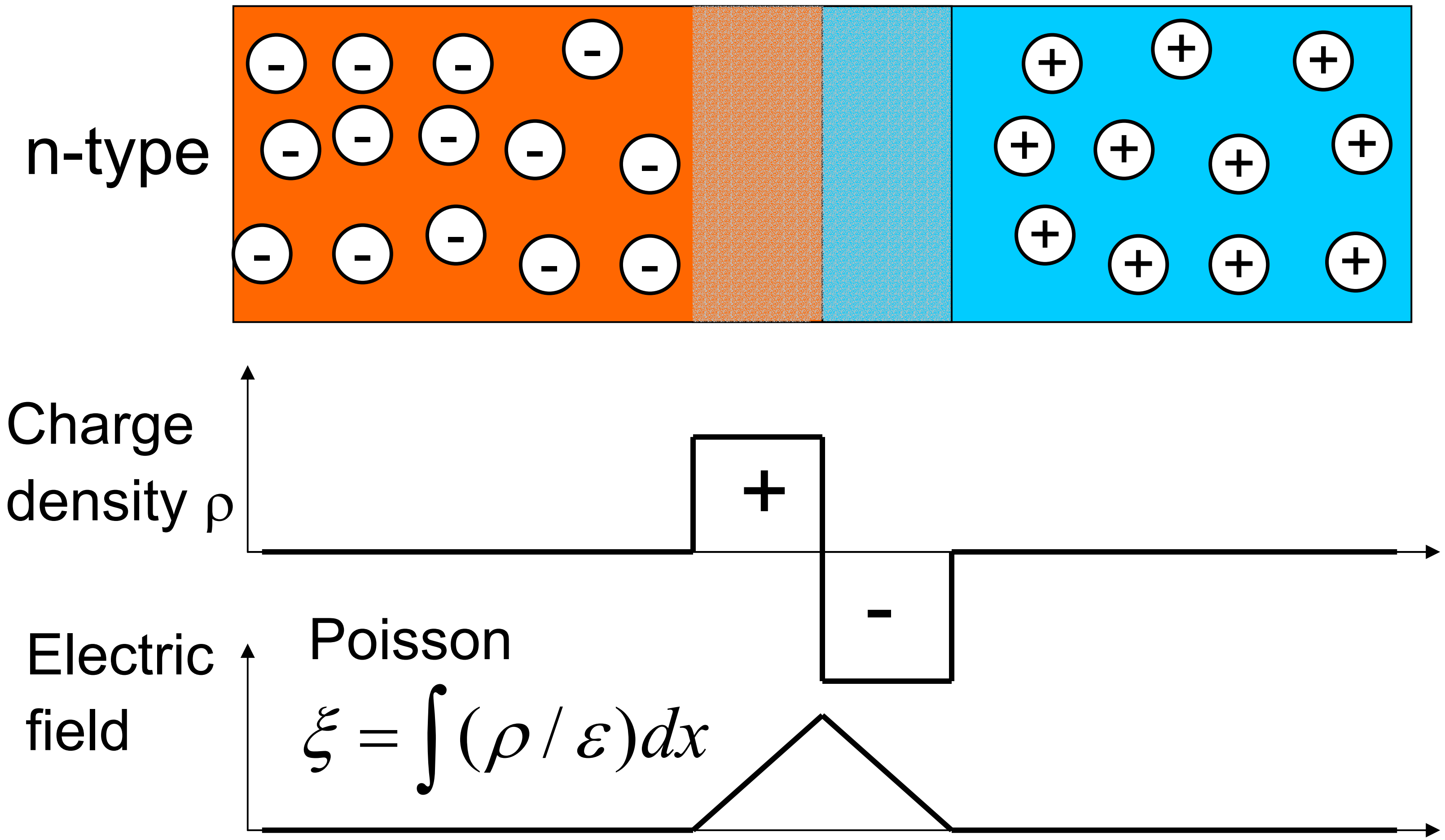
n-type



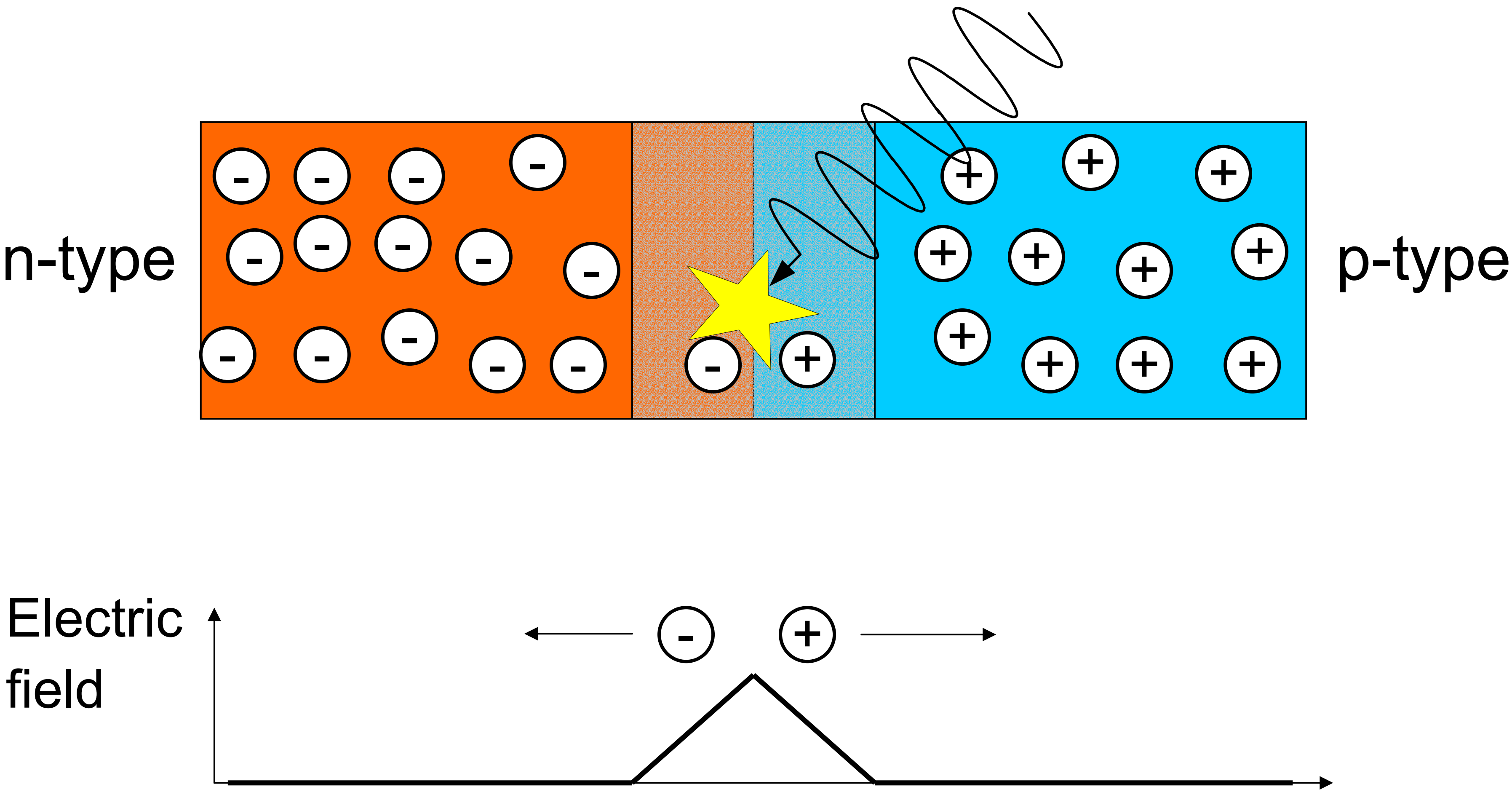
p-type

Depletion region

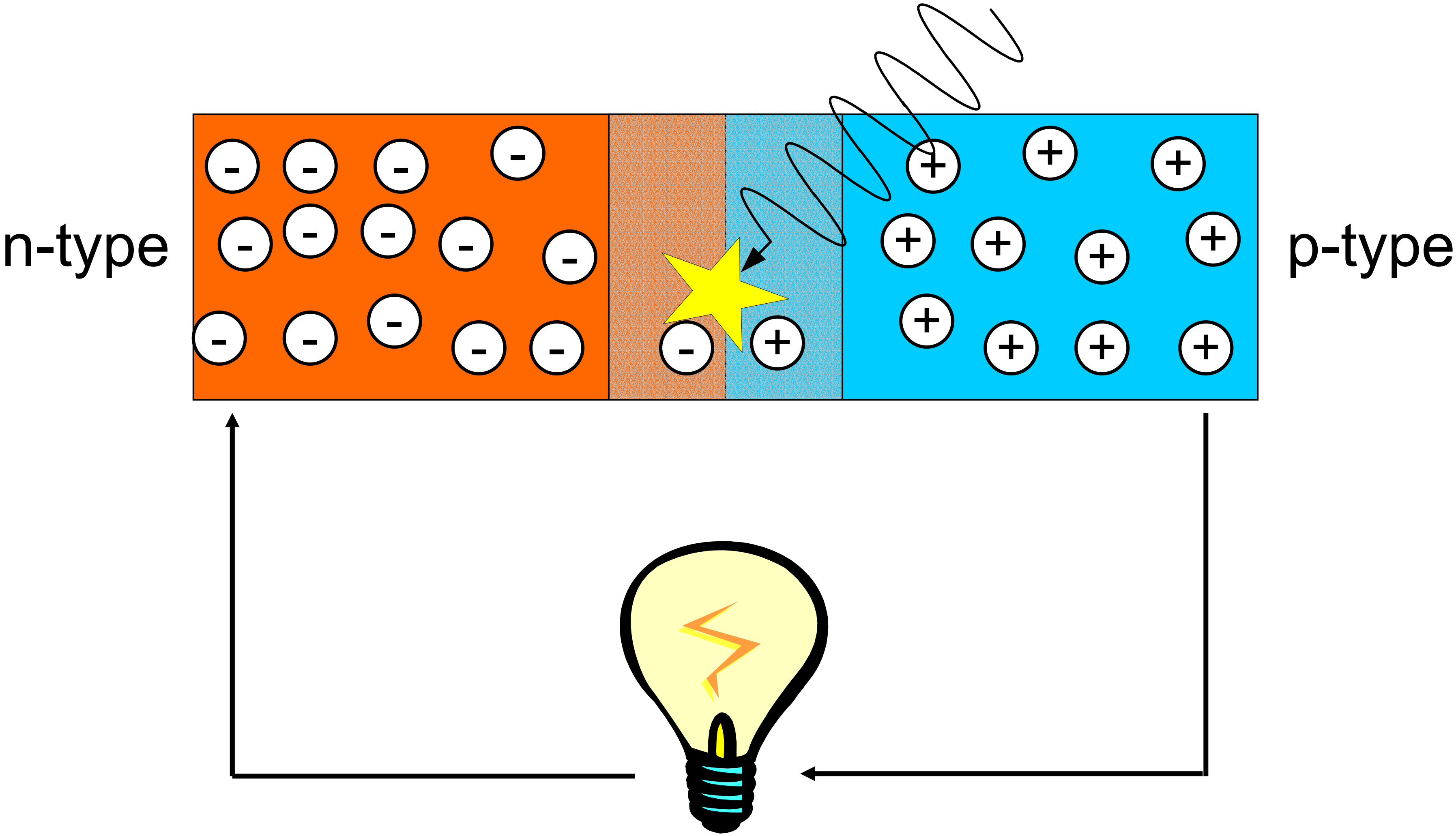
p-n junction


n-type
p-type
Charge
density ρ
+
-
Electric
field
Poisson
$\xi = \int (\rho / \varepsilon) dx$

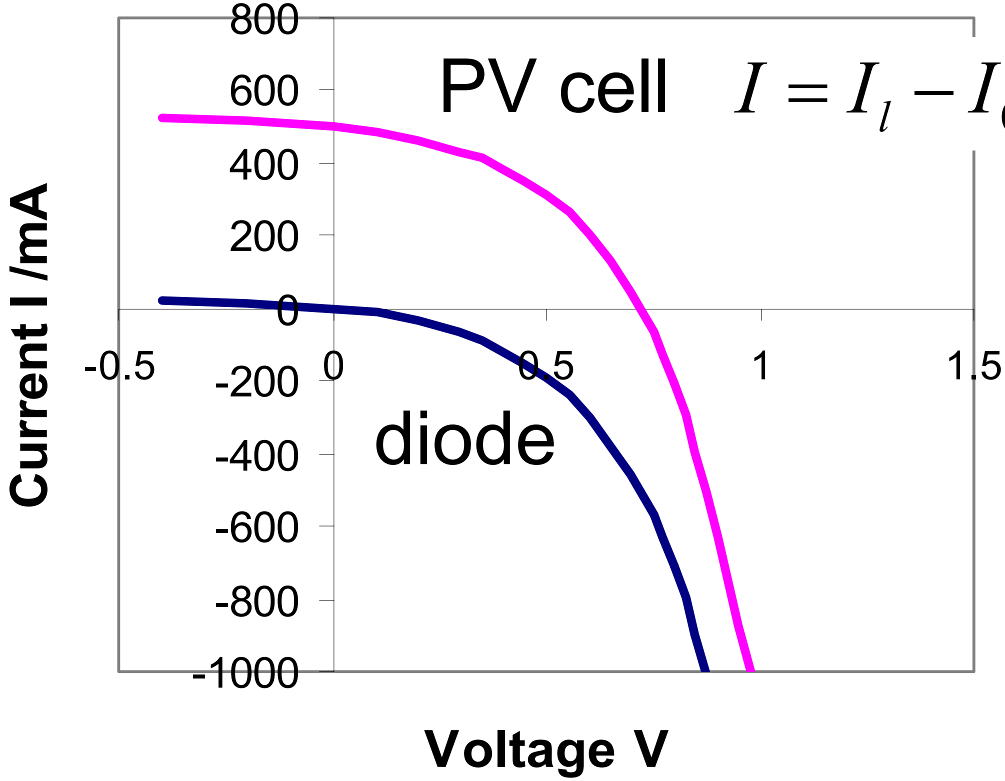
Photogeneration at p-n junction



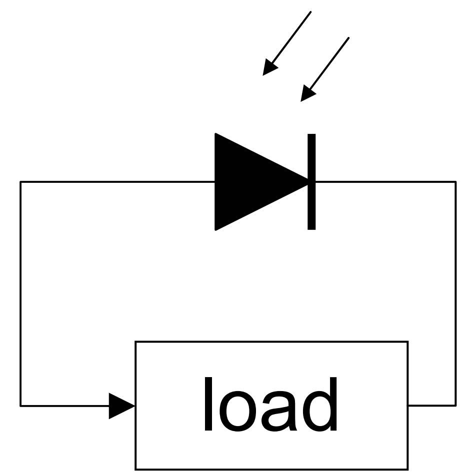
Photogeneration at p-n junction



I-V curve



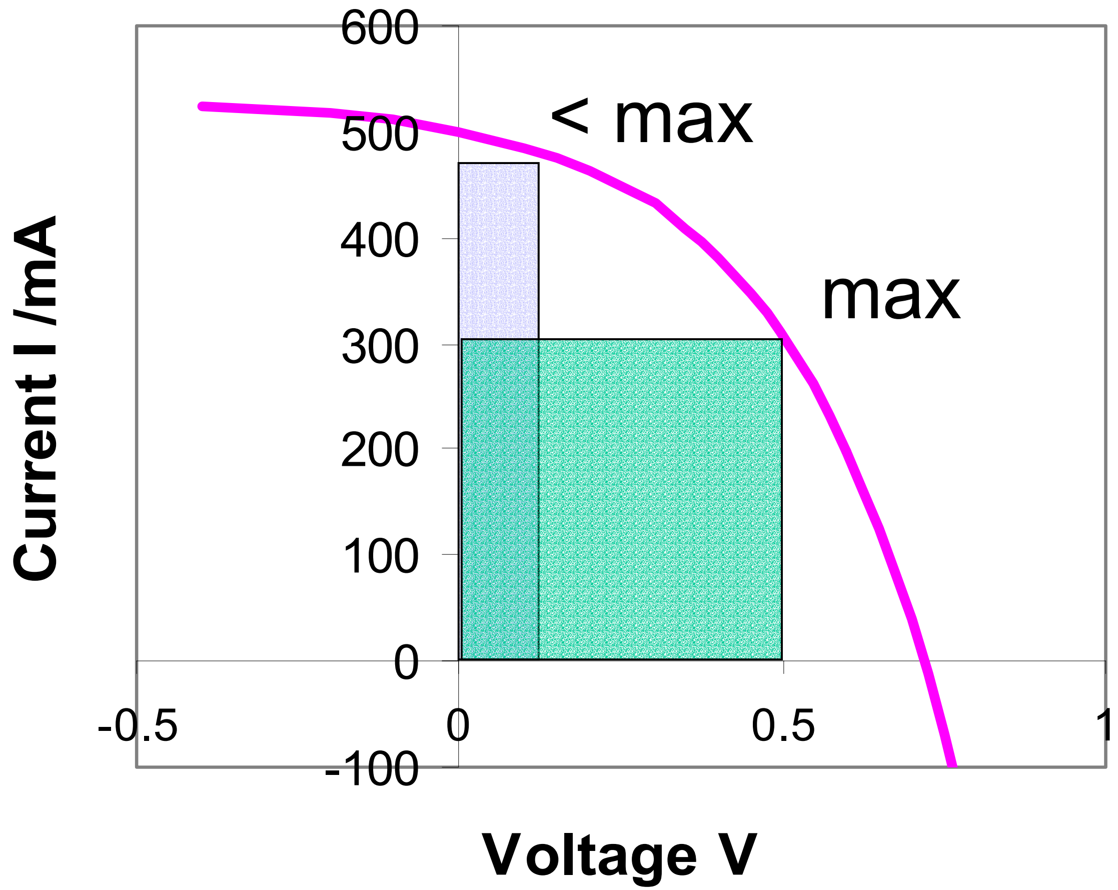
$$I = I_l - I_0\left[\exp(qV/kT) - 1\right]$$

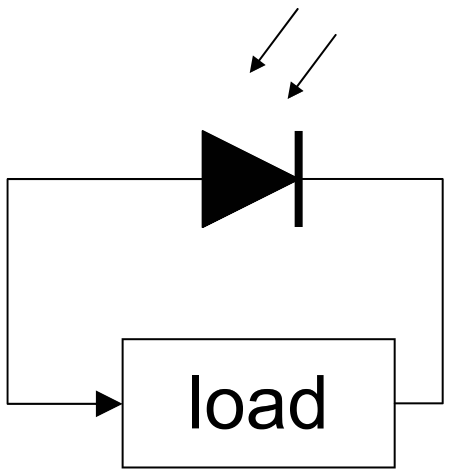


k is Boltzmann's constant, q is the charge of an electron, T is absolute temperature

Maximum power point

$P = I\,V$

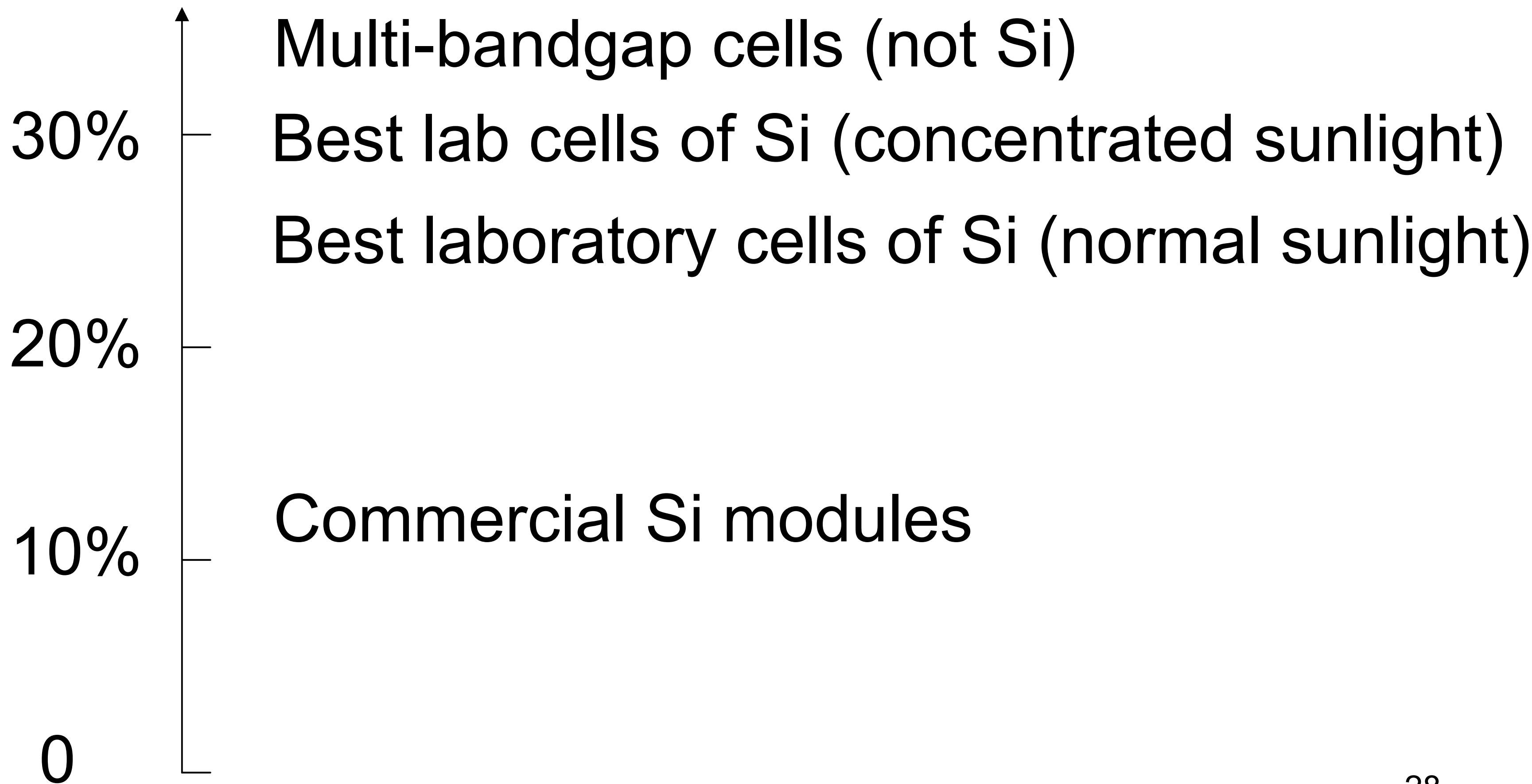




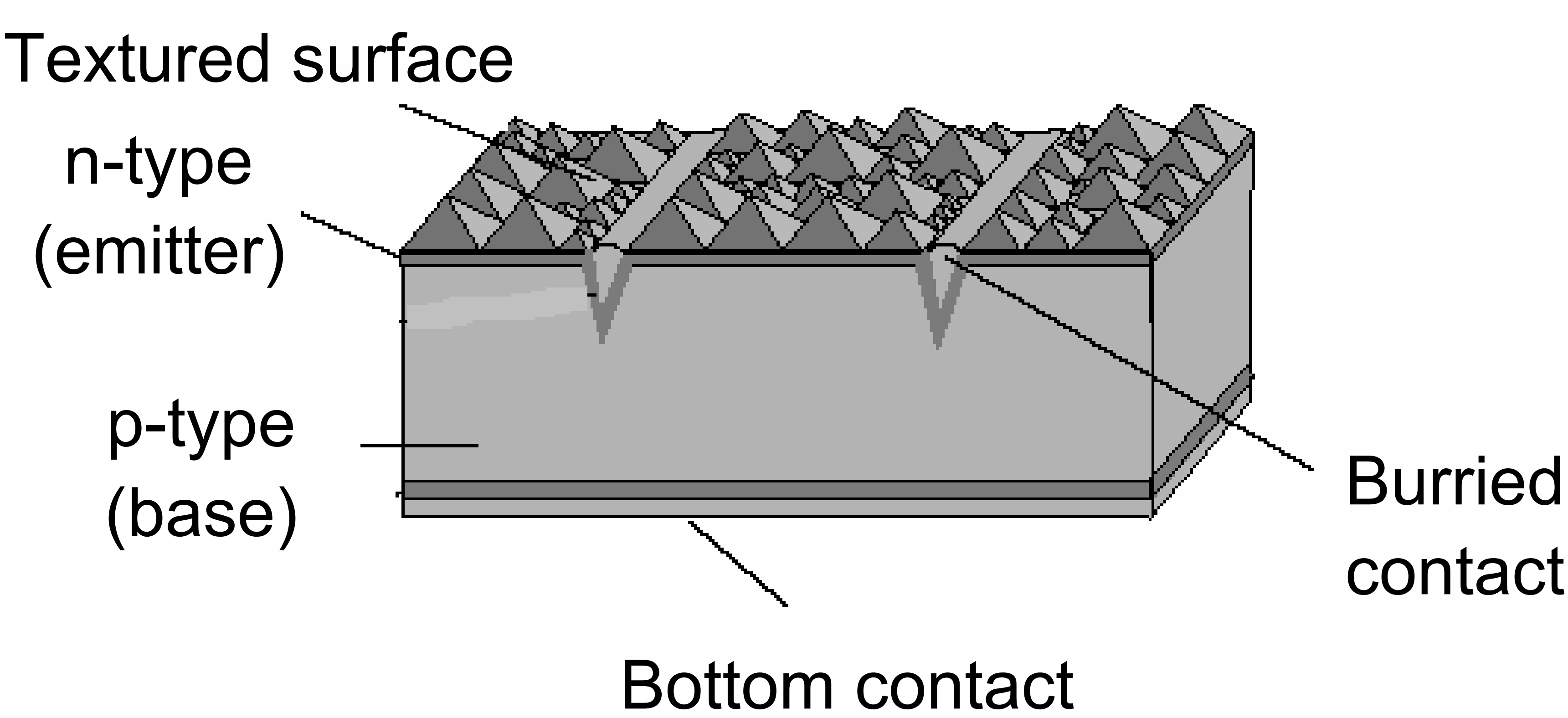
Limitations to efficiency

- Sunlight contains a spectrum of photons of varying energy E
  - If $E<$bandgap then the photon is useless
  - If $E>$bandgap, then the excess energy becomes heat
- Optical effects: reflections, incomplete absorption, shading by contacts ..
- Recombination

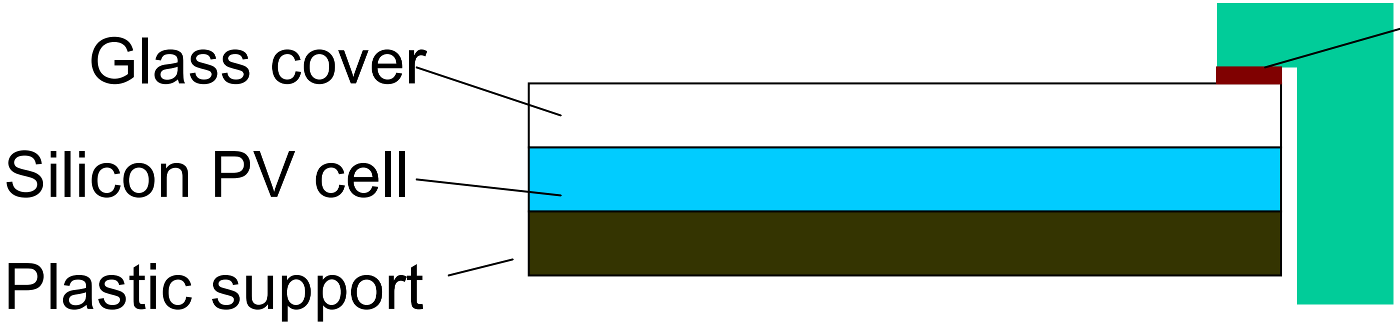
Efficiencies achieved

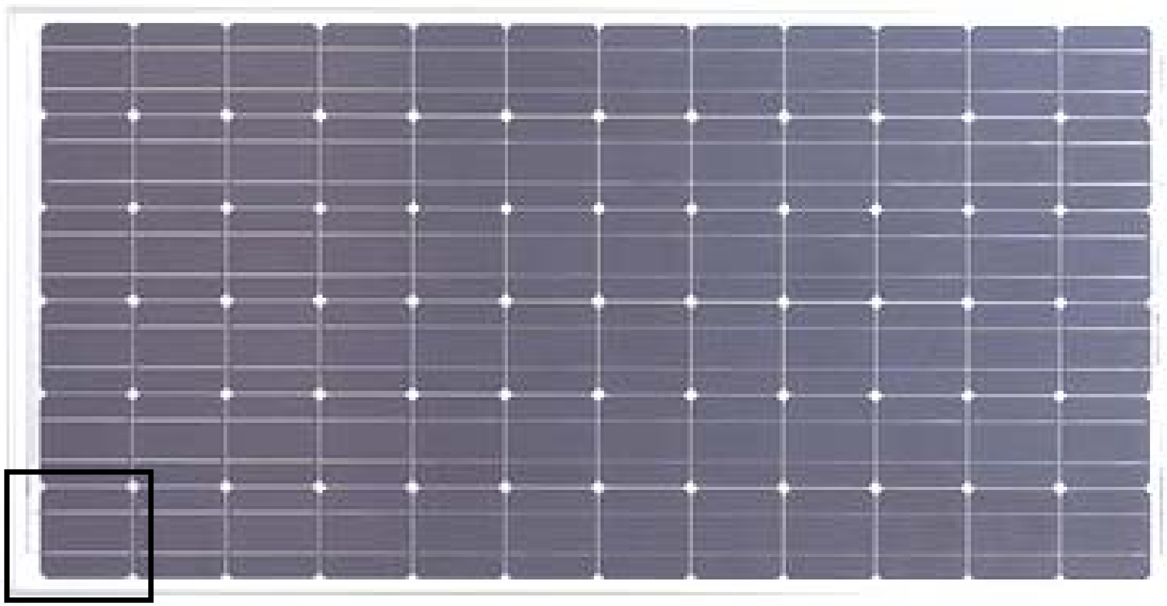


Structure of PV Cell



PV module





Individual cell

Conclusions

- Photovoltaic (PV) cells convert sunlight directly into electricity
- They are made of doped semiconductor arranged to give a p-n junction
- The junction creates an electric field
- Light generates electrons and holes in the semiconductor
- These are separated by the field
- A current is thereby induced when the PV cell is connected in a circuit.