ECE4904 Lecture 5

Energy Band Diagram Review

- E_F flat in equilibrium

pn Junction

- Doping profile (5.1.1)
  - Step junction approximation
- pn Junction: Handwaving
- Qualitative Electrostatics (5.1.2, 3)
- Built-in Potential (5.1.4)
- Depletion Appriximation (5.1.5)

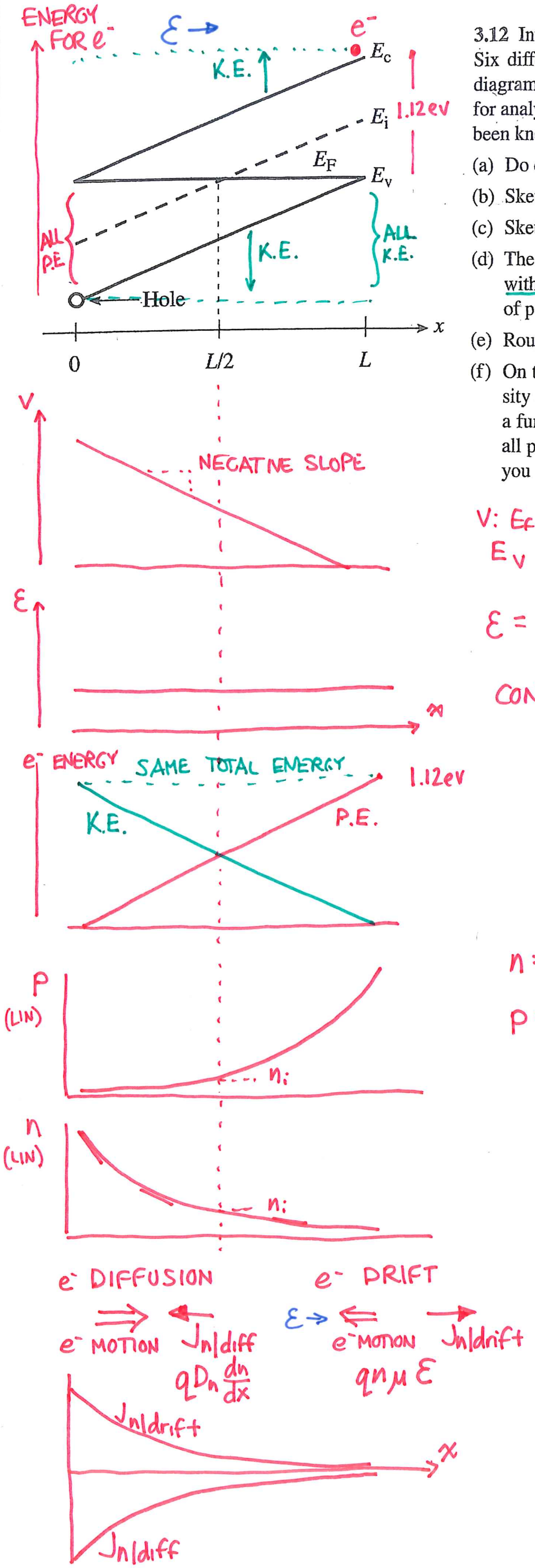
Quantitative Electrostatics (5.2)

- Qualitative forward, reverse bias (5.2.4)

Hand In: HW 2

Handouts

- HW Set 2 problem 3.12
- Text Figure 5.1: Doping Profile
- pn Junction: Handwaving
- pn junction: Electrostatics
- Depletion region equations
- Forward-Zero-Reverse bias



3.12 Interpretation of Energy Band Diagrams

Six different silicon samples maintained at 300 K are characterized by the energy band diagrams in Fig. P3.12. Answer the questions that follow after choosing a specific diagram for analysis. Possibly repeat using other energy band diagrams. (Excessive repetitions have been known to lead to the onset of insanity.)

(a) Do equilibrium conditions prevail? How do you know? YES: E_F FLAT

(b) Sketch the electrostatic potential (V) inside the semiconductor as a function of x. $V\ \frac{J}{coul}$

(c) Sketch the electric field ($\mathcal{E}$) inside the semiconductor as a function of x.

(d) The carrier pictured on the diagram moves back and forth between $x = 0$ and $x = L$ without changing its total energy. Sketch the K.E. and P.E. of the carrier as a function of position inside the semiconductor. Let E_F be the energy reference level.

(e) Roughly sketch n and p versus x.

(f) On the same set of coordinates, make a rough sketch of the electron drift-current density ($J_{N|drift}$) and the electron diffusion-current density ($J_{N|diff}$) inside the Si sample as a function of position. Be sure to graph the proper polarity of the current densities at all points and clearly identify your two current components. Also briefly explain how you arrived at your sketch.

V: E_F AS 0V REFERENCE, E_V FOR V

E_V UPSIDE DOWN (e^- IS NEG CHARGE)

$$\mathcal{E} = \frac{-dV}{dx}$$

$\mathcal{E} \rightarrow$

CONSTANT POSITIVE   POINTING IN $+x$ DIRECTION

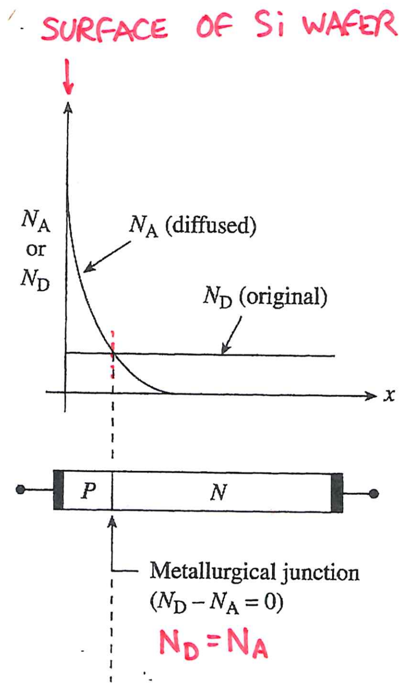
$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT}$$

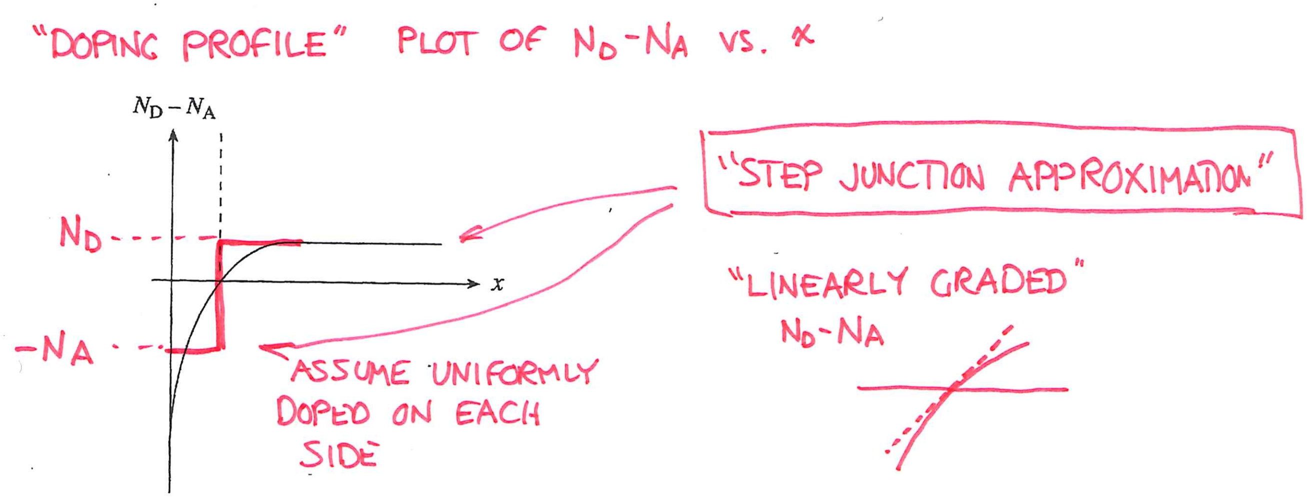
$J_{n|drift} = -J_{n|diff}$ EVERYWHERE!

$J_{n|TOTAL} = 0$ EVERYWHERE!

EQUILIBRIUM!



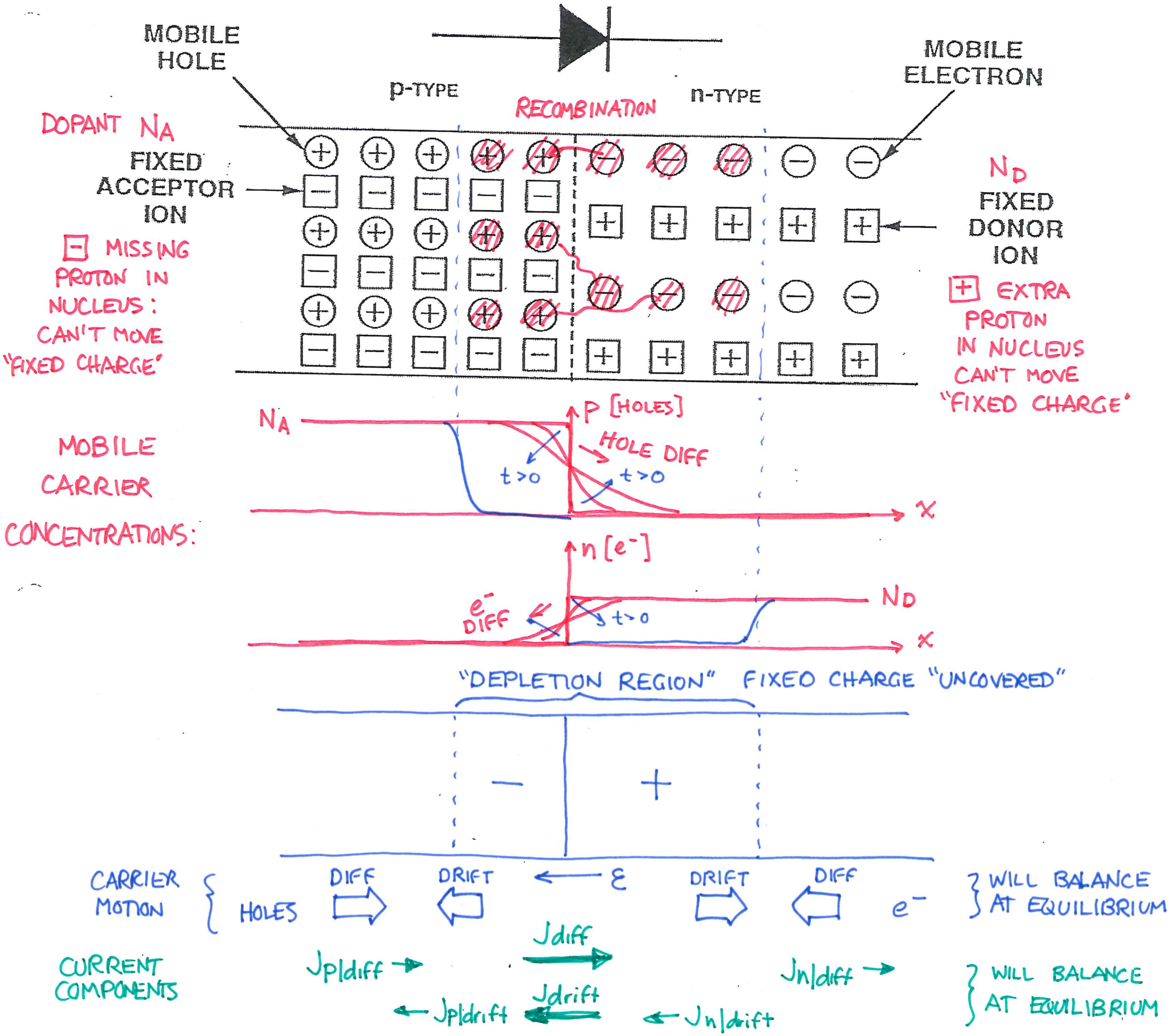
(a)



(b)

Figure 5.1 Junction definitions: (a) Location of the metallurgical junction, (b) doping profile—a plot of the net doping versus position.

EVERYTHING ELECTRICALLY NEUTRAL

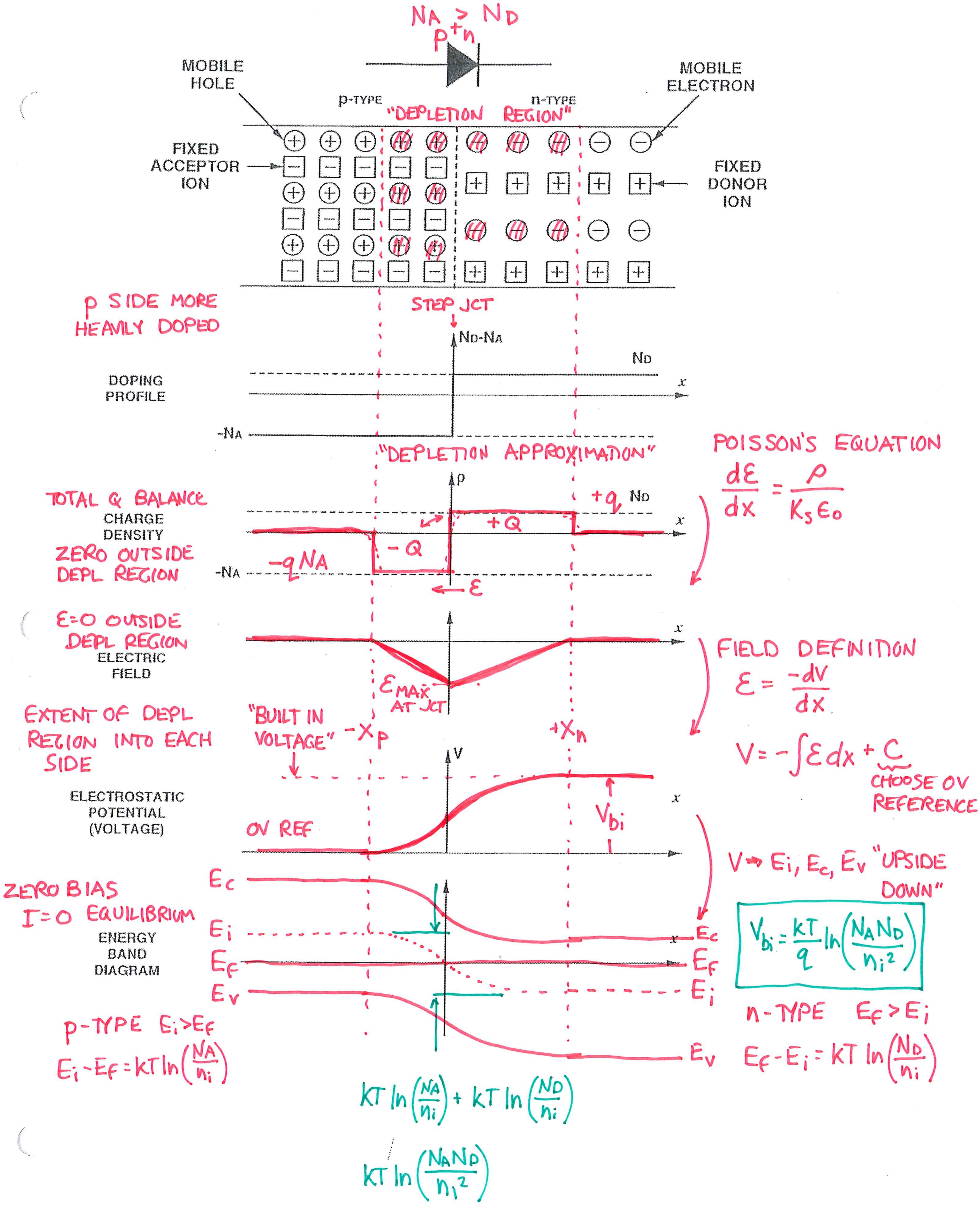


INITIALLY: ε = 0 EVERYWHERE

NO DRIFT

CARRIERS WILL MOVE DUE TO DIFFUSION

e^--HOLE PAIR RECOMBINATION



$N_A > N_D$
p^+n
MOBILE HOLE
p-TYPE
"DEPLETION REGION"
n-TYPE
MOBILE ELECTRON
FIXED ACCEPTOR ION
FIXED DONOR ION
p SIDE MORE HEAVILY DOPED
STEP JCT
$N_D - N_A$
N_D
DOPING PROFILE
$-N_A$
"DEPLETION APPROXIMATION"
POISSON'S EQUATION
$\frac{d\mathcal{E}}{dx} = \frac{\rho}{K_s \epsilon_0}$
TOTAL Q BALANCE
CHARGE DENSITY
ZERO OUTSIDE DEPL REGION
ρ
$+qN_D$
$+Q$
$-Q$
$-qN_A$
$-N_A$
$\mathcal{E}$
$\mathcal{E}=0$ OUTSIDE DEPL REGION
ELECTRIC FIELD
$\mathcal{E}_{MAX}$ AT JCT
FIELD DEFINITION
$\mathcal{E} = \frac{-dV}{dx}$
EXTENT OF DEPL REGION INTO EACH SIDE
"BUILT IN VOLTAGE"
$-X_p$
$+X_n$
V
$V = -\int \mathcal{E}\, dx + C$
CHOOSE 0V REFERENCE
ELECTROSTATIC POTENTIAL (VOLTAGE)
0V REF
V_{bi}
$V \rightarrow E_i, E_c, E_v$ "UPSIDE DOWN"
ZERO BIAS
I=0 EQUILIBRIUM
ENERGY BAND DIAGRAM
E_c
E_i
E_F
E_v
$\boxed{V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$
p-TYPE $E_i > E_F$
$E_i - E_F = kT \ln\left(\frac{N_A}{n_i}\right)$
n-TYPE $E_F > E_i$
$E_F - E_i = kT \ln\left(\frac{N_D}{n_i}\right)$
$kT \ln\left(\frac{N_A}{n_i}\right) + kT \ln\left(\frac{N_D}{n_i}\right)$
$kT \ln\left(\frac{N_A N_D}{n_i^2}\right)$

AFTER MUCH MATH (SEE CH. 5)

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

EXAMPLE:

$N_A = 1E+17\ /cm^3$
$N_D = 1E+14\ /cm^3$ $\Big\}\ N_A >> N_D$

@ T = 300K

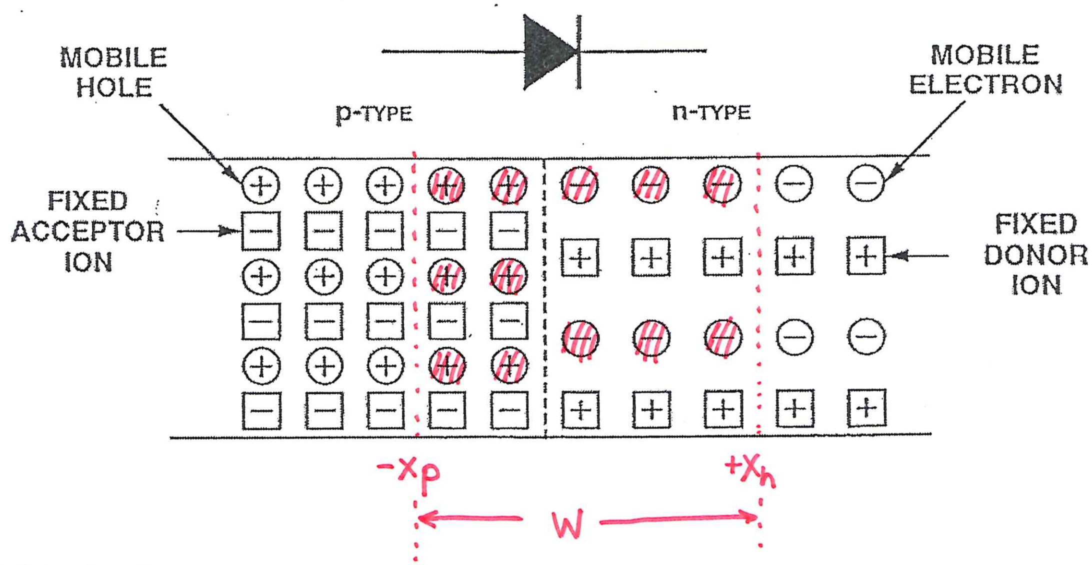
$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$25.9\text{mV}\ \ln\left(\frac{1E+31}{1E+20}\right)$$

$V_{bi} = 0.659\ V$

$x_n = 2.93\ E{-4}\ cm = 2.93\ \mu m$

$x_p = 2.93\ E{-7}\ cm = 2.93\ nm$



APPROX: $N_A >> N_D$

$$x_p = \sqrt{\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A}\frac{1}{N_A + \cancel{N_D}}V_{bi}} \qquad x_n = \sqrt{\frac{2K_S\varepsilon_0}{q}\frac{\cancel{N_A}}{N_D}\frac{1}{\cancel{N_A} + \cancel{N_D}}V_{bi}} \qquad W = \sqrt{\frac{2K_S\varepsilon_0}{q}\left(\frac{\cancel{N_A} + \cancel{N_D}}{\cancel{N_A} N_D}\right)V_{bi}}$$

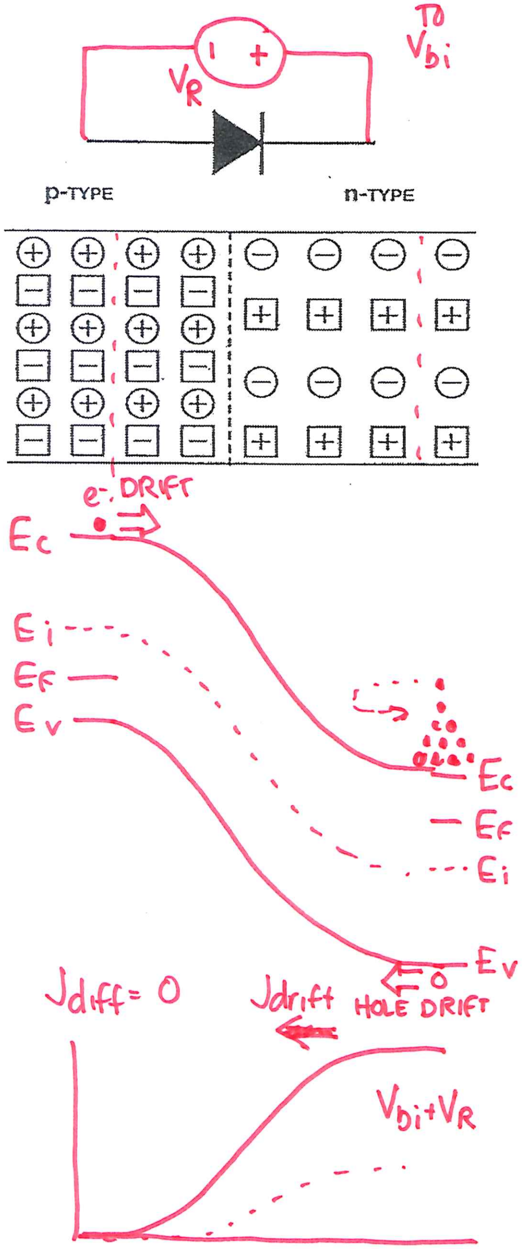
$$x_p \approx \sqrt{\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A^2}V_{bi}} \qquad x_n \approx \sqrt{\frac{2K_S\varepsilon_0}{q}\frac{1}{N_D}V_{bi}} \iff W = \sqrt{\frac{2K_S\varepsilon_0}{q}\frac{1}{N_D}V_{bi}}$$

SAME!

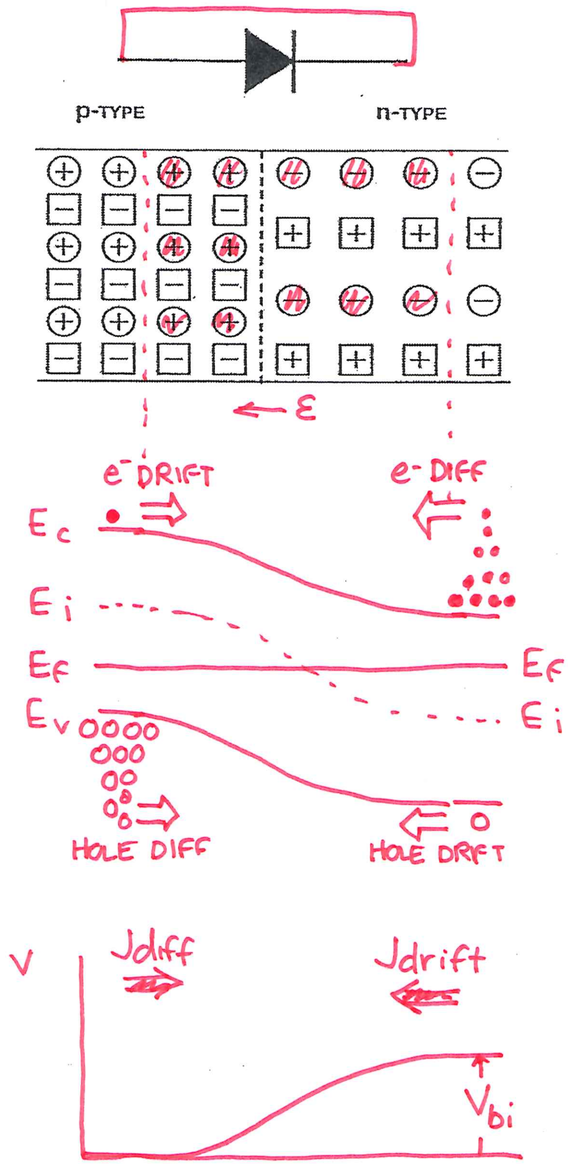
DEPLETION REGION EXISTS MOSTLY IN LIGHTLY DOPED SIDE!

W DEPENDS ONLY ON "LIGHTLY DOPED SIDE" DOPING

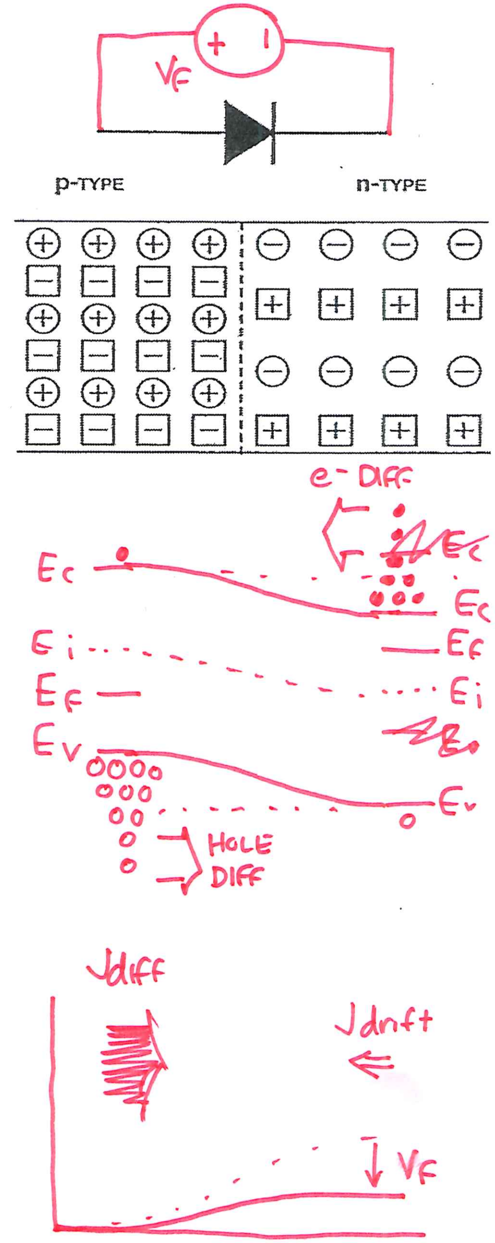
NON EQUILIBRIUM
REVERSE BIAS



ZERO BIAS
$V_A = 0$ } EQUILIB



NON EQUILIBRIUM
FORWARD BIAS



DIFFUSION