# Course 6

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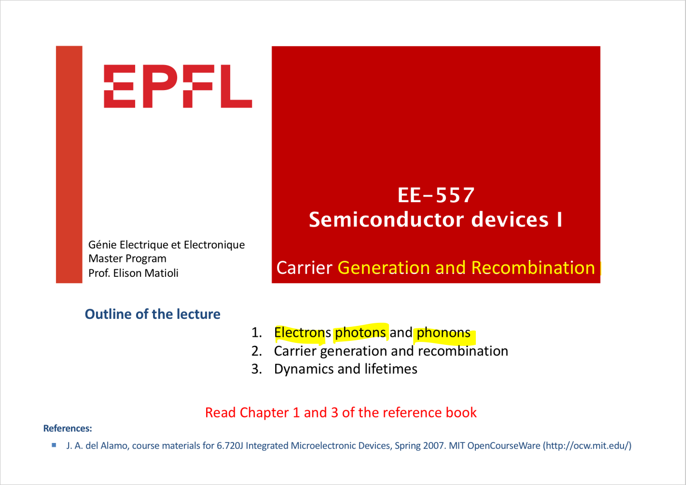
EE557Course 6 -...



EE-557

Semiconductor devices I

Carrier Generation and Recombination

Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

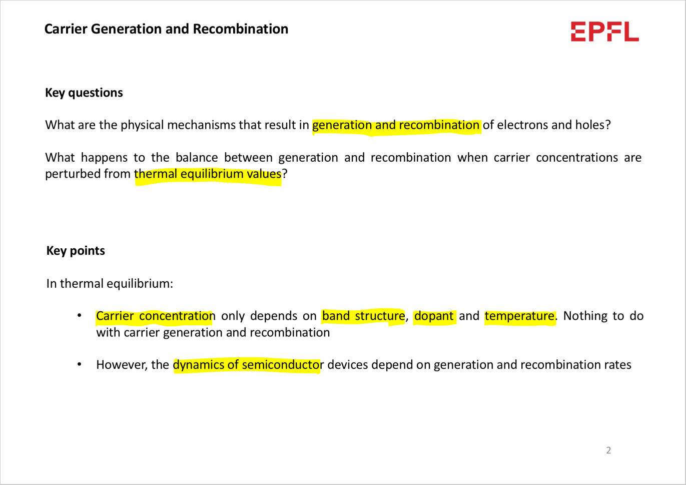
**Outline of the lecture**

1. Electrons photons and phonons
2. Carrier generation and recombination
3. Dynamics and lifetimes

Read Chapter 1 and 3 of the reference book

**References:**

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)



**Carrier Generation and Recombination**

**Key questions**

What are the physical mechanisms that result in generation and recombination of electrons and holes?

What happens to the balance between generation and recombination when carrier concentrations are perturbed from thermal equilibrium values?

**Key points**

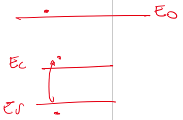
In thermal equilibrium:

- Carrier concentration only depends on band structure, dopant and temperature. Nothing to do with carrier generation and recombination
- However, the dynamics of semiconductor devices depend on generation and recombination rates

## Phonons, Photons and Electrons

Plank's constant

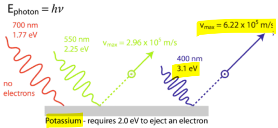
frequency

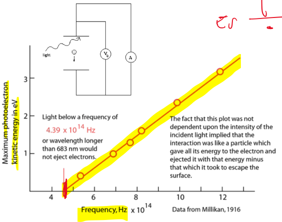


**Photons** $E_{photon} = h\nu = \hbar\omega$

The frequency of photons, which defines their color, determines their energy

### Photo-electric effect


$E_{photon} = h\nu$
700 nm
1.77 eV
no electrons
550 nm
2.25 eV
$v_{max} = 2.96 \times 10^5$ m/s
400 nm
3.1 eV
$v_{max} = 6.22 \times 10^5$ m/s
Potassium - requires 2.0 eV to eject an electron



Data from Millikan, 1916

Photons have large $\lambda$ (400 – 700 nm for the visible light)

Kinetic energy of photo-generated electrons:
- Independent on intensity of light
- There is a threshold frequency that depends on the metal work function

**Photons** are particles with **large energy** and **very small momentum**, thus they can change significantly the energy, not the momentum of electrons

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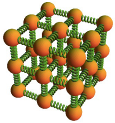
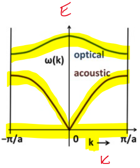
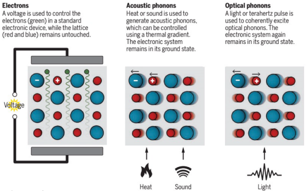
## Phonons, Photons and Electrons

**Phonons:** Collective vibration of the atoms in a solid (coupled system)







**Electrons**
A voltage is used to control the electrons (green) in a standard electronic device, while the lattice (red and blue) remains untouched.

**Acoustic phonons**
Heat or sound is used to generate acoustic phonons, which can be controlled using a thermal gradient. The electronic system remains in its ground state.

**Optical phonons**
A light or terahertz pulse is used to coherently excite optical phonons. The electronic system again remains in its ground state.

D. M. Juraschek, N. A. Spaldin, *Science* 2017

- Quantized nature of the vibration energy: vibration modes = phonons
- If electrons donate energy to the lattice: emission of a phonon
- If the lattice donates energy to the electron: absorption of a phonon

Energy of optical phonons:
- Si: 63 meV
- GaAs: 35 meV
- GaN: 92 meV

Which are much smaller than the band gap, but their momentum can be very large.

The density of optical phonons is much larger than that of acoustic phonons.

## Phonons, Photons and Electrons

**In summary:**

- **Photons**: have large energy and very small momentum, thus they can change significantly the energy, not the momentum of electrons

  Energy of **visible** photons: 1.7 - 3.2eV
  (of course UV photons have larger energy, and IR photons smaller than this range)

- **Phonons**: have small energy and very large momentum, thus they can change significantly the momentum, not the energy of electrons

  Energy of **optical phonons**:
  - Si: 63 meV
  - GaAs: 35 meV
  - GaN: 92 meV

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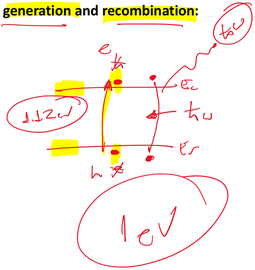
## Mechanisms of Generation and Recombination

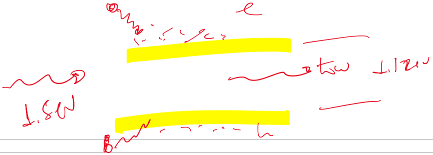
**We will see the following mechanisms for band-to-band generation and recombination:**

1. Thermal: negligible
2. Optical
3. Auger
4. Trap-assisted



And some that are induced by **strong electric fields**:

- Impact ionization
- Tunneling



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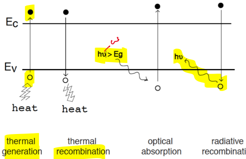
## Mechanisms of Generation and Recombination

**Thermal and Optical generation and recombination:**

Semiconductors are highly dynamic systems: electrons are continuously being generated and recombined.



In thermal equilibrium, there is a dynamic balance between these events

**Phonons (thermal)**: covalent bond is ruptured by thermal vibrations in the lattice
energy of phonons (0.06 eV) is much smaller than the band gap (1.1eV)

Very unlikely process as this requires many phonons simultaneously

**Photons (optical)**:
- photon delivers enough energy to break a covalent bond: **optical absorption**
- photon is emitted when an electron recombines with a hole:
**Radiative recombination:** Basis for optoelectronic devices

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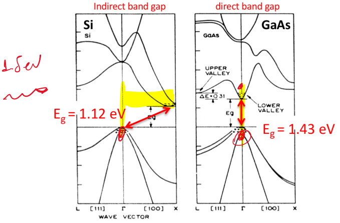
## Mechanisms of Generation and Recombination

**Electrons and holes:** have energy and momentum since they have mass and are moving around atoms

**Photons:** have zero rest mass and always move at the speed of light within vacuum

Direct band gap: momentum can be conserved
photon emission is a likely process, thus takes place at **high rates**

Indirect band gap: a third particle is required, such as a phonon, in addition to a photon
photon emission is much less likely: **small rates**



Radiative recombination:
- Unlikely in Si, "indirect" bandgap material, since it needs a phonon to conserve momentum
- More likely in III-Vs semiconductors
- It is a 2-particle process (proportional to *np*)

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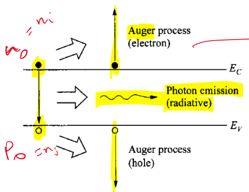
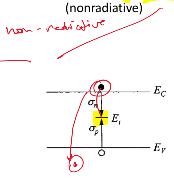
## Summary of mechanisms of Generation and Recombination

**Band-to-band recombination**

**Recombination through single-level traps** (nonradiative)





(a) (b)

**Band-to-band electron-hole recombination**: energy of an electron in transition from the conduction band to the valence band is conserved by **emission of a photon (radiative process)** or by **transfer of the energy** to another free electron or hole (**Auger process**).

Inverse processes of **direct optical absorption**, and **impact ionization.**

**Band-to-band transitions are more probable for direct-band gap** semiconductors, which are more common among III-V compounds

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## Carrier Generation and Recombination

**Thermal equilibrium: principle of detailed balance**

Define:

$G_i$ ≡ generation rate by process *i* [$cm^{-3}\,s^{-1}$]
$R_i$ ≡ recombination rate by process *i* [$cm^{-3}\,s^{-1}$]
$G$ ≡ total generation rate [$cm^{-3}\,s^{-1}$]
$R$ ≡ total recombination rate [$cm^{-3}\,s^{-1}$]

In thermal equilibrium:

$$R_o = \Sigma R_{oi} = G_o = \Sigma G_{oi}$$

equilibrium

**Principle of Detailed Balance:**

In the presence of several paths for G & R, each has to balance out in detail:

$$\boxed{R_{oi} = G_{oi}} \quad \text{for all } i$$

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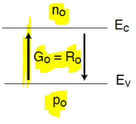
## Generation and Recombination

In thermal equilibrium:

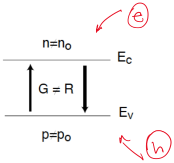
$$\begin{aligned} n &= n_o \\ p &= p_o \\ G_{oi} &= R_{oi} \\ G_o &= R_o \end{aligned}$$



thermal equilibrium

Out of thermal equilibrium (carrier concentrations disturbed from thermal equilibrium):

$$\begin{aligned} n &\neq n_o \\ p &\neq p_o \\ G_i &\neq R_i \\ G &\neq R \end{aligned}$$



outside thermal equilibrium

## Generation and Recombination

We define *net recombination rate, U*:

$$U = R - G$$

Reflects imbalance between internal G&R mechanisms:

- if $R > G \rightarrow U > 0$, net recombination prevails
- if $R < G \rightarrow U < 0$, net generation prevails
- if $R = G \rightarrow U = 0$, thermal equilibrium

If there are several mechanisms acting simultaneously, we define:

$$U_i = R_i - G_i$$

$$U = \Sigma U_i$$

What happens to the G&R rates of the various mechanisms outside thermal equilibrium?

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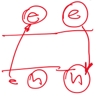
## Band-to-band Generation and Recombination in thermal equilibrium

### Optical Generation and Recombination

At finite *T*, semiconductor is immersed in "bath" of blackbody radiation ⇒ optical generation

Plenty of bonds available and only a small number are broken at any one time

*G* ⇒ depends only on *T*:



$$\boxed{G_{o,rad}} = g_{rad}(T)$$

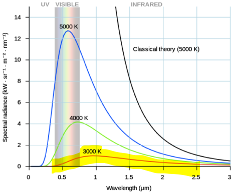
(G: generation of carriers, not photons)

A recombination process demands one electron and one hole

*R* ⇒ depends on $n_o p_o$:

$$\boxed{R_{o,rad}} = r_{rad}(T)\, n_o p_o$$

$r_{rad}(T)$ is a rate constant that depends on materials and temperature



**Black-body radiation** is the thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment

Si: $r_{rad} \doteq 2 \times 10^{-15}\ cm^{-3}/s$ at R.T.

GaAs: $r_{rad} \doteq 7 \times 10^{-10}\ cm^{-3}/s$

In TE, detailed balance implies:

$$\boxed{g_{rad} = r_{rad} n_o p_o = r_{rad} n_i^2}$$

for example:

n-type Si, $N_D = 10^{17}\ cm^{-3}$ at R.T. :

in T.E: $G_{o,rad} = R_{o,rad}$

$$N_D = 10^{17}\ cm^{-3} \Rightarrow \begin{cases} n_o = 10^{17}\ cm^{-3} \\ p_o = 10^{3}\ cm^{-3} \end{cases}$$

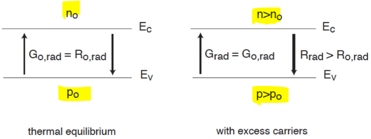
$$G_{o,rad} = R_{o,rad} = r_{rad}(T) \cdot n_o \cdot p_o$$

$$= 2\times10^{-15}\, cm^{-3}/s \cdot 10^{17}\, cm^{-3} \cdot 10^{3}\, cm^{-3}$$

$$= 2\times10^{5}\, cm^{-3}/s$$

## Generation and Recombination out of equilibrium

**Optical**



Optical generation rate unchanged since number of available bonds unchanged:

$$G_{rad} = g_{rad} = r_{rad} n_o p_o$$

Optical recombination rate affected if electron and hole concentrations have changed:

$$R_{rad} = r_{rad} np$$

Define *net recombination rate*:

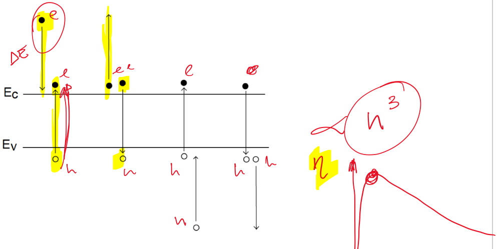
$$\boxed{U_{rad} = R_{rad} - G_{rad} = r_{rad}(np - n_o p_o)}$$

**Proportional to: (carrier concentration)²**

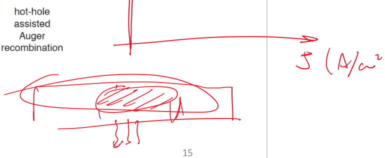
- if $np > n_o p_o$, $U_{rad} > 0$, net recombination prevails
- if $np < n_o p_o$, $U_{rad} < 0$, net generation prevails

## Mechanisms of Generation and Recombination

**Auger recombination:**



| hot-electron assisted Auger generation | hot-electron assisted Auger recombination | hot-hole assisted Auger generation | hot-hole assisted Auger recombination |
|---|---|---|---|



**Auger generation:** energy provided by ”hot” carrier

**Auger recombination:**

- 3-particle process (proportional to $np^2$ or $pn^2$)
- energy given to third carrier; **needs lots of carriers**;

## Generation and Recombination in thermal equilibrium

**Auger Generation and Recombination**

**Involving hot electrons (energetic electrons):**

The more electrons there are, the more likely it is to have hot ones capable of Auger generation:

$$G_{o,eeh} = g_{eeh}(T)n_o$$

Hot electrons are the fraction of $n_o$ at the tail of the distribution

A recombination event demands ***two* electrons and *one* hole**: 3-particle collision

A second electron absorbs the energy released from an electron-hole recombination.

$$R_{o,eeh} = r_{eeh}n_o^2 p_o$$

For Si at R.T:

$r_{eeh} = 1.8 \times 10^{-31}\ cm^{+6}/s$

In TE, detailed balance implies:

$$\boxed{g_{eeh} = r_{eeh}n_o p_o}$$

**Involving hot holes:** similar but substitute $n_o$ for $p_o$ and *eeh* by *ehh* above.

**Auger recombination** and generation rates can become **significant under high carrier concentration**

n-type Si, $N_D = 10^{17}\ cm^{-3}$

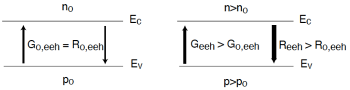
$r_{eeh} = 1.8 \times 10^{-31}\ cm^6/s$

$G_{o,eeh} = R_{o,eeh} = r_{eeh} \cdot n_o^2 p_o = 1.8 \times 10^{-31}\ cm^6/s \cdot (10^{17}\ cm^{-3})^2 \cdot (10^3\ cm^{-3})$

$= 1.8 \times 10^6\ cm^{-3}/s$

## Generation and Recombination out of equilibrium

### Auger



thermal equilibrium with excess carriers

$$G_{eeh} = g_{eeh} n$$

$$R_{eeh} = r_{eeh} n^2 p$$

If relationship between $g_{eeh}$ and $r_{eeh}$ unchanged from TE:

$$U_{eeh} = R_{eeh} - G_{eeh} = r_{eeh} n (np - n_o p_o)$$

$$\boxed{U_{ehh} = r_{ehh} p (np - n_o p_o)}$$

**Proportional to:**
**(carrier concentration)$^3$**

It is similar involving **hot holes,** thus the total Auger net recombination rate is:

$$\boxed{U_{Auger} = (r_{eeh} n + r_{ehh} p)(np - n_o p_o)}$$

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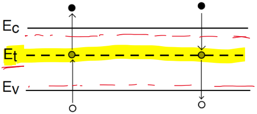
## Mechanisms of Generation and Recombination

**Trap-assisted generation and recombination**, relying on electronic states in middle of gap (”deep levels” or ”traps”) that arise from:

- crystalline defects
- impurities

Energy state within the gap:
2 separate events to bring an electron to the conduction band



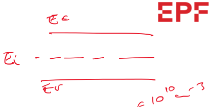
trap-assisted thermal generation

trap-assisted thermal recombination

- States in the gap are not allowed, but defects and imperfections result in such states.
- Thermal recombinations are enhanced by mid-gap traps.
- Different from dopants (foreign atoms).
- Trap-assisted generation and recombination is:
  - Dependent on the trap density $N_t$
  - Dominant effect in Si: affects significantly micro-electronic devices
  - Engineerable: we can introduce deep levels to Si to enhance it

## Generation and Recombination in thermal equilibrium

### Trap-assisted Generation and Recombination



**Shockley-Read-Hall model:** (** Derivation is on moodle)
Consider a trap at $E_t = E_i$ in concentration $N_t$:

$< 10^{10}$ cm$^{-3}$

Trap occupation probability: $$f(E_t) = f(E_i) = \frac{1}{1+\exp\frac{E_i - E_F}{kT}} \overset{**}{=} \frac{n_i}{n_i + p_o}$$

Concentration of traps occupied by an electron: $$n_{to} = N_t f(E_i) = N_t \frac{n_i}{n_i + p_o}$$

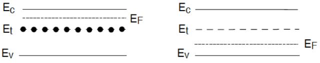
Concentration of empty traps: $$N_t - n_{to} = N_t - N_t \frac{n_i}{n_i + p_o} = N_t \frac{p_o}{n_i + p_o}$$

$10^3$ $10^{10}$

Trap occupation depends on doping:

n-type: $p_o << n_i \rightarrow n_{to} \approx N_t$, most traps are full

p-type: $p_o >> n_i \rightarrow n_{to} << N_t$, most traps are empty



n-type p-type

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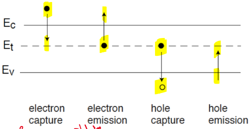
## Generation and Recombination in thermal equilibrium

### Trap-assisted Generation and Recombination

Four basic processes:



Rates of four sub-processes in TE:

electron capture: $$\underbrace{r_{o,ec} = c_e n_o}_{\# e}\underbrace{(N_t - n_{to})}_{\text{\# available trap states}}$$

electron capture coefficient

electron emission: $$r_{o,ee} = e_e n_{to}$$

# occupied traps

hole capture: $$r_{o,hc} = c_h p_o n_{to}$$

hole emission: $$r_{o,he} = e_h (N_t - n_{to})$$

In thermal equilibrium, detailed balance demands:

$$r_{o,ec} = r_{o,ee}$$

$$r_{o,hc} = r_{o,he}$$

$$\boxed{C_e = C_h = 10^{-11} \text{ cm}^3/\text{s}}$$

## Generation and Recombination in thermal equilibrium

### Trap-assisted Generation and Recombination

We can also define:

$$\tau_{eo} = \frac{1}{N_t c_e} \qquad c_e:\ \mathrm{cm}^3/\mathrm{s} \quad N_t:\ \mathrm{cm}^{-3} \qquad \equiv [s]$$

$$\tau_{ho} = \frac{1}{N_t c_h}$$

$\tau_{eo}$ and $\tau_{ho}$ are characteristic of the nature of the trap and its concentration. They have units of *s*.

All together, rates of communication of trap with CB and VB:

$$r_{o,ec} = r_{o,ee} \overset{**}{=} \frac{1}{\tau_{eo}} \frac{n_i^2}{n_i + p_o} \qquad\qquad \tau_{eo} = \frac{1}{N_t c_e}$$

where

$$r_{o,hc} = r_{o,he} = \frac{1}{\tau_{ho}} \frac{n_i p_o}{n_i + p_o} \qquad\qquad \tau_{ho} = \frac{1}{N_t c_h}$$

Rates depend on trap nature and density $N_t$ and doping level.

** Proof on moodle

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## Generation and Recombination in thermal equilibrium

### Trap-assisted Generation and Recombination

For n-type semiconductor:

$$r_{o,ec} = r_{o,ee} \simeq \frac{\overset{10^{10}}{n_i}}{\tau_{eo}}$$

$$r_{o,hc} = r_{o,he} = \frac{\overset{10^{3}}{p_o}}{\tau_{ho}}$$

$$\tau_{eo} = \frac{1}{N_t c_e} = \frac{1}{10^{16} \times 10^{-11}} = 10^{-5}\,s$$

$$\tau_{ho} = \frac{1}{N_t c_h} = \frac{1}{10^{16} \times 10^{-11}} = 10^{-5}\,s$$

$$N_t = 10^{16}\,\mathrm{cm}^{-3}$$

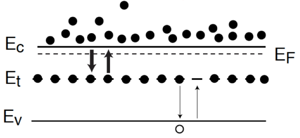
$$r_{o,ec} = \frac{10^{10}}{10^{-5}} = 10^{15}\,\mathrm{cm}^{-3}/s$$

$$r_{o,hc} = \frac{10^{3}}{10^{-5}} = 10^{8}\,\mathrm{cm}^{-3}/s$$

If $\tau_{eo}$ not very different from $\tau_{ho}$,

$$r_{o,ec} = r_{o,ee} \gg r_{o,hc} = r_{o,he}$$

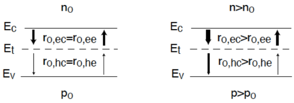
The rate at which trap communicates with CB much higher than VB.



lots of electrons in CB and trap ⇒ $r_{o,ec} = r_{o,ee}$ high
few holes in VB and trap ⇒ $r_{o,hc} = r_{o,he}$ small

## Generation and Recombination out of equilibrium

### Trap-assisted



thermal equilibrium

with excess carriers

Out of equilibrium, if rate constants are not affected:

$$\begin{aligned} r_{ec} &= c_e n(N_t - n_t) \\ r_{ee} &= e_e n_t = c_e n_i n_t \\ r_{hc} &= c_h p n_t \\ r_{he} &= e_h(N_t - n_t) = c_h n_i (N_t - n_t) \end{aligned}$$

Recombination: capture of one electron + one hole ⇒

$$\begin{aligned} net\ recombination\ rate &= net\ electron\ capture\ rate \\ &= net\ hole\ capture\ rate \end{aligned}$$

$$U_{tr} = r_{ec} - r_{ee} = r_{hc} - r_{he}$$

From this, derive $n_t$, and finally get $U_{tr}$:

$$\boxed{U_{tr} = \frac{np - n_o p_o}{\tau_{ho}(n + n_i) + \tau_{eo}(p + n_i)}}$$

---

## Generation and Recombination out of equilibrium

***All processes combined***

$$\boxed{U = U_{rad} + U_{Auger} + U_{tr}}$$

## Mechanisms of Generation and Recombination

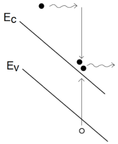
Other generation mechanisms dependent on electric field

**Impact ionization:**

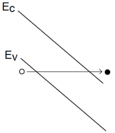
- Auger generation event triggered by electric-field-heated carrier
- Can result in avalanche multiplication: in addition to the primary carriers, the generated electrons produce more impact ionization events

**Zener tunneling or field ionization:**

Strong electric field rips an electron from the covalent band
Direct tunneling of electron from VB to CB in presence of strong electric field



impact ionization



Zener tunneling

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## Generation and Recombination - Low-level Injection (LLI) case

## Generation and Recombination - Low-level Injection (LLI) case

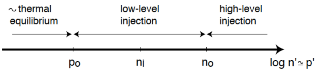
**Low-level Injection (LLI) case**

Define *excess* carrier concentrations:

$$n = n_o + n'$$

$$p = p_o + p'$$

LLI: Equilibrium minority carrier concentration overwhelmed, but majority carrier concentration negligibly disturbed



- for n-type:

$$p_o \ll n' \simeq p' \ll n_o$$

- for p-type:

$$n_o \ll n' \simeq p' \ll p_o$$

---

## Generation and Recombination out of equilibrium

In LLI:

$$np - n_o p_o = n_o p_o + n_o p' + p_o n' + n' p' - n_o p_o \simeq (n_o + p_o) n'$$

All expressions of *U* follow the form:

$$U_i \simeq \frac{n'}{\tau_i}$$

$\tau_i$ is *carrier lifetime* of process *i*, a constant characteristic of each G&R process:

$$\tau_{rad} = \frac{1}{r_{rad}(n_o + p_o)}$$

$$\tau_{Auger} \simeq \frac{1}{(r_{eeh} n_o + r_{ehh} p_o)(n_o + p_o)}$$

$$\tau_{tr} \simeq \frac{\tau_{ho} n_o + \tau_{eo} p_o}{n_o + p_o}$$

Under LLI, net recombination rate depends linearly on *excess carrier concentration* through a constant that is characteristic of material and temperature.

## Generation and Recombination out of equilibrium

If all G&R processes are independent, combined process:

$$U \simeq \frac{n'}{\tau} \qquad \frac{1}{\tau} = \Sigma \frac{1}{\tau_i}$$

The G&R process with the ***smallest*** **lifetime dominates.**

Physical meaning of ***carrier lifetime***:

- *U* is net recombination rate in unit volume in response to excess carrier concentration *n'* (linear with *n'*) [$cm^{-3} \cdot s^{-1}$]
- *U/n'* is net recombination rate in unit volume per unit excess carrier [$s^{-1}$]
- $\tau$ = n'/U is the mean time between recombination event *per excess carrier* [*s*] or average time excess carrier will ”survive” before recombining → constant characteristic of material

---

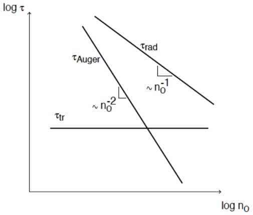
## Generation and Recombination out of equilibrium

For n-type material, $n_o >> p_o$:

$$\tau_{rad} = \frac{1}{r_{rad} n_o}$$

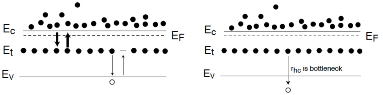
$$\tau_{Auger} = \frac{1}{r_{eeh} n_o^2}$$

$$\tau_{tr} = \tau_{ho} \propto \frac{1}{N_t}$$

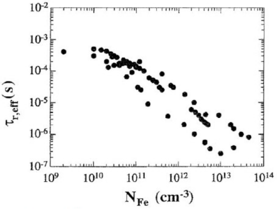


## Generation and Recombination out of equilibrium

**Trap recombination (n-type material):**
Lifetime does not depend on $n_o$ [trap occupation probability rather insensitive to $n_o$]



**Lifetime** depends on trap concentration as $\tau \propto N_t^{-1}$



Schroder, D. K. "Carrier Lifetimes in Silicon." *IEEE Transactions on Electron Devices* 44, no. 1 (1997): 160-170.
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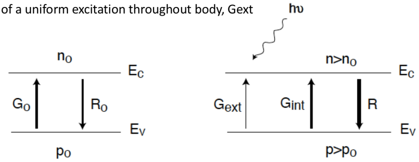
## Dynamics of excess carriers in uniform situations

Let's consider the case of a uniform excitation throughout body, Gext



thermal equilibrium

under external illumination

If there is imbalance between total generation and recombination, carrier concentrations change in time:

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R$$

- if $G > R \Rightarrow n,\ p \uparrow$
- if $G < R \Rightarrow n,\ p \downarrow$

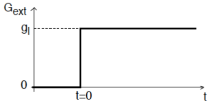
Distinguish between internal and external generation:

$$G = G_{ext} + G_{int}$$

## Dynamics of excess carriers in uniform situations

Example 1: Turn-on transient

Semiconductor is subject to a uniform generation rate $g_l$



$$n'(t) = g_l \tau (1 - e^{-t/\tau}) \qquad \text{for } t \geq 0$$

*steady-state* $\equiv$ initial transient died out (need a few $\tau$'s)

In steady state:

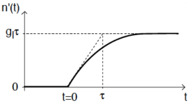
$$generation = recombination$$

or

$$g_l = \frac{n'}{\tau}$$

Then

$$n' = g_l \tau$$



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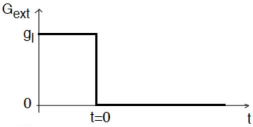
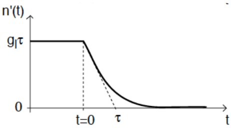
## Dynamics of excess carriers in uniform situations

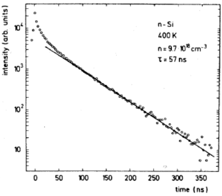
Example 2: Turn-off transient





$$n'(t) = g_l \tau e^{-t/\tau} \qquad \text{for } t \geq 0$$

By observing the luminescence decay, one can extract the carrier lifetime



J., and W. Schmid. "Auger Coefficients for Highly Doped and Highly Excited Silicon."*Applied Physics Letters* 31, no. 5 (1977): 346-348. Copyright 1977, American Institute of Physics

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## Key conclusions

- Dominant generation/recombination mechanisms in Si: *trap-assisted* and *Auger*.
- In TE, *G* and *R* processes must be balanced *in detail*.
- Auger R rate in TE is proportional to the *square* of the majority carrier concentration and is *linear* on the minority carrier concentration.
- Trap-assisted G/R rates in TE depend on the nature of the trap, its concentration, the doping type and the doping level.
- In n-type semiconductor, mid-gap trap communicates preferentially with conduction band. In p-type semiconductor, mid-gap trap communicates preferentially with valence band.