N. Wyrsch

Transport and recombination in crystalline and disordered semiconductors

PV-lab
IEM NEUCHATEL

Charge transport mechanism

- Both types of carriers contributing (majority / minority carriers)
- Drift conductivity (for one type of carrier)

$$\sigma_{drift} = en_{free}\mu_0 F = en_{tot}\mu_D F$$

- Diffusion conductivity (for one type of carrier)

$$j_{diffusion} = -D\nabla n_{free}$$

- In (disordered) semiconductors: given by **mobile** (mostly free) carriers

$$\mu_D = \mu_0 \cdot \frac{n_{free}}{n_{total}} = \mu_0 \cdot \frac{n_{free}}{n_{free} + n_{trapped}}$$

(Multiple trapping mechanism, mobility gap)

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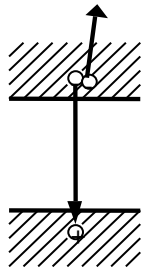
Generation and recombination

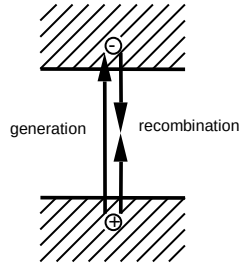
- In steady-state conditions:

  photogeneration of carriers rate* = *recombination rate

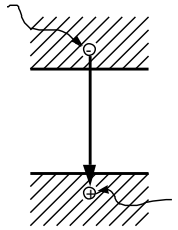
- In semiconductors: several recombination mechanisms possible
  - Auger recombination



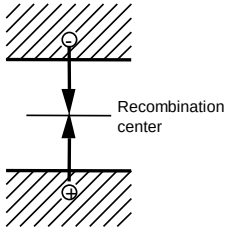
  - Geminate recombination



  - Bi-molecular recombination



  - **Mono-molecular recombination (trap assisted)**



  - Radiative, non radiative
- In principle, they can all exist in parallel, but usually one of them is dominant under given experimental conditions (excitation, temperature)

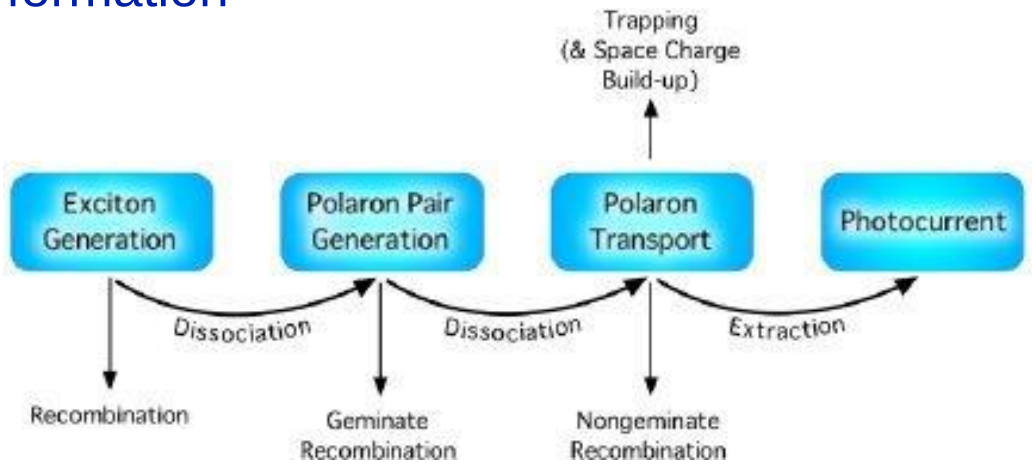
Photoconductivity

- Photoconductivity given by density of free carriers (n_{free}, p_{free})
- Steady-state condition: G=R
- Generation G given by absorption coefficient (controlled by DOS)
- Recombination
  - Direct recombination
  - Recombination R («trap assisted») given by recombination centers
    - → **Relationship between R and n_{free}, p_{free} *needed***
    - → **R given by the occupation (function) of recombination centers**
    - → **Recombination centers must be identified**

Recombination in semiconductors

Recombination in low mobility semiconductors

- Given by Langevin theory (Langevin, Ann. Chim. Phys. 28, 433, 1903)
- Stochastic movement
- Lifetime given by
  - «Direct» recombination
  - «Meeting» of charge opposite charge carriers (given by mobility)
- Photocurrent formation



steps from light generation / exciton generation to photocurrent
(from https://blog.disorderedmatter.eu/2008/03/02/how-do-organic-solar-cells-function-part-one/)

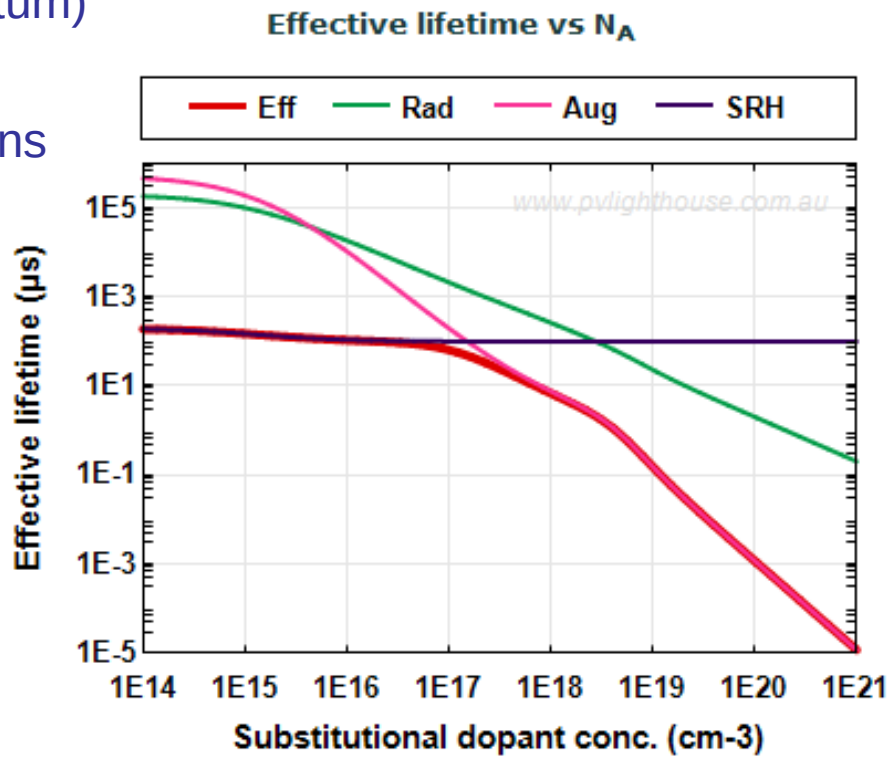
Recombination in crystalline semiconductors

- Recombination channels
  - Radiative (band to band)
    - Effect is the base of LEDs
    - Effective only in direct gap semiconductors (because photon carries very little momentum)
  - Auger
    - Only significant in non-equilibrium conditions when the carrier density is very high (high doping or high injection)

$$U_{Aug} = \Gamma_n\, n(np - n_i^2) + \Gamma_p\, p(np - n_i^2)$$

  - Trap assisted : Shockley–Read–Hall (SRH)
- Lifetime

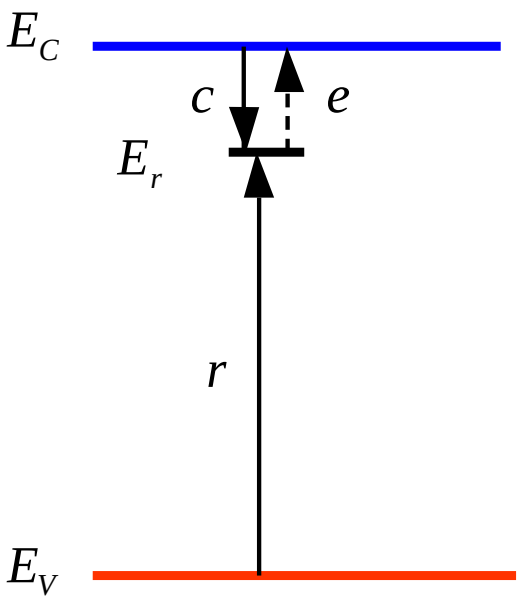
$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{Band}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}$$



Example p-doped c-Si

(https://www2.pvlighthouse.com.au/calculators/Recombination)

Traps and recombination centers



- Consider a localized state at energy E_r
  - c : capture probability of an electron
  - e : emission probability of an electron
  - r : capture probability of a hole

- State at energy E_r acts as a **trap** if

$$e > r$$

- State at energy E_r acts as a **recombination center** if

$$e < r$$

Quasi Fermi levels

- **Thermal equilibrium:** Population of electrons at energy E given by Fermi-Dirac function and Fermi level E_F

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

- **Out of equilibrium** (bias voltage, illumination) : Distribution function of electrons or holes (in quasi thermal equilibrium) are given separately by Fermi-Dirac functions and quasi Fermi levels

  - Free electrons can be described by and E_{F_n} $$f(E) = \frac{1}{1 + e^{\frac{E - E_{F_n}}{kT}}}$$

  - Free holes can be described by and E_{F_p} $$f(E) = \frac{1}{1 + e^{\frac{E - E_{F_p}}{kT}}}$$

Traps and recombination centers

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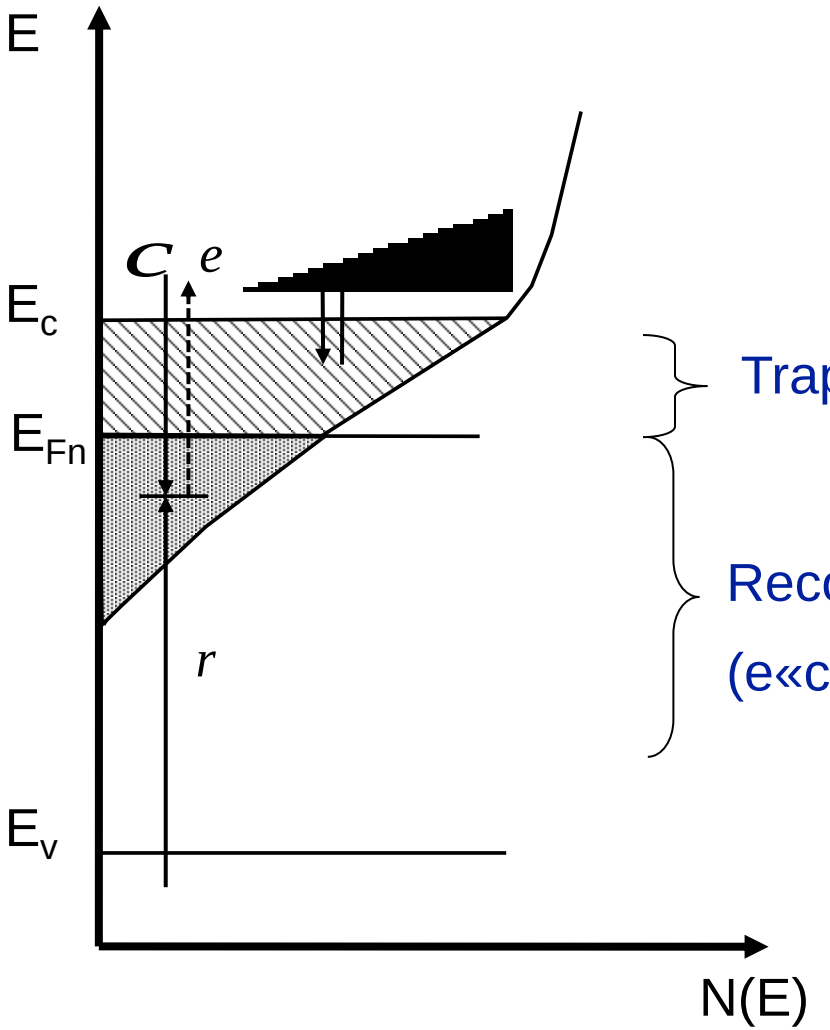


Traps (states in thermal equilibrium with CB)

Recombination centers

(e«c → recombination dominant)

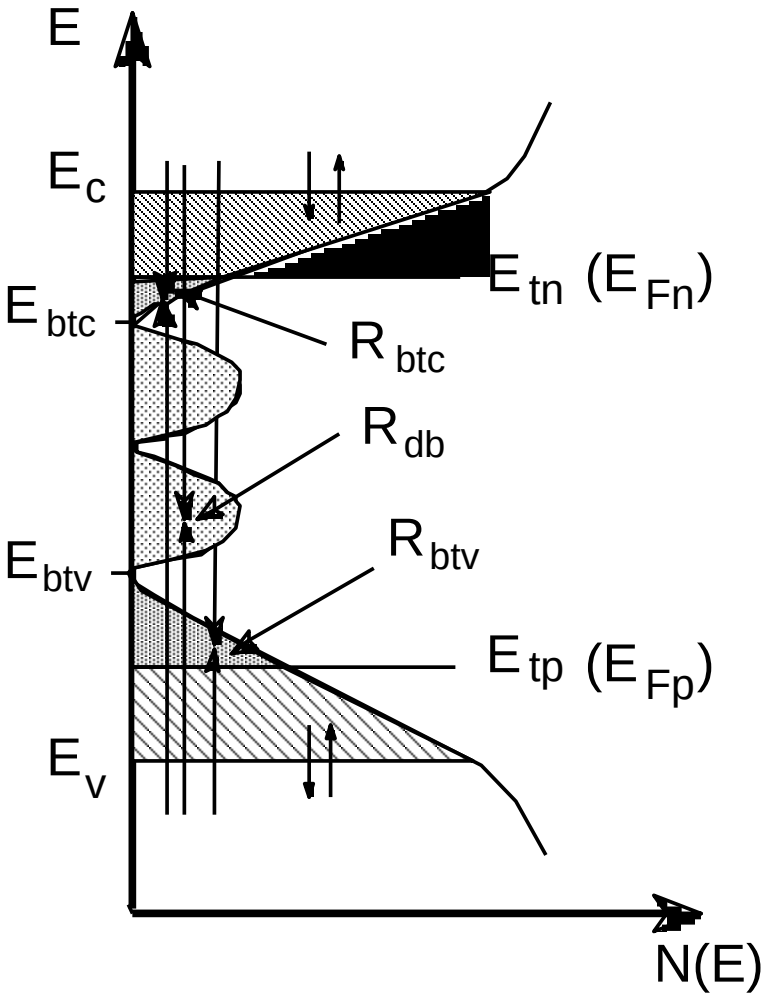
Transient vs steady-state

- Transient behavior
  1. Perturbation: change of excitation condition (illumination, temperature, bias voltage,…)
  2. System tends to equilibrium: through thermal excitation and recombination
  - Temporal change of the occupation of each energy level states (band tails and conduction levels)

- Steady-state
  - Constant occupation of all energy level states (band tails and conduction levels)
  - In thermal equilibrium : **detailled balance**

Transition rate to any energy state = transition rate from that energy state

Quasi Fermi levels in a-Si:H



- **Quasi-Fermi levels** E_{Fn} for electrons and E_{Fp} for holes to describe free carrier densities out of equilibrium
- If E_F far away from band edges:

$$E_{Fn} = E_{Fo} + k_B T \ln\left[\frac{n_f}{n_{fo}}\right]$$

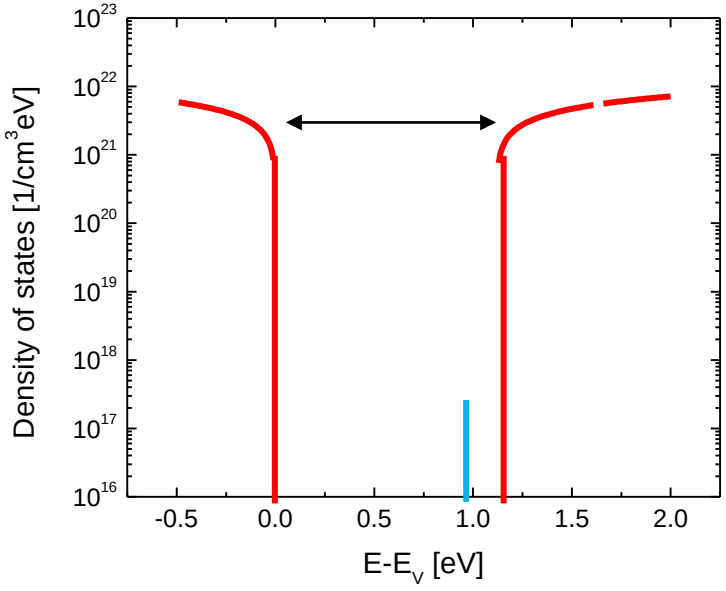
$$E_{Fp} = E_{Fo} + k_B T \ln\left[\frac{p_f}{p_{fo}}\right]$$

(subscript o : thermal equilibrium concentrations)

- **Quasi-Fermi levels** E_{tn} for trapped electrons and E_{tp} for trapped holes:
  - as the energy level at which thermal re-emission probability is equal to hole capture (i.e. recombination) probability
  - Separate traps from recombination levels
  - $E_{tn} \approx E_{fn}$, $E_{tp} \approx E_{fp}$

Recombination models

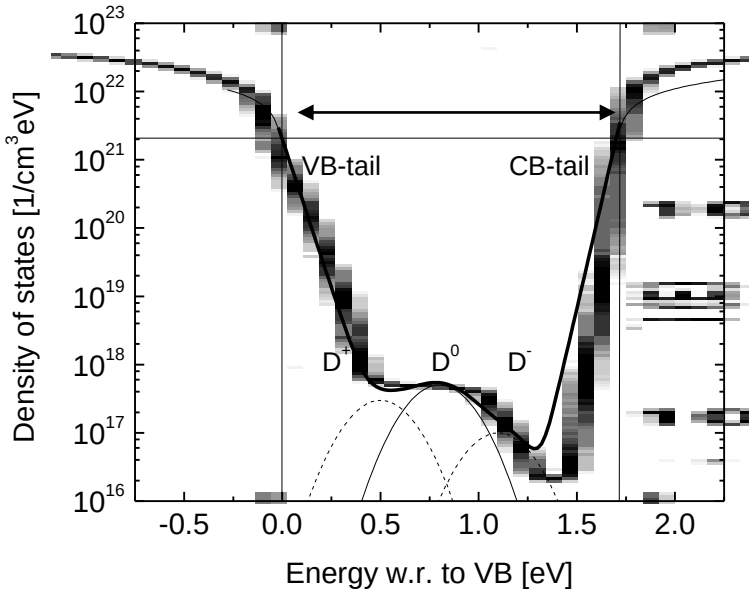
Crystalline semiconductors (e.g. c-Si)



Sharp band edges
Sharp gap states (defects, impurities)

→ Shockley-Reed-Hall model

Disordered semiconductors (e.g. a-Si:H)

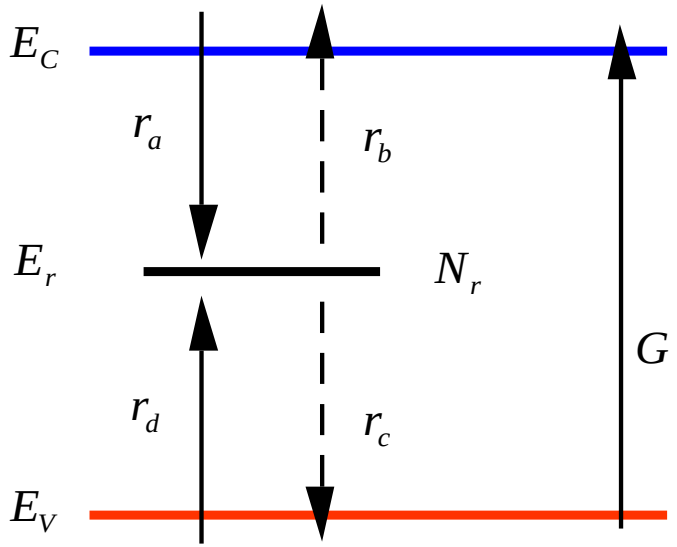


Band tails
Distribution of gap states

→ Taylor&Simmons model +
DB recombination model

Shockley-Read-Hall (SRH) recombination

First recombination model, very successful (crystalline semiconductors), but originally designed for crystalline Ge devices



Assumptions:

- one recombination level
- occupation with one electron or empty
- equivalent view: empty or occupied with one hole

Shockley, PR 87(5), p835 (1952)
Hall, 87(2), p387 (1952)

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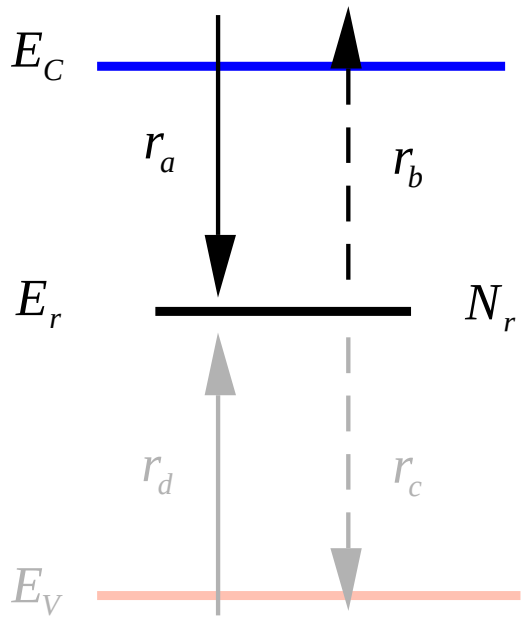
Electron capture and emission



Occupation function at E: $f(E)$
(depends on generation!)

Capture:

$$dr_a = c(E_r) \cdot g(E) f(E) \cdot N_r [1 - f(E_r)] dE$$

capture coeff.

available number of electrons

number of free rec. centres

Emission:

$$dr_b = e(E_r) \cdot N_r f(E_r) \cdot g(E) [1 - f(E)] dE$$

emission coeff.

number trapped electrons

number of free states

(Equivalent processes for holes)

Detailed balance

In thermal equilibrium, there is no net capture, for any given energy the processes must be in balance: $f(E) = f_D(E) = \frac{1}{1+e^{\frac{E-E_F}{kT}}}$

$$dR_n = dr_a - dr_b =$$
$$= \left[\left(1 - f_D(E_r)\right) f_D(E) - \underbrace{e/c\; f_D(E_r)\left(1 - f_D(E)\right)}_{=0}\right] c\, N_r\, g(E)\, dE$$

This defines a relation between the capture c and emission e coefficients:

$$e/c = \exp\left\{\left(E_r - E\right)/kT\right\}$$

Equivalent conclusion for hole capture and emission

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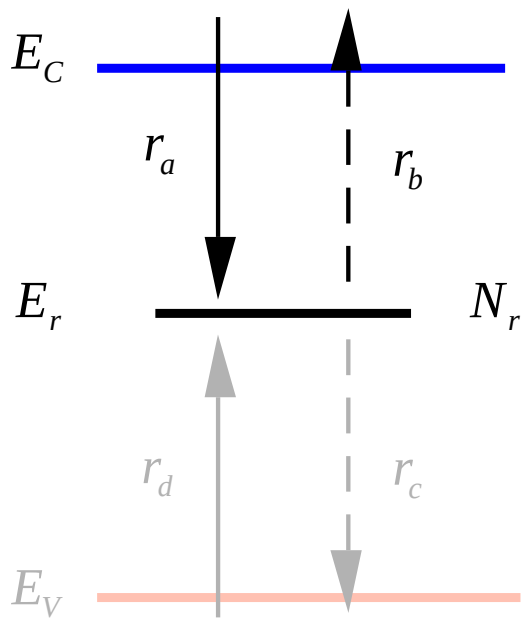
Electron capture and emission



(Equivalent processes for holes)

- Free electrons are in quasi-thermal equilibrium

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

with E_{F_n} the quasi Fermi level for electrons

- Occupation function $f_r(E_r)$ of recombination center E_r is unknown
- Capture:

$$dr_a = c(E_r) \cdot g(E) f(E) \cdot N_r [1 - f_r(E_r)] dE$$

- Emission:

$$dr_b = e(E_r) \cdot N_r f_r(E_r) \cdot g(E) [1 - f(E)] dE$$

- Overall capture properties for all energies:

$$R_n = \int dR_n = \int dR_a - \int dR_b$$

Application to non-degenerate semiconductor

Boltzmann approximation:

$$R_n \approx \nu_n \sigma_n \left[(1 - f_r) n - \underbrace{f_r \cdot N_C e^{\frac{(E_r - E_C)}{kT}}}_{n_1} \right]$$

Analogously for holes:

$$R_p \approx \nu_p \sigma_p \left[f_r p - (1 - f_r) p_1 \right]$$

- Summary of physical parameters in SHR model:
  - N_r : **density of recombination centers**
  - $\nu_{n,p,}$: **thermal velocity:** $(3kT/m_{n,p}^{*})^{1/2} \approx 10^7$ cm/s at 300 K
  - σ : **capture cross-section** ($\approx 10^{-16}$ cm^2)
  - $\nu_{th}\sigma = \langle c \rangle$ (averaged capture rate)
- Lifetimes $\tau_{n,p}$ are defined as : $$\frac{1}{\tau_{n,p}} = \nu_{n,p} \sigma_{n,p} N_r$$

Illuminated case (non-equilibrium)

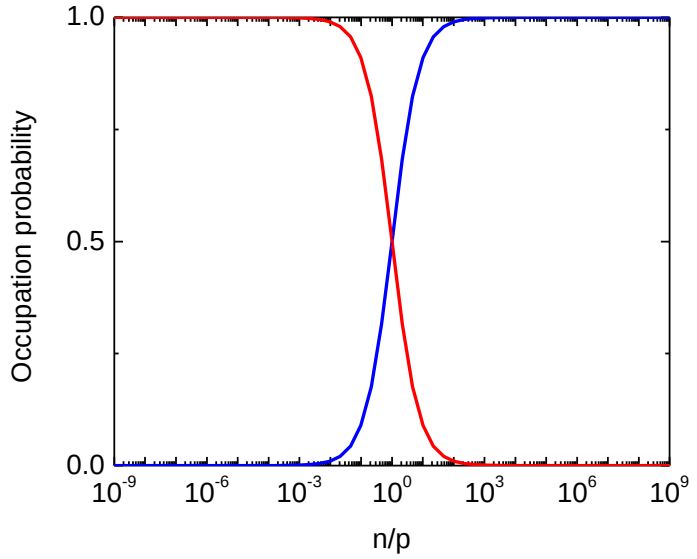
Distribution function f_r (occupation of state at E_r) is unknown!

It can be determined from steady state conditions:

$G = R_n = R_p$ (G: generation rate in $cm^{-3}s^{-1}$),

write n_f and p_f for densities of generated free carriers

$$f_r = \frac{\sigma_n n_f + \sigma_p p_1}{\sigma_n (n_f + n_1) + \sigma_p (p_f + p_1)} \qquad 1 - f_r = \frac{\sigma_n n_1 + \sigma_p p_f}{\sigma_n (n_f + n_1) + \sigma_p (p_f + p_1)}$$



SRH recombination

Recombination function $R_{SRH} = R_n = R_p$

$$R_{SRH} = \frac{n_f p_f - n_1 p_1}{\frac{(n_f + n_1)}{\sigma_p} + \frac{(p_f + p_1)}{\sigma_n} v_{th} N_r}$$

or, $v_{th} N_r \sigma_{n,p} = 1/\tau_{n,p}$

$$R_{SRH} = \frac{n_f p_f - n_1 p_1}{(n_f + n_1)\tau_p + (p_f + p_1)\tau_n}$$

$p_1 n_1 = n_i^2$, n_i intrinsic carrier density at thermal equilibrium

If n_f and $p_f \gg n_i$:
(thermal emissions can be neglected):

$$R_{SRH} \approx \frac{n_f p_f}{n_f \tau_p + p_f \tau_n}$$

Doped semiconductors: n-type ($n_f \gg p_f$)

$$R \approx \frac{p_f}{\tau_p}$$

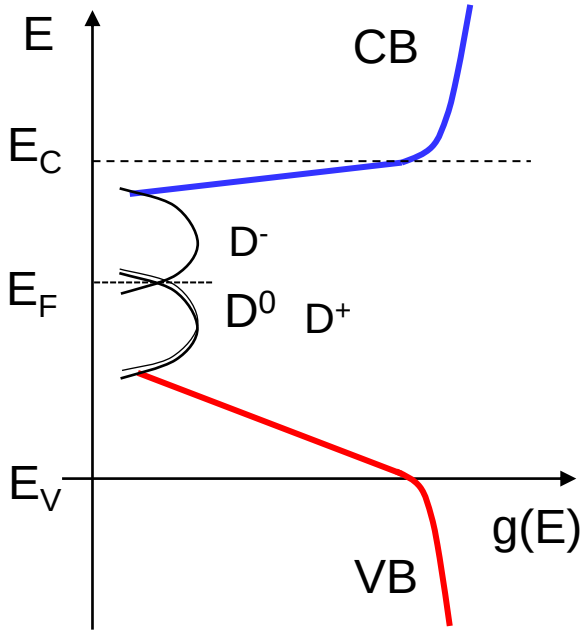
p-type ($p_f \gg n_f$)

$$R \approx \frac{n_f}{\tau_n}$$

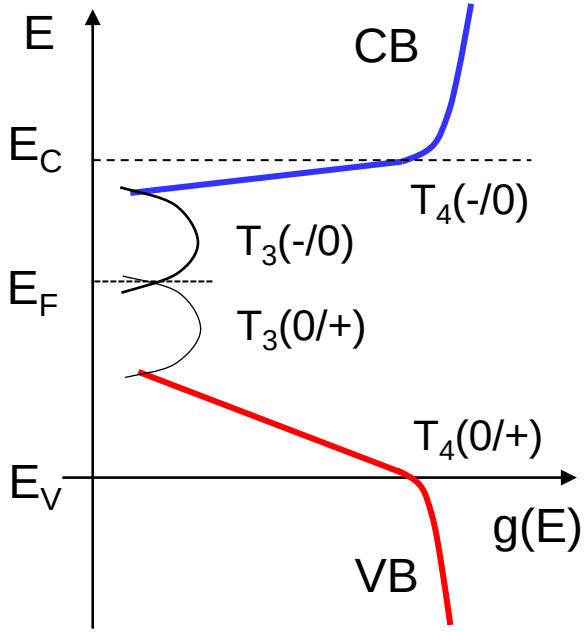
$\tau_{n,p}$ are minority carrier lifetimes

a-Si:H DOS representations

State (charge) representation

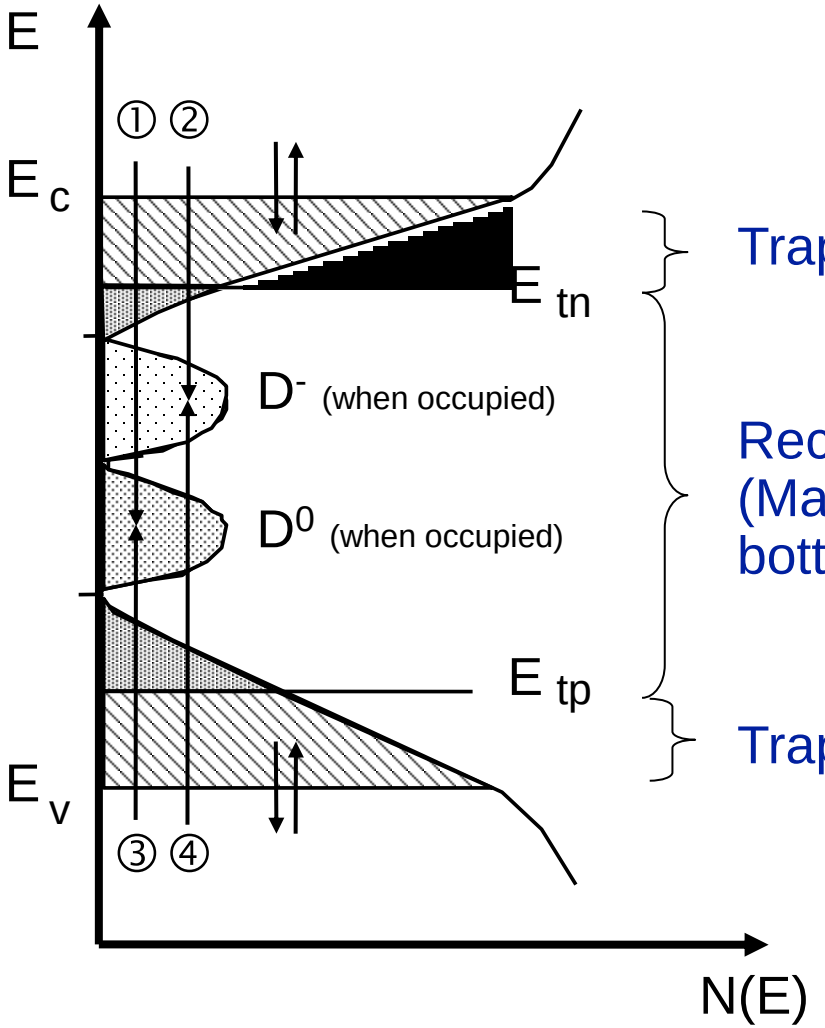


Transition (acceptor / donor) representation



- T_3:3-fold coordinated
- T_4:4-fold coordinated

DOS, traps and recombination centers



Traps

Recombination centers
(Mainly dangling bonds,
bottom of band tails negligible)

Traps

Traps act as charge reservoir, no direct contribution to charge transport

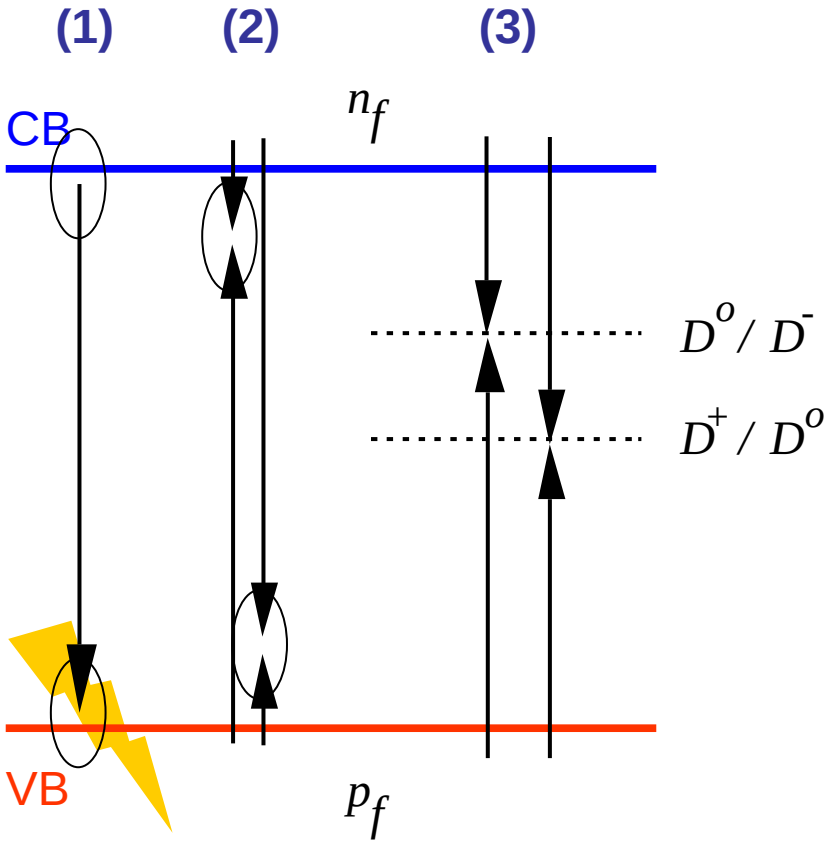
①: Capture of an electron by a D^+

②: Capture of an electron by a D^0

③: Capture of a hole by a D^0

④: Capture of a hole by a D^-

Possible recombination in a-Si:H



1. At temperatures below 250 K: radiative recombination between band tail states (efficiency >70%) → photo luminescence.

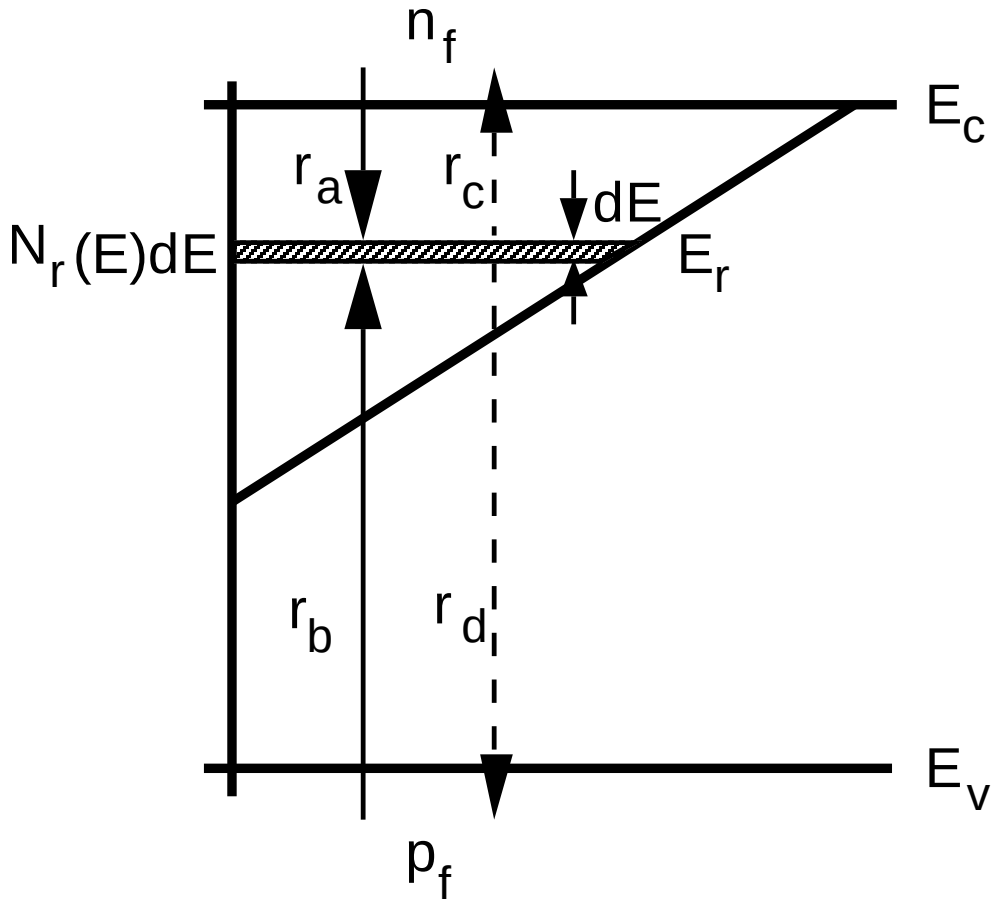
2. Non-radiative from band edges via band tail states, not very effective because not mid-gap

3. From band edges via dangling bonds (amphoteric D^+, D^0, D^-) dominant at room temperature:

Note: The defect is here **not** denoted by its charge states (three),

but by an approximation with two transitions (a group of a donor-like and an acceptor-like defect)

Recombination in bandtails



- Taylor and Simmons model (treatment analog to SRH
- Recombination functions

$$R_{btc} = \frac{n_f\ p_f}{n_f \tau_{pc} + p_f \tau_{nc}}$$

$$R_{btv} = \frac{n_f\ p_f}{n_f \tau_{pv} + p_f \tau_{nv}}$$

with the lifetimes given by

$$\frac{1}{\tau_{nc}} = \nu_{th}\sigma_n \int_{E_{btc}}^{E_{tn}} N(E)dE \qquad \frac{1}{\tau_{pc}} = \nu_{th}\sigma_p \int_{E_{btc}}^{E_{tn}} N(E)dE$$

$$\frac{1}{\tau_{nv}} = \nu_{th}\sigma_n \int_{E_{tp}}^{E_{btv}} N(E)dE \qquad \frac{1}{\tau_{pv}} = \nu_{th}\sigma_p \int_{E_{tp}}^{E_{btv}} N(E)dE$$

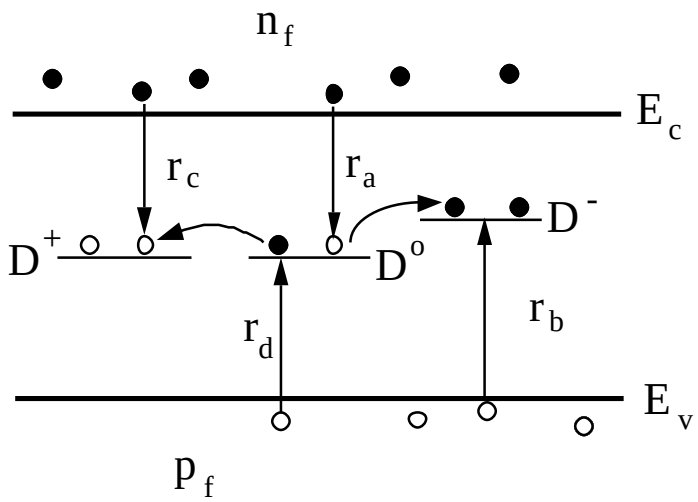
- Recombination in bandtails can be neglected in a-Si:H under usual illumination levels

Taylor, Simmons, JNCS 8 (1972) 940

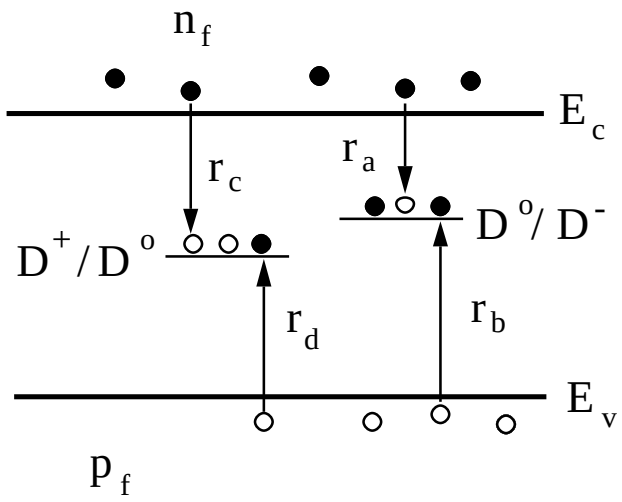
Recombination in dangling bonds

SRH not valid (**amphoteric** character of DB's)

Charge state representation



Equivalent D/A representation



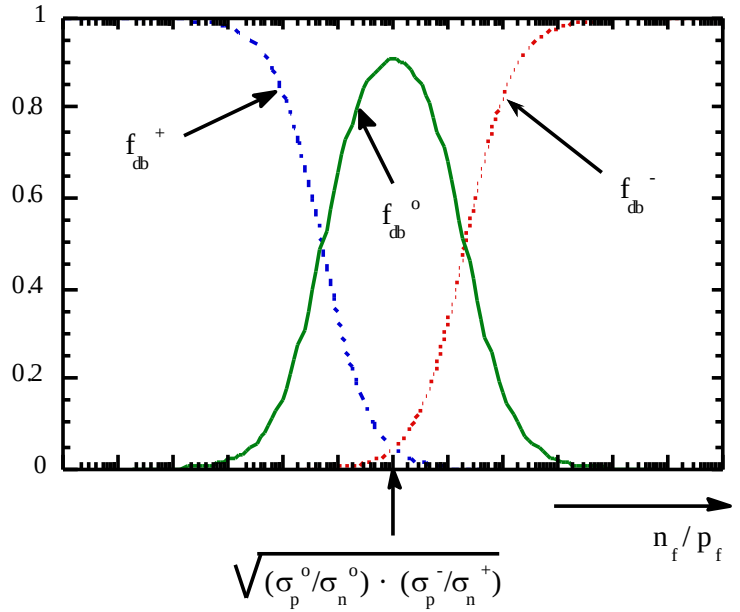
Recombination function $$R_{db} = \frac{\frac{p_f^2 n_f}{\tau_n^+ \tau_p^- \tau_p^o} + \frac{p_f n_f^2}{\tau_p^- \tau_n^o \tau_n^+}}{\frac{p_f^2}{\tau_p^o \tau_p^-} + \frac{p_f n_f}{\tau_n^+ \tau_p^-} + \frac{n_f^2}{\tau_n^o \tau_n^+}} \nu_{th} N_{db}$$

Hubin et al , Phil. Mag. Lett. 66(3), p 115 (1992)

Occupation function of DB

- Occupation function under illumination
- One occupation function for each DB state

$$f^{+} = \frac{\frac{p_f^2}{\tau_p^o \tau_p^-}}{\frac{p_f^2}{\tau_p^o \tau_p^-} + \frac{p_f n_f}{\tau_n^+ \tau_p^-} + \frac{n_f^2}{\tau_n^o \tau_n^+}} \qquad f^{-} = \frac{\frac{n_f^2}{\tau_n^o \tau_n^+}}{\frac{p_f^2}{\tau_p^o \tau_p^-} + \frac{p_f n_f}{\tau_n^+ \tau_p^-} + \frac{n_f^2}{\tau_n^o \tau_n^+}} \qquad f^{o} = 1 - f^{+} - f^{-}$$



Recombination in a-Si:H (doped)

- Recombination in bandtails can usually be neglected (at RT under reasonable illumination levels)
- Usually we assume $\tau_p^o \approx \tau_n^o \quad \tau_p^- \ll \tau_p^o \quad \tau_n^+ \ll \tau_n^o$
- Particular cases (doped materials)
  - $n_f \gg p_f$ (n-doped material)
    - $f^- \rightarrow 1$, $f^+ = 0$

    $\Rightarrow$ Recombination function: $R_{db} \approx \frac{p_f}{\tau_p^-}$ **similar to SRH for n-doped c-Si**
  - $n_f \ll p_f$ (p-doped material)
    - $f^- = 0$, $f^+ \rightarrow 1$

    $\Rightarrow$ Recombination function: $R_{db} = \frac{n_f}{\tau_n^+}$ **similar to SRH for p-doped c-Si**

Recombination in a-Si:H (undoped)

- Given $\tau_p^o \approx \tau_n^o \quad \tau_p^- \ll \tau_p^o \quad \tau_n^+ \ll \tau_n^o$
- (Nearly) intrinsic material
  - $n_f \approx p_f$, assuming $\frac{n_f}{p_f} \ll \frac{\sigma_p^-}{\sigma_n^o}$ and $\frac{p_f}{n_f} \ll \frac{\sigma_n^+}{\sigma_p^o}$
    - $f^- \ll 1$, $f^+ \ll 1$ (almost all DB are neutral)

    $\Rightarrow$ Recombination function:

    $$R_{db} = \frac{n_f}{\tau_n^0} + \frac{p_f}{\tau_p^0}$$

    - If the material is slightly n-type (case of undoped a-Si:H), we have $\frac{n_f}{\tau_n^0} \gg \frac{p_f}{\tau_p^0}$

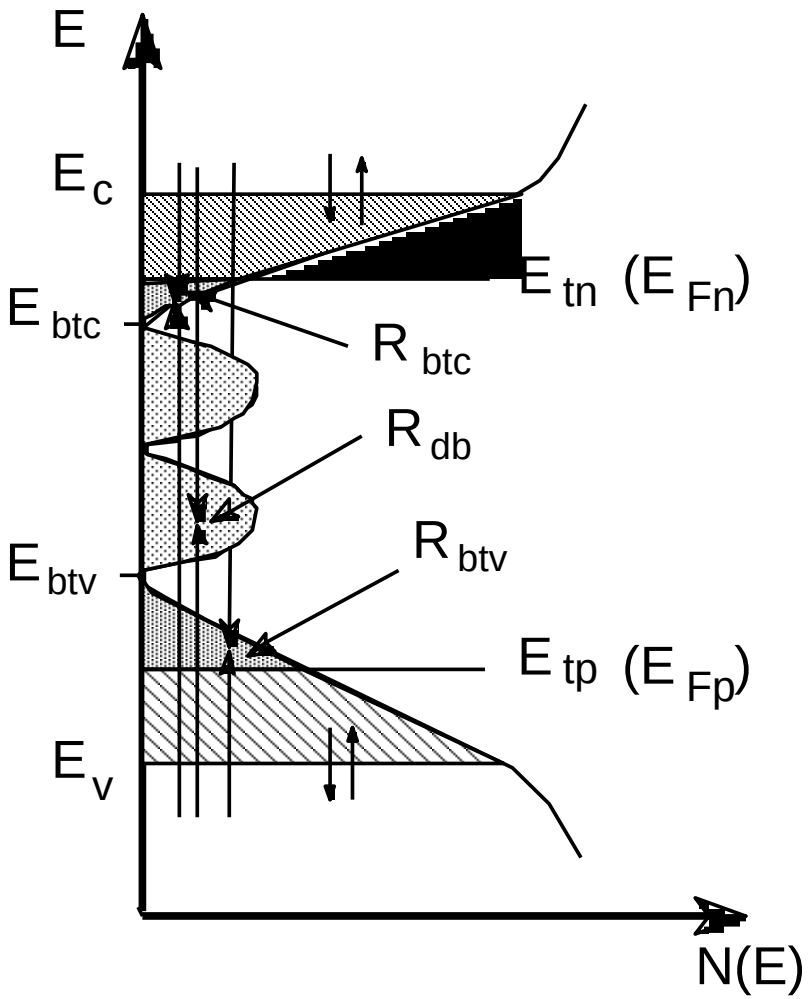
    $\Rightarrow$ Recombination function:

    $$R_{db} = \frac{n_f}{\tau_n^0}$$

    Controlled by majority carriers !

    $\Rightarrow$ Quite different from SRH $\frac{1}{R_{SRH}} = \frac{\tau_n}{n_f} + \frac{\tau_p}{p_f}$ where minority carriers dominate

Total recombination



- Total recombination:

$$R_{tot} = R_{db} + R_{vbt} + R_{cbt}$$

- Under usual illumination levels (no sun light concentration)

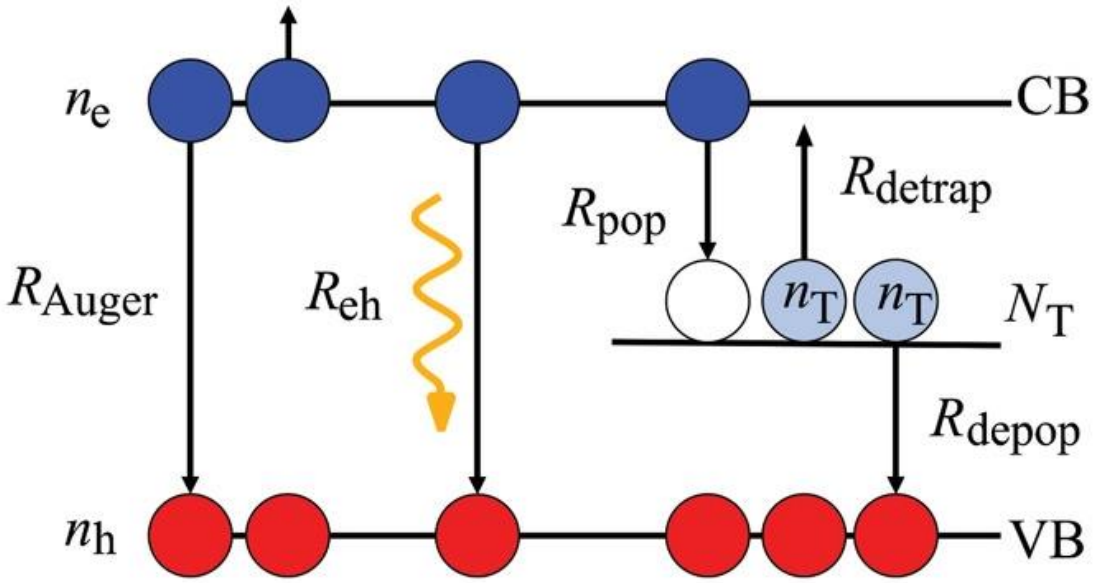
$$R_{tot} = R_{db}$$

- Band tails act as traps and charge reservoir; most photo-generated carriers are sitting in band tails (do not contribute to the current)

Recombination summary

Recombination at RT and illumination ≤ 1 sun	Crystalline semiconductors (e.g. c-Si, c-Ge, …)	Disordered semiconductor (e.g. a-Si:H, a-Ge:H related alloys,…)
Main recombination centers	Defects, impurities (0,-,--/0,+,++)	Dangling bonds Amphoteric state (-,0,+)
Doped semiconductor	SRH recombination Minority carrier controlled	SRH recombination Minority carrier controlled
Intrinsic semiconductor	SRH recombination Minority carrier controlled	Recombination at amphoteric state Majority carrier controlled

Recombination channels in Perovskites



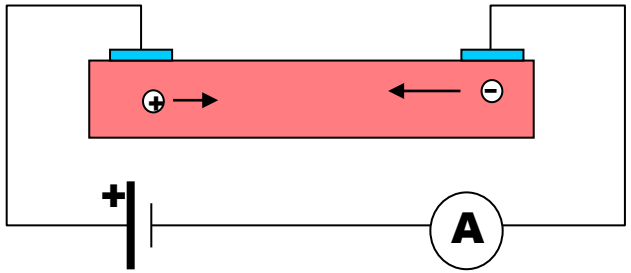
- Major channel through traps (mono-molecular) with contribution of radiative (bi-molecular)

Trimpl et al. , Adv. Funct. Mater. 30 (2020) 2004312

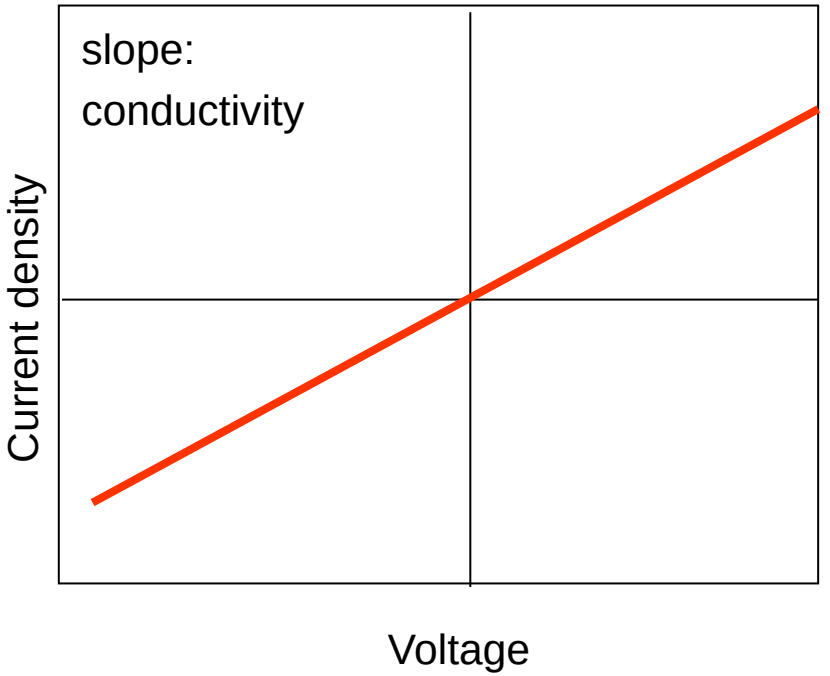
Practical aspects

Photoconductivity measurements

Dark conductivity



ohmic contacts



$$\sigma_{dark} = 1/\rho_{dark} = l/R \cdot A_c$$

R: measured resistance

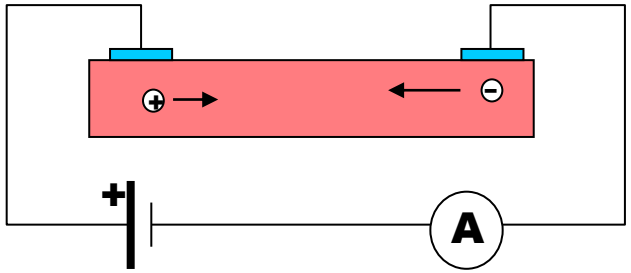
l: distance between contacts

A_c: cross-sectional area
length of contact x film thickness

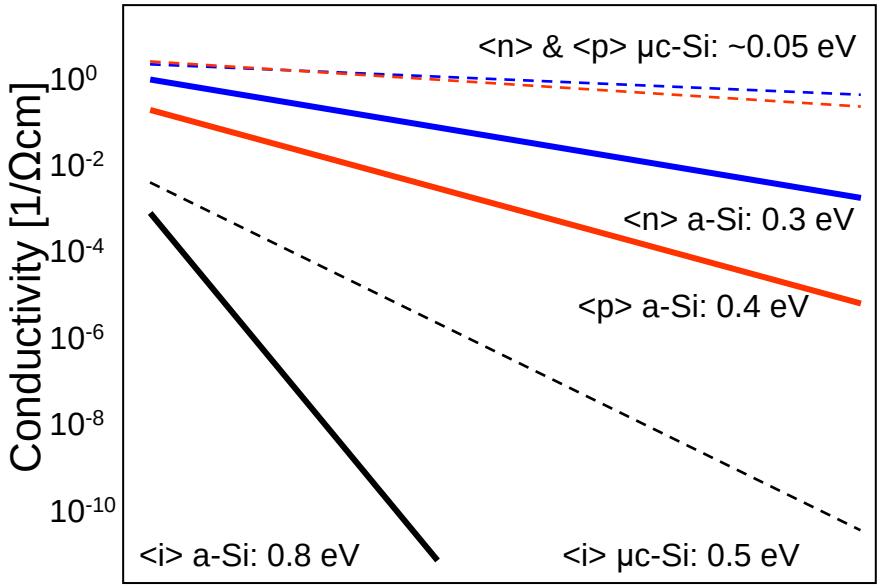
$$\sigma_{dark} = q(\mu_e n_f + \mu_p p_f)$$

Current transport by the free charge carriers
(trapped charge in band tails do not contribute to current !)

Dark conductivity



ohmic contacts



Normal mode of operation:

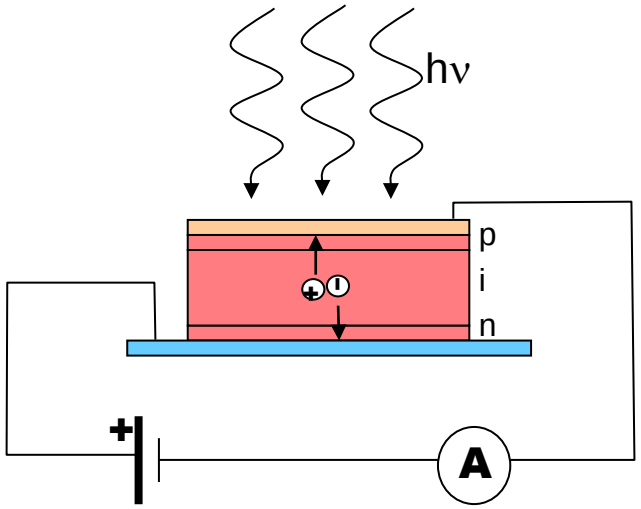
temperature dependence $\sigma_{\text{dark}}(T) = \sigma_0 e^{-\frac{E_a}{kT}}$

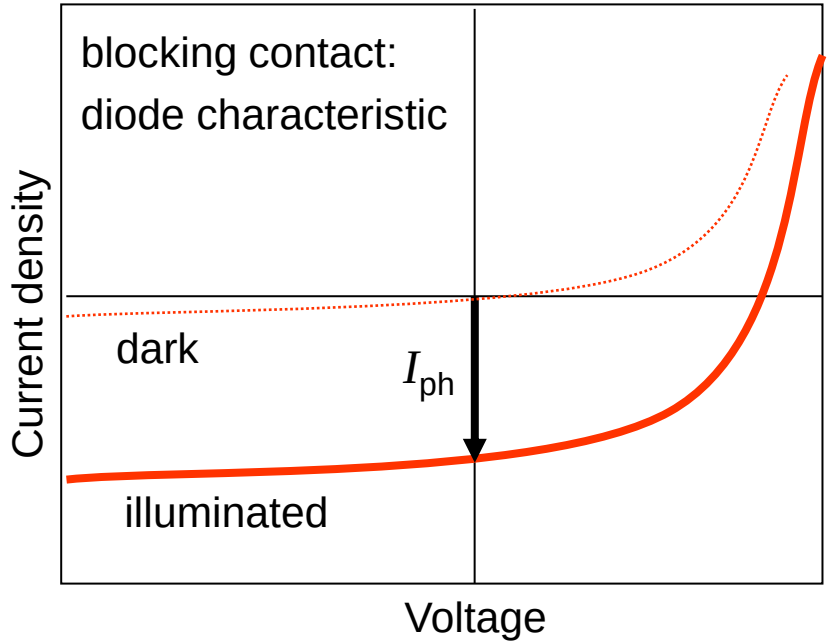
- Important quantity: activation energy
- Doped material: Transport by majority carriers, minority carriers recombine close to contact

  n-type: $E_a \approx E_C - E_F$

  p-type: $E_a \approx E_F - E_V$
- Intrinsic material:
  Recombination throughout whole slab: $E_a = E_g / 2$

Primary photoconductivity: blocking contacts

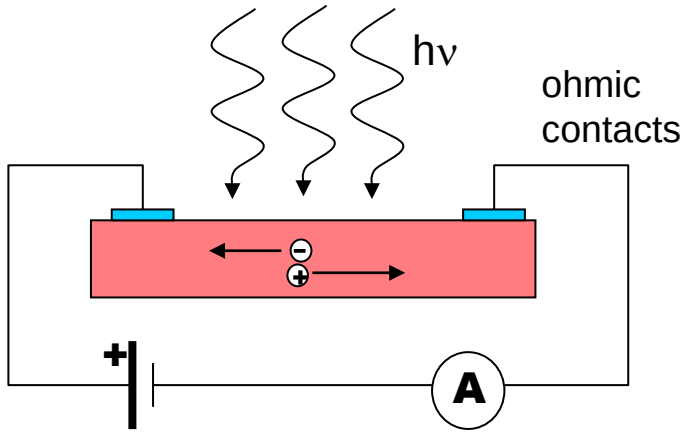


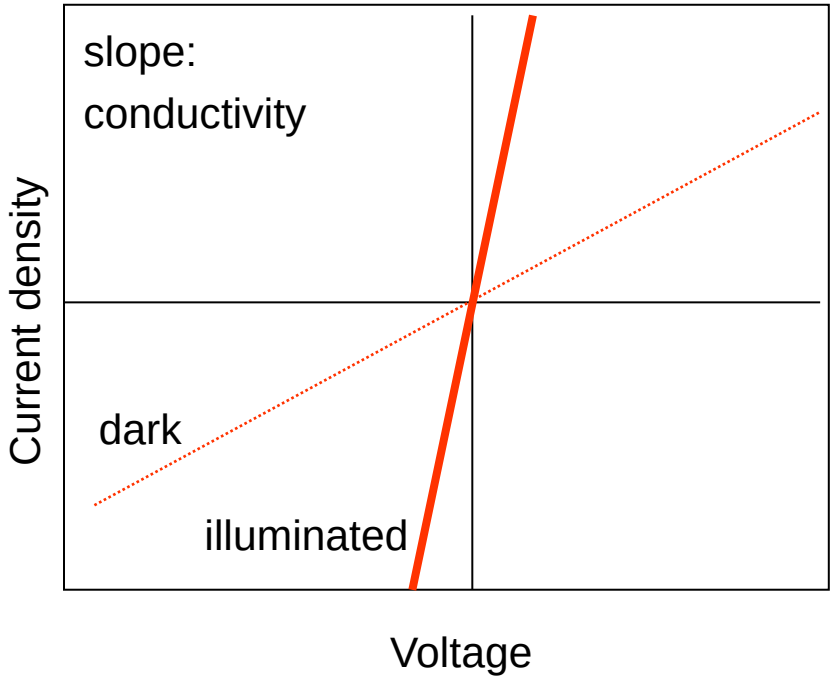


Primary photoconductivity:

- collection of photo-generated carriers in devices with **blocking** contacts (photodiodes, solar cells): in **photo-detectors** or **optoelectronic detectors**.
- $I_{ph}=Ge\eta$ with η : quantum efficiency, $\eta \rightarrow 1$ (a-Si:H cells)
- Linear change of I_{ph} with G (in contrast to secondary photocond.)

Secondary photoconductivity



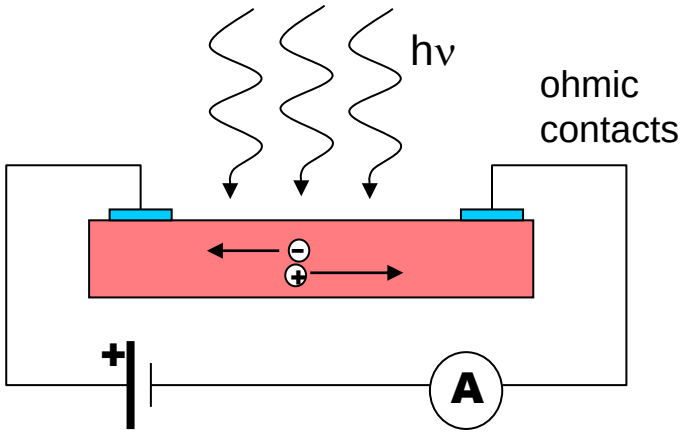


- **Secondary photoconductivity** takes place in devices with **ohmic contacts (photoconductors)**
- given by the increase of the conductivity of an illuminated **intrinsic layer**
- $\sigma_{tot} = \sigma_{dark} + \sigma_{photo} = \sigma_{dark} + e\,(\mu_n\, n_f + \mu_p\, p_f)$

$\mu_{n,p}$: band mobilities n_f, p_f: photo-generated free carrier densities

N. Wyrsch

Photoconductivity



In steady-state: $G = R\ (= n_f/\tau_n = p_f/\tau_p)$

$$\sigma_{photo} = e\,G\,(\mu_n\tau_n + \mu_p\tau_p)$$

where $\tau_{n,p}$ are free carrier recombination times

- if σ_{dark} is low (high bandgap) $\Rightarrow$ large difference in layer conductivity under illumination.
- σ_{photo} controlled by the larger $\mu\tau$ product (useful for material quality determination)

- both $\mu\tau$ products should be measured for reliable material quality determination
- Several photoconductivity based techniques for material characterization

Characterization techniques

- SSPC (Steady-state photoconductivity)
  - Secondary photoconductivity, mobility-lifetime product of majority carriers
- CPM (Constant Photocurrent Measurement)
  - Determination of absorption coefficient in small absorption regime
  - Similar techniques: DBP (Dual Beam Photoconductivity, FTPS (Fourier-Transform Photocurrent Sectroscopy)
- SSPG (Steady-State Photocarrier Grating Method)
  - mobility-lifetime product of minority carriers
- MPC (Modulated Photocurrent Spectroscopy)
  - DOS determination
- Switch-on and Switch-off Transients
  - Mobility, trap distribution
- TPC (Transient Photocurrent Spectroscopy)
  - DOS information
- TOF (Time-of-Flight)
  - Mobility, mobility-lifetime product and trap information

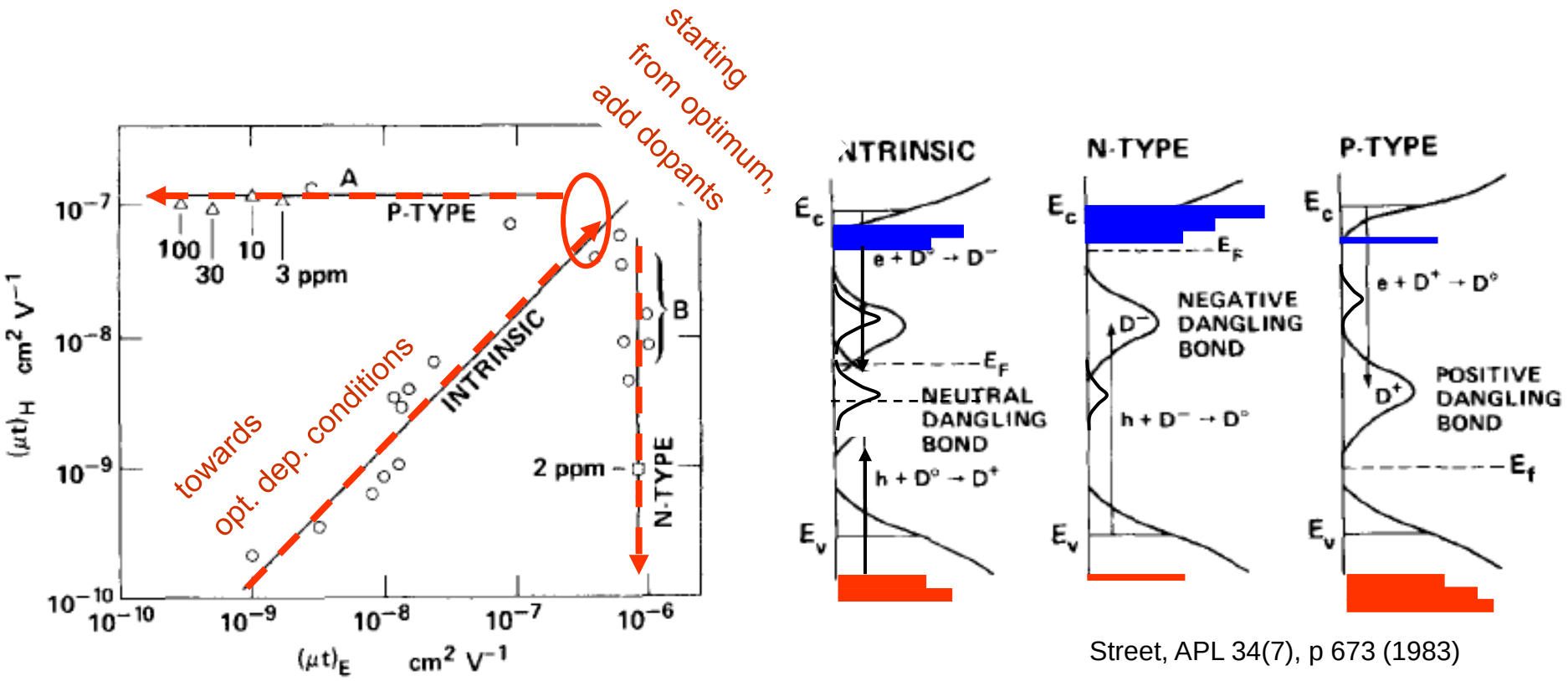
S. Reynolds et al, https://doi.org/10.1007/978-3-319-48933-9_7

Photoconductivity of thin-film Si

- c-Si :
  - E_g=1.1 eV
  - σ_o = 1.14·10^4 (Ωcm)$^{-1}$
  - $\sigma_{photo}/\sigma_{dark} \approx 10$
- a-Si:H:
  - E_g=1.75 eV
  - σ_o = 150 (Ωcm)$^{-1}$
  - $\sigma_{photo}/\sigma_{dark} \approx 10^5$

Material	μ_n [cm^2/Vs]	μ_p [cm^2/Vs]	$\mu_n\tau_n$ [cm^2/V]	$\mu_p\tau_p$ [cm^2/V]
c-Si (doped:10^{18}cm^{-3})	1350	480	3x10^{-3}	5x10^{-3}
a-Si:H (undoped)	≈10	≈2	**≈ 3x10^{-6}**	**≈ 1x10^{-7}**

Defect density and recombination



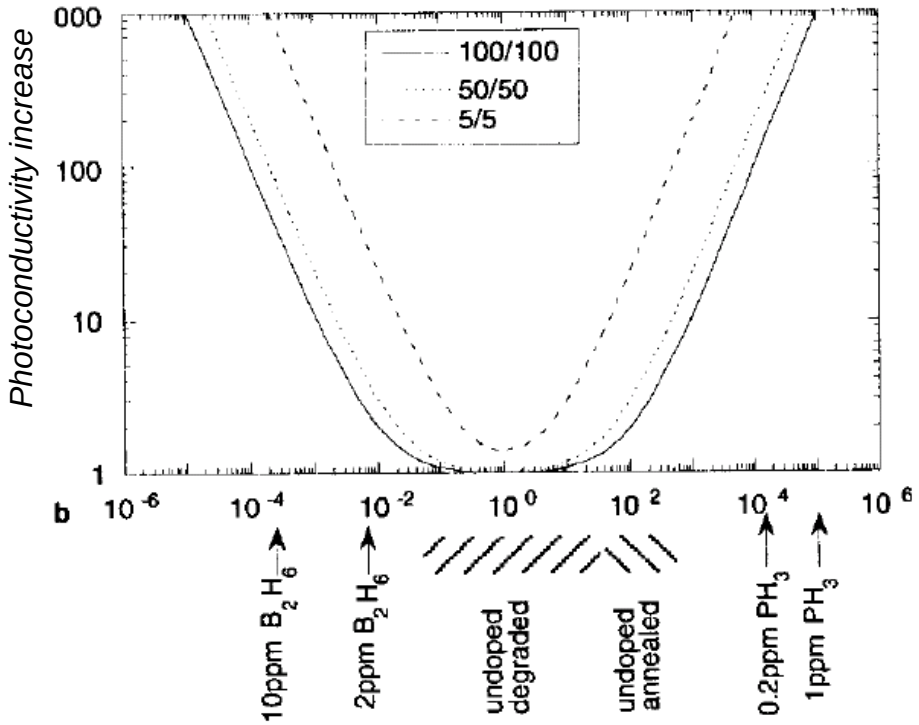
Street, APL 34(7), p 673 (1983)

- Doping changes preferentially the minority lifetimes (SHR model for doped materials!) for low doping levels.
- Data from transient experiments, reliable measurement of minority carriers in steady state is tricky!

Secondary photoconductivity

Secondary photoconductivity: $\sigma_{\text{photo}} \approx eG \cdot \mu\tau$

- Lifetime $\tau = 1/(v_{th} N_r \sigma_{\text{capture}})$ depends on
  - Defect density N_r
  - Fermi level / doping (through defect occupation)
  - Temperature (through defect occupation / quasi Fermi levels splitting)
- Photoconductivity changes sub-linearly with generation G
  - Change of recombination center density (splitting of quasi Fermi levels)

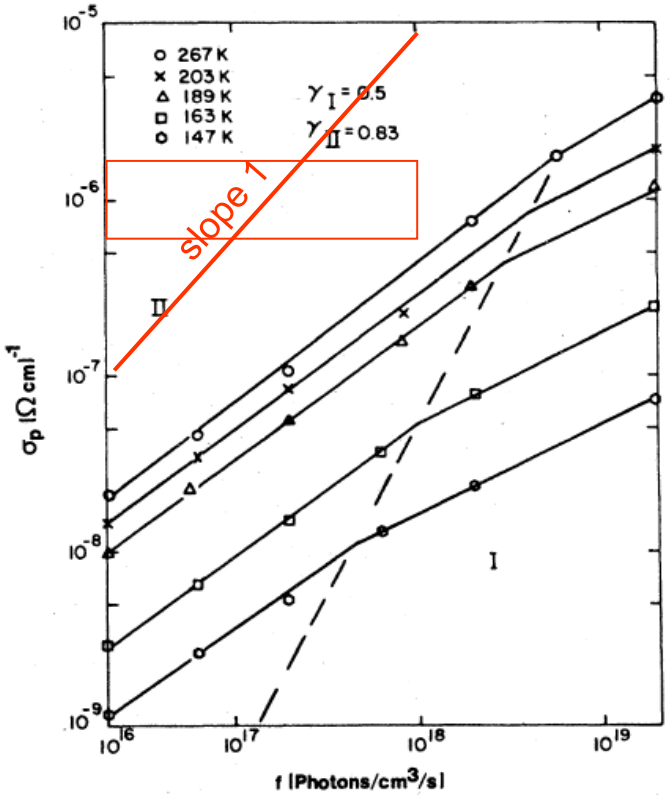


Wyrsch et al., Solid State Phenomena 44-46 (1995) 525

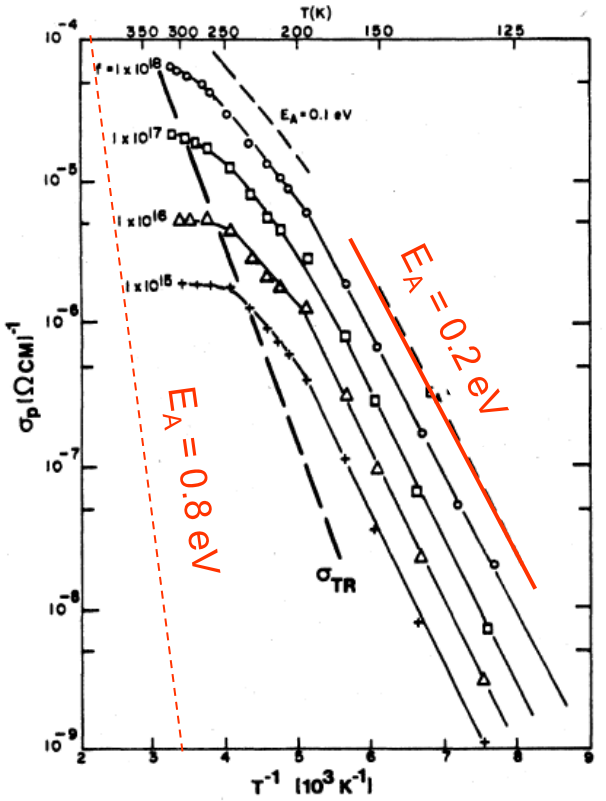
Photoconductivity – practical aspects

$$\sigma_{photo} \approx eG \cdot \underbrace{\mu\tau}_{} = eG\mu \cdot /(\underbrace{v_{th} N_r}_{} \sigma_{capture})$$

depend on temperature !



$$\sigma_{photo} \sim G^{\gamma}, \gamma < 1$$

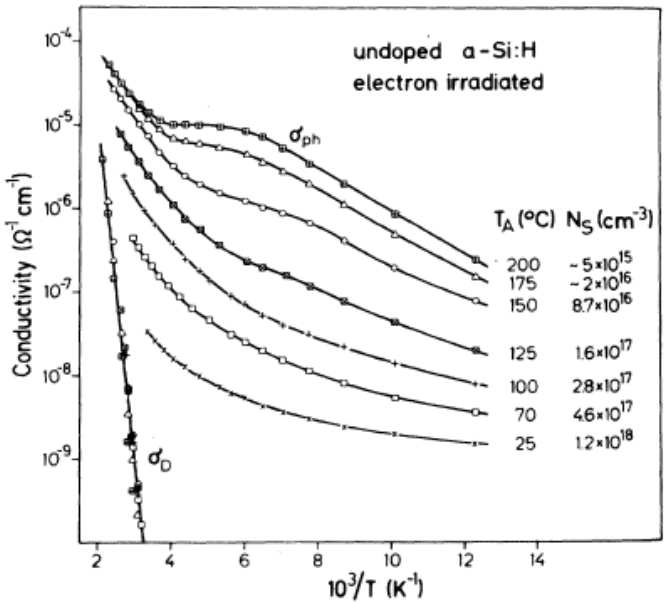


$$\sigma_{photo} \sim e^{E_a/kT}, E_a = 0.2eV$$

Wronski, PRB 23(2), p794 (1981)

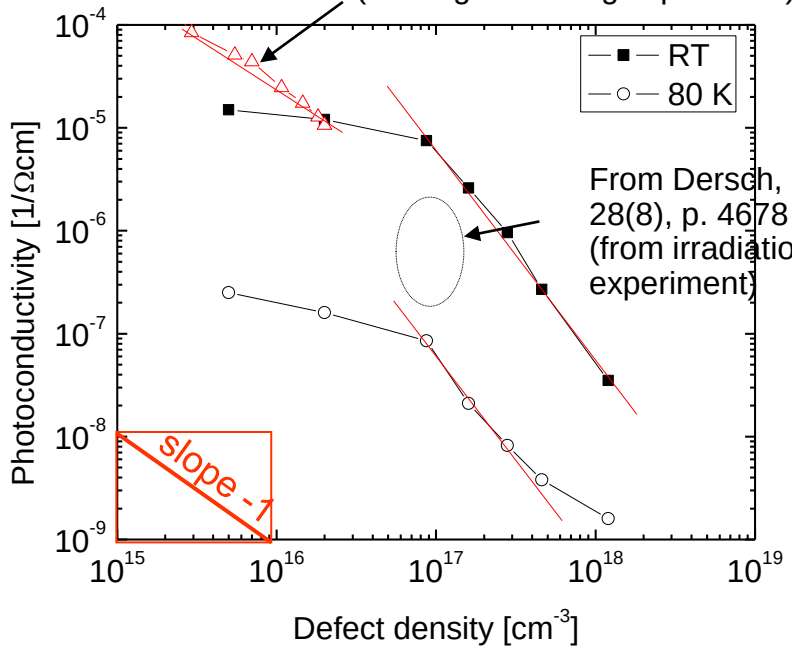
Photoconductivity – practical aspects

$$\sigma_{\text{photo}} \approx eG \cdot \mu\tau = eG\mu \cdot /(\nu_{th} N_r \sigma_{\text{capture}})$$



Dersch, PRB 28(8), p. 4678 (1983)

Stuzmann, PRL 67(17), p. 2347 (1981)
(from light-soaking experiment)



From Dersch, PRB 28(8), p. 4678 (1983) (from irradiation experiment)

$$\sigma_{\text{photo}} \sim N_r^{-\delta}, \delta = 1...2$$

Proportionality between σ_{photo} and N_r not systematic !

Multiple trapping conduction (out of therm. eq.)

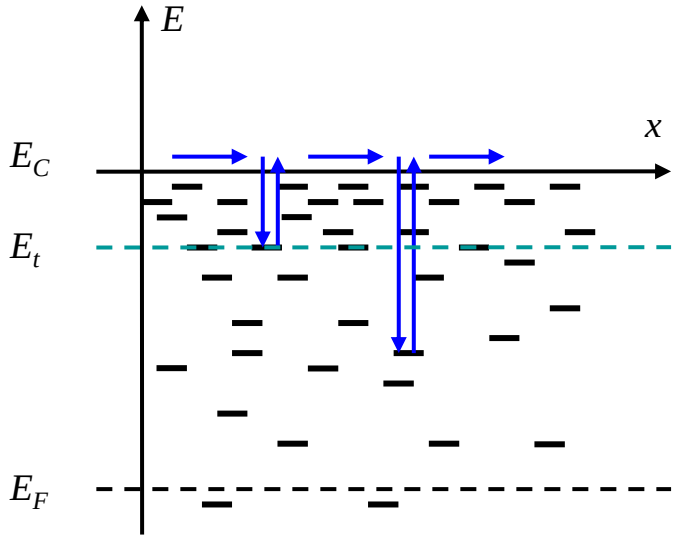
Assumptions:

exponential distribution of states

$$N_t(E) = N_C e^{E/kT_0}$$

thermally activated residence time

$$t = \upsilon^{-1} e^{-(E_t/kT)}$$



Trap occupation: changing with time (in contrast to thermal eq.)

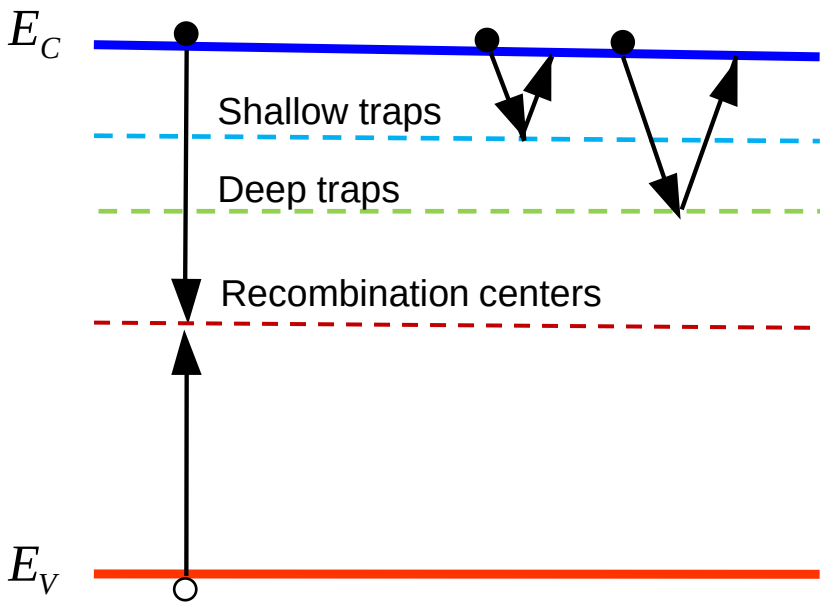
$\Rightarrow$ maximum trap occupation at

- energy E_C if characteristic energy of band tails $E_0 = kT_0 < kT$
- energy E_t below E_C if characteristic energy of band tails $E_0 = kT_0 > kT$

(See previous chapter on conductivity and bandtails)

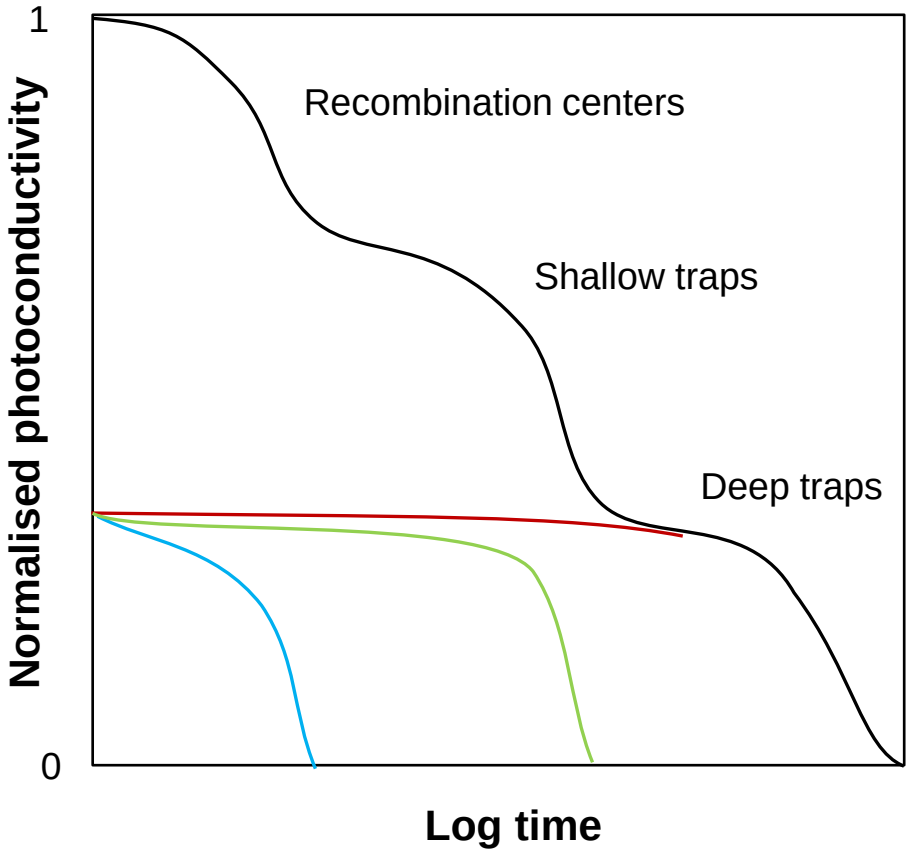
Photoconductivity decay

- Simple example with two trap levels and one level of recombination centers

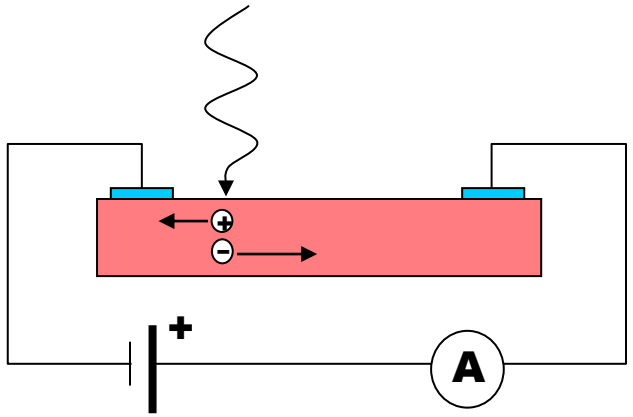


- Carriers in traps have to be released before being able to recombine

- Recombination dynamics following a switch off of light

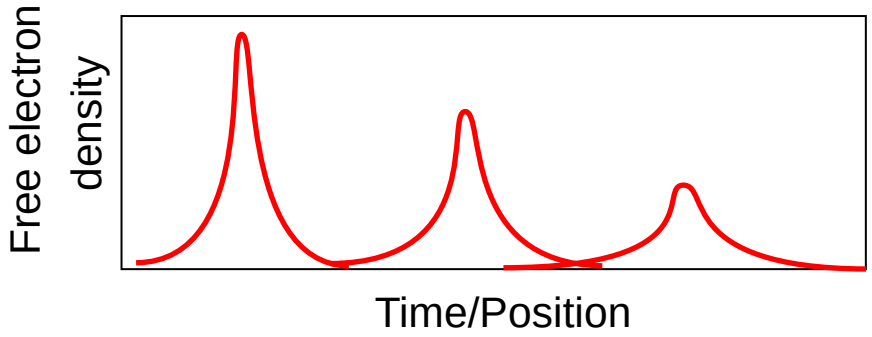


Transient photoconductivity

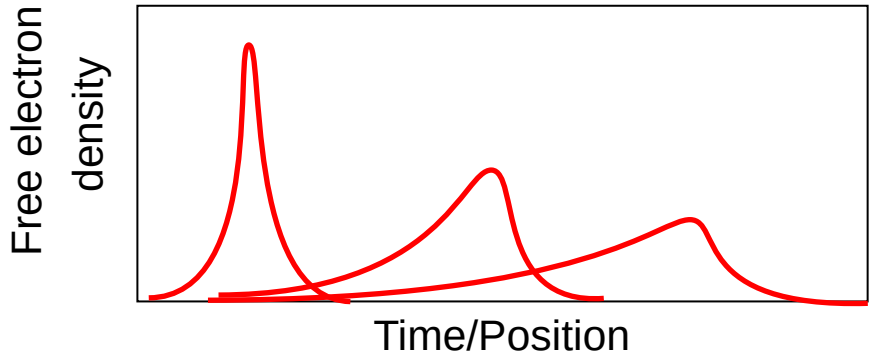


- Current given by (moving) free charges
- Temporal behaviour given controlled by
  - Thermal activated release (proportional to Boltzman factor)
  - Capture (proportional to trap density and capture cross-section)

Normal dispersion (semiconductors without traps)



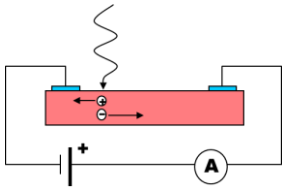
Anomalous dispersion (semiconductors with distribution of traps)



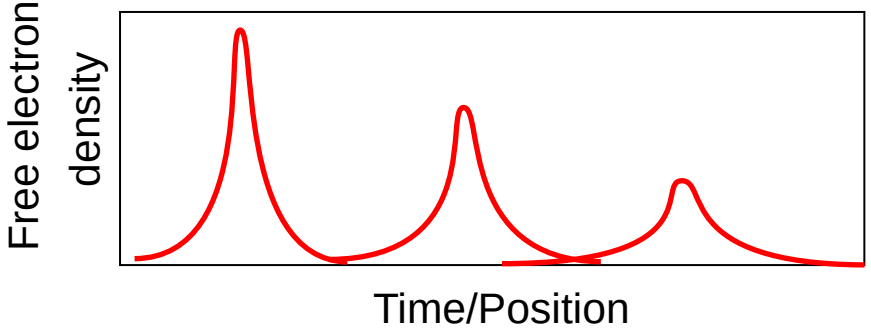
Charge “left behind” in traps

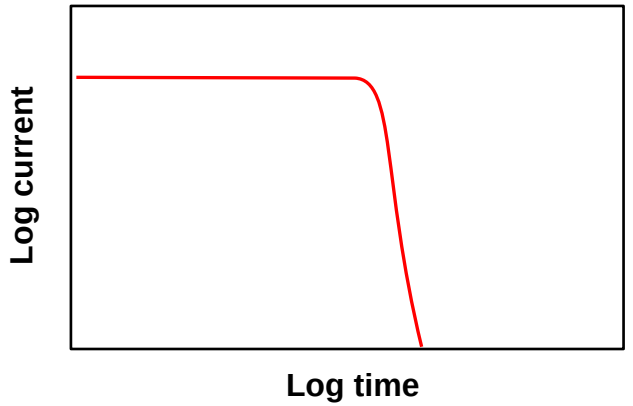
(see multiple trapping section in lecture on conductivity)

Transient photoconductivity (2)

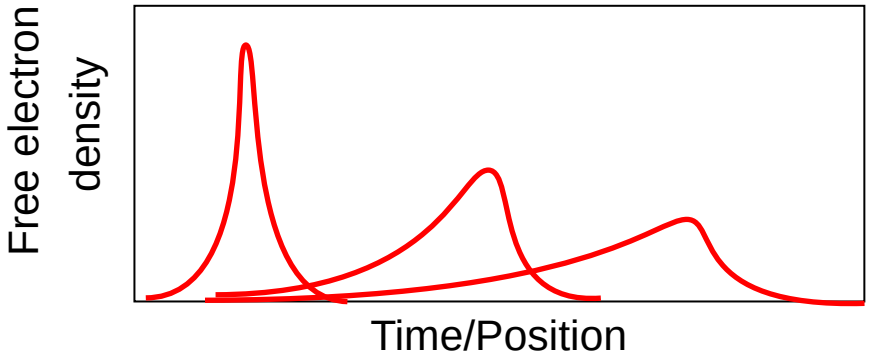


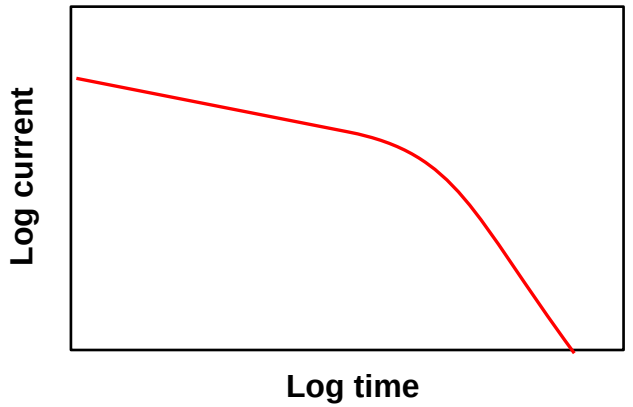
Normal dispersion (semiconductors without traps)





Anomalous dispersion (semiconductors with distribution of traps)





Global kinetics / lifetime

Define global (new) lifetime which is experimentally accessible

- injection of δ carriers by flash $\quad n = n_0 + \delta \qquad p = p_0 + \delta$
- observe exponential decay $\quad n(t) = n_0 + \delta \exp\{-t/\tau\}$
- then: $\boxed{\tau = \delta / R}$

- Difficult to infer information on the DOS for disordered semiconductors (modelling necessary !)

Example: lifetime test for c-Si

- flash excitation
- conductivity due to free carriers, e.g. inductive measurement
- monitor decay