

VE 320 Fall 2021

Introduction to Semiconductor Devices

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Lecture 6

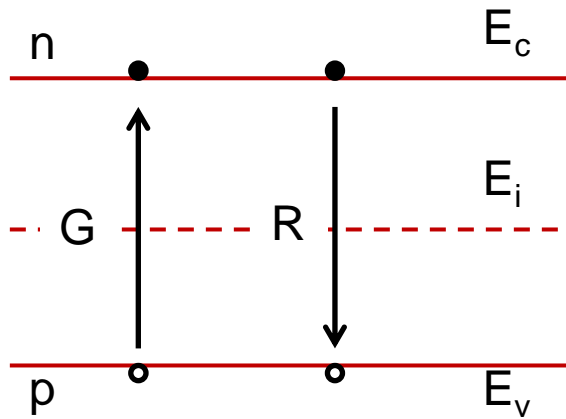
Nonequilibrium excess carriers (Chapter 6)

Nonequilibrium

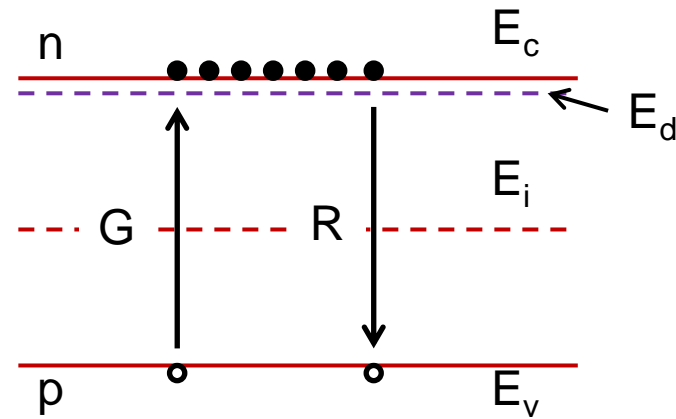
- Chapter 4: thermal equilibrium
- Chapter 5: there are voltages applied, so it should be nonequilibrium, but assumed that the equilibrium is not heavily perturbed
- Chapter 6: External excitation applied, excess carriers

Carrier generation and recombination

- Direct recombination



Intrinsic: $n=p=n_i$



n type : $n \gg n_i \gg p$

Generation rate G or Recombination rate R :

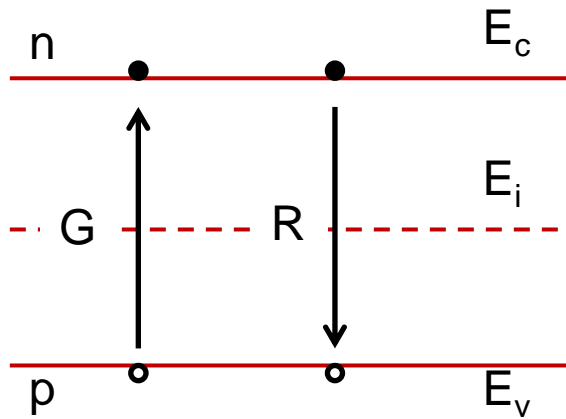
The number of charge carriers generated or recombined per unit volume per second

Thermal equilibrium:

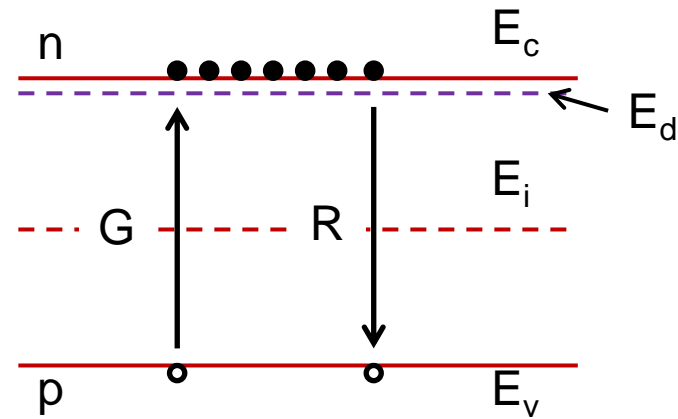
$$G_{n0} = G_{p0} = R_{n0} = R_{p0}$$

Unit: $\#/cm^3 \cdot s$

Carrier generation and recombination



Intrinsic: $n=p=n_i$



n type : $n \gg n_i \gg p$

Excess electrons and excess holes

Excess electron and hole generation rates $g'_n = g'_p$

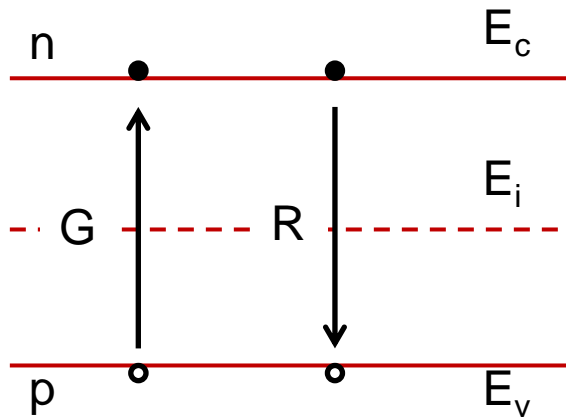
No longer thermal equilibrium

$$n = n_0 + \delta n \quad p = p_0 + \delta p$$

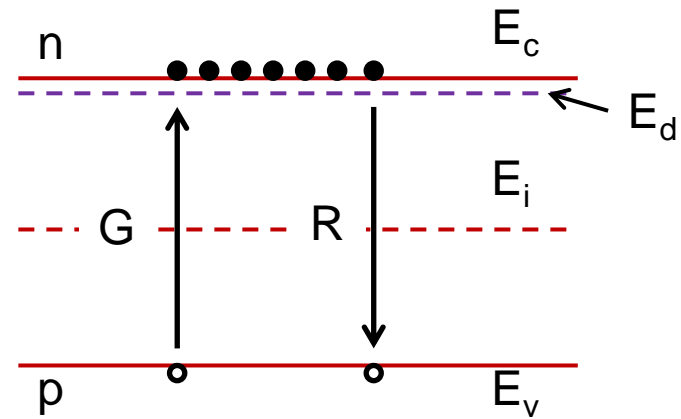
$$np \neq n_0 p_0 = n_i^2$$

Carrier generation and recombination

- Direct recombination



Intrinsic: $n=p=n_i$



n type : $n \gg n_i \gg p$

First, look at R

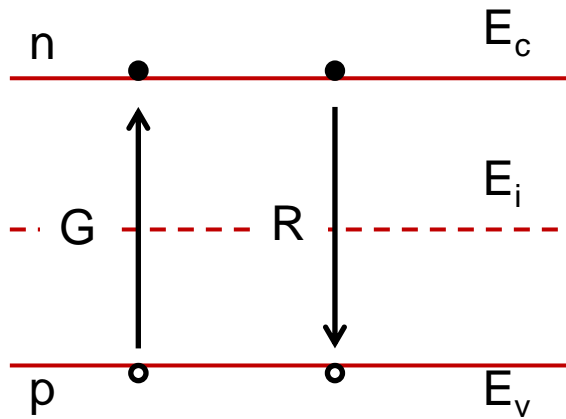
$$R \sim n, \quad R \sim p$$

$$\Rightarrow R \sim np$$

$$\Rightarrow R = \alpha_r np \text{ where } \alpha_r \text{ is a constant}$$

Carrier generation and recombination

- Direct recombination



Intrinsic: $n=p=n_i$

First, look at R

Assume: the probability of an electron and hole recombining is constant with time

$$R \sim n, \quad R \sim p$$

$$\Rightarrow R \sim np$$

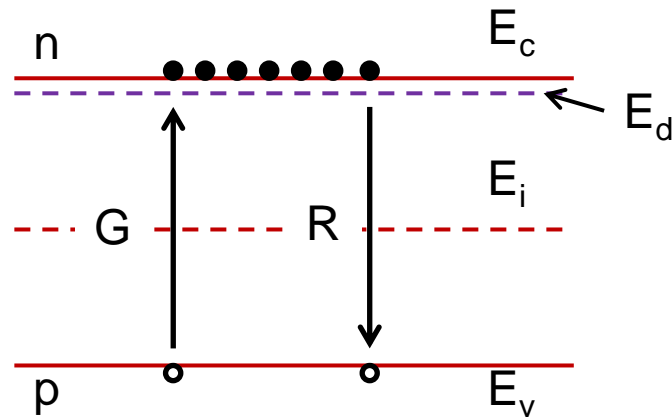
$$\Rightarrow R = \alpha_r np \text{ where } \alpha_r \text{ is a constant}$$

Then, look at G

Can we write similar equations?

$$G \sim n? \quad R \sim p?$$

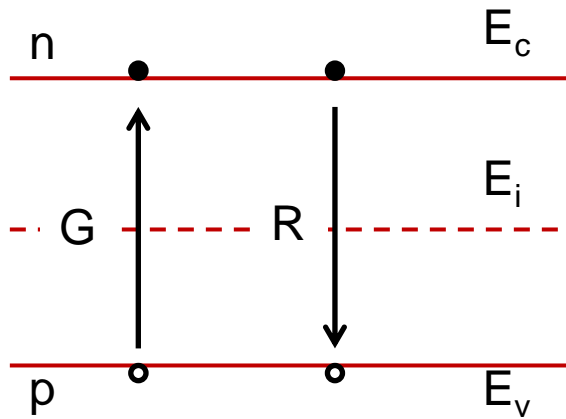
No! G_0 is intrinsic and only a function of T



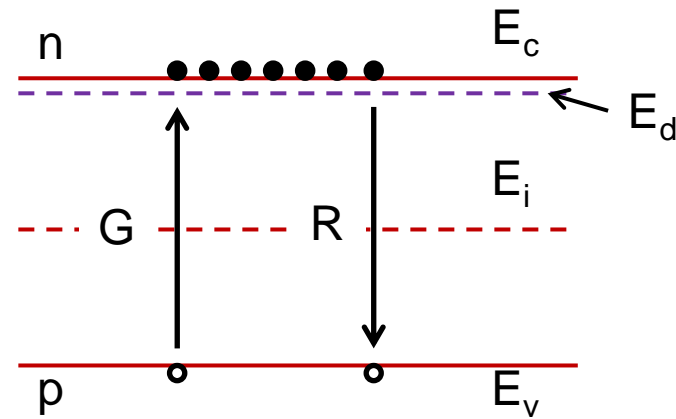
n type : $n \gg n_i \gg p$

Carrier generation and recombination

- Direct recombination



Intrinsic: $n=p=n_i$



n type : $n \gg n_i \gg p$

At equilibrium, we must have

$$n_i^2 = N_c N_v \exp \left[\frac{-(E_c - E_v)}{kT} \right] = N_c N_v \exp \left[\frac{-E_g}{kT} \right]$$

$$G_0 = \alpha_r \cdot n_0 \cdot p_0 = \alpha_r \cdot n_i^2 \text{ where } \alpha_r \text{ is a constant}$$

Boltzmann approximation

At non-equilibrium

- ① Light illumination
- ② current injection: forward biased pn junction

Carrier generation and recombination

- Direct recombination

At non-equilibrium

- ① Light illumination ② current injection: forward biased pn junction

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$

$$\delta n = \delta p$$

$$R = \alpha_r \cdot n \cdot p = \alpha_r \cdot (n_0 + \delta n) \cdot (p_0 + \delta p)$$

$$G = G_0 = R_0 = \alpha_r \cdot n_i^2$$

Net recombination rate:

$$R'_n = R - G_0 = \alpha_r \cdot (n_0 + \delta n) \cdot (p_0 + \delta p) - \alpha_r \cdot n_i^2$$

$$= \alpha_r \cdot (n_0 \cdot p_0 + \delta n \cdot p_0 + n_0 \cdot \delta p + \delta n \cdot \delta p) - \alpha_r \cdot n_i^2$$

$$= \alpha_r \cdot [n_i^2 + \delta n \cdot (p_0 + n_0) + (\delta n)^2] - \alpha_r \cdot n_i^2$$

$$= \alpha_r \cdot \delta n \cdot (p_0 + n_0) + \alpha_r \cdot (\delta n)^2$$

Carrier generation and recombination

Low-level injection

Net recombination rate:

$$R'_n = \alpha_r \cdot \delta n \cdot (p_0 + n_0) + \alpha_r \cdot (\delta n)^2$$

p-type material: $\delta n \ll p_0$

$$R'_n = \alpha_r \cdot \delta n \cdot p_0$$

$$\frac{d(\delta n(t))}{dt} = -\alpha_r p_0 \delta n(t)$$

Solution: $\delta n(t) = \delta n(0)e^{-\alpha_r p_0 t} = \delta n(0)e^{-t/\tau_{n0}}$

$$\tau_{n0} = \frac{\delta n}{R'_n} = \frac{1}{\alpha_r p_0}$$

Excess minority carrier lifetime

$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{n0}}$$

n-type material: $\delta n \ll n_0$

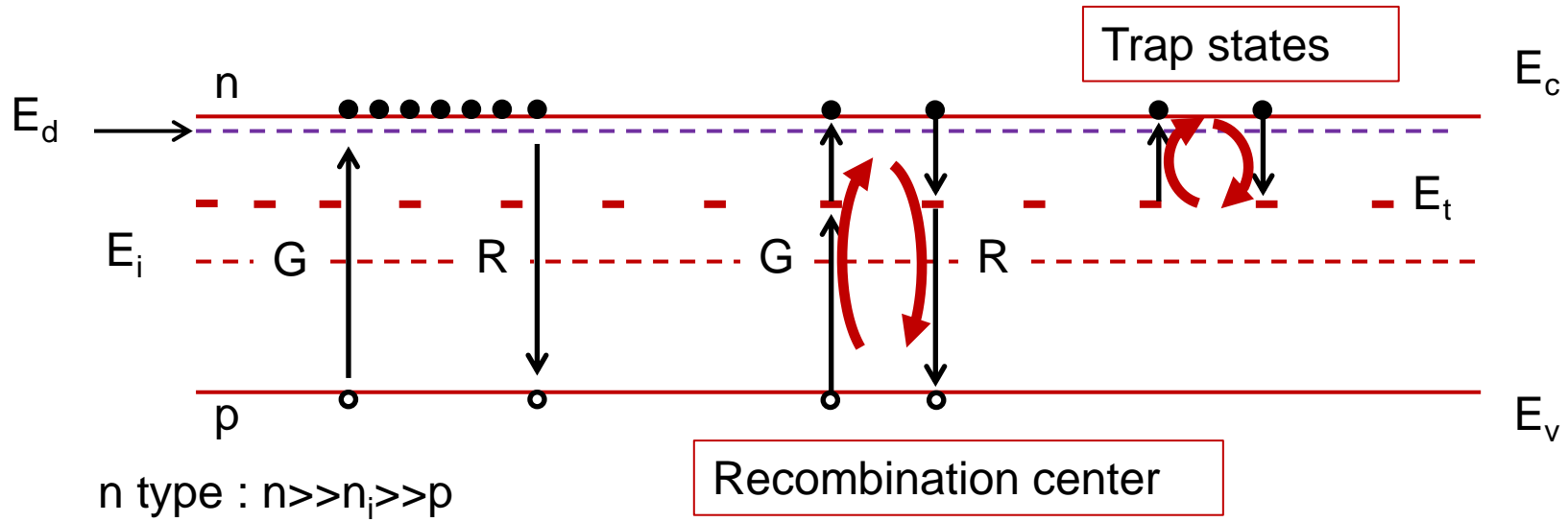
$$R'_n = R'_p = \frac{\delta n(t)}{\tau_{p0}}$$

$$\tau_{p0} = \frac{1}{\alpha_r n_0}$$

In general $\tau = \frac{1}{\alpha_r (n_0 + p_0)}$

Carrier generation and recombination

- Indirect recombination



Carrier generation and recombination

- Indirect recombination

$$R'_n = \frac{np - n_i^2}{\tau_p \left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right) \right] + \tau_n \left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right) \right]}$$

$$\text{where } \tau_p = \frac{1}{N_t \alpha_{rp}}, \tau_n = \frac{1}{N_t \alpha_{rn}}$$

Carrier generation and recombination

- Surface recombination

Bulk recombination rate:

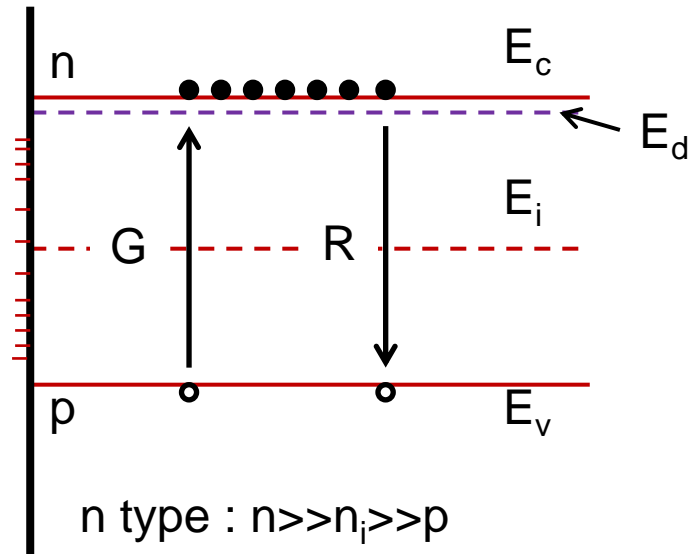
number of recombined carriers
in a unit volume at a give unit
time

$$\tau = \frac{\delta n}{R'_n} \Rightarrow R'_n = \delta n \frac{1}{\tau}$$

Surface recombination rate:

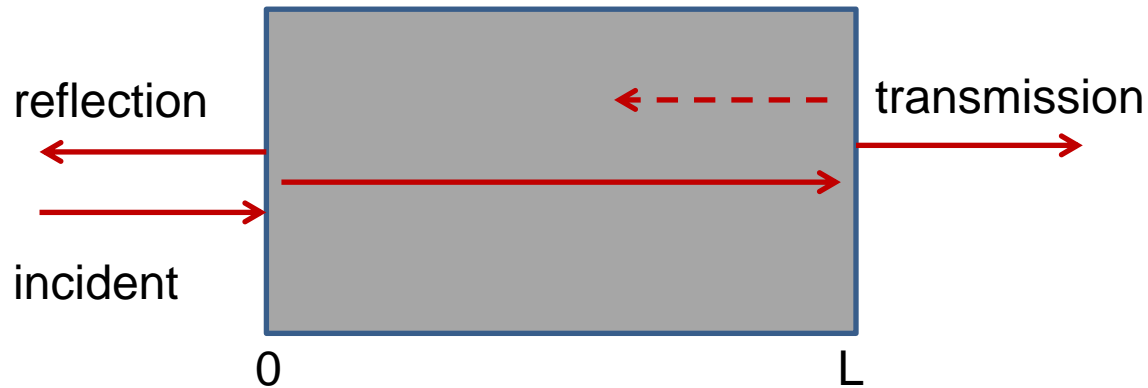
number of recombined carriers in a
unit surface area at a give unit time

$$R'_{ns} = R'_n \cdot (\Delta x)_s = \delta n \frac{\Delta x}{\tau} = \delta n \cdot s$$



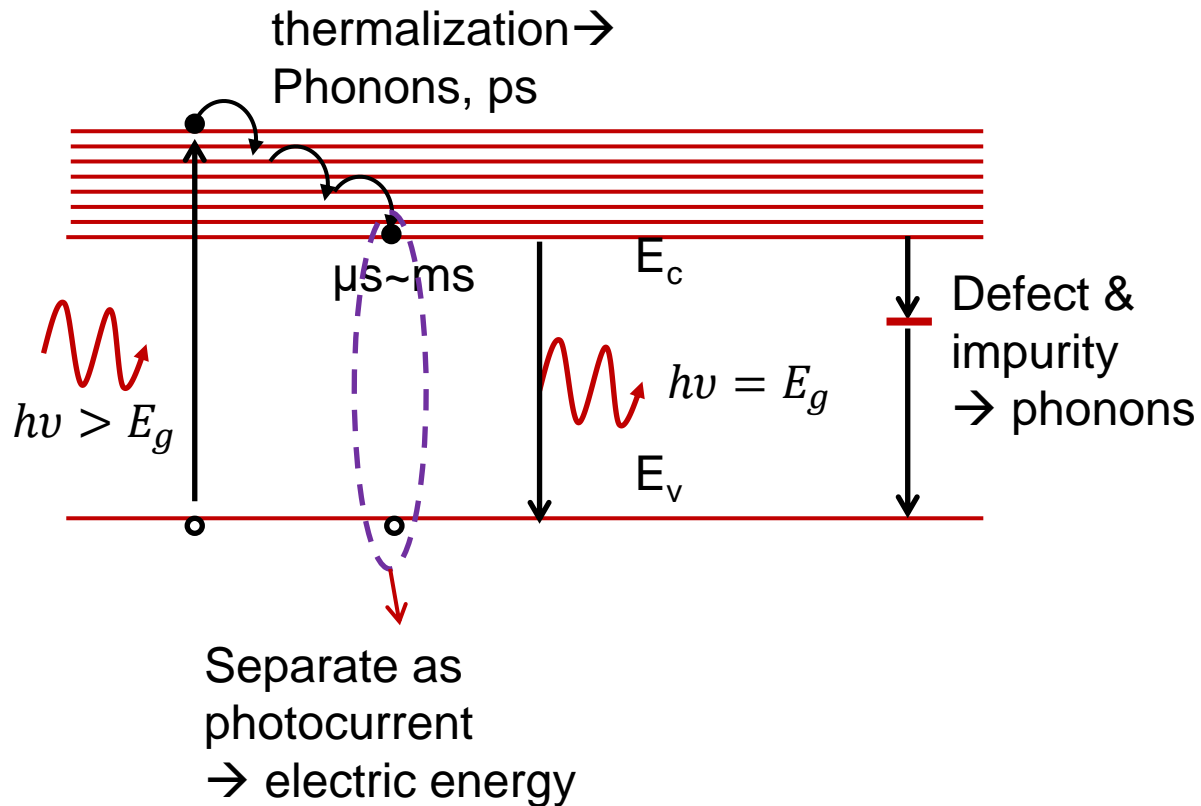
Light absorption by semiconductors

Absorption coefficient α

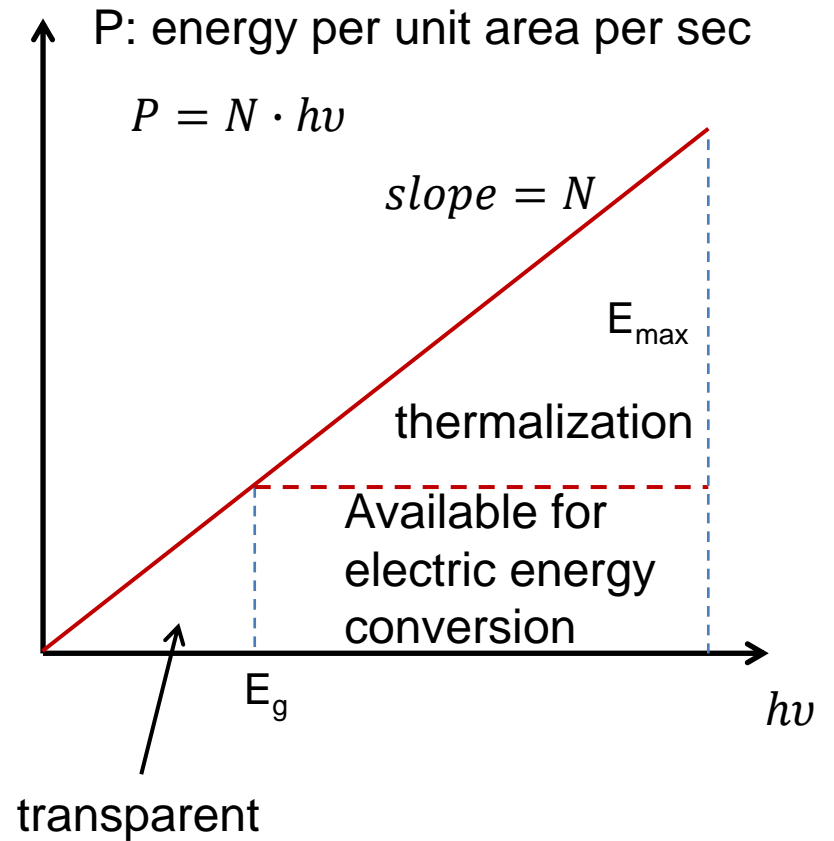
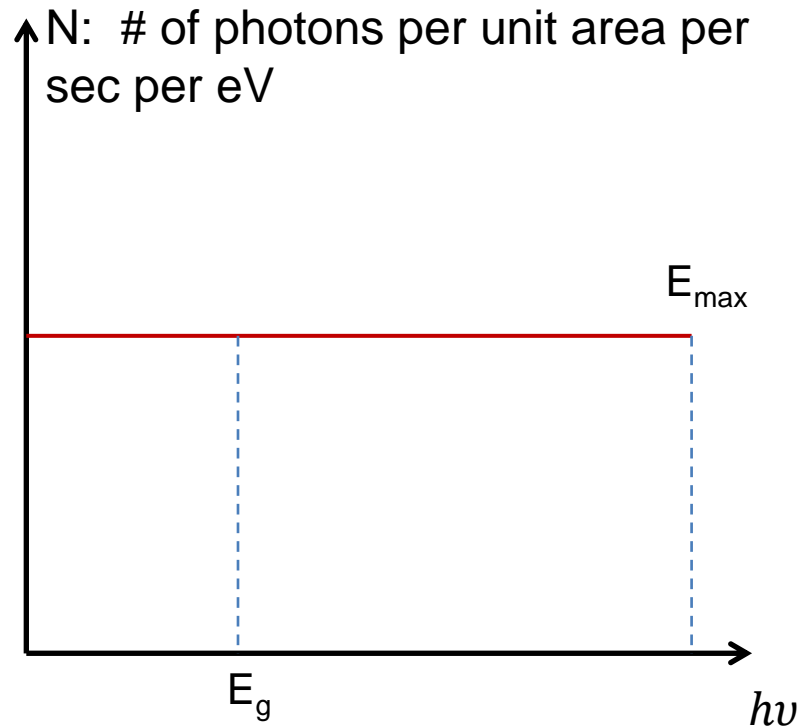


$$I = I_0 e^{-\alpha x}$$

Light absorption by semiconductors

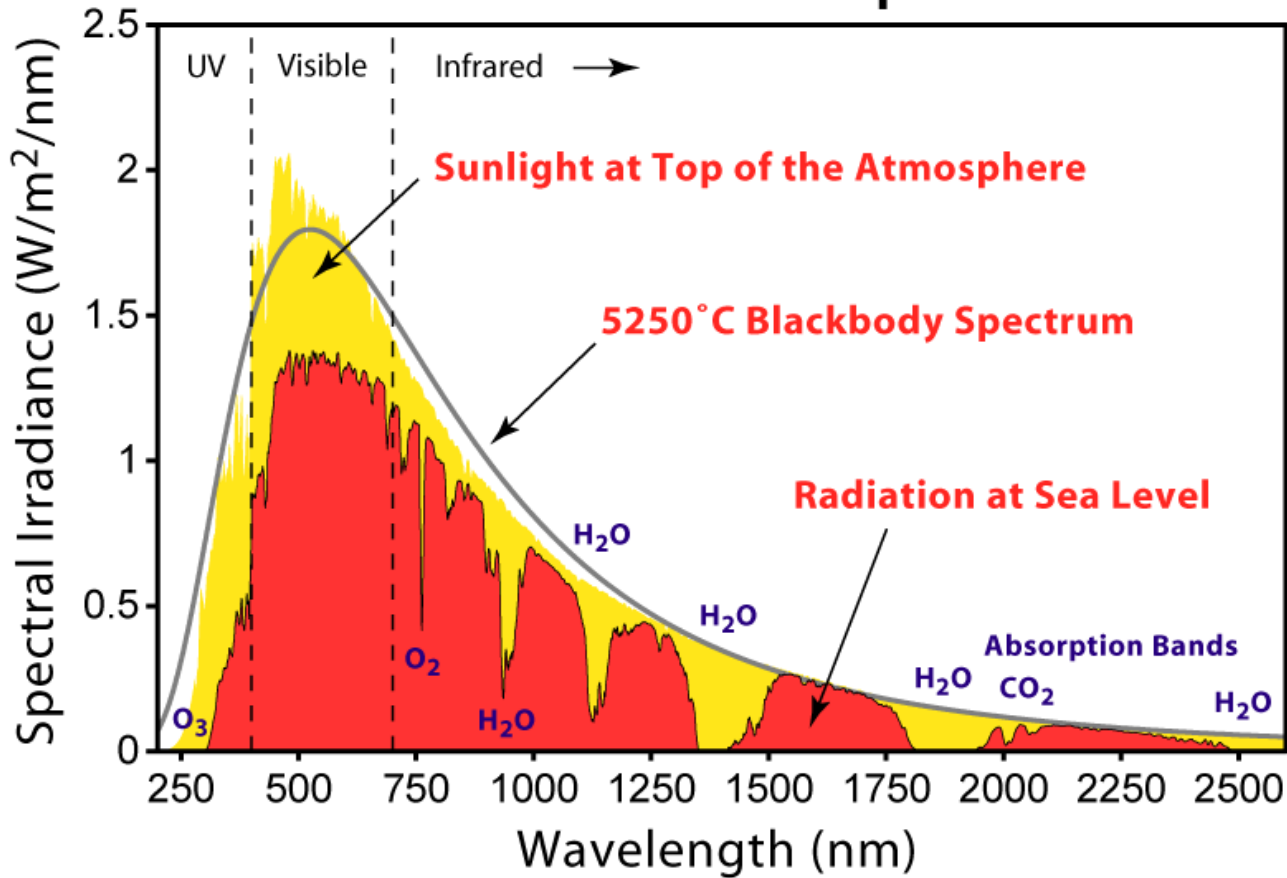


Light absorption by semiconductors



Light absorption by semiconductors

Solar Radiation Spectrum



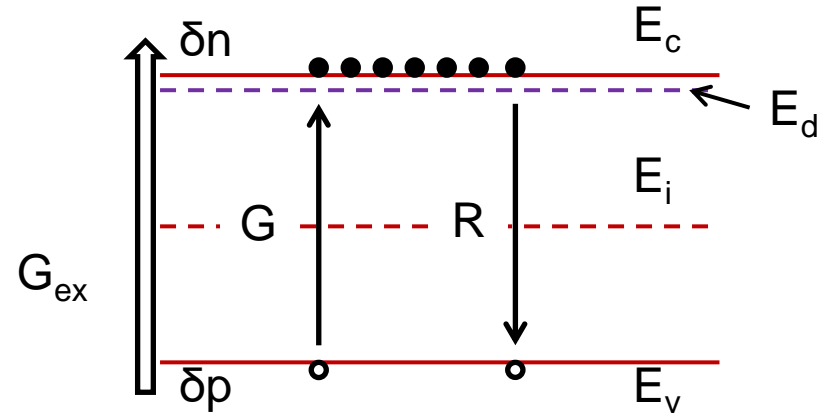
Carrier concentration at non-equilibrium

- Time dependent

Once light illumination is switched off:

$$t_1: \delta p(t)$$

$$t_2: \delta p(t + \Delta t)$$



n type : $n \gg n_i \gg p$

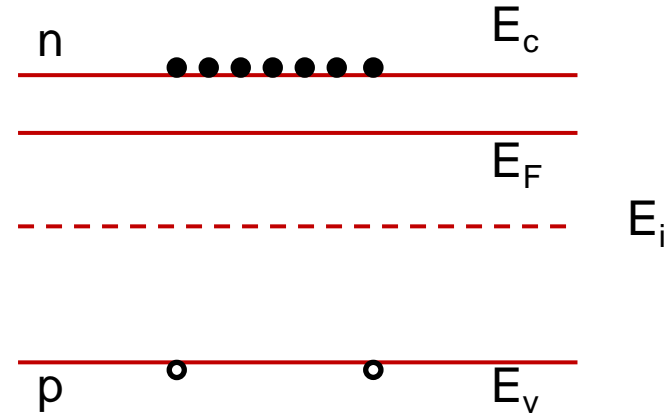
$$\left| \lim_{\Delta t \rightarrow 0} \frac{\delta p(t) - \delta p(t + \Delta t)}{t - (t + \Delta t)} \right| = \text{recombination rate} = \frac{\delta p(t)}{\tau}$$

$$\Rightarrow \frac{d\delta p(t)}{dt} = -\frac{\delta p(t)}{\tau}$$

Carrier concentration at non-equilibrium

- Quasi Fermi level

Excess carriers in a semiconductor: no thermal Equilibrium,
Fermi energy is no longer defined



n type : $n \gg n_i \gg p$

$$n_0 \times p_0 = n_i^2$$

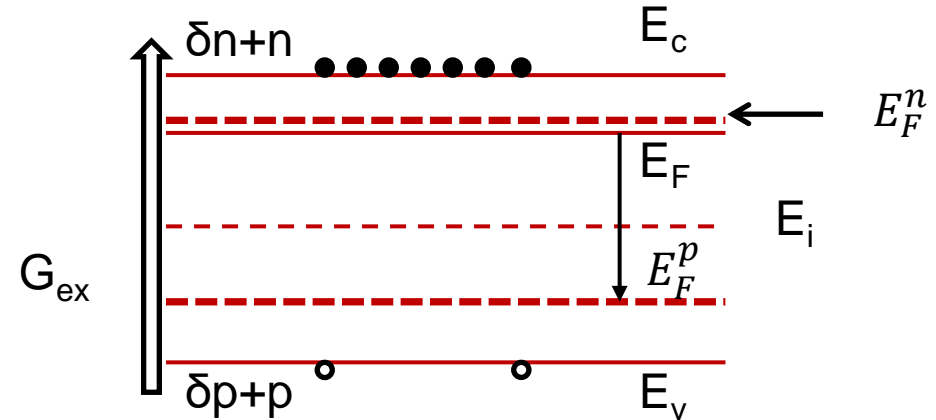
$$n_0 = N_c \exp\left(\frac{E_F - E_c}{kT}\right) \quad p_0 = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$n_0 = n_i \exp\left(\frac{E_F - E_i}{kT}\right) \quad p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

Carrier concentration at non-equilibrium

- Quasi Fermi level

Excess carriers in a semiconductor:
no thermal Equilibrium
Strictly, Fermi energy is no longer
defined



$$(n_0 + \delta n) \times (p_0 + \delta p) = n_i^2 \exp\left(\frac{E_F^n - E_F^p}{kT}\right)$$

$$n_0 + \delta n = N_c \exp\left(\frac{E_F^n - E_c}{kT}\right) \quad p_0 + \delta p = N_v \exp\left(\frac{E_v - E_F^p}{kT}\right)$$

$$n_0 + \delta n = n_i \exp\left(\frac{E_F^n - E_i}{kT}\right) \quad p_0 + \delta p = n_i \exp\left(\frac{E_i - E_F^p}{kT}\right)$$

$$N_c \approx 10^{19} \text{ cm}^{-3}$$

$$N_v \approx 10^{19} \text{ cm}^{-3}$$

$$n_i \approx 10^{10} \text{ cm}^{-3}$$

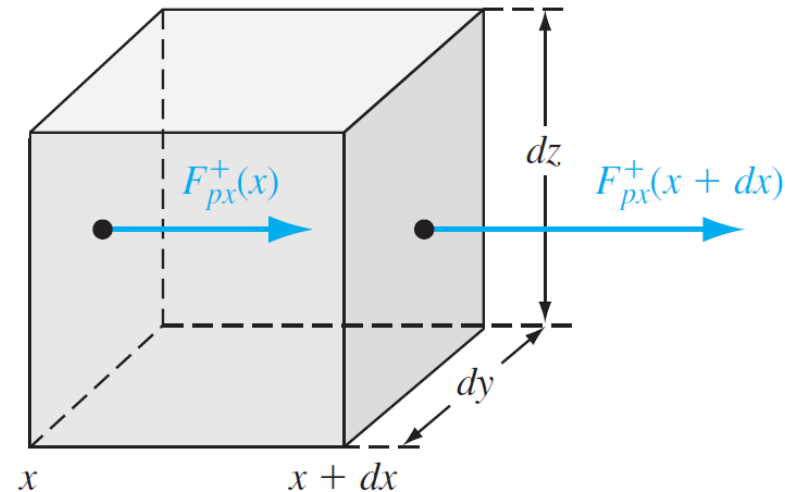
Continuity equation

Hole particle flux

Taylor expansion, for small dx

$$F_{px}^+(x + dx) = F_{px}^+(x) + \frac{\partial F_{px}^+}{\partial x} \cdot dx$$

The net increase in the number of holes per unit time within the differential volume due to the hole flux



$$\frac{\partial p}{\partial t} dx dy dz = -\frac{\partial F_p^+}{\partial x} dx dy dz + g_p dx dy dz - \frac{p}{\tau_{pt}} dx dy dz$$

where $-\frac{\partial F_p^+}{\partial x} dx = F_{px}^+(x) - F_{px}^+(x + dx)$

recombination rate for holes is given by p/τ_{pt} where τ_{pt} includes both the thermal-equilibrium carrier lifetime and the excess carrier lifetime

Continuity equation for holes

$$\frac{\partial p}{\partial t} = -\frac{\partial F_p^+}{\partial x} + g_p - \frac{p}{\tau_{pt}}$$

Continuity equation for electrons

$$\frac{\partial n}{\partial t} = -\frac{\partial F_n^-}{\partial x} + g_n - \frac{n}{\tau_{nt}}$$

Time dependent diffusion equation

For diffusion:

Previously we have current density $J_p = e\mu_p pE - eD_p \frac{\partial p}{\partial x}$

$$J_n = e\mu_n nE + eD_n \frac{\partial n}{\partial x}$$

Then the flux for electron
and hole

$$\frac{J_p}{(+e)} = F_p^+ = \mu_p pE - D_p \frac{\partial p}{\partial x}$$

$$\frac{J_n}{(-e)} = F_n^- = -\mu_n nE - D_n \frac{\partial n}{\partial x}$$

Remember we have $\frac{\partial p}{\partial t} = -\frac{\partial F_p^+}{\partial x} + g_p - \frac{p}{\tau_{pt}}$ $\frac{\partial n}{\partial t} = -\frac{\partial F_n^-}{\partial x} + g_n - \frac{n}{\tau_{nt}}$

Take the derivative of the flux $\frac{\partial p}{\partial t} = -\mu_p \frac{\partial(pE)}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} + g_p - \frac{p}{\tau_{pt}}$

$$\frac{\partial n}{\partial t} = +\mu_n \frac{\partial(nE)}{\partial x} + D_n \frac{\partial^2 n}{\partial x^2} + g_n - \frac{n}{\tau_{nt}}$$

Time dependent diffusion equation

$$\frac{\partial p}{\partial t} = -\mu_p \frac{\partial(pE)}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} + g_p - \frac{p}{\tau_{pt}}$$

$$\frac{\partial n}{\partial t} = +\mu_n \frac{\partial(nE)}{\partial x} + D_n \frac{\partial^2 n}{\partial x^2} + g_n - \frac{n}{\tau_{nt}}$$

We always have $\frac{\partial(pE)}{\partial x} = E \frac{\partial p}{\partial x} + p \frac{\partial E}{\partial x}$

Time-dependent diffusion equations for holes and electrons

$$D_p \frac{\partial^2 p}{\partial x^2} - \mu_p \left(E \frac{\partial p}{\partial x} + p \frac{\partial E}{\partial x} \right) + g_p - \frac{p}{\tau_{pt}} = \frac{\partial p}{\partial t}$$

$$D_n \frac{\partial^2 n}{\partial x^2} + \mu_n \left(E \frac{\partial n}{\partial x} + n \frac{\partial E}{\partial x} \right) + g_n - \frac{n}{\tau_{nt}} = \frac{\partial n}{\partial t}$$

Homogeneous semiconductor:
 n_0 and p_0 are not a function of
time or space coordinate

$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \mu_p \left(E \frac{\partial(\delta p)}{\partial x} + p \frac{\partial E}{\partial x} \right) + g_p - \frac{p}{\tau_{pt}} = \frac{\partial(\delta p)}{\partial t}$$

$$D_n \frac{\partial^2(\delta n)}{\partial x^2} + \mu_n \left(E \frac{\partial(\delta n)}{\partial x} + n \frac{\partial E}{\partial x} \right) + g_n - \frac{n}{\tau_{nt}} = \frac{\partial(\delta n)}{\partial t}$$

Carrier concentration at non-equilibrium

- Drift & diffusion current

for holes

for electrons

Drift Diffusion	$\vec{J}_p = e \vec{F}_p = -eD_p \frac{d\delta p}{dx} \vec{x}$	$\vec{J}_n = -e \vec{F}_n = eD_n \frac{d\delta n}{dx} \vec{x}$
	$(\vec{J}_p)_{drift} = ep\mu_p \vec{E}, \text{ where } p = p_0 + \delta p$	$(\vec{J}_n)_{drift} = -en\mu_n \vec{E},$ where $n = n_0 + \delta n$

$$\vec{J} = \vec{J}_p + \vec{J}_n$$

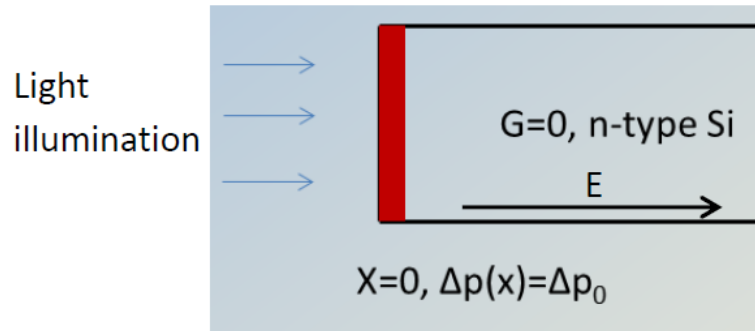
$$\vec{J}_p = (\vec{J}_p)_{diff} + (\vec{J}_p)_{drift}$$

$$\vec{J}_n = (\vec{J}_n)_{diff} + (\vec{J}_n)_{drift}$$

Continuity equation

- Examples

A light beam is illuminated on the surface of a silicon wafer, generating excess carriers Δp_0 at the surface ($x=0$). The wafer is placed in a constant electric field with a known intensity E . We assume there is no external generation inside the wafer. The thickness of the wafer is infinite. Find the excess minority carriers at equilibrium as a function of the distance away from the surface ($x=0$). Small injection condition is always maintained and the wafer is uniformly doped as N_d .



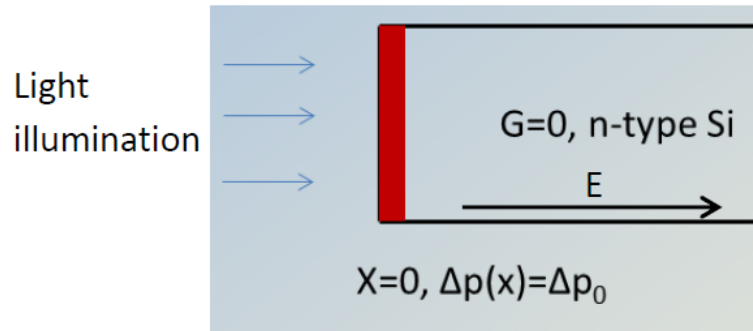
We can usually cancel the generation and recombination rate for the thermal equilibrium part, because they are the same

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p \mu_p \frac{\partial E}{\partial x} + \frac{p}{\tau_{pt}} + g_p$$

Continuity equation

- Examples

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$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p \mu_p \frac{\partial E}{\partial x} + -\frac{\delta p}{\tau} + g'_p$$

Red arrows indicate boundary conditions: $\delta p = 0$ at $x=0$ and $x \rightarrow \infty$, and $\delta p = \Delta p_0$ at $x=0$.

Continuity equation

- Examples

$$D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p E \frac{\partial \delta p}{\partial x} - \frac{\delta p}{\tau} = 0$$

The solution likely looks like this:

$$\delta p = A \exp(\lambda x) + C$$

$$\frac{\partial \delta p}{\partial x} = A \lambda \exp(\lambda x) \qquad \frac{\partial^2 \delta p}{\partial x^2} = A \lambda^2 \exp(\lambda x)$$

$$D_p [A \lambda^2 \exp(\lambda x)] - \mu_p E [A \lambda \exp(\lambda x)] - \frac{A \exp(\lambda x)}{\tau} - \frac{C}{\tau} = 0$$

$$A \exp(\lambda x) \left(D_p \lambda^2 - \mu_p E \lambda - \frac{1}{\tau} \right) - \frac{C}{\tau} = 0 \qquad \text{True for all } x$$

$$D_p \lambda^2 - \mu_p E \lambda - \frac{1}{\tau} = 0, C = 0$$

Continuity equation

- Examples

$$D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p E \frac{\partial \delta p}{\partial x} - \frac{\delta p}{\tau} = 0$$

$$\tau D_p \lambda^2 - \tau \mu_p E \lambda - 1 = 0 \quad L_p = \sqrt{\tau D_p} \quad L_p(E) = \tau \mu_p E$$

$$\lambda = \frac{L_p(E) \pm \sqrt{L_p^2(E) + 4L_p^2}}{2L_p^2}$$

$$\delta p = (\delta p)_0 \exp \left(\frac{L_p(E) - \sqrt{L_p^2(E) + 4L_p^2}}{2L_p^2} x \right)$$

Continuity equation

- Examples

$$D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p E \frac{\partial \delta p}{\partial x} - \frac{\delta p}{\tau} = 0$$

$$\delta p = (\delta p)_0 \exp\left(\frac{L_p(E) - \sqrt{L_p^2(E) + 4L_p^2}}{2L_p^2} x\right) \quad L_p = \sqrt{\tau D_p} \quad L_p(E) = \tau \mu_p E$$

Case #1: E is small so that $L_p(E) \ll L_p$

$$\delta p = (\delta p)_0 \exp\left(-\frac{x}{L_p}\right)$$

Case #2: E is big so that $L_p(E) \gg L_p$

$$\delta p = (\delta p)_0 \exp\left(-\frac{x}{L_p(E)}\right)$$

Continuity equation

Examples

A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. At equilibrium, the excess minority carrier concentration is $(\delta p)_0$. Start from zero time $t=0$, the illumination is cut off. Find how does the concentration of the excess minority carriers change over time. Small injection condition is always maintained.

Continuity equation

Examples

A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. At equilibrium, the excess minority carrier concentration is $(\delta p)_0$. Start from zero time $t=0$, the illumination is cut off. Find how does the concentration of the excess minority carriers change over time. Small injection condition is always maintained.

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p \mu_p \frac{\partial E}{\partial x} - \frac{\delta p}{\tau} + g'_p$$

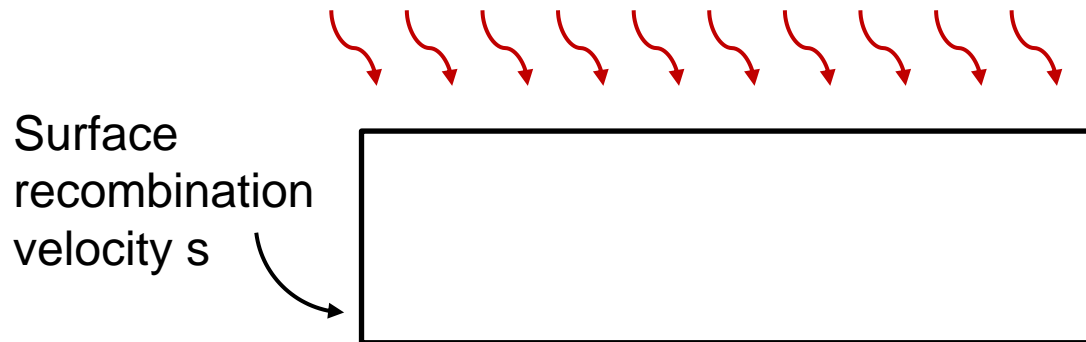
Diagram illustrating the continuity equation for excess minority carrier concentration δp in a n-type semiconductor wafer. The equation is shown in a red box, with red arrows pointing to the terms that are zero under the given conditions:

- $\frac{\partial^2 p}{\partial x^2} \rightarrow 0$ (uniform illumination)
- $\mu_p E \frac{\partial p}{\partial x} \rightarrow 0$ (no electric field)
- $p \mu_p \frac{\partial E}{\partial x} \rightarrow 0$ (no electric field)
- $g'_p \rightarrow 0$ (illumination is cut off)

Continuity equation

Examples

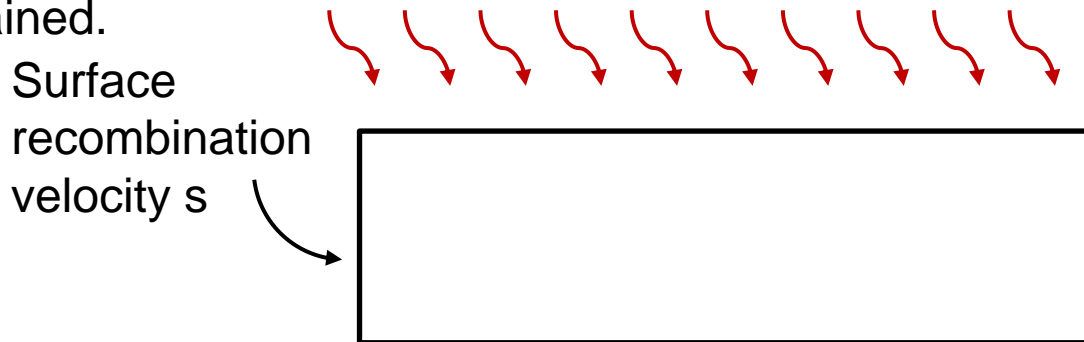
A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. The illumination generation rate is g and the minority carrier lifetime is τ . The semiconductor is long enough on the right side. On the left side edge, the surface recombination velocity is s . Find how does the concentration of the excess minority carriers change along x coordinate. Small injection condition is always maintained.



Continuity equation

Examples

A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. The illumination generation rate is g and the minority carrier lifetime is τ . The semiconductor is long enough on the right side. On the left side edge, the surface recombination velocity is s . Find how does the concentration of the excess minority carriers change along x coordinate at equilibrium. Small injection condition is always maintained.

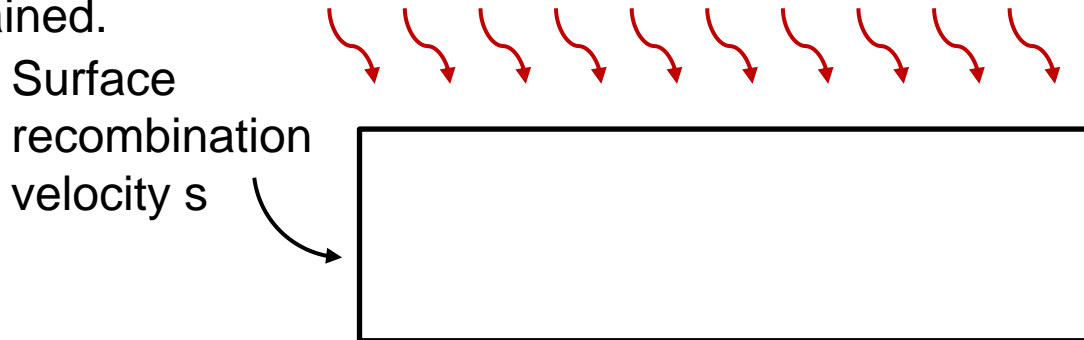


$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p E \frac{\partial p}{\partial x} - p \mu_p \frac{\partial E}{\partial x} - \frac{\delta p}{\tau} + g'_p$$

Continuity equation

Examples

A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. The illumination generation rate is g and the minority carrier lifetime is τ . The semiconductor is long enough on the right side. On the left side edge, the surface recombination velocity is s . Find how does the concentration of the excess minority carriers change along x coordinate at equilibrium. Small injection condition is always maintained.



$$0 = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau} + g'_p$$

The solution likely looks like this:

$$\delta p = A \exp(\lambda x) + C$$

Continuity equation

$$0 = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau} + g'_p$$

The solution likely looks like this:

$$\delta p = A \exp(\lambda x) + C$$

$$\frac{\partial \delta p}{\partial x} = A \lambda \exp(\lambda x) \qquad \frac{\partial^2 \delta p}{\partial x^2} = A \lambda^2 \exp(\lambda x)$$

$$D_p [A \lambda^2 \exp(\lambda x)] - \frac{A \exp(\lambda x)}{\tau} - \frac{C}{\tau} + g = 0$$

$$A \exp(\lambda x) \left(D_p \lambda^2 - \frac{1}{\tau} \right) - \frac{C}{\tau} + g = 0$$

$$D_p \lambda^2 - \frac{1}{\tau} = 0; \quad -\frac{C}{\tau} + g = 0 \Rightarrow \lambda = \pm \sqrt{D_p \tau}; \quad C = g \tau$$

Continuity equation

$$0 = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau} + g$$

The solution likely looks like this:

$$\delta p = A \exp(\lambda x) + g\tau$$

$$D_p \lambda^2 - \frac{1}{\tau} = 0; \quad -\frac{C}{\tau} + g = 0 \Rightarrow \lambda = \pm \frac{1}{\sqrt{D_p \tau}}; \quad C = g\tau$$

Boundary conditions:

$$\textcircled{1} \quad x \rightarrow \infty, \quad \delta p \text{ limited} \Rightarrow \delta p = A \exp\left(-\frac{x}{\sqrt{D_p \tau}}\right) + g\tau$$

$$\textcircled{2} \quad x = 0, \quad -F_p = s \cdot \delta p(x = 0) \Rightarrow D_p \frac{\partial \delta p(x)}{\partial x} \Big|_{x=0} = s \cdot \delta p(x = 0)$$

Continuity equation

$$0 = D_p \frac{\partial^2 \delta p}{\partial x^2} - \frac{\delta p}{\tau} + g$$

The solution likely looks like this:

$$\delta p = A \exp(\lambda x) + g\tau$$

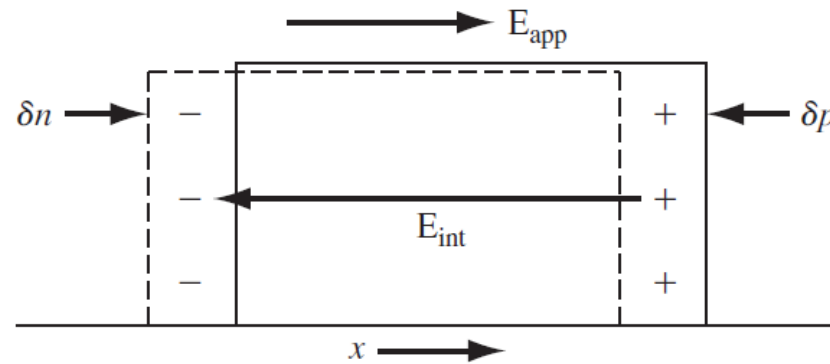
$$\textcircled{1} \ x \rightarrow \infty, \quad \delta p \text{ limited} \Rightarrow \delta p = A \exp\left(-\frac{x}{\sqrt{D_p \tau}}\right) + g\tau$$

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$$\Rightarrow -D_p \frac{A \exp\left(-\frac{x}{\sqrt{D_p \tau}}\right)}{\sqrt{D_p \tau}} \Big|_{x=0} = s \cdot (A + g\tau)$$

$$\Rightarrow -D_p \frac{A}{\sqrt{D_p \tau}} = s \cdot (A + g\tau) \Rightarrow A = -\frac{g\tau s}{s + D_p/L_p}$$

Ambipolar transport

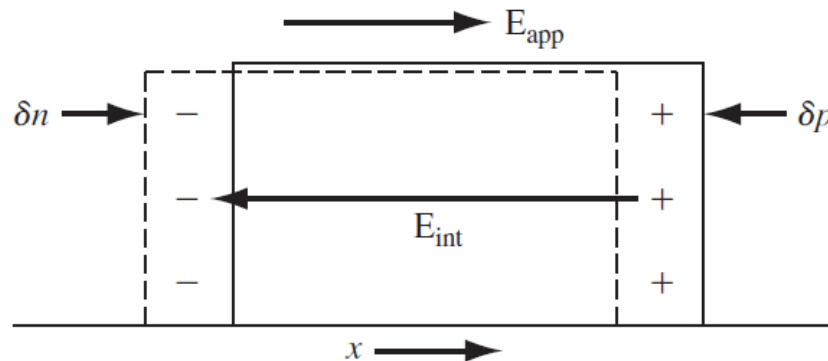


$$E = E_{app} + E_{int}$$

E_{app} is the applied electric field and E_{int} is the induced internal electric field

The negatively charged electrons and positively charged holes then will drift or diffuse together with a single effective mobility or diffusion coefficient, which are those of the minority carriers. This phenomenon is called **ambipolar diffusion or ambipolar transport**.

Ambipolar transport



How to simplify problems

Specification	Effect
Steady state	$\frac{\partial(\delta n)}{\partial t} = 0, \quad \frac{\partial(\delta p)}{\partial t} = 0$
Uniform distribution of excess carriers (uniform generation rate)	$D_n \frac{\partial^2(\delta n)}{\partial x^2} = 0, \quad D_p \frac{\partial^2(\delta p)}{\partial x^2} = 0$
Zero electric field	$E \frac{\partial(\delta n)}{\partial x} = 0, \quad E \frac{\partial(\delta p)}{\partial x} = 0$
No excess carrier generation	$g' = 0$
No excess carrier recombination (infinite lifetime)	$\frac{\delta n}{\tau_{n0}} = 0, \quad \frac{\delta p}{\tau_{p0}} = 0$