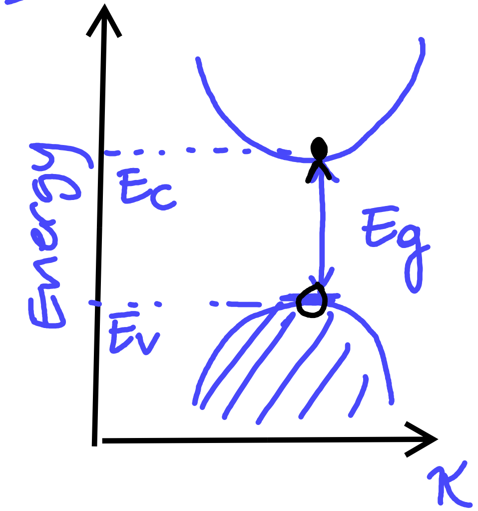
Semiconductors

Lecture 2

Recap

SEMICONDUCTORS

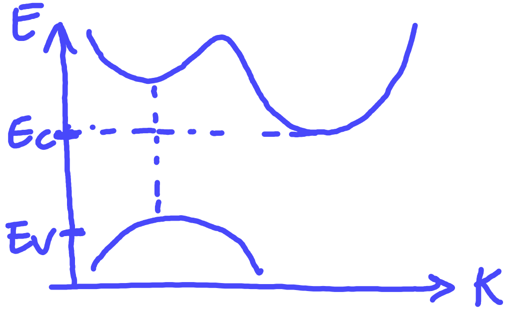


Conduction Band

Valence Band

* DIRECT BAND GAP

* INDIRECT BAND GAP



$\boxed{\text{Hole}}$

$$\left\{\begin{array}{l} \bar{K}_h = -\bar{K}_e \\ E_h(\bar{K}_h) = -E_e(K_e) \\ v_h = v_e \\ m^*_h = -m^*_e \\ q_{hole} = +e \end{array}\right.$$

Recap

* concentration of e^- in the C.B. $\quad n(T) \propto e^{-\frac{(E_c-\mu)}{K_B T}}$
* concentration of h^+ V.B $\quad p(T) \propto e^{-\left(\frac{\mu-E_v}{K_B T}\right)}$

* Low of mass action $\quad n \cdot p = 4\left(\frac{K_B T}{2\pi\hbar^2}\right)(m_e^* m_h^*)^{3/2} e^{-E_g/K_B T}$ $\qquad E_g = E_c - E_v$

* Intrinsic semiconductor $\quad n_i = p_i$

$$\mu(T) = \frac{E_v + E_c}{2} + \frac{3}{4} K_B T \ln \frac{m_h^*}{m_e^*}$$

Intrinsic mobility

do not confuse it with the chemical potential!

Mobility. $\boxed{\mu_i = \frac{|v|}{E}}$ $\left[\frac{m^2}{Vs}\right]$ μ_i is defined positive for both e- and h!

- electric conductivity $(\sigma = 1/\rho)$

$$\sigma_e = \frac{j_e}{E} = \frac{n(T)\, e\, v_e}{E} = n(T)\, e\, \mu_e$$

$$\sigma_h = \cdots = p(T)\, e\, \mu_h$$

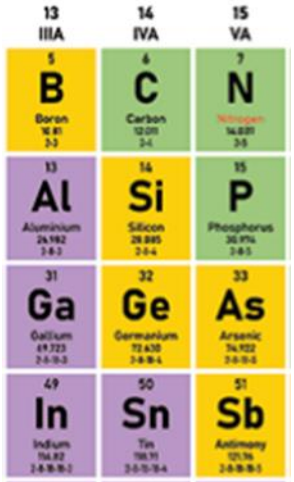
$$\sigma_{TOTAL} = \sigma_e + \sigma_h = n(T)\, e\, \mu_e + p(T)\, e\, \mu_h$$

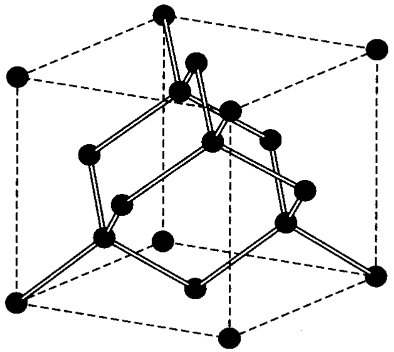
- drift velocity $v = \frac{q \tau E}{m} \Rightarrow \mu_e = \frac{e \tau_e}{m_e^*}$ & $\mu_h = \frac{e \tau_h}{m_h^*}$

τ: collision time

Doping of semiconductors

Ex 0.001% of B in Si ⟶ conductivity × 1000 !

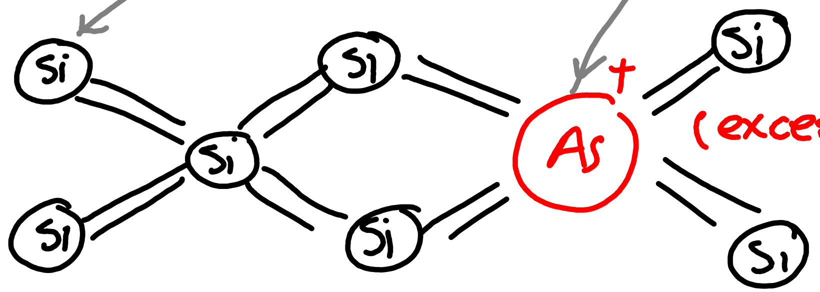




Diamond structure (Si, Ge)

Si has valence 4

As valence 5



(excess positive charge)

− excess e^- (from As)

⇒ semiconductor type-n

As = Donor (e^-)

Where is the energetic level of the impurity?

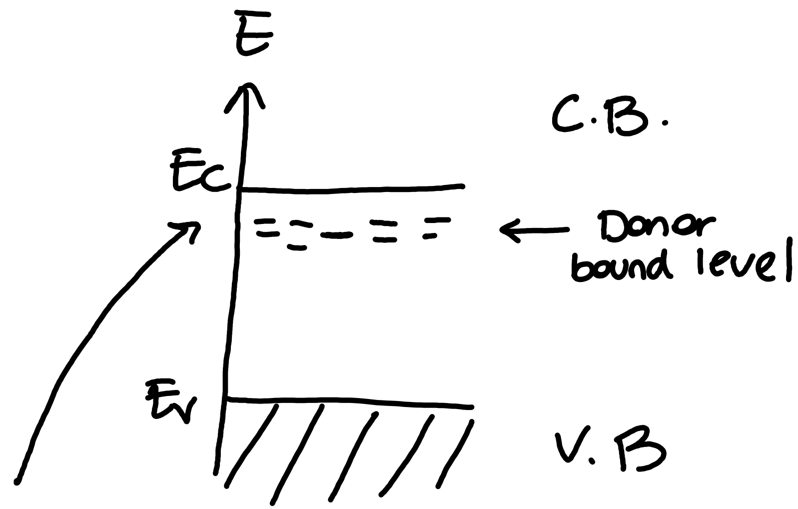
Hydrogen atom $E_{ion} = -\dfrac{e^4 m}{2(4\pi\varepsilon_0\hbar)^2} = 13.6\,eV$

$E_c - E_{donor} = \dfrac{e^4 m_e^*}{2(4\pi\varepsilon\varepsilon_0\hbar)^2} \sim 10\,meV$

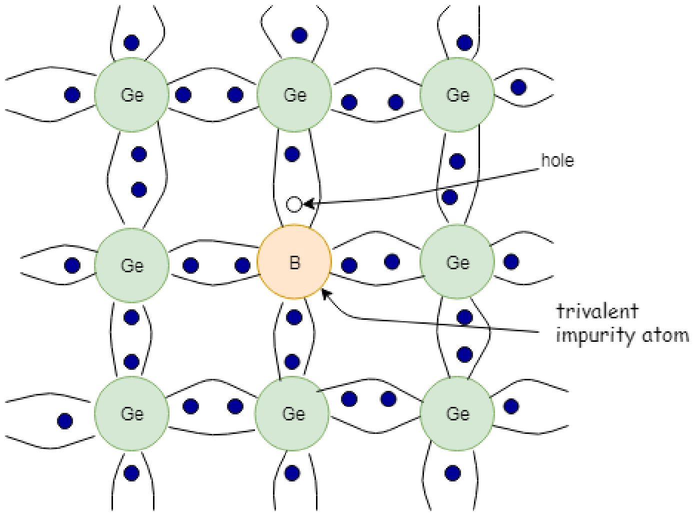
$\varepsilon \sim 10$

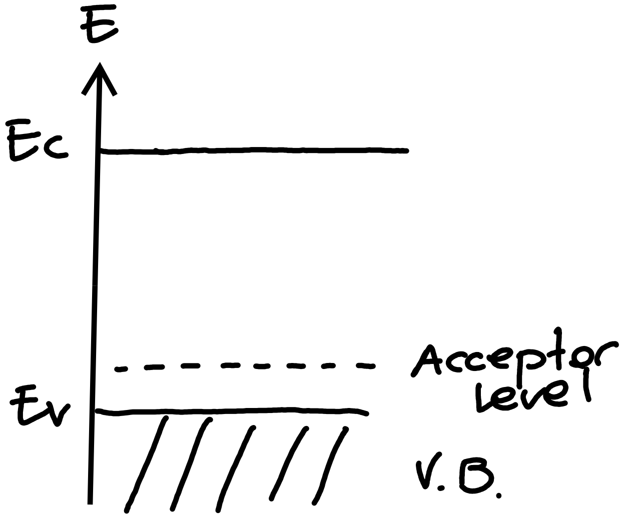
$m_e^* \sim 0.1 m_e$

↳ Donor impurity forms an energy eigenstate just below the bottom of C.B



Acceptors





Doping type-P : the doped semiconductor has excess of holes

Nomenclature

Type n : carriers are free e^- in the conduction band given at RT by ionized donors

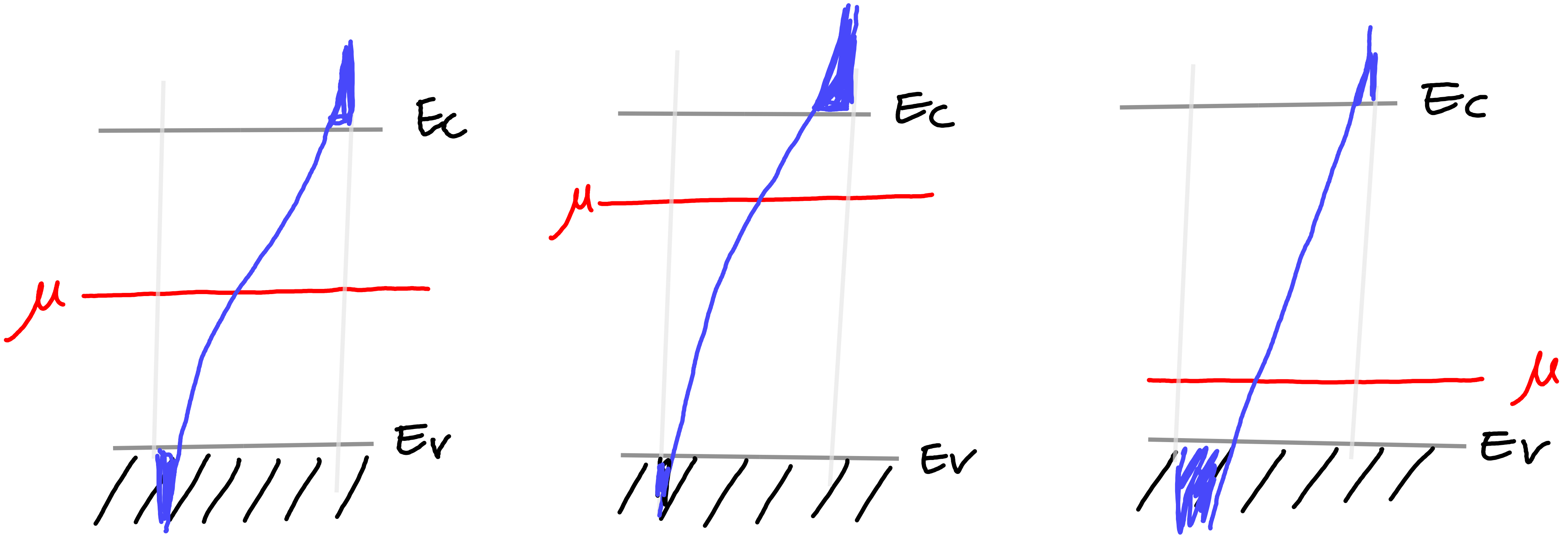
Type p : carriers are free holes in the valence band given at RT by ionized acceptors

Intrinsic : pur semiconductor, $n = p$ without doping

For all n and p, np only depends on :

- intrinsic material
- temperature

Fermi level changes if one modifies the balance n,p



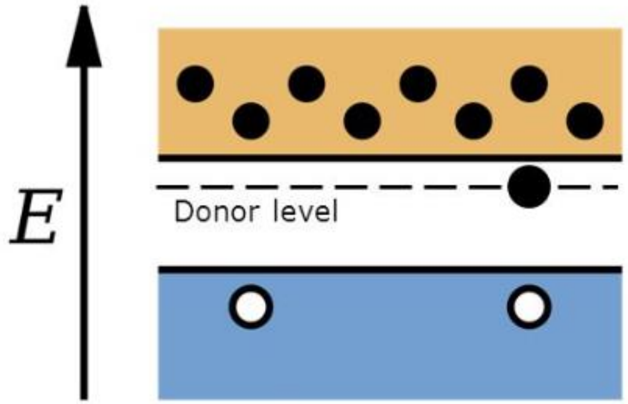
$n=p$ | $n>p$ | $n<p$

absence of impurities, the Fermi level (chemical potential at 0K) is in the middle of the gap

Donnors

Acceptors

n-type band structures :



Group IV semiconductors:

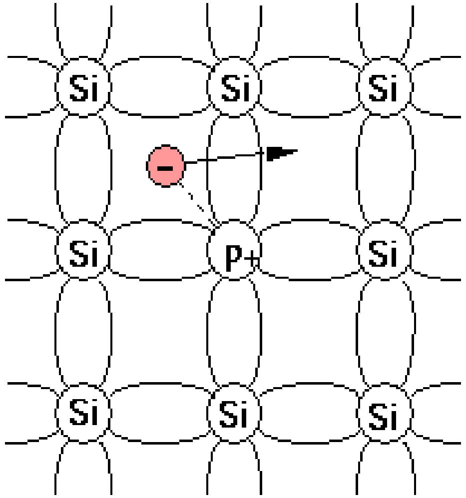
Si and Ge

Donors: P and As

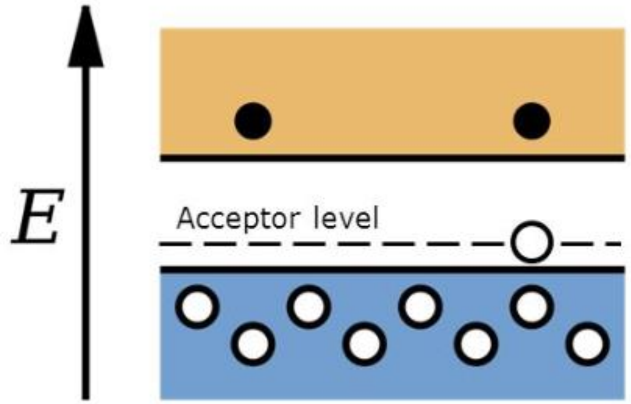
Group III-V semiconductors:

GaAs and GaN

Donors: Se, Te, Si and Ge



p-type band structures :



Group IV semiconductors:

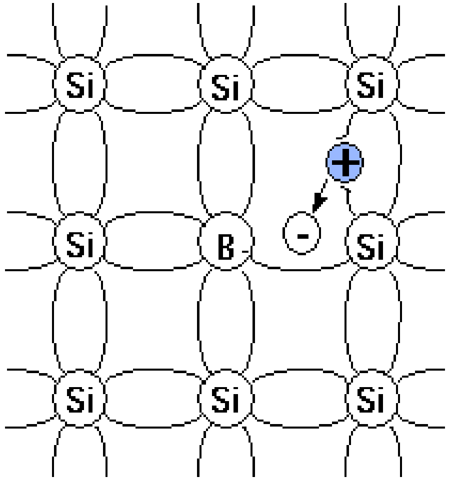
Si and Ge

Acceptors: B and Al

Group III-V semiconductors:

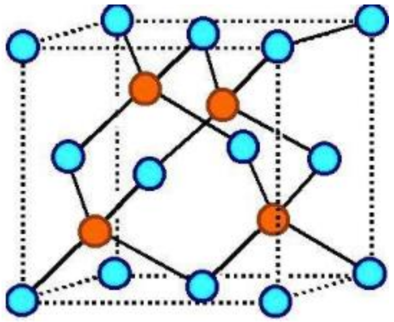
GaAs and GaN

Acceptors: Be, Zn, Cd and Ge



Semiconductor devices

Band structure engineering



zinc blende structure

Designing band gaps

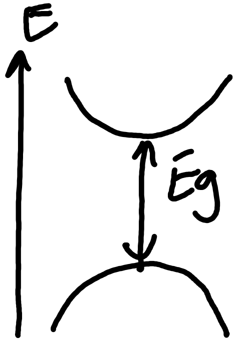
GaAs – $E_{gap} = 1.4\,eV$

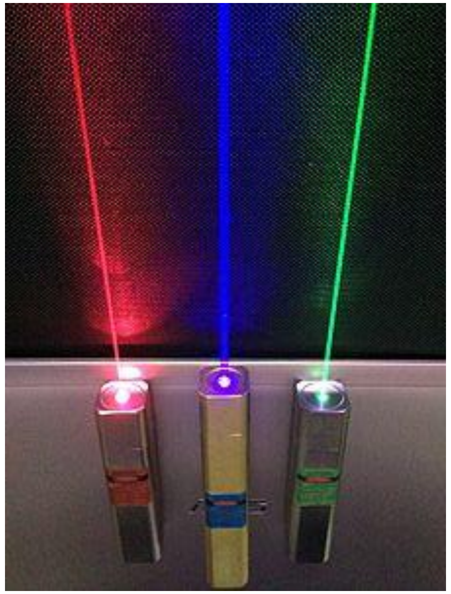
AlAs – $E_{gap} = 2.7\,eV$

$Al_x Ga_{1-x} As$ (Alloy)

$$E_{gap}(x) = (1-x)\, 1.4\,eV + x\, 2.7\,eV$$

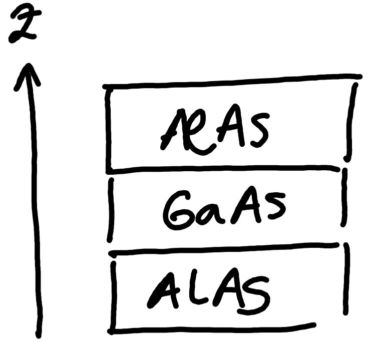
As first approx., the direct band gap interpolates those of GaAs and AlAs



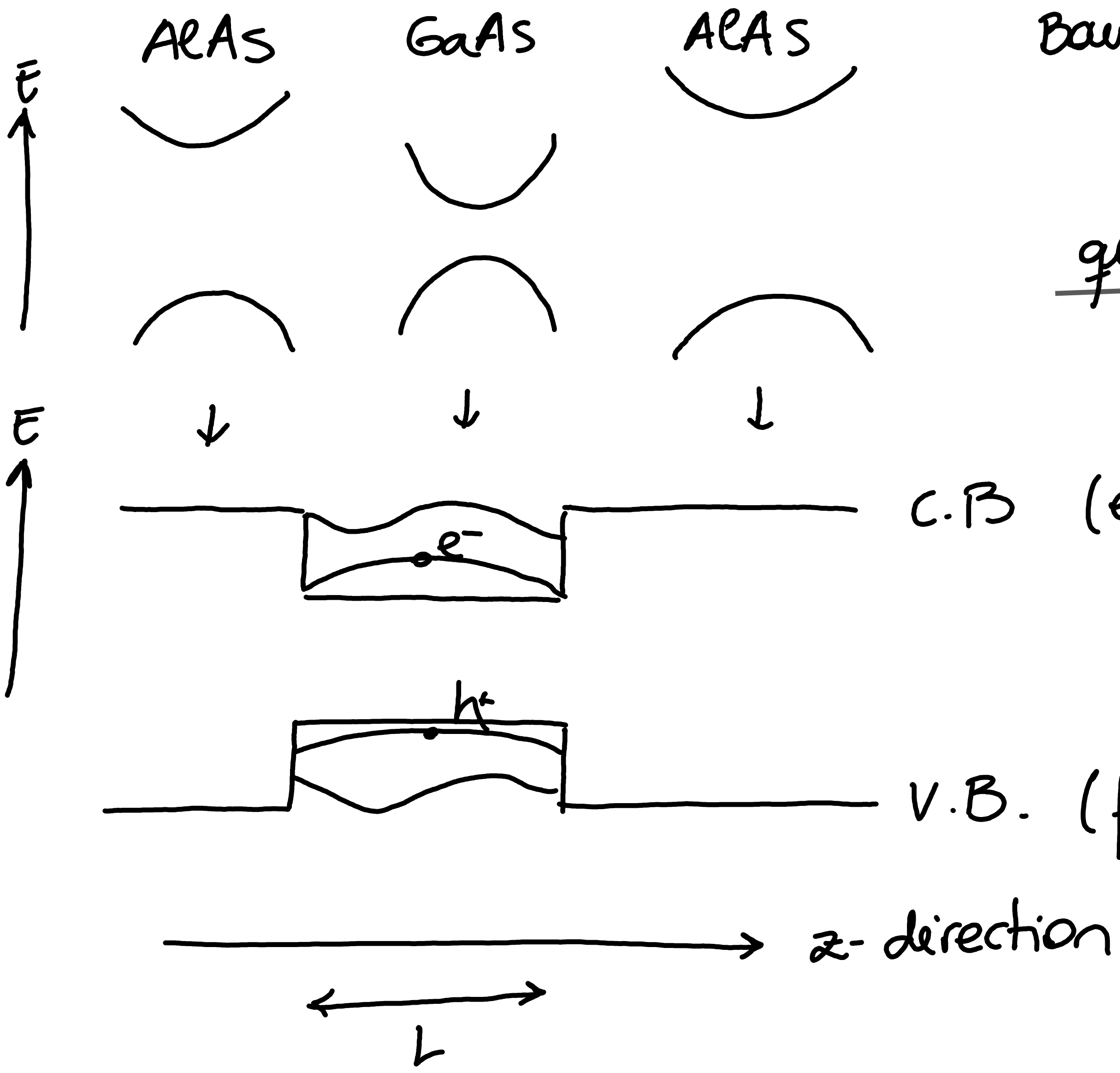


Semiconductor lasers
(520nm, 445nm, 635nm)

Non-homogeneous band gaps



heterostructure



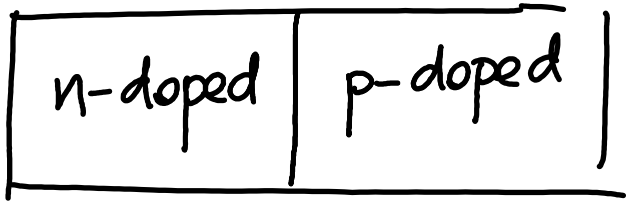
Bandgap GaAs < AlAs

quantum well

e's in a semiconductor see the energy in the C.B. bottom as a potential as function of position in which they can be trapped.

(idem for holes and top of the V.B.)

p-n Junction



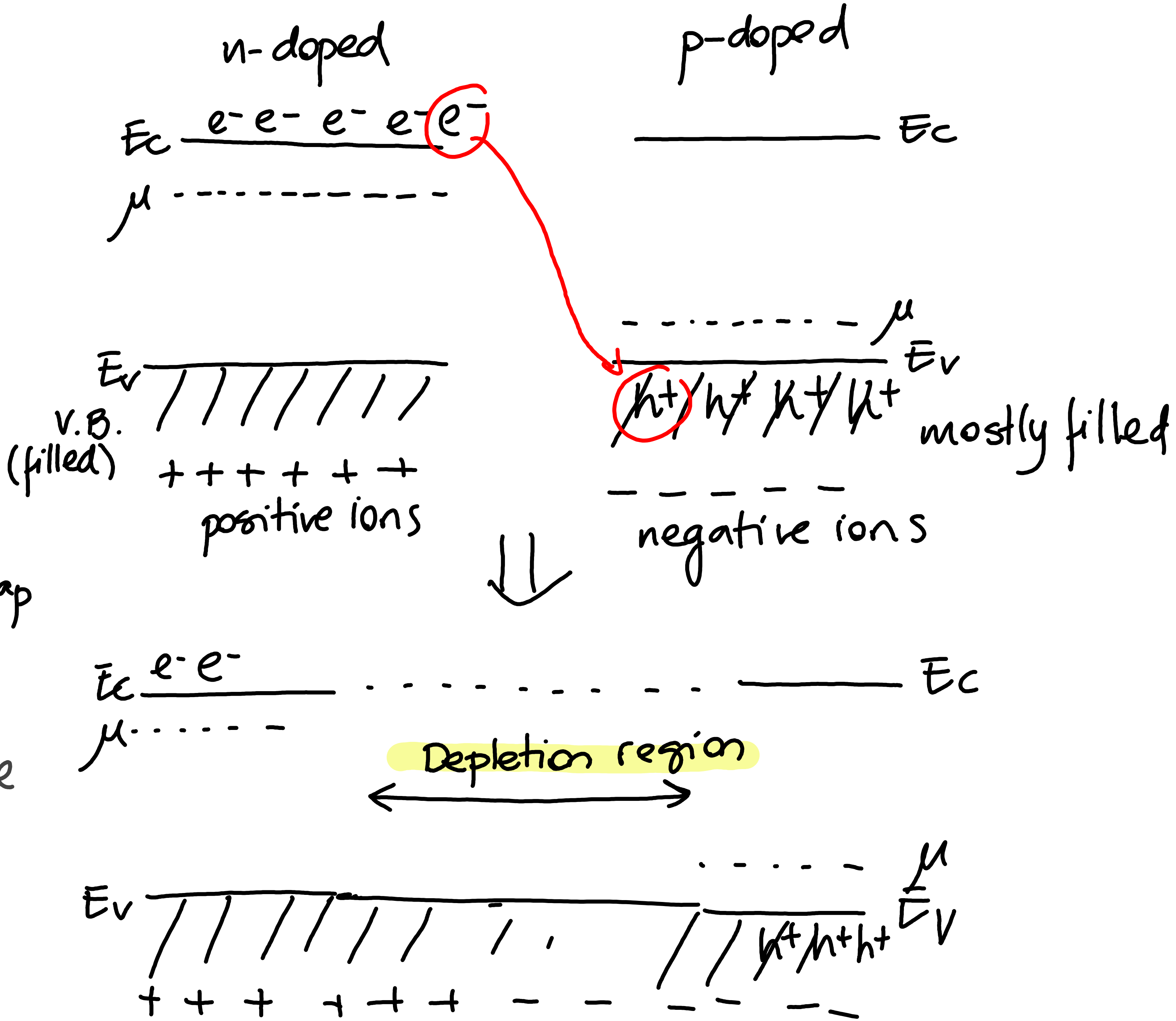
When the 2 materials are brought together, e⁻ in C.B. will fall in the V.B. to annihilate holes

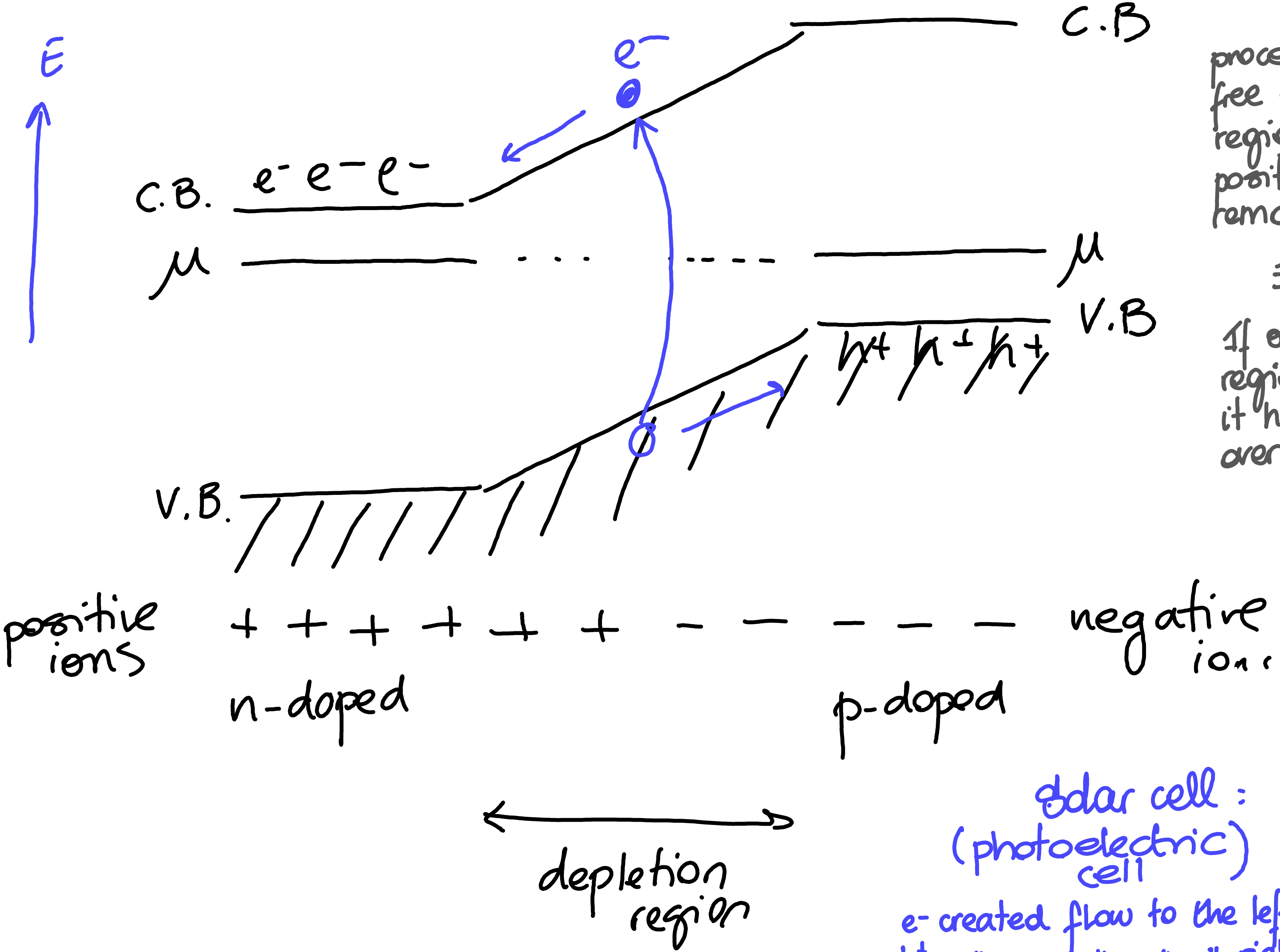
→ this annihilating process gains an energy E_{gap}

⇓

As a result, there will be a region close to the interface where there are no more free carriers

⇒ "depletion region" or "space charge region"





Due to annihilating processes, there are no more free carriers in the depletion region, but the negative and positive charged ions still remain there

$\Downarrow$

$\exists$ now a net electric field

If one e^- wants to cross this region to annihilate a h^+, it has an energy cost to overcome $-e\Delta\phi$ / electrostatic potential

$\Downarrow$

Depletion region width determined by energy compensation

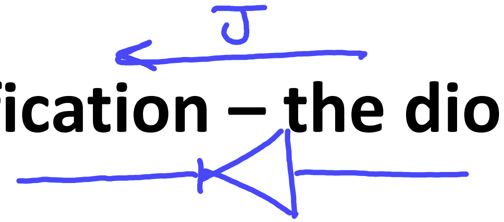
$E_g = e\Delta\phi$

solar cell (photoelectric cell) : put in phonons $\rightarrow$ get current

e^- created flow to the left (n-doped)
h^+ " " " " right (p-doped)

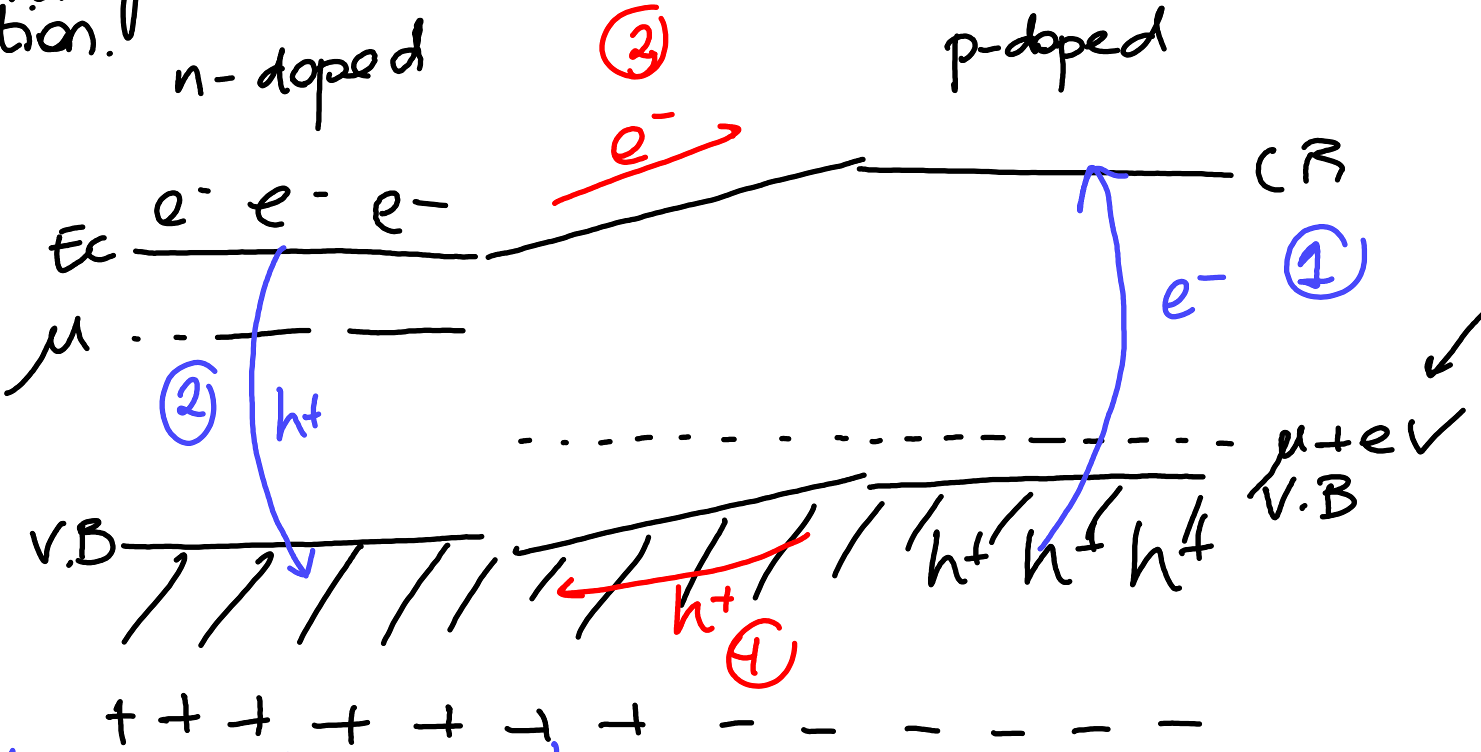
In both cases, current is moving to the right

p-n Junction: Rectification – the diode



another property of p-n junctions: allows current to flow easily in one direction but with very high R in the other

Let's apply a voltage to a pn junction.



bend downwards due to the applied voltage

Processes that can create current

①, ② # of carriers : typically activated form ~ e^{-E_g/k_BT} : $I_{right} \propto e^{-E_{gap}/k_BT}$

③ ④ e- in the CB at n-doped side (left diagram) might be termally activated to climb slope in the depletion region, and then annihilate with h at p side

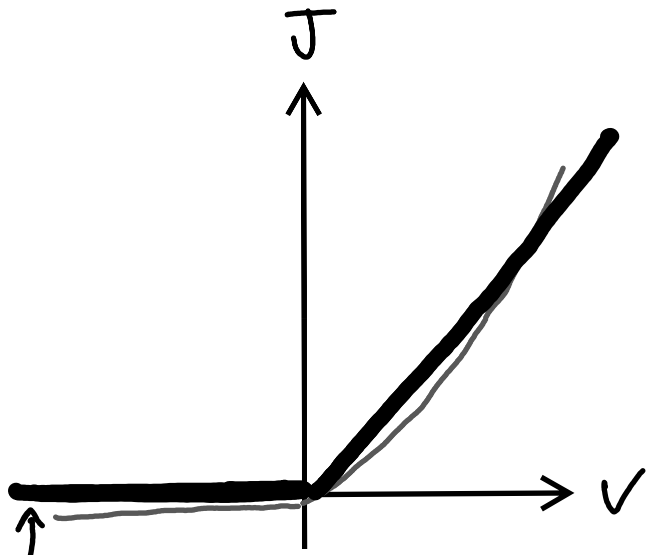
idem with holes

If voltage applied, height potential becomes E_g+eV ⇒ current of these processes $I_{left} \propto e^{-\left(\frac{E_{gap}+eV}{k_B}\right)}$

Total current $I_{left} + I_{right}$, and taking into account that $J(V=0)=0$:

$$J \sim \underbrace{e^{-\frac{E_{gap}}{k_B T}}}_{J_s\,=\,\text{saturation current}} \left(e^{-\frac{eV}{k_B T}} - 1\right)$$

DIODE EQUATION



Diode thought as circuit

symbol (current flows easy in the arrow direction)