VE 320 Summer 2019

Introduction to Semiconductor Devices

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Lecture 6

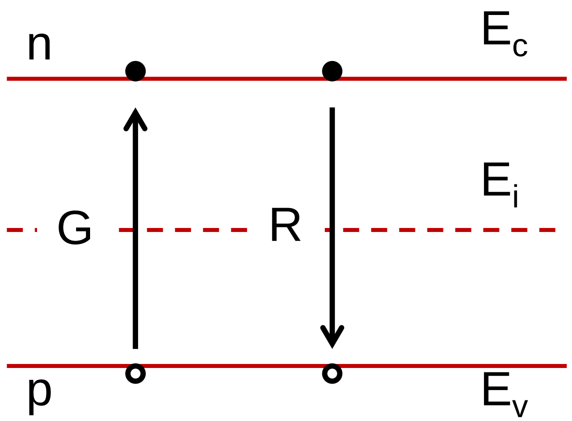
Nonequilibrium excess carriers
(Chapter 6)

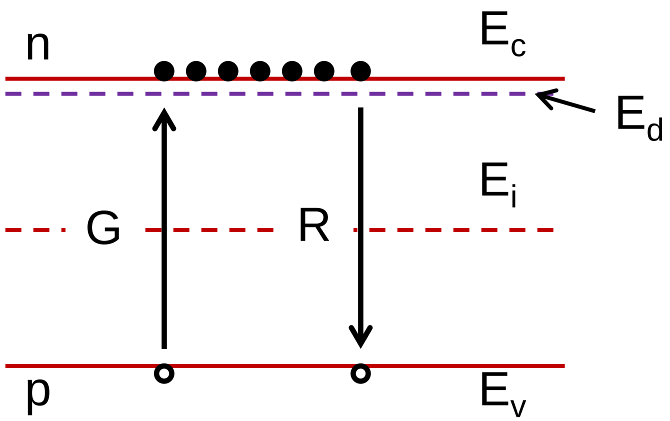
Nonequilibrium

- 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:

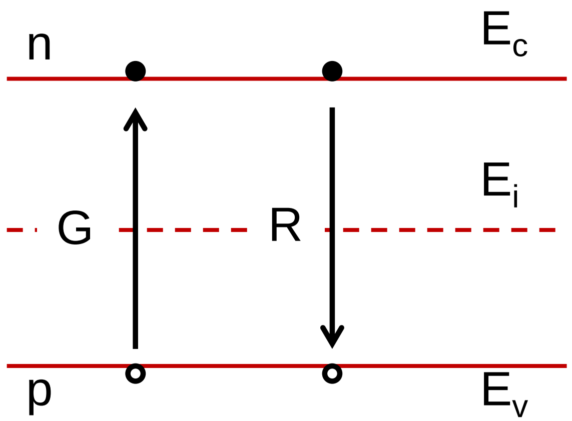
The number of charge carriers generated or recombined per unit volume per second

Thermal equilibrium:

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

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

Carrier generation and recombination



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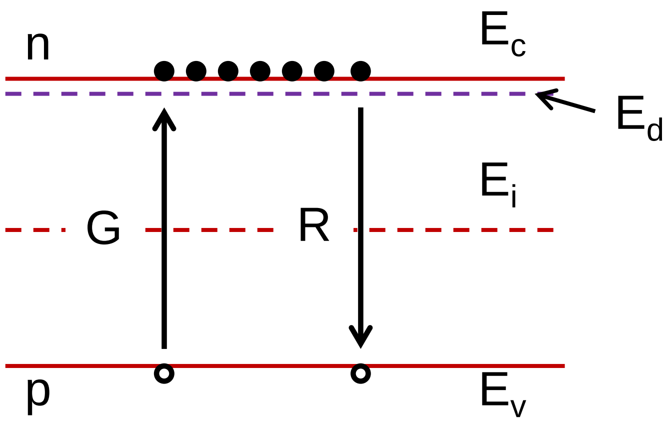


n type : $n>>n_i>>p$

Excess electrons and excess holes

Excess electron and hole generation rates $g_n' = g_p'$

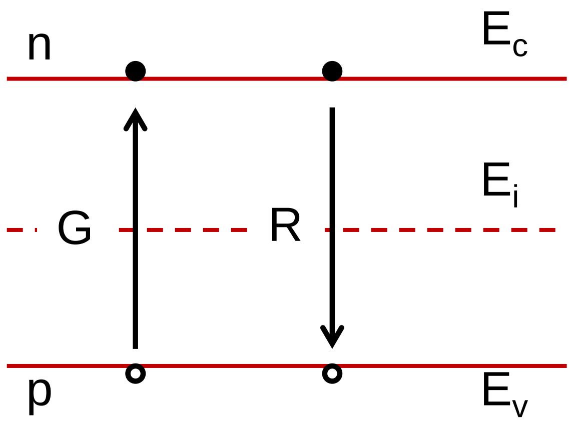
No longer thermal equilibrium

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

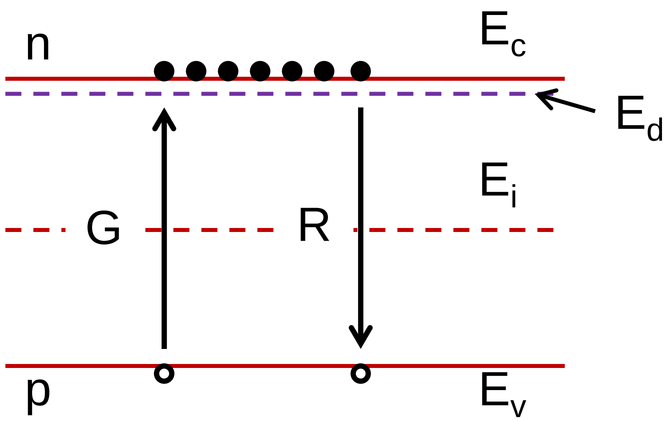
$$np \neq n_0 p_0 = n_i^2$$

Carrier generation and recombination

- Direct recombination



Intrinsic: $n=p=n_i$



n type : $n>>n_i>>p$

First, look at R

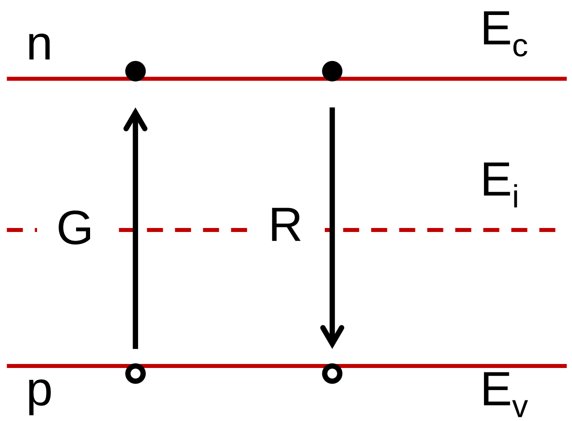
$R \sim n, \qquad R \sim p$

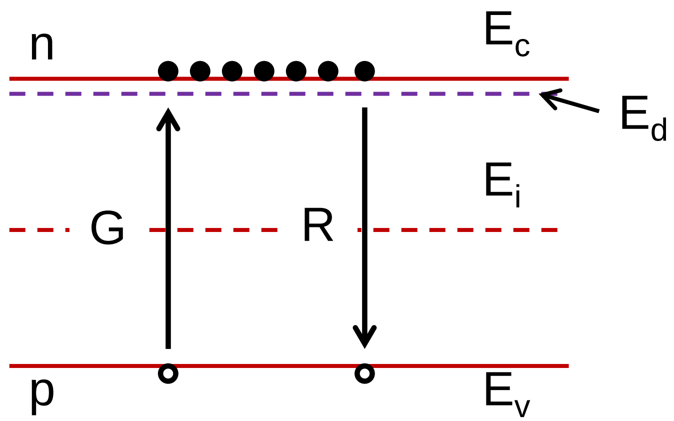
$\Rightarrow R \sim np$

$\Rightarrow R = \alpha_r np \;\; where\ \alpha_r\ is\ a\ constant$

Carrier generation and recombination

- Direct recombination





Intrinsic: $n=p=n_i$

n type : $n>>n_i>>p$

First, look at R

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

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

$\Rightarrow R \sim np$

$\Rightarrow R = \alpha_r np$ *where* α_r *is a constant*

Then, look at G

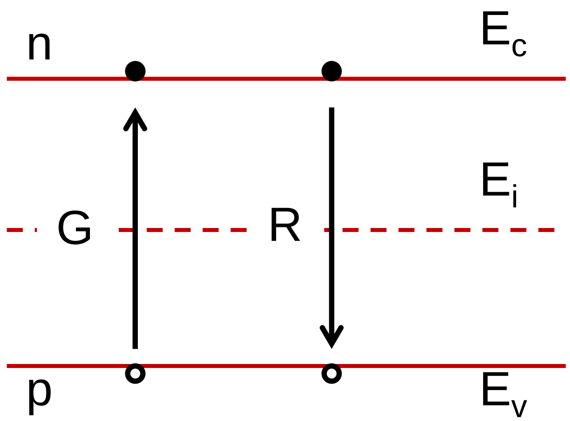
Can we write similar equations?

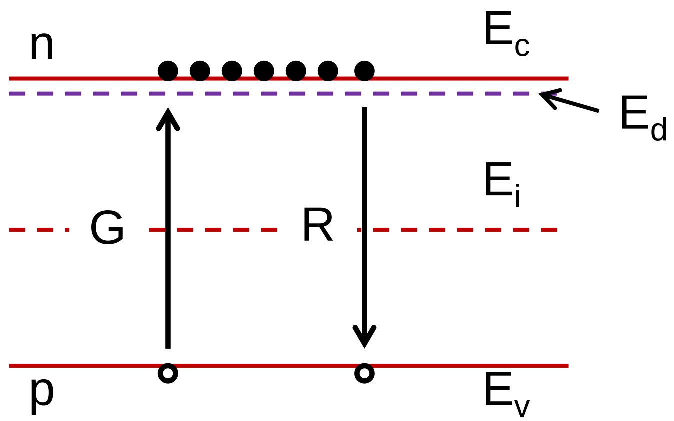
G~n ? R~p ?

No! G_0 is intrinsic and only a function of T

Carrier generation and recombination

- Direct recombination





Intrinsic: $n=p=n_i$

n type : $n>>n_i>>p$

At equilibrium, we must have

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

Boltzmann approximation

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

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: $$\boxed{R_n' = \alpha_r \cdot \delta n \cdot (p_0 + n_0) + \alpha_r \cdot (\delta n)^2}$$

p-type material: $\delta n << p_0$ $$\boxed{R_n' = \alpha_r \cdot \delta n \cdot p_0}$$

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

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: $\delta n << n_0$

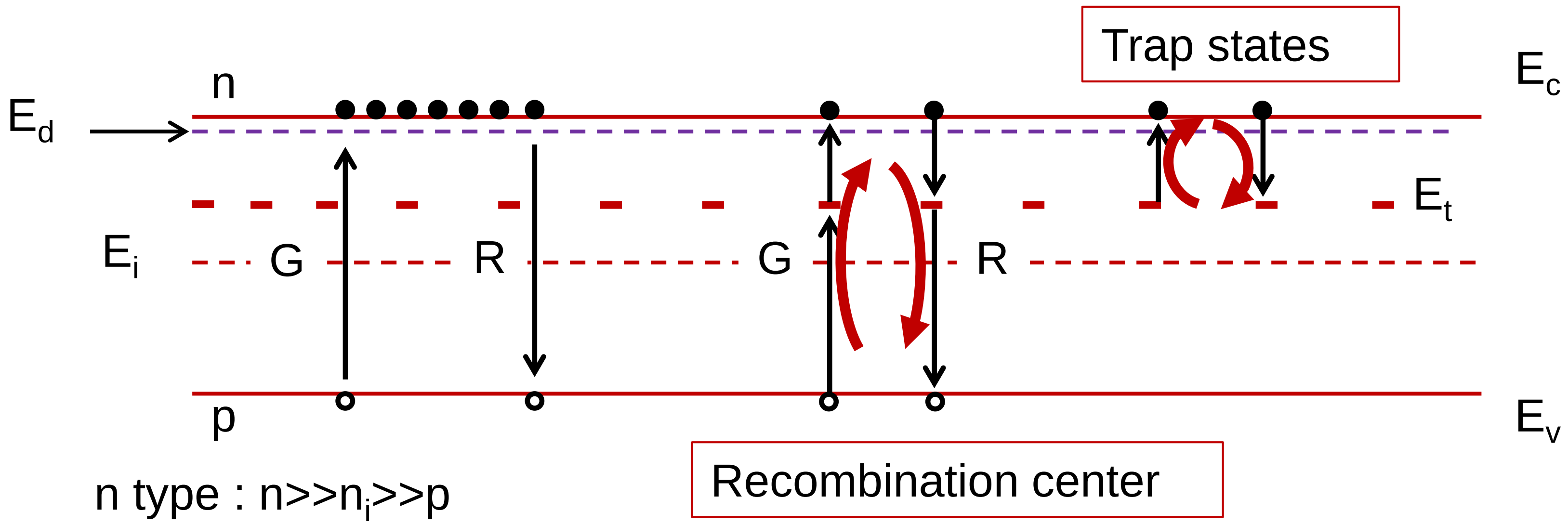
$$R_n' = R_p' = \frac{\delta n(t)}{\tau_{p0}}$$

$$\tau_{n0} = \frac{1}{\alpha_r n_0}$$

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

Carrier generation and recombination

- Indirect recombination



Carrier generation and recombination

- Indirect recombination

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

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

Carrier generation and recombination

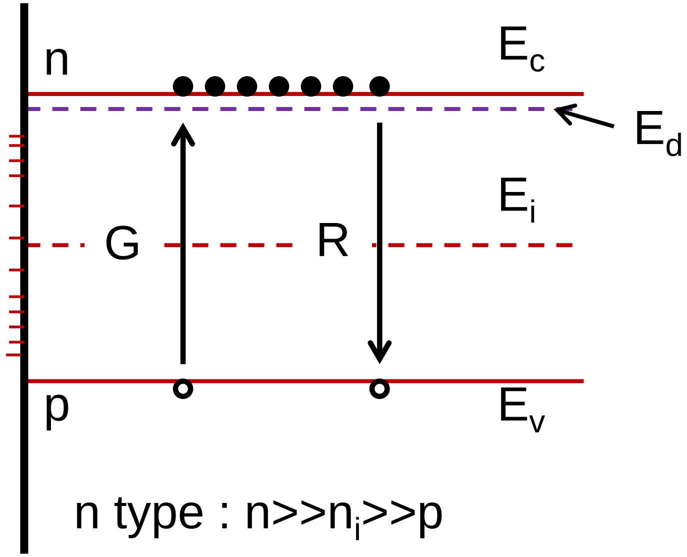
- Surface recombination

<u>Bulk recombination rate:</u>
number of recombined carriers in a unit volume at a give unit time

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

<u>Surface recombination rate:</u>
number of recombined carriers in a unit surface area at a give unit time

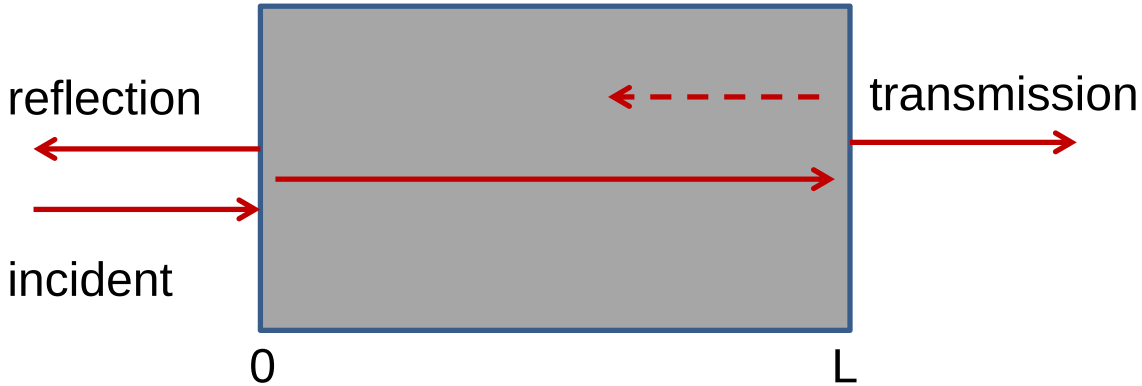
$$R_{ns}' = R_n' \cdot (\Delta x)_s = \delta n \frac{\Delta x}{\tau} = \delta n \cdot s$$



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

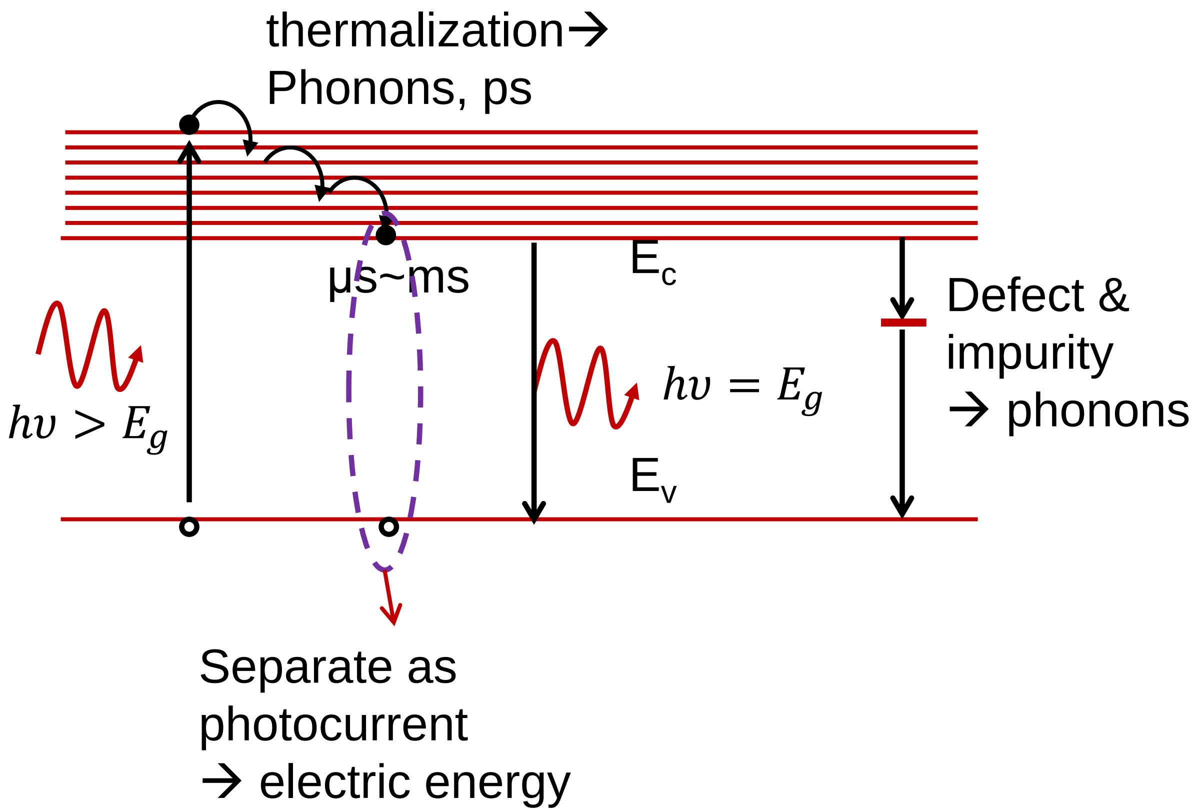
Light absorption by semiconductors

Absorption coefficient α

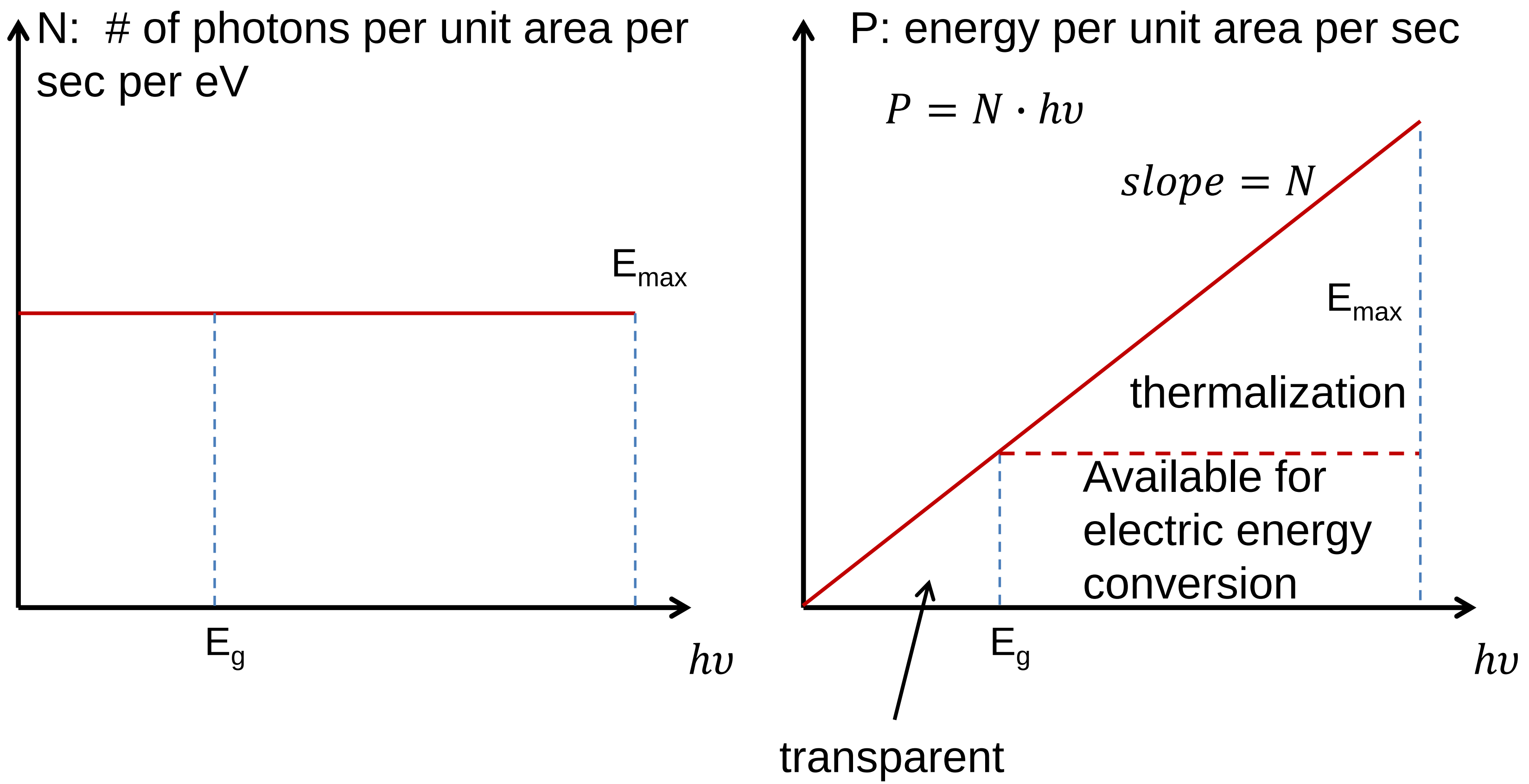


$$I = I_0 e^{-\alpha x}$$

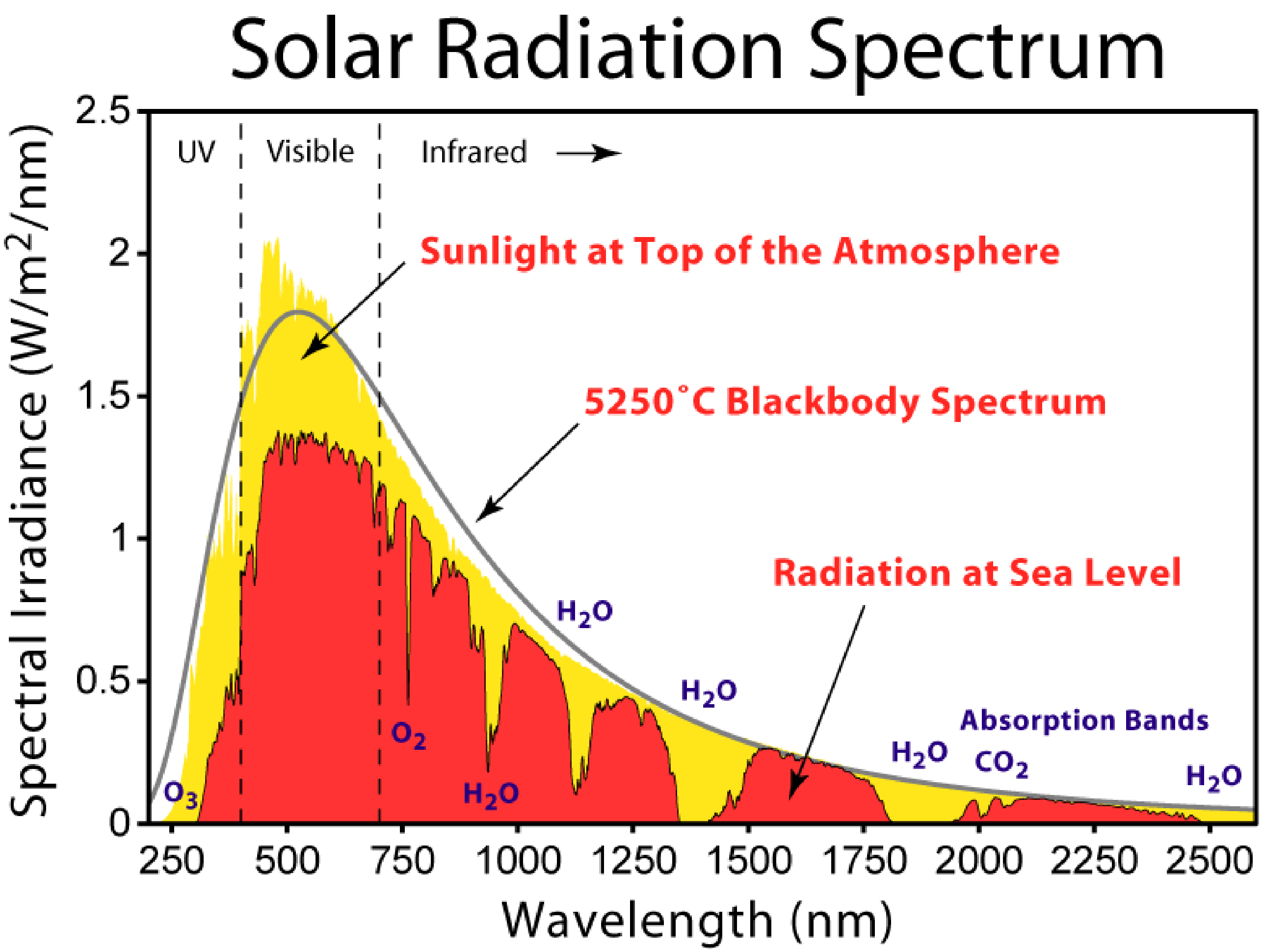
Light absorption by semiconductors



Light absorption by semiconductors



Light absorption by semiconductors



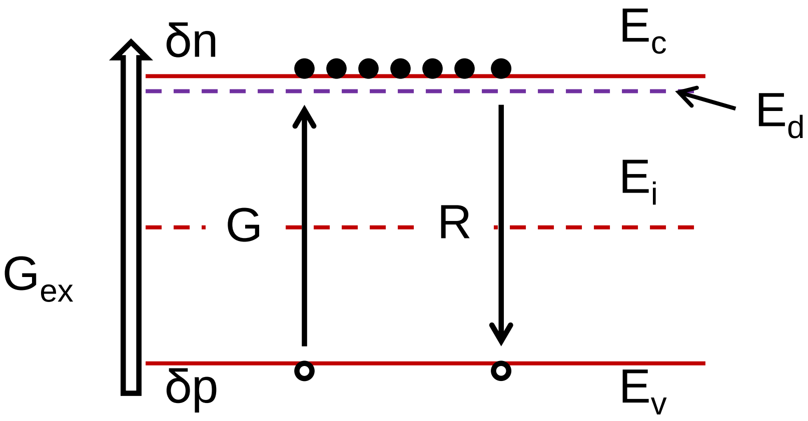
Carrier concentration at non-equilibrium

- Time dependent

Once light illumination is switched off:

t_1: $\delta p(t)$

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



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

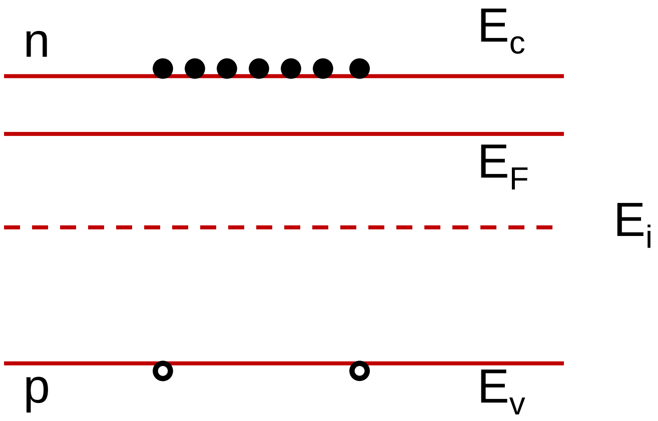
$$\left|\lim_{\Delta t\to 0}\frac{\delta p(t)-\delta p(t+\Delta t)}{t-(t+\Delta t)}\right| = recombination\ rate = \frac{\delta p(t)}{\tau}$$

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

Carrier concentration at non-equilibrium

- Quasi Fermi level

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



n type : $n >> n_i >> p$

$$\boxed{n_0 \times p_0 = {n_i}^2}$$

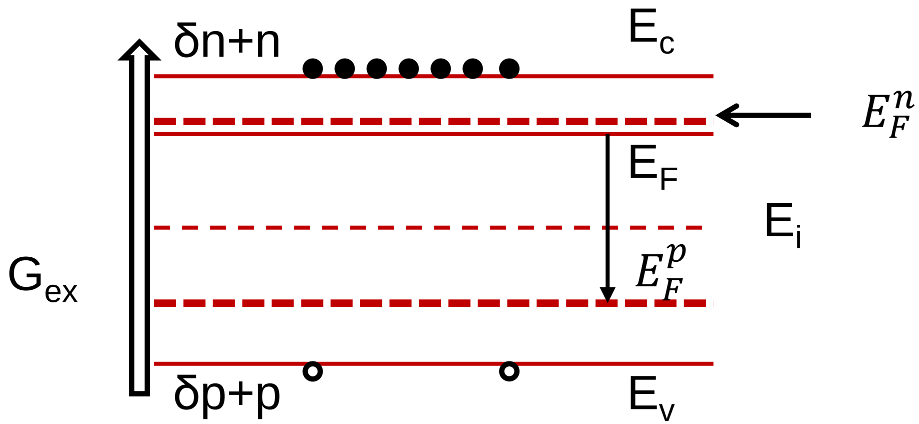
$$n_0 = N_c \exp\left(\frac{E_F - E_c}{kT}\right) \qquad p_0 = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$$

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

Carrier concentration at non-equilibrium

- Quasi Fermi level

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



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

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

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

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

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

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

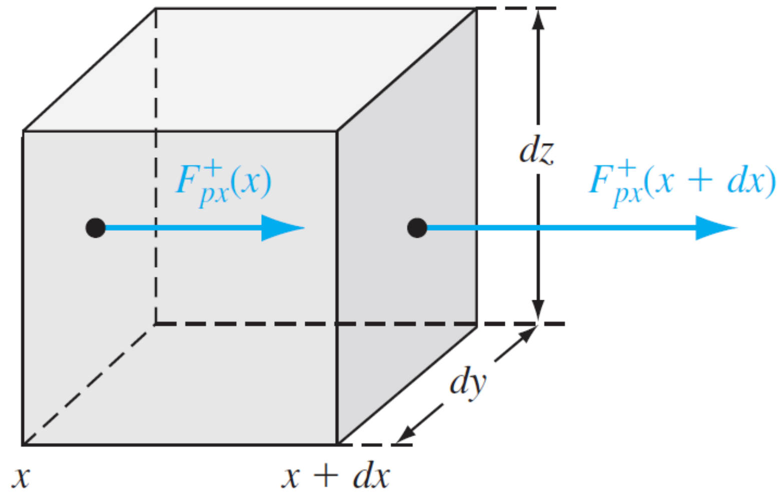
Continuity equation

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

$$J_p = e\mu_p p\mathrm{E} - eD_p \frac{\partial p}{\partial x}$$

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

Then the flux for electron and hole

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

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

Remember we have

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

Take the derivative of the flux

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

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

Time dependent diffusion equation

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

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

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

Time-dependent diffusion equations for holes and electrons

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

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

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

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

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

Carrier concentration at non-equilibrium

- Drift & diffusion current

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

$$J = J_p + J_n$$

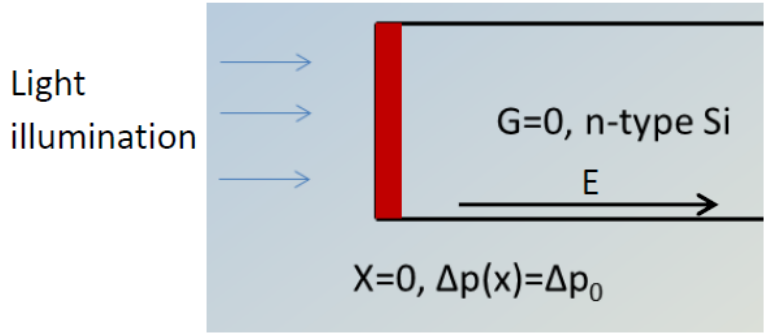
$$J_p = (J_p)_{diff} + (J_p)_{dift}$$

$$J_n = (J_n)_{diff} + (J_n)_{dift}$$

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

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

Continuity equation

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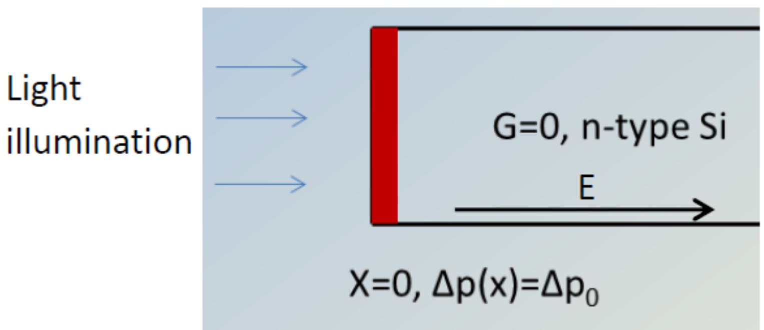


$$\boxed{\cancelto{0}{\frac{\partial p}{\partial t}} = D_p \cancelto{\delta p}{\frac{\partial^2 p}{\partial x^2}} - \mu_p E \cancelto{\delta p}{\frac{\partial p}{\partial x}} - p\mu_p \cancelto{0}{\frac{\partial E}{\partial x}} + -\frac{\delta p}{\tau} + \cancelto{0}{g'_p}}$$

Continuity equation

- Examples

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

$$\textit{The solution likely looks like this:}$$

$$\delta p = Aexp(\lambda x) + C$$

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

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

$$\mathrm{Aexp}(\lambda x)\,(D_p\lambda^2 - \mu_p E\lambda - \frac{1}{\tau}) - \frac{C}{\tau} = 0$$

True for all x

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

Continuity equation

- Examples

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

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

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

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

Continuity equation

- Examples

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

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

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

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

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

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

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

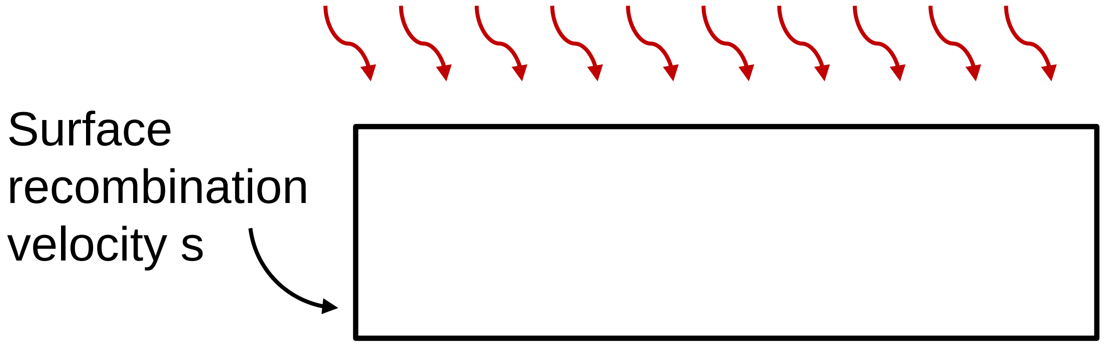
A n-type semiconductor wafer is uniformly doped and uniformly illuminated by light. There is no electric field. At equilibrium, the excess minority carrier concentration is $(\delta p)_0$. Start from zero time t=0, the illumination is cut off. Find how does the concentration of the excess minority carriers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

$$\boxed{\frac{\partial p}{\partial t} = D_p \cancelto{0}{\frac{\partial^2 p}{\partial x^2}} - \mu_p E \cancelto{0}{\frac{\partial p}{\partial x}} - p\mu_p \cancelto{0}{\frac{\partial E}{\partial x}} - \frac{\delta p}{\tau} + \cancelto{0}{g'_p}}$$

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. Small injection condition is always maintained.



Continuity equation

Examples

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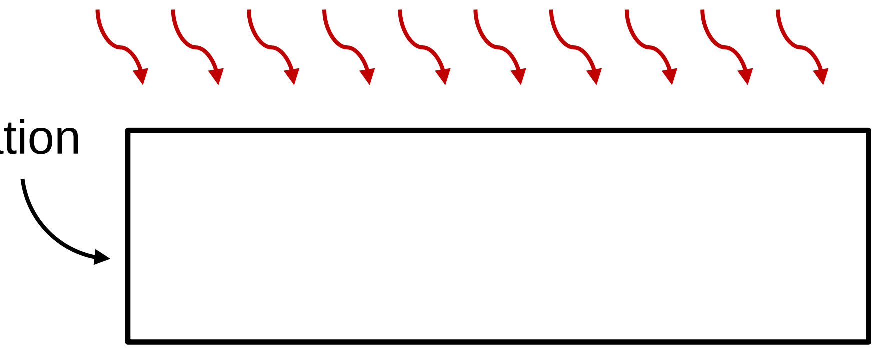
Surface recombination velocity s



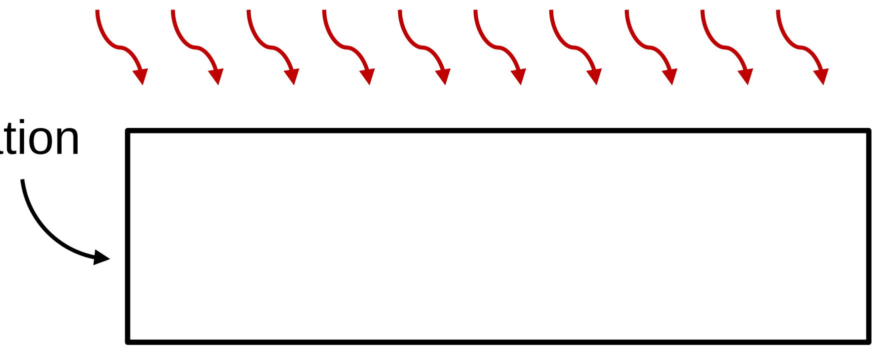
$$\boxed{\cancelto{0}{\frac{\partial p}{\partial t}} = D_p \frac{\partial^2 \cancelto{\delta p}{p}}{\partial x^2} - \cancelto{0}{\mu_p E} \frac{\partial p}{\partial x} - p\mu_p \cancelto{0}{\frac{\partial E}{\partial x}} - \frac{\delta p}{\tau} + g_p'}$$

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.

Surface recombination velocity s



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

$\textit{The solution likely looks like this}$:

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

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

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

$$\text{Aexp}(\lambda x)\,(D_p\lambda^2 - \frac{1}{\tau}) - \frac{C}{\tau} + g = 0$$

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

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Boundary conditions:

$$① \ x \to \infty, \qquad \delta p \ limited \ \ \Rightarrow \ \delta p = Aexp\left(-\frac{x}{\sqrt{D_p \tau}}\right) + g\tau$$

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

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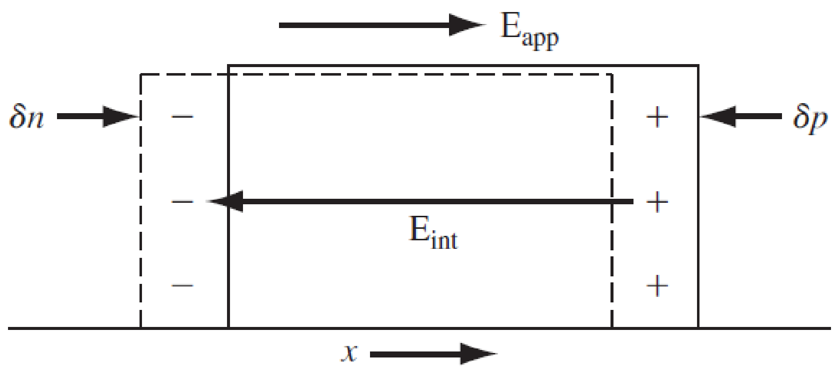
$$\Rightarrow -D_p \frac{Aexp\left(-\frac{x}{\sqrt{D_p \tau}}\right)}{\sqrt{D_p \tau}}|_{x=0} = s \cdot (A + g\tau)$$

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

Ambipolar transport

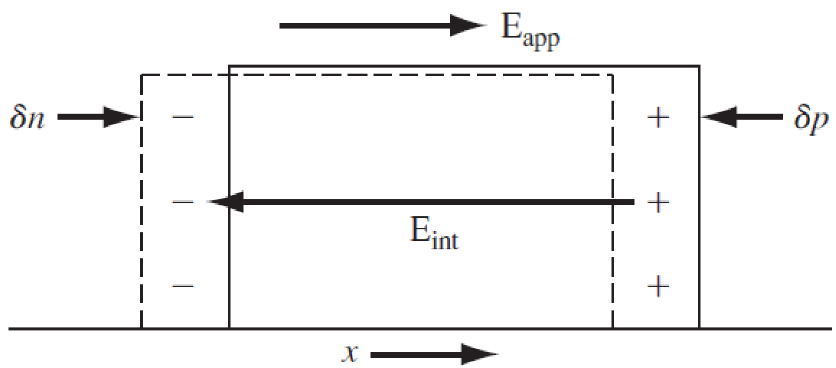


$$E = E_{app} + E_{int}$$

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)	$D_n \frac{\partial^2(\delta n)}{\partial x^2} = 0, \quad D_p \frac{\partial^2(\delta n)}{\partial x^2} = 0$
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)	$\frac{\delta n}{\tau_{n0}} = 0, \quad \frac{\delta p}{\tau_{p0}} = 0$