EE 116 Lecture 26

“Short” P-N diode

- Read: Ch. 4.4.2.5
- Let’s recall some math:

$$\sinh(x) = \frac{1}{2}\left(e^{x} - e^{-x}\right) \qquad \cosh(x) = \frac{1}{2}\left(e^{x} + e^{-x}\right)$$

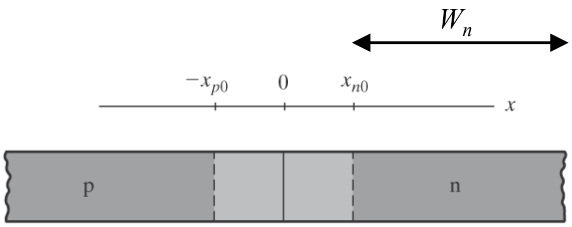
$$\tanh(x) = \frac{\sinh(x)}{\cosh(x)} \qquad \mathrm{ctnh}(x) = \frac{1}{\tanh(x)}$$

$$e^{-x} = 1 - x + \frac{x^2}{2!} - \frac{x^3}{3!} + \cdots + (-1)^n \frac{x^n}{n!} + \cdots$$

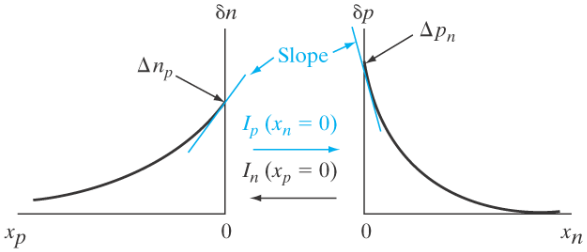
(what if $0 < x << 1$?)

- What is a typical minority carrier diffusion length in Si?
- How does it compare to modern device lengths?

- Let’s revisit p-n carrier distributions:



- Draw “usual” distributions under forward bias:



- Now if the n-side is shorter than the diffusion length ($W_n < L_p$):

- Remember, the metal contacts at the ends of the p-n junction can be thought of as infinite source/sink of carriers
- So instead of the "long" ($W_n >> L_p$) exponentially decaying…

$$\delta p_n(x) = \Delta p_{n0} e^{-x/L_p} = p_{no}(e^{qV/kT} - 1)e^{-x/L_p}$$

- We have the "narrow" or "short" $W_n < L_p$ linear approximation:

$$\delta p(x) = \Delta p_{n,0}\left(1 - \frac{x}{W_n}\right) = \frac{n_i^2}{N_D}\left(e^{qV/kT} - 1\right)\left(1 - \frac{x}{W_n}\right)$$

- What is the physical meaning of the diffusion length L_p?
- Note the diode is now too "short" (narrow) for any hole recombination in the n-region. So, all recombination happens at the contact which forces $\delta p(x=W_n) = 0$

- Total injected (stored) minority charge at forward bias is the area under the "triangle":

$$Q_p = \frac{1}{2} q \Delta p\left(AW_n\right) = \frac{1}{2} qAW_n \frac{n_i^2}{N_D}\left(e^{qV/kT} - 1\right)$$

- Easy to write the hole diffusion current for "short" diode:

$$J_p = -qD_p \frac{dp}{dx} = q \frac{D_p}{W_n} \frac{n_i^2}{N_D}(e^{qV/kT} - 1)$$

- Compare with "long" diode hole diffusion current:

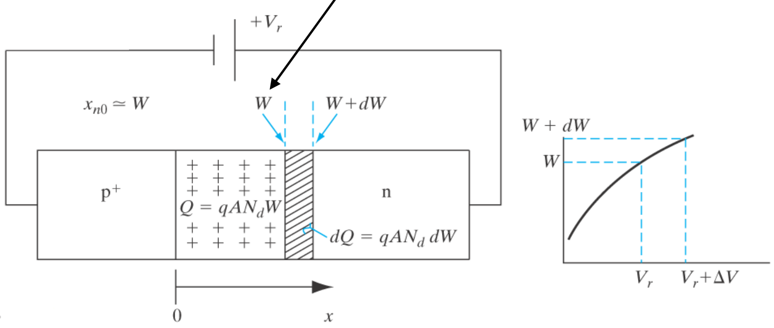
$$J_p = q \frac{D_p}{L_p} \frac{n_i^2}{N_D}(e^{qV/kT} - 1)$$

- Total diode current if:
  - It's a p+/n ($N_A >> N_D$) diode → $J = J_p$
  - It's a p/n ($N_A \sim N_D$) diode → $J = J_p + J_n$

EE 116 Lecture 27

P-N diode capacitance

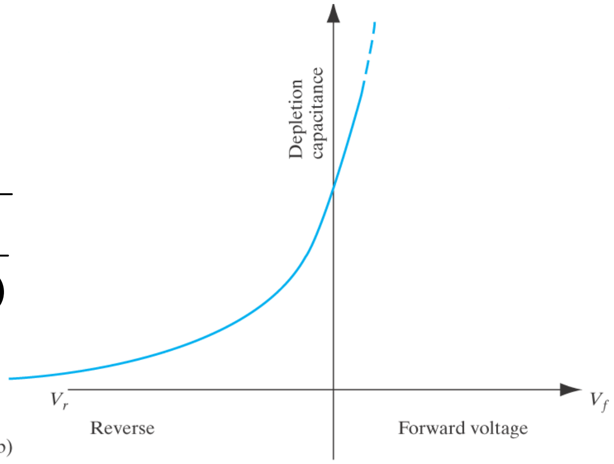
notation: this is “our” x_d



- Read: Ch. 4.3.4
- At V < ϕ_i fixed charge is *stored* in the junction, as the depletion width widens with decreasing V
- Why? How does x_d change with voltage?

$$C_J = C_{depl} = \left|\frac{dQ}{dV}\right| = \frac{\varepsilon_s A}{x_d} \approx A\sqrt{\frac{q\varepsilon_s N_D}{2(\phi_i - V)}}$$

(for a one-sided p^+n diode)



(b)

- If we measure and plot $1/C_J^2$ vs. V, I can get ___________

$$\frac{1}{C_J^{\ 2}} = \left(\frac{x_d}{\varepsilon_s A}\right)^2 \cong \frac{2}{A^2 q\varepsilon_S N}(\phi_i - V)$$

- **Ex:** Diode with area 100x100 μm^2, slope of $(1/C_J)^2$ vs. V is -2×10^{23} F^{-2}V^{-1}, and intercept is 0.84 V. If $N_A >> N_D$, find the two sides' doping.

- We've (nearly) exhausted the p-n junction. Now we know:

1) Why and how it conducts current (forward, reverse)
2) How to calculate depletion width, field, built-in voltage
3) How diodes break down
4) How diodes store charge as capacitors

5) How to make an LED or photodiode