ECE 340: Semiconductor Electronics

Chapter 5: Junctions (part III)

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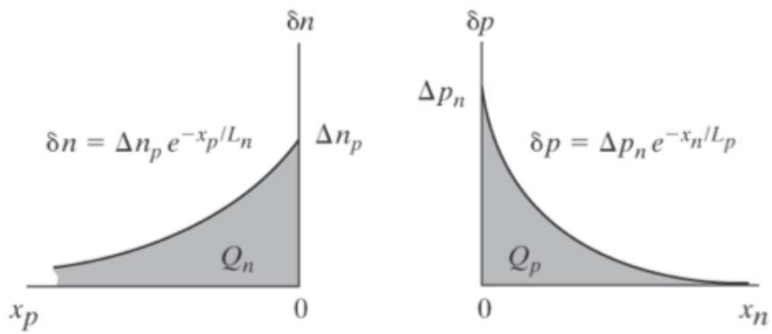
Outline

- Transient and a-c conditions
  - Time variation of stored charge
  - Capacitance in pn junction
    - Definition of capacitance
    - Parallel plate capacitance
    - Depletion capacitance
    - Diffusion capacitance

Transient and a-c conditions

- A change in current leads to a change in the amount of stored charge
- Building up or depleting charge takes some time



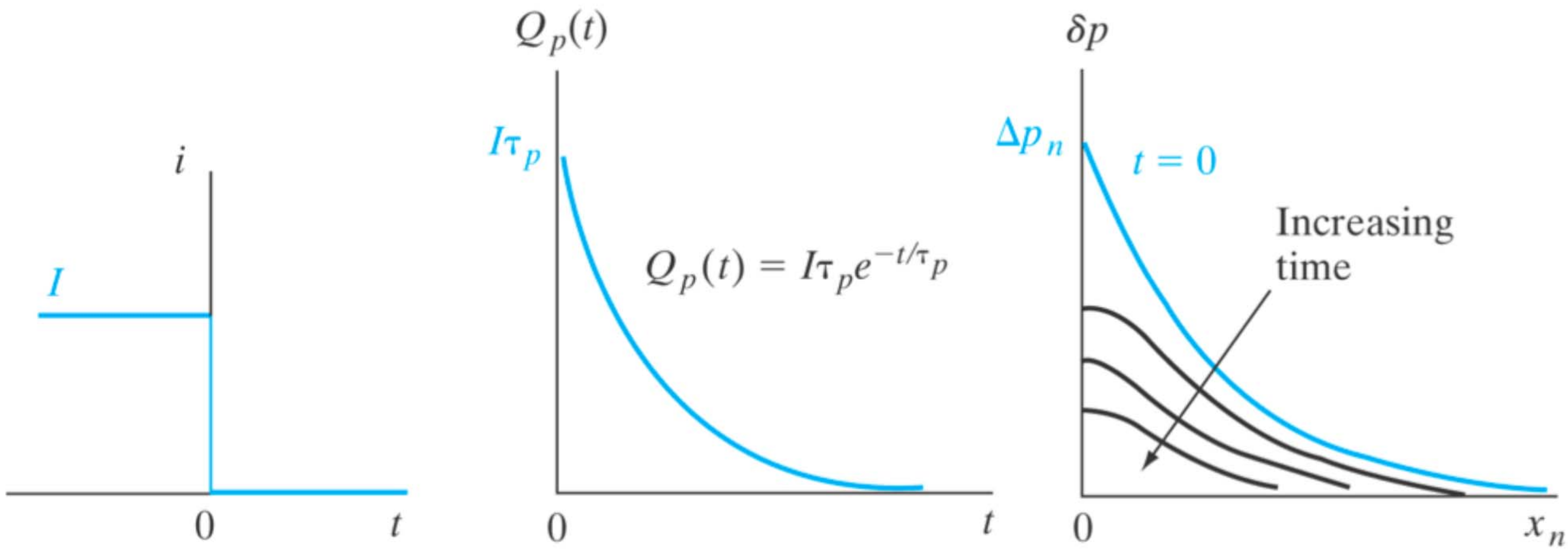
$$-\frac{\partial J_p}{\partial x} = q\frac{\delta p}{\tau_p} + q\frac{\partial \delta p}{\partial t}$$

$$J_p(0) - J_p(\infty) = q\int_0^\infty \left(\frac{\delta p}{\tau_p} + \frac{\partial \delta p}{\partial t}\right) dx$$

$$i(t) = J_p(0)\cdot A = \frac{Q_p}{\tau_p} + \frac{dQ_p(t)}{dt}$$

Effect of turn-off step

Current | **Decay of total stored charge** | **excess hole distribution**



Outline

- **Transient and a-c conditions**
  - **Time variation of stored charge**
  - **Capacitance in pn junction**
    - **Review: parallel plate capacitance**
    - **Depletion capacitance**
    - **Diffusion capacitance**

What is capacitance?

- **General definition of capacitance:.**

$$C = \frac{dQ}{dV}$$

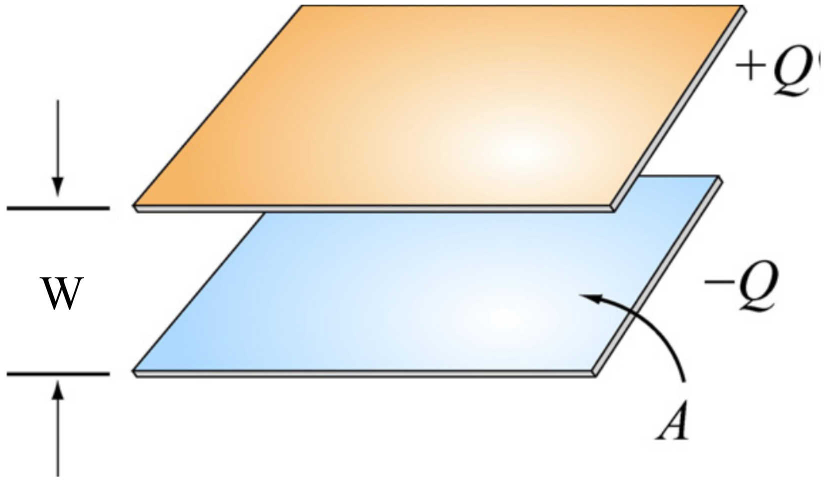
$$\text{Unit:} \quad 1\ \text{Farad} = 1\,\frac{\text{coulomb}}{\text{Volt}} \qquad 1\,F = 1\,\frac{C}{V}$$

Review: Parallel plate capacitor

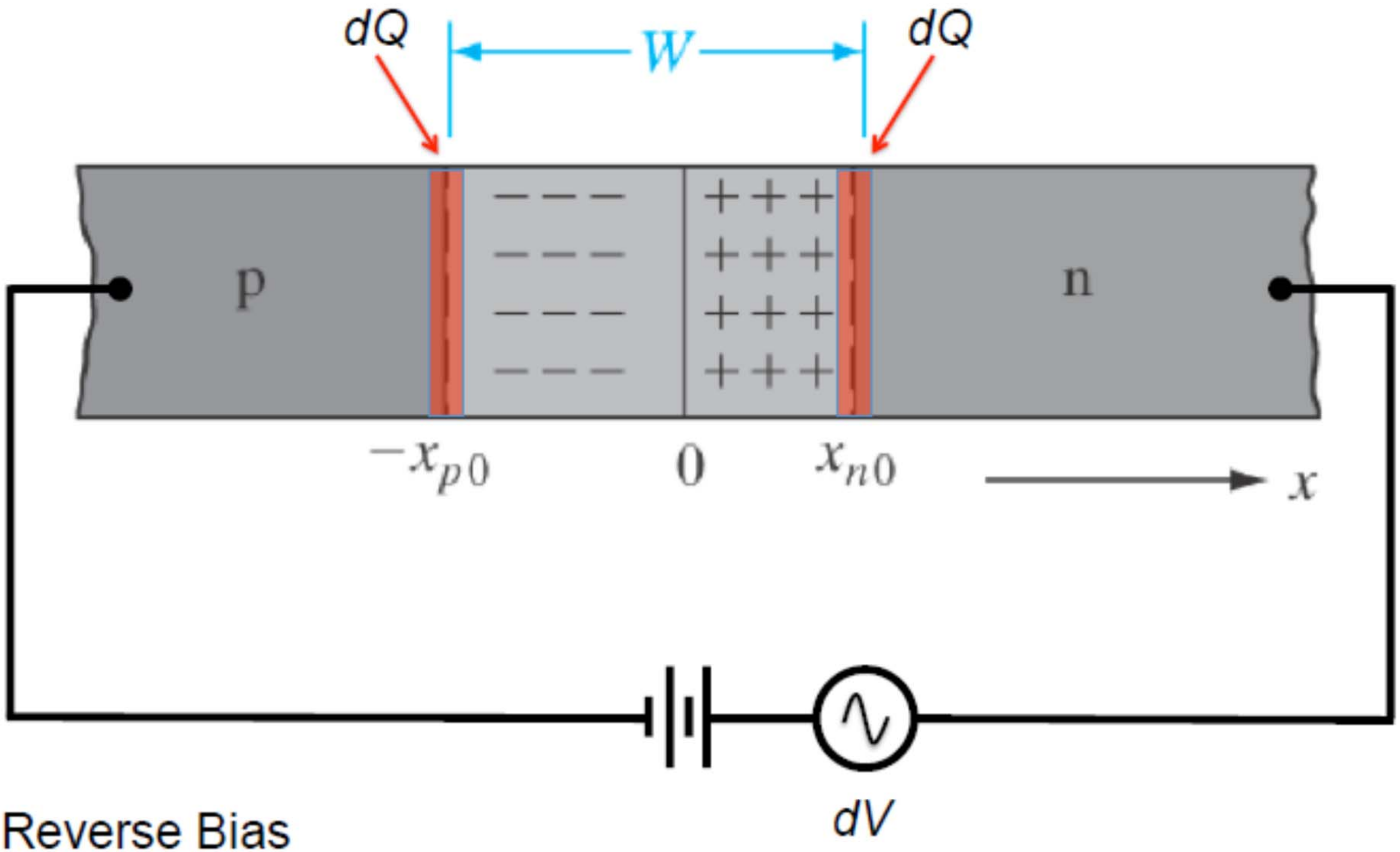
- From Gaussian's law:

$$Q = \varepsilon E \mathrm{A} = \varepsilon \frac{V}{w} \mathrm{A}$$

$$\Rightarrow \quad C = \frac{dQ}{dV} = \frac{Q}{V} = \frac{\varepsilon A}{w}$$



Depletion capacitance



Reverse Bias

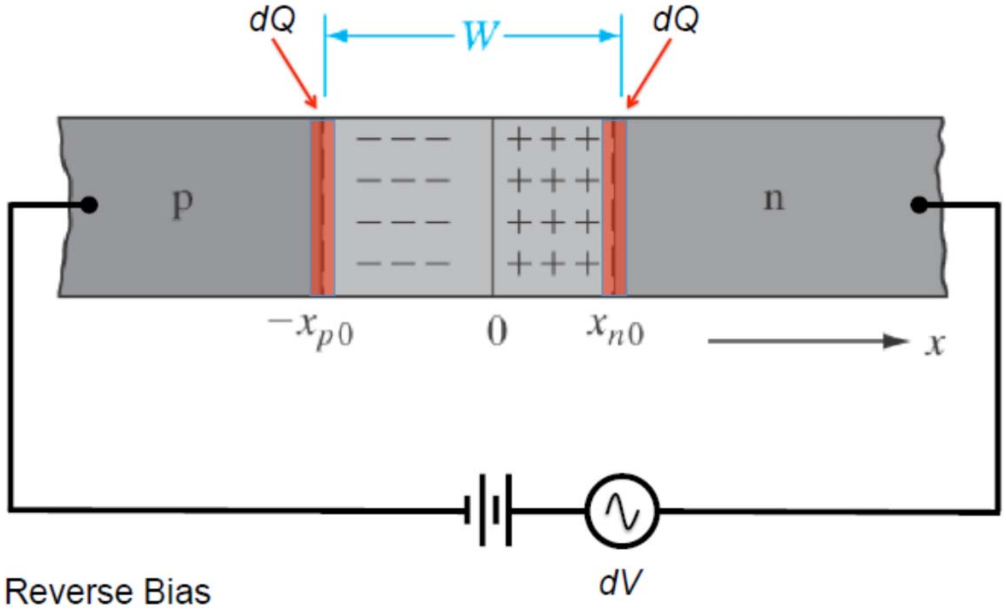
Depletion capacitance

- In reverse bias, (V<0) fixed charge is *stored* in the junction, as the depletion width widens with more negative V.

$$W = \sqrt{\frac{2\epsilon(V_0 - V_a)}{q}\frac{N_a + N_d}{N_d N_a}}$$

$$|Q| = qAx_{p0}N_a$$

$$x_{p0} = W\frac{N_d}{N_a + N_d}$$



Junction capacitance

- The uncompensated charge on each side:

$$|Q| = qA\frac{N_d N_a}{N_a + N_d}W = A\sqrt{\boldsymbol{2}\epsilon\boldsymbol{q}(\boldsymbol{V_0} - \boldsymbol{V})\frac{N_d N_a}{N_a + N_d}}$$

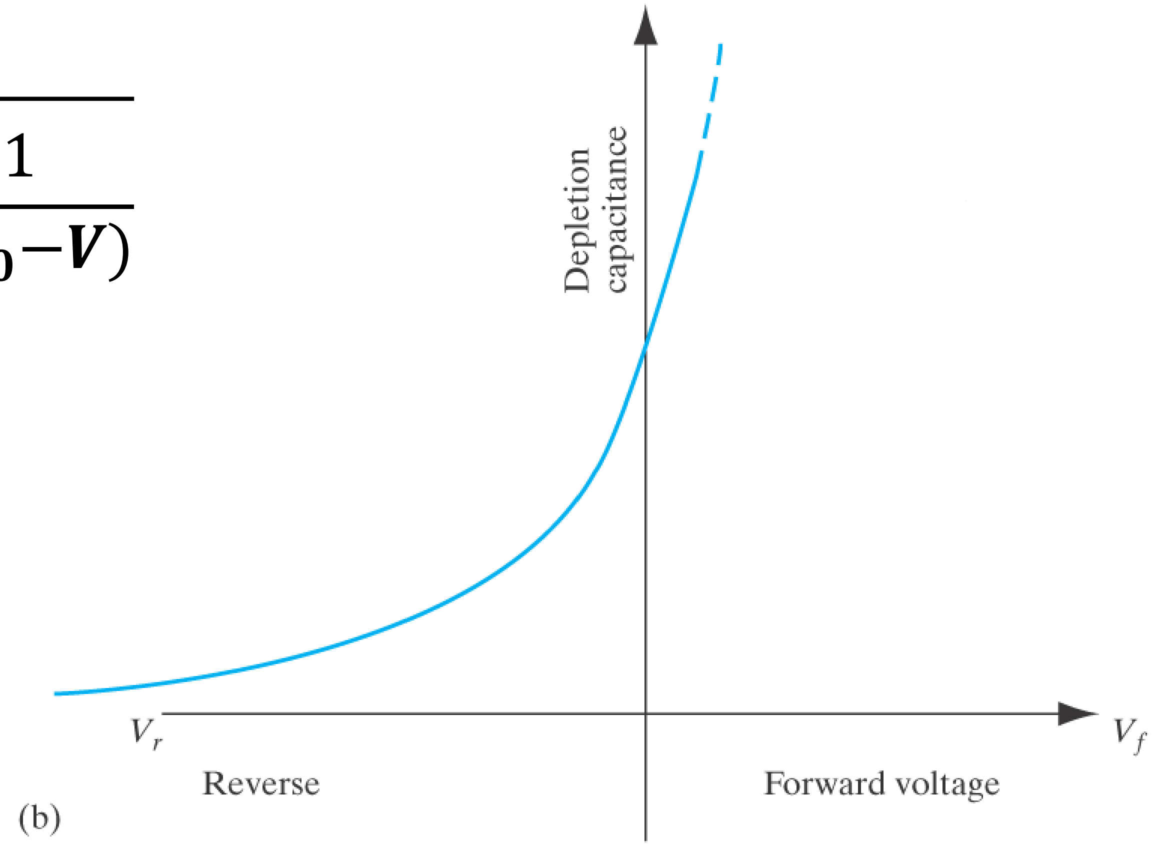
- The junction capacitance

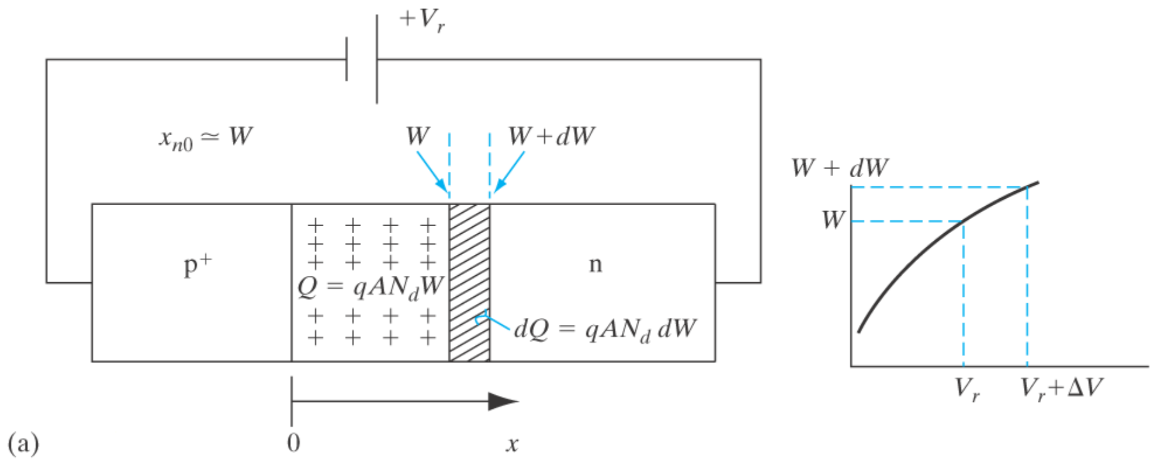
$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = A\sqrt{\frac{q\epsilon}{2(\boldsymbol{V_0} - \boldsymbol{V})}\frac{N_d N_a}{N_a + N_d}} = \frac{\epsilon A}{W}$$

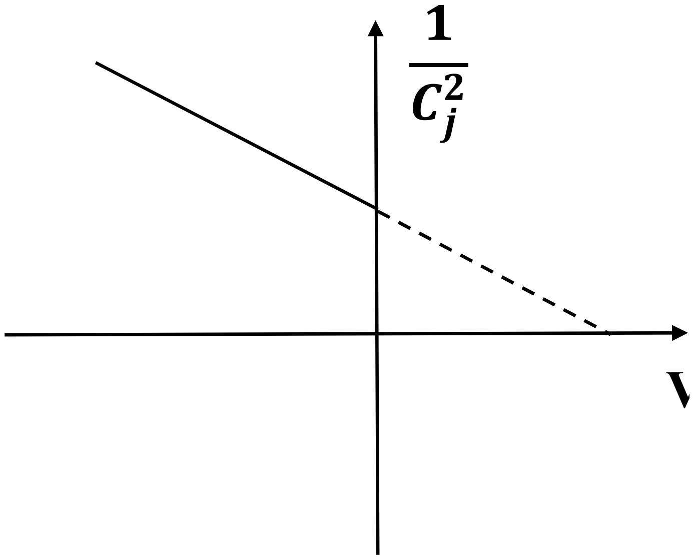
Junction capacitance

- **Junction capacitance is voltage variable capacitance**

$$C_j = \frac{\epsilon A}{W} \propto \sqrt{\frac{1}{(\boldsymbol{V_0} - \boldsymbol{V})}}$$







- If one side is heavily doped, ex: p+-n junction, $N_a \gg N_d$

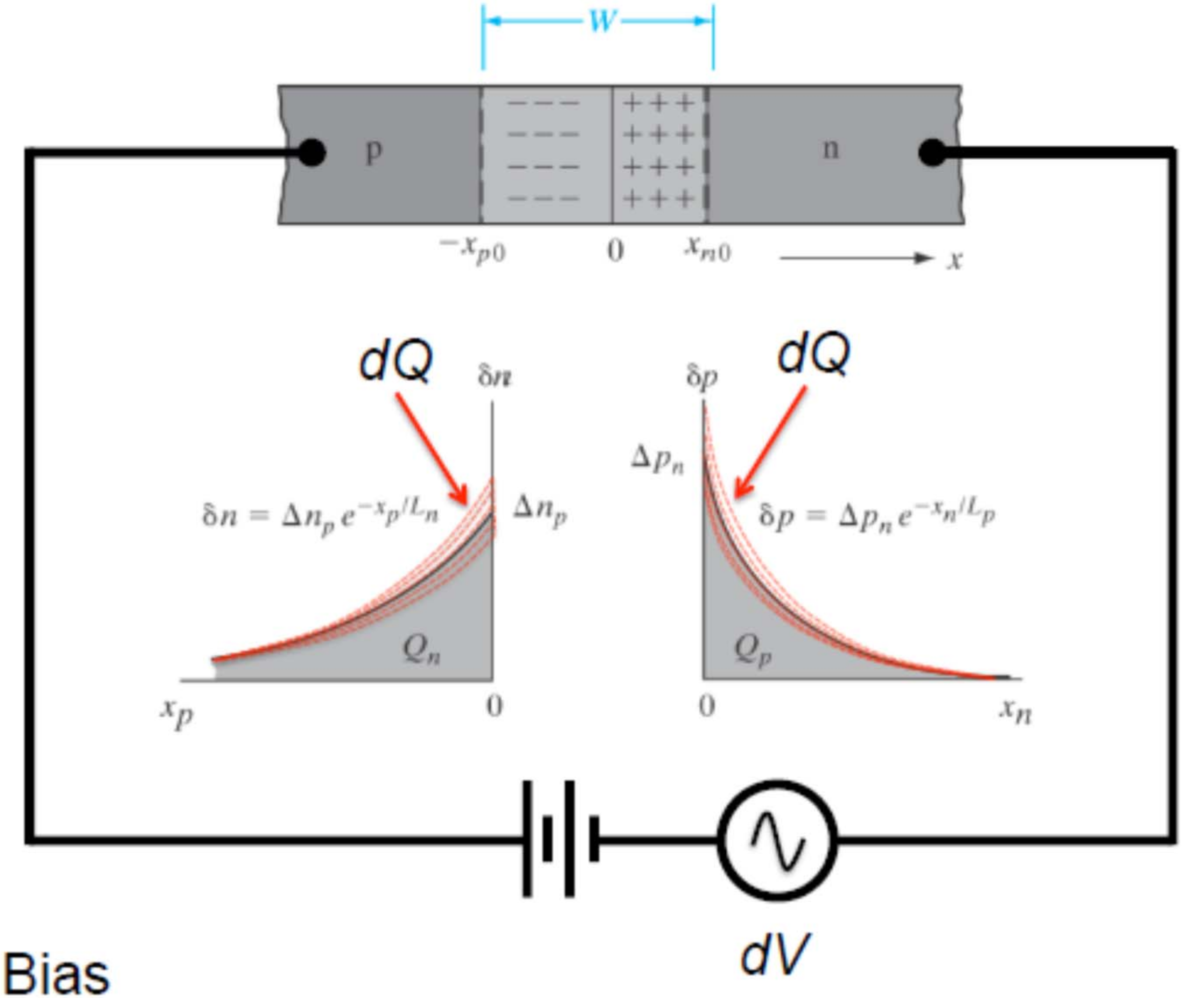
$$C_j = \frac{\epsilon A}{W} = A\sqrt{\frac{q\epsilon}{2(\boldsymbol{V_0} - \boldsymbol{V})}\frac{N_d N_a}{N_a + N_d}} \approx A\sqrt{\frac{q\epsilon}{2(\boldsymbol{V_0} - \boldsymbol{V})}N_d}$$

- If we measure and plot $\frac{1}{C_j^2}$ vs. V,

$$\frac{1}{C_j^2} = \frac{2}{A^2 q\epsilon}\frac{1}{N_d}(\boldsymbol{V_0} - \boldsymbol{V})$$

I can get ___________

Diffusion capacitance

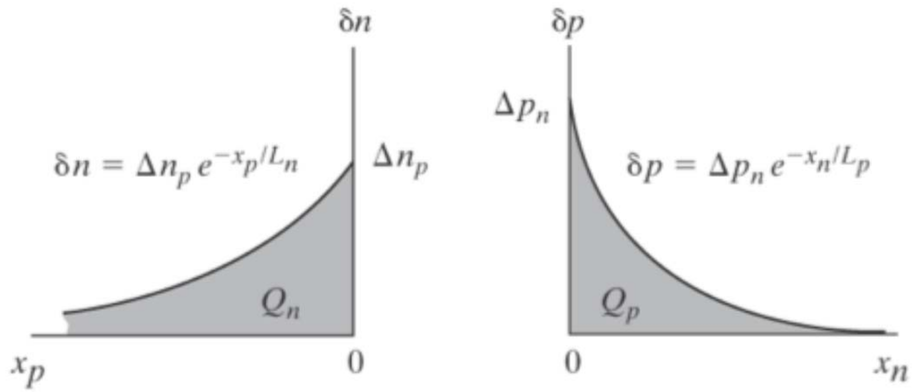


Forward Bias

Diffusion capacitance

- In forward bias, *excess* minority carriers are stored in the quasi-neutral regions of the p-n diode.

- **For long diode, sample length much larger than diffusion length:**



$$Q_p = qA\int_0^{\infty} \delta p(x_n)dx_n = qAL_p\Delta p_n = qAL_p p_n e^{qV/kT}$$

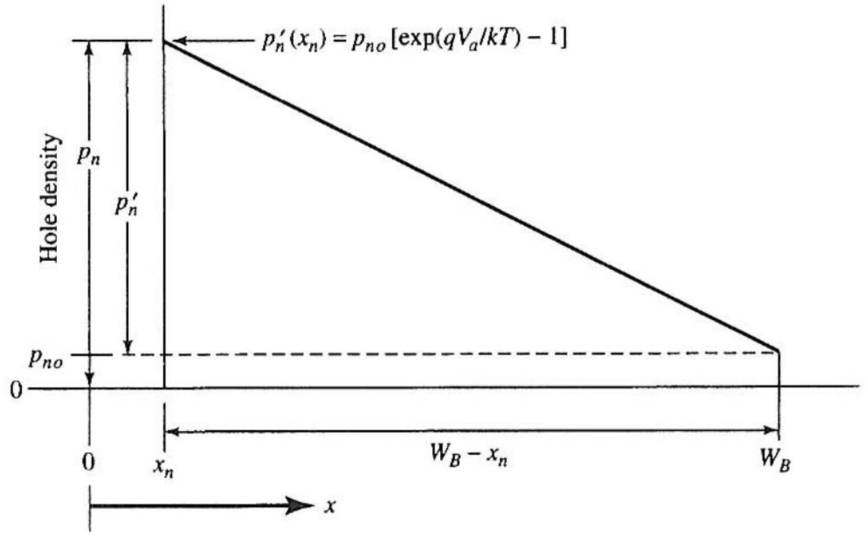
$$C_s = \frac{dQ_p}{dV} = \frac{q}{kT}Q_p$$

Short diode diffusion capacitance

- For short diode:

$$\delta p(x) = a + b\frac{x - x_{n0}}{L_p}$$

$$when\ x = W_B, \qquad \delta p(W_B) = 0$$

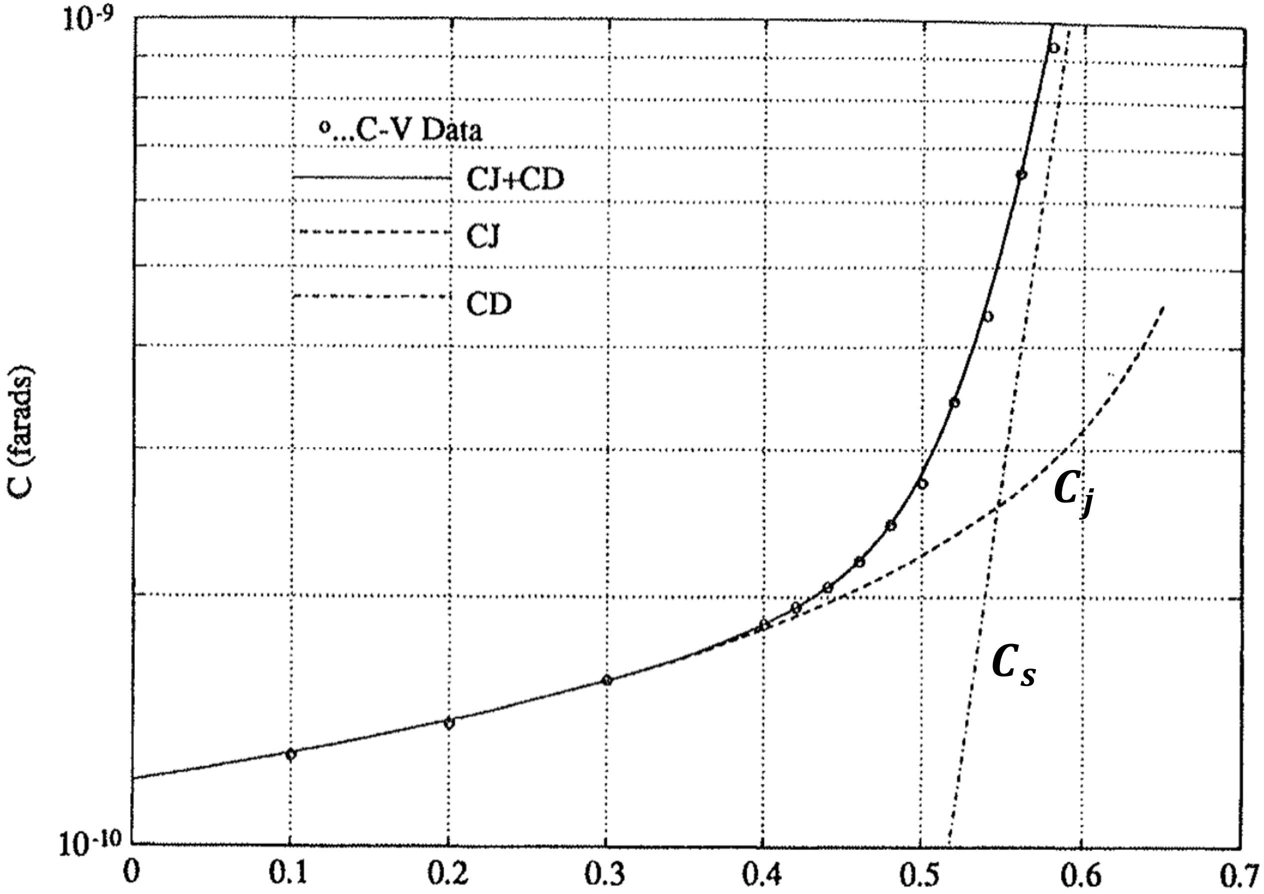


$$\delta p(x) = p_n(e^{qV/kT} - 1)(1 - \frac{x - x_{n0}}{W_B - x_{n0}})$$

$$Q_p = \frac{qA(W_B - x_n)}{2} p_n(e^{qV/kT} - 1)$$

$$C_s = \frac{dQ_p}{dV} = \frac{q}{kT} Q_p$$

Total capacitance



$$C = C_j + C_s$$

Ac conductance

- Long diode

$$I = \frac{Q_p}{\tau_p} = \frac{qAL_p p_n}{\tau_p}\left(e^{qV/kT}\right)$$

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

Summary

- Depletion capacitance: reverse bias, uncompensated donor or acceptor charge

$$C_j = \frac{\epsilon A}{W}$$

P+--n junction $$C_j \approx A\sqrt{\frac{q\epsilon}{2(\boldsymbol{V_0} - \boldsymbol{V})}N_d}$$

- Diffusion capacitance: forward bias, minority carriers

$$\boldsymbol{C_s = \frac{dQ_p}{dV} = \frac{q}{kT}Q_p}$$

Example

If the slope of the $(1/C_{dep})^2$ *vs.* V_A characteristic is $2\text{x}10^{23}$ $F^{-2}\,V^{-1}$, the intercept is 0.84V, and A is 1 μm^2, find the lighter and heavier doping concentrations N_l and N_h.