EECS130
Integrated Circuit Devices

Professor Ali Javey

9/20/2007

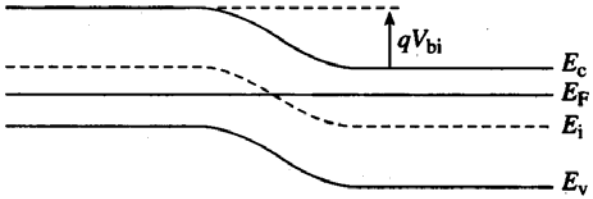
PN Junctions
Lecture 2

Reading: Chapter 5

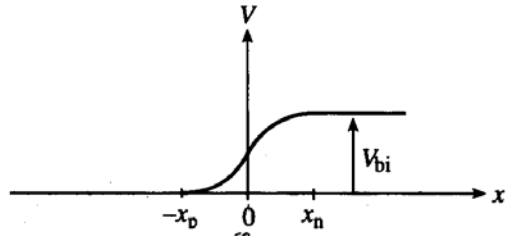
Announcements

- For THIS WEEK ONLY, Prof. Javey's office hours will be held on Tuesday, Sept 18 3:30-4:30 pm and Wednesday, Sept 19 5-6 pm.
- *Exam 1 (Oct 4) will cover Semiconductor Fundamentals, Fabrication, and PN junctions.*
- HW2 is due…… right now.
- HW3 is now posted on the web.
- You can check your grades on bspace.
- Check out the group discussion board.

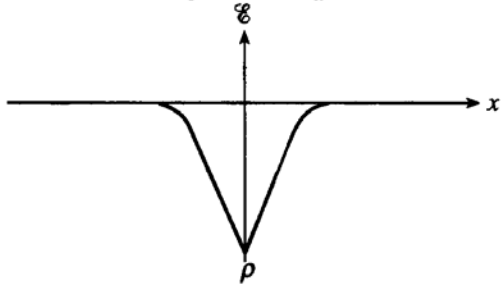
Review: Qualitative Electrostatics



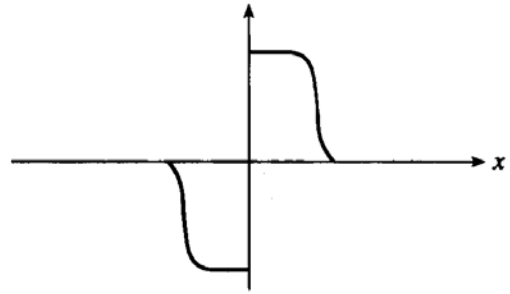
Band diagram

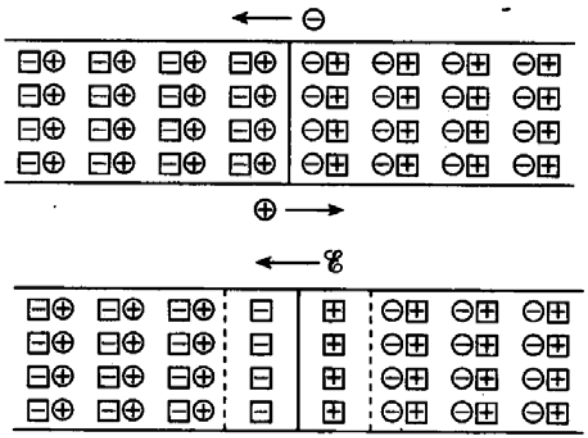


Built in-potential



From ε=-dV/dx





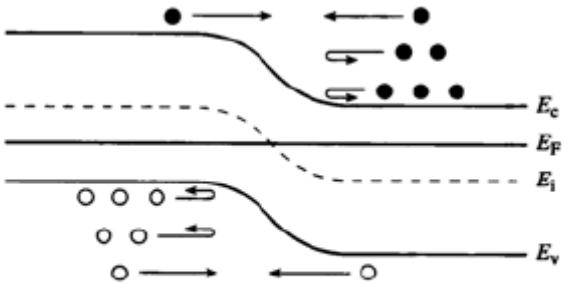
Review: Poisson's Equation

$$\frac{d^2V}{dx^2} = -\frac{d\mathcal{E}}{dx} = -\frac{\rho}{\varepsilon_s}$$

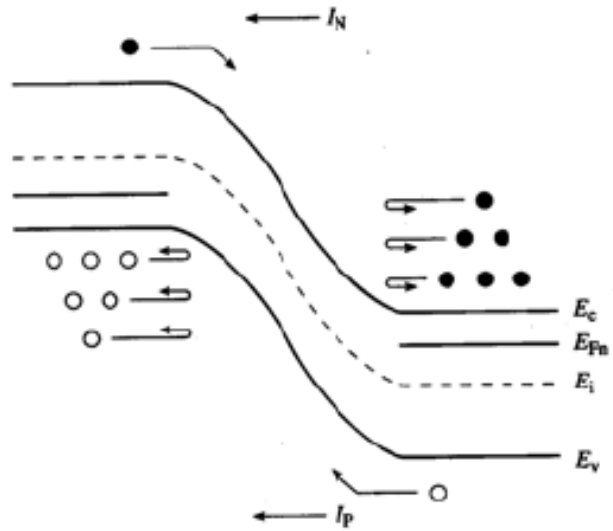
→ ***What can Poisson's equation tell us?***

ε_s: semiconductor permittivity (~12ε_o for Si)
ρ: charge density (C/cm^3)

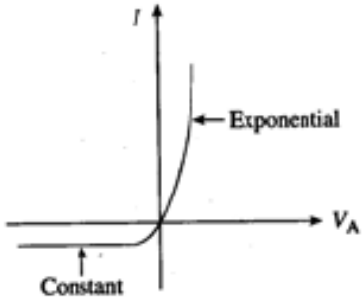
Reverse-Biased PN Junction



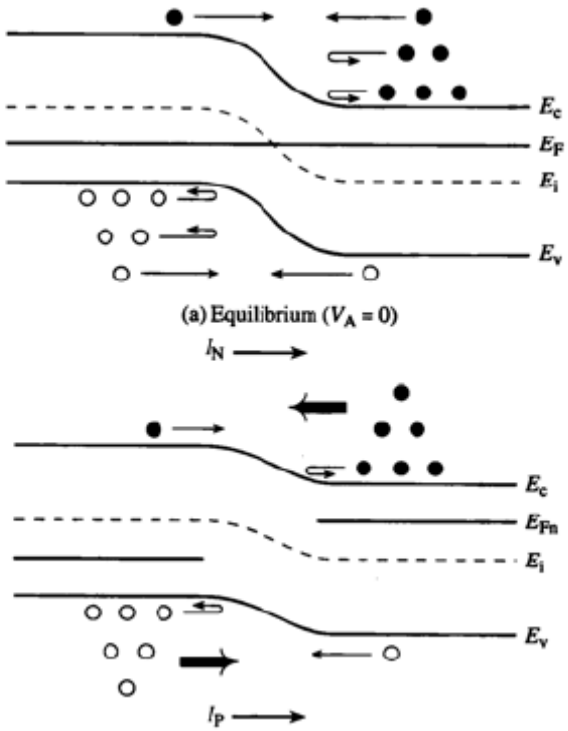
(a) Equilibrium ($V_A = 0$)



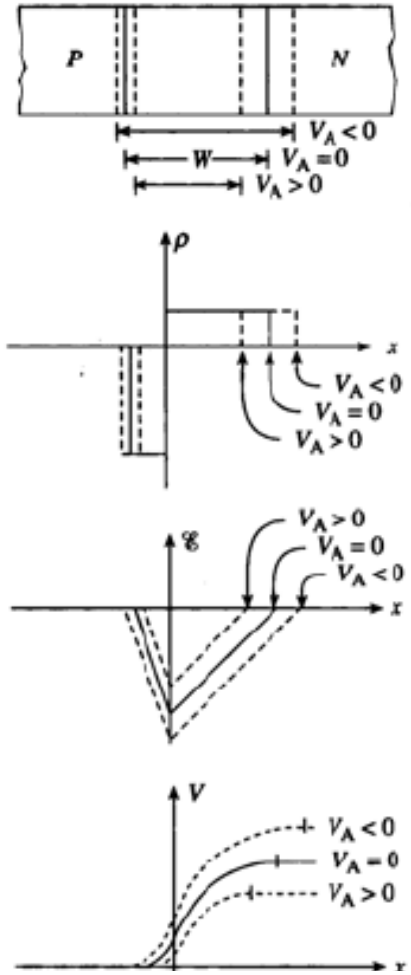
(c) Reverse bias ($V_A < 0$)

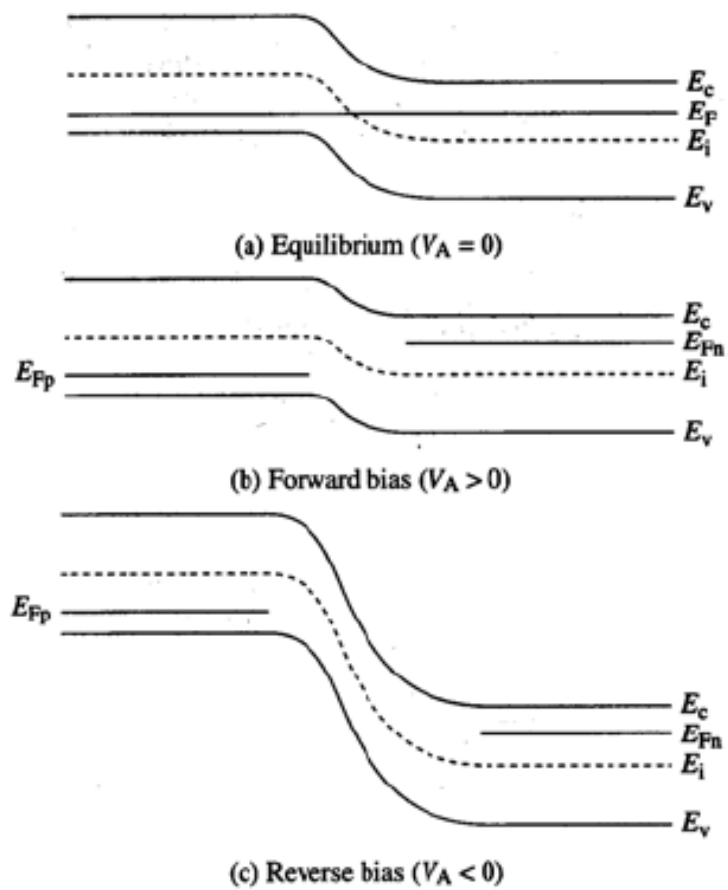


Forward Biased PN Junction



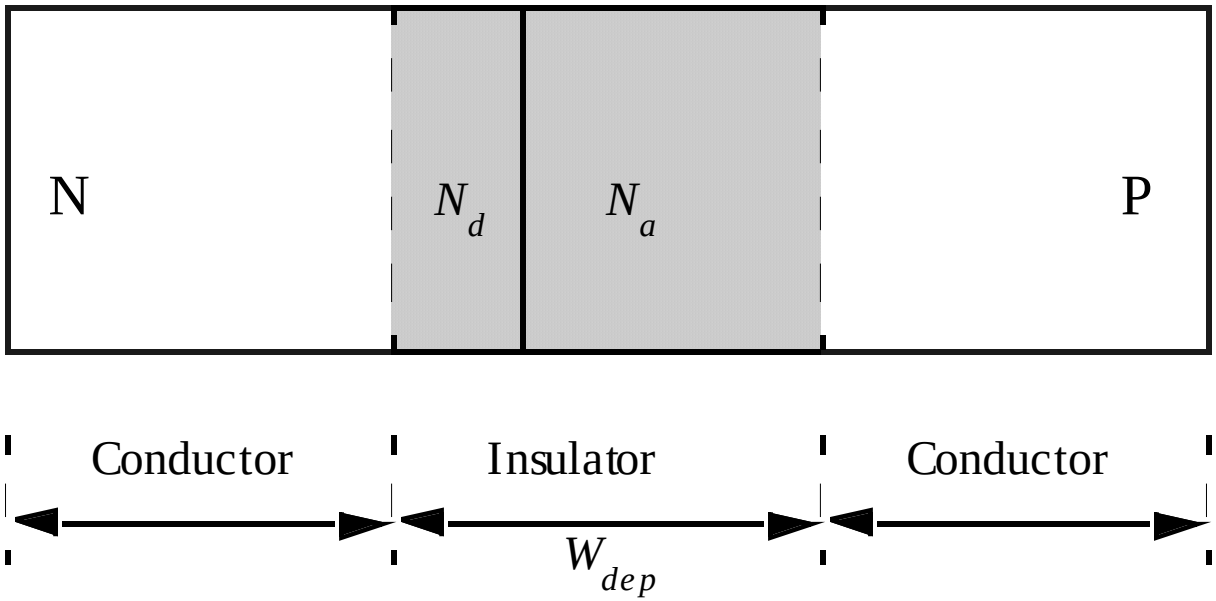
Effect of Bias on Electrostatics





Note: simply replace V_{bi} with V_{bi}-V_A

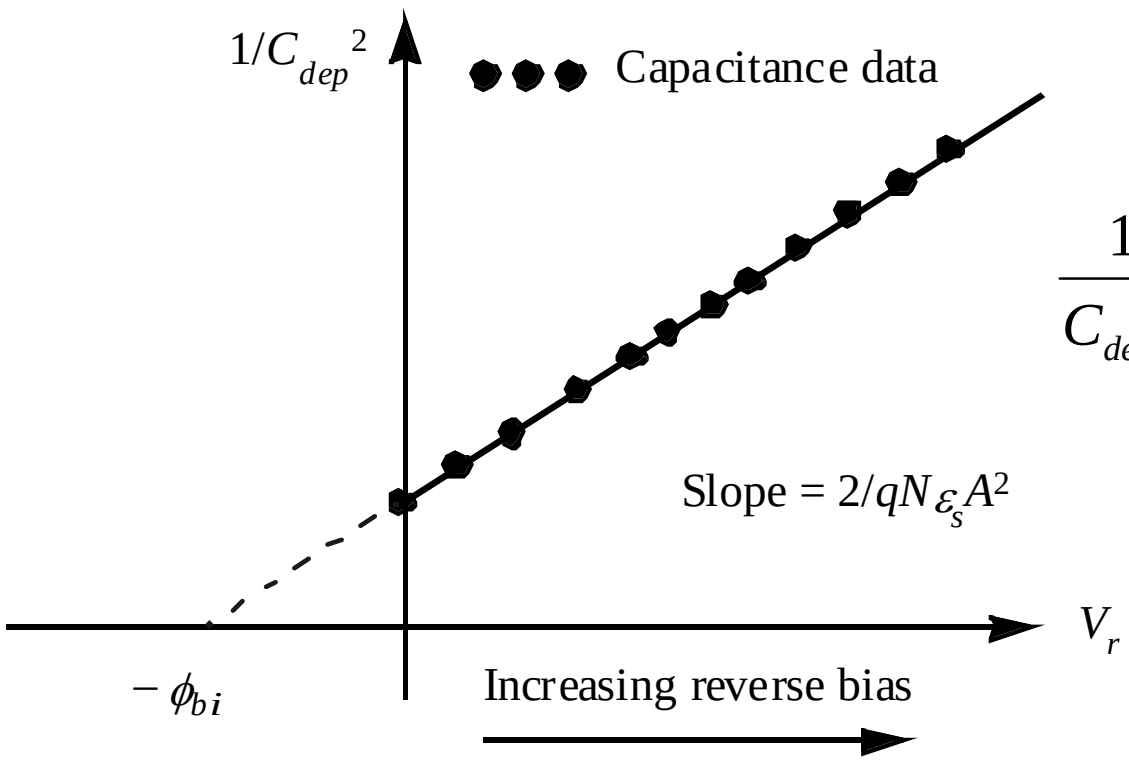
Capacitance-Voltage Characteristics



$$C_{dep} = A\frac{\varepsilon_s}{W_{dep}}$$

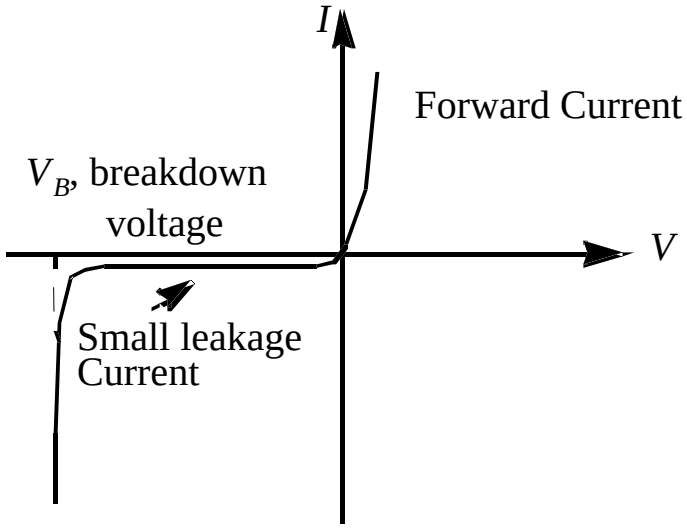
- Is C_{dep} a good thing?
- What are three ways to reduce C_{dep}?

Capacitance-Voltage Characteristics



$$\frac{1}{C_{dep}^{\ 2}} = \frac{W_{dep}^{\ 2}}{A^2 \varepsilon_s^{\ 2}} = \frac{2(\phi_{bi} + V)}{qN\varepsilon_S A^2}$$

Junction Breakdown



A ***Zener diode*** is designed to operate in the breakdown mode.

Reverse Bias Junction Breakdown

A large reverse current flows when the voltage exceeds certain value. Not destructive unless power dissipation causes excessive heating.

For a p^+n or pn^+ diode: $V_{BR} \propto N^{-1}$

where V_{BR} is the breakdown voltage and N is the (bulk) doping on the lightly doped side.

<u>Two processes</u>:

Avalanching: Dominant process in lightly doped diodes

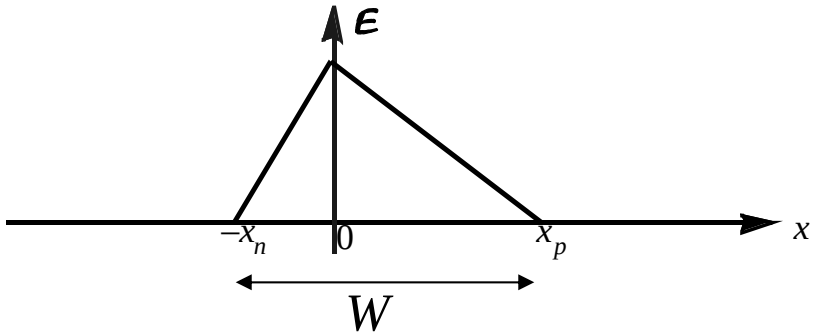
Zener process: More important in heavily doped diodes

Peak Electric Field

$$\left| \int \mathcal{E}\, dx \right| = \frac{1}{2} |\mathcal{E}(0)| W = V_{bi} - V_A$$

- For a **one-sided junction**: $W \cong \sqrt{\frac{2\varepsilon_s}{qN}(V_{bi} - V_A)}$

therefore $\mathcal{E}(0) = \frac{2(V_{bi} - V_A)}{W} \cong \sqrt{\frac{2qN(V_{bi} - V_A)}{\varepsilon_s}}$



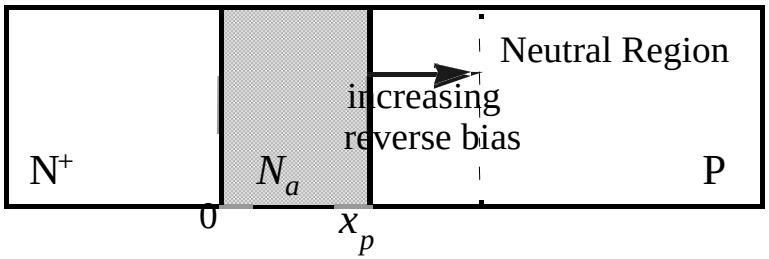
- If $V_{reverse} = -V_A$ is so large such that the peak electric field exceeds a critical value $\mathcal{E}_{crit}$, then the junction will break down (large reverse current will flow)

$$\mathcal{E}_{crit} = \sqrt{\frac{2qN(V_{bi} + V_{BR})}{\varepsilon_s}}$$

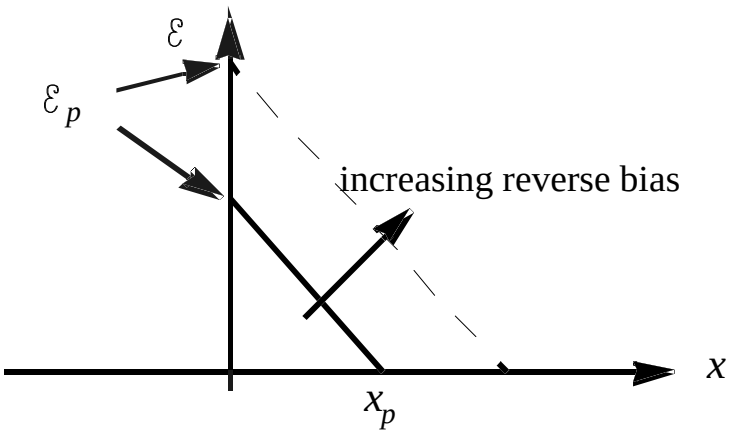
- Thus, the reverse bias at which breakdown occurs is

$$V_{BR} = \frac{\varepsilon_s \mathcal{E}_{crit}^{\ 2}}{2qN} - V_{bi}$$

Peak Electric Field



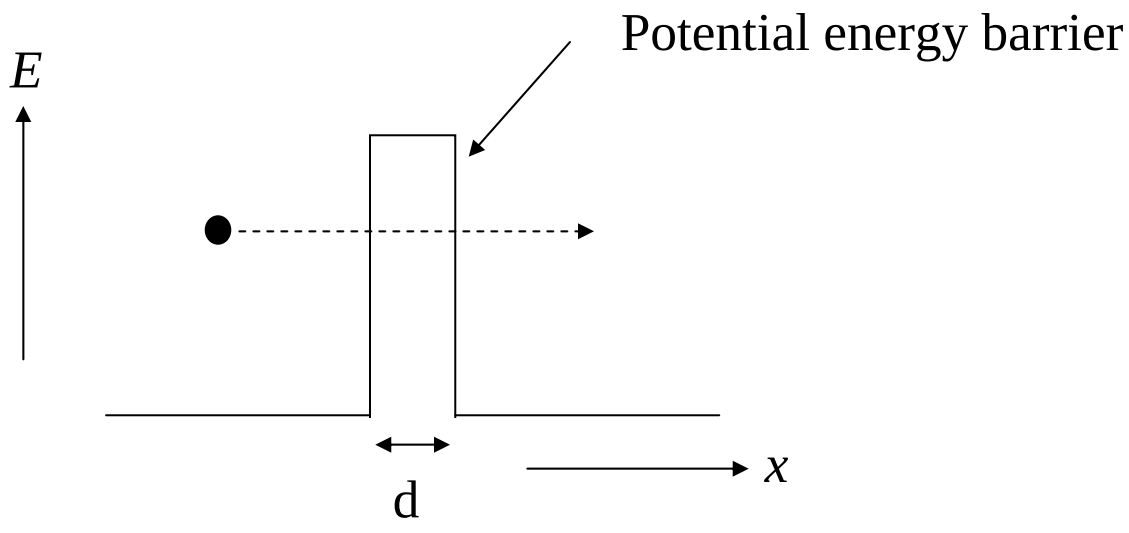
(a)



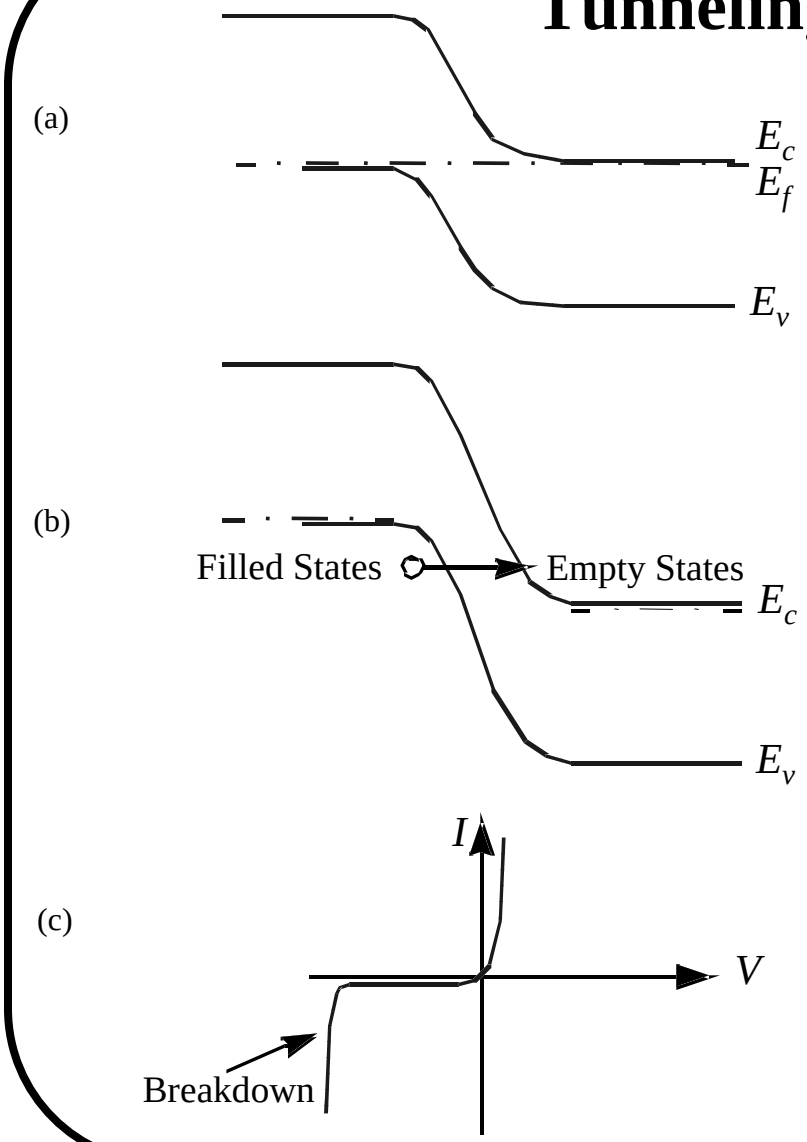
(b)

$$\mathcal{E}_p = \mathcal{E}(0) = \left[\frac{2qN}{\varepsilon_s} (\phi_{bi} + |V_r|) \right]^{1/2}$$

Quantum Mechanical Tunneling



Tunneling Breakdown

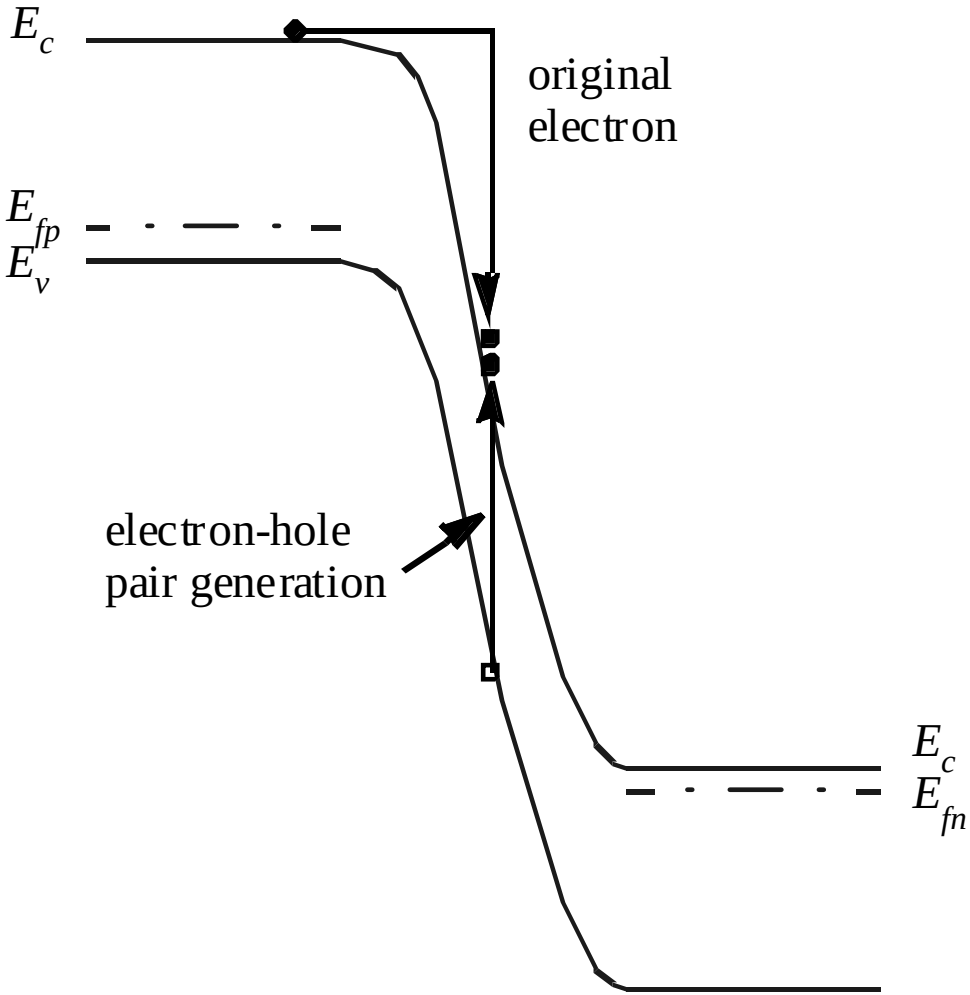


Dominant breakdown cause when both sides of a junction are very heavily doped.

$$V_B = \frac{\varepsilon_s \mathcal{E}_{crit}^{\ 2}}{2qN} - \phi_{bi}$$

$$\mathcal{E}_p = \mathcal{E}_{crit} \approx 10^6 \text{ V/cm}$$

Avalanche Breakdown



impact ionization

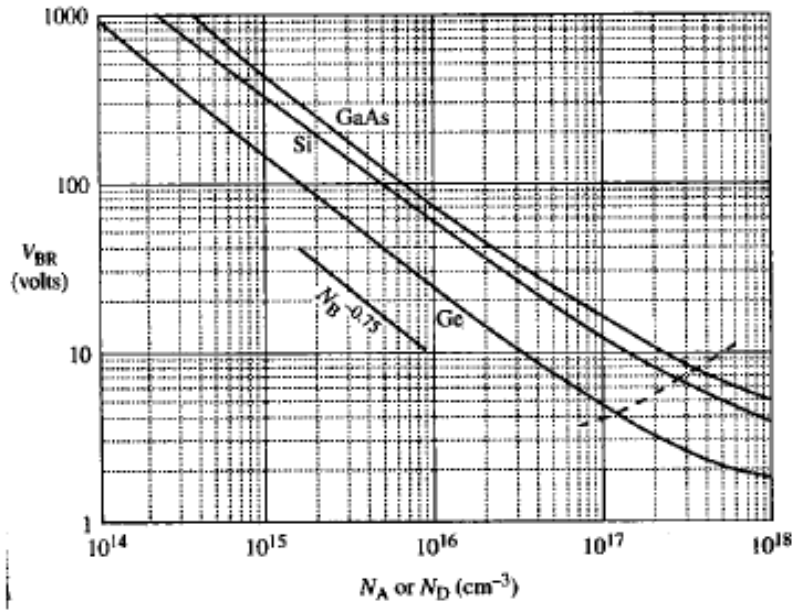
↓

avalanche breakdown

$$V_B = \frac{\varepsilon_s \mathcal{E}_{crit}^{\ 2}}{2qN}$$

$$\boxed{V_B \propto \frac{1}{N}} = \frac{1}{N_a} + \frac{1}{N_d}$$

Empirical Observations of V_{BR}

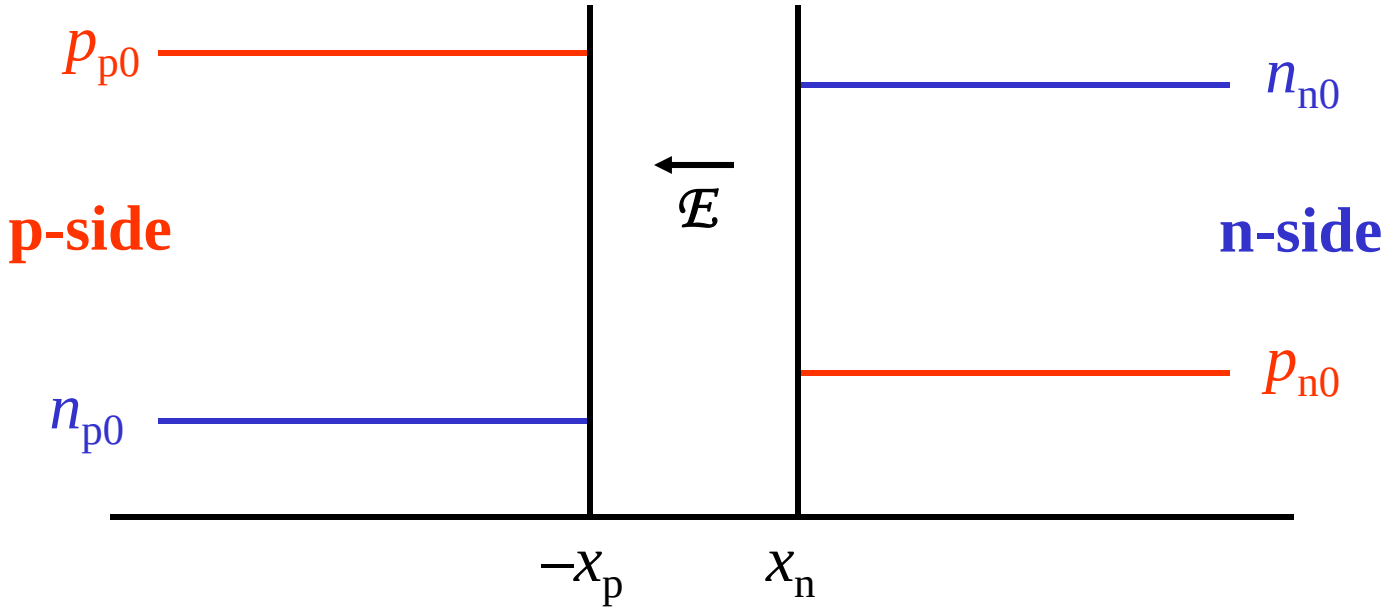


- V_{BR} decreases with increasing N
- V_{BR} decreases with decreasing E_G

Question:

What happens to V_{BR} of the avalanche breakdown as T is increased?

Carrier Concentrations at Equilibrium



p-side

$$p_{p0}(-x_p) = N_A$$

$$n_{p0}(-x_p) = \frac{n_i^2}{N_A}$$

n-side

$$n_{n0}(x_n) = N_D$$

$$p_{n0}(x_n) = \frac{n_i^2}{N_D}$$

Majority and minority carrier concentration under bias

When an external voltage is applied, the minority carrier concentration at the edge of the depletion layer will change. If a forward voltage (V_A=positive) is applied, the barrier will be lower and carrier injection (diffusion part) will increase. The minority carrier concentration at the edge of the depletion layer will increase.

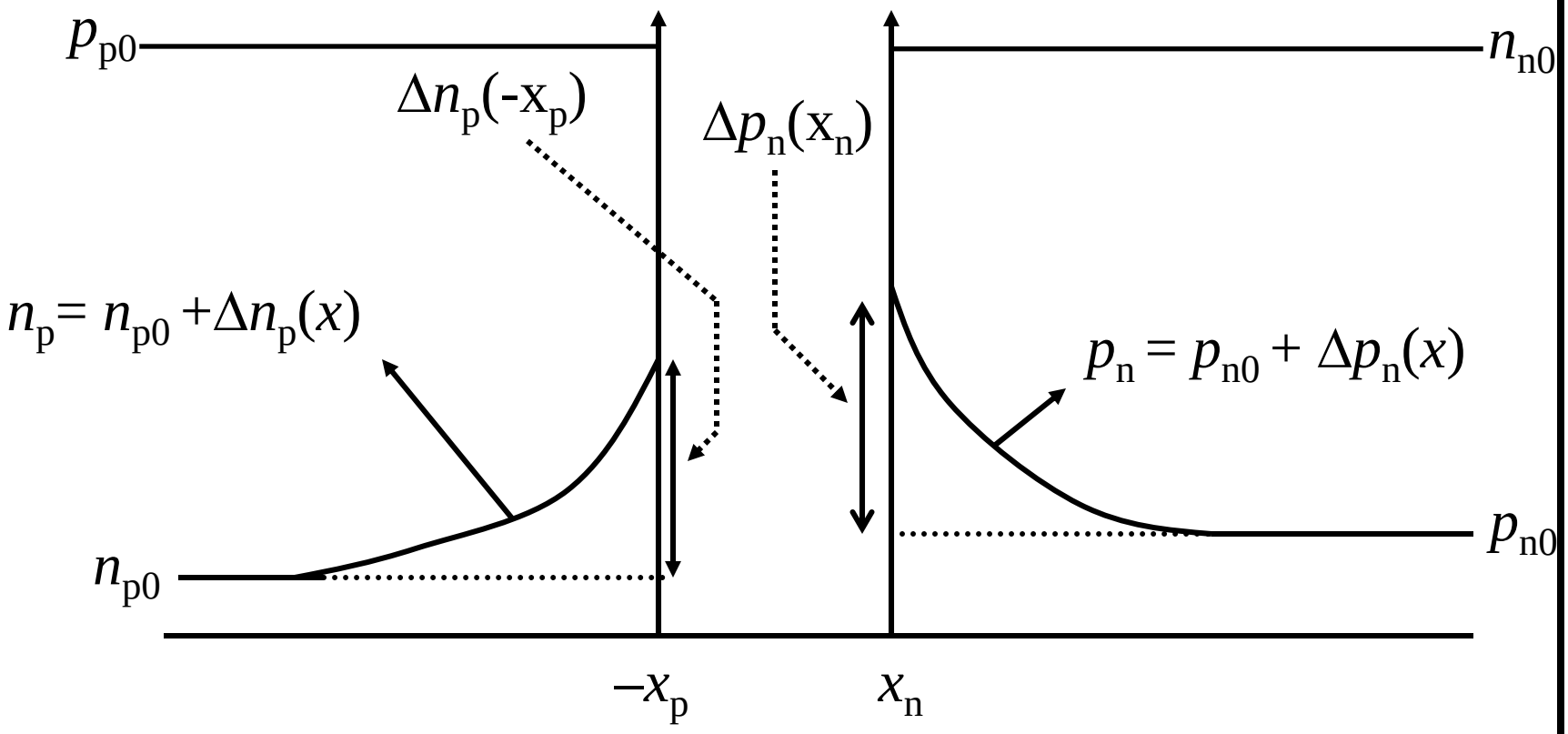
If a reverse voltage (V_A = negative) is applied, the barrier for carrier injection (diffusion part) will increase, and the minority carrier concentration at the edge of the depletion layer will decrease.

The drift of minority carriers across the junction does not change much with applied voltage. Why?

At $V_A = 0$, the carrier injection and the drift of minority carriers cancel each other such that an equilibrium conc. is maintained.

If “low-level-injection” condition is assumed, then the majority carrier concentration will not change under any of the above conditions.

Carrier concentration profile under bias



The Junction Law

pn product at the edge of the depletion when junction is biased:

$$pn = n_i^2 e^{qV_A / kT}$$

Excess Carrier Concentrations at $-x_p$, x_n

p-side

$$p_p(-x_p) = N_A$$

$$n_p(-x_p) = \frac{n_i^2 e^{qV_A/kT}}{N_A}$$

$$= n_{p0} e^{qV_A/kT}$$

$$\Delta n_p(-x_p) = \frac{n_i^2}{N_A}\left(e^{qV_A/kT} - 1\right)$$

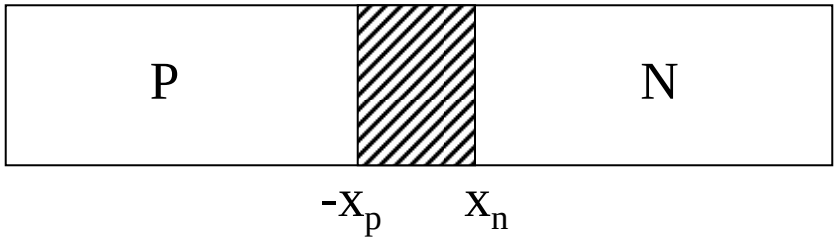
n-side

$$n_n(x_n) = N_D$$

$$p_n(x_n) = \frac{n_i^2 e^{qV_A/kT}}{N_D}$$

$$= p_{n0} e^{qV_A/kT}$$

$$\Delta p_n(x_n) = \frac{n_i^2}{N_D}\left(e^{qV_A/kT} - 1\right)$$



EXAMPLE: Carrier Injection

A PN junction has $N_a=10^{19}cm^{-3}$ and $N_d=10^{16}cm^{-3}$. The applied voltage is 0.6 V.

***Question**: What are the minority carrier concentrations at the depletion-region edges?*

***Solution**:*

$$n(0) = n_{P0}e^{qV/kT} = 10 \times e^{0.6/0.026} = 10^{11}\ \text{cm}^{-3}$$

$$p(0) = p_{N0}e^{qV/kT} = 10^{4} \times e^{0.6/0.026} = 10^{14}\ \text{cm}^{-3}$$

***Question**: What are the excess minority carrier concentrations?*

***Solution**:*

$$n'(0) = n(0) - n_{P0} = 10^{11} - 10 = 10^{11}\ \text{cm}^{-3}$$

$$p'(0) = p(0) - p_{N0} = 10^{14} - 10^{4} = 10^{14}\ \text{cm}^{-3}$$

Current density in PN junctions

- Remember the minority carrier diffusion equation from chapter 3?

$$\frac{\partial \Delta p}{\partial t} = D_{\mathrm{p}} \frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_{\mathrm{p}}} + G_{\mathrm{L}}$$

$$\frac{\partial \Delta n}{\partial t} = D_{\mathrm{n}} \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_{\mathrm{n}}} + G_{\mathrm{L}}$$

Steady state: $\frac{\partial \Delta n}{\partial t} = 0$ Only thermal/direct R-G: $G_{\mathrm{L}} = 0$

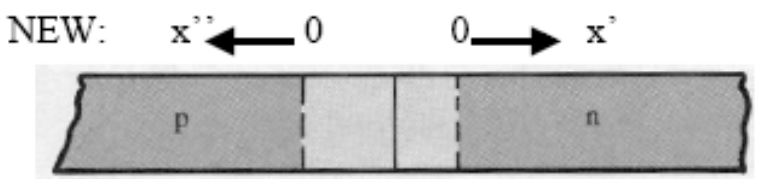
Excess Carrier Distribution

- From the minority carrier diffusion equation: $\frac{d^2\Delta p_n}{dx^2} = \frac{\Delta p_n}{D_p \tau_p} = \frac{\Delta p_n}{L_p^{\ 2}}$

- We have the following boundary conditions:

$$\Delta p_n(x_n) = p_{no}(e^{qV_A/kT} - 1) \qquad \Delta p_n(\infty) \to 0$$

- For simplicity, we will develop a new coordinate system:



- Then, the solution is of the form:

$$\Delta p_n(x') = A_1 e^{x'/L_p} + A_2 e^{-x'/L_p}$$

$$\Delta p_n(x') = A_1 e^{x'/L_p} + A_2 e^{-x'/L_p}$$

From the $x = \infty$ boundary condition, $A_1 = 0$.

From the $x = x_n$ boundary condition, $A_2 = p_{no}(e^{qV_A/kT} - 1)$

Therefore, $\Delta p_n(x') = p_{no}(e^{qV_A/kT} - 1)e^{-x'/L_p}, \; x' > 0$

Similarly, we can derive

$$\Delta n_p(x'') = n_{po}(e^{qV_A/kT} - 1)e^{-x''/L_n}, \; x'' > 0$$

- Current density $J = J_n(x) + J_p(x)$

$$J_n(x) = q\mu_n n\mathcal{E} + qD_n \frac{dn}{dx} = q\mu_n n\mathcal{E} + qD_n \frac{d(\Delta n)}{dx}$$

$$J_p(x) = q\mu_p p\mathcal{E} - qD_p \frac{dp}{dx} = q\mu_p p\mathcal{E} - qD_p \frac{d(\Delta p)}{dx}$$

- J is constant throughout the diode, but $J_n(x)$ and $J_p(x)$ vary with position

pn Diode *I-V* Characteristic

p-side: $J_n = -qD_n \dfrac{d\Delta n_p(x'')}{dx''} = q\dfrac{D_n}{L_n} n_{p0}(e^{qV_A/kT} - 1)e^{-x''/L_n}$

n-side: $J_p = -qD_p \dfrac{d\Delta p_n(x')}{dx'} = q\dfrac{D_p}{L_p} p_{n0}(e^{qV_A/kT} - 1)e^{-x'/L_p}$

$$J = J_n\Big|_{x=-x_p} + J_p\Big|_{x=x_n} = J_n\Big|_{x''=0} + J_p\Big|_{x'=0}$$

$$J = qn_i^2\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right](e^{qV_A/kT} - 1)$$

Assumption: *No R-G in the depletion layer: Jn and Jp are constant in depletion layer*