GENERATION AND RECOMBINATION OF CHARGE CARRIERS IN SOLAR CELLS; TRANSPORT MECHANISMS: DRIFT AND DIFFUSION

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Principles and Varieties of Solar Energy (PHYS 4400)
and
Fundamentals of Solar Cells (PHYS 6980)

- generation of free carriers
- recombination of electrons and holes
- Transport:
  - Drift
  - Diffusion

Charge carriers (electrons and holes)

Masses:

$m_e = 9.11 \times 10^{-31}$ kg
$m_n = 1.67 \times 10^{-27}$ kg
$m_p = 1.67 \times 10^{-27}$ kg

Electron charge = -1.602×10^{-19} C
Hole charge = $+1.602 \times 10^{-19}$ C

Effective Mass of electrons and holes:

A particle's **effective mass** is the mass it appears to carry in transport in a crystal. Electrons and holes in a crystal respond to electric and magnetic fields almost as if they were particles with a mass dependent on their direction of travel (an effective mass tensor). **Simplified picture**: ignoring crystal anisotropies, electrons and holes behave as free particles in a vacuum, but with a different mass.

http://en.wikipedia.org/wiki/Effective_mass_(solid-state_physics)

Material	Electron effective mass	Hole effective mass
	Group IV	
Si (4.2K)	1.08 m_e	0.56 m_e
Ge	0.55 m_e	0.37 m_e
	III-V	
GaAs	0.067 m_e	0.45 m_e
InSb	0.013 m_e	0.6 m_e
	II-VI	
ZnO	0.19 m_e	1.21 m_e
ZnSe	0.17m_e	1.44 m_e

Important charge carrier processes in semiconductors

The free electron and hole concentrations in bulk semiconductors can be modified by the processes of generation and recombination, and also by the transport of electrons and holes through drift and diffusion.

Generation: e.g., absorption of a photon generates a free electron and a free hole (an electron-hole pair).

Recombination: can be **radiative**, in which case a photon is emitted as the electron returns to the valence band, or **non-radiative**, in which case the energy associated with the e-h pair is converted to heat, or transferred to another charge carrier (Auger recombination) – non-radiative corresponds to no photon.

Transport is the movement of charge carriers under forces based either on an electric field, or on a concentration gradient:

Drift refers to the motion of charge carriers under the force of an electric field. Motion is typically not "ballistic", and instead includes the resistive action of scattering.

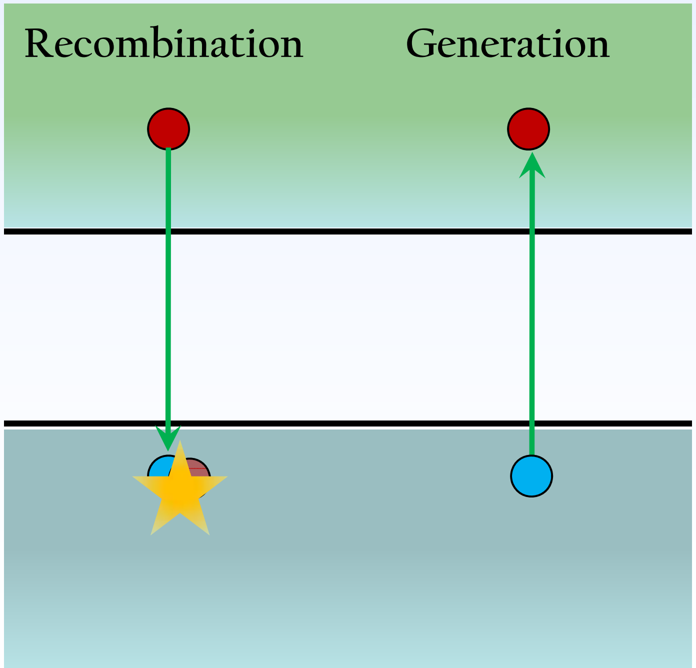
Diffusion refers to motion of electron and holes due to the presence of a concentration gradient.

Generation and recombination

Charge carriers move between valence and conduction bands under thermal influence (thermal excitation within the Boltzmann tail of the Fermi-Dirac distribution). In the dark and at equilibrium, the concentration of electrons and holes are unaffected by these processes.

Generation, under influence of light absorption for example, promotes electrons from the valence band to the conduction band, resulting in a new free electron in the CB, and a new hole in the VB.

Recombination is essentially the reverse process, in which an electron returns to the valence band, giving up it electronic potential energy to a photon, or a third carrier, or to phonons.



Absorption of light

Light incident on a semiconductor consist of photons with energy E = hν = hc/λ. Photons interact with the semiconductor depending on their energy:

$E_{photon} < E_g$: Photons with energy below the band gap energy are transmitted through the material;

$E_{photon} = E_g$: These photons have sufficient energy to be absorbed in a band-to-band transition, and generate an electron-hole pair. Absorption of these photons will be relatively weak.

$E_{photon} > E_g$: Photons with significantly greater energy than the semiconductor's bandgap are relatively strongly absorbed, and generate electron-hole pairs with initial excess kinetic energy. This excess kinetic energy is, in general, quickly lost to the lattice as phonons).

Absorption of light – the generation rate

The generation rate quantifies the number of electron-hole pairs created per unit time. As the light enters and travels through the semiconductor, the intensity of the light drops exponentially as the photons are converted to electron-hole paires by the process of "photogeneration":

$$I = I_0 e^{-\alpha x}$$

where a is the absorption coefficient typically in cm^{-1}, and x is the distance into the material. I_0 is the light intensity just inside the surface of the semiconductor.

Since each photon absorbed generates an e-h pair, this exponential decay also mimics the generation of carriers as a function of depth.

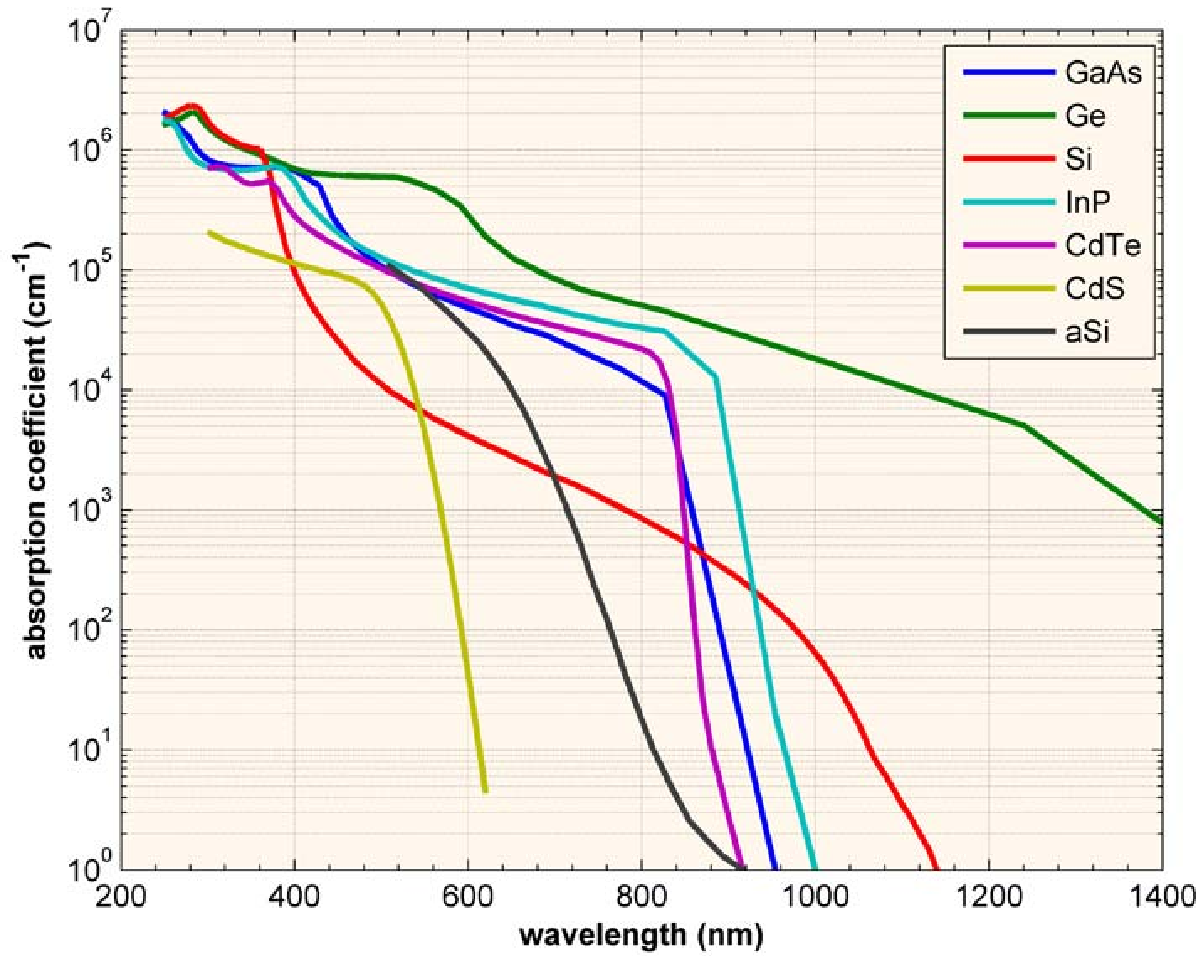
The generation rate, G, is given by:

$$G = \alpha N_0 e^{-\alpha x}$$

where N_0 is the photon flux at the surface (photons/unit-area/sec), α is absorption coefficient, and x is the distance into the material.

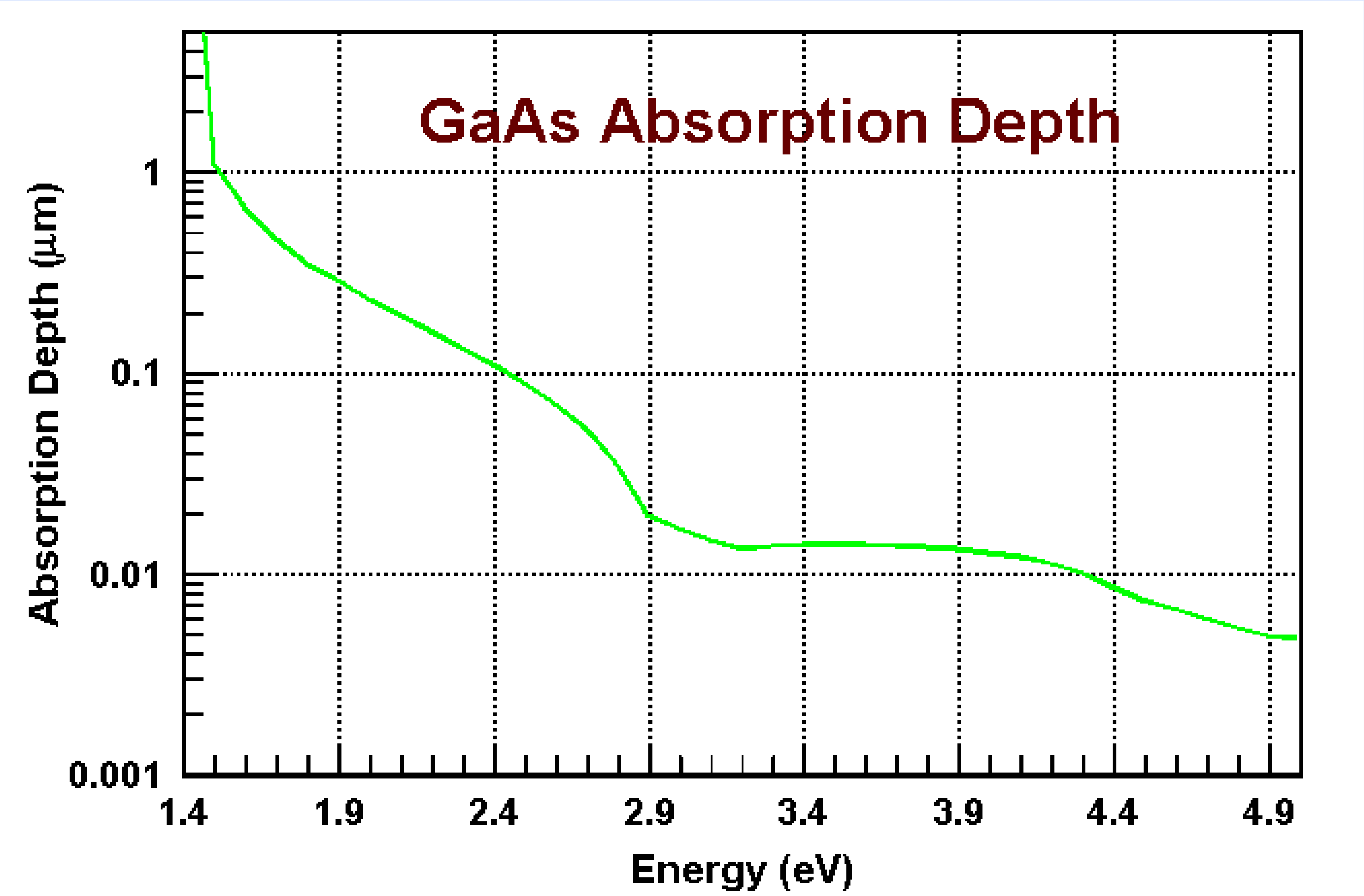
Absorption *coefficient*

Generation occurs in PV cells by absorption of light, and the formation of electron-hole pairs. The absorption coefficient, α, in units of cm^{-1}, provides a measure of the strength of the light absorption at a given photon energy.



Absorption *depth*

The absorption depth for a materials is photon-energy-dependent, and is simply the inverse of the absorption coefficient. I.e., it is the depth at which the intensity of the light has dropped to a value of $(1/e)*I_0(\lambda)$.



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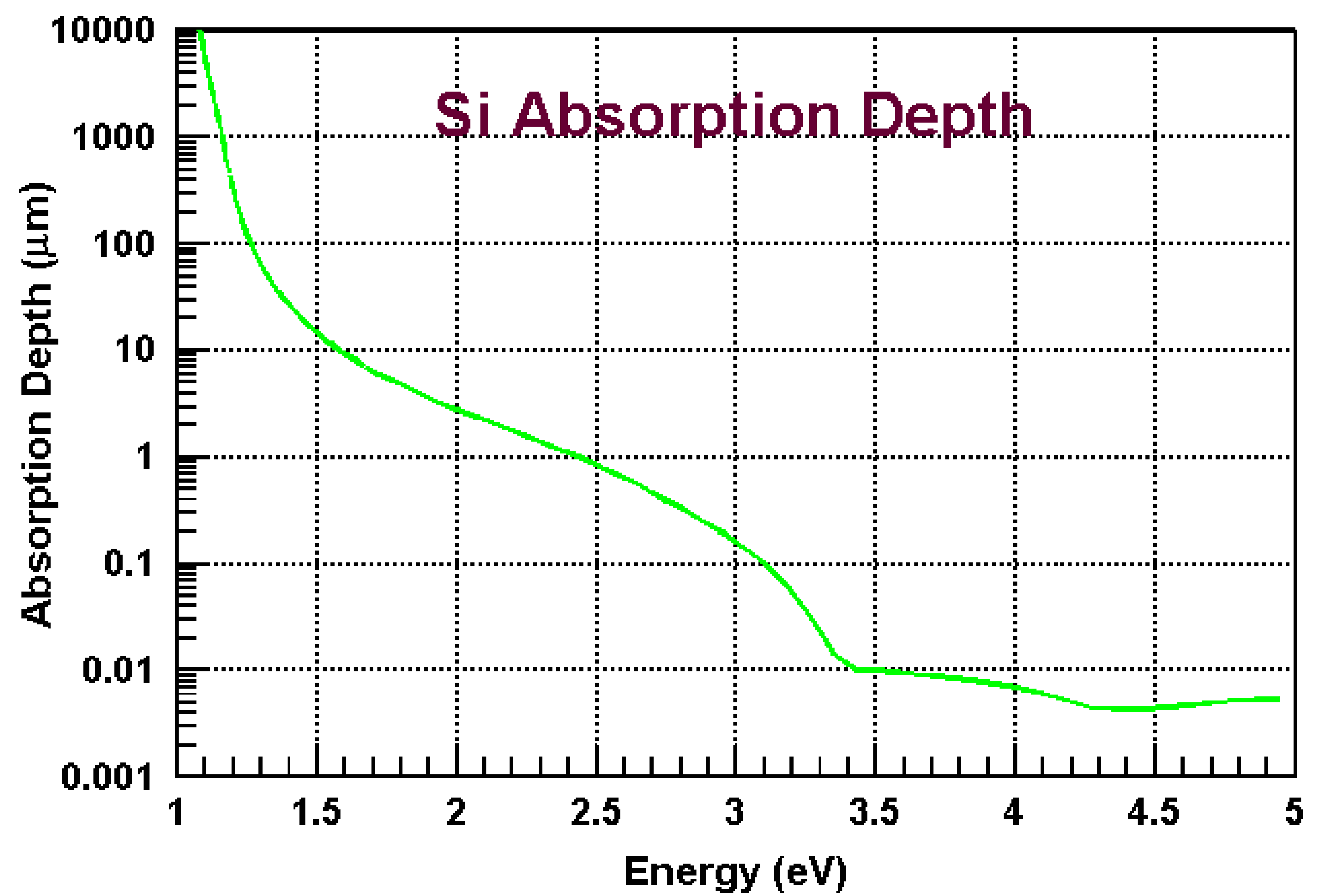

Recombination of electrons and holes in a semiconductor

Photons incident on the surface of a semiconductor will be either reflected from the top surface, absorbed, or transmitted. For PV, reflection and transmission are typically considered loss mechanisms (photons which are not absorbed do not generate power). An absorbed photon will raise an electron from the valence band to the conduction band (this process is called ***generation***). A key factor in determining if a photon is absorbed or transmitted is the energy of the photon.

An electron which exists in the conduction band is in a meta-stable state and will eventually fall back to a lower energy position in the valence band. It must move back into an empty valence band state and consequently, when the electron falls back down into the valence band, it effectively removes a hole. This process is called ***recombination***. There are three basic types of recombination in the bulk of a single-crystal semiconductor. These are:

(1)Radiative (band-to-band) recombination
(2)Auger recombination
(3)Shockley-Read-Hall (SRH) recombination

Free carriers (free electrons and holes)

Free carriers -- consisting of electrons, holes, or both – are able to carry current in a semiconductor material or solar cell.

In contrast, trapped carriers are bound to a specific impurity atom, defect (such as a vacancy) in the crystal, or bound to a specific surface state. Trapped carriers are typically not in the valence band, and cannot carry current.

Free carriers are subject to move under the mechanisms of drift (as in an electric field, with force of qE where q is the electron charge and E is the electric field strength), and of diffusion.

Drift of free carriers in solar cells

Drift refers to the motion of a charged particle within an electric field (typically DC and in a steady direction);

The **drift velocity** is the average velocity that a particle, such as an electron, attains due to an electric field. In general, an electron will 'rattle around' in a conductor at the Fermi velocity randomly. An applied electric field will give this random motion a small net velocity in one direction.

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

Diffusion of free carriers in solar cells

Diffusion describes the spread of particles through random motion from regions of higher concentration to regions of lower concentration. The time dependence of the statistical distribution in space is given by the diffusion equation. The concept of diffusion is tied to that of mass transfer driven by a concentration gradient, but diffusion can still occur when there is no concentration gradient (but there will be no net flux).

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

Diffusion current is a current in a semiconductor caused by the diffusion of charge carriers (holes and/or electrons). Diffusion current can be in the same or opposite direction of a drift current.

At equilibrium (i.e., in the dark) in a p-n junction, the forward diffusion current in the depletion region is balanced with a reverse drift current, so that the net current is zero.

Current based on fundamental transport mechanisms

For compositionally invariant material, at a uniform temperature, the current density (A/cm^2) due to drift and diffusion of electrons and holes are given by:

$$J_n(r) = qD_n \nabla n + q\mu_n En$$

$$J_p(r) = qD_p \nabla p + q\mu_p Ep$$

where q is the carrier charge (-e, or +e), $D_{n,p}$ are the diffusion coefficients (cm^2 s^{-1}), ∇n and ∇p are the concentration gradients for electron and holes (cm^{-4}), $\mu_{n,p}$ are the mobilities for electrons and holes (cm^2 V^{-1} s^{-1}), E is the electric filed strength (V cm^{-1}), and *n,p* are the electron and hole concentrations (cm^{-3}).