(c) Deviation from ideality

See Fig. 6.9

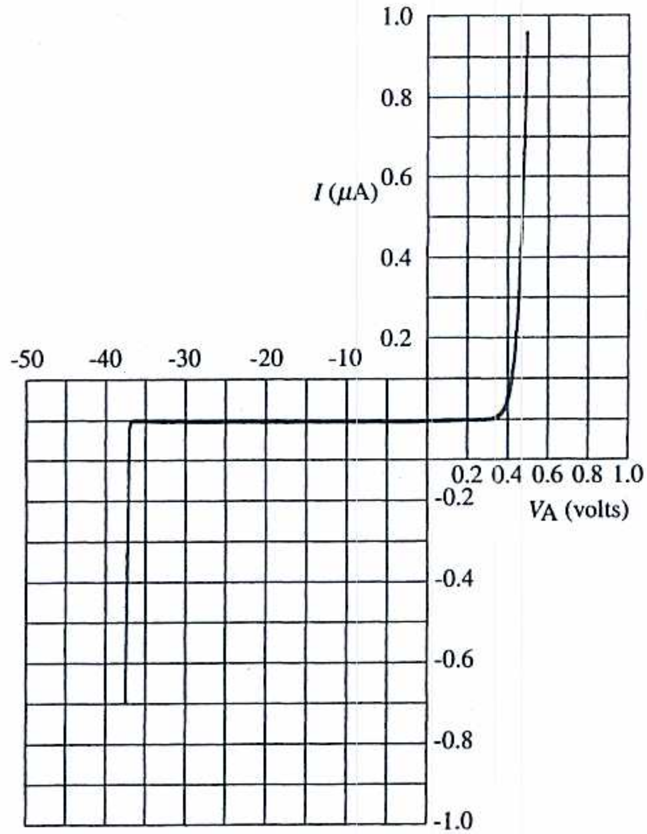


Figure 6.9 Linear plot of the measured I–V characteristic derived from a commercially available Si *pn* junction diode maintained at room temperature. The plot permits a coarse evaluation of the diode characteristic. Note the change in voltage scale in going from forward to reverse bias.

in Semi-log plot we get Fig 6.10a and Fig 6.10b

Some observations :

Reverse Bias

- For $V_A < 0$, the current does not saturate (Fig 6.10b) but continue to increase (still very small) and finally we get a "breakdown" for large reverse bias.

Forward Bias

- For $V_A > 0$, ideal characteristics are obtained between (0.35 – 0.7V); for small V_A the slope (in Fig. 6.10a) is $\neq$ than q/k_BT and equal to $\frac{q}{2k_BT}$; for large V_A ($V_A \to V_{bi}$) the slope progressively decreases $\Rightarrow$ "slope over"

(ii) The R-G current

we consider Generation/Recombination in the depletion region (transition region).

we know that these processes are proportional to $np - n_i^2$.

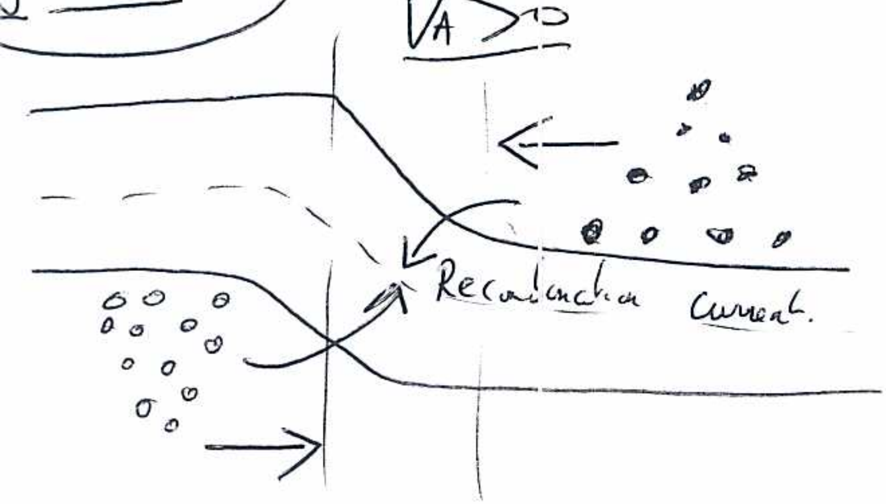
in the transition region we established that

$$\boxed{np = n_i^2 e^{qV_A/k_BT}} \quad (6.12)$$

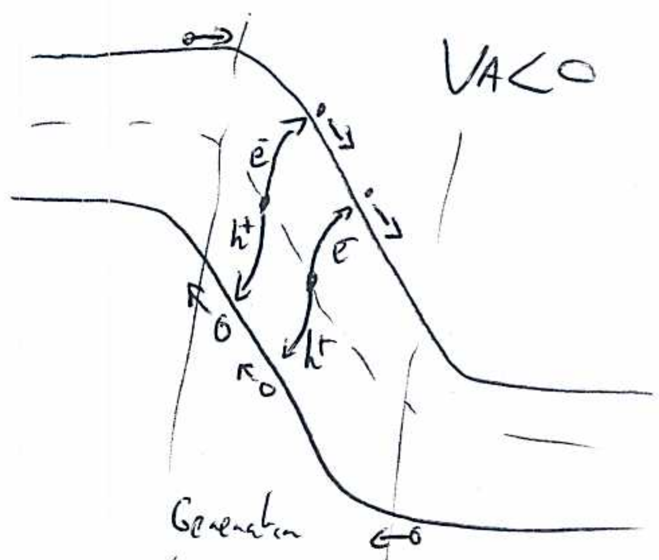
if $V_A > 0$ $\quad np > n_i^2 \Rightarrow$ Recombination current can be observed in the transition region

if $V_A < 0$ $\quad np < n_i^2 \Rightarrow$ Generation current will be observed in the transition region.

Fig 6.15 b/a



R-G current will decrease ideal current.



R-G current will be added to ideal current.

For the ideal case we said that U_n and $U_p = 0$

in 6.7a / 6.7b and then $\left[\begin{array}{l} J_n(x_n) = J_n(-x_p) \\ J_p(x_n) = J_p(-x_p) \end{array}\right.$

the current is constant in the transition region.

here we have $\boxed{\dfrac{dJ_n}{dx} = -\dfrac{dJ_p}{dx} = qU}$ from continuity equation at the steady states

U is the intrinsic R/G

$$\Rightarrow \int_{-x_p}^{x_n} \frac{dJ_n}{dx}\, dx = \int_{-x_p}^{x_n} qU(x)\, dx$$

$$\Rightarrow \quad J_n(x_n) = J_n(-x_p) + q \int_{-x_p}^{x_n} U(x)\, dx$$

the net current is

$$J = J_p(x_n) + J_n(x_n) = \underbrace{J_p(x_n) + J_p(-x_p)}_{J_{ideal/diff}} + J_{G/R}$$

(6.47) $$\boxed{J = J_{diff} + J_{G/R}}$$

using the SRH mechanism (trap assisted) ~~we~~

one can derive an expression for $J_{G/R}$

we can obtain expression (6.45)

$$\boxed{J_{R/G} = q\frac{n_i}{2\tau_0} W \frac{e^{qV_A/k_BT} - 1}{\left(1 + \frac{V_{bi} - V_A}{k_BT/q} \frac{\sqrt{\tau_n \tau_p}}{2\tau_0} e^{qV_A/2k_BT}\right)}}$$

if $V_A > 0$ (forward)

Small bias

the I-V follows $\left[\exp\left(\frac{qV_A}{2k_BT}\right)\right]$ law $\Rightarrow$ [Characteristics of a Recombination dominated current]

Larger bias

the I-V follows $\left[\exp\left(\frac{qV_A}{k_BT}\right)\right]$ law $\Rightarrow$ [Diffusion current takes over and completely overshadows the Recombination current]

if $V_A < 0$

$J_{R/G}$ is added to J_{diff}.

So the current keep increasing (slowly) with $V_A \searrow$

(ii) Junction breakdown

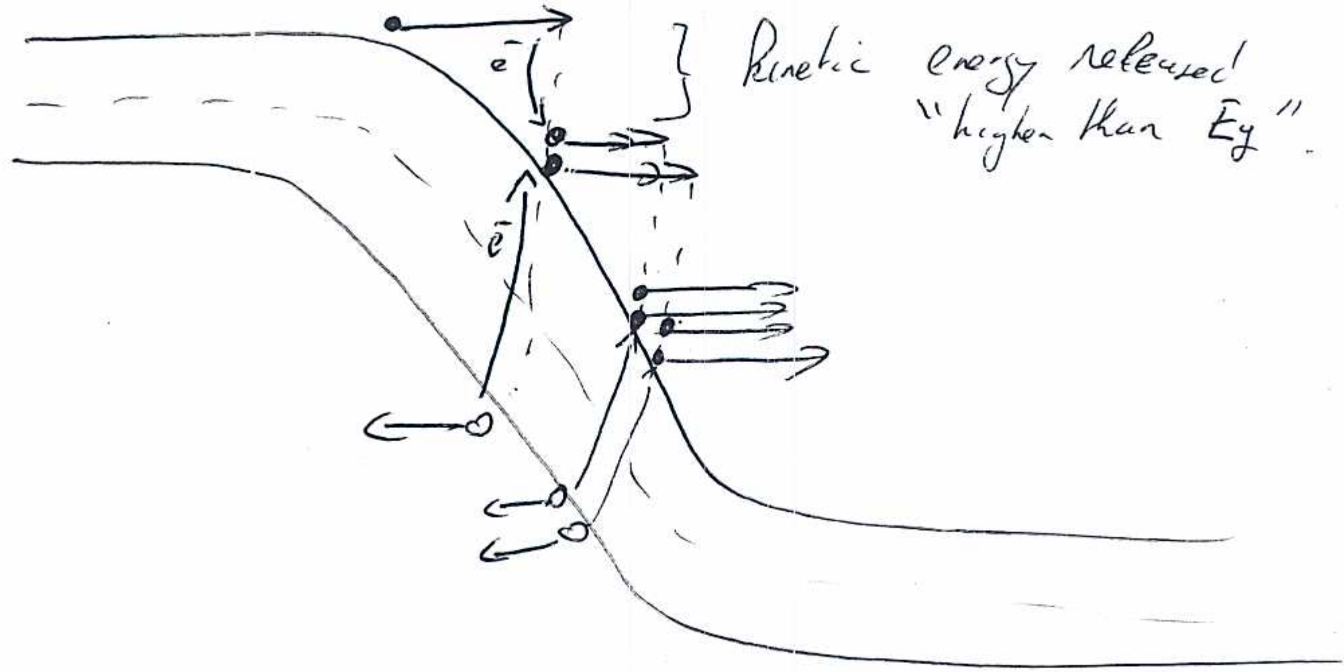
if $V_A < 0$ strongly reversed biased, $\vec{\mathcal{E}}$ near the metallurgical junction can reach high values. Carriers accelerated in that field can accumulate enough kinetic energy that they can, through a collision process, generate $\bar{e}$-h^+ pairs through "impact ionization".

Impact ionization :

when an $\bar{e}$ is accelerated to high electric field, its kinetic energy can be equal or larger than the bandgap E_g. That energy can be released through a collision event, while creating an $\bar{e}/h^+$ pair. So instead of having one $\bar{e}$ at high energy, we get 2 free e^- + 1 hole. We call it "generation by impact ionization"

$\Rightarrow$ avalanche multiplication phenomenon.

Fig 6.12

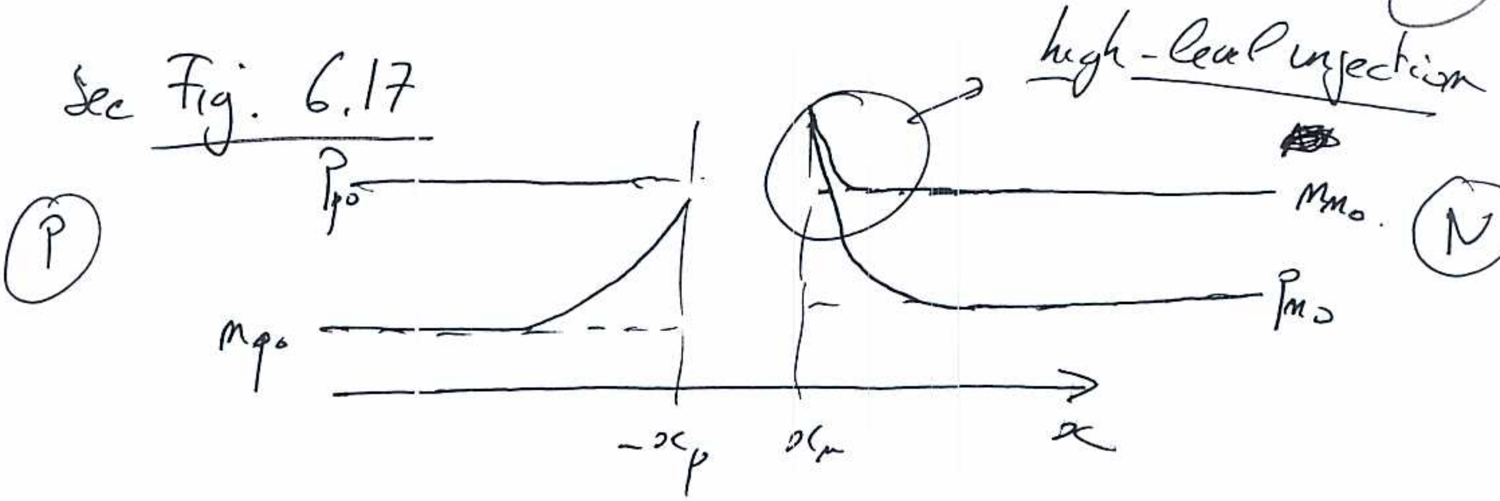


In the P-N junction a sudden increase of current is observed $\Rightarrow$ breakdown.

(iii) <u>high-level injection</u>

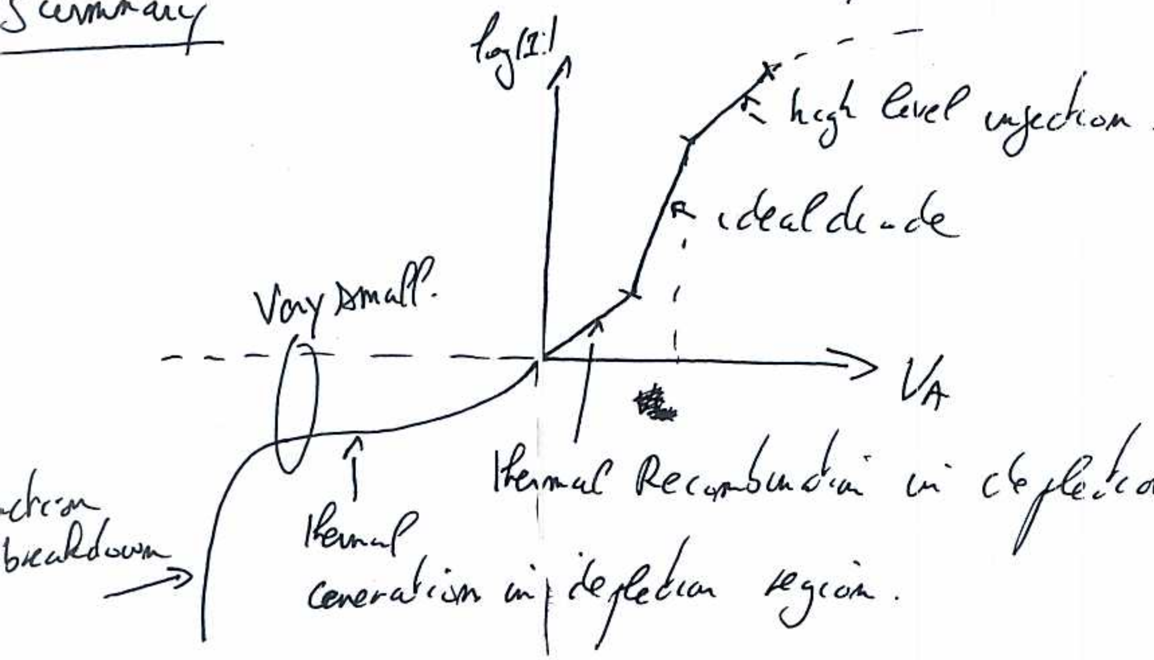
if $V_A \to V_{bi}$ the ideal diode equation begins to fail. Indeed the low-level injection of h^+ from $N \to P$ or e^- for $P \to N$ is not valid anymore.

See Fig. 6.17



The new current will vary ~ as $\exp\left(\frac{q}{2k_BT}\right)$

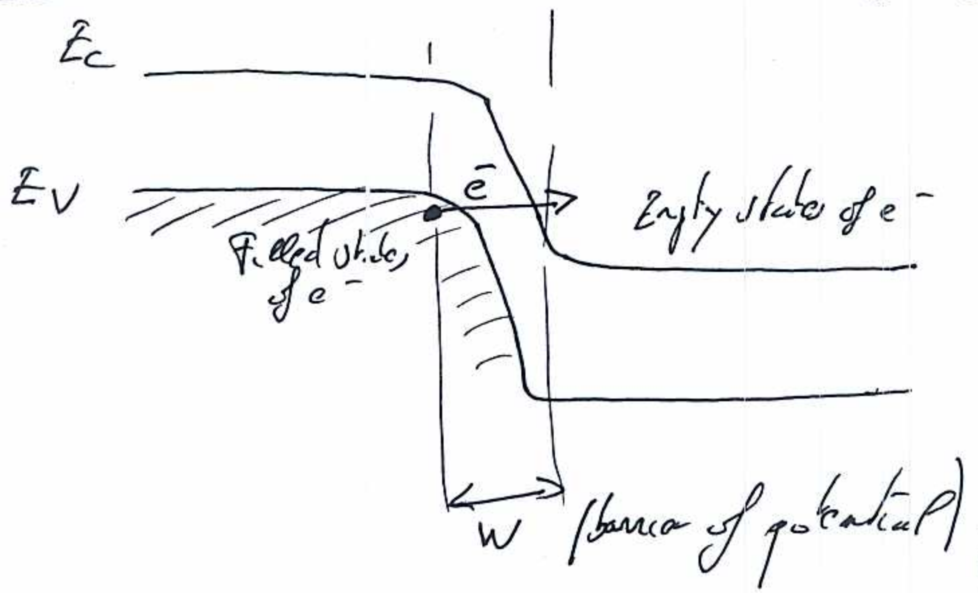
Summary



(d) Zener diodes

if N-type and P-type are heavily doped, the width of the transition region is very small.
$\Rightarrow$ quantum tunneling appears in Reverse-bias regime.

Fig 6.14



$\bar{e}$ can directly ~~tunnel~~ tunnel from P-type valence band to N-type conduction band!

$\Rightarrow$ equivalent to

Fig 6.13

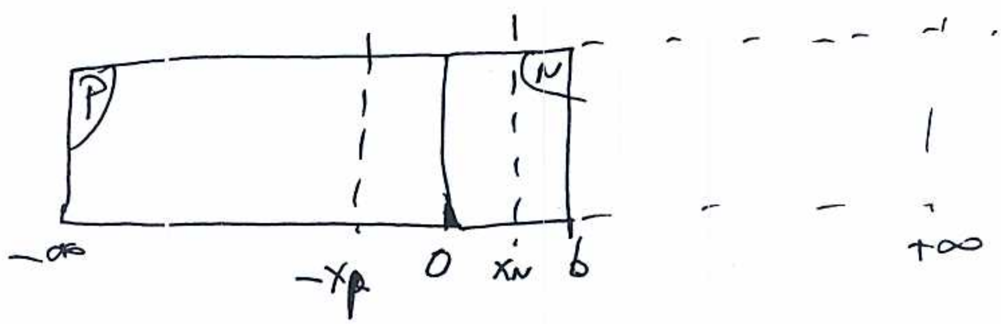
These diodes are called "Zener diodes" when the ~~the~~ voltage breakdown can be accurately controlled while adjusting the impurity concentration.

Zener diodes are then used as voltage reference.

(e) Narrow-base diodes

previously, we assumed that the length of the P and N regions $\gg$ diffusion length of the minority carriers (L_p, L_n).

the term (short-base) or (narrow-base) comes from bipolar transistors that consist in 2 P-N junctions PNP or NPN and the central region is called 'base'.



the previous assumption for calculating the minority carriers in the N region $p_n(x \to +\infty) = p_{no}$ must be replaced by $p_n(b) = p_{no}$.

Also $\Rightarrow$ the minority holes will not be able to recombine in the narrow base $(b \sim L_p)$ $\Longrightarrow$ J_p is then constant $0 \leq x < b$.

etween $\;\; J_p = -qD_p \frac{dp}{dx} \Rightarrow \boxed{p(x) = -\frac{J_p x}{qD_p} + B}$ $\;\; p(x)$ is linear
$\leq x \leq b$

at $x = x_n$ we know that $\Big\}\; p(x_n) = p_{no} \exp\left(\frac{qV_A}{k_BT}\right)$

$$\Rightarrow \quad B = p_{no} \exp\left(\frac{qV_A}{k_BT}\right) + \frac{J_p x_n}{qD_p}$$

$$\Rightarrow \quad p(x) = -\frac{J_p}{qD_p}(x - x_n) + p_{no} \exp\left(\frac{qV_A}{k_BT}\right)$$

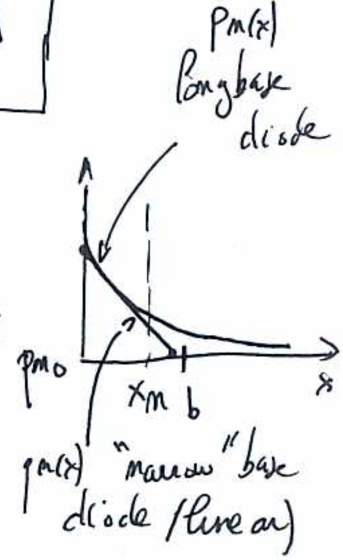
at $\underline{x = b}$

$$p(b) = -\frac{J_p}{qD_p}(b - x_n) + p_{no} \exp\left(\frac{qV_A}{k_BT}\right) = p_{no} .$$

$$\Rightarrow \boxed{J_p = \frac{qD_p\, p_{no}}{b - x_n}\left[\exp\left(\frac{qV_A}{k_BT}\right) - 1\right]}$$

quation
equivalent to
.68)
.69)
e
miting case
6.71a / 6.72a
6.73
nd explanation below.

~~Summary~~



6 P_N junction Capacitance.

So far, we considered steady state characteristics, however, it is also important to know how quickly the device can adjust to a new bias condition.

Capacitance calculations will help to estimate this "time response" of the device.

- Capacitance is a measure of charge stored per unit charge of voltage.

⇒ this means if capacitance is large, 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 junctions, two major capacitance:

(a) Capacitance associated with the charge which must be moved in or out of the depletion region.

$\Rightarrow$ depletion capacitance.

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

(a) <u>Depletion capacitance</u>

we know that

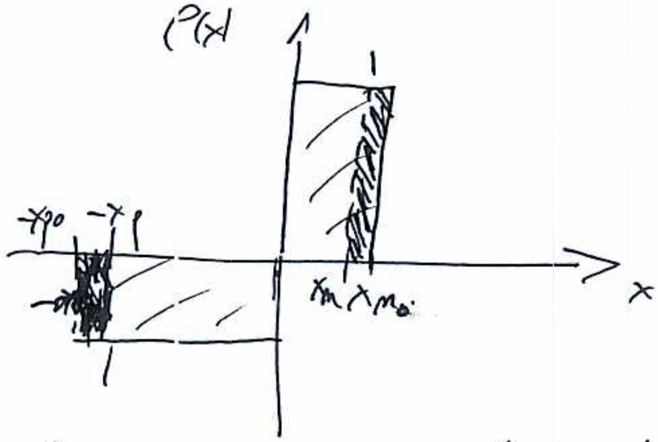
$$x_p = \sqrt{\frac{2\epsilon}{q}\frac{N_d(V_{bi}-V_A)}{N_A(N_A+N_d)}}$$

$$x_n = \sqrt{\frac{2\epsilon}{q}\frac{N_A(V_{bi}-V_A)}{N_D(N_A+N_D)}}$$

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

$$\boxed{Q = A\,q N_d x_n = A q N_A x_p}$$

A = cross section of the device.



$x_{no}, -x_{po} \Rightarrow V_A$

$x_n, -x_p \Rightarrow V_A + \Delta V_A$

$\Delta V_A > 0$

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

after calculation

$$\Rightarrow \boxed{C_T = \frac{A \epsilon}{x_n + x_p}} = \frac{A \epsilon}{W} \quad (x_n + x_p = W).$$

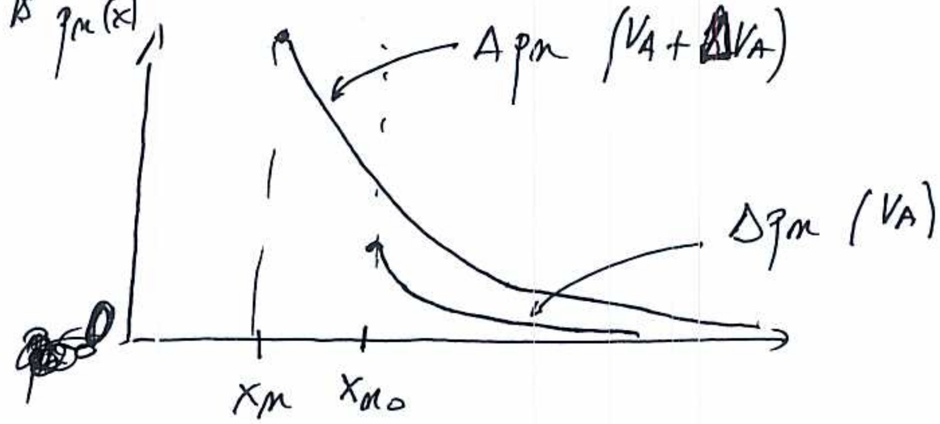
$\Rightarrow$ it is the capacitance of parallel plate capacitor with a dielectric of permittivity ϵ.

(B) Diffusion capacitance

Let us look at the hole concentration in the N-type region.

$$p_n(x) = p_{no} + p_{no}\left[\exp\left(\frac{qV_A}{k_BT}\right) - 1\right] e^{-\frac{(x-x_n)}{L_p}}$$

excess concentration is $\Delta p_n(x) = p_n(x) - p_{n0}$.



$$Q = q \int_{x_n}^{+\infty} \Delta p_n(x) = q\, p_{n0} \left(\exp\left(\frac{qV_A}{k_BT}\right) - 1 \right) * L_p .$$

$$\boxed{C_{D_p} = \frac{dQ}{dV_A} = \frac{q^2 L_p}{k_BT}\, p_{n0} \, \exp\left(\frac{qV_A}{k_BT}\right)}$$

diffusion capacitance for P-side

Also $\quad C_{Dp} = \dfrac{q\,\tau_p}{k_BT} J_p(x_n)$

Similarly $\quad C_{Dn} = \dfrac{q\,\tau_n}{k_BT} J_n(-x_p)$

$$\boxed{C_D = C_{Dp} + C_{Dn} = \frac{q}{k_BT}\left[\tau_p J_p(x_n) + \tau_n J_n(-x_p)\right]}$$