Solar cell operating principles

Solar cell operation is based on the photovoltaic effect:
The generation of a voltage difference at the junction of two different materials in response to visible or other radiation.

1. Absorption of light - Generation of charge carriers
2. Separation of charge carriers
3. Collection of the carriers at the electrodes
Semiconductor based solar cells

p-n junction

- n-type Si membrane
- p-type Si absorber
- p++-type Si membrane
- back contact
- front contact
Solar cell materials

- Cover glass
- Transparent adhesive
- Passivation layer/ARC
- n-type Si
- front contact
- p-type Si
- p++-type Si
- back contact
- Encapsulant/glass
Solid materials
- crystalline (regular atomic structure: long range order)
- amorphous (amorphous network: short range order)

Electrical conductivity based upon mobile electrons
- conductors ($\sigma > 10^4 \text{ } \Omega^{-1} \text{ cm}^{-1}$)
- semiconductors ($10^4 \text{ } \Omega^{-1} \text{ cm}^{-1} > \sigma > 10^{-8} \text{ } \Omega^{-1} \text{ cm}^{-1}$)
- insulators ($\sigma < 10^{-8} \text{ } \Omega^{-1} \text{ cm}^{-1}$)

Thermal behavior of electrical conductivity
Control of electrical conductivity by doping
Semiconductors

Important properties for a solar cell:

**Optical properties**
- band gap
- absorption coefficient
- index of refraction

**Carriers concentration**
- Concentration of dopant atoms

**Transport properties**
- mobility of carriers (drift)
- diffusion coefficient (diffusion)

**Recombination**
- lifetime of minority carriers and diffusion length
- distribution of density of energy states
**Silicon**

**Atom**

- Atomic number: 14
- Atomic weight: 28.08
- Ground state electron configuration: 4 valence electrons

**Crystal**

- Covalent bond
- Basic unit: 5 Si atoms
- Crystal lattice:
  - diamond lattice unit
  - lattice constant 5.4 Å
Silicon

Unit cell

Si atom
Silicon

Bonding model

Si atom  electron
Silicon

Bonding model

\[ n = p \]

Covalent bond  hole
Introducing Phosphorus

Phosphorus atom:
5 valence electrons

Introducing Boron

Boron atom:
3 valence electrons
Silicon

Bonding model

n > p

P atom

n < p

B atom
Silicon

Energy band diagram

A plot of the allowed electron energy states in a material as a function of position along pre-selected direction.

\[ kT E = E_n + kT E_p = kT E_F \]

\[ n = p = n_i \]
\[ n_i = 1.5 \times 10^{10} \text{ cm}^{-3} \]

Fermi-Dirac distribution function

\[ f(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \]

Concentration of electrons and holes

\[ n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right) \]
\[ p = N_V \exp\left(-\frac{E_F - E_V}{kT}\right) \]
\[ N_C = 3.2 \times 10^{19} \text{ cm}^{-3} \]
\[ N_V = 1.8 \times 10^{19} \text{ cm}^{-3} \]
Silicon

n-type Si

\( n > p \quad n \times p = n_i^2 \)

\[ n \approx N_D \quad (T=300 \text{ K}) \]

\( N_D = n = 1.0 \times 10^{17} \text{ cm}^{-3} \)
\( p = n_i^2/n = 2.25 \times 10^3 \text{ cm}^{-3} \)
\( E_C - E_F = 0.14 \text{ eV} \)

p-type Si

\( n < p \quad n \times p = n_i^2 \)

\[ p \approx N_A \quad (T=300 \text{ K}) \]

\( N_A = p = 1.0 \times 10^{20} \text{ cm}^{-3} \)
\( n = n_i^2/p = 2.25 \text{ cm}^{-3} \)
\( E_F - E_V = 0.04 \text{ eV} \)
About 55% of solar energy is not usable by PV cells
Semiconductors

Band gap ($E_G$)

![Graph showing solar spectrum and power density vs. wavelength for different solar cell materials.](image)
Semiconductors

Transport

**Drift**: Charged-particle motion in response to electric field

- Drift current:
  \[ J_{N\text{ drift}} = q n \mu_n \xi \quad J_{P\text{ drift}} = q p \mu_p \xi \]

- **Mobility**:
  - Phonon scattering
  - Ionized impurity scattering
    \[ \mu \propto T^{-3/2} \left( N_D^+ + N_A^- \right) \]

- **Electrical conductivity**:
  \[ \sigma = q \mu_n n + q \mu_p p \]
**Transport**

**Diffusion**: A process whereby particles tend to spread out from regions of high particle concentration into regions of low particle concentration as a result of random thermal motion.

**Diffusion current**:

\[
J_{N/\text{diff}} = qD_n \frac{dn}{dx}
\]

\[
J_{P/\text{diff}} = -qD_p \frac{dp}{dx}
\]

**Diffusion coefficient**:

\[
D_n = \frac{kT}{q} \mu_n \quad D_p = \frac{kT}{q} \mu_p
\]
Semiconductors

Recombination: A process whereby electrons and holes (carriers) are annihilated or destroyed.

Generation: A process whereby electrons and holes are created.

Minority carrier lifetime:
\[\tau_n = \frac{1}{C_n N_T}\]
\[\tau_p = \frac{1}{C_p N_T}\]

Diffusion length:
\[L_n = \sqrt{D_n \tau_n}\]
\[L_p = \sqrt{D_p \tau_p}\]
Band-to-band recombination

Heat

Light

Light (photons)

$E_C$

$E_V$

$E_C$

$E_V$
R-G center

- dominant recombination-generation mechanism