Since $\delta p(x=0) = \Delta P$ is maintained constant,

→ steady state. So use steady-state equations.

Solution to 2nd-order differential equations have the form:

$\delta p(x) =$

Evaluate C_1 and C_2 from boundary conditions

$\delta p(x=\infty) = 0$ so $C_1 = 0$

$\delta p(x=0) = \Delta P$ so $C_2 = \Delta P$

so $\delta p(x) =$

and L_p = length over which Δp decays to $\Delta p \cdot e^{-1}$.

and $p = p_0 + \Delta p \, e^{-x/L_p} = p_0 + \delta p(x)$

Diffusion <u>current</u> decays too. Since

$J_p =$

$=$

proportional to excess carriers

Actually, <u>very</u> <u>important</u> for p-n junctions

→ injection of minority carriers across junctions

Recombination Probability

$$\delta p(x) = \Delta p \, e^{-x/L_p}$$

Probability that hole survives to x without recombination is:

$$\frac{\delta p}{\Delta p} = e^{-x/L_p}$$

Probability that hole recombines in subsequent interval dx is:

$$\frac{\delta p(x) - \delta p(x+dx)}{\delta p(x)} = \frac{-(d\,\delta p(x)/dx)\,dx}{\delta p(x)} = \frac{1}{L_p} \cdot dx$$

Total probability that hole injected at $x=0$ recombines in given dx is product of probabilities:

average distance $\langle x \rangle = \int_0^\infty \frac{x}{L_p} e^{-x/L_p} dx = L_p$

since $\int x e^{ax} dx = \frac{e^{ax}}{a^2}(ax-1)$ where $a = -\frac{1}{L_p}$

$$\frac{e^{-x/L_p}}{\left(-\frac{1}{L_p}\right)^2}\left(-\frac{x}{L_p}-1\right)\Big|_0^\infty = L_p^2 \text{ at } x=0$$

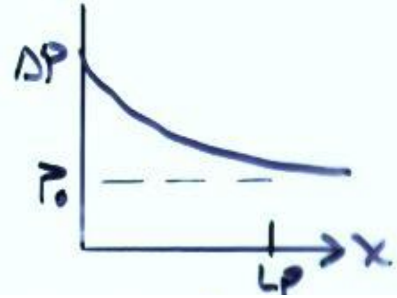
so $\langle x \rangle =$

Injected Current and Stored Charge

$$I_p = -qAD_p\frac{dp}{dx} = qA\frac{D_p}{L_p}\Delta p\, e^{-x/L_p}$$

current changes with x!

$$Q_p = qA\int_0^{\infty}\Delta p\, e^{-x/L_p}\,dx$$



=

Diffusion length memory device:

small animals crossing amazon — piranha

Example: Solve for L_p where the bar is Si, $N_A = 10^{15}/cm^3$, $\tau_p = 10^{-6}$ sec

$L_p =$ state-state diffusion

$=$ Einstein relation

$$= \left[(0.0259\ V)(458\ cm^2/V\text{-}sec)(10^{-6}\ sec) \right]^{1/2}$$

" $\frac{kT(300K)}{q}$

Fig. 3-23

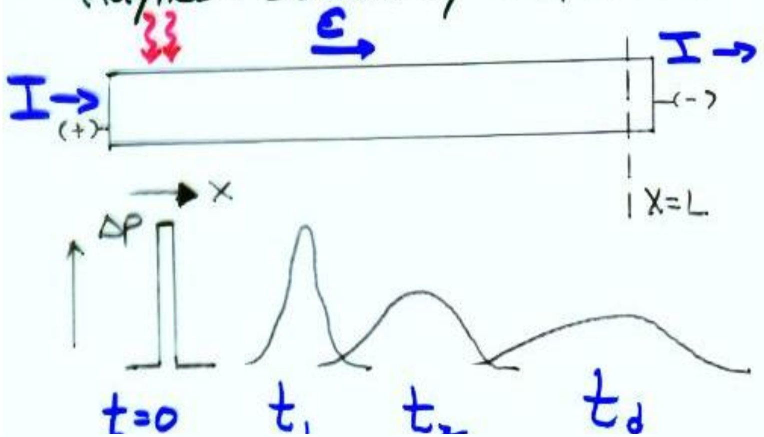
$\cong$

Independent of ΔP (or doping)

~ sort of same

u depends on doping

Haynes-Schockley Experiment



Measure μ and D independently

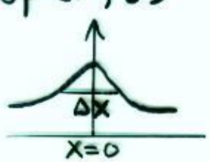
$\mu =$

But pulse spreads out.
Measure D from the spread

Diffusion Equation neglecting recombination τ_p

$$\delta p(x,t) = \left[\frac{\Delta P}{2\sqrt{\pi D_p t}}\right] e^{-x^2/4D_p t}$$

Gaussian Distribution



$$D_p = \frac{(\Delta x)^2}{16\, t_d}$$

Dp is a constant, so as t_d increases, so

Read S&B 4.4.5

Gradients of Fermi Levels

Relate currents to quasi-E_F gradients

Equilibrium: $\frac{dE_F}{dx} = 0 \rightarrow J = 0$

Nonequilibrium: $J \neq 0$

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

$n(x) =$ (Definition)

$$\left[\frac{dF_n}{dx} - \frac{dE_i}{dx}\right]$$

$$= \frac{n(x)}{kT}\left[\,\cdot\ \ \cdot\,\right]$$

(Einstein)

$$J_n(x) = q\mu_n n(x)\cancel{\mathcal{E}(x)} + n(x)\mu_n\left[\frac{dF_n}{dx} - \cancel{\frac{dE_i}{dx}}\right]$$

$$\mathcal{E}(x) = \frac{1}{q}\left(-\frac{dE_i}{dx}\right)$$

$=$

Net effect of drift and diffusion

(Likewise for holes)

Modified Ohm's Law:

$$J_n(x) = q\mu_n n(x) \frac{d(F_n/q)}{dx} = \sigma_n(x) \frac{d(F_n/q)}{dx}$$

$$J_p(x) = q\mu_p p(x) \frac{d(F_p/q)}{dx} = \sigma_p(x) \frac{d(F_p/q)}{dx}$$

Gradients $\rightarrow$ Currents (J)

No " $\rightarrow$ No " (J)

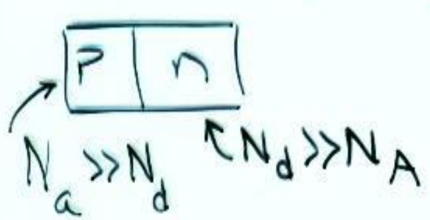
No J $\rightarrow$ No gradient

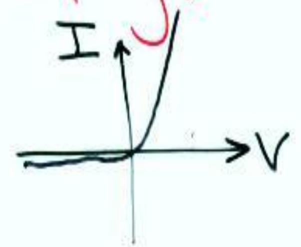
Junctions

So far: Generation, Recombination
Drift, Diffusion, Diffusion Length

What happens if we intentionally set up carrier gradients?

Instead of uniform doping, have





Rectifying Diode

How to fabricate?

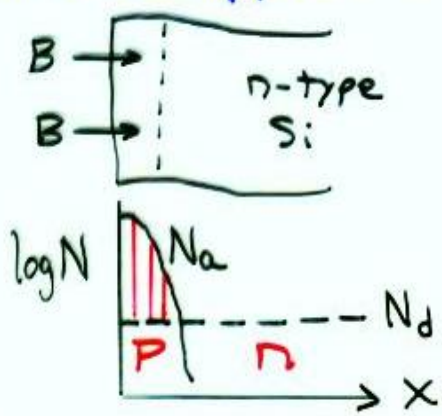
Read Streetman §5.1

5.1 Fabricate p-n junctions (ECE 5037!)

5.1.1 Grown junctions (change doping in mid-growth)
More flexible methods today.
with epitaxial growth, can still change on monolayer scale.

5.1.2 Alloyed Junctions (regrowth)

5.1.3 Diffused Junctions



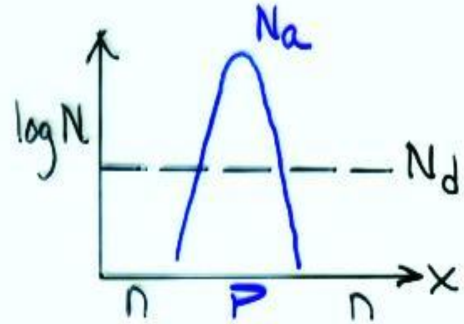
Si: vacancies at 1000 °C
B atom moves in.

p-type where $N_a > N_d$.

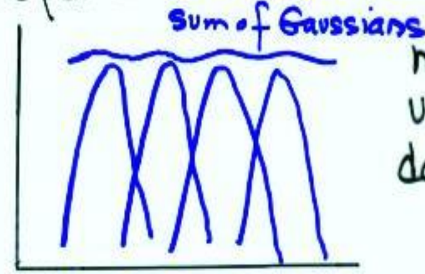
5.1.4 Ion Implantation

Si And B acceptors AND Defects

1000°C Anneal to remove defects



or



more uniform doping

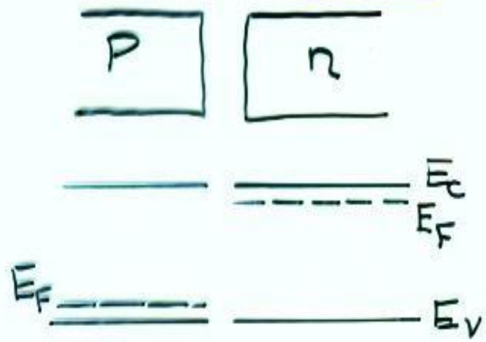
5.2 Equilibrium Conditions

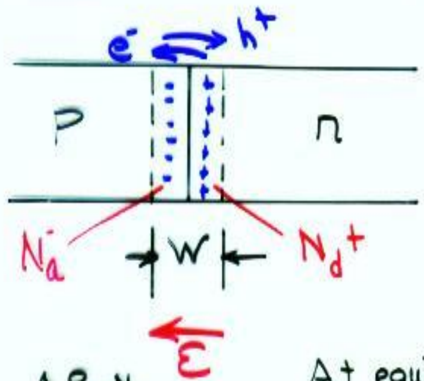
- Step Junctions (versus diffused, graded)

→ Simplifies the math: get the "big picture", make corrections later

Will see: 4 Currents balance to zero
p-type drift, diffusion, n-type drift, diffusion
Applied bias unbalances them.

5.2.1 The Contact Potential



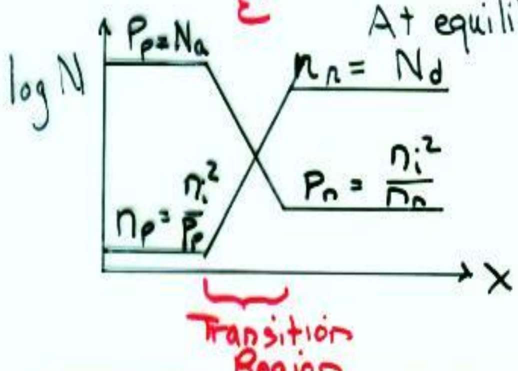


h^+ diffuses →

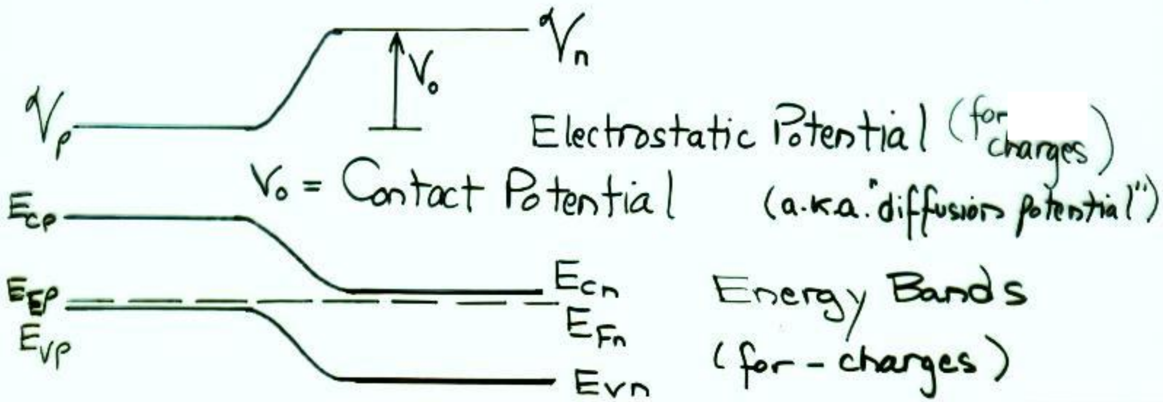
e^- diffuses ←

$\mathcal{E}$ set up ←
to balance diffused charge

At equilibrium, $\mathcal{E}$ extends over width W.



Gives n and p
on both sides of the junction



Major Big Deal! * !

e^-'s and h^+'s diffuse and set up $\mathcal{E}$ and V_o.

E_F's align.

Particle Flow	p | n	Current Flow	
→	Hole Diffusion	→	
←	Hole Drift	←	
←	Electron Diffusion	→	opposite charge
→	Electron Drift	←	" "

For each carrier, drift balances diffusion.
Set up by electric field $\mathcal{E}$.

Can get V_o from dopant concentration and balance between and diffusion

$$J_p = 0 = q\left[\mu_p p(x)\mathcal{E}(x) - D_p \frac{dp(x)}{dx}\right]$$

$$\frac{\mu_p}{D_p}\mathcal{E}(x) = \frac{1}{p(x)}\frac{dp(x)}{dx}$$

$$\mathcal{E}(x) = -\frac{d\mathcal{V}(x)}{dx}$$

subscript
denotes carrier

Einstein Relation

$$\frac{-q}{kT}\frac{d\mathcal{V}(x)}{dx} = \frac{1}{p(x)}\frac{dp(x)}{dx}$$

Integrate across transition region

$$\int_{V_p}^{V_n} \frac{-q}{kT} \frac{dV(x)}{dx} dx = \int_{p_p}^{p_n} \frac{1}{p} \frac{dp}{dx} dx$$

$$\frac{-q}{kT}(V_n - V_p) = \frac{-q}{kT} V_0 = \ln \frac{p_n}{p_p}$$

$p_p = N_a$ $\quad\quad$ $p_n = \frac{n_i^2}{N_d}$

$N_a = p_p \quad N_d = n_n$

majority concentration

~ doping concentration

(good except when $N_a \sim N_d$)

Very Valuable for I-V calculations
(V_0 measured by forward bias to flat bands)

Alternate Form:

$$n_p p_p = n_i^2 = p_n n_n$$

$$\therefore \quad \frac{p_p}{p_n} = \frac{n_n}{n_p}$$

Check out Example 5.1 Get V_0 2 ways.

(Easier way is $\frac{N_a N_d}{n_i^2}$)