Reverse Bias – Junction C dominates reactance.

Forward Bias – Charge Storage C dominates.

Here, have I and $\mathcal{E}$ so some charge Q across junction. But V lags I.

→ Due to stored charge.

Stored charge in injected hole distribution.

S&B Figure 5-16(b)

$$Q_p = qA\int_0^{\infty} \delta p(x_n)\, dx_n$$

$$= qA\,\Delta p_n \int_0^{\infty} e^{-x/L_p}\, dx_n$$

$$= qA\,\Delta p_n L_p$$

$$= qA L_p p_n \left(e^{qV/kT} - 1\right)$$

$$= qA L_p p_n e^{qV/kT}$$ for $qV \gg kT$ in forward bias

Capacitance due to small changes in Q

$$C_s = \frac{dQ_p}{dV} = \frac{q^2 A L_p p_n}{kT} e^{qV/kT}$$

$$=$$

So C_s directly proportional to Q_p

Note: $\frac{q}{kT} = \frac{\text{charge}}{\text{energy}} = \frac{\text{charge}}{\text{charge-voltage}} = \frac{1}{\text{Voltage}}$

So $C_s \propto \frac{Q}{\text{Voltage}}$ analogous form as parallel plate capacitor

---

$$I = \frac{Q_p}{\tau_p} = \frac{\text{stored charge}}{\text{characteristic time to replenish recombining charge}}$$

$C_s =$

So C_s directly proportional to τ_p

(Need to reduce for high-ω circuits)

D/L = L/τ since $L^2 = D\,\tau$

Now can get AC conductance.

$$G_s = \frac{dI}{dV} = \frac{d}{dV}\left(qA\frac{L_p}{\tau_p}p_n e^{qV/kT}\right)$$

$$= q^2 A \frac{L_p}{\tau_p kT} p_n e^{qV/kT}$$

$$= \frac{q}{kT}\frac{Q_p}{\tau_p} = \frac{q}{kT} I = \frac{C_s}{\tau_p}$$

$$i_{AC} = \frac{dQ}{dt} = \frac{d}{dt}(C_s v_{a\text{-}c}) = \frac{dC_s}{dt} v_{a\text{-}c} + C_s \frac{dv_{a\text{-}c}}{dt}$$

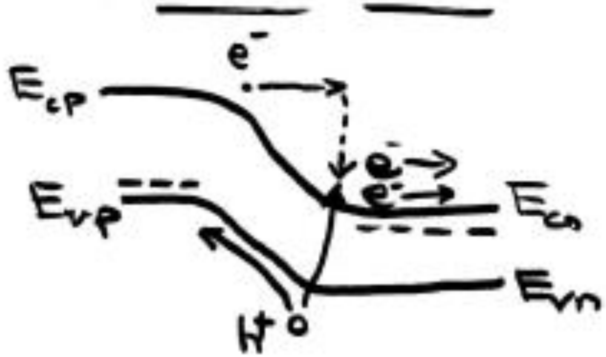
$$= G_s v_{a\text{-}c} + G_s \tau_p \frac{dv_{a\text{-}c}}{dt}$$

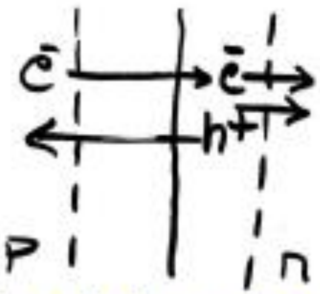
$$C_s = \frac{q}{kT} I \tau_p$$

$$\frac{dC_s}{dt} = \frac{q}{kT} I_{d\text{-}c} = G_s$$

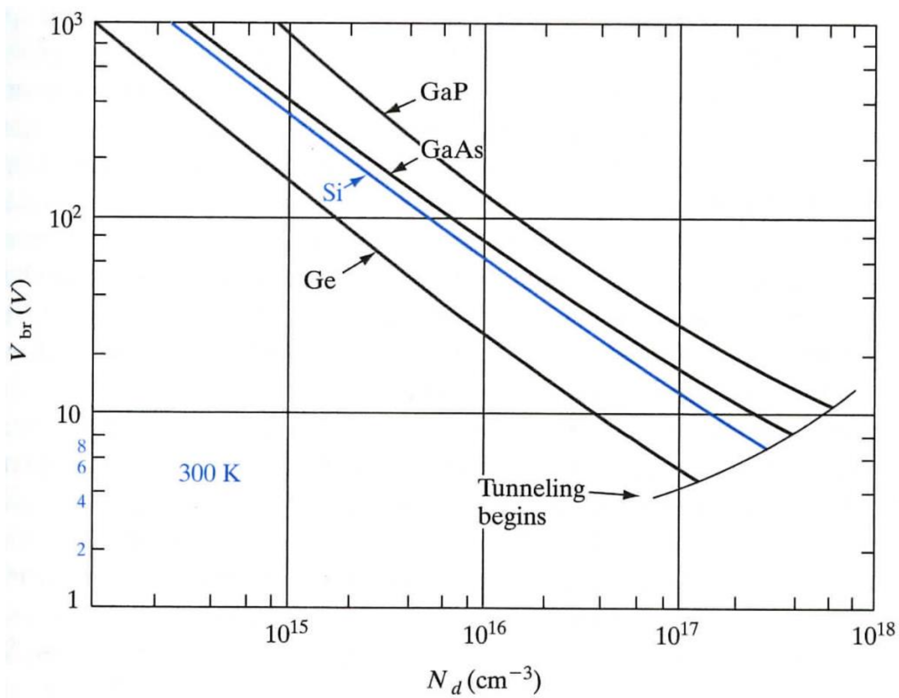
Reduce τ_p to improve a-c response.

P-N Junction: Avalanche Breakdown

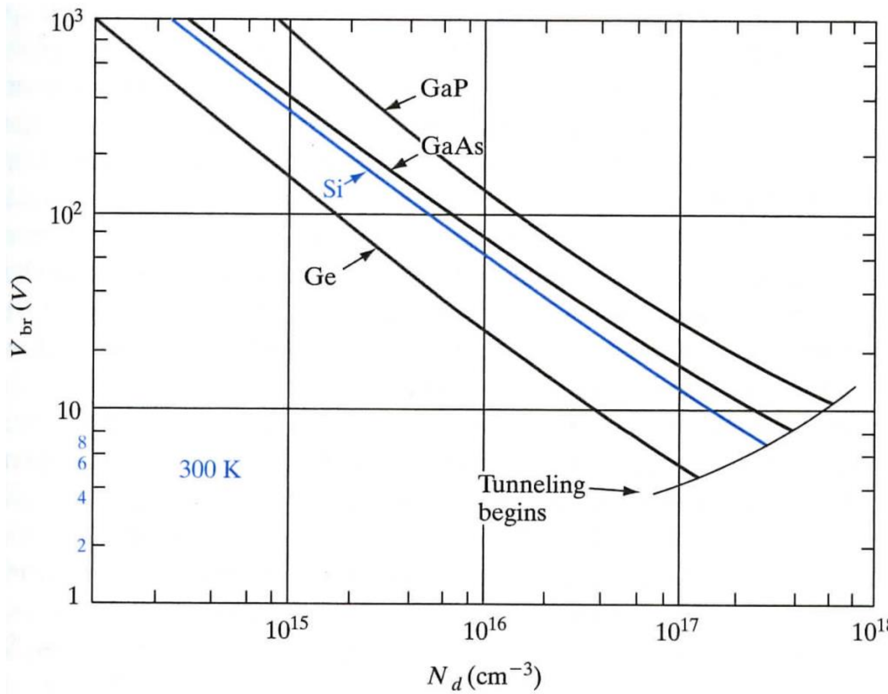




Electron's extra kinetic energy creates electron-hole pairs

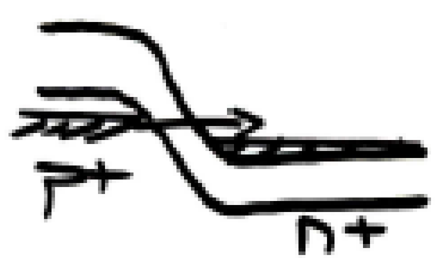


S&B Figure 5-22



Breakdown Voltage V_{Br} increases with ______ and decreases with ______ ______

Tunneling:



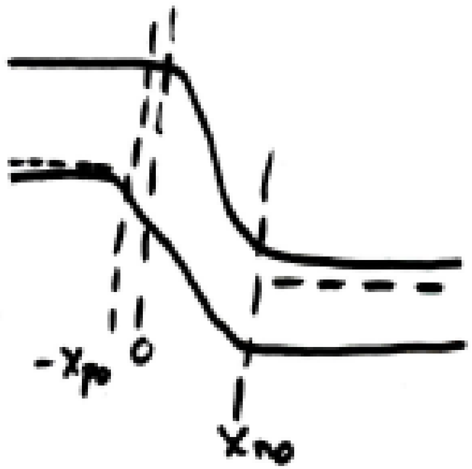
W very narrow

Critical Field at Breakdown

Consider p^+-n "one-sided" junction

$$x_{no} \gg x_{po}$$

$$W = x_{no} + x_{po} \sim x_{no}$$



$$\max \mathcal{E} = -\frac{q N_d x_{no}}{\epsilon}$$

$$x_{no} = \frac{W N_a}{N_a + N_d} = \frac{N_a}{N_a + N_d}\left[\frac{2\epsilon V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

For $N_a \gg N_d$, $x_{no} = \left[\dfrac{2\epsilon V_0}{q N_d}\right]^{1/2}$

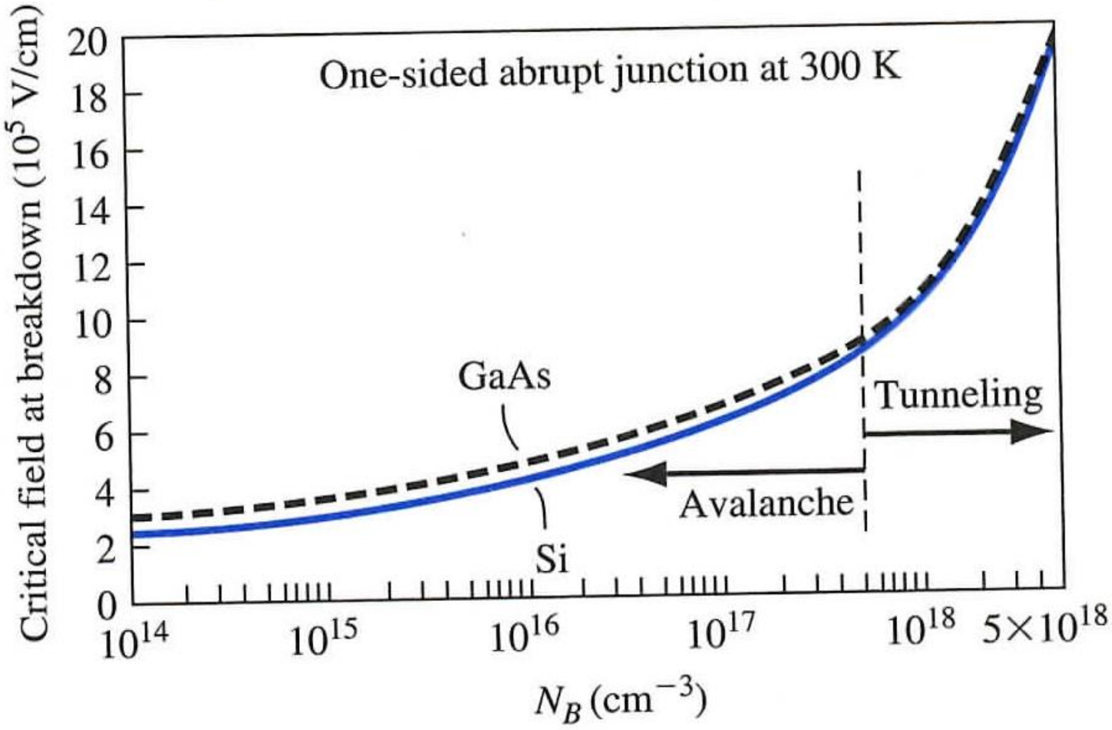
For reverse bias

$$X_{no} = \left[\frac{2\epsilon (V_o + V_r)}{q N_d} \right]^{1/2}$$

$$X_{no} = \frac{\epsilon \mathcal{E}_{max}}{q N_d} = \left[\frac{2\epsilon (V_o + V_r)}{q N_d} \right]^{1/2}$$

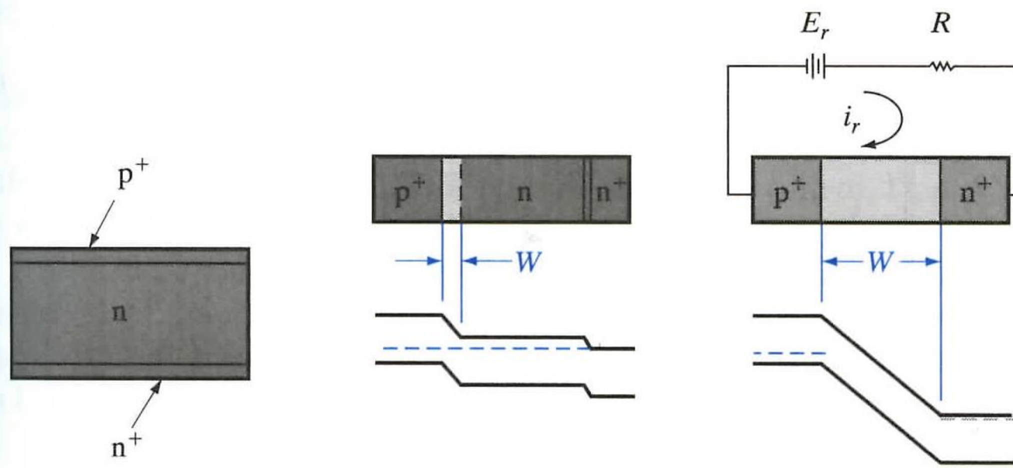
$$(V_o + V_r) = \frac{\epsilon^2 \mathcal{E}_{max}^2}{q^2 N_d^2} \cdot \frac{q N_d}{2\epsilon} = \frac{\epsilon \mathcal{E}_{max}^2}{2 q N_d}$$

$= \mathcal{E}_{critical}$ (



Neamen
Fig. 7-14

P-N Junction "Punch-Through"



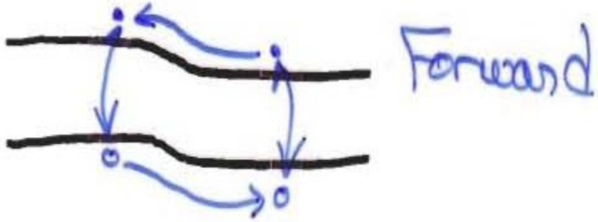
Depletion width expands across entire length L of n-region

→ Breakthrough occurs below V_{Br}

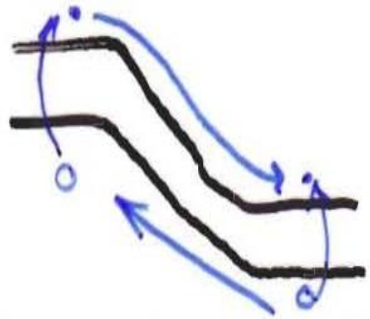
$$X_{no} = \left[\frac{2\epsilon(V_o + V_r)}{qN_d}\right]^{1/2} = L$$

Recombination / Generation in Transition Region

We assumed $W \ll L_n, L_p$ so



Recombination in Neutral Regions



Generation + Diffusion of minority carriers to transition regions.

Now consider Transition region processes too for $W \sim L_n, L_p$

so recombination takes place both outside and inside W.

Forward

Free carriers available $\propto n_i$

Calculation shows:

$$I^{\text{transition}}_{\text{recombination}} \propto e^{qV/2kT}$$

inside W

vs. P_n and n_p, a.k.a.

plus increases as $e^{qV/kT}$ outside W.

$$I_{total} = I^{\text{neutral}}_{\text{recombination}} + I^{\text{inside W, transition region}}_{\text{recombination}}$$

Outside Inside

$$= I_1\left(e^{qV/kT} - 1\right) + I_2\left(e^{qV/kT\cdot 2} - 1\right)$$

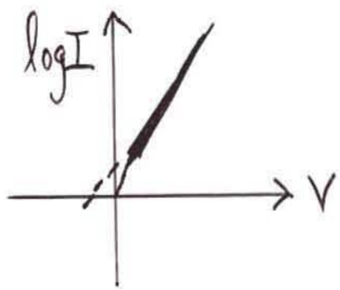
$$\simeq I_0'$$

analogous to diode equation

$n \equiv$ ideality factor

$n > 1$ represents departure from ideality

$$\text{Ratio: } \frac{I^{\text{neutral}}_{\text{recombination}}}{I^{\text{transition}}_{\text{recombination}}} \propto \frac{n_i^{2} e^{qV/kT}}{n_i e^{qV/2kT}} \propto n_i e^{qV/2kT}$$



When ratio is small, n goes up.

Ratio small for n_i small

Ratio small for V small.

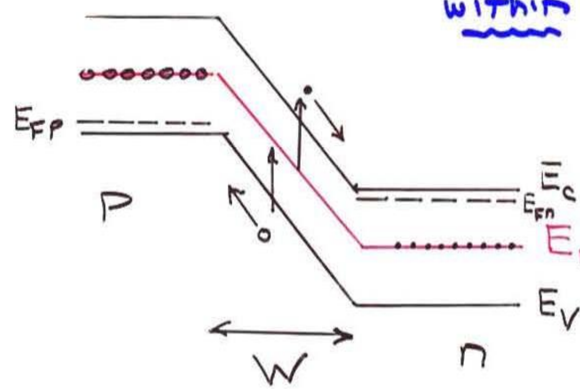
Reverse

- Now generate carriers within W thermally.

correction

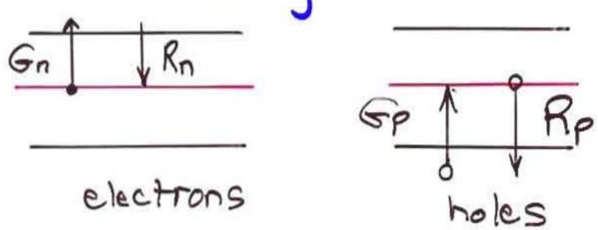
Reverse: generation

Forward: recombination



Recombination

For $V=0$, generation and recombination balance.

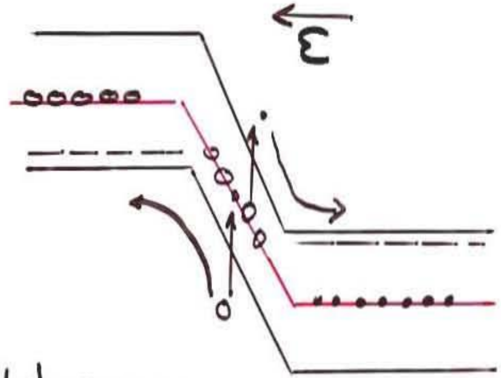


For $V = V_{reverse}$, carriers swept out,

so recombination negligible.

Net result: generation $G_n \gg R_n$
$G_p \gg R_p$

→ Net current flow.



Levels near mid-gap
most effective.

Net reverse current

Why?
Minimum E required to excite both e^- and h^+

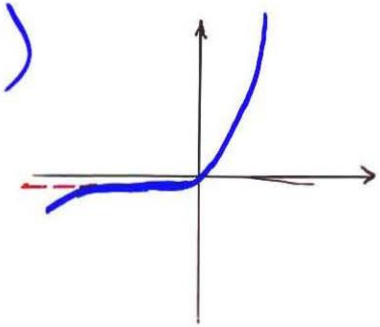
How to get?

Also Ohio State research!

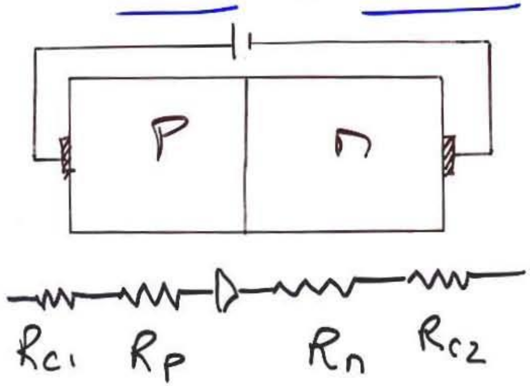
Generation increases with V_r.

Why?

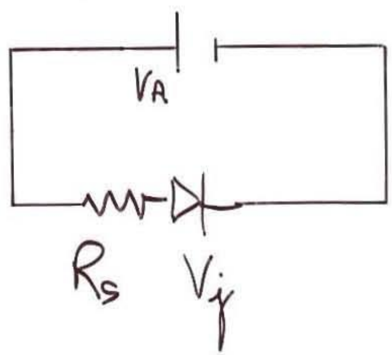
( )



Ohmic (or Contact) Losses



Can't neglect resistance in neutral region or external contacts



R_c = contact resistance (typically 10^{-5} – 10^{-6} Ω cm)

$R =$

R_s = series resistance

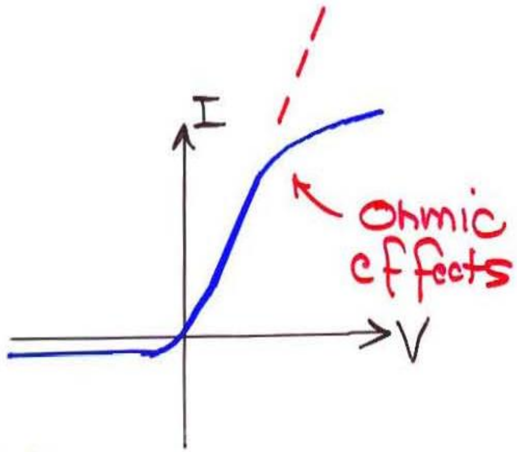
$= R_c + R_n + R_p$

R_s = series resistance

$= R_c + R_n + R_p$

V_A = applied voltage

$V_j = V_{junction} = V_A - IR_s$



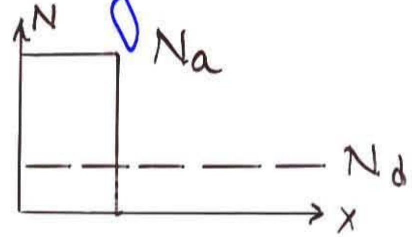
Added complication: $\sigma = ne\mu$ increases with higher voltage so R_n and R_p decrease $R_n(I)$, $R_p(I)$

Avoid ohmic effects: Large A; operate device at I below non-ohmic range.

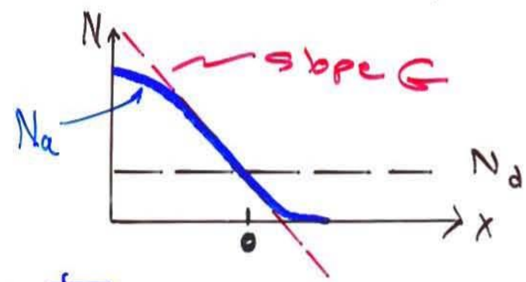
Graded Junctions

Contrast abrupt step junction (alloy, epi growth) with graded junction (diffused)

Recall abrupt:



Graded:



N profile spreads out

$N_d - N_a = Gx$ $\qquad$ G = gradient

$$\frac{d\mathcal{E}}{dx} = \frac{q}{\epsilon}\left(p - n + N_d^+ - N_a^-\right)$$

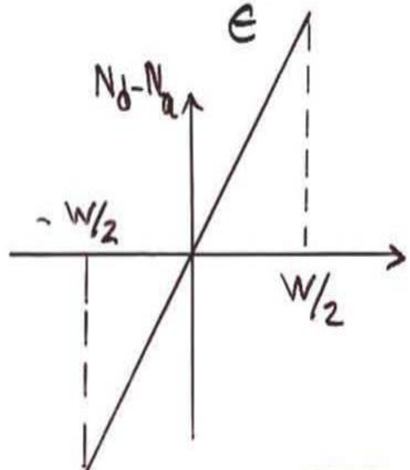
$$\simeq \frac{q}{\epsilon}\, a x$$

assume $N_d = N_d^+$

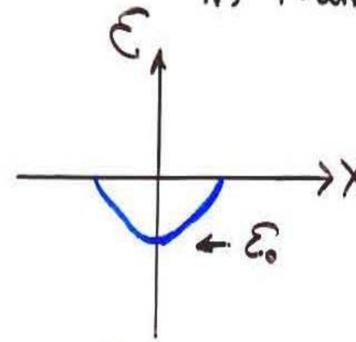
$N_a = N_a^-$

and $n \sim p \sim 0$

in transition region

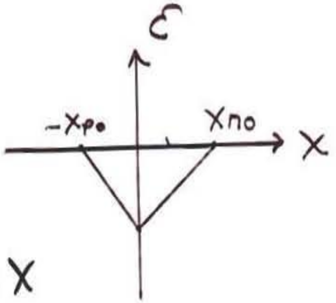


Net Impurity Profile



$\mathcal{E} \propto x^2$ so Parabolic

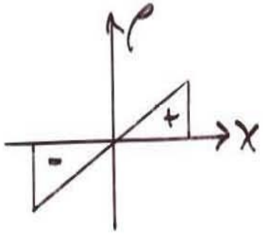
versus linear:



$$|Q| = \int \rho A\, dx = qA\int_0^{W/2} G x\, dx$$

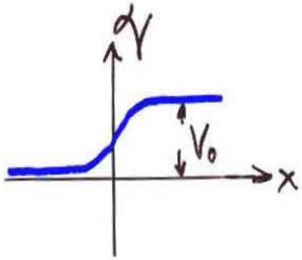
$$= qA\frac{G}{2}x^2\Big|_0^{W/2}$$

$$= qA\frac{GW^2}{8}$$



Charge greatest at edges of transition region

$$V = -\int \mathcal{E}\, dx \propto x$$



Most results derived for abrupt junctions can also apply to graded junctions (e.g., generation, recombination, injection)

But some alterations in functional form of equations.

So basic concepts still hold.