“Solar Energy” WS 2021/2022

Lecture 4: Generation & Recombination

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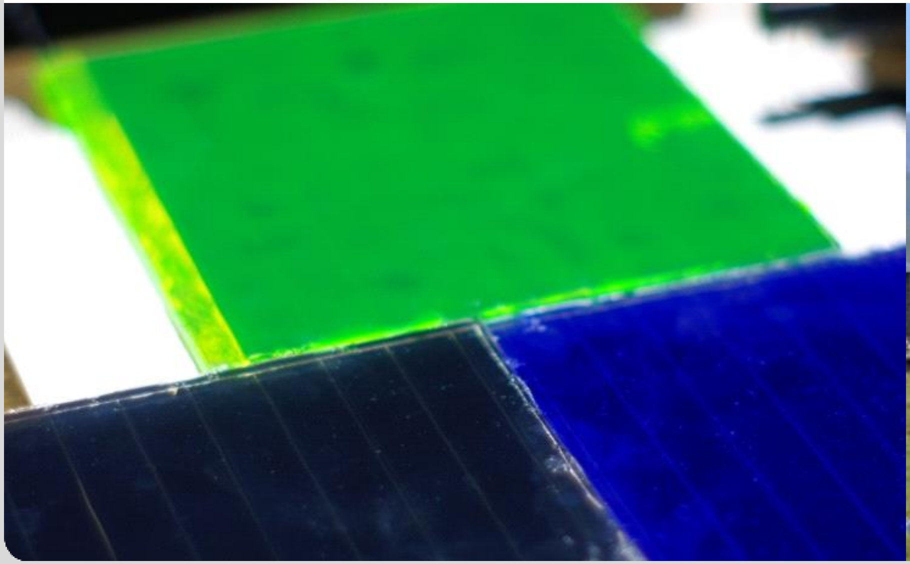
KIT Focus Optics & Photonics



Information

“Solar Energy“ lecture (23745) and tutorials (23750)

Lecturers: **Prof. Dr. Bryce Richards**

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Information

- Tutors: Benni Hacene (benjamin.hacene@kit.edu)
  Emmanuel Ogunniyi (emmanuel.ogunniyi@kit.edu)

- Slides and further information will be available as PDF files for download at IIAS https://ilias.studium.kit.edu
- Six tutorial sessions throughout the course
- One lab demonstration
- One excursion – to the KIT Solar Park (1MW PV installation)
- Exam will be a 2 hour written exam, **Wed 08th March 2022**

"Solar Energy" lecture plan – WS 2020-2021 – Prof. Bryce Richards & T.T.Prof. Uli Paetzold

LTI Hörsaal, Geb. 30.34, Monday 10:00 – 11:30	LTI Hörsaal, Geb. 30.34, Thursday 12:00 – 13:30
Mon 18 Oct 2021	Thu 21 Oct 2021
Lecture 1: Introduction (Chpt 1 – 3) (Prof. Richards)	Lecture 2: Solar Radiation (Chpt 5) (Prof. Richards)
Mon 25 Oct 2021	Thu 28 Oct 2021
Lecture 3: Basics of Electrodynamics & Semiconductor Physics (Chpt. 4 & 6) (Prof. Paetzold)	Lecture 4: Generation & Recombination (Chpt 7) (Prof. Paetzold)
Mon 1 Nov 2021	Thu 4 Nov 2021
NO LECTURE or TUTORIAL	Tutorial 1: Chpts 1 – 6
Mon 8 Nov 2021	Thu 11 Nov 2021
Lecture 5: Semiconductor Junctions (Chpt 8) (Prof. Paetzold)	Lecture 6: Solar Cell Parameters (Chpt 9) (Prof. Paetzold)
Mon 15 Nov 2021	Thu 18 Nov 2021
Lecture 7: Crystalline Silicon Solar Cells (Chpt 11 & 12) (Prof. Richards)	Tutorial 2: Chpts 7 – 9
Mon 22 Nov 2021	Thu 25 Nov 2021
Lecture 8: Thin-Film Solar Cells: inorganic (Chpt 13) (Prof. Richards)	Lecture 9: Thin-Film Solar Cells: OPV/perovskite (Chpt 13) (Prof. Paetzold)
Mon 29 Nov 2021	Thu 2 Dec 2021
Lecture 10: PV Modules (Chpt 15) (Prof. Richards)	Tutorial 3: Chpts 11 – 13
Mon 6 Dec 2021	Thu 9 Dec 2020
Lecture 11: PV Systems & Components (Chpt 17 & 19) (Prof. Richards)	Lecture 12: Location Issues + PV System Design + PV in developing countries (Chpt 18 & 20) (Prof. Richards)

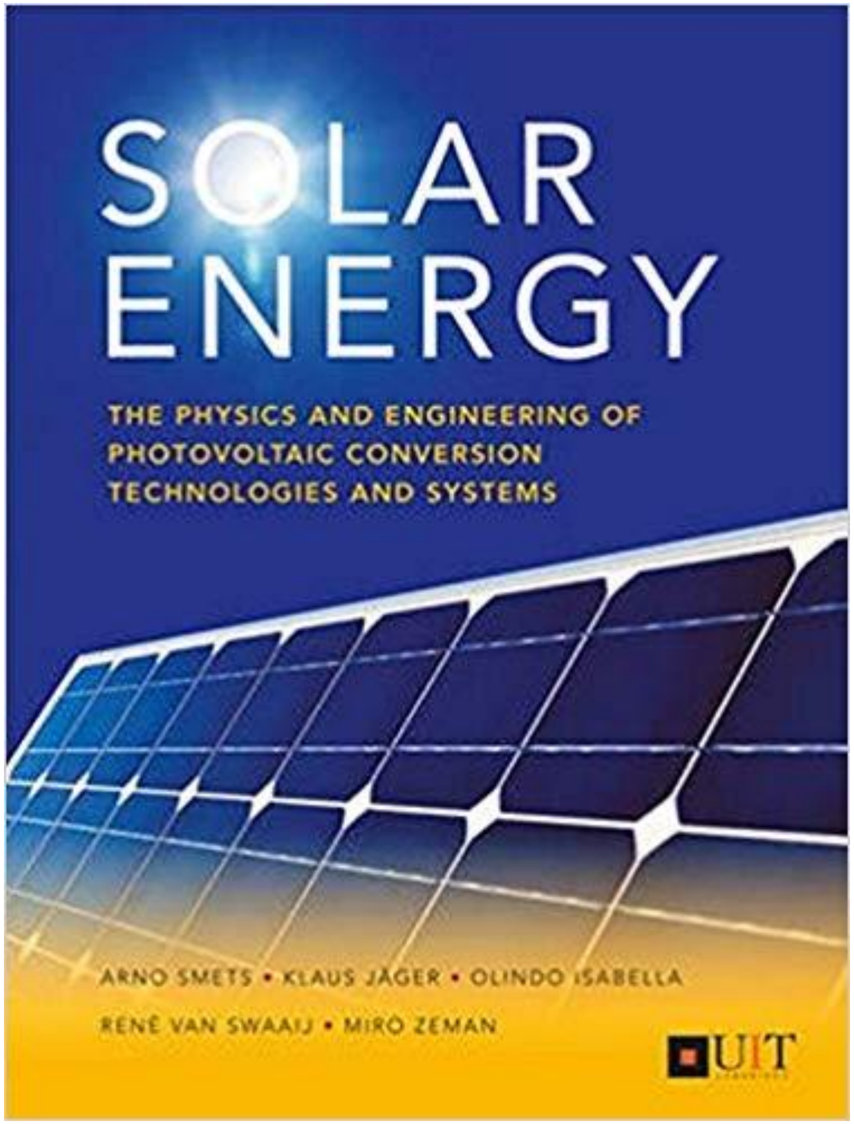
Mon 13 Dec 2021	Thu 16 Dec 2020
Lecture 13: PV System Economics & Environmental Aspects (Chpt 21) (Prof. Richards)	Tutorial 4: Chpts 15, 17, 19
Mon 20 Dec 2021	Thu 23 Dec 2021
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 27 Dec 2021	Thu 30 Dec 2021
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 3 Jan 2022	Thu 6 Jan 2022
NO LECTURE or TUTORIAL	*NO LECTURE or TUTORIAL*
Mon 10 Jan 2022	Thu 13 Jan 2022
Demo: Getting hands-on with solar cells (Bahram Abdollahi)	Lecture 14: Spectral conversion for PV (extra) (Prof. Richards)
Mon 17 Jan 2022	Thu 20 Jan 2022
Tutorial 5: Chpts 18 & 20-21	Lecture 15: Light management for PV (Chpt 10 + extra) (Prof. Paetzold)
Mon 24 Jan 2022	Thu 27 Jan 2022
Lecture 16: Losses, Efficiency Limits and Third Gen. Concepts (Chpts 10 & 16) (Prof. Paetzold)	Lecture 17: Tandem Solar Cells (extra) (Prof. Paetzold)
Mon 31 Jan 2022	Thu 3 Feb 2022
Tutorial 6: Chpt 10 + 16 + extra	EXCURSION Visit to KIT Solar Park (Prof. Richards)
Mon 7 Feb 2022	Thu 10 Feb 2022
Mock exam	Review and Q&A session (Prof. Paetzold & Prof. Richards)

Textbook

- “*Solar Energy: The physics and engineering of photovoltaic conversion, technologies and systems*” (2016)

  by Smets, Jäger, Isabella, van Swaaij (TU Delft)

- Online: €30.50 (paperback)
  €0.00 (Kindle)
- Technological focus
- Lectures largely follow chapters in textbook:
  - Some chapters skipped
  - Some material supplemented
  - Data updated



Source: textbook

Outline

- RECAP: Charge carrier statistics & continuity equation
- Part I: Photogeneration of charge carriers
- Part II: Recombination of charge carriers
  - Radiative
  - Shockley-Read-Hall
  - Auger Recombination
  - Surface Recombination
- Part III: Charge Carrier Lifetime & Diffusion Length

RECAP: Charge carrier statistics

Solar cells as well as any optoelectronic device make use of functionalized materials, wherein the charge carriers are not in necessarily in equilibrium or even steady-state. But in any scenario, the continuity equations need to be fulfilled as **charge is a conserved quantity**.

Continuity equations

- We can formulate the overall continuity equation for the charge carrier concentration of electron *n* (similar for holes):

$$\left.\frac{\partial n}{\partial t}\right| = \left.\frac{\partial n}{\partial t}\right|_{diff} + \left.\frac{\partial n}{\partial t}\right|_{drift} + \left.\frac{\partial n}{\partial t}\right|_{R} + \left.\frac{\partial n}{\partial t}\right|_{G}$$

with

$$q\frac{\partial n}{\partial t} + \left(\frac{\partial J_x}{\partial x}\right) + \left(\frac{\partial J_y}{\partial_y}\right) + \left(\frac{\partial J_z}{\partial z}\right) = 0$$

- Any change in charge carrier concentration w. time in a certain volume is determined by either of these processes:
  - Drift: $J_{n\_drift} = q\, n\, \mu_n\, E_x,$
  - Diffusion: $J_{n\_diff} = qD_n \frac{dn}{dx}$
  - Generation (rate G_n)
  - Recombination (rate: R_n)

$$\boxed{\frac{\partial n}{\partial t} + 1/q\left(\Delta \cdot \vec{J}_n\right) - Rn + Gn = 0}$$

Source: textbook

RECAP: Charge carrier statistics

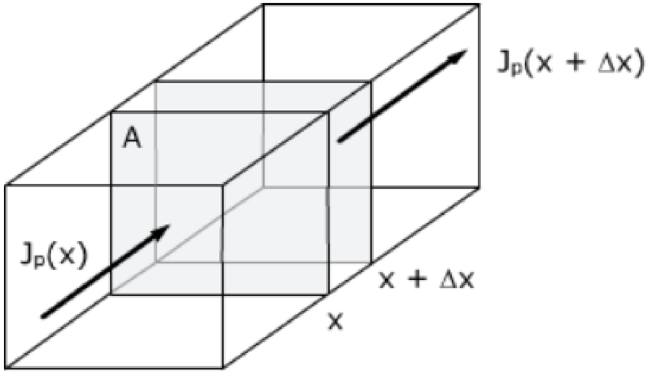


Illustration of the continuity equation in 2D:

- Assumption: drift and diffusion current only in one dimension
- Steady state, net rate of increase must be zero i.e. $\frac{\partial n}{\partial t} = 0,$

Rate of entering& exiting: $\frac{A}{q}\{-J_n(x) - [-J_n(x+\Delta x)]\} = \frac{A}{q}\frac{dJ_n}{dx}\Delta x$

Rate of generation – rate of recombination: $\frac{A}{q}\,\Delta x\,(G_n - R_n)$

Using the continuity equation, we get:

$$\frac{1}{q}\frac{dJ_n}{dx}\Delta x = U - G$$

Similar to the generalized form introduced before.

Source: textbook

PART I: GENERATION

Generation

- The process whereby the energy of a photon is initially converted to electrical energy through the creation of an electron hole pair.
- The absorption of light and the generation of an electron hole pair is fundamental to the operation of a solar cell.

Remember:

Photons incident on semiconductor will be either:

1. reflected from the top surface,
2. absorbed in the material or,
3. Transmitted through the material.

For PV devices, i) reflection and iii) transmission are losses

$\Rightarrow$ photons which are not absorbed do not generate power

Note that next to photogeneration, electron hole pairs are also generated at T > 0° by thermodynamic statistics (see last lecture).

Source: textbook

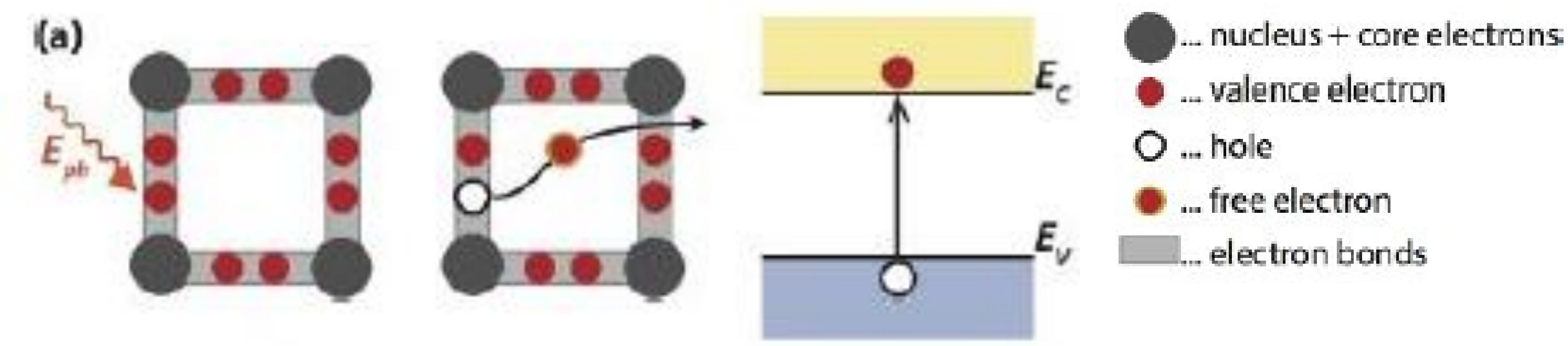
Photogeneration

For absorption, possibility of exciting an e^- from E_v to E_c but depends on energy of photon, E_{ph}:

$E_{ph} < E_g$: pass through semiconductor as if it were transparent

$E_{ph} = E_g$: enough energy to create an e^--h^+ pair and are efficiently absorbed

$E_{ph} > E_g$: strongly absorbed, but the excess photon energy is wasted as carriers quickly thermalize back down to the band edges

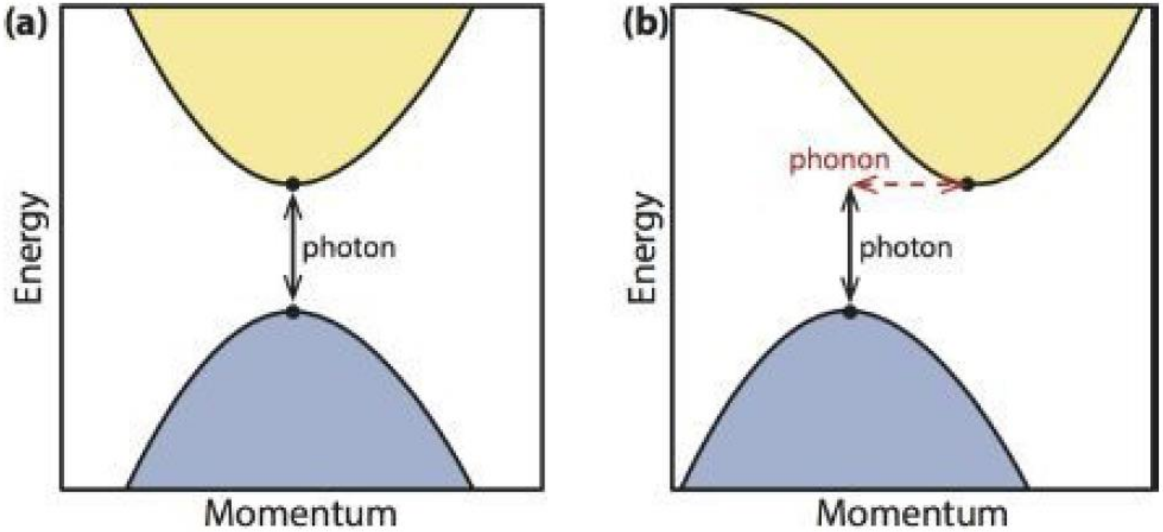


Visualization of bandgap-to-bandgap generation processes using the bonding model and the energy band diagram:

Source: textbook

Photogeneration in a Semiconductor

Direct vs. indirect semiconductor



<u>Direct semiconductor:</u> highest point of the valence band is vertically aligned with the lowest point of the conduction band. No additional momentum is required for light absorption

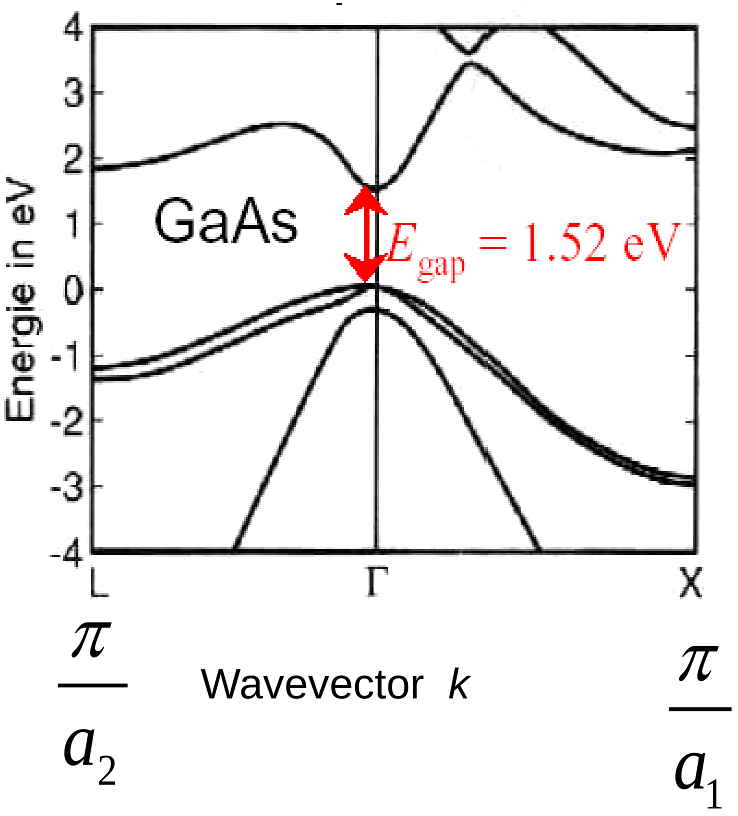
<u>Indirect semiconductor:</u> highest point of the valence band is not aligned with the lowest point of the conduction band. Exciting an electron from the valence to the conduction band requires energy provided by a photon and momentum provided from vibrations of the crystal lattice (i.e. phonons)

Source: textbook

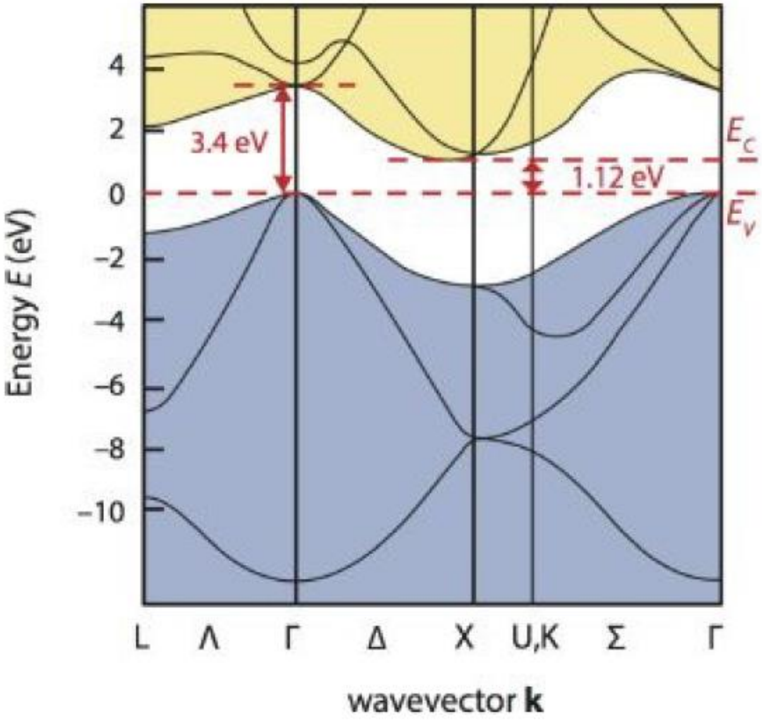
Photogeneration in a Semiconductor

Real dispersion diagrams

GaAs is a direct bandgap semiconductor (bandgap 1.52eV)



c-Si is an indirect semiconductor (bandgap of 1.12 eV)



Note, Si has also a direct bandgap at 3.4eV.

Source: textbook

Photogeneration - Absorption of Light

Neglecting reflection, the amount of light absorbed and the thickness of the absorber correlate. Intensity of light can be calculated according to:

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

where:

α is absorption coefficient (cm^{-1});

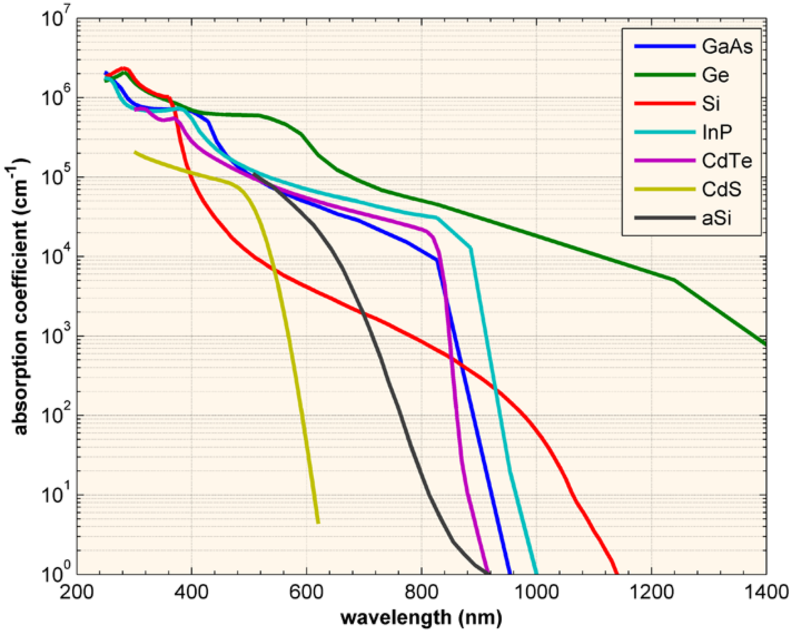
x is the distance into the material; and

I_0 is the light intensity at the top surface

Absorption coefficient (α) determines how far light of a particular wavelength can penetrate before it is absorbed.

- α is low for $E < E_g$
- α is high for $E > E_g$

At higher energies, more e^- can interact with photon ⇒ increased absorption.



Source: textbook

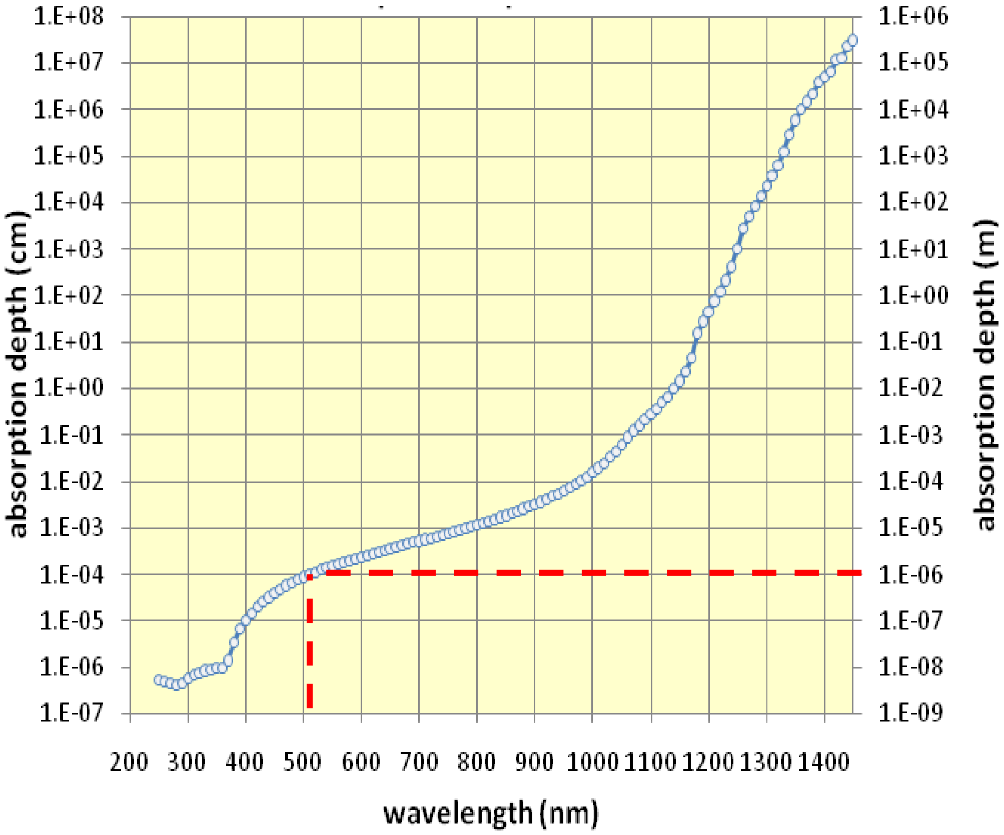
Photogeneration - Absorption of Light

From a device perspective, the absorption depth (d = 1/α) is a relevant figure of merit to understand which absorber layer thickness is needed to absorb the incident photons.

The absorption depth defines the thickness at which the light intensity has fallen to 36% (1/e) of its original value.

Example of Si (see right graph):

- The absorption depth d in crystalline Si > 1 μm for λ > 500nm.



Source: http://www.pveducation.org/pvcdrom/materials/optical-properties-of-silicon

Photogeneration – Generation Rate

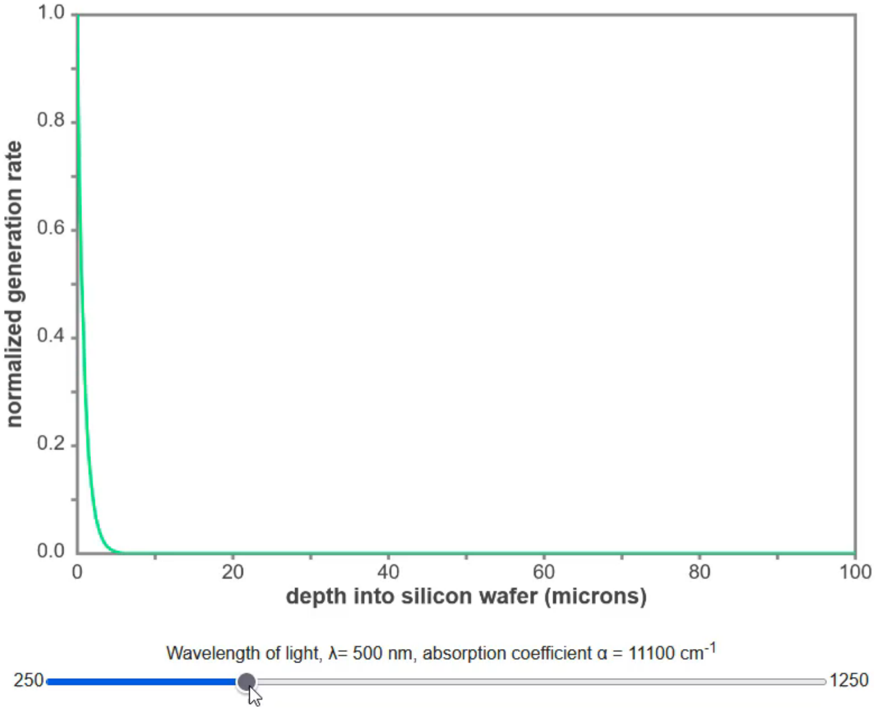
Using the Lambert-Beer Law, we can also calculate the number of e^{-}-h^{+} pairs being generated in a solar cell. We use the photon flux $\Phi_{ph}(x,\lambda)$ to account for the wavelengths dependent absorption.

$\Phi_{ph}(\lambda,x) = \Phi_{ph}^{0}(\lambda)\, e^{-\alpha(\lambda)x}$, where $\Phi_{ph}^{0}(\lambda)$, is the incident photon flux.

The spectral generation rate will be $G_{ph}(\lambda,x) = \eta_g \Phi_{ph}(\lambda,x)$ with the generation quantum efficiency η_g that is generally assumed to be 1.

The total generation rate is then:

$$G_{ph}(x) = \int_{\lambda_1}^{\lambda_2} G_{ph}(\lambda,x)\, d\lambda$$

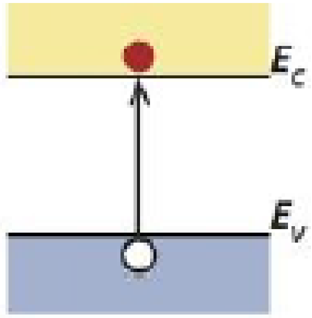


Source: Adapted from http://www.pveducation.org/pvcdrom/pn-junction/generation-rate

Photogeneration – Charge carriers

- Absorption of photons creates both a majority and a minority carrier

$$\left.\frac{\partial n}{\partial t}\right|_{light} = \left.\frac{\partial p}{\partial t}\right|_{light} = GL$$



- The additional charge carriers will disturb the semiconductor from the state of thermal equilibrium.
  - VB: Excess concentration of holes $p > p_0$ (p_0: equilibrium concentr.)
  - CB: Excess concentration of electron $n > n_0$ (n_0: equilibium concentr.)

  $\Rightarrow$ **Non-equilibrium, where $np > n_i^2$.**

Important note: the number of light-generated carriers are typically << the number of majority carriers and >> the minority carriers already present in the solar cell due to doping. This implies :

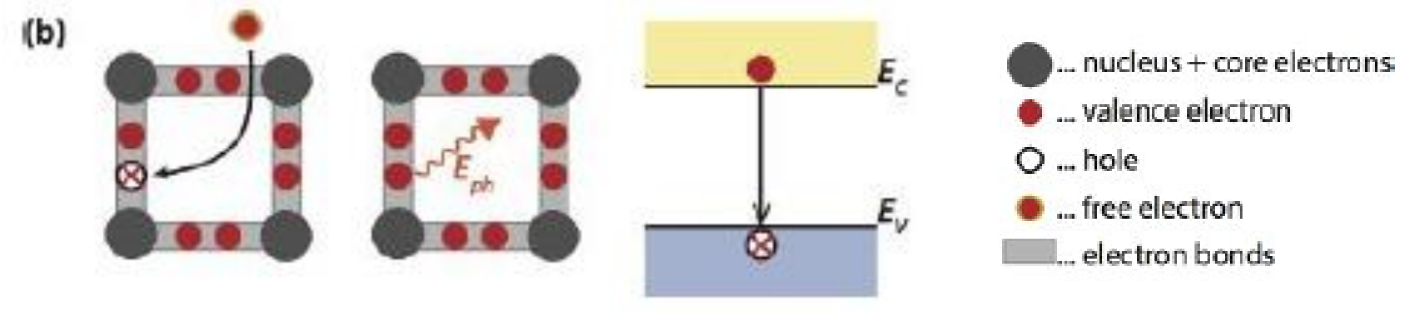
- For an n-type material: $n \approx N_D$ (majority), $n >> p$ (minority)
- For an p-type material: $p \approx N_A$ (majority), $p >> n$ (minority)

Source: textbook

PART II: RECOMBINATION

Recombination

- Recombination is the opposite process to generation.
- An electron recombines with a hole and gives up the energy to produce either heat or light.
- A device where the recombination is optimized to give off light is also called a light emitting diode (LED).



The driving force behing recombination is that any e^- in E_c is in meta-stable state and will eventually stabilize to a lower energy position in E_v

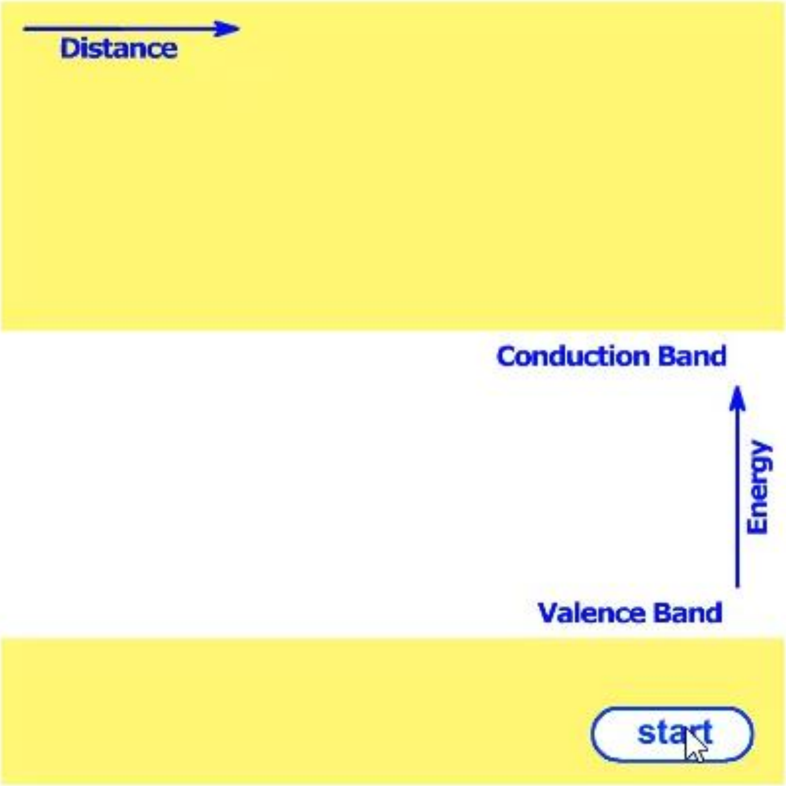
For this to happen, it must move into an empty valence band state. Thus, when e^- stabilizes back down into E_v it effectively removes a h^+
$\Rightarrow$ process called <u>recombination</u>

Source: textbook

Recombination

There are three basic types of recombination in the bulk of a single-crystal semiconductor. These are:

- *Radiative recombination*
  (Band to Band recombination)
- *Auger recombination*
- *Shockley-Read-Hall recombination*



In addition, at the boundary of finite semiconductor materials such as the interfaces of thin-films or grains in microcrystalline semiconductors, so called *surface recombination,* occurs.

Source: http://www.pveducation.org/pvcdrom/pn-junction/types-of-recombination

Radiative Recombination

- Dominates in direct bandgap semiconductors

- Light produced from a LED is most obvious example of radiative recombination in a semiconductor device

- In some concentrator and space solar cells that are made from direct bandgap materials (e.g. GaAs) $\Rightarrow$ radiative recombination dominates

- However, >90% of terrestrial solar cells are made from Si, which is an indirect bandgap semiconductor
  $\Rightarrow$ radiative recombination is low at the point of operation

- Radiative recombination is the fundamental reverse process of photogeneration. It is inevitable, as thermodynamics require that the photogeneration process is reversible.

Radiative Recombination

Thermal equilibrium: In *thermal equilibrium* for a given T > 0 K, the crystal lattice vibrations lead to the generation of e-h pairs at a generation rate G_{th}.

As we are in thermal equilibrium, the expression $np = n_i^2$ must be valid.

$\Rightarrow$ recombination takes place at the same rate as generation: $R_{th} = G_{th}$

Since the recombination rate is proportional to the concentration of electrons in the CB and to the concentration of the available holes in the VB:

$$R^* = \beta \cdot n \cdot p.$$

where β is a proportionality factor. For the thermal recombination we have

$$R_{th} = \beta \cdot n \cdot p.$$

Radiative Recombination

Illuminated scenario:

- We now look at a situation where the semiconductor is illuminated such that a constant generation rate G_L is present (steady state, not equilibrium).
- Excess electrons and holes are created. As the electron and hole concentrations increase, the recombination rate will also increase.
- In the *steady state (G = R*)* situation the total recombination and generation rates are:

$$R^* = \beta\,(n_0 + \Delta n)(p_0 + \Delta p)$$
$$G = G_L + G_{th}$$

where n_0 and p_0 are the equilibrium concentrations and the excess carrier concentrations $\Delta p = p - p_0$, $\Delta n = n - n_0$.

- In steady state R^* must be equal G are equal, hence

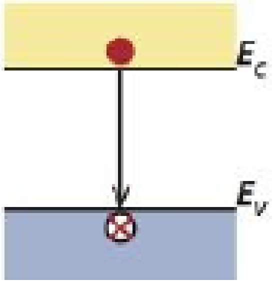
$$G_L = R^* - G_{th} = R_d \qquad \Leftrightarrow \; G_L = R_d = \beta\,(np - n_0 p_0)$$

where **R_d denotes the *net* radiative recombination rate.**

Source: textbook

Radiative Recombination

Illuminated scenario:



- Assume p-type and the low injection limit, which means that $\Delta p \ll p$ and $n \ll p$.

$$\boxed{R_d \approx \beta\, p_0 (\Delta n) = (\Delta n)/\tau_{rad}}$$

this provides the *radiative lifetime of the minority charge carriers* :

$$\tau_{rad} = \frac{1}{\beta\, p_0} \approx \frac{1}{\beta\, N_D}$$

(equivalent an n-type semiconductor, but $\tau_{rad} = \frac{1}{\beta\, n_0} \approx \frac{1}{\beta\, NA}$)

- Note, if no excess carriers are present ($\Delta n = n - n_0$ or $\Delta p = p - p_0$), no radiative recombination can occur ($R_\mathrm{d} = 0$).
- Also note the excess charge carrier concentration: $\tau_{rad} * G_L = \Delta p$,

Source: textbook

Shockley-Read-Hall Recombination

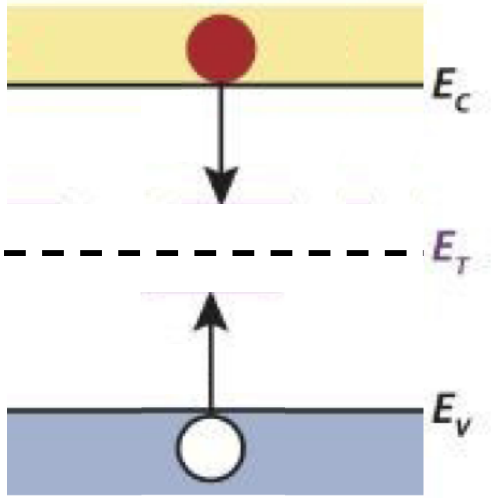
Shockley-Read-Hall (SRH) recombination only occurs in materials w. defects

- SRH is typically non-radiative and the excess energy is dissipated into the lattice in the form of heat (=> it is a loss for the solar cell).

SRH recombination is a two-step process.

i) e^- (or h^+) is trapped by a trap energy state (E_T) within the bandgap, introduced through lattice defects or impurity atoms. Defects can be either unintentionally introduced or introduced intentionally (e.g. doping)

ii) if h^+ (or e^-) moves up to the same energy state before the e^- is thermally re-emitted into E_c, SRH recombination occurs.

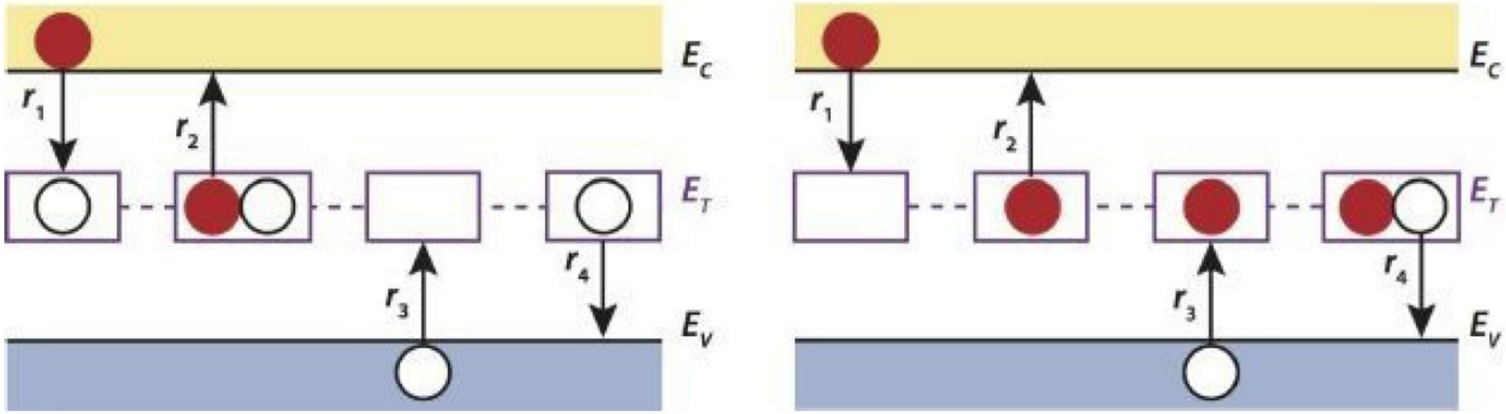


Source: textbook

Recombination Shockley-Read-Hall

The SRH statistics are based on four processes that are involved in recombination in a single-electron trap:

- *r*1: capture of an electron from the conduction band;
- *r*2: emission of an electron to the conduction band;
- *r*3: capture of a hole from the valence band; and
- *r*4: emission of a hole to the valence band.



Schematic illustration of the processes involved with SRH recombination in a singleelectron trap state for (left) a donor-type; and (right) an acceptor-type trap.

Recombination Shockley-Read-Hall

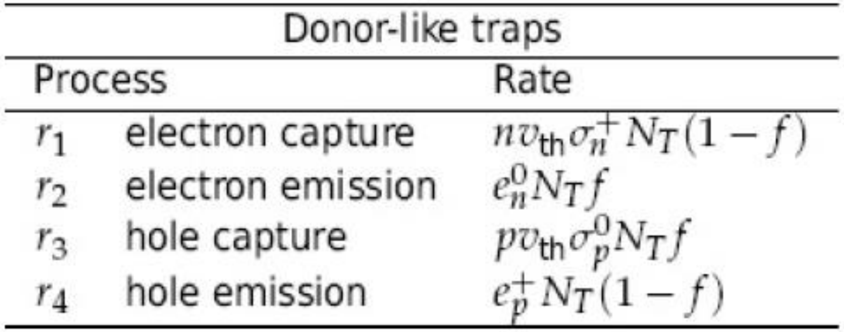
The electron and hole capture rates (r1, r3) are proportional to the free carrier concentration (*n* or *p*), the thermal velocity (v_{th}), the trap density (N_T), the trap occupancy (electrons: *f*, holes: 1 − *f*), and the electron and hole capture cross-section of the traps (σ_n and σ_p)

The emission rates (r2, r4) are proportional to N_T, occupancy of the trap occupancy (electrons: *f*, holes: 1 − *f*), and emission coefficient (e_n or e_p).

- *Thermal velocity* v_{th}: average velocity of e and h due thermal movement

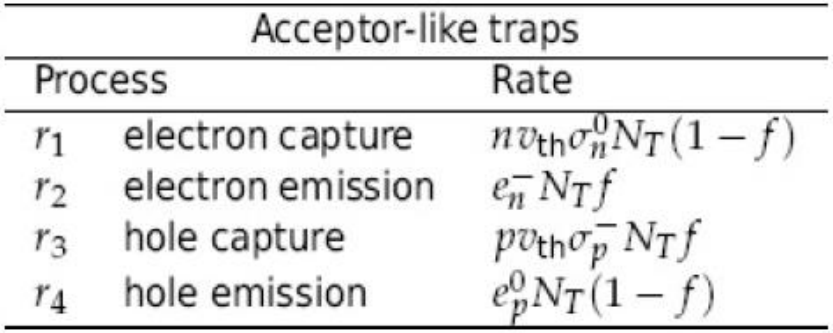
$$\frac{1}{2} m_n^* v_{th,n}^2 = \frac{3}{2}\ kBT \qquad \frac{1}{2} m_p^* v_{th,p}^2 = \frac{3}{2}\ kBT$$

- The electron capture cross–section σ_n describes the effectiveness of the trap state to capture an electron.



Donor-like traps

Process		Rate
r_1	electron capture	$n v_{\mathrm{th}} \sigma_n^+ N_T (1-f)$
r_2	electron emission	$e_n^0 N_T f$
r_3	hole capture	$p v_{\mathrm{th}} \sigma_p^0 N_T f$
r_4	hole emission	$e_p^+ N_T (1-f)$



Acceptor-like traps

Process		Rate
r_1	electron capture	$n v_{\mathrm{th}} \sigma_n^0 N_T (1-f)$
r_2	electron emission	$e_n^- N_T f$
r_3	hole capture	$p v_{\mathrm{th}} \sigma_p^- N_T f$
r_4	hole emission	$e_p^0 N_T (1-f)$

Source: textbook

Recombination Shockley-Read-Hall

As SRH recombination involves exactly one *e*$^-$ and one *h*$^+$, at steady state the rate at which the electrons leave the conduction band equals the rate at which the holes leave the valence band.

$$R_{SRH} = \frac{dn}{dt} = \frac{dp}{dt} = r_1 - r_2 = r_3 - r_4$$

Using the rates shown in the table before and some further derivation (slightly complex, see textbook page 74/75), we get for an *n*-type semic. :

$$R_{SRH} = v_{th}\sigma N_T \frac{p-p_0}{1+\frac{2ni}{n_0}\cosh\left(\frac{E_T-EFi}{k_BT}\right)} = c_p N_T(p\text{-}p_0) = \frac{p-p_0}{\tau_{p,SRH}}$$

where c_p is called the *hole capture coefficient*, $\tau_{p,\mathrm{SRH}}$ is the lifetime of holes in an *n*-type semiconductor. Similar for a p-type semiconductor:

$$R_{SRH} = v_{th}\sigma N_T \frac{n-n_0}{1+\frac{2ni}{p_0}\cosh\left(\frac{E_T-EFi}{k_BT}\right)} = c_n N_T(n\text{-}n_0) = \frac{n-n_0}{\tau_{n,SRH}}$$

Recombination Shockley-Read-Hall

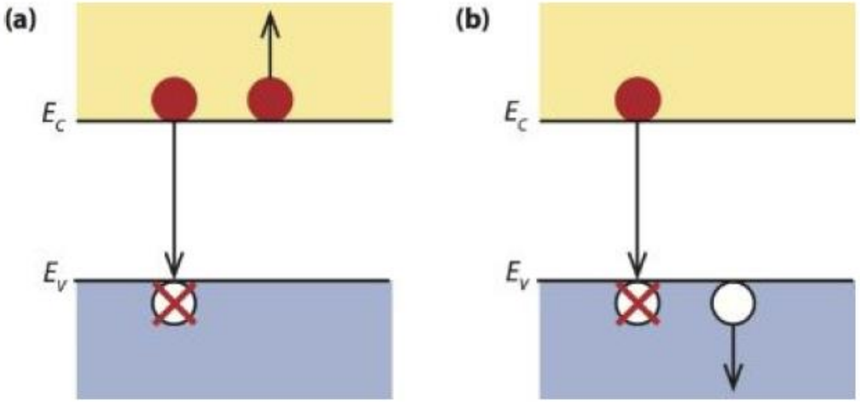
- We see that the lifetime is related to the capture coefficients via

$$\tau_{p,\,SRH} = \frac{1}{c_p N_T} \qquad and \qquad \tau_{n,\,SRH} = \frac{1}{c_n N_T}$$

- The lifetime of the minority carriers due to Shockley–Read–Hall recombination therefore is indirectly proportional to the trap density N_T.
  => **For a good semiconductor device it is crucial to keep N_T low.**
- The values of the minority-carrier lifetimes can vary a lot. When the trap concentration in c-Si is very low, τ_n (τ_p) can achieve values around 1 ms. On the other hand, the traps induced e. g. gold atoms into Si, can decrease τ_n (τ_p) to values around 1 ns.
- For an efficient collection of photo–generated carriers in c-Si solar cells, τ_n (τ_p) should be in the range of tens of milliseconds!
  (often is only in the range of around 1 μs for Si in IC industry)

Auger Recombination

Auger Recombination involves three carriers. An e^- and h^+ recombine, but rather than emitting the energy as heat or as a photon, the energy is given to a third carrier, an e^- electron in E_c. This e^- then thermalizes back down to edge of E_c. edge.



- In comparison to radiative and SRH recombination that involve two particles (e^- and h^+), Auger recombination is a *three particle process.* => It is more likely to occur in indirect semiconductors, where radiative recombination is already a three particle process (electron, hole, phonon)
- Auger recombination thermalizes the energy of a photogenerated elelctron => *it is a loss mechanism in solar cells.*
- Auger recombination is most important at high carrier concentrations caused by: i) heavy doping or ii) high level injection (high light intensity) under concentrated sunlight

Source: textbook

Auger Recombination

As Auger recombination is a three particle process, the Auger recombination rate R_{Aug} strongly depends on n and p. The recombination rates for electron-electron-hole (eeh) and electron-hole-hole (ehh) processes are given by

$$R_{Aug} = Ree_h + Rehh = C_n n^2 p + C_p n p^2$$

where where C_n and C_p are the proportionality constants that are strongly dependent on the temperature.

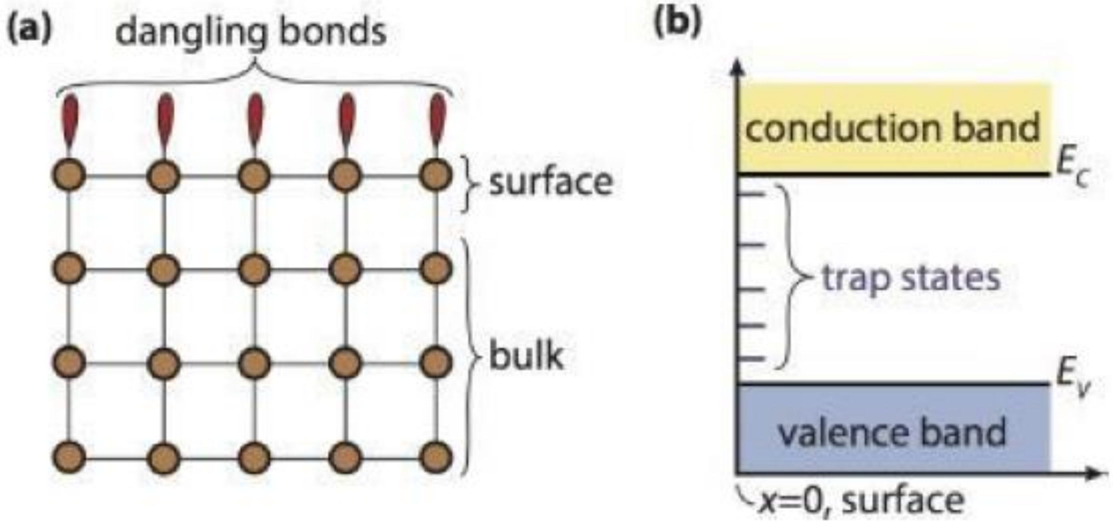
- R_{eeh} is dominant when the electrons are the majority charge carriers, while R_{ehh} is dominant when the holes are the majority charge carries.
- In strongly doped *p*-type silicon with a donor concentration N_A under low-level injection we can assume that $p \approx N_A$ and hence that the ehh process is dominant.

$$R_{ehh} = C_p N_A^2 n \qquad \tau_{ehh} = \frac{1}{C_p N_A^2}$$

Surface Recombination

Surface recombination is high as large amounts of defects exist where the crystal lattice is disrupted. Understanding the impacts and the ways to limit surface recombination leads to better and more robust solar cell designs.

The surface defects will create trap states of various energies which will induce some SRH like recombination. In very pure semiconductors, recombination might be dominated by surface recombination.



Note, all the recombination mechanisms (radiative, SRH, and Auger) discussed so far are *bulk recombination* mechanisms.

Source: textbook

Surface Recombination

Karlsruher Institut für Technologie

High recombination rate at a surface depletes this region of minority carriers

$\Rightarrow$ localized region of low carrier concentration causes carriers to flow into this region from the surrounding, higher concentration regions

$\Rightarrow$ surface recombination rate is limited by the rate at which minority carriers move towards the surface!

The *surface recombination rate Rs* for an *p*-type semiconductor can be approximated with

$$R_S \approx vth\, \sigma_n\, N_{ST}\,(n_s\text{-}n_0)$$

With the material specific *surface velocity* $S_r := v_{th}\, \sigma N_{ST}$

where v_{th} is the thermal velocity in cm/s [see Eq. (7.29)], N_{sT} is the surface trap density in cm^{-2}, and σ_p is the capture cross–section for holes in cm^2. p_s is the hole concentration at the surface and p_0 is the equilibrium hole concentration in the *n*-type semiconductor.

Surface Recombination

- Surface recombination velocity (S_R, units: cm/s) ≡ parameter used to specify recombination rate at a surface. E.g., for a surface with infinitely fast recombination, the movement of carriers towards this surface is limited by the maximum velocity they can attain (typically ~1 x 10^7 cm/s)
- For high quality solar cells it is crucial to have a low S_R, which can be achieved in two different ways:
  - Reducing the trap density N_{sT} at the surface by so-called *passivation*: The defect density is reduced by depositing a thin layer that forms covalent bonds with the “dangling” surface bonds.
  - The excess minority carrier concentration at the surface (*ps* or *ns*) can be reduced, for example by high doping of the region just underneath the surface in order to create a barrier.

PART III: CHARGE CARRIER LIFETIME & DIFFUSION LENGTH

Minority carrier lifetime

Minority carrier lifetime (denoted by τ_n or τ_p) ≡ average time that a carrier can spend in an excited state after e^-- h^+ generation before recombining

Warning: often just called "lifetime" but has nothing to do with long-term material stability or environmental stability!

For material under low-level injection (where the number of minority carriers is less than the doping), the lifetime is related to the recombination rate by:

$$\tau = \frac{\Delta n}{R}$$

It is one of the most important parameters for the characterization of semiconductor wafers used in the preparation of power electronic devices and photovoltaic solar cells.

Consider now the situation, where the light is suddenly switched of (t = 0). As there is no longer any generation ($G_L = 0$), the excess charge carrier concentration will change according to this concentration:

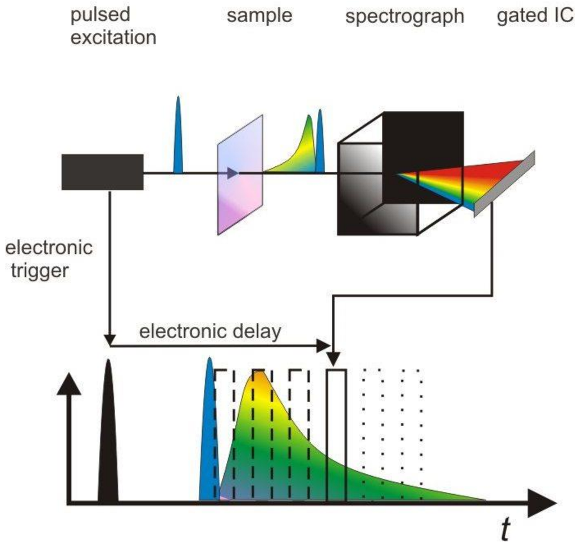
$$\frac{dp}{dt} = \frac{p(t) - p_0}{\tau_p}$$

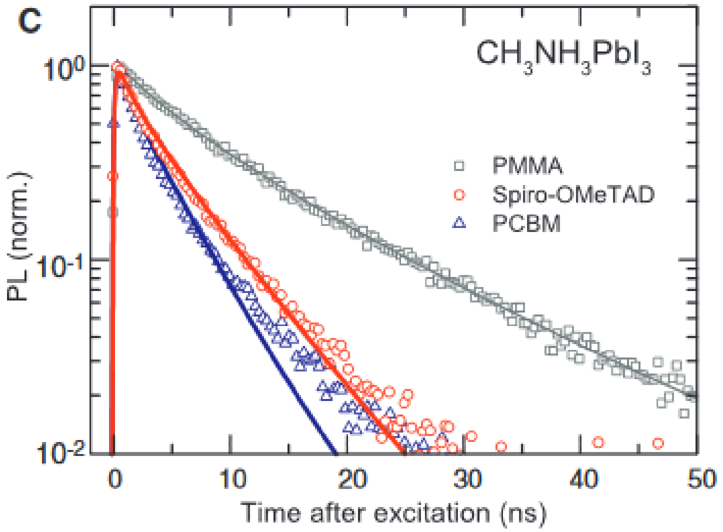
Recombination - Minority carrier lifetime

Considering $p(t=0) = p_0 + GL\tau_p$,

we find: $$p\,(t) = p_0 + G_L\tau_p e^{-\frac{t}{\tau_p}}.$$

- <u>Minority charge carrier lifetime is the time constant at which an excess charge carrier concnetration decays exponentially.</u>
- In fact, the minority charge carrier lifetime is often determined by transient PL measurements that mimic this scenario:





[1] Courtesy Dr. I. Howard
[2] S. D. Stranks, et al., Science (80). 342, 341 (2013).

Recombination - Minority carrier lifetime

In a real solar cell, the several recombination mechanisms coexist:

$$\mathrm{R}_{\mathrm{tot}} = \mathrm{R}_1 + \mathrm{R}_2 + \mathrm{R}_3 + \ldots \quad => \quad R_{tot} = \frac{p(t)-p_0}{\tau_{p1}} + \frac{p(t)-p_0}{\tau_{p2}} + \frac{p(t)-p_0}{\tau_{p3}} + \ \ldots$$

This implies:

$$\frac{1}{\tau_{n,tot}} = \frac{1}{\tau_{n,1}} + \frac{1}{\tau_{n,2}} + \frac{1}{\tau_{n,3}} + \ \ldots$$

The more recombination mechanisms are present, the shorter the total lifetime of the excess charge carriers. But the recombination mechanism with the shortest lifetime dominates! (reciprocal sum).

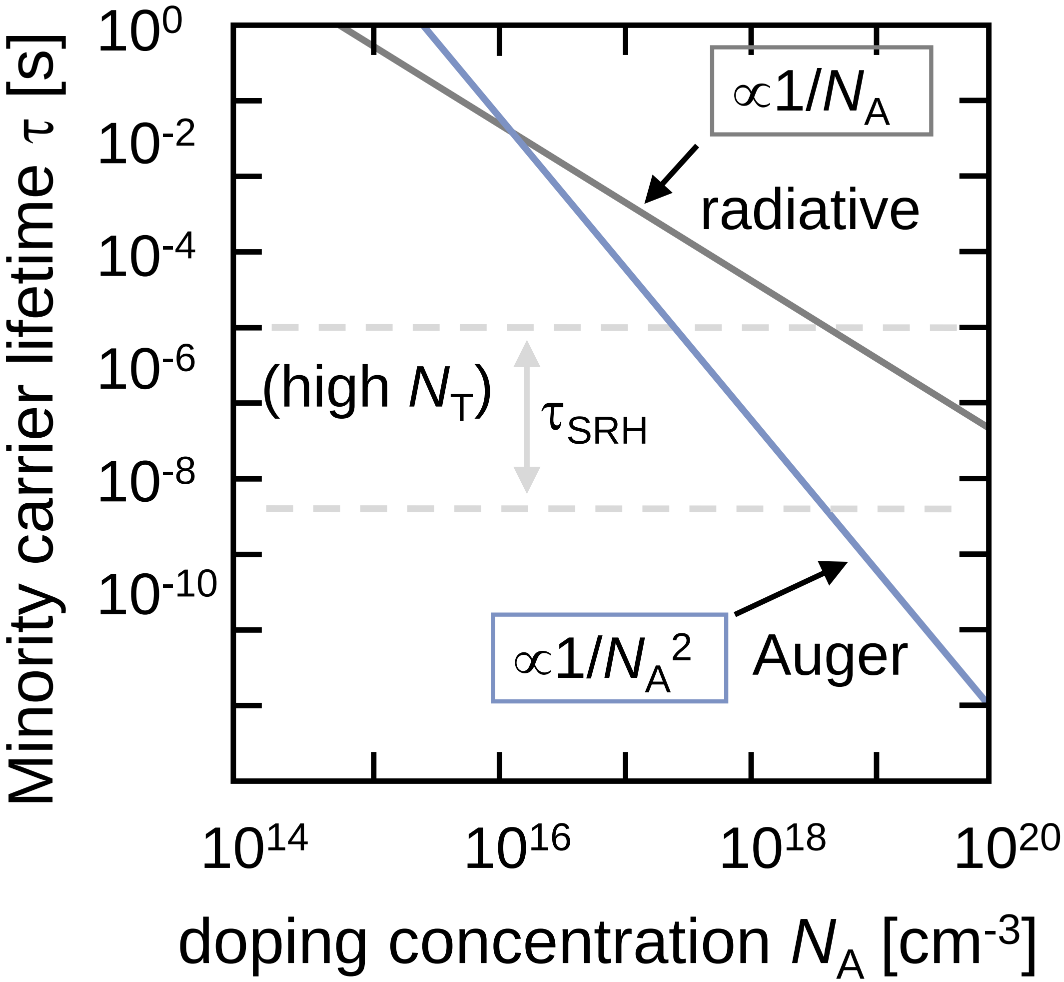
For a real solar cell, we can write:

$$\boxed{\frac{1}{\tau_{tot}} = \frac{1}{\tau_{surface}} + \frac{1}{\tau_{bulk}}}$$

with

$$\boxed{\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Auger}}}$$

Recombination - Minority carrier lifetime



Radiative, Auger-, and Shockley-Read-Hall-recombination in c-Si. Low SRH- lifetime for high N_T.

Courtesy to Uwe Rau

Minority Carrier Diffusion Length

Another key parameter related to recombination rate, is minority carrier diffusion length ≡ average distance a carrier can move from point of generation until it recombines (see last lecture / Diffusion)

The diffusion length $L_{p/n}$ is related to τ by the diffusivity according to:

$$L_{p/n} = \sqrt{D_{p/n}\tau_{p/n}}$$

where $L_{p/n}$ is the diffusion length in meters and D is the diffusivity in m²/s. (Diffusivity is again related to mobility by $D_{\mathrm{n/p}} = \mu_{\mathrm{n/p}} k_B T /q$)

e.g. in Si, τ can be ≥ 1 ms ⇒ for single crystal silicon solar cell, diffusion length L ~ 100 – 300 μm ⇒ gives indication of material quality ⇒ typical Si wafer thickness 200 μm

APPENDIX

Quick Test

- What is the continuity equation for charge carriers in a semiconductor?
- What is the difference between a direct and an indirect semiconductor?
- What is the absorption coefficient / absorption length? Relevance for a solar cell? How to calculate the absorption length for a given absorption coefficient?
- What is the state of the semiconductor if we illuminate w. light? (equilibrium or steady state? Definitions of these?)
- What are the excess charge carriers?
- Which excess charge carrier concentration determines recombination? (Minority or Majority) Why?
- Name the three bulk recombination meachanisms. Which ones are inevitable?

Quick Test

- What is the dependence of the minority charge carrier lifetime of (1) radiative, (2) SRH, and (3) Auger recombination on the dominant doping concentration?
- How to add up the minority lifetimes of various recombination mechanisms to calc. the total lifetime?
- Explain the principle of:
  - Radiative recombination
  - SRH recombination
  - Auger recombination
  - Surface recombination
- What is the charge carrier diffusion length?