Semiconductor Devices

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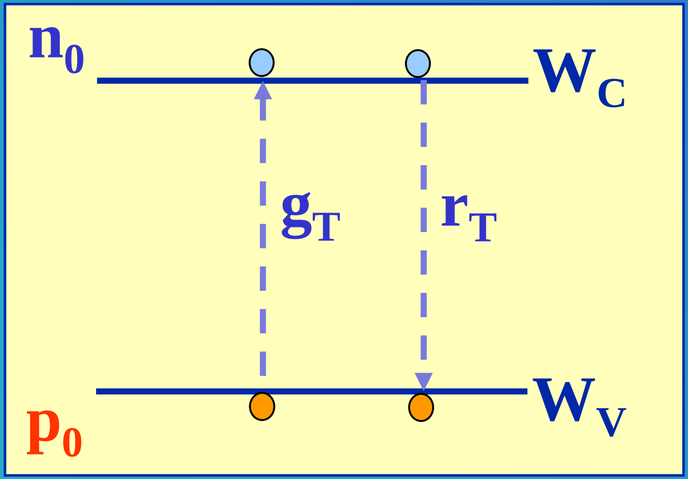
Chapter 2
Phenomena in Semiconductors

Recombination processes



Equillibrum state:

g_T – rate of electron-hole pairs thermal generation

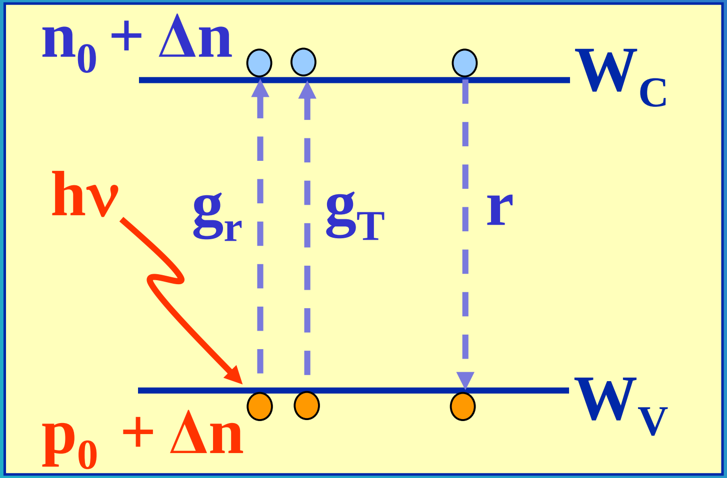
r_T – rate of electron-hole pairs thermal anihilation

$$g_T = r_T$$

Steady state

constant carrier concentrations

Recombination processes



Non-equillibrum state:

g_T – rate of electron-hole pairs thermal generation

g_r – rate of electron-hole pairs radiative generation

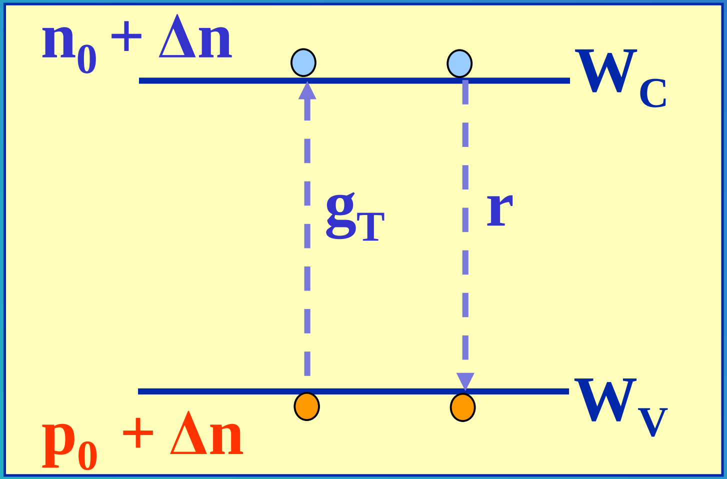
r – rate of electron-hole pairs anihilation

Steady state

constant carrier concentrations

$$g_r + g_T = r$$

Recombination processes



Non-equillibrum state:

g_T – rate of electron-hole pairs thermal generation

r – rate of electron-hole pairs anihilation

Transient state

vary carrier concentrations

$$g_T < r$$

$$R = r - g_T$$

R – recombination rate

Recombination processes

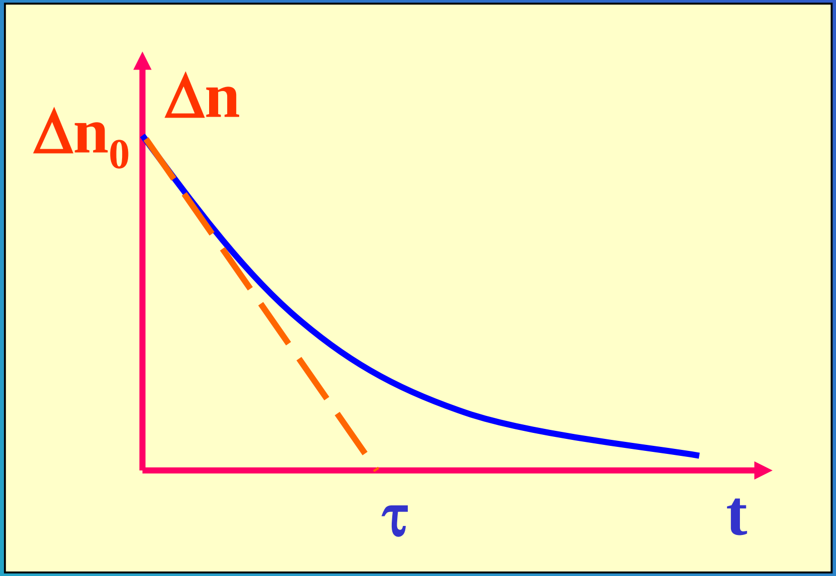
$$R = -\frac{dn}{dt} = \frac{\Delta n}{\tau}$$

$n = n_0 + \Delta n$

τ - lifetime

$\Delta n = \Delta n_0 \exp(-t/\tau)$

$\Delta n(3\tau) = 0.05\Delta n_0$



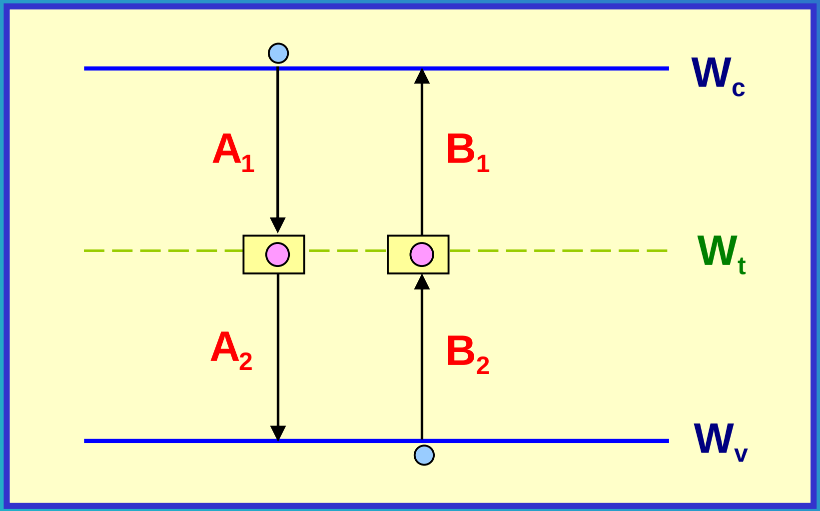
Recombination processes

- **Phonon Recombination – the whole energy Wg is taken by the thermal vibration of atoms in the lattice, called phonons (R_{ph} , τ_{ph})**
- **Auger (impact) Recombination – the whole energy Wg is taken be third carrier, electron or hole, called the hot carrier (R_A , τ_A)**
- **Radiative Recombination – the whole energy Wg is taken be a new created photon that can leave the crystal e.g. as the visible radiation (R_r , τ_r)**

$$R = R_{ph} + R_A + R_r$$

$$\frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_A} + \frac{1}{\tau_r}$$

Phonon recombination – SRH model



W_t – recombination centre level

$$R = \frac{(np - n_i^2)}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}$$

$$\tau_f = \tau_{p0}\frac{n_0 + n_1 + \Delta n}{n_0 + p_0 + \Delta n} + \tau_{n0}\frac{p_0 + p_1 + \Delta n}{n_0 + p_0 + \Delta n}$$

Model constants:

τ_{p0}, τ_{n0} - efficiency of B_2 and A_1

n_1, p_1 - position of W_t inside W_g

$$n_1 = N_c \exp\left(\frac{W_c - W_t}{kT}\right)$$

$$p_1 = N_v \exp\left(\frac{W_t - W_v}{kT}\right)$$

Phonon recombination – SRH model

$$\tau_f = \tau_{p0}\frac{n_0 + n_1 + \Delta n}{n_0 + p_0 + \Delta n} + \tau_{n0}\frac{p_0 + p_1 + \Delta n}{n_0 + p_0 + \Delta n}$$

- **_low injection level_ -** ***$\Delta n << max(n_0, p_0)$***

n-type ⇐

$$\tau_f = \tau_{p0}\frac{n_0 + n_1}{n_0 + p_0} + \tau_{n0}\frac{p_0 + p_1}{n_0 + p_0}$$

⇒ **p-type**

usually $n_1 = p_1 = n_i$

n-type: ⇓ **$n_0 >> max(p_0, n_i)$** ⇓ $\tau_f = \tau_{p0}$

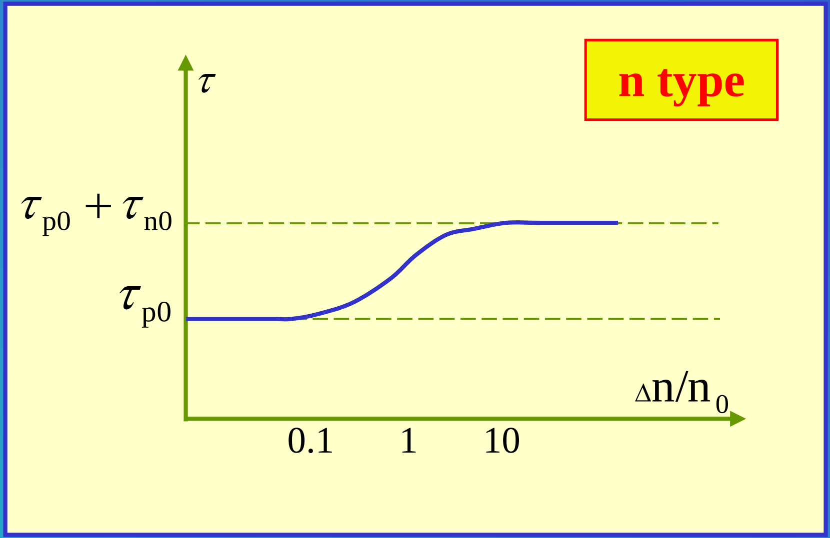
p-type: ⇓ **$p_0 >> max(n_0, n_i)$** ⇓ $\tau_f = \tau_{n0}$

Phonon recombination – SRH model

$$\tau_f = \tau_{p0}\frac{n_0 + n_1 + \Delta n}{n_0 + p_0 + \Delta n} + \tau_{n0}\frac{p_0 + p_1 + \Delta n}{n_0 + p_0 + \Delta n}$$

- ***high injection level*** - *Δn >> max (n_0, p_0, n_i)*

$$\tau_f = \tau_{p0} + \tau_{n0}$$



Auger (impact) recombination

electron-electron-hole process

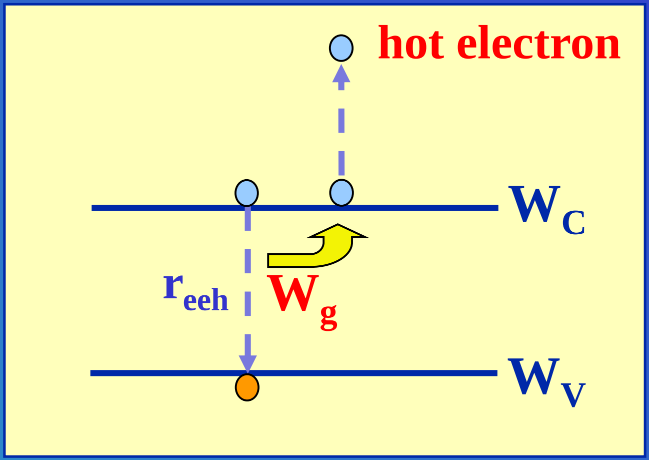
$$r_{eeh} = C_{An}n^2p$$

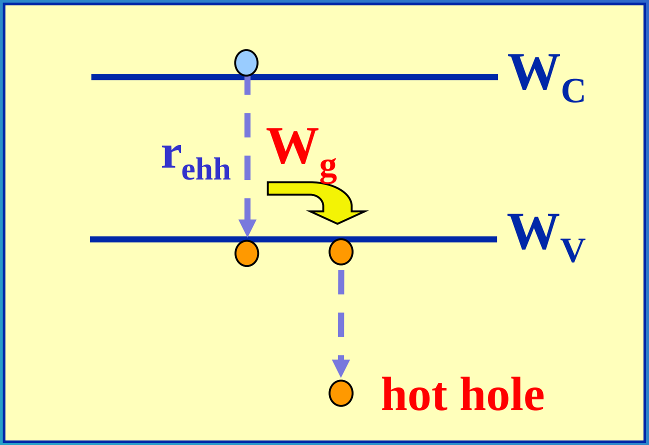
C_{An} – Auger recombination constant for e-e-h process

electron-hole-hole process

$$r_{ehh} = C_{Ap}np^2$$

C_{Ap} – Auger recombination constant for e-h-h process





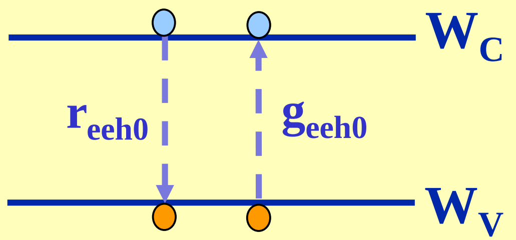
Auger (impact) recombination

electron-electron-hole process in steady state:

$$R_{An} = r_{eeh0} - g_{eeh0} = 0$$

$$g_{eeh0} = r_{eeh0} = C_{An} n_0^2 p_0$$

Steady-state impact electron-hole pair generation and annihilation in e-e-h processes

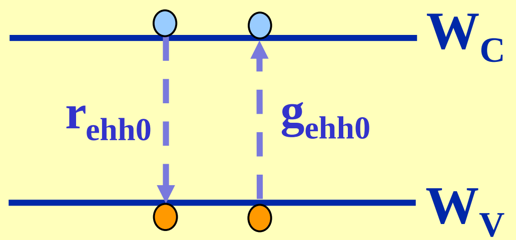


electron-hole-hole process in steady state:

$$R_{Ap} = r_{ehh0} - g_{ehh0} = 0$$

$$g_{ehh0} = r_{ehh0} = C_{Ap} n_0 p_0^2$$

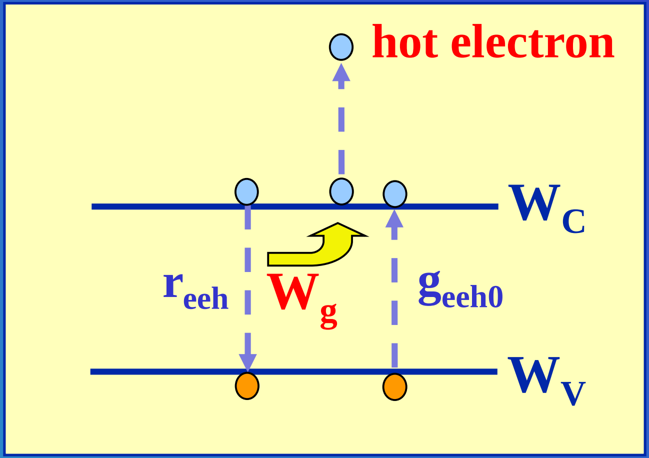
Steady-state impact electron-hole pair generation and annihilation in e-h-h processes



Auger (impact) recombination

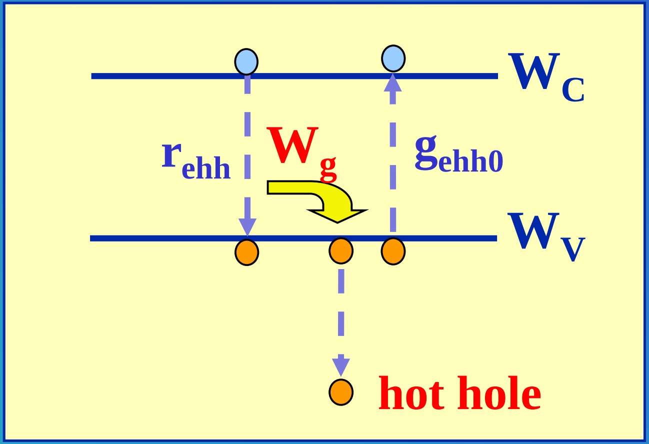
Recombination rate in the electron-electron-hole process:

$$R_{An} = r_{eeh} - g_{eeh0} = $$
$$= C_{An}n^2p - C_{An}n_0^2p_0$$



Recombination rate in the electron-hole-hole process:

$$R_{Ap} = r_{ehh} - g_{ehh0} = $$
$$= C_{Ap}np^2 - C_{Ap}n_0p_0^2$$



Auger (impact) recombination

- **General expresission:**

$$R_A = C_{An}\left[n^2 p - n_0^2 p_0\right] + C_{Ap}\left[np^2 - n_0 p_0^2\right]$$

- ***low injection level***

n type → $n_0 = N_D >> \max(p_0, \Delta n)$ →

$$\tau_A = \tau_{An} = \frac{1}{C_{An} n_0^2} = \frac{1}{C_{An} N_D^2}$$

p type → $p_0 = N_A >> \max(n_0, \Delta n)$ →

$$\tau_A = \tau_{Ap} = \frac{1}{C_{Ap} p_0^2} = \frac{1}{C_{Ap} N_A^2}$$

Auger (impact) recombination

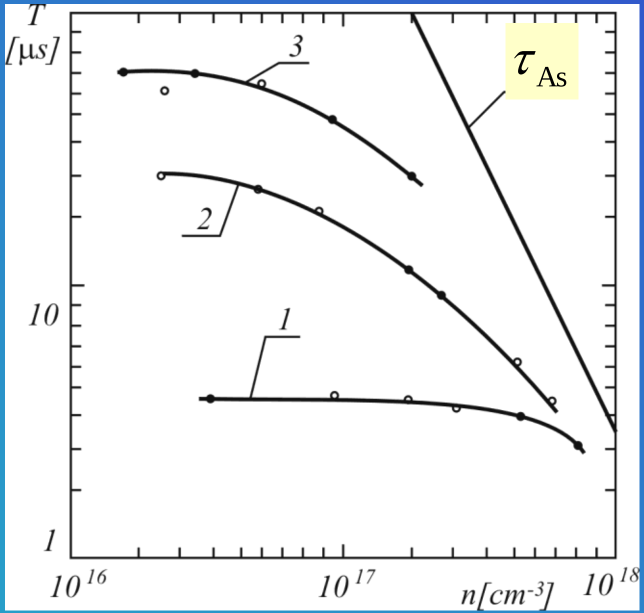
- **General expresission:**

$$R_A = C_{An}\left[n^2p - n_0^2p_0\right] + C_{Ap}\left[np^2 - n_0p_0^2\right]$$

- ***high injection level***

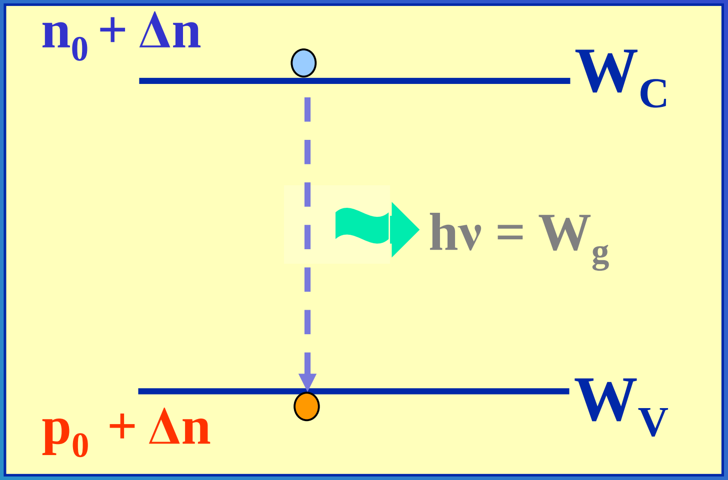
$\Delta n \gg \max(n_0, p_0)$

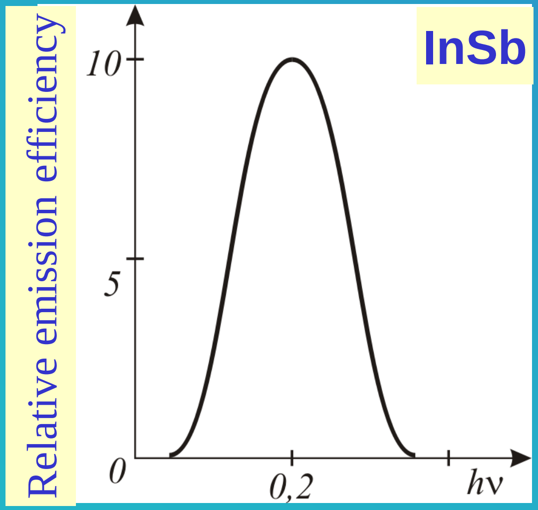
$$\tau_A = \tau_{As} = \frac{1}{(C_{An} + C_{Ap})(\Delta n)^2} = \frac{1}{C_A(\Delta n)^2} = \frac{1}{C_A n^2}$$



Radiative recombination

- **hν – photon – quant of radiative energy**
- **ν – frequency of emitted electromagnetic waves determining the colour of emitted light**



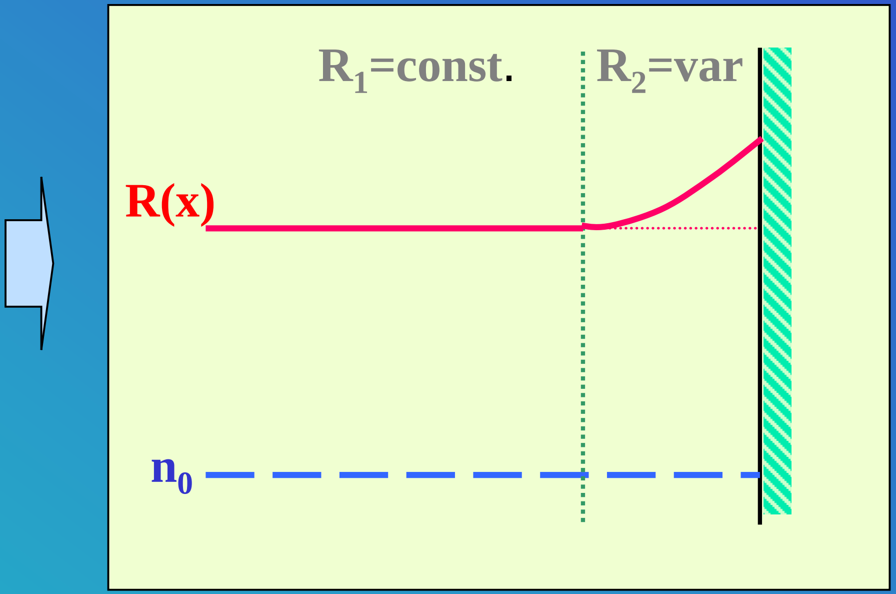


Radiative recombination gives almost monochromatic radiation with the colour depended on W_g

Surface recombination

At the surface, the number of recombination centres responsible for phonon recombination is larger than in the whole volume due to the larger number of defects and outside agents interference.

As result, in the border layer of semiconductor structure, the recombination rate, R(x) increases (R_2=var.) in comparison to its value inside the structure where usually it is constant (R_1=const.),

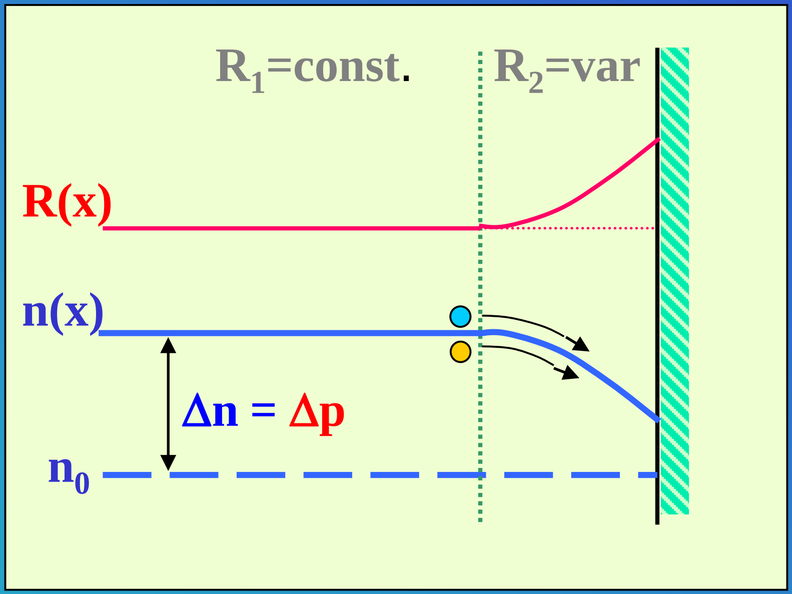


Surface recombination

When the excess carriers, Δn and Δp, occur in the semiconductor structure, their recombination is faster in the border layer than in the whole volume disrupting their homogeneous distribution.

As result, the diffusion current of electron-hole pairs from inside towards the border layer appears.

Since the electon-hole pair is electrically neutral, its move gives no electrical current, lowering the inside excess carrier concentration only.

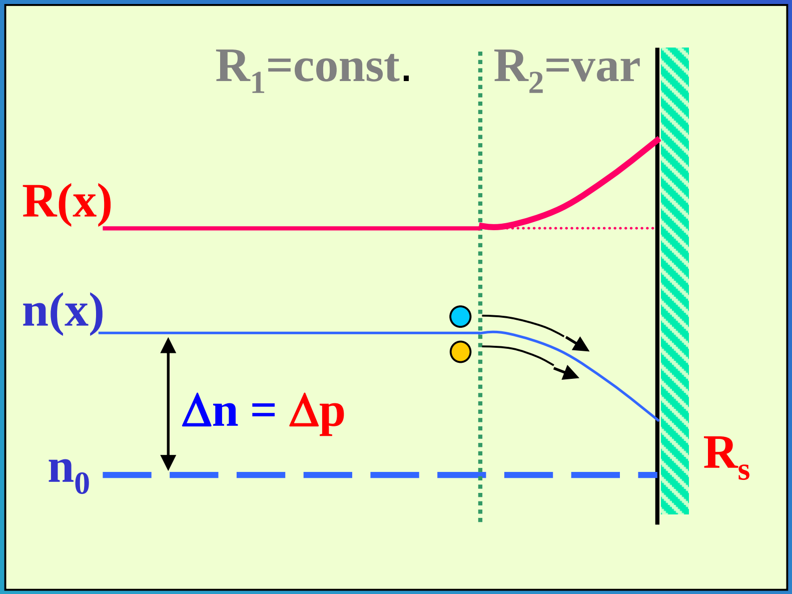


Surface recombination

The border layer essentially influence the recombination process in the whole structure accelerating it since part of electron-hole pairs move to it and recombines there.

If the recombination is to be described properly, the stream of electon-hole pairs toward border must be taken into account.

It can be done by considering R_2= var or by introduction of surface recombination model .

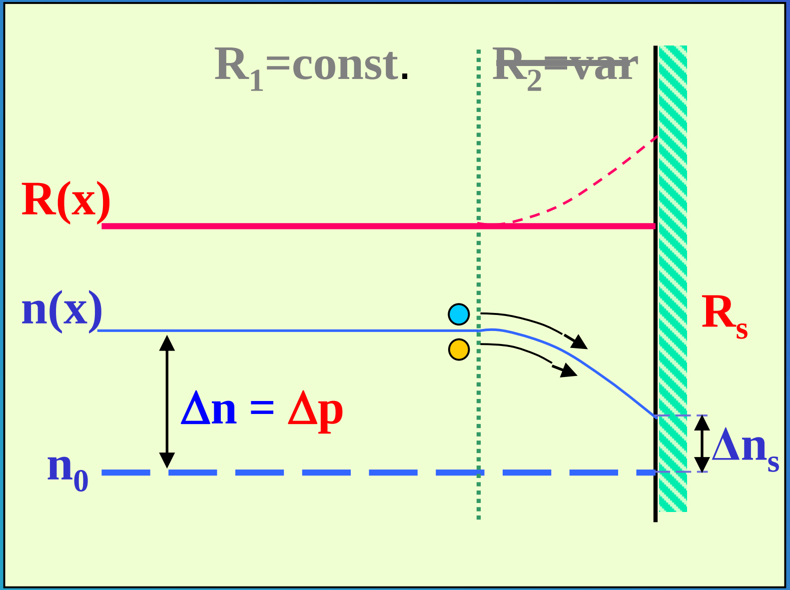


Surface recombination

The surface recombination concept consists in the assumption that in the border layer no changes in the recombination rate take place and the electron-hole pair stream towards the border is caused by annihilation of excess electron-hole pairs at the border.

The surface recombination rate, R_s, presents the density of excess electron-hole pairs stream flowing towards the surface and captured by it.

It is treated as a new parameter describing the features of semiconductor surface



Surface recombination

The surface recombination rate is defined by the expression:

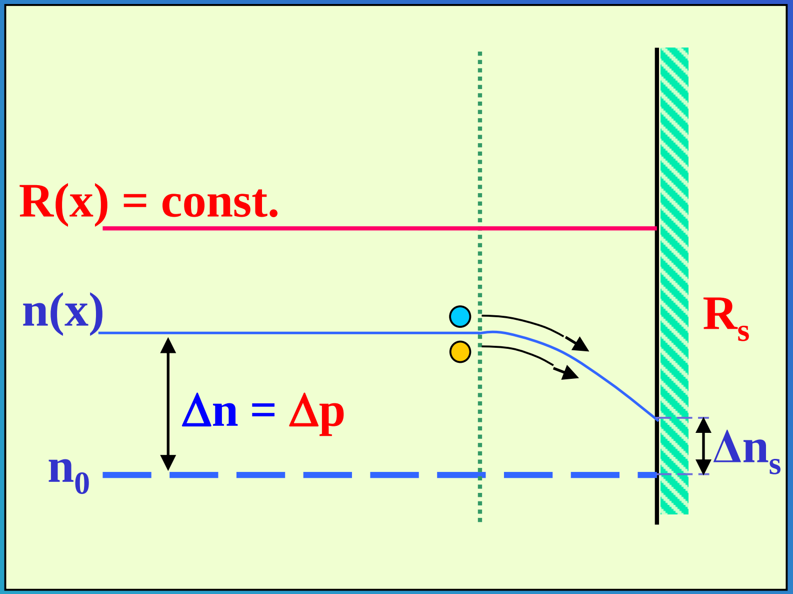
$$R_s = s\,\Delta n_s$$

Δn_s – excess carrier concentration at the surface [cm^{-3}]

s – coefficient of surface recombination [cm/s]

Coefficient s can change in wide range depending on the surface state, e.g. in Ge:

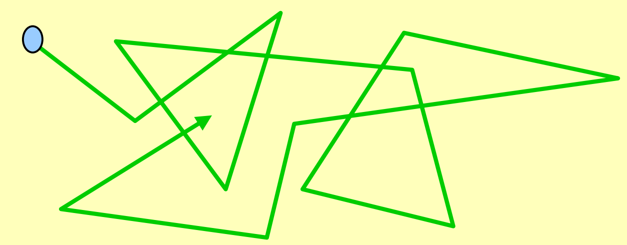
from 10^2 cm/s – for etched surface to 10^4 cm/s – for a surface after sanding



Electron and hole movement in crystal

- ***Thermal movement of electrons*:**

chaotic,
from collision to collision,
average velocity = 0



$$E = 0 \quad v_{th} = f(T)$$

There are the collisions both with other electrons and with the defects of crystal (e.g. thermal vibration of atoms in the lattice nodes)

v_{th} – instantaneous velocity increasing with the temperature (in Si at the room temperature in the order of 10^7 cm/s)

τ_r – relaxation time – the average time between two collisions (in Si at the room temperature in the order of 10^{-9} s)

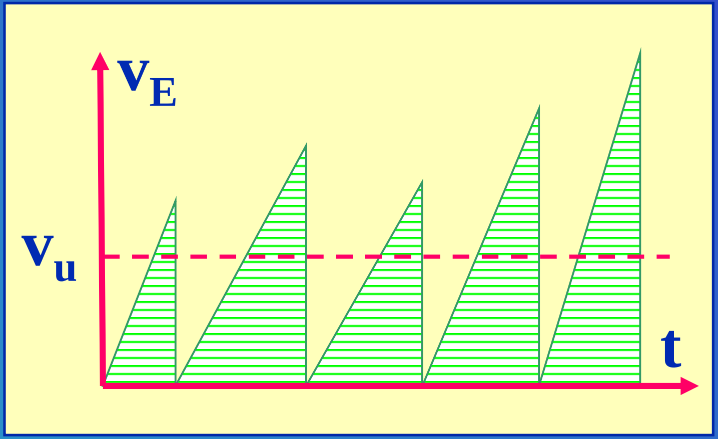
Electron and hole movement in crystal

- ***Thermal movement in presence of electric field:***

- Electric field accelerates electrons

$F = qE$ ⇨ $a = F/m$ ⇨ $v_E = at$

$$\bar{v} = \bar{v}_{th} + \bar{v}_E$$



- Electric field results in a constant drift velocity:

$$v_u = \mu E$$

where: μ - mobility

v_E – velocity compound in the direction of electric field **E**

v_u – drift velocity – the average velocity in the direction of electric field **E**

Electron and hole movement in crystal

- ***Electron drift current:***

$$v_{ue} = \mu_n E$$

$$J_{un} = qnv_{ue} = qn\mu_n E$$

μ_n – electron mobility

- ***Hole drift current:***

$$v_{uh} = \mu_p E$$

$$J_{up} = qpv_{uh} = qp\mu_p E$$

μ_p – hole mobility

Electron and hole movement in crystal

- ***Ohm law for semiconductors*:**

$$J_u = J_{un} + J_{up} =$$

$$= q(n\mu_n + p\mu_p)\,E =$$

$$= \sigma E = E/\rho$$

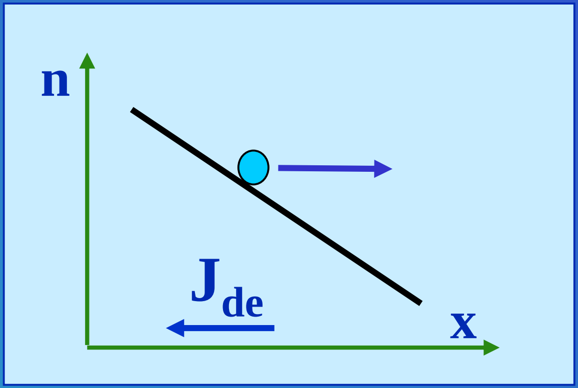
where: σ – electrical conductivity
ρ – electrical resistivity

Electron and hole movement in crystal

- ***Electron diffusion current:***

Electron stream S_n is proportional to concentration slope:

$$S_n = -D_n \frac{dn}{dx}$$



Electron stream S_n creates the electrical current:

$$J_{dn} = -qS_n = qD_n \frac{dn}{dx}$$

3D

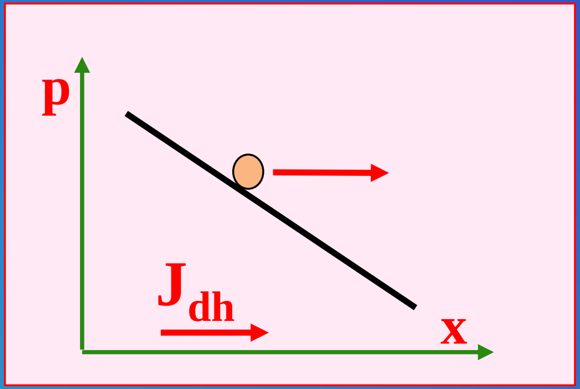
$$J_{dn} = qD_n \operatorname{grad} n$$

Electron and hole movement in crystal

- ***Hole diffusion current:***

Hole stream S_p is proportional to concentration slope:

$$S_p = -D_p \frac{dp}{dx}$$



Hole stream S_p creates the electrical current:

$$J_{dp} = qS_p = -qD_p \frac{dp}{dx}$$

3D ⇒

$$J_{dp} = -qD_p \text{grad } p$$

Electron and hole movement in crystal

- ***Transport equations:***

$$J_{dn} = q\left(n\mu_n E + qD_n \frac{dn}{dx} \right)$$

$$J_{dp} = q\left(p\mu_p E - qD_p \frac{dp}{dx} \right)$$

3D

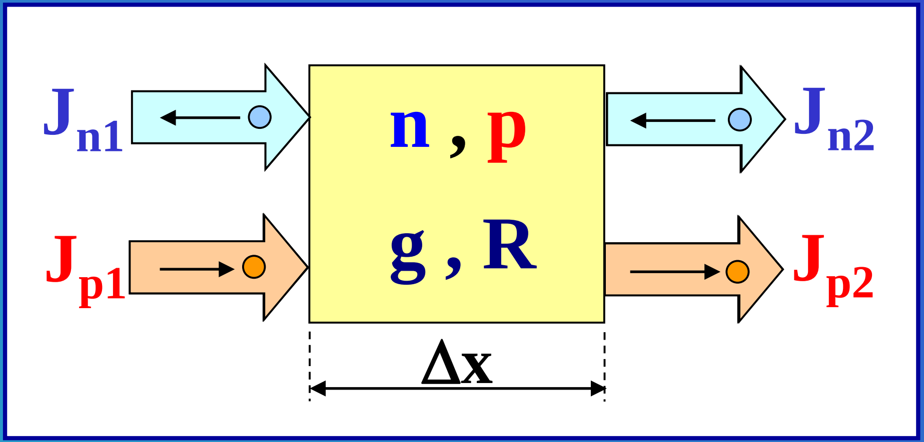
$$J_n = q(n\mu_n E + D_n \text{grad } n)$$

$$J_p = q(p\mu_p E - D_p \text{grad } p)$$

Electron and hole movement in crystal

- ***Continuity equations*:**

Let consider changes of carrier densities, n and p, during Δt inside the area Δx in the presence of recombination R, generation g and the carriers flow.



Carrier density balance for Δt time interval :

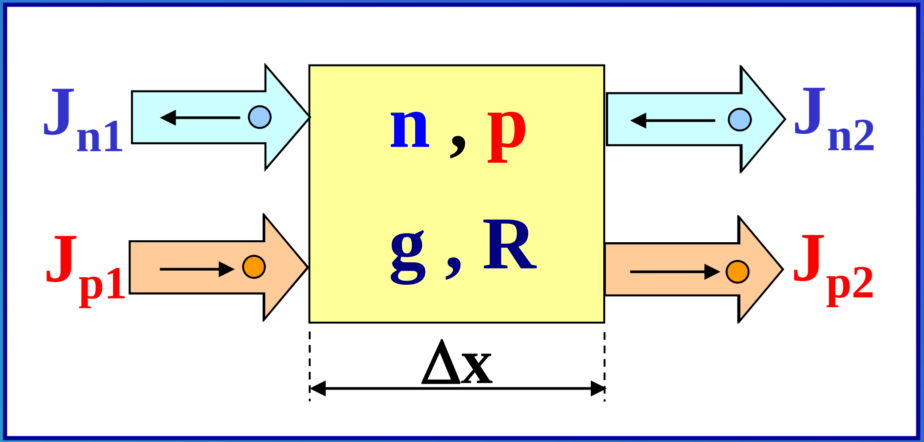
$$\Delta n = (g - R)\Delta t + \frac{(J_{n2} - J_{n1})\Delta t}{q\,\Delta x}$$

$$\Delta p = (g - R)\Delta t + \frac{(J_{p1} - J_{p2})\Delta t}{q\,\Delta x}$$

Electron and hole movement in crystal

- ***Continuity equations*:**

Let consider changes of carrier densities, n and p, during Δt inside the area Δx in the presence of recombination R, generation g and the carriers flow.



After both side division by Δt:

$$\frac{\Delta n}{\Delta t} = (g - R) + \frac{1}{q}\frac{(J_{n2} - J_{n1})}{\Delta x}$$

$$\frac{\Delta p}{\Delta t} = (g - R) - \frac{1}{q}\frac{(J_{p2} - J_{p1})}{\Delta x}$$

Electron and hole movement in crystal

- ***Continuity equations:***

$$\frac{\partial n}{\partial t} = g - R + \frac{1}{q}\,\mathrm{div}\, J_n$$

$$\frac{\partial p}{\partial t} = g - R - \frac{1}{q}\,\mathrm{div}\, J_p$$

3D

After the demand Δx → ∞ and Δt → ∞:

$$\frac{dn}{dt} = (g - R) + \frac{1}{q}\frac{dJ}{dx}$$

$$\frac{dp}{dt} = (g - R) - \frac{1}{q}\frac{dJ_p}{dx}$$

Basic set of semiconductor structure equations

- ***Transport equations:***

$$J_n = q(n\mu_n E + D_n \text{grad } n) \qquad J_p = q(p\mu_p E - D_p \text{grad } p)$$

- ***Continuity equations:***

$$\frac{\delta n}{\delta t} = g - R + \frac{1}{q}\,\text{div } J_n \qquad \frac{\delta p}{\delta t} = g - R - \frac{1}{q}\,\text{div } J_p$$

- ***Poisson equation:***

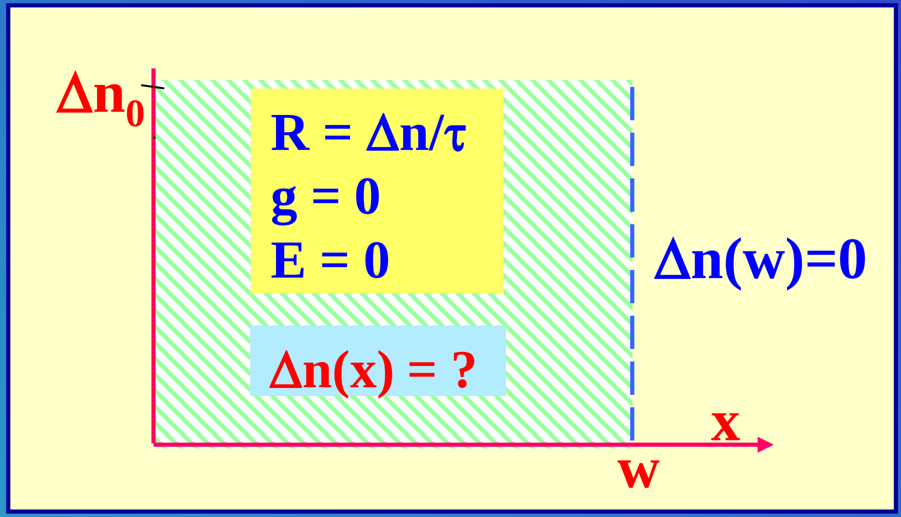
$$\text{div } E = \frac{4\pi}{\varepsilon} q(p - n + N_d - N_a)$$

- ***Kirchhoff equation:***

$$J = J_n + J_p$$

Carrier injection

Let consider the excess carrier transfer, Δn, through the layer of width w under the conditions shown in the figure.



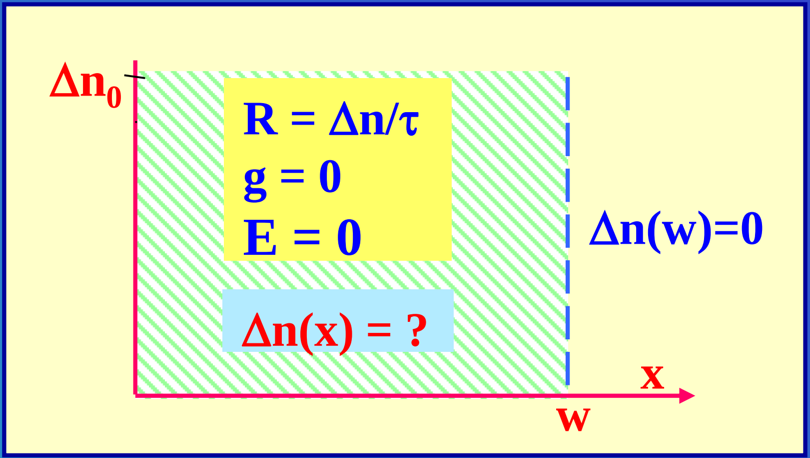
For these conditions the basic set of semiconductor structure equations can be reduced to the equation:

$$L^2 \frac{d^2(\Delta n)}{dx^2} = \Delta n$$

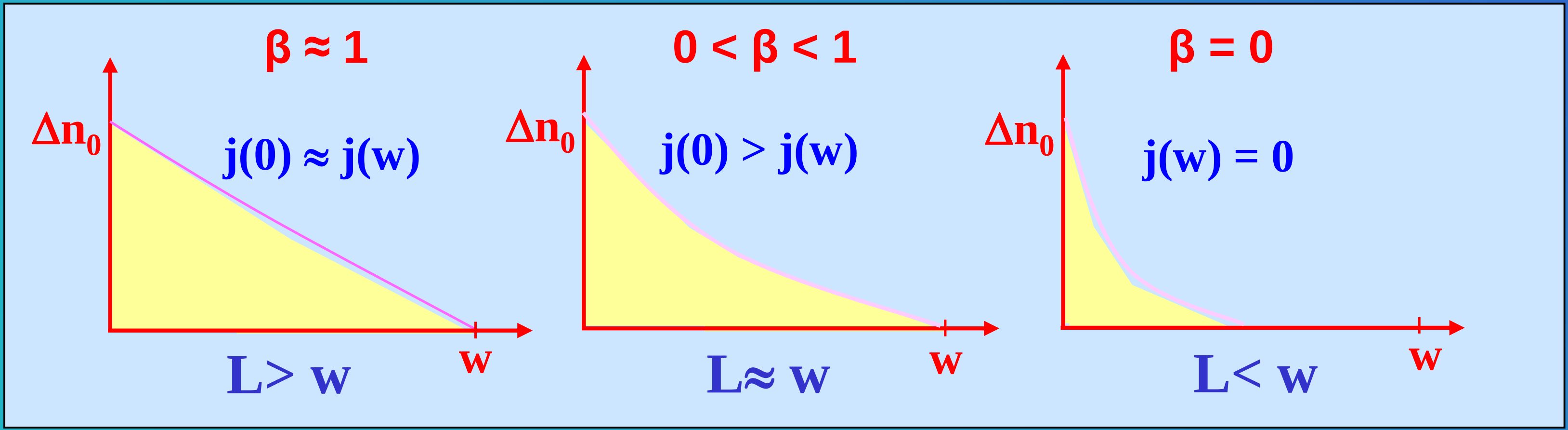
where: $L = (D\tau)^{0.5}$ - diffusion length

Carrier injection

For the problem, one can find an analytical solution that gives excess carrier distributions shown below.



$\beta = j(w)/j(0)$ – transport coefficient

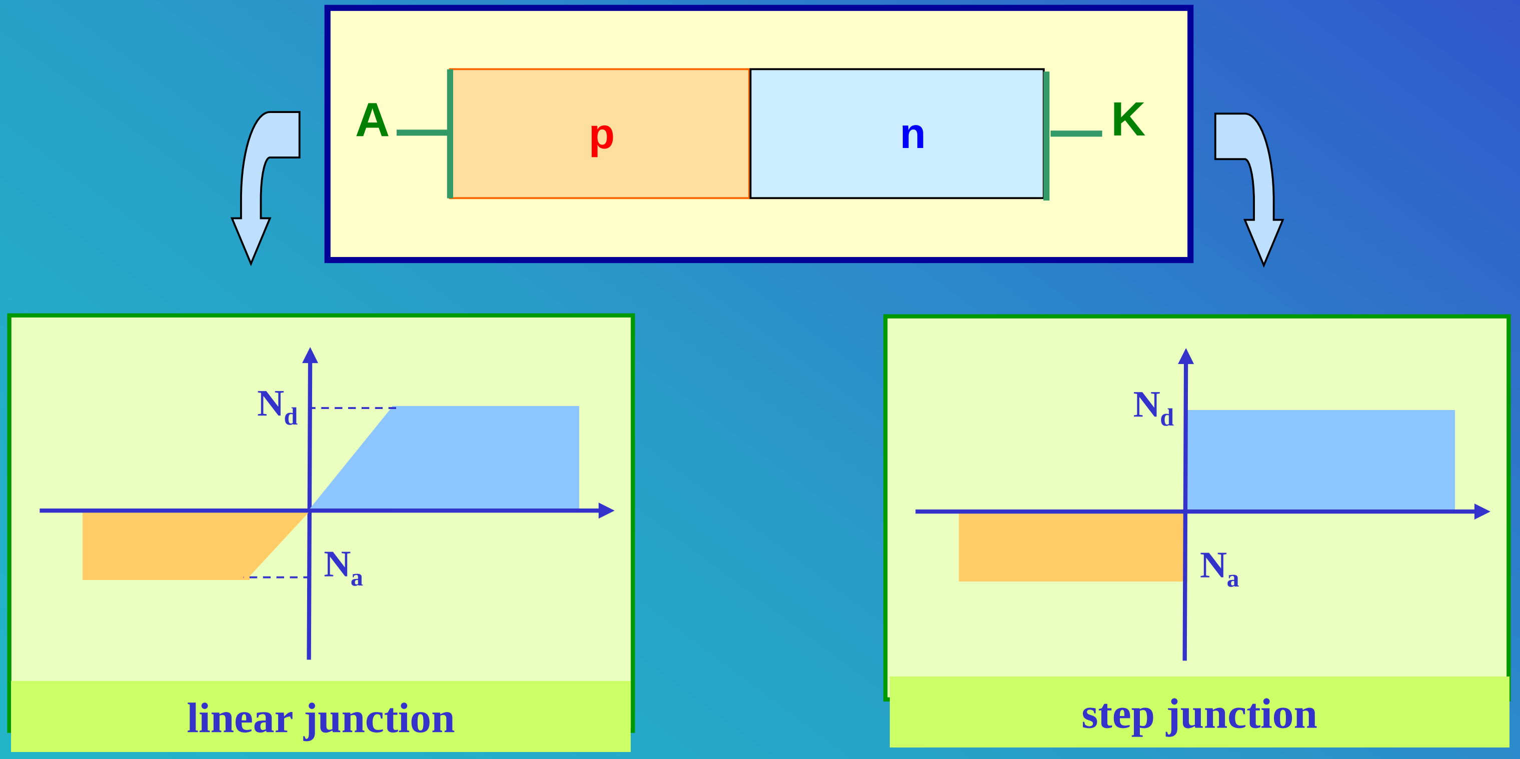


Carrier injection

- The situation, when the excess carriers flow into the layer due to the border concentration of the excess carriers, is called **injection of excess carriers**. Such a situation we have in the considered layer.
- The excess carriers injected into a layer diffuse across the layer and their density decreases due to the recombination processes.
- The layer can be transparent or opaque for the diffusion current of the injected excess carriers depending on the layer thickness.
- In each place of the layer, the charge neutrality occurs what means that at each point $\Delta n = \Delta p$.
- The integral over the excess carrier distribution defines some stored charge that quantity corresponds to the actual value of the border density Δn_0. The slope of the distribution determines the diffusion current and any change of the distribution requires an adequate change of the stored charge. This phenomenon is called **diffusion capacity.**

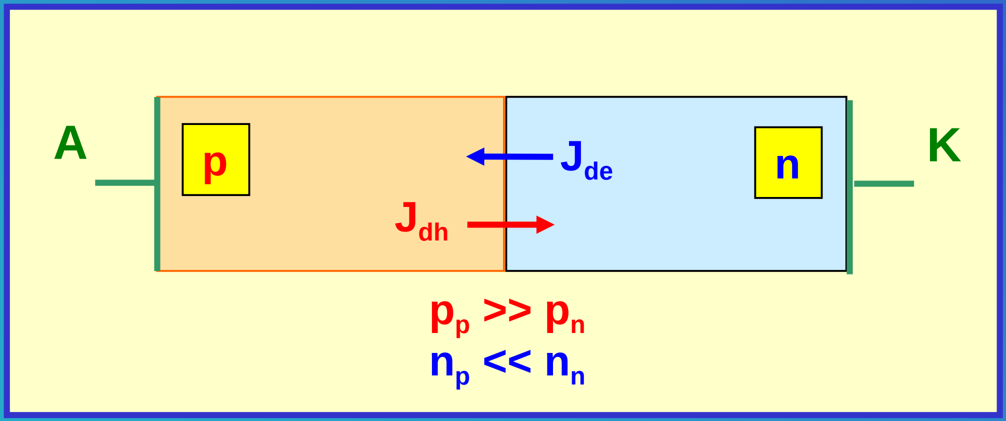
P-n junction

The p-n junction comes into being when the type of semiconductor changes from n-type into p-type inside the same crystal lattice:



P-n junction

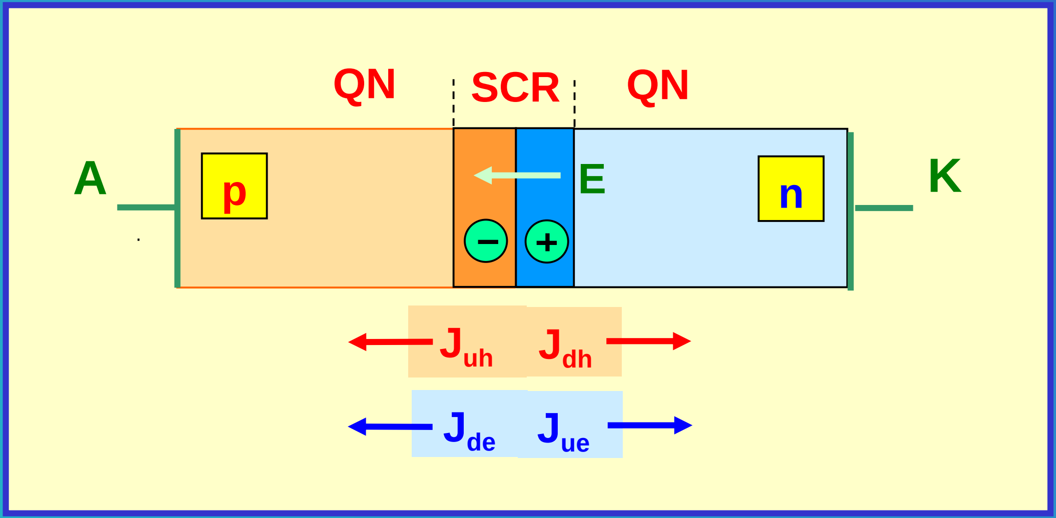
Sharp change in the carrier density at the border leads to the diffusion currents, J_{de} and J_{dh}, through the junction plane



A – anode **K - cathode**

P-n junction

The carriers leave the dopand ions that, as uncompensated, create the space-charge region, SCR, over the junction plane. As result, in the SCR, the electric field, E, that develops the drift currents compensating the diffusion ones occurs :



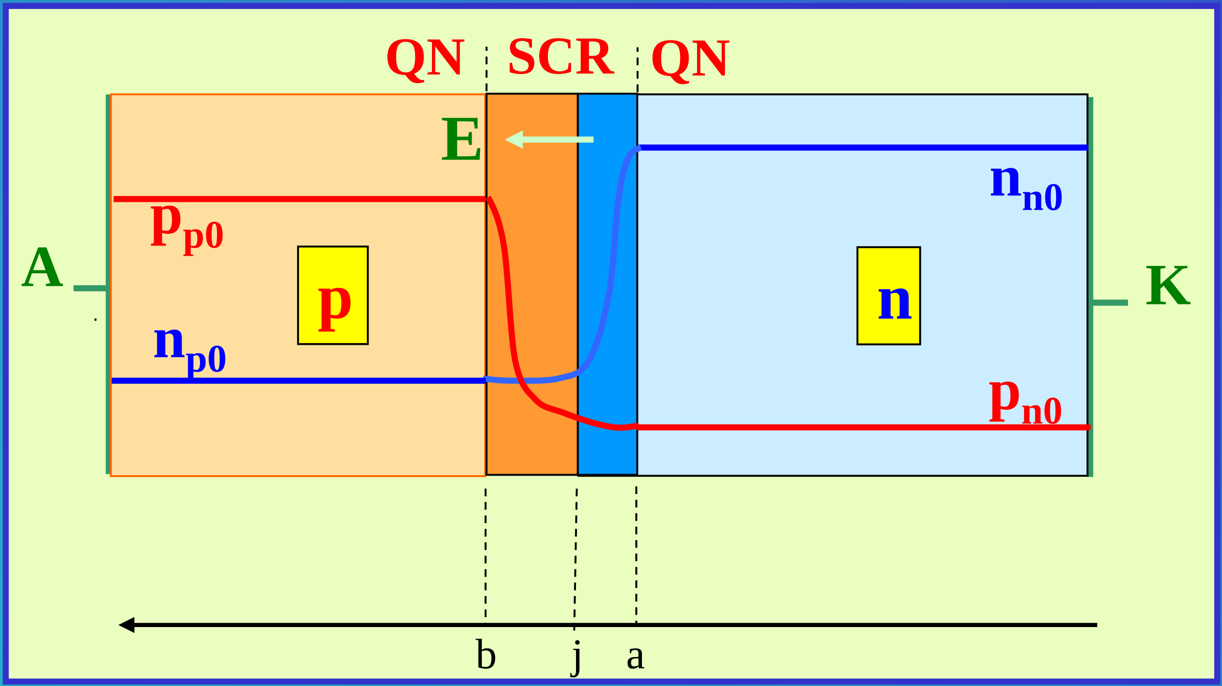
P-n junction – equilibrium state

At the QN/SCR borders :

- carrier concentration is flat – no diffusion current
- no electric field – no drift current

$U_{AK} = 0$

$I_D = 0$



P-n junction – equilibrium state

In SCR area :

- on the n-side $N_d >> n_n \Rightarrow Q_n = q(N_d + p_n - n_n) \approx qN_d$
- on the p-side $N_a >> p_p \Rightarrow Q_p = q(- N_a - n_p + p_p) \approx - qN_a$

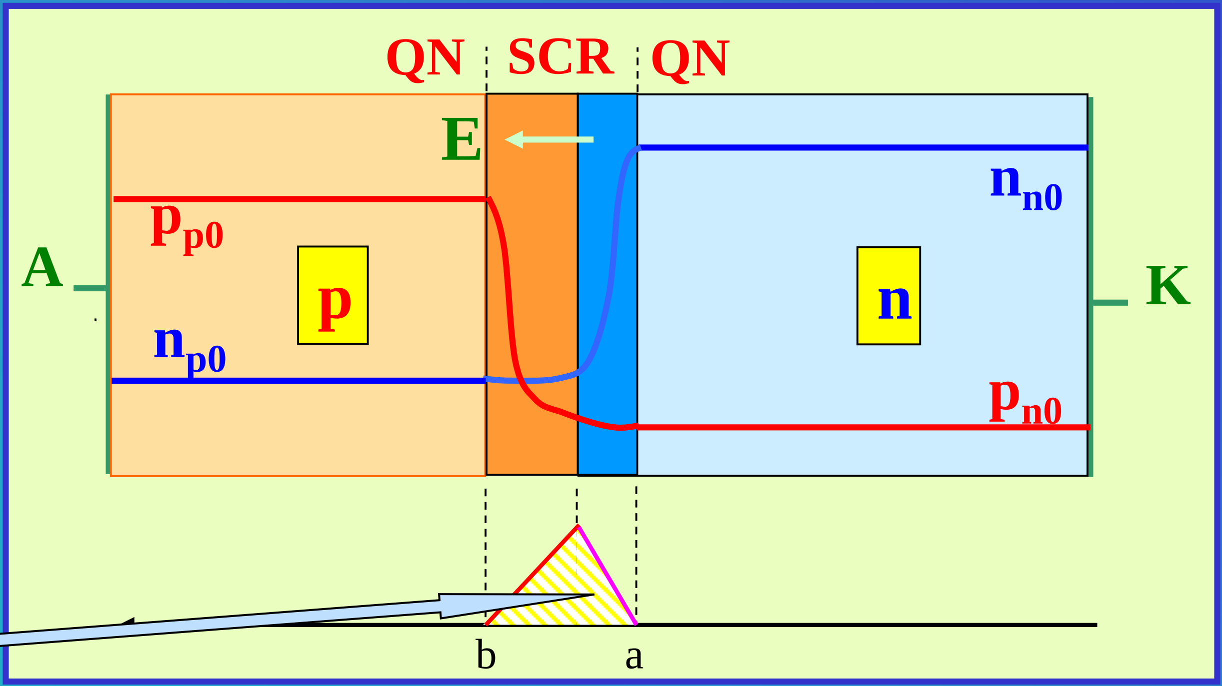
on n-side:

$$\frac{dE}{dx} = \frac{4\pi}{\varepsilon} Q_n$$

for x>a

$$E = \frac{4\pi q}{\varepsilon} N_d x + C$$

E increases linearly



P-n junction – equilibrium state

In SCR area :

- on the n-side $N_d >> n_n \Rightarrow Q_n = q(N_d + p_n - n_n) \approx qN_d$
- on the p-side $N_a >> p_p \Rightarrow Q_p = q(- N_a - n_p + p_p) \approx - qN_a$

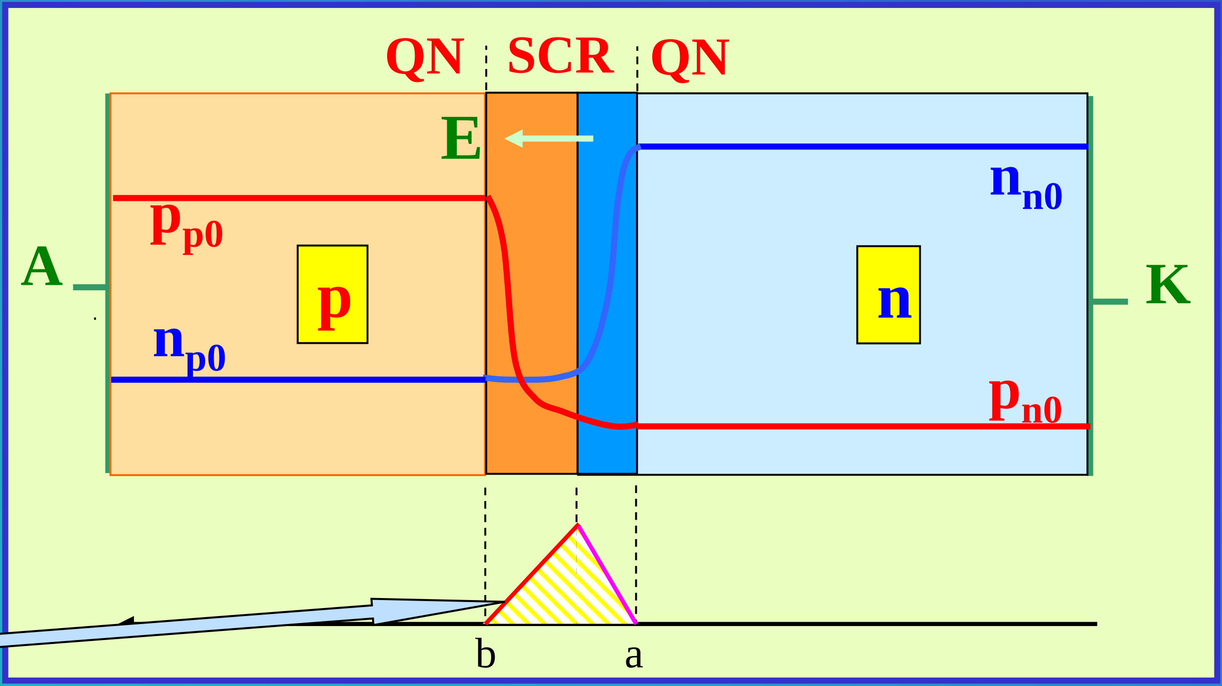
on p-side:

$$\frac{dE}{dx} = \frac{4\pi}{\varepsilon} Q_p$$

for x<b

$$E = C - \frac{4\pi q}{\varepsilon} N_a x$$

E decreases linearly



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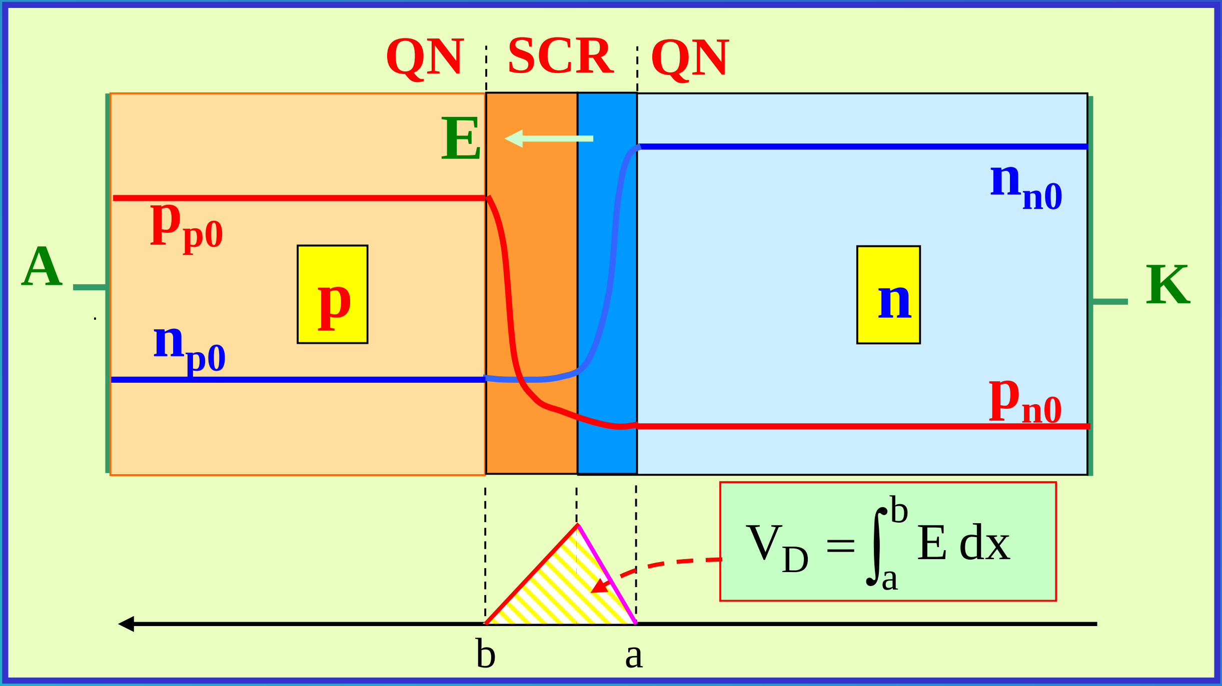
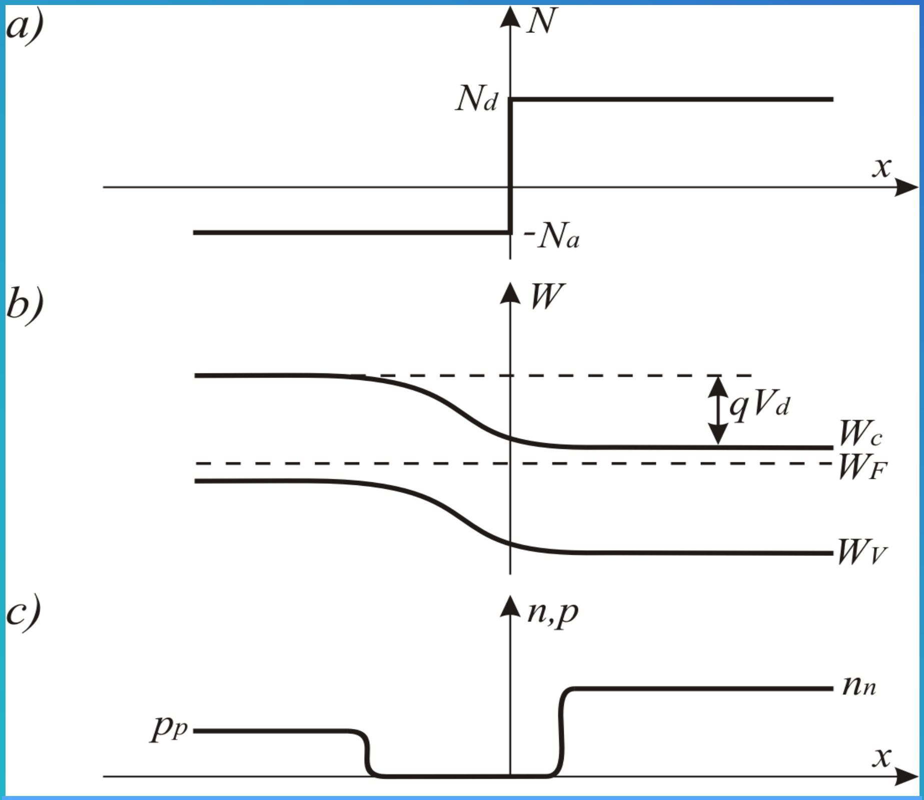
Voltage between two points:

$$V_{AB} = \int_B^A E\,dx$$

V_D - diffusion potential



P-n junction – equilibrium state



Doping profile

Band model

Majority carrier distribution

P-n junction – reverse bias

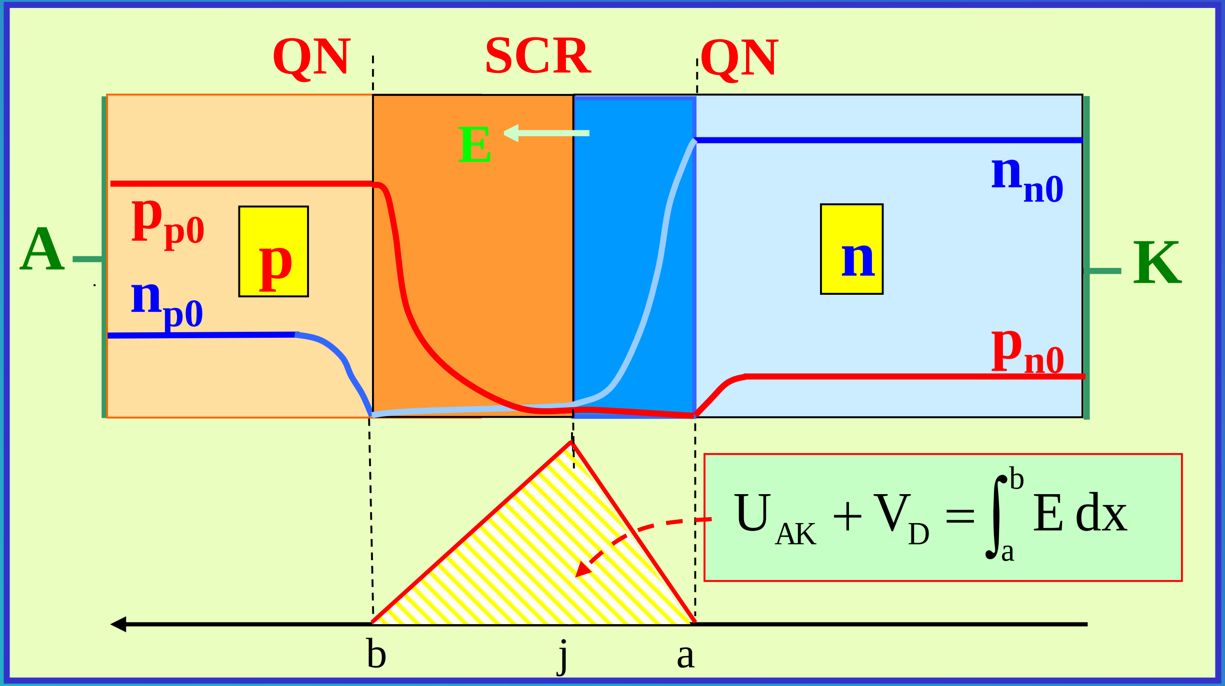
At the QN/SCR borders :

- minority cariers concentrations at the border decrease with the applied voltage running to 0

$U_{AK} \rightarrow -\infty$

$n_p(b) \rightarrow 0$

$p_n(a) \rightarrow 0$



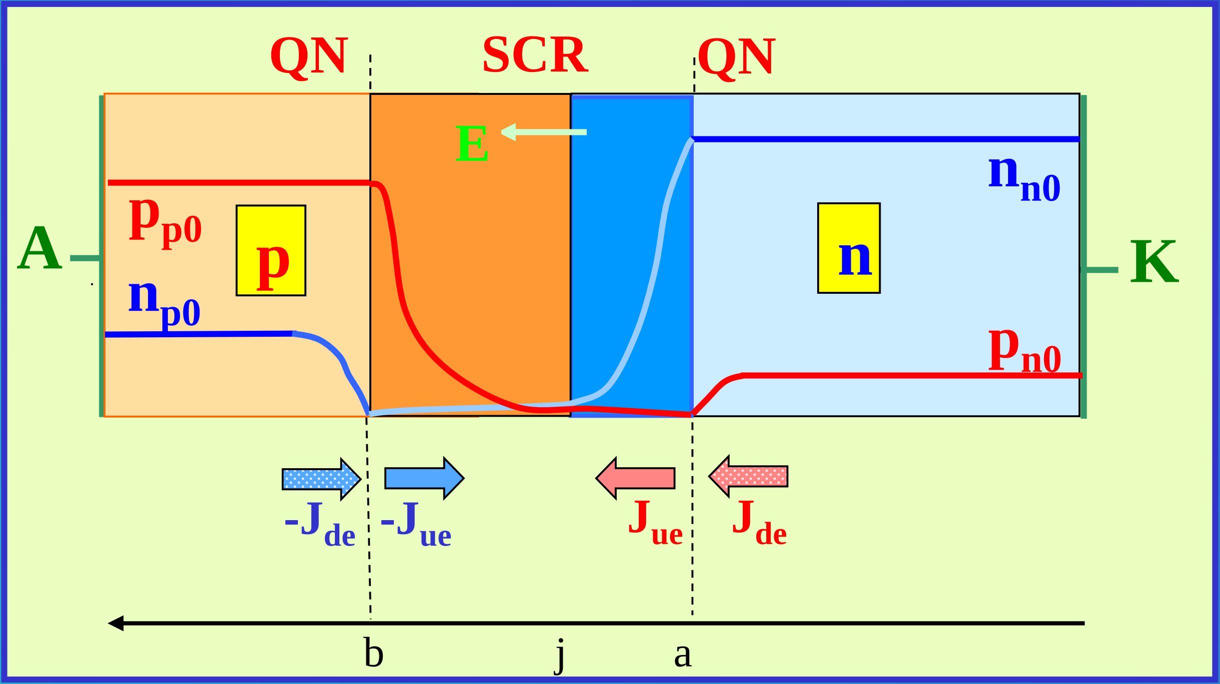
P-n junction – reverse bias

In the SCR area :

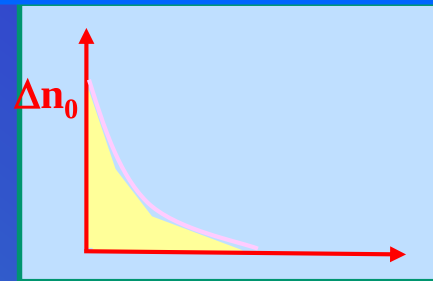
- diffusion current << drift current
- magnitude of drift currents, J_{ue} and J_{uh}, limited by the number of carriers

$J_{ue}(b) = J_{de}(b) =$
$= qD_n\, dn_p(b)/dx$

$J_{uh}(a) = J_{dh}(a) =$
$= -\, qD_n\, dn_p(b)/dx$



P-n junction – forward bias



At the QN/SCR borders :

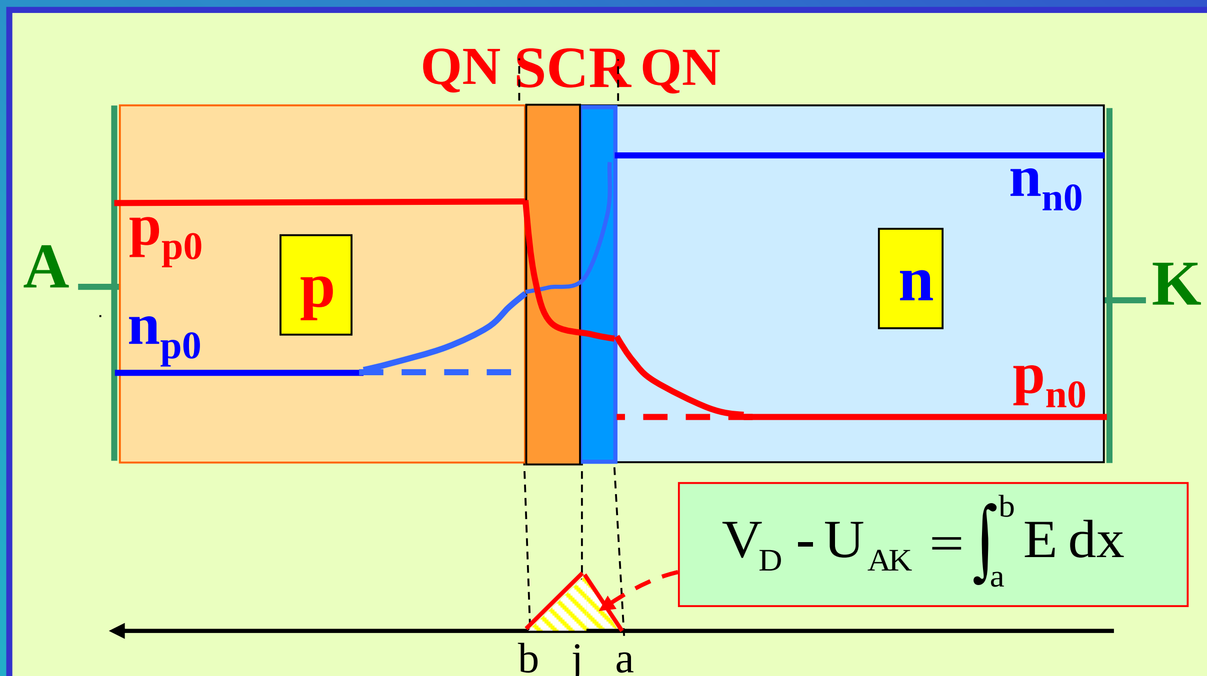
- minority carriers concentrations at the border increase with the applied voltage leading to the minority carrier injection

$U_{AK} > 0V$

⇩

$n_p(b) > n_{p0}$

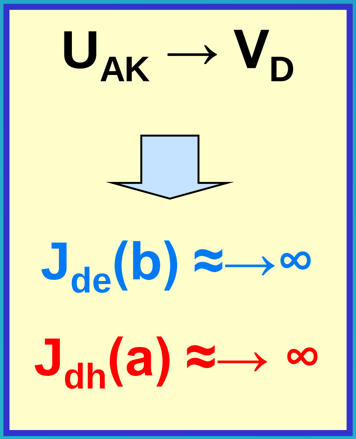
$p_n(a) > p_{n0}$

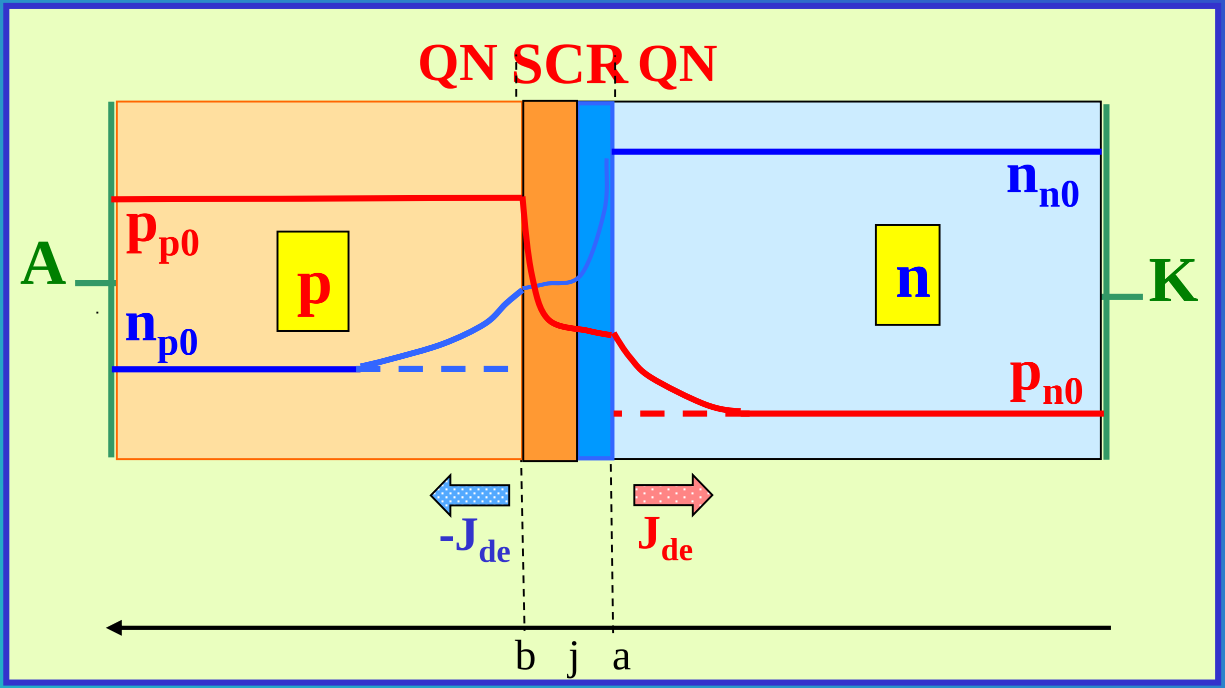


P-n junction – forward bias

In *the QN layers :*

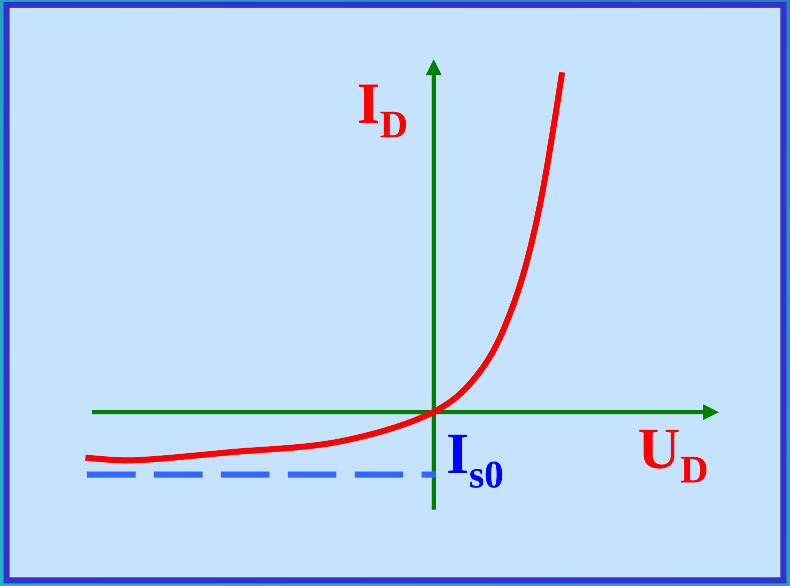
- injected minority carriers create diffusion currents in the area close to the SCR, which disappear as result of recombination





P-n junction – ideal diode equation

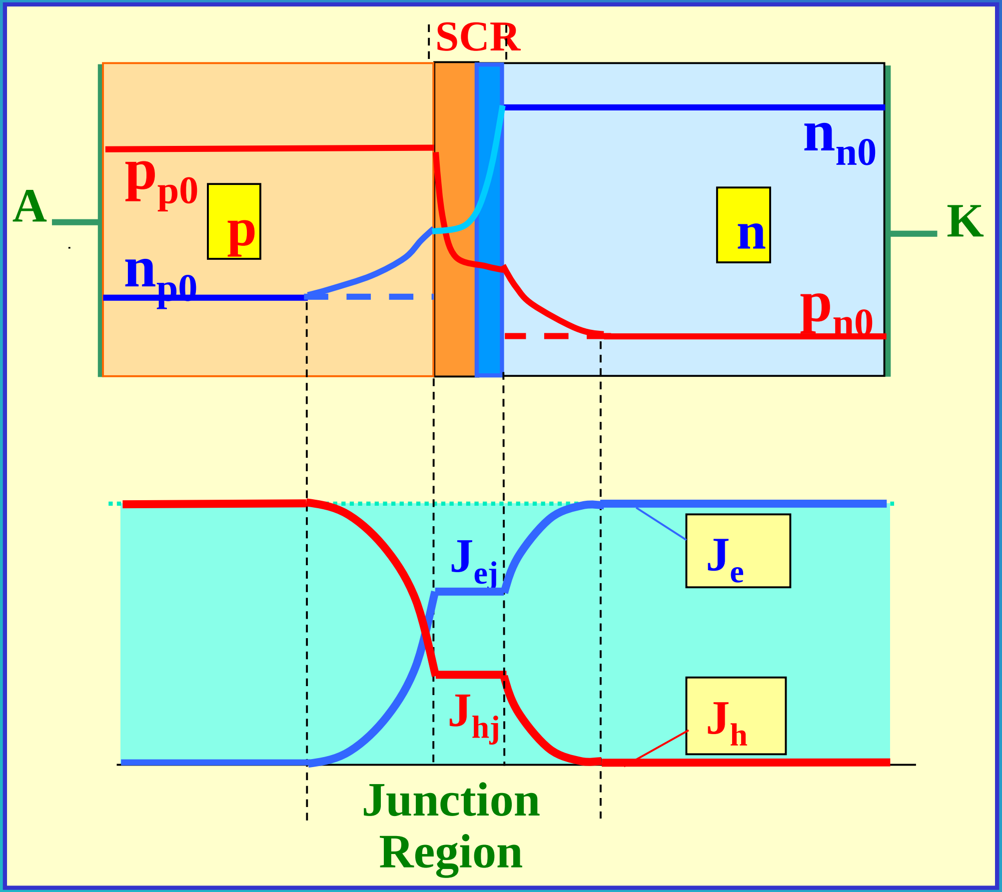
Ideal diode I-V characteristics :



$$I_D = I_{s0}\left(\exp\frac{qU}{kT} - 1\right)$$

I_{s0} – saturation current

P-n junction – injection coefficient



Injection coefficient for electrons:

$$\gamma_{e\rightarrow p} = \frac{J_{ej}}{J}$$

Injection coefficient for holes:

$$\gamma_{h\rightarrow n} = \frac{J_{hj}}{J}$$