Semiconductor Devices

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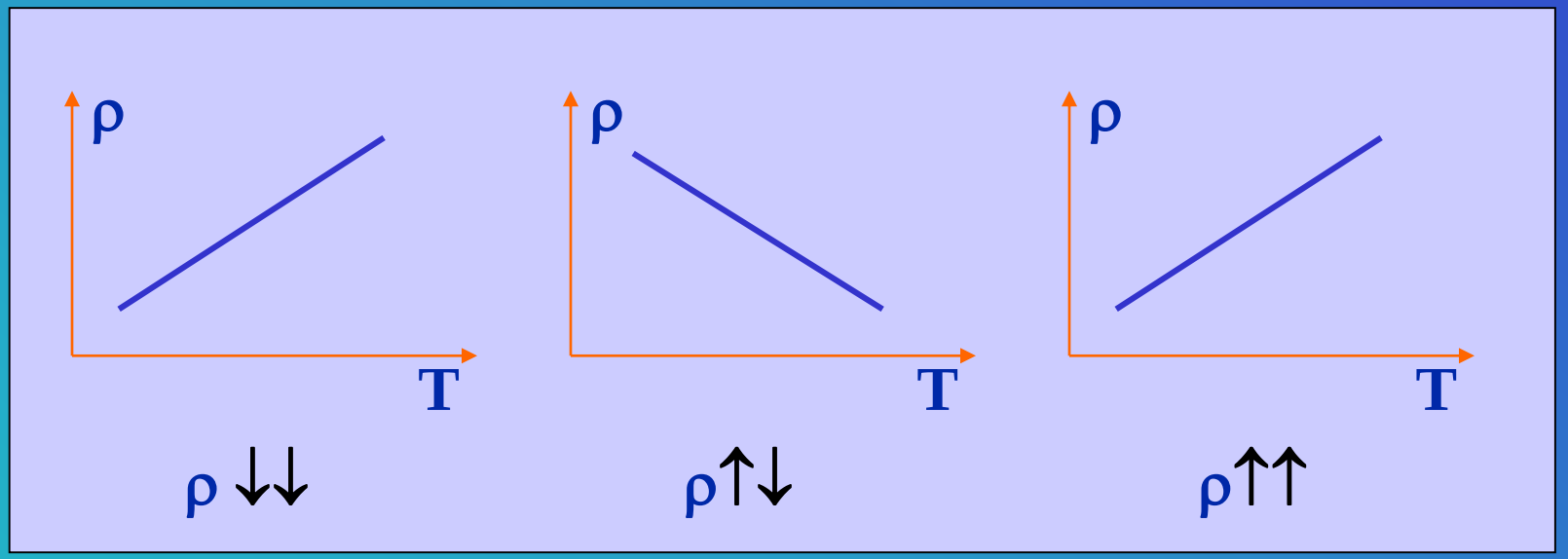
lectures 30 hours

lab. exercises 30 hours

Metal **Semiconductor** **Isolator**



very low medium very large

What are semiconductors ?

1. They are crystals
2. They can be:
   - atom crystals like: Si, Ge, C-diamond
   - compound crystals like: GaAs, InSb, SiC, GaN
3. When they are pure, their resistivity is in a middle range

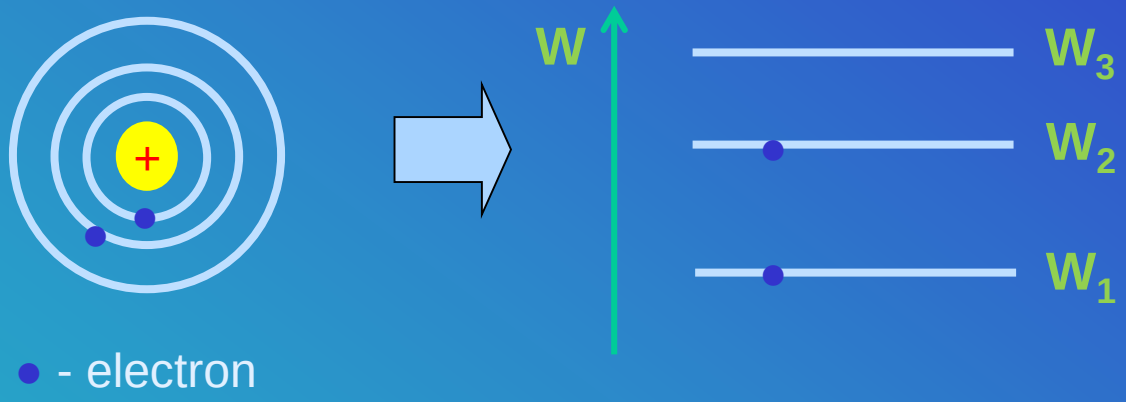
Basic semiconductors:

Si - silicon
Ge - germanium
GaAs - gallium arsenide
SiC - silicon carbide
GaN - gallium nitride

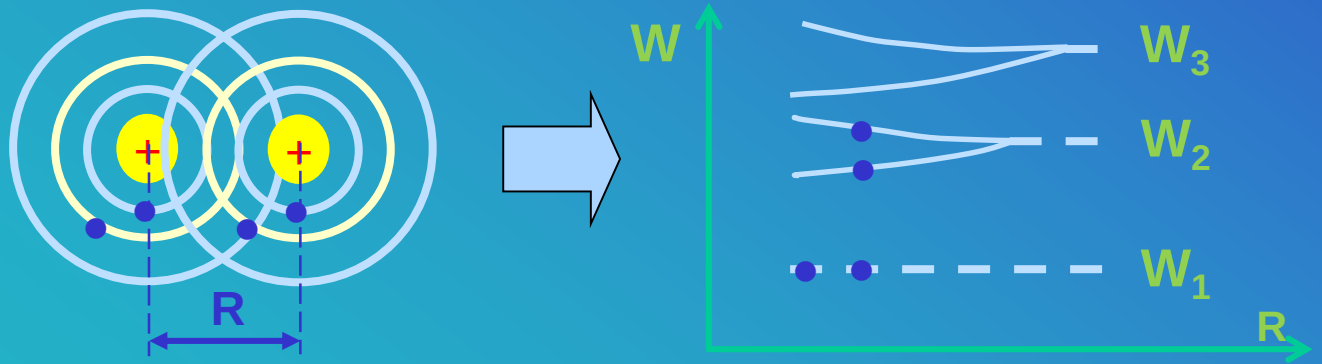
Structure of crystal – energy band model

Pauli restriction – elektrons must be recognisable

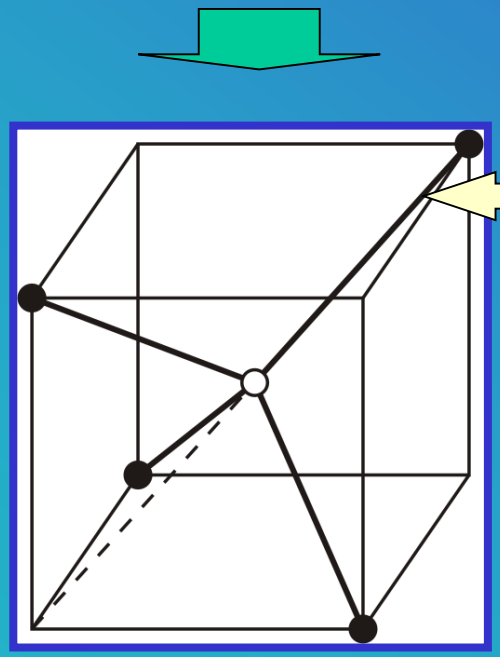
single atom



atoms in crystal



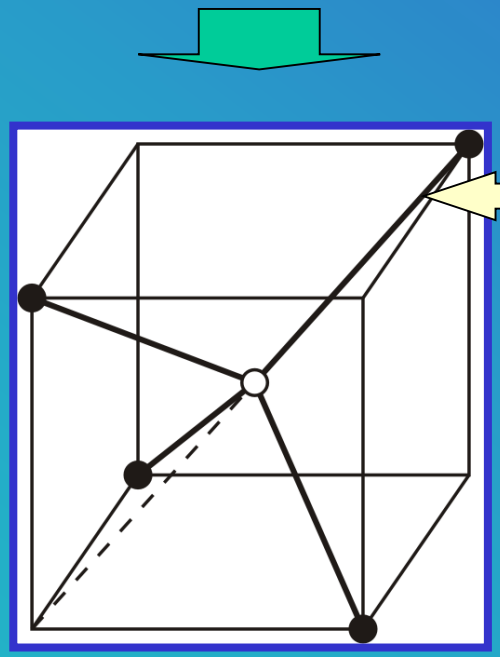
Structure of silicon crystal – so called diamond structure



Crystal bond between 2 atoms

The bond arises when 2 atoms are so close that two of their valance electrons become common, which results in quantum nature attraction

Structure of silicon crystal – so called diamond structure



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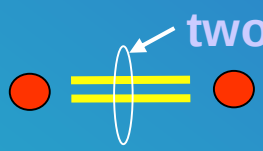
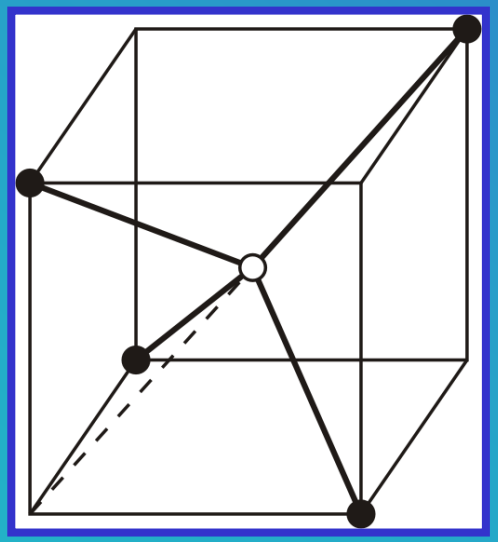
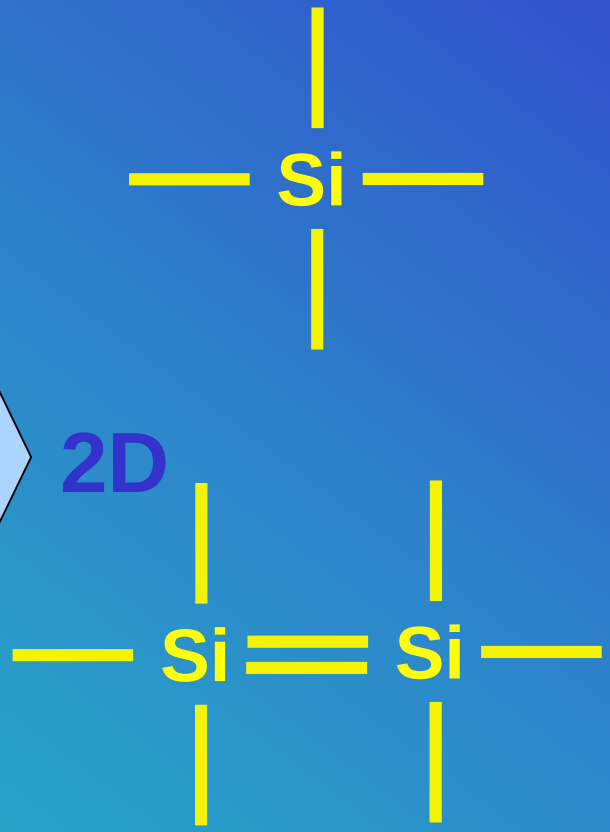


two atoms molecula

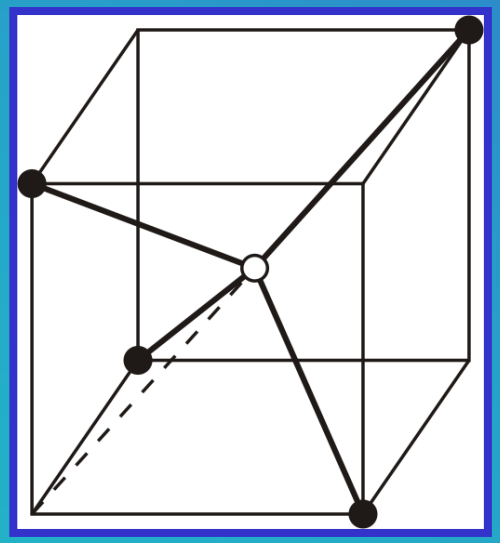
Structure of silicon crystal – so called diamond structure

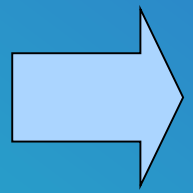


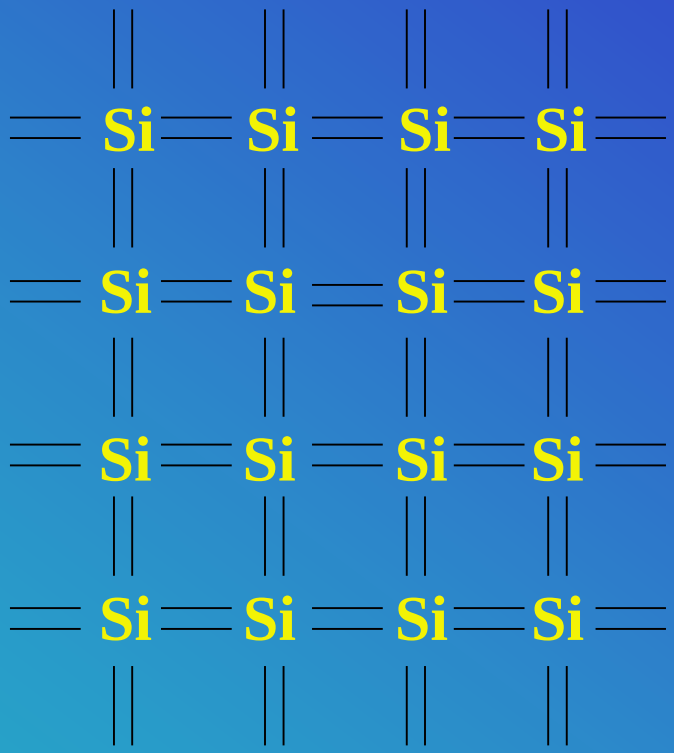
3D → 2D



Structure of silicon crystal – 2D representation

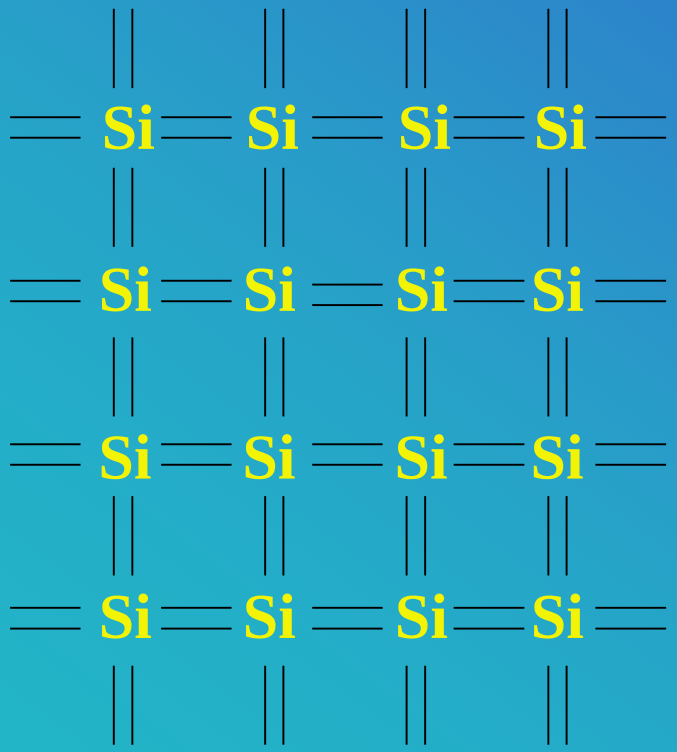




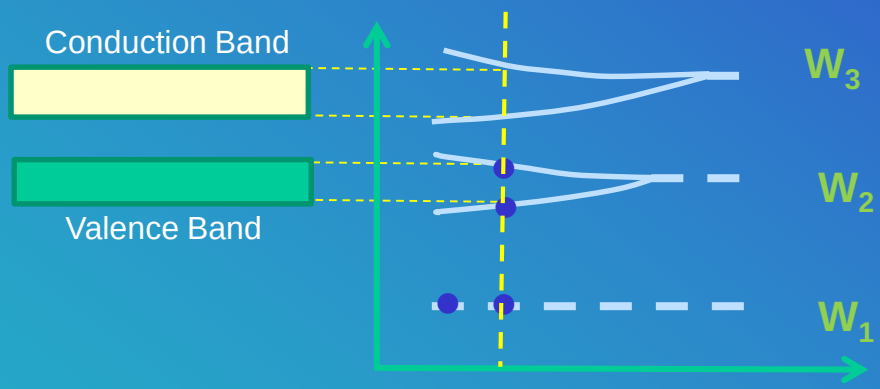


2D Structure of silicon crystal

T = 0 K



If the temperature of crystal T = 0K all the valance electrons take part in the atom bonds



2D Structure of silicon crystal

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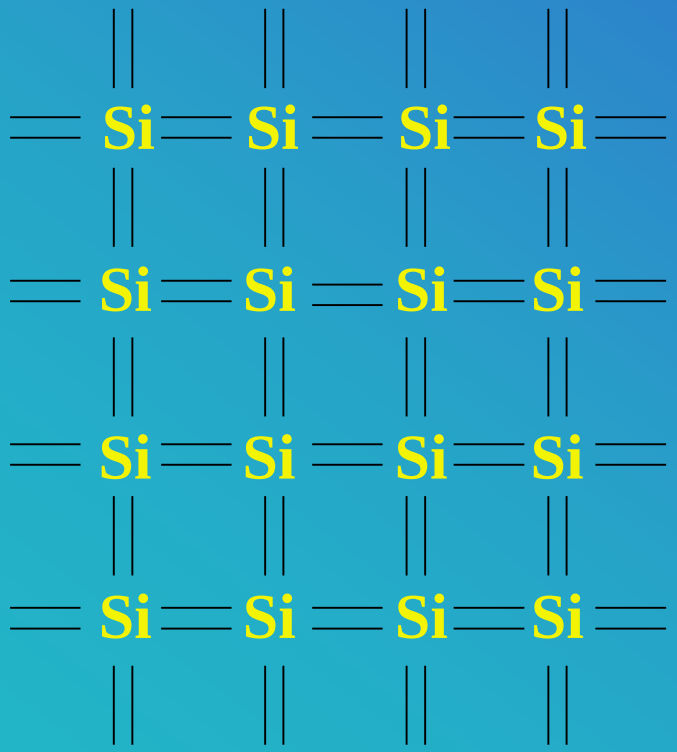


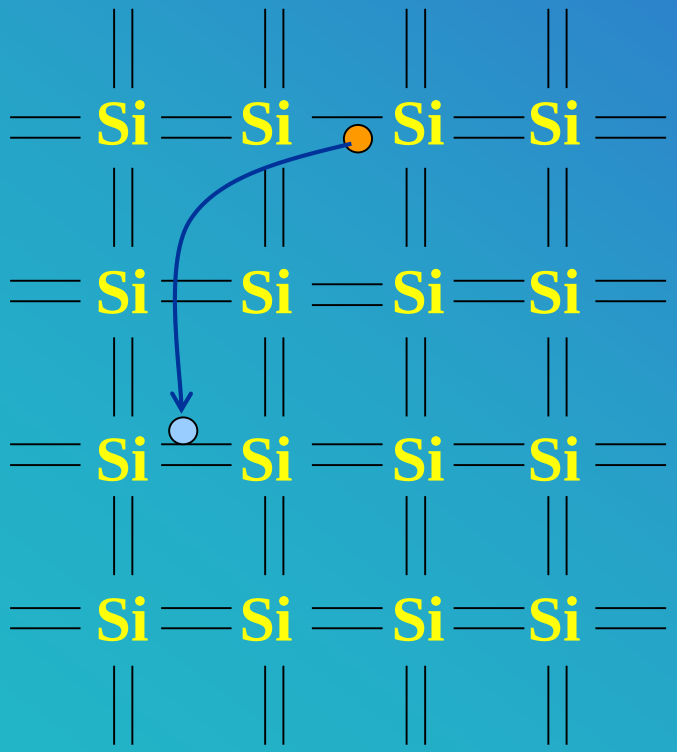
If the crystal temperature T = 0K all the valance electrons take part in the atom bonds

The crystal temperature can, however, increase and then T> 0K.

If the sufficient energy is delivered to the valance electron, it can leave its position in the interatom bond and can become a free electron.

2D Structure of silicon crystal

T > 0 K

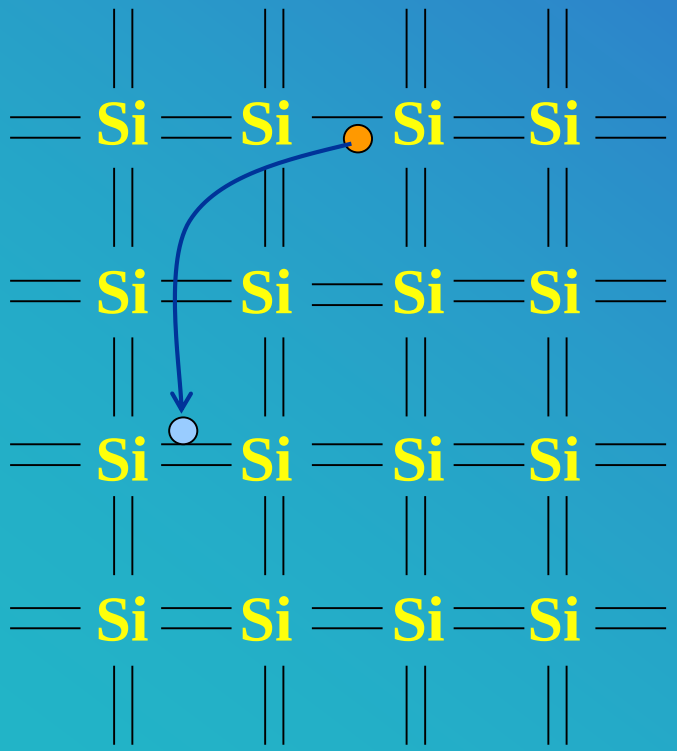


The valance electron taking sufficient energy leaves its position in the bond and becomes free electron.

Such a free electron can move in the crystal without any restriction and is called conduct electron in contrast to the electrons in bonds called valance electrons

2D Structure of silicon crystal

T > 0 K

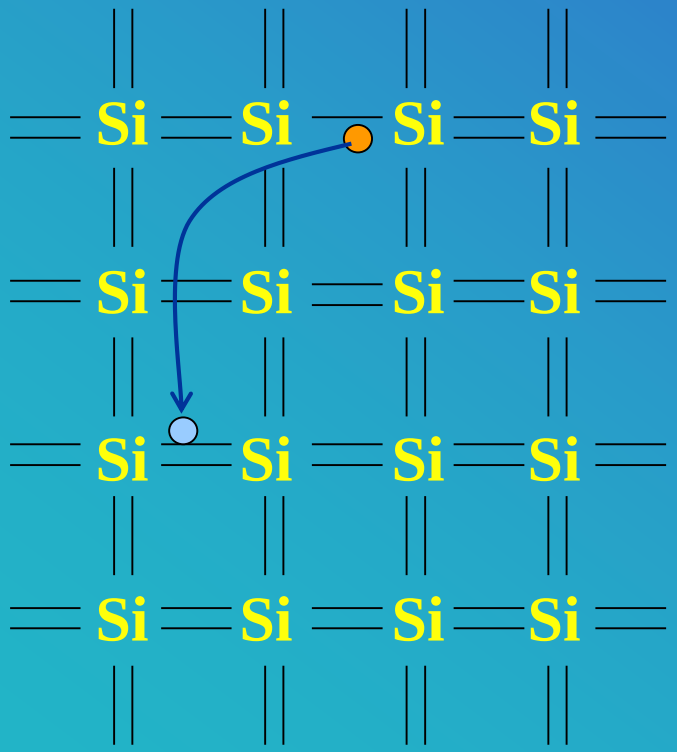


The valance electron taking sufficient energy leaves its position in the bond and becomes free electron.

The empty place in the bond structure is called hole and can also move through the crystal as the result of valance electrons hopping from one bond to another.

2D Structure of silicon crystal

T > 0 K

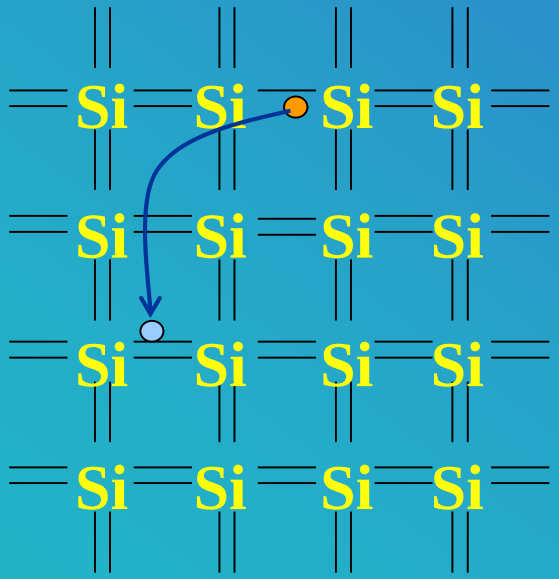


Conduct electrons are not connected with any bonds and can freely move inside the crystal. Since they are negative charge –q their movement can create an electric current

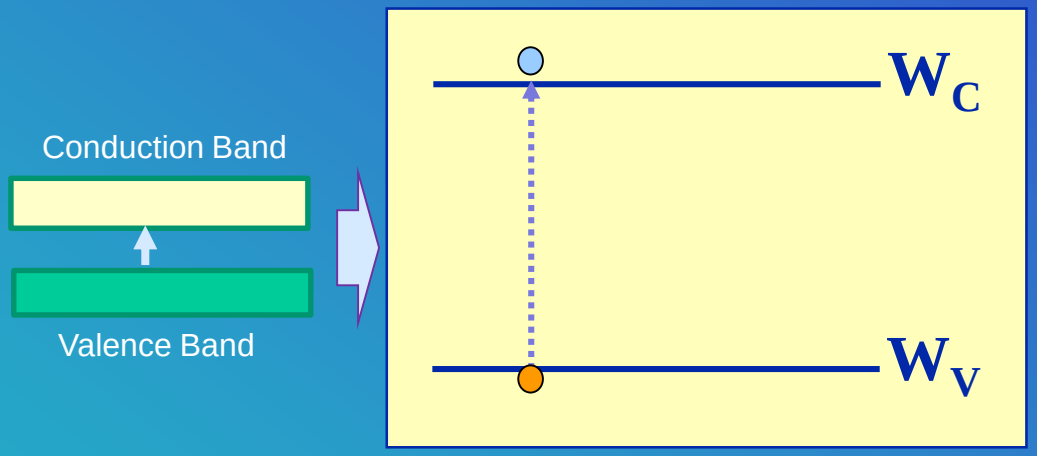
Holes are not connected with any particular bond and can freely move inside the crystal. Since the hole means the lack of an electron, it is connected with the local excess of positive charge +q. This charge moves together with the hole creating an electric current.

2D Structure of silicon crystal

T > 0 K



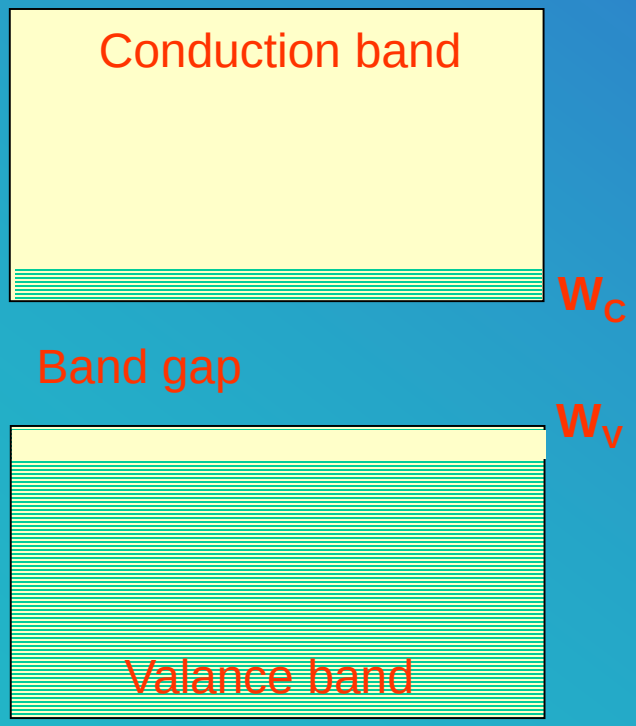
The presented process is called **electron-hole pair generation** and has its energy band model:



$$W_g = W_c - W_v$$

2D Structure of silicon crystal

Electrons – fermions fulfilling the Pauli restriction



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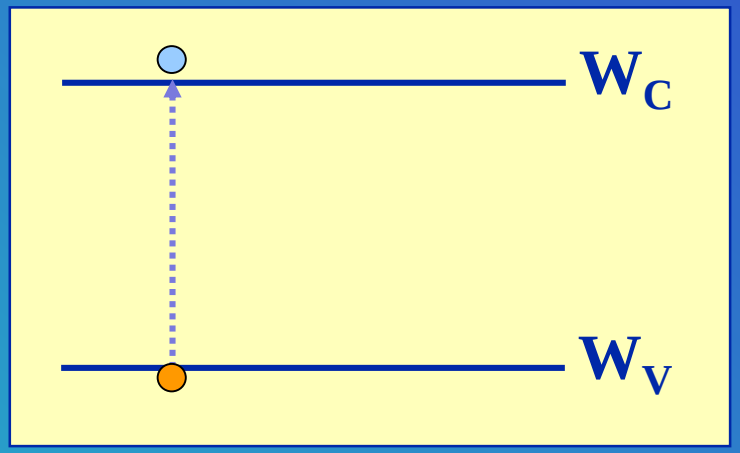
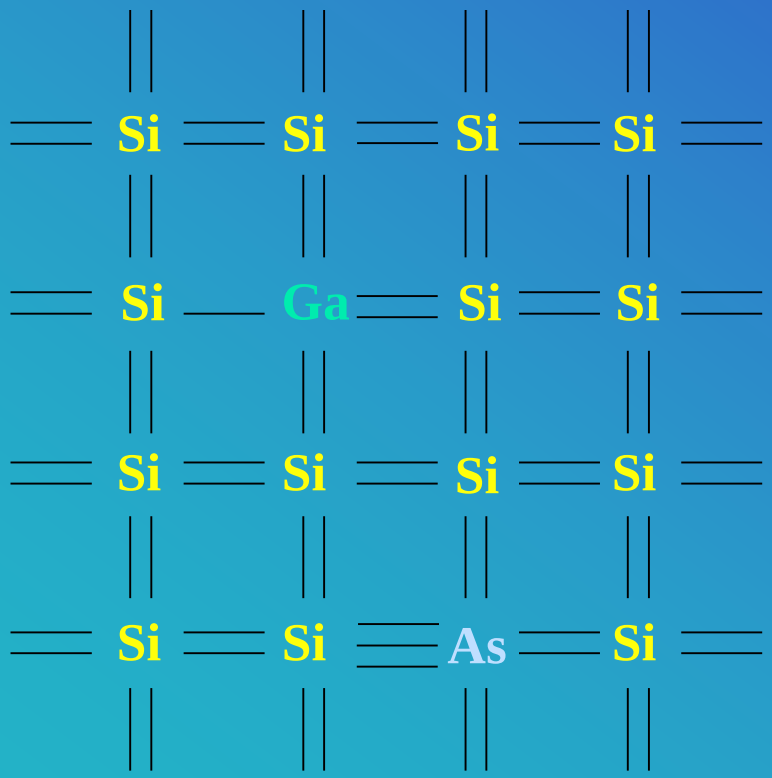


$$W_g = W_c - W_v$$

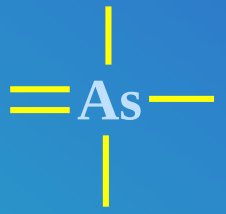
Dopands in Silicon T = 0K



acceptors

III Mendeleiew group

Ga, B, Al

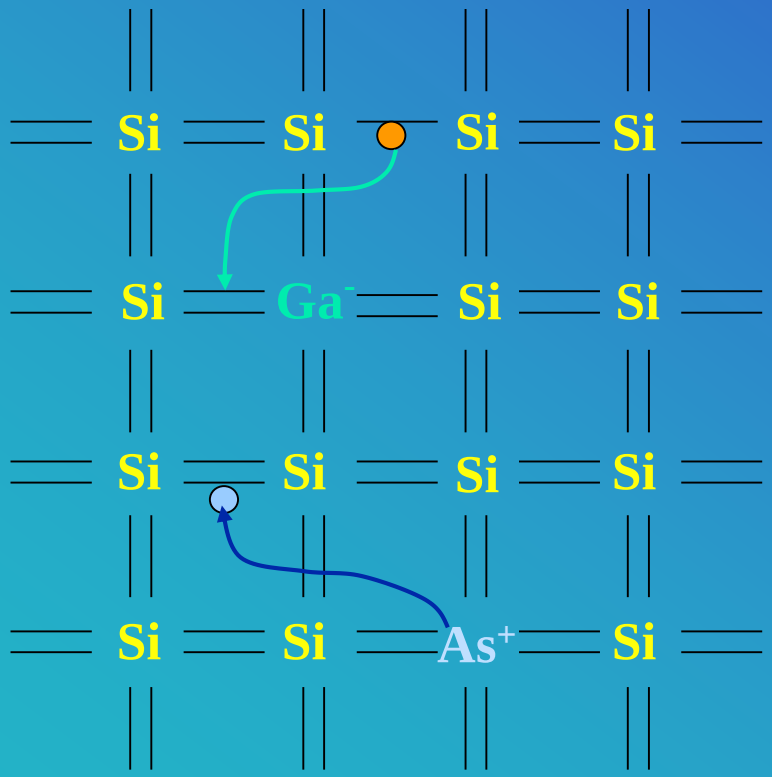


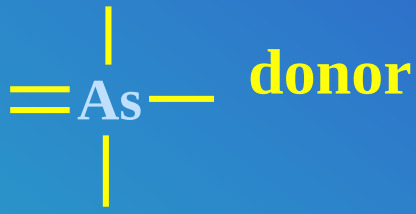
donors

V Mendeleiew group

As, Sb, P

Dopands in Silicon T > 0K

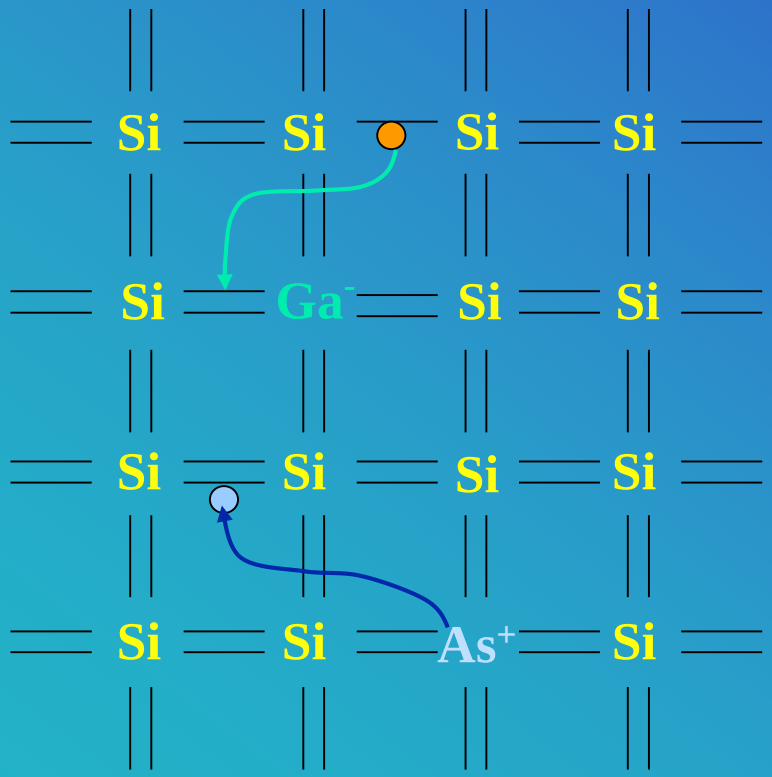




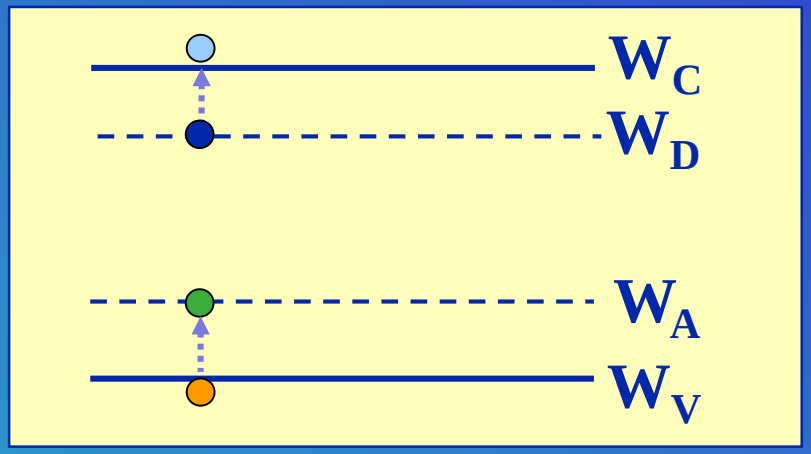
Ionization energy of dopands is very low

$W_i << W_g$

Dopands in Silicon T > 0K



Energy band model:



Ionization energy of dopands is very low

$W_i << W_g$

Carrier concentration in doped semiconductor

Charge balance:

$$n_d + N_a + n_T = p_T + N_d + p_a$$

$$n_0 + N_a = p_0 + N_d$$

Types of semiconductors

$N_a > N_d \Rightarrow p_{p0} > n_{p0}$		p-type
$N_a < N_d \Rightarrow p_{n0} < n_{n0}$		n-type
$N_a = N_d \Rightarrow p_0 = n_0 = n_i$		i-type

Equilibrium carrier concentration

n_0 , p_0

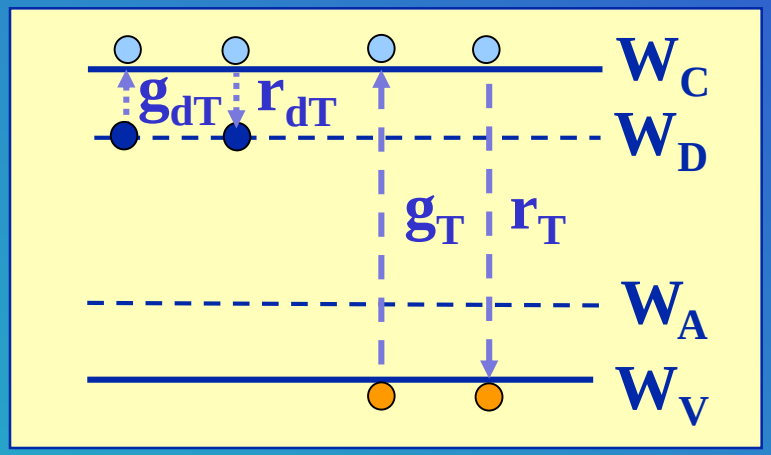
Thermodynamic equilibrium state

The state of the system being in constant temperature without any energy exchange with surroundings - so called adiabatic conditions.

The equilibrium densities of electrons and holes, n_0 and p_0, result from the balance of generation and annihilation processes:

$$g_{dT}=r_{dT} \text{ and } g_T=r_T$$

Type n



Statistical physics

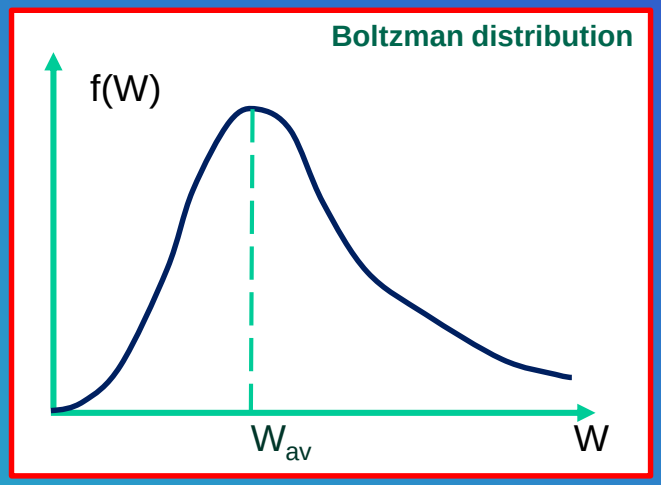
- It is used to describe physical phenomena that are created by huge number of elements – e.g. properties of gases that can be considered as the set of molecules.
- The phenomenon is described by the parameters that represent the behaviour of the set of elements being related to the average value of particular element feature

Temperature	– average kinetic energy of molecules
Pressure	– average momentum of molecules

Statistical physics

- **The set of elements is characterised by the probability function that determines the probability that the considered parametr of an element has particular magnitude.**

- **In the classical approach, the probability function has a bell-like shape with the maximum value corresponded to the average value of parameter (energy in the figure) .**



Statistical physics

- **If we want to know how many particles (e.g. electrons) have their energy in the range $<W_1, W_2>$, it is enough to calculate the integral:**

$$n = \int_{W_1}^{W_2} N(W)\, f(W)\, dW$$

where:

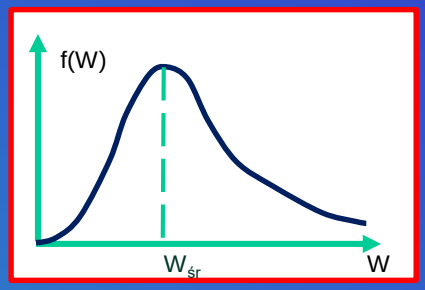
N(W) – **state density function (in classical approach, total number of particles *N(W) = N*)**

f(W) – **probability that the state of energy W is occupied**

Statistical physics

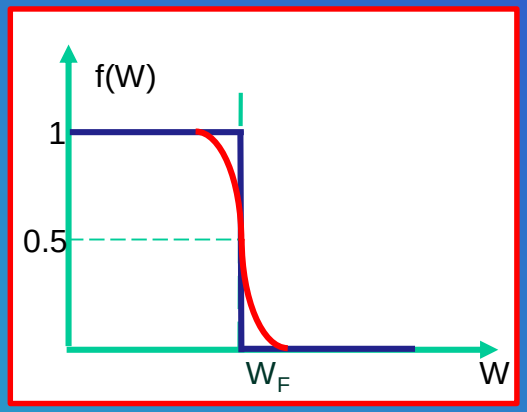
Classical approach – Bolzmann distribution

$$f(W) = \exp\left(-\frac{W}{kT}\right)$$



Quantum approach – Fermi-Dirac distribution

$$f(W) = \frac{1}{\exp\left(\frac{W - W_F}{kT}\right) + 1}$$



W_F – Fermi energy (*Fermi lavel*)

Statistical physics

Classical approximation – $(W - W_F) > 2kT$

$$f(W) = \exp\left(-\frac{W - W_F}{kT}\right)$$

Quantum approach – Fermi-Dirac distribution

$$f(W) = \frac{1}{\exp\left(\frac{W - W_F}{kT}\right) + 1}$$

W_F – **Fermi energy** (*Fermi lavel*)

Statistical physics

Classical approximation – $(W - W_F) > 2kT$

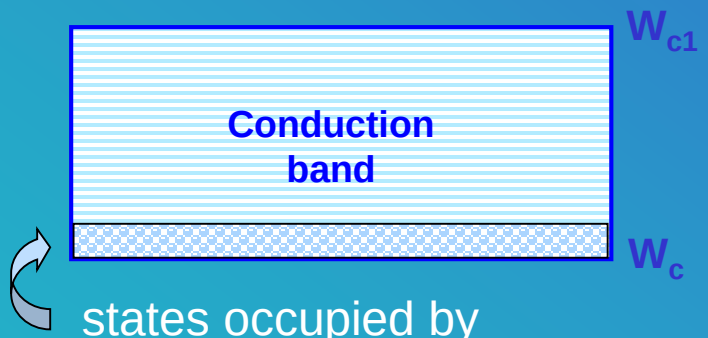
$$f(W) = \exp\left(-\frac{W - W_F}{kT}\right)$$

If this approach can be used to estimate the electron and hole density in semiconductor, such a semiconductor is called non-degenerated

Only such semiconductors will be considered in our lectures

Equilibrium carrier concentration

Classical aproximation for electrons



Concentration of electrons in conduction band:

$$n_0 = \int_{W_C}^{W_{C1}} N(W)\, f(W)\, dW$$

Under the assumption: $W_{C1} \Rightarrow \infty$

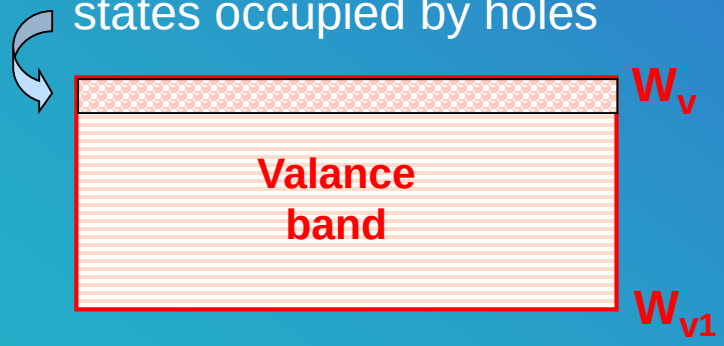
$$N_C = \left(\frac{2\pi m_{efe} kT}{h^2} \right)^{3/2}$$

$$n_0 = N_C \exp\left(-\frac{W_C - W_F}{kT} \right)$$

N_C – **effective density of states in the conduction band**

Equilibrium carrier concentration

Classical aproximation for holes



Concentration of holes in valance band:

$$p_0 = \int_{W_{V1}}^{W_V} N(W)\left(1 - f(W)\right)dW$$

Under the assumption: $W_{V1} \Rightarrow -\infty$

$$p_0 = N_V \exp\left(-\frac{W_F - W_V}{kT}\right)$$

$$N_V = \left(\frac{2\pi m_{efh} kT}{h^2}\right)^{3/2}$$

N_V – **effective density of states in the valance band**

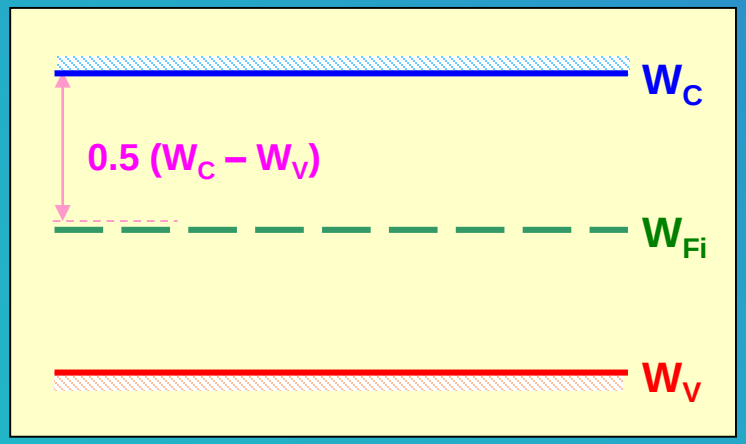
Equilibrium in intrinsic semiconductor

$n_0 = p_0$

From the equilibrium condition:

$$N_C \exp\left(-\frac{W_C - W_{Fi}}{kT}\right) = N_V \exp\left(-\frac{W_{Fi} - W_V}{kT}\right)$$

one can calculate W_{Fi}, the Fermi energy for intrinsic semiconductor :



$$W_{Fi} = \frac{1}{2}\left(W_C + W_V\right) + \frac{1}{2}kT \ln\frac{N_V}{N_C} =$$

$$= \frac{1}{2}\left(W_C + W_V\right) + \frac{3}{4}kT \ln\frac{m_{efh}}{m_{efe}}$$

Equilibrium in doped semiconductor

$n_0 \neq p_0$

Transformation of electron equation:

$$n_0 = N_C \exp\left(-\frac{W_C - W_F}{kT}\right) =$$

$$= N_C \exp\left(-\frac{W_C - W_{Fi} + W_{Fi} - W_F}{kT}\right) =$$

$$= N_C \exp\left(-\frac{W_C - W_{Fi}}{kT}\right) \exp\left(-\frac{W_{Fi} - W_F}{kT}\right) =$$

$$= n_i \exp\left(-\frac{W_{Fi} - W_F}{kT}\right)$$

Equilibrium in doped semiconductor

$n_0 \neq p_0$

Transformation of hole equation:

$$p_0 = N_V \exp\left(-\frac{W_F - W_V}{kT}\right) =$$

$$= N_V \exp\left(-\frac{W_F - W_{Fi} + W_{Fi} - W_V}{kT}\right) =$$

$$= n_i \exp\left(\frac{W_{Fi} - W_F}{kT}\right)$$

Equilibrium in doped semiconductor

$n_0 \neq p_0$

Product of hole and electron concentration:

$$n_0 p_0 = n_i \exp\left(-\frac{W_{Fi} - W_F}{kT}\right) n_i \exp\left(\frac{W_{Fi} - W_F}{kT}\right)$$

$$n_0 p_0 = n_i^2$$

At constant temperature n_0p_0 is constant independently on the dopand concentration

Equilibrium in doped semiconductor

$n_0 \neq p_0$

Transformation of hole and electron product:

$$n_i^2 = n_0 p_0$$

$$n_0 p_0 = N_C \exp\left(-\frac{W_C - W_F}{kT}\right) N_V \exp\left(-\frac{W_F - W_V}{kT}\right)$$

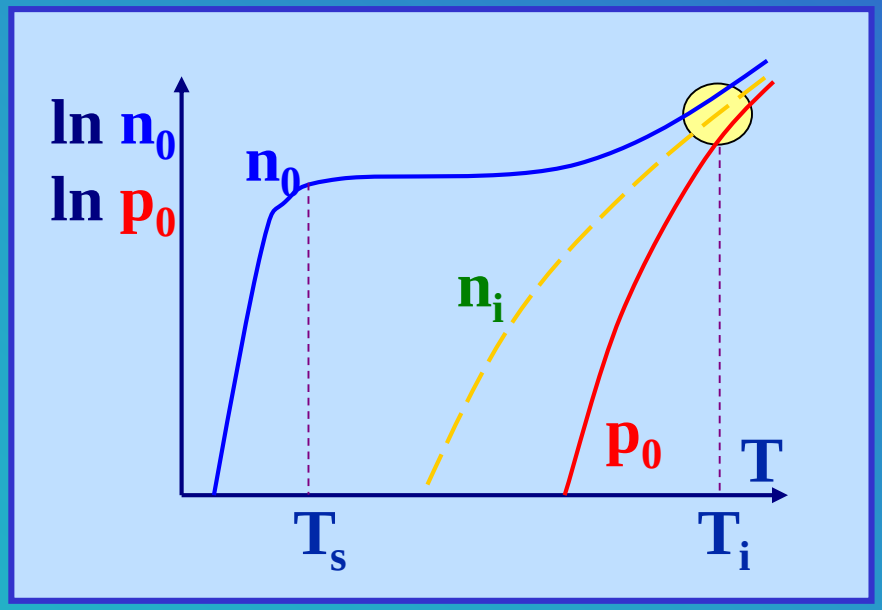
$$n_i^2 = N_C \exp\left(-\frac{W_C - W_F}{kT}\right) N_V \exp\left(-\frac{W_F - W_V}{kT}\right) =$$

$$= N_C N_V \exp\left(-\frac{W_C - W_V}{kT}\right) = N_C N_V \exp\left(-\frac{W_g}{kT}\right) =$$

$$= B^2 \left(\frac{T}{300}\right)^3 \exp\left(-\frac{W_g}{kT}\right)$$

$n_i = f(T)$

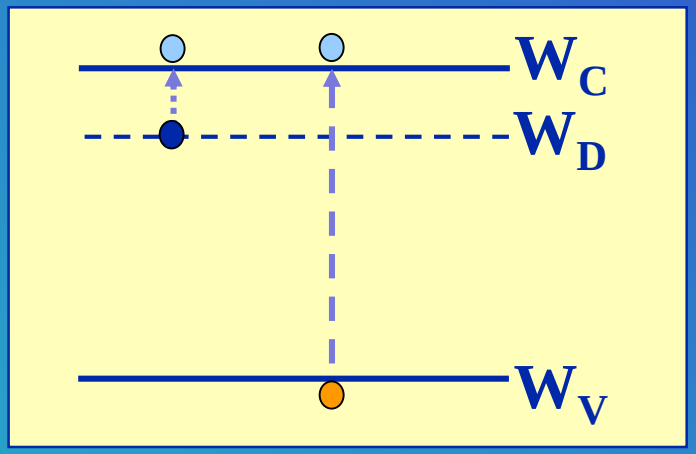
Carrier concentration in doped semiconductor



Typ n

$n_0 = n_d + n_T$

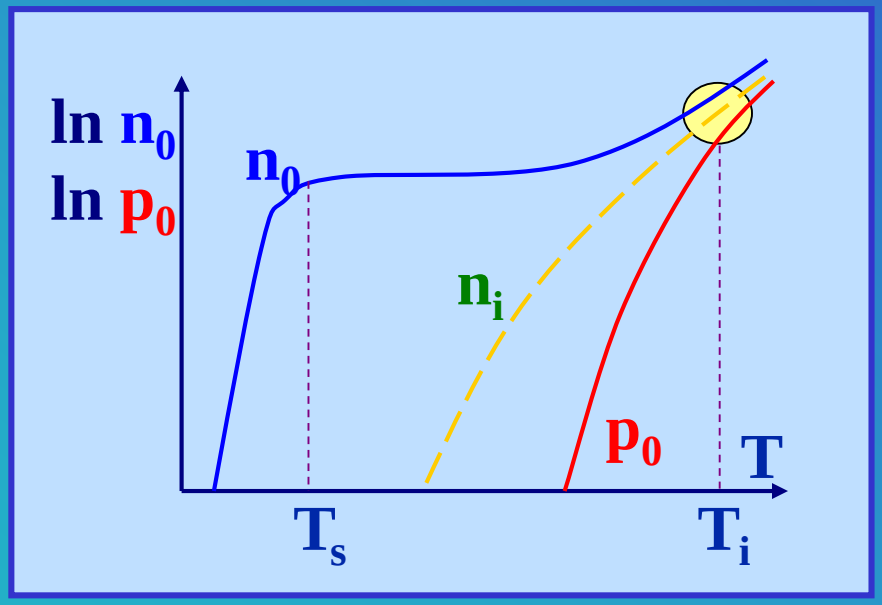
$p_0 = p_T$



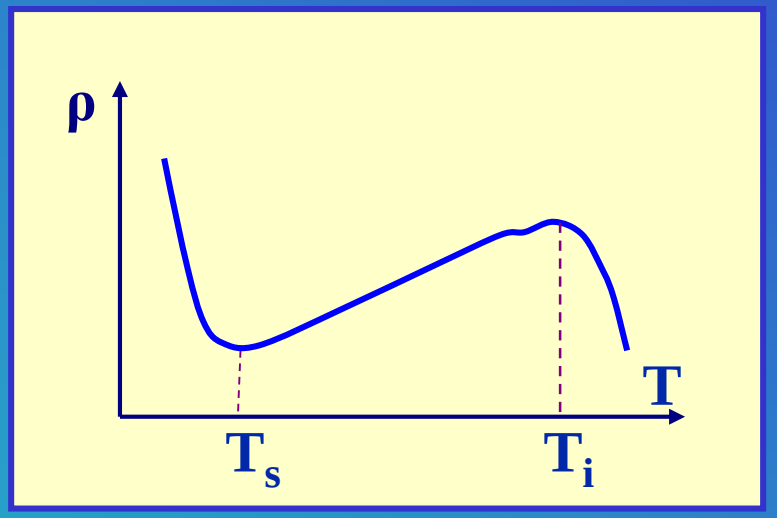
T_s – saturation temperature

T_i – intrinsic temperature

Carrier concentration in doped semiconductor



Type n



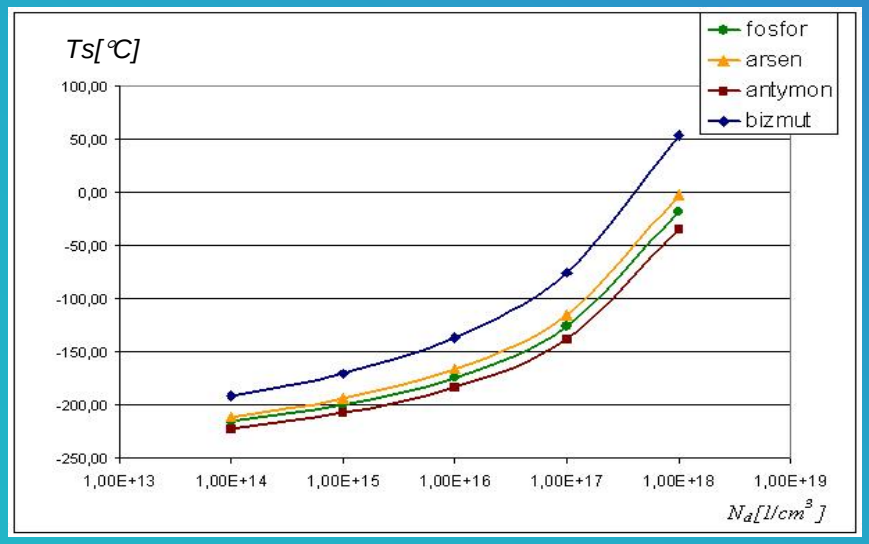
T_s – saturation temperature

T_i – intrinsic temperature

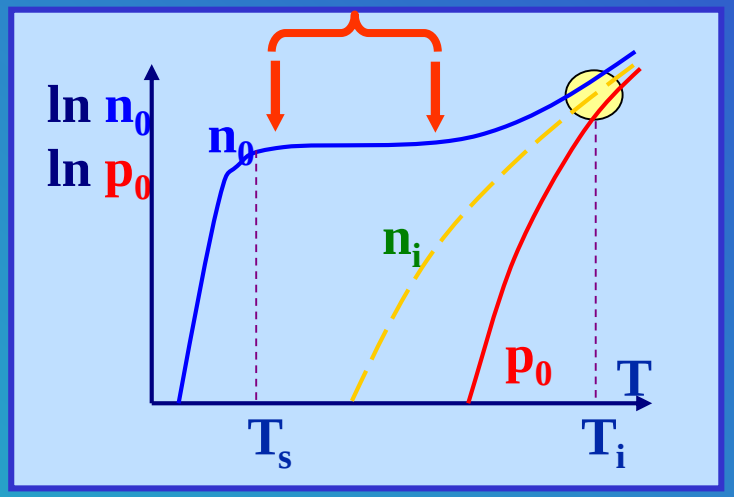
Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. Condition 1: It is true when T_{min} not lower than T_s.

For Si $T_{min} \approx$ -50 °C



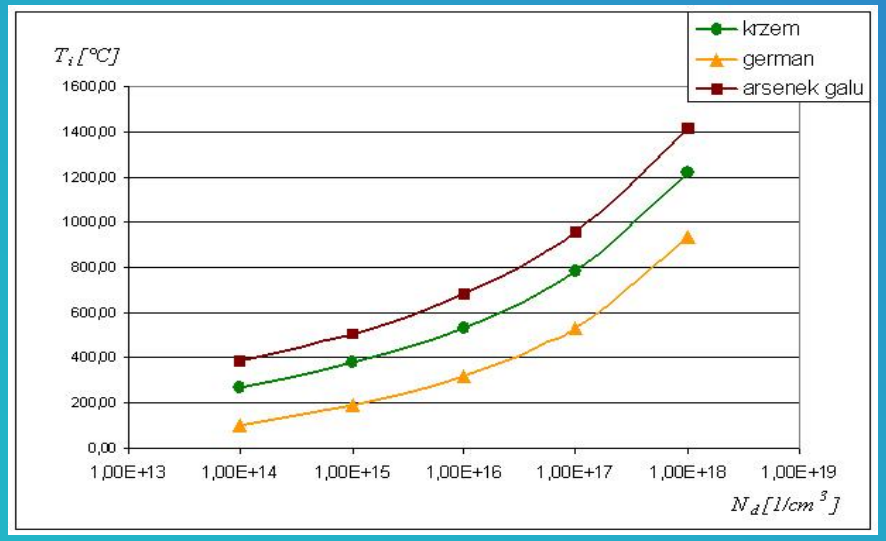
Recommended area



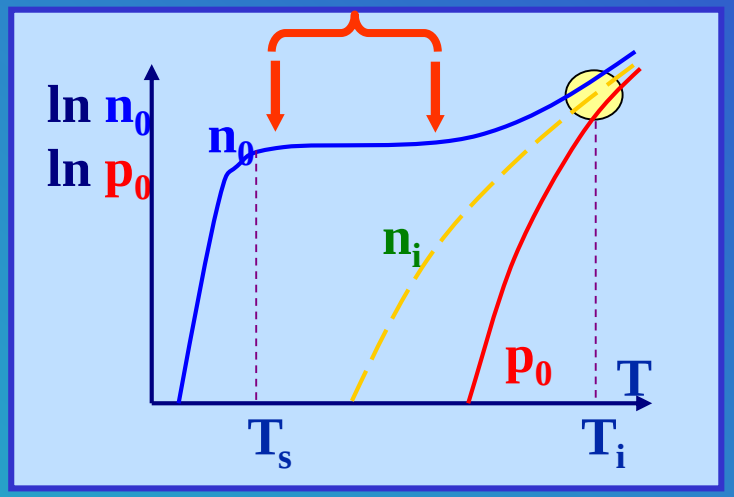
Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. Condition 2: **It is true when T_{max} lower than T_i.**

For Si T_{max} < 400 °C



Recommended area

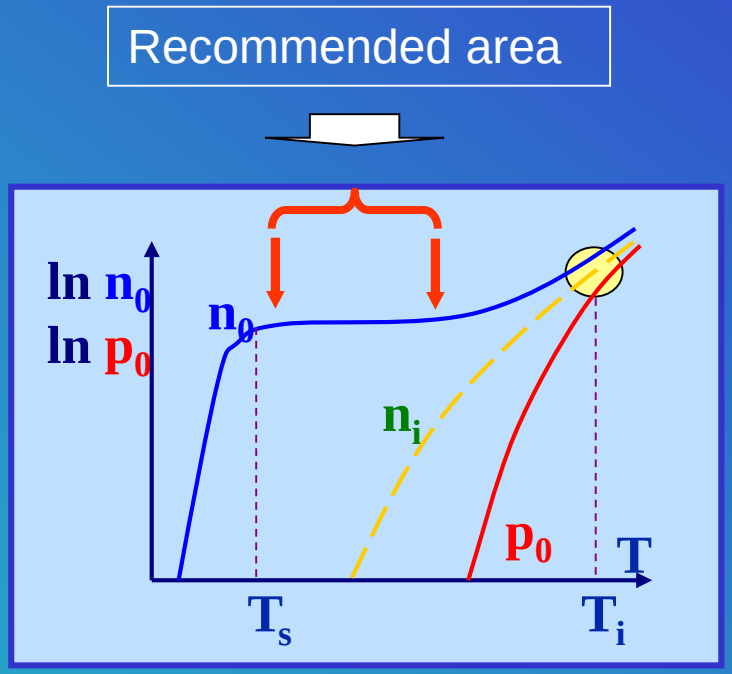


Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. Condition 2: **It is true when T_{max} lower than T_i.**

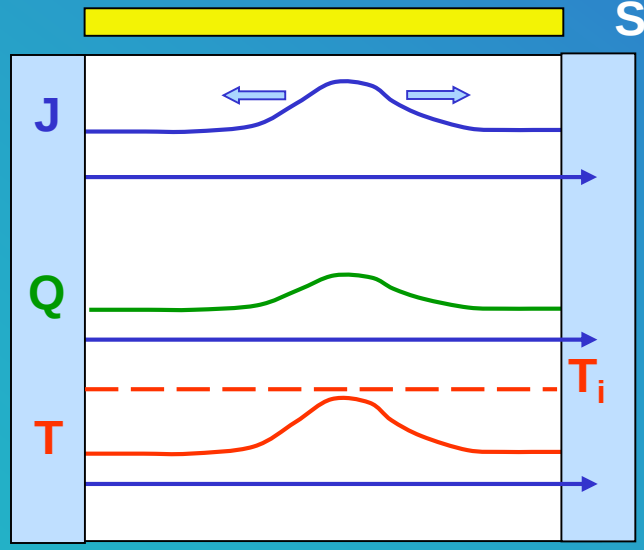
Typical ranges defined for silicon devices in catalogues:

Range	[°C]
Commercial	0 – 70
Industrial	-25 – 85
Extended industrial	-40 – 125
Military	-55 – 125



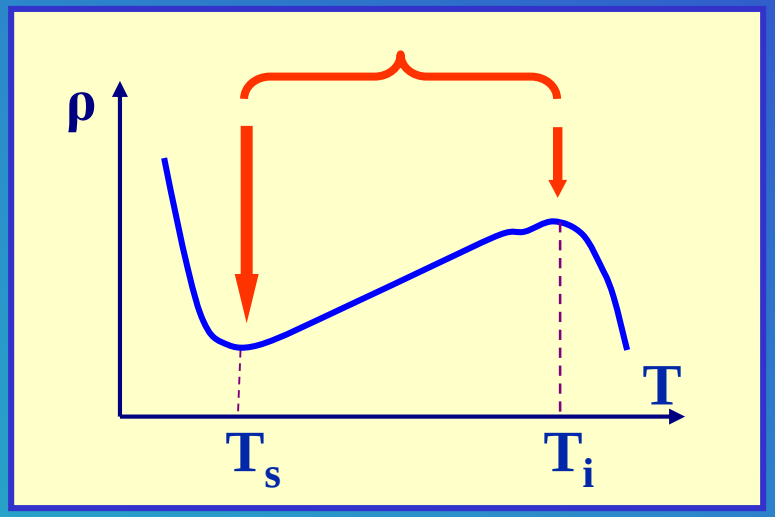
Current filamentation – hot spot

If T inside <T_s,T_i>, the negative thermal feedback occurs:



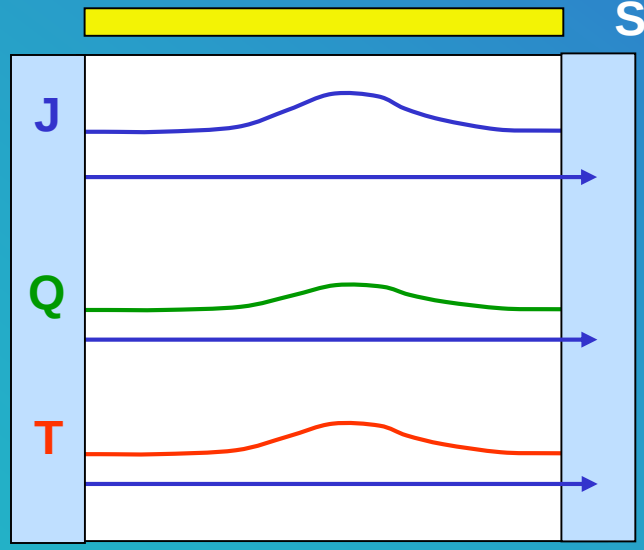
Current is pushed out from warmer area and heat dissipation decreases

Safe area

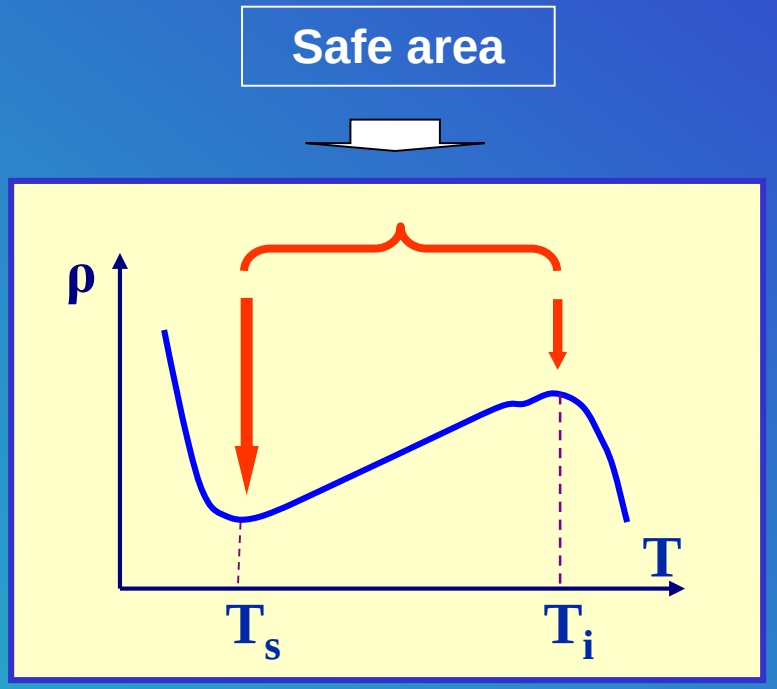


Current filamentation – hot spot

If T inside <T_s,T_i>, the negative thermal feedback occurs:

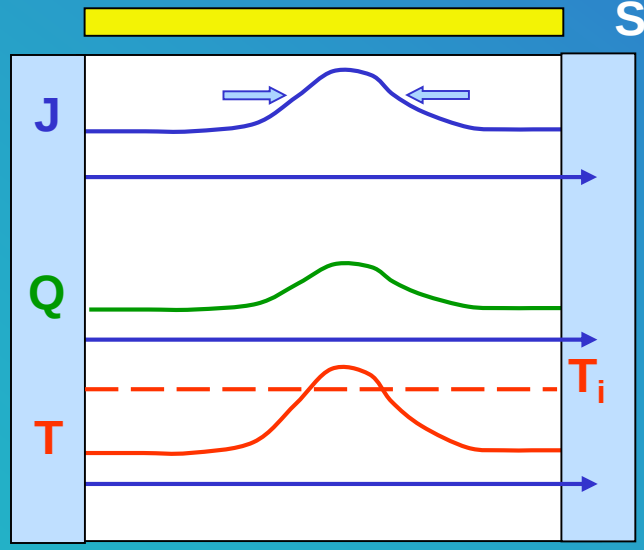


Current is pushed out from warmer area and heat dissipation decreases



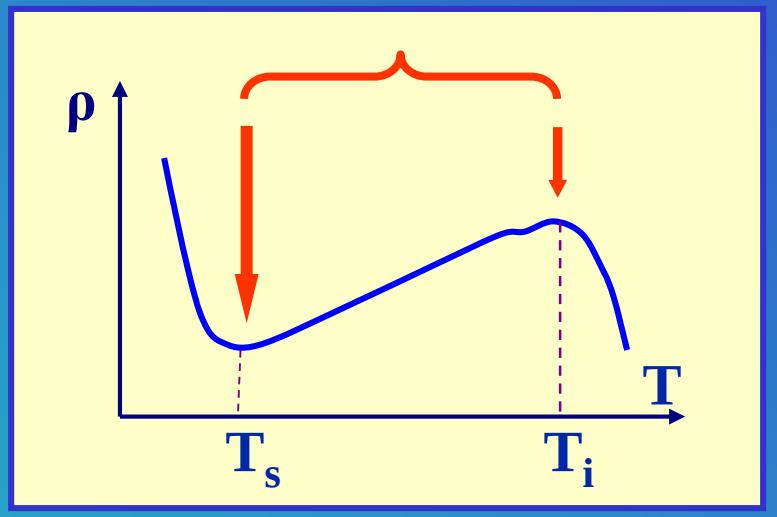
Current filamentation – hot spot

If T outside <T_s,T_i>, the positive thermal feedback occurs:



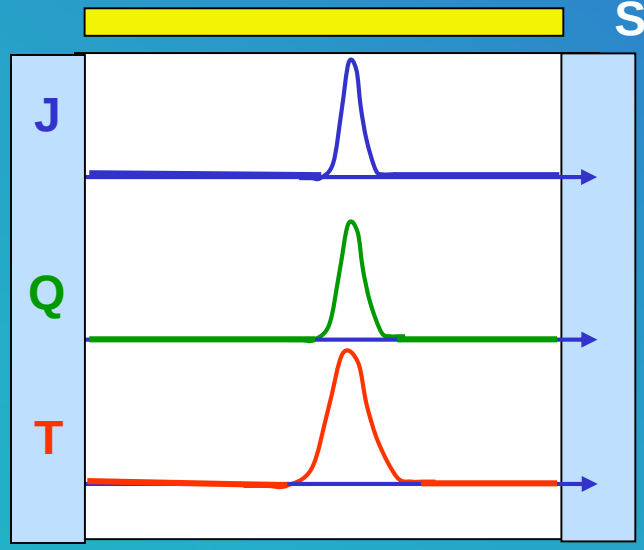
Current is squeezed in warmer area and heat dissipation increases

Safe area



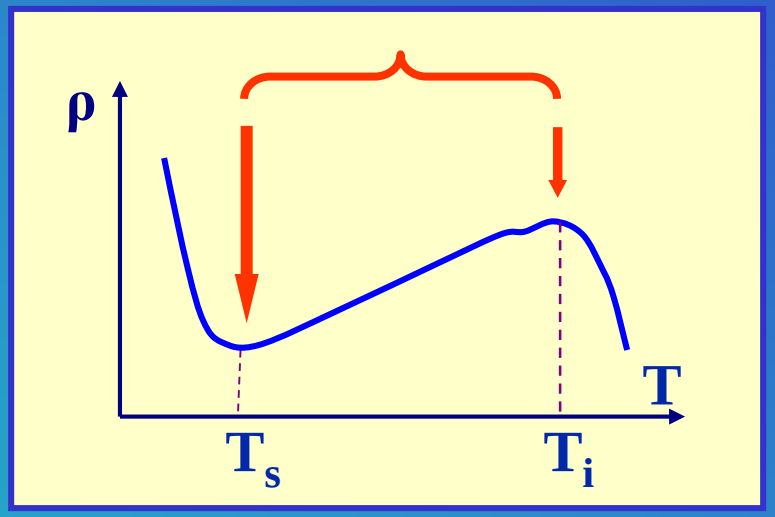
Current filamentation – hot spot

If T outside <T_s,T_i>, the positive thermal feedback occurs:



Current is squeezed into small area and hot spot is generated

Safe area



Nonequilibrium carrier concentration

Equilibrium concentrations

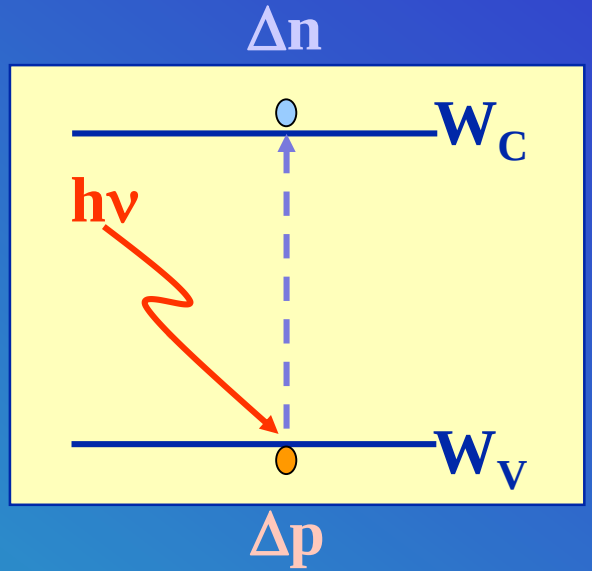
$$n_0 \, , \, p_0$$

Nonequillibrum concentrations

$$n = n_0 + \Delta n$$

$$p = p_0 + \Delta p$$

Δn, Δp – **excess concentrations**



usually:
$\Delta n = \Delta p$

Nonequilibrium carrier concentration

Quasi-Fermi level

$$n = n_0 + \Delta n$$

$$p = p_0 + \Delta p$$

$$n_0 = N_C \exp\left(-\frac{W_C - W_F}{kT}\right)$$

$$p_0 = N_V \exp\left(-\frac{W_F - W_V}{kT}\right)$$

$$n = N_c \exp\left(-\frac{W_c - W_F}{kT}\right) + \Delta n = N_c \exp\left(-\frac{W_c - W_{Fe}}{kT}\right)$$

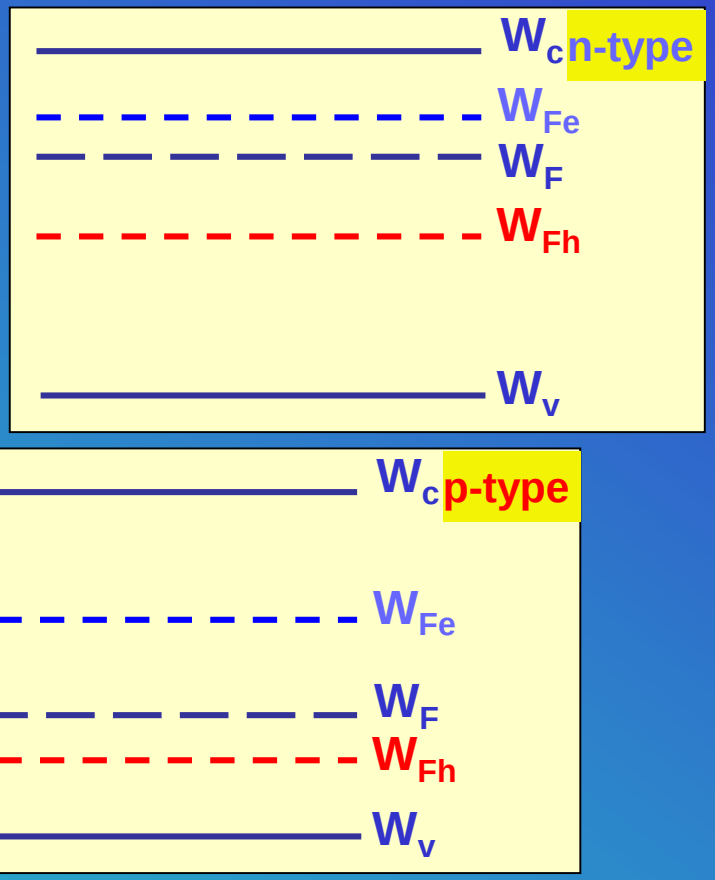
$$p = N_v \exp\left(-\frac{W_F - W_v}{kT}\right) + \Delta p = N_v \exp\left(-\frac{W_{Fh} - W_v}{kT}\right)$$

Nonequilibrium carrier concentration

Quasi-Fermi level

$$n = n_0 + \Delta n = N_c \exp\left(-\frac{W_c - W_{Fe}}{kT}\right)$$

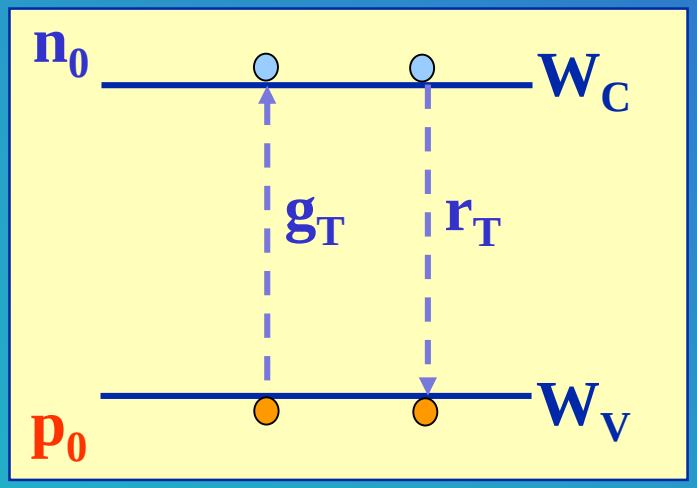
$$p = p_0 + \Delta p = N_v \exp\left(-\frac{W_{Fh} - W_v}{kT}\right)$$



W_{Fe} – quasi-Fermi level for electrons

W_{Fh} – quasi-Fermi level for holes

Recombination processes



Equillibrum state:

g_T – rate of electron-hole pairs thermal generation

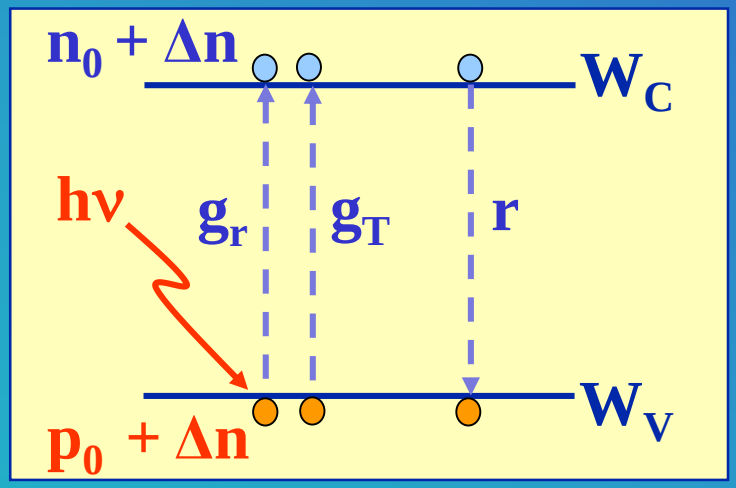
r_T – rate of electron-hole pairs thermal anihilation

$$g_T = r_T$$

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

$$g_r + g_T = r$$