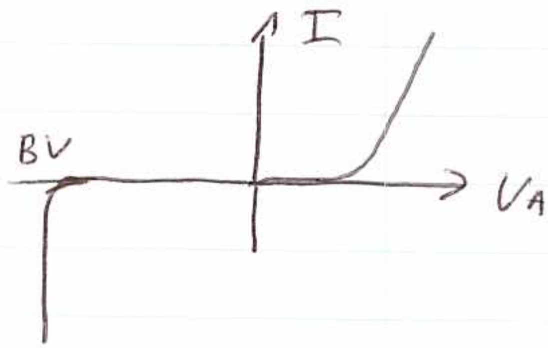
"impact ionization"

when an e^- is accelerated to high $\vec{\mathcal{E}}$, its kinetic energy can be equal or larger than the bandgap E_g.
That energy can be released through a collision event while creating e^--hole pair. So instead of having $1e^-$ at high energy, we have 2 free e^- + 1 hole.
we call it generation "by impact ionization".
$\Rightarrow$ avalanche multiplication phenomenon.

In the P-N junction a sudden increase of current is observed $\Rightarrow$ breakdown.



[BV = junction breakdown voltage.

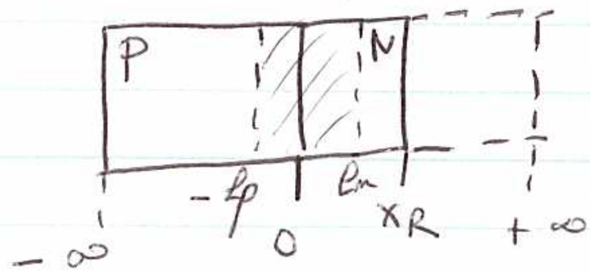
Remark:
If N-type and P-type region are heavily doped, the width of the depletion region is very small, and e^- can directly tunnel from P-type valence into N-type conduction band.
These diodes are called "Zener diodes" where can be accurately controlled while adjusting concentration.
Zener diode are then used as voltage reference.

(e) Short-base diode

previously we assume that the length of the P and N quasi-neutral region $\gg$ diffusion length of the minority carriers

the term 'short base' comes from bipolar transistors that consist in two P-N junctions PNP or NPN and the central region is called 'base'.

Consider a P-type region $\gg L_n$
a N-type region 'short base' compared to L_p.



the previous assumption $p_n(x \to +\infty) = p_{n0}$ must be replaced by $p_n(x_R) = p_{n0}$.

In addition the minority holes will not be able to recombine in the base $\Rightarrow J_p =$ cte. (constant)

$$J_p = -q D_p \frac{dp}{dx} \Rightarrow p(x) = -\frac{J_p x}{q D_p} + B \quad \left(\text{linear function}\right)$$

at $x = l_n$ $\quad p(x = l_n) = p_{n0} \exp(q V_A \beta)$.

$$\Rightarrow B = p_{n0} \exp(q V_A \beta) + \frac{J_p l_n}{q D_p}$$

* Abs

$$p(x_R) = p_{no} = -\frac{J_p x_R}{qD_p} + p_{no}\exp(qV_A\beta) + \frac{J_p l_n}{qD_p}$$

$$\Rightarrow \boxed{J_p = \frac{qD_p p_{no}}{x_R - l_n}\left[\exp(qV_A\beta) - 1\right]}$$

(4) PN junction Capacitance

So far we considered only steady state characteristics. In practical application, it is important to know how quickly the device can adjust to a new bias condition ('transient effects').

Capacitance calculation will help to estimate this 'time response' of the device.

Capacitance is measure of charge stored per unit change of voltage ⇒ if capacitance is large, this means more charge must be moved in or out, so that for a fixed current ⇒ more time is needed to complete the process.

In P-N junction two major capacitance:

(i) capacitance associated with the charge which must be moved in or out of the depletion region.
⇒ depletion capacitance

(ii) "diffusion capacitance" under forward bias due to minority carriers.

(1) <u>depletion capacitance</u>

we know that

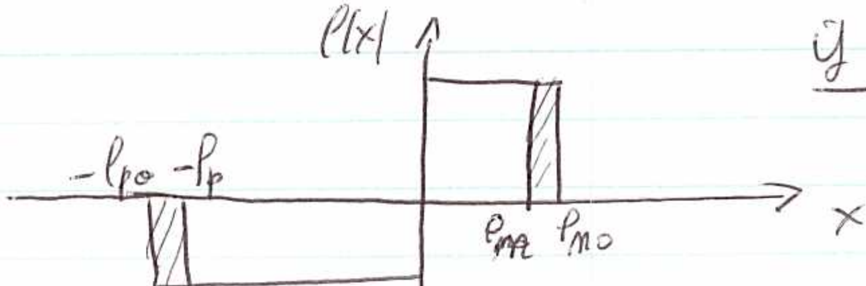
$$\begin{cases} l_p = \sqrt{\dfrac{2\epsilon}{q}\dfrac{(V_0 - V_A)N_d}{N_A(N_A+N_d)}} \\ l_n = \sqrt{\dfrac{2\epsilon}{q}\dfrac{(V_0 - V_A)N_A}{N_d(N_A+N_D)}} \end{cases}$$

the charge of the fixed, ionized doping impurities in each depletion region is (absolute value)

$$\boxed{Q = A\,q\,N_d\,l_n = A\,q\,N_A\,l_p}$$

in Coulombs.

[A = cross-section of the junction.



if $V_A > 0$

capacitance is $C_T = \left|\dfrac{dQ}{dV_a}\right| = A\,q\,N_d\left|\dfrac{dl_n}{dV_A}\right|$

$$\Rightarrow \boxed{C_T = A\frac{\epsilon}{l_n + l_p}}$$

== [Capacitance of parallel plate capacitor with a dielectric of permittivity ϵ.

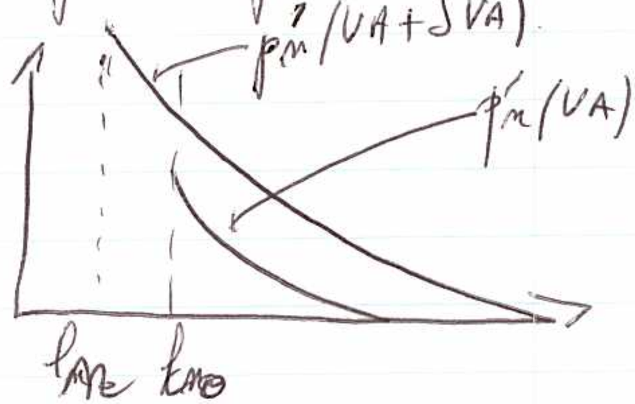
(ii) Diffusion capacitance

hole concentration in the n-type region

$$p_n(x) = p_{no} + p_{no}\left[\exp(q\beta V_A) - 1\right]\exp\left(\frac{-(x-l_n)}{L_p}\right)$$

excess concentration

$$p_n'(x) = p_n(x) - p_{no}$$



$\int_{l_n}^{+\infty} \ldots$ //

$$Q = q\int_{l_n}^{\infty} p_n'(x) = q\,p_{no}\left[\exp(qV_A\beta) - 1\right] \times L_p$$

$$\boxed{C_{D_p} = \frac{dQ}{dV_A} = \beta q^2 L_p\, p_{no}\exp(qV_A\beta)}$$

Also $\boxed{C_{D_p} = \beta q \tau_p J_p(l_n)}$

Similarly $C_{D_N} = \beta q \tau_n J_n(-l_p)$

$$\Rightarrow \boxed{C_D = C_{Dp} + C_{DN} = \beta q\left[\tau_p J_p(l_n) + \tau_n J_n(-l_p)\right]}$$

II Metal-semiconductor contacts

2 different types of metal-semiconductor contacts:

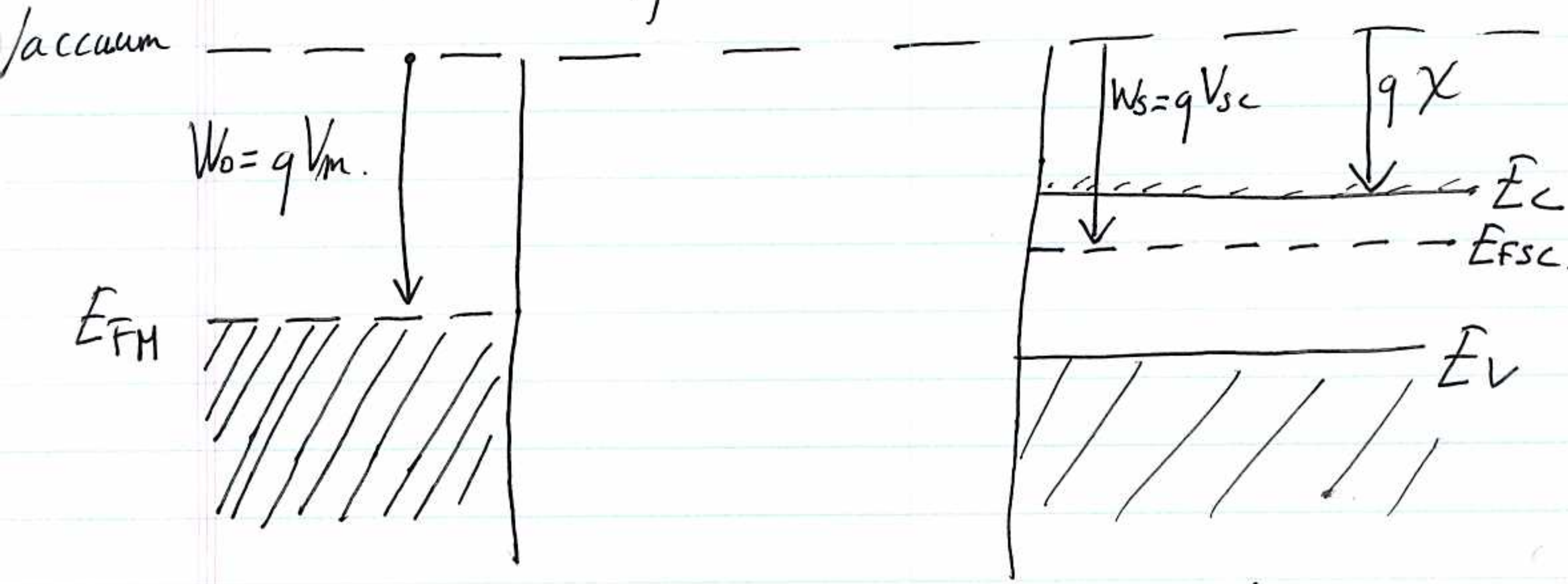
(i) a Schottky contact = non-linear, rectifying current voltage characteristics.

(ii) an Ohmic contact = linear, non-rectifying

(I) Schottky diode

(a) Unbiased junction

Consider a N-type semiconductor and a metal.



Metal

E_{FM} = Fermi-level of the metal.

W_0 = Work function

energy required to extract an e^- at E_{FM}

Semiconductor - N-type

E_{FSC} = Fermi level

W_S = Work-function.

$q\chi = e^-$ affinity

⇒ energy required to extract an e^- from the CB to vaccum.

(energy of e^- in CB ~ E_c).

We consider $E_{FM} < E_{FSC}$.

* Since $E_C > E_{FM}$, e^- flow from the semiconductor to the metal until a new equilibrium will be reached. e^- leave behind positively charged donor atoms and a depletion region is formed in the semiconductor. (W is the width)

Because of the alignement of the Fermi-levels ⇒

we get a band curvature $qV_i = q(V_m - V_{sc})$ which correspond to a potential barrier preventing further e^- to migrate into the metal.

E^- in the metal see a potential barrier V_b.

$$qV_b = q(V_m - \chi) = qV_i + (E_C - E_F).$$

qV_i, qV_B much larger than $\frac{k_BT}{q}$, only few e^- can overcome them at room temperature.
the resulting current of e^- migrating from the semiconductor to the metal is $I_{m \to s}$ (negative charge).

At thermodynamic equilibrium $I_{m \to s} = -I_{s \to m}$.

(b) biased junction

* if a forward bias $V_A > 0$ is applied to the junction

$$V_i \to V_i - V_A$$

more e^- can flow from the semiconductor to the metal. however $I_{S \to M}$ remains constant since V_b is unchanged

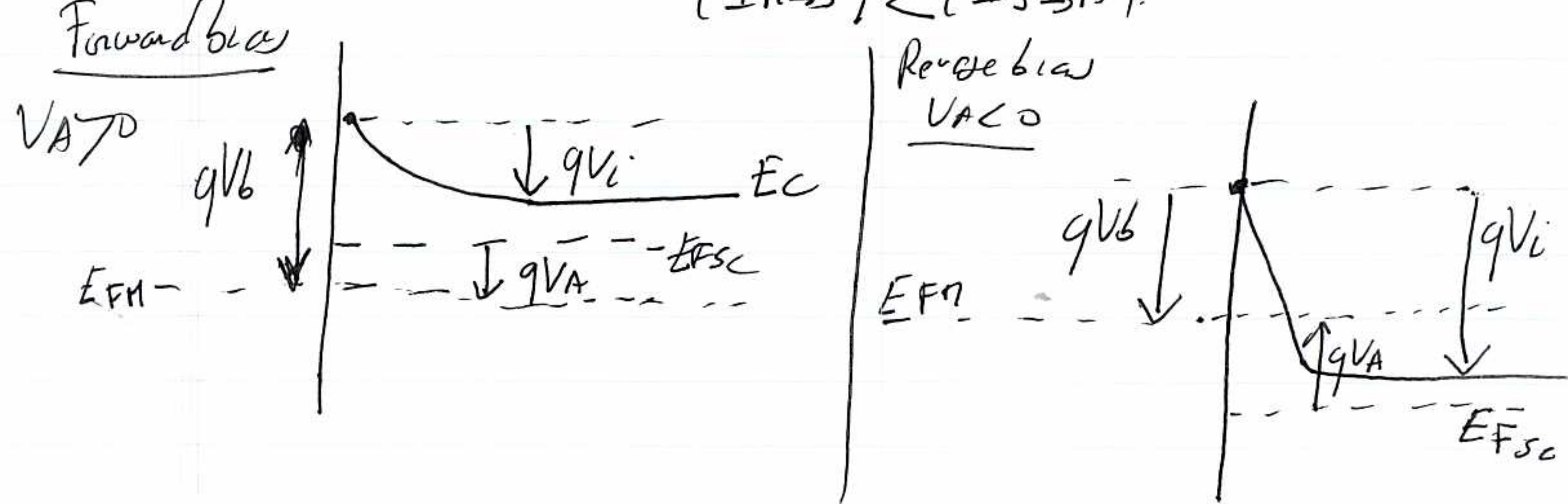
$$|I_{M \to S}| > |I_{S \to M}|$$

* if Reverse bias $V_A < 0$ is applied to the junction.

$$V_i \to V_i - V_A$$

the electron flow from the semiconductor to the metal is reduced. $I_{S \to M}$ remains unchanged

$$|I_{M \to S}| < |I_{S \to M}|.$$



The width of the depletion zone can be calculated using the Poisson equation + depletion approximation.

$$-\frac{d^2 V(x)}{dx^2} = \frac{\rho}{\epsilon} = +\frac{q N_d}{\epsilon}$$

at $x = W$ $V(W) = 0$ and $\frac{dV(W)}{dx} = 0$.

$$\Rightarrow \quad +\frac{dV(x)}{dx} = \frac{q N_d}{\epsilon}(W - x)$$

$$\boxed{V(x) = -\frac{q N_d}{2\epsilon}(W - x)^2}$$

at $x = 0$ $V(0) = V_i - V_A$.

$$\Rightarrow \quad -(V_i - V_A) = -\frac{q N_d}{2\epsilon} W^2$$

$$\Rightarrow \quad \boxed{W = \sqrt{\frac{2\epsilon}{q N_d}(V_i - V_A)}}$$

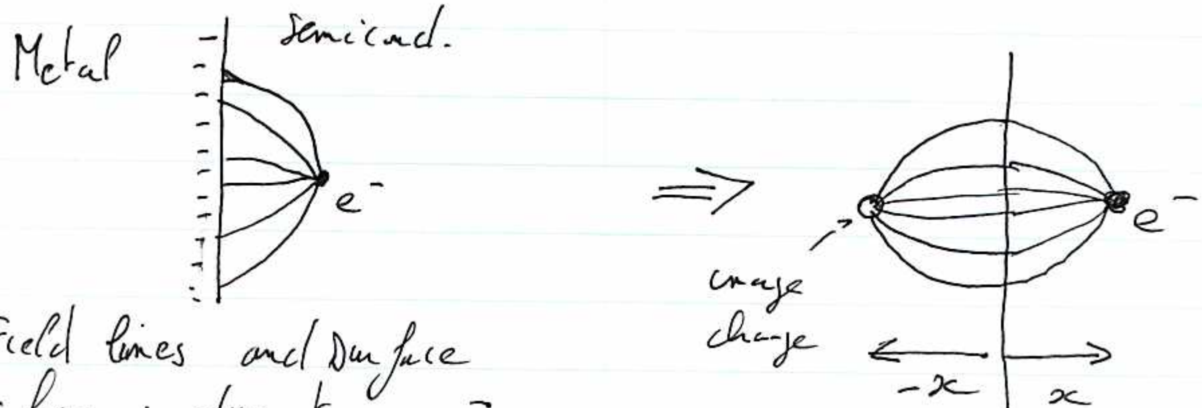
$$\Rightarrow \quad \boxed{\mathcal{E}(0) = \frac{-q N_d}{\epsilon} W = -\sqrt{\frac{2 q N_d}{\epsilon}(V_i - V_A)}}$$

$$\boxed{\mathcal{E}(x) = -\frac{q N_d}{\epsilon}(W - x)}$$

(c) Schottky effect

A lowering of V_b is observed due to a mirror charge produced in the metal by e^- in the semicond

From Electrostatics, we know that when a charge is near a "perfect conductor", a mirror charge of same magnitude but opposite sign is created inside the conductor.



Field lines and surface charges due to an e^- in close proximity to a perfect conductor

electrostatics force between 2 particles $\Rightarrow$

$$F(x) = \frac{-q^2}{4\pi\epsilon(2x)^2} \Rightarrow \text{potential energy } \phi(x) = -\int_x^\infty \frac{F}{q}\,dx$$

$F = q\mathcal{E}$
$\mathcal{E} = -\nabla V$
$U = -qV$

$$\mathcal{E} = \frac{\nabla U}{q} \Rightarrow F = \nabla U \Rightarrow \boxed{U = \frac{-q^2}{16\pi\epsilon x}} \quad \frac{-q^2}{16\pi\epsilon x}$$

For an e^- in the conduction band the potential energy is $\frac{-q^2 N_d (W-x)^2}{2\epsilon} + E_c$