Primer on Semiconductors

# Unit 4: Carrier Transport, Recombination, and Generation

# Lecture 4.4: Carrier recombination

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# Equilibrium and non-equilibrium

In **equilibrium**:

$$n_0 = N_C e^{(E_F - E_C)/k_B T} \qquad\qquad p_0 = N_V e^{(E_V - E_F)/k_B T}$$

**Out of equilibrium**, there can be additional "excess carriers":

$$n = n_0 + \Delta n \qquad\qquad p = p_0 + \Delta p$$

(The excess carrier concentrations can be positive or negative.)

**Question:** How do the excess carrier concentrations vary with time?

# Carrier recombination

P-type, equilibrium

$$\Delta n(t=0)$$

$$p_0 = 10^{17}\ \text{cm}^{-3} \qquad n_0 = n_i^2 / p_0 = 10^3\ \text{cm}^{-3}$$

**Expect**:

$$\Delta n(t) = \Delta n(t=0)e^{-t/\tau}$$ *Δn* may be either positive or negative.

**Goal:** Understand the recombination lifetime, $\tau_n$.

# How can excess carriers recombine?

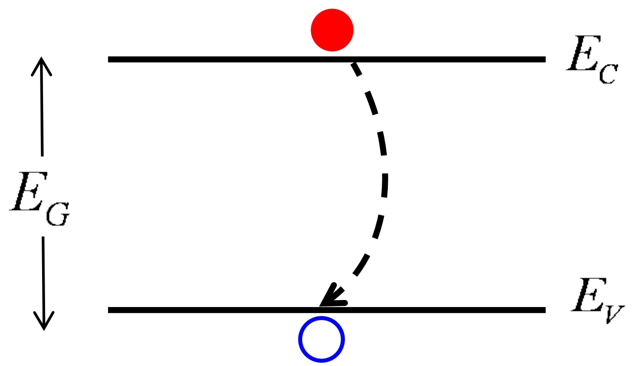
We will discuss three different ways:

1) Band-to-band (radiative) recombination

2) Auger recombination

3) SRH (defect-assisted) recombination

# 1) Band-to-band (radiative) recombination




$E = hf \approx E_G$

energy given to photon

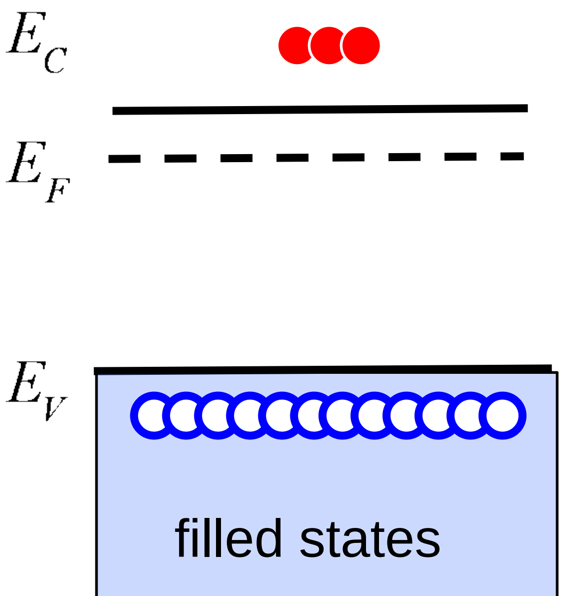
$$\left.\frac{\partial n}{\partial t}\right|_{b-b} = \left.\frac{\partial p}{\partial t}\right|_{b-b} = -B\left(np - n_i^2\right) \qquad \left(n_0 p_0 = n_i^2\right)$$

(Note that this is zero in equilibrium – as it should be.)

# Low level injection

The term “low level injection” means that the excess carrier concentration is **orders of magnitude smaller than the equilibrium majority carrier concentration** but **orders of magnitude larger that the equilibrium minority carrier concentration**.

# Example: Low level injection in a p-type semiconductor




$p_0 = 10^{17}\ \text{cm}^{-3}$

$n_0 = 10^{3}\ \text{cm}^{-3}$

$$n = n_0 + \Delta n$$

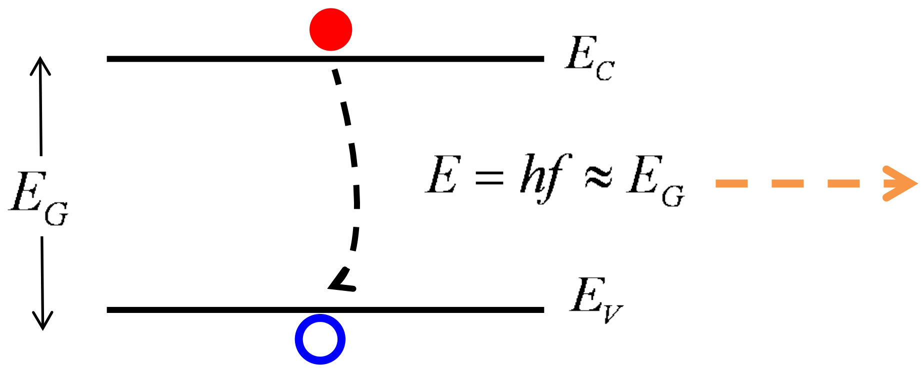
$$p = p_0 + \Delta p$$

$$\Delta n \approx \Delta p$$

$$\Delta n = 10^{8}\ \text{cm}^{-3} >> n_0$$

$$\Delta p \approx \Delta n = 10^{8}\ \text{cm}^{-3} << p_0$$

# Low level injection in a p-type semi




$$\left.\frac{\partial n}{\partial t}\right|_{b-b} = -B\left(np - n_i^2\right)$$

$$n = n_0 + \Delta n \approx \Delta n$$

$$p = p_0 + \Delta p \approx N_A$$

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{b-b} \approx -BN_A \Delta n = -\frac{\Delta n}{\tau_{bb}}$$

$$\boxed{\tau_{bb} = \frac{1}{BN_A}}$$

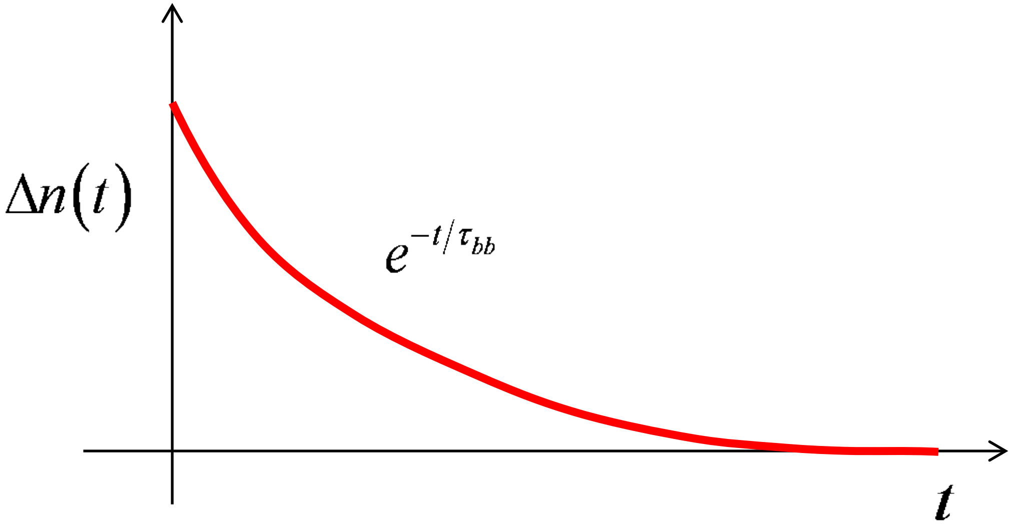
$$np \approx \Delta n N_A >> n_i^2$$

# Excess carrier concentration vs. time

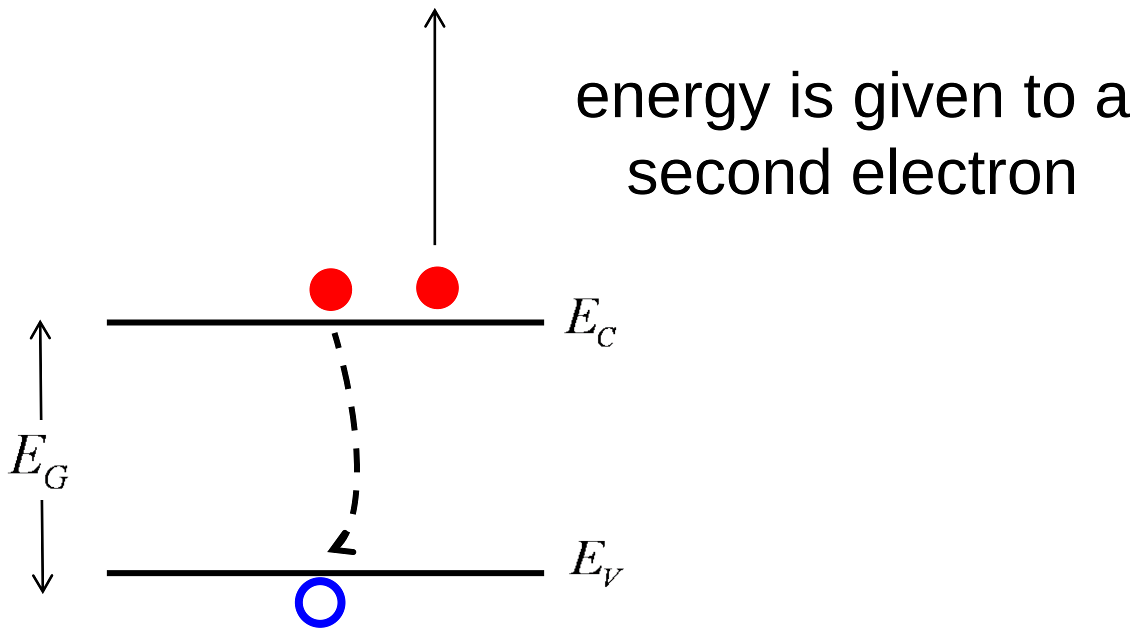
$$\left.\frac{\partial n}{\partial t}\right|_{b-b} = -B\left(np - n_i^2\right) \qquad \left.\frac{\partial \Delta n}{\partial t}\right|_{b-b} \approx -\frac{\Delta n}{\tau_{bb}} \qquad \tau_{bb} = \frac{1}{BN_A}$$

$$\Delta n(t) = Ce^{-t/\tau_{bb}}$$

$$\Delta n(t) = \Delta n(t=0)e^{-t/\tau_{bb}}$$



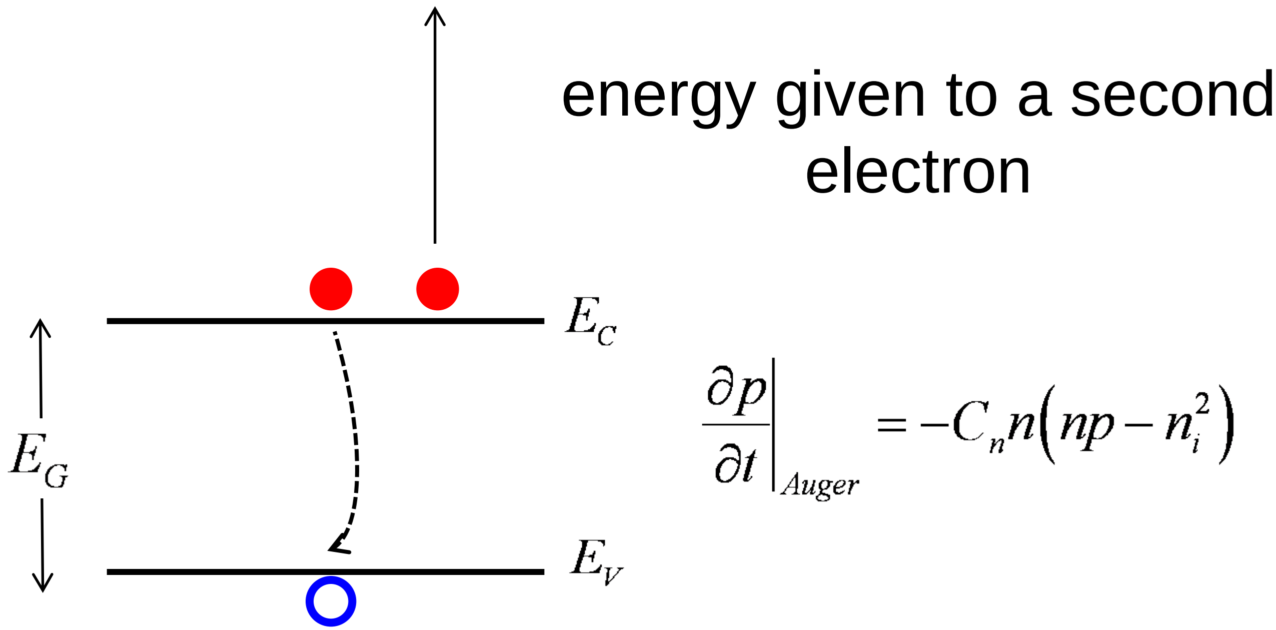
# 2) Auger recombination




$$\left.\frac{\partial p}{\partial t}\right|_{Auger} = C_n n\left(np - n_i^2\right) + C_p p\left(np - n_i^2\right)$$

(Note that this is zero in equilibrium – as it should be.)

# Low level injection in an n-type semiconductor




$$\left.\frac{\partial p}{\partial t}\right|_{Auger} = -C_n n\left(np - n_i^2\right)$$

$$n = n_0 + \Delta n \approx N_D$$

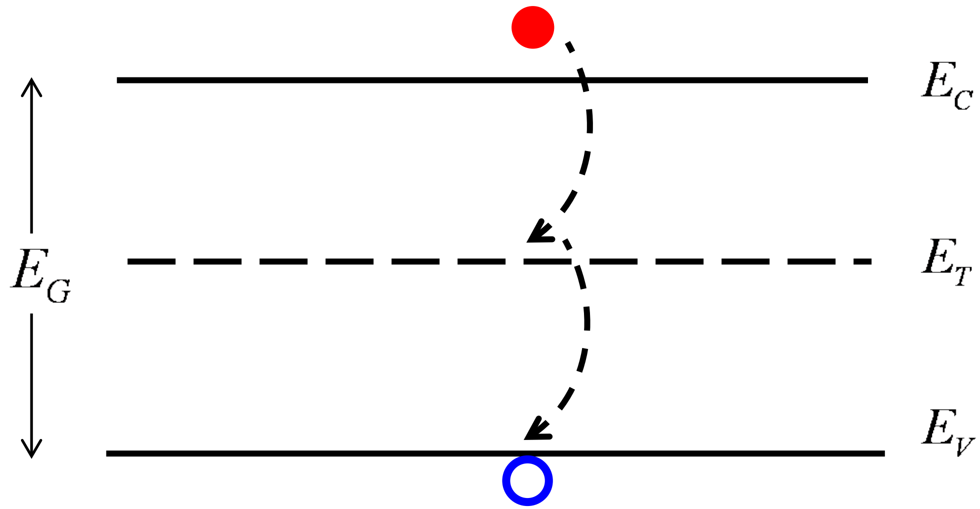
$$p = p_0 + \Delta p \approx \Delta p$$

$$\left.\frac{\partial \Delta p}{\partial t}\right|_{Auger} \approx -C_n N_D^2 \Delta p = -\frac{\Delta p}{\tau_{Auger}}$$

$$\boxed{\tau_{Auger} = \frac{1}{C_n N_D^2}}$$

$$np \approx \Delta p\, N_D >> n_i^2$$

# 3) SRH (defect-assisted) recombination




recombination centers

energy released as thermal energy

$$\left.\frac{\partial n}{\partial t}\right|_{SRH} = \left.\frac{\partial p}{\partial t}\right|_{SRH} = \frac{-\left(np - n_i^2\right)}{\tau_p\left(n+n_1\right)+\tau_n\left(p+p_1\right)}$$

$$\tau_n = 1/c_n N_T$$

$$\tau_p = 1/c_p N_T$$

$$n_1, p_1 \approx n_i$$

(Shockley Read Hall recombination)

# Low level injection in a p-type semiconductor

$$\left.\frac{\partial n}{\partial t}\right|_{SRH} = \left.\frac{\partial p}{\partial t}\right|_{SRH} = \frac{-\left(np - n_i^2\right)}{\tau_p\left(n + n_1\right) + \tau_n\left(p + p_1\right)}$$

$$n = n_0 + \Delta n \approx \Delta n$$

$$p + p_1 >> n + n_1$$

$$p = p_0 + \Delta p \approx N_A$$

$$p >> p_1$$

$$np \approx \Delta n\, N_A >> n_i^2$$

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{SRH} = -\frac{\Delta n}{\tau_n}$$

$$\boxed{\tau_{SRH} = \frac{1}{c_n N_T}}$$

# Recombination under low level injection

band-band

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{b-b} = -\frac{\Delta n}{\tau_{b-b}} \qquad \tau_{b-b} = \frac{1}{BN_A}$$

Auger

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{Auger} = -\frac{\Delta n}{\tau_{Auger}} \qquad \tau_{Auger} = \frac{1}{C_p N_A^2}$$

SRH

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{SRH} = -\frac{\Delta n}{\tau_n} \qquad \tau_n = \frac{1}{c_n N_T}$$

The minority carrier lifetime is a key parameter for solar cells, bipolar transistors, etc.

# Multiple recombination processes

$$\left.\frac{\partial \Delta n}{\partial t}\right|_{tot} = -\frac{\Delta n}{\tau_{eff}} \qquad \frac{1}{\tau_{eff}} = \frac{1}{\tau_{b-b}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}$$

$$\Delta n(t) = \Delta n(0) e^{-t/\tau_{eff}}$$

# Discussion

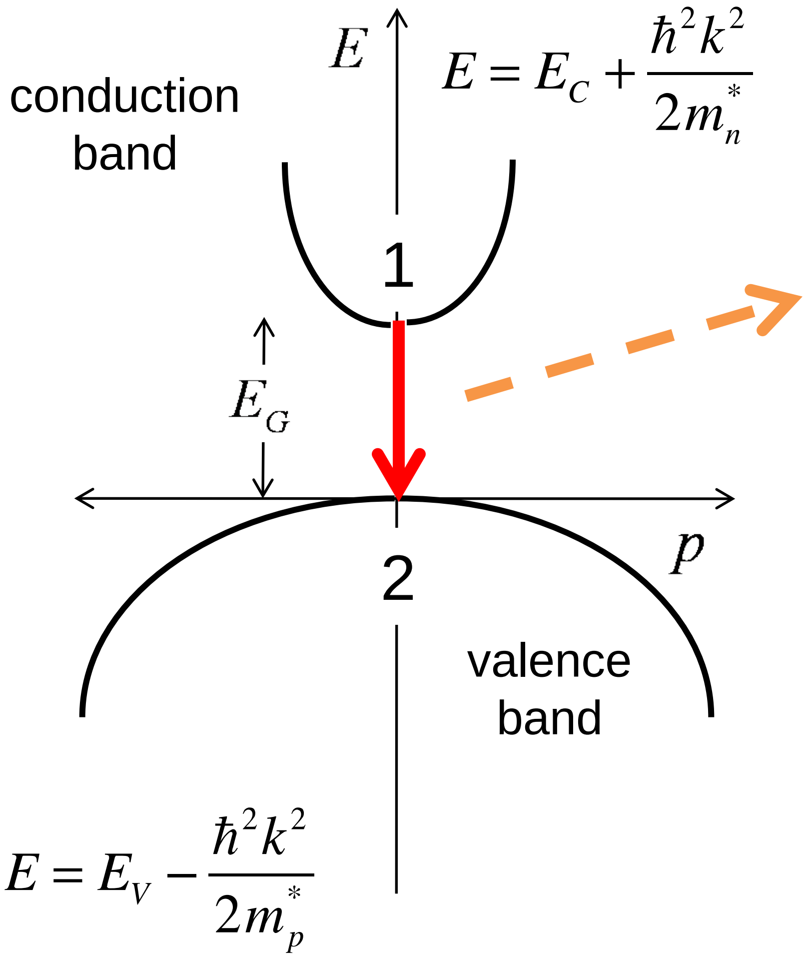
When are the various recombination processes dominant?

1) Auger: For heavily doped semiconductors $\tau_{Auger} = \dfrac{1}{C_p N_A^2}$

2) SRH: When defects are present and other effects don't dominate.

3) Radiative: **Only for direct gap semiconductors**.

# BB recombination in **direct gap** semiconductors




Conservation of energy:

$$E_{ph} = hf \approx E_G$$

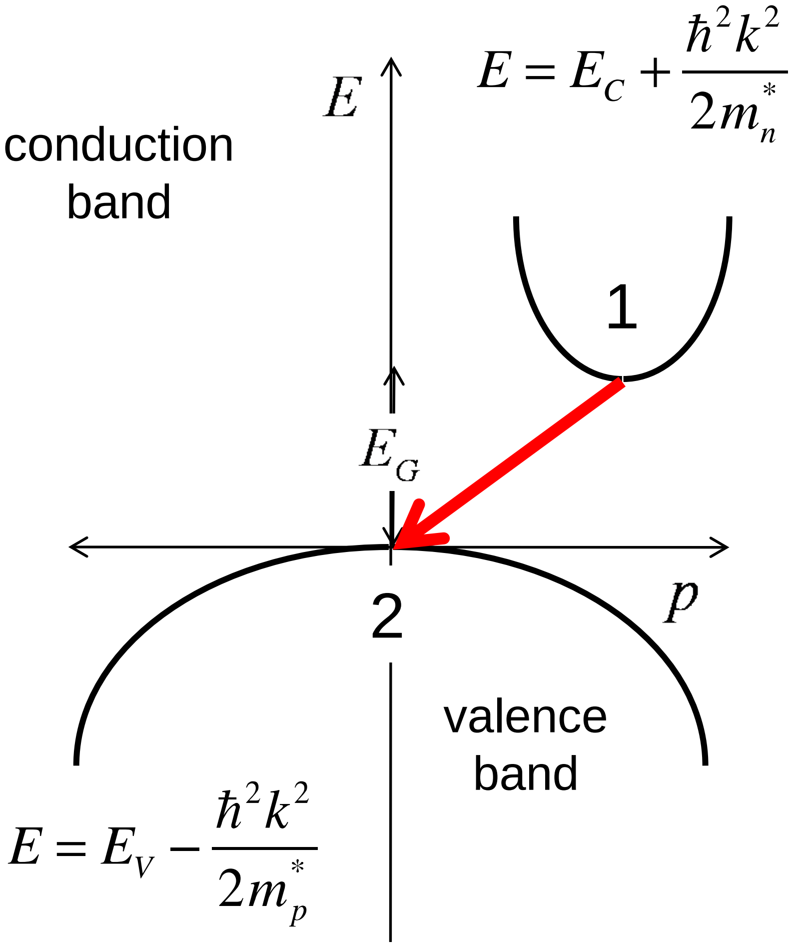
Conservation of momentum:

$$\hbar k_1 - \hbar k_2 = \hbar k_{ph} \approx 0$$

$$k_1 \approx k_2$$

("vertical transitions" photons have very little momentum)

# BB recombination in **indirect gap** semiconductors




Conservation of energy:

$$E_{ph} = hf = E_G \pm \hbar\omega_{lv}$$

Conservation of momentum:

$$\hbar k_1 - \hbar k_2 = \hbar k_{ph} + \hbar k_{lv}$$

(must involve a lattice vibration with the right momentum)

**BB recombination in indirect semiconductors is very weak!**

# Three type of recombination

**1) Band-to-band radiative recombination**

dominates in direct gap semiconductors
makes lasers and LEDs possible

**2) Auger recombination**

dominates when the carrier densities are very high
(heavily doped semiconductors or lasers)

**3) SRH recombination**

dominates in indirect gap semiconductors
and in low quality direct gap semiconductors

# Recombination-**generation**

$$R = X\left(np - n_i^2\right)$$

$$X = B$$

band-to-band
radiative

$$X = C_n n + C_p p$$

Auger

$$X = \frac{1}{\tau_p\left(n + n_1\right) + \tau_n\left(p + p_1\right)}$$

SRH

$\left(np > n_i^2\right)$

net recombination

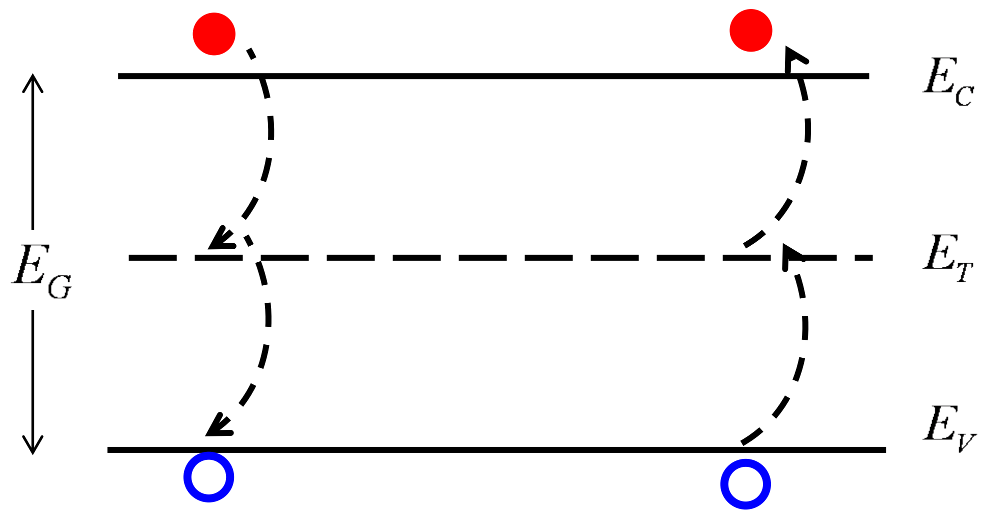
$\left(np < n_i^2\right)$

**net generation**

# 3) SRH (defect-assisted) **generation**

*R* > 0:
recombination

*R* < 0:
generation




$np > n_i^2$

$np < n_i^2$

releases thermal energy

requires thermal energy

# Summary

When excess carriers are introduced, a semiconductor responds by trying to restore equilibrium.

In the simplest, and quite common case, the perturbation decays exponentially with time.

$$\boxed{\Delta n(t) = \Delta n(t=0)\, e^{-t/\tau_n}}$$

(low level injection)

The minority carrier lifetime is controlled by radiative, Auger, or defect-assisted process – or by some combination of these.