

5.2 – Contact Potential & Depletion Region



Si
IV
Host
 $\sim 5 \times 10^{22}/\text{cc}$
 $n_i \sim 1 \times 10^{10}/\text{cc}$



B
III
Acceptor
 $N_A \gg n_i$

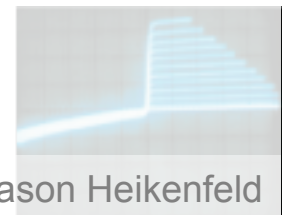
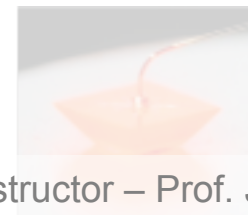
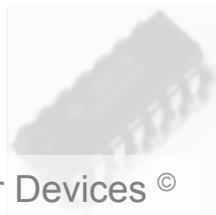
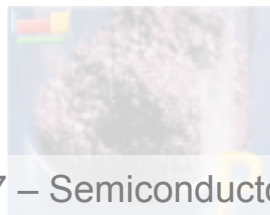
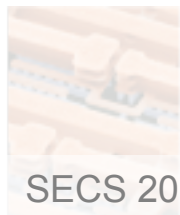


P
V
Donor
 $N_D \gg n_i$

This and the next lecture are arguably the most important for all of Semiconductor Devices. If you can 100% follow these lectures, then you are well on your way to understanding all semiconductor devices!

Supplemental Info: www.nanohub.org/simulation_tools/pnjunction_tool_information

If you are not solid on drift vs. diffusion current, go over lecture 2 again! Carrier dynamics...

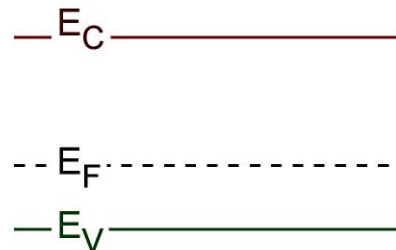


- ▶ Lets get ready to make a PN junction (keep separate for a moment).
- ▶ Assume all donors or acceptors ionize at 300 K

▶ p-type side:

$$p_0 = N_A$$

$$n_0 p_0 = n_i^2$$



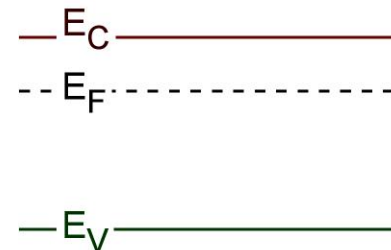
$$p_0 = N_v e^{-(E_F - E_v)/kT} = N_A$$

$$n_{0p} = N_c e^{-(E_c - E_F)/kT} = \frac{n_i^2}{N_A}$$

▶ n-type side:

$$n_0 = N_D$$

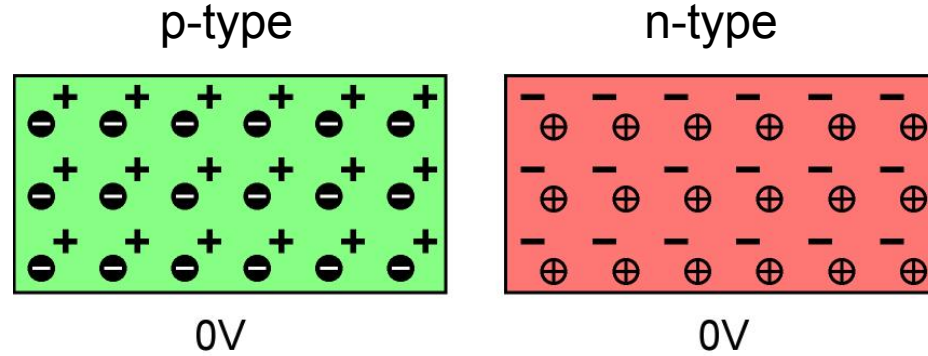
$$n_0 p_0 = n_i^2$$



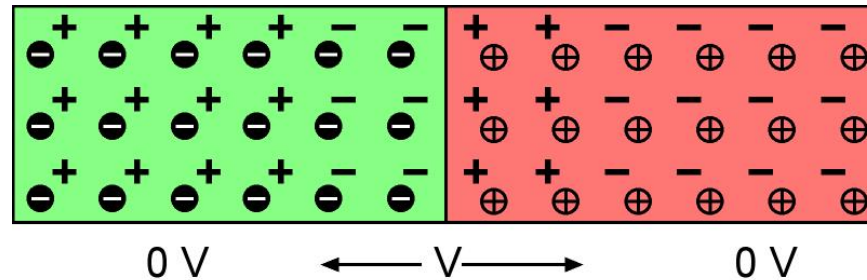
$$n_0 = N_c e^{-(E_{cn} - E_{Fn})/kT} = N_D$$

$$p_{0n} = N_v e^{-(E_F - E_v)/kT} = \frac{n_i^2}{N_D}$$

1) Join materials...
What do you think will happen?

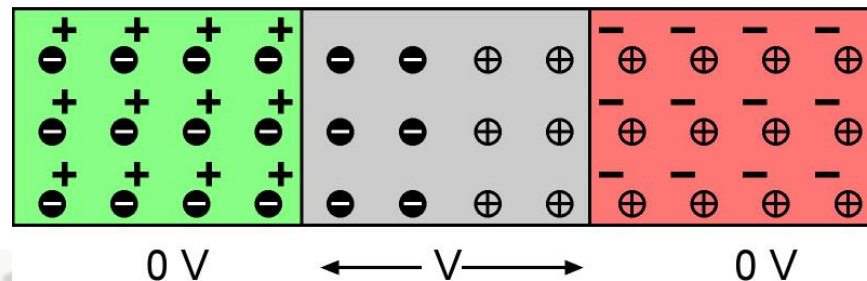


2) Free particles diffuse and creates an E field



'Space Charge Region', '**Depletion Region**'
Transition Region

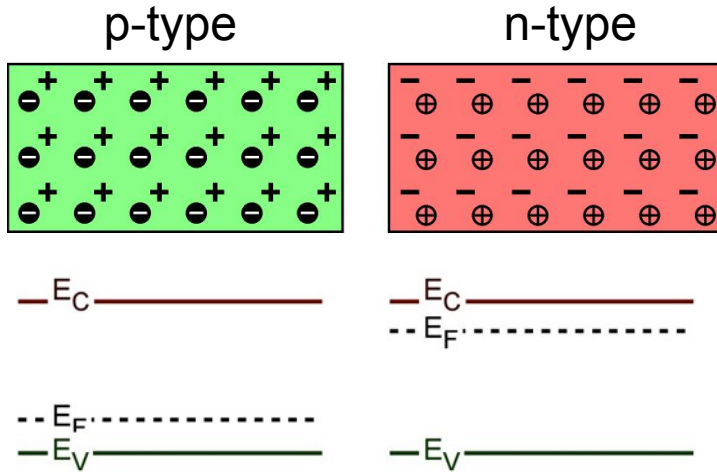
3) E-field sweeps out charge and creates a depletion region



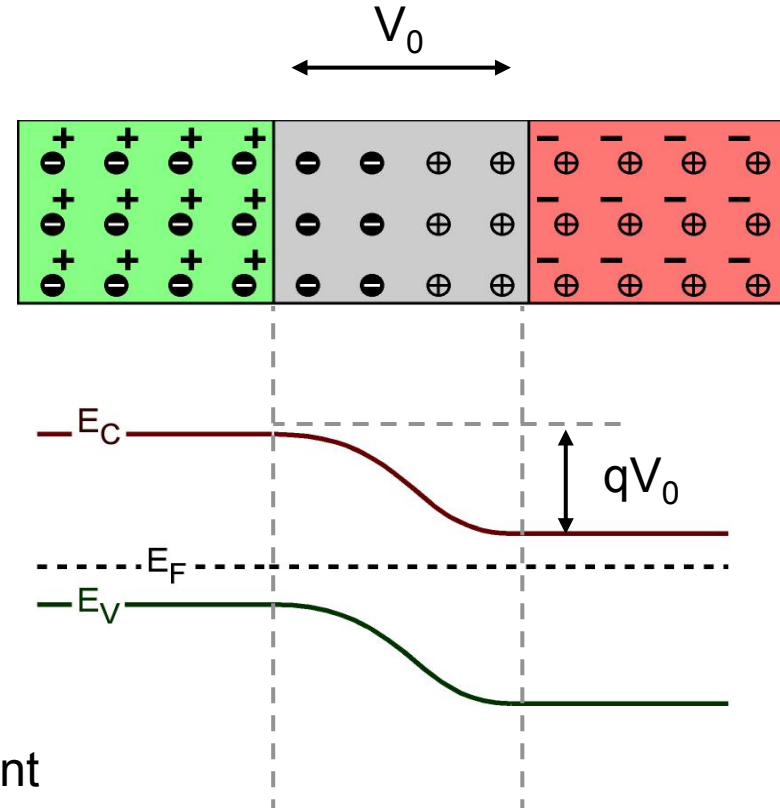
forces balance!

contact potential: V_0

► Band Diagram



At thermal equil. Fermi levels line up every time...
 ... why the q in front of V_0 ?

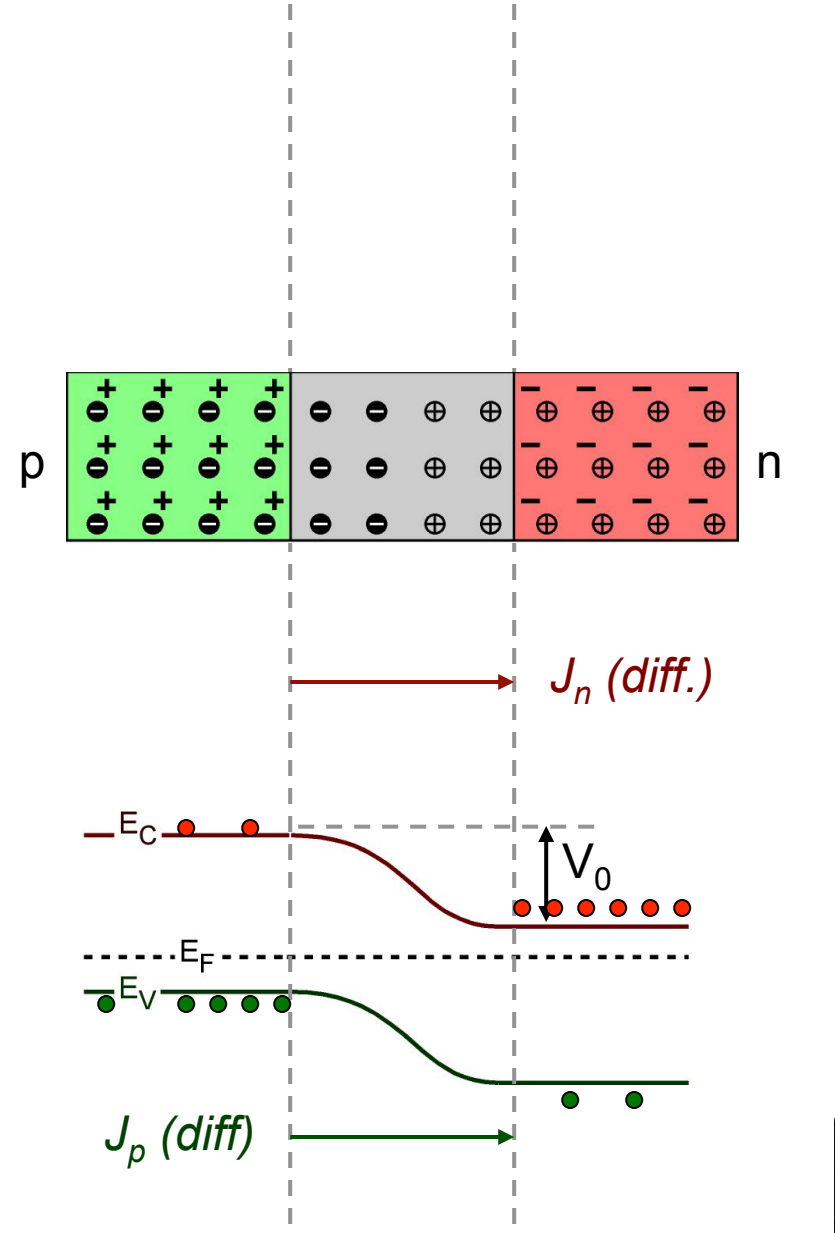


► Contact potential does what to carrier diffusion, to drift? How can we determine the contact potential?

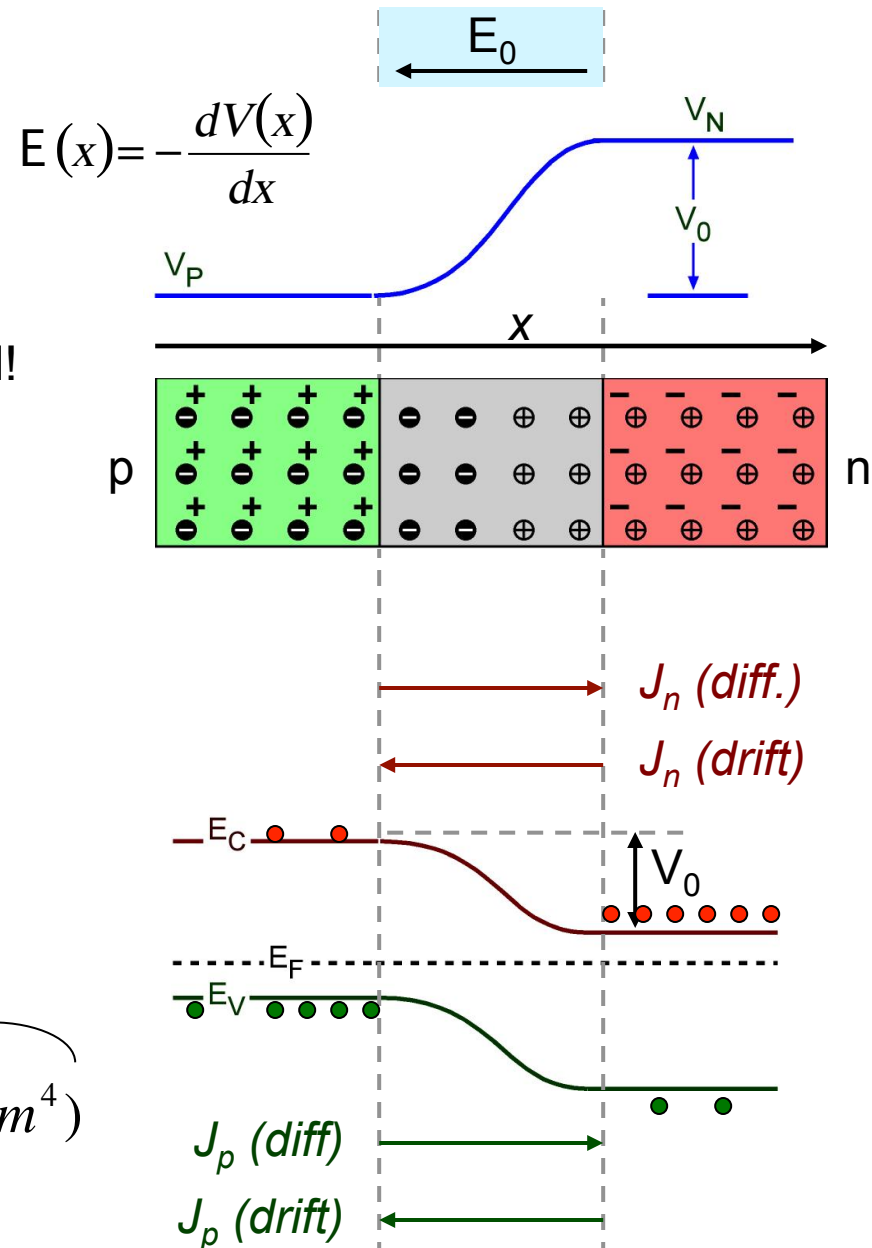
When we reach thermal equilibrium (constant V_0) the diffusion current exactly cancels the oppositely directed drift current ($J=0$).



- ▶ Diffusion Current at equilibrium $J(\text{diff.})$:
 - majority carriers move away from high concentration
 - *carriers never still at 300K!* $E > qV_0$



- ▶ Diffusion Current at equilibrium $J(\text{diff.})$:
 - majority carriers move away from high concentration
 - *carriers never still at 300K!* $E > qV_o$
- ▶ Drift Current at equilibrium $J(\text{drift})$:
 - minority carriers ($n_p = n_i^2$) also never still! if near edge, then swept by E field...
 - *think soda pop: $e^- = \text{liquid}$, $h^+ = \text{bubbles}$*
- ▶ At thermal equilibrium $J(\text{total}) = 0$



$$J_n(\text{drift}) + J_n(\text{diff.}) = 0$$

$$J_p(\text{drift}) + J_p(\text{diff.}) = 0$$

$$q\mu_p p(x) E(x) = qD_p \frac{dp(x)}{dx}$$

$$q \frac{(cm/s)}{(V/cm)} (1/cm^3)(V/cm) = q (cm^2/s)(1/cm^4)$$

► 'Fun' with math...

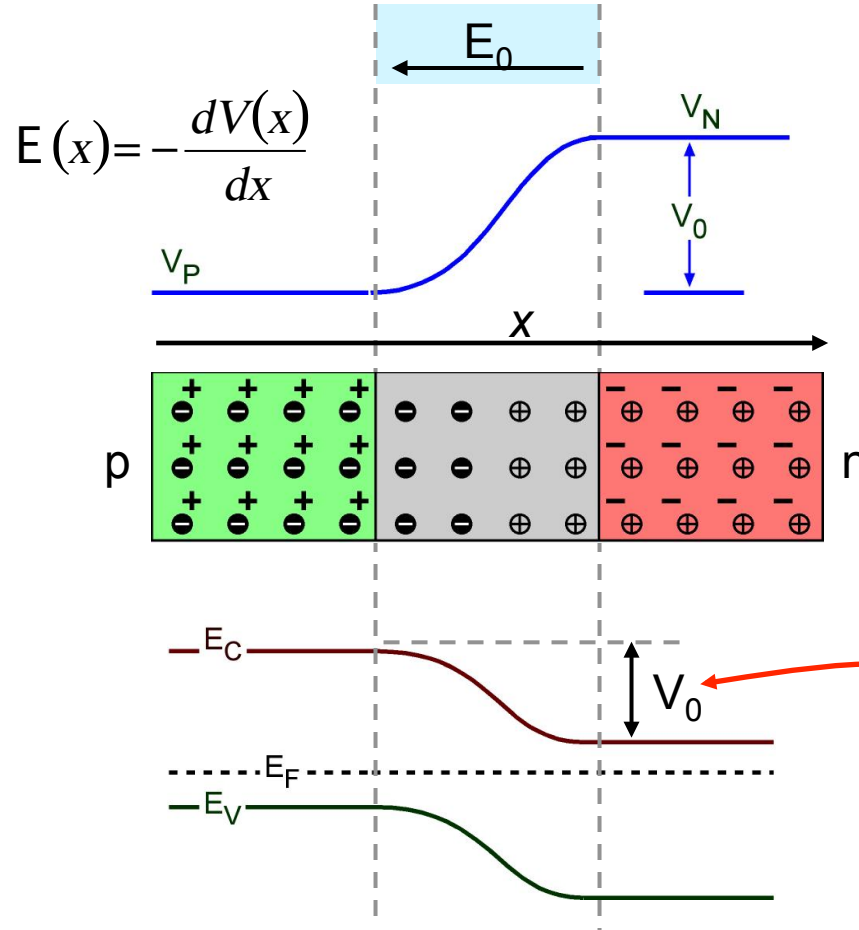
$$q\mu_p p(x) E(x) = qD_p \frac{dp(x)}{dx}$$

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

$$\frac{\mu}{D} = \frac{q}{kT} \quad E(x) = -\frac{dV(x)}{dx}$$

$$-\frac{q}{kT} dV(x) = \frac{1}{p(x)} dp(x)$$

$$-\frac{q}{kT} \int_{V_p}^{V_n} dV = \int_{p_p}^{p_n} \frac{1}{p} dp \Rightarrow -\frac{q}{kT} (V_n - V_p) = \ln p_n - \ln p_p = \ln \frac{p_n}{p_p} \Rightarrow V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}$$



8 ■ Deriving Contact Potential

► Useful alternate forms...

$$p_p = N_A \quad n_n = N_D, \quad p_n = \frac{n_i^2}{N_D}$$

➔ $V_0 = \frac{kT}{q} \ln \frac{p_p}{p_n}$

➔ $\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$

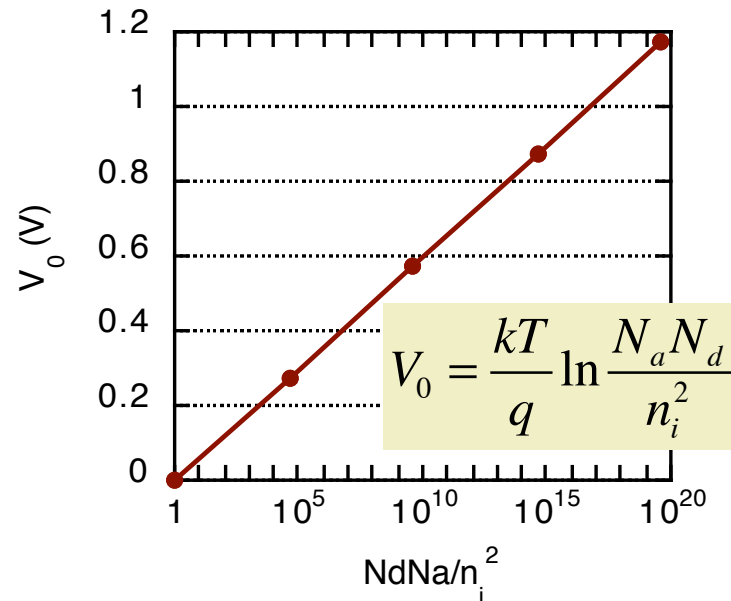
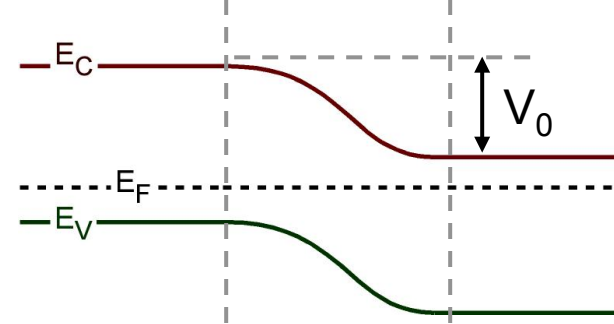
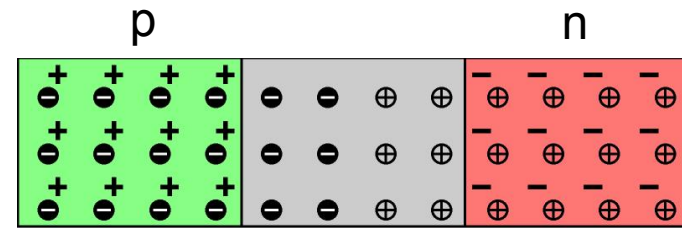
$p_n = N_v e^{-(E_{Fn} - E_{vn})/kT}$
 $p_p = N_v e^{-(E_{Fp} - E_{vp})/kT}$

$$\frac{N_v e^{-(E_{Fp} - E_{vp})/kT}}{N_v e^{-(E_{Fn} - E_{vn})/kT}} = e^{qV_0/kT}$$

$$e^{(E_{Fn} - E_{Fp})/kT} e^{(E_{vp} - E_{vn})/kT} = e^{qV_0/kT}$$

➔ $qV_0 = E_{vp} - E_{vn}$

- More doping = stronger diffuse = more V_0 (more charge uncovered).
- Also think of E_F doping dependence...



%Vbi Computation (p+/n and n+/p junctions)

%Constants

EG=1.12;
kT=0.0259;
ni=1.0e10;

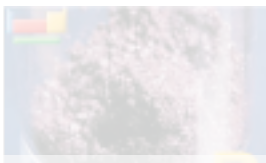
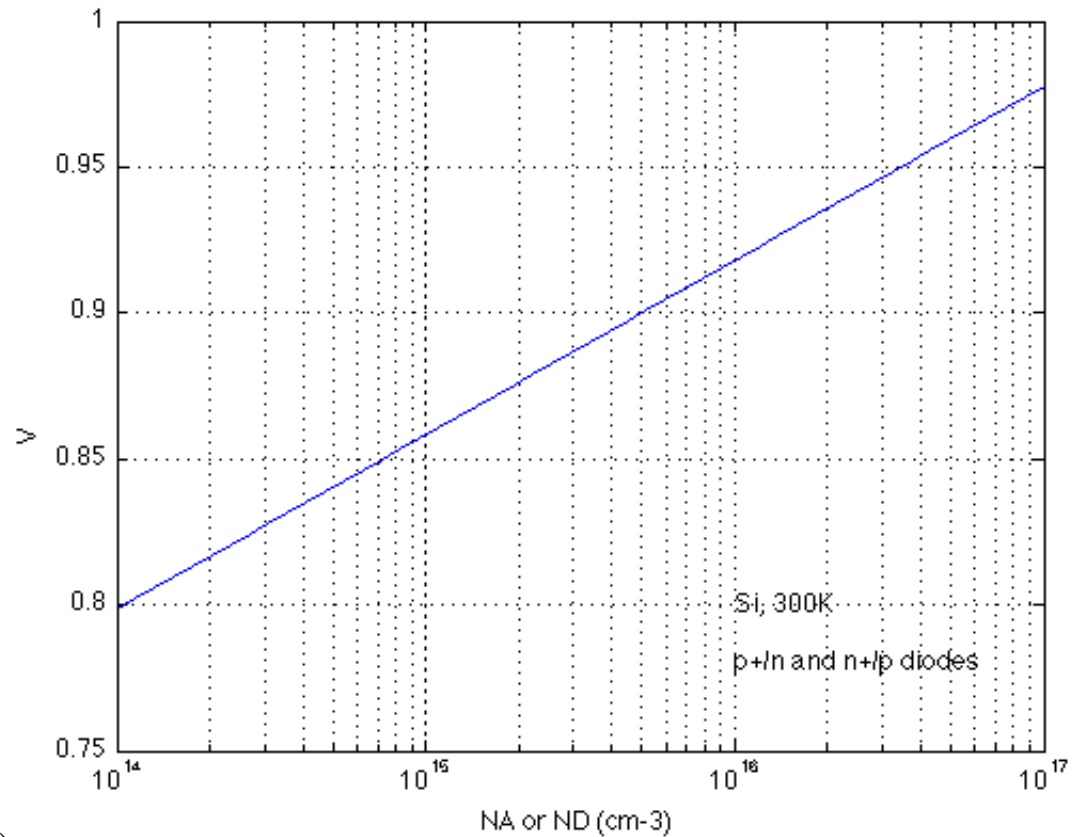
%Computation

ND=logspace(14,17);
Vbi=EG/2+kT.*log(ND./ni);

%Plotting

close
semilogx(ND,Vbi); grid
axis([1.0e14 1.0e17 0.75 1])
xlabel('NA or ND (cm-3)'); ylabel('Vbi (volts)')
text(1e16,0.8,'Si, 300K')
text(1e16,0.78,'p+/n and n+/p diodes')

From Pierret 5.1

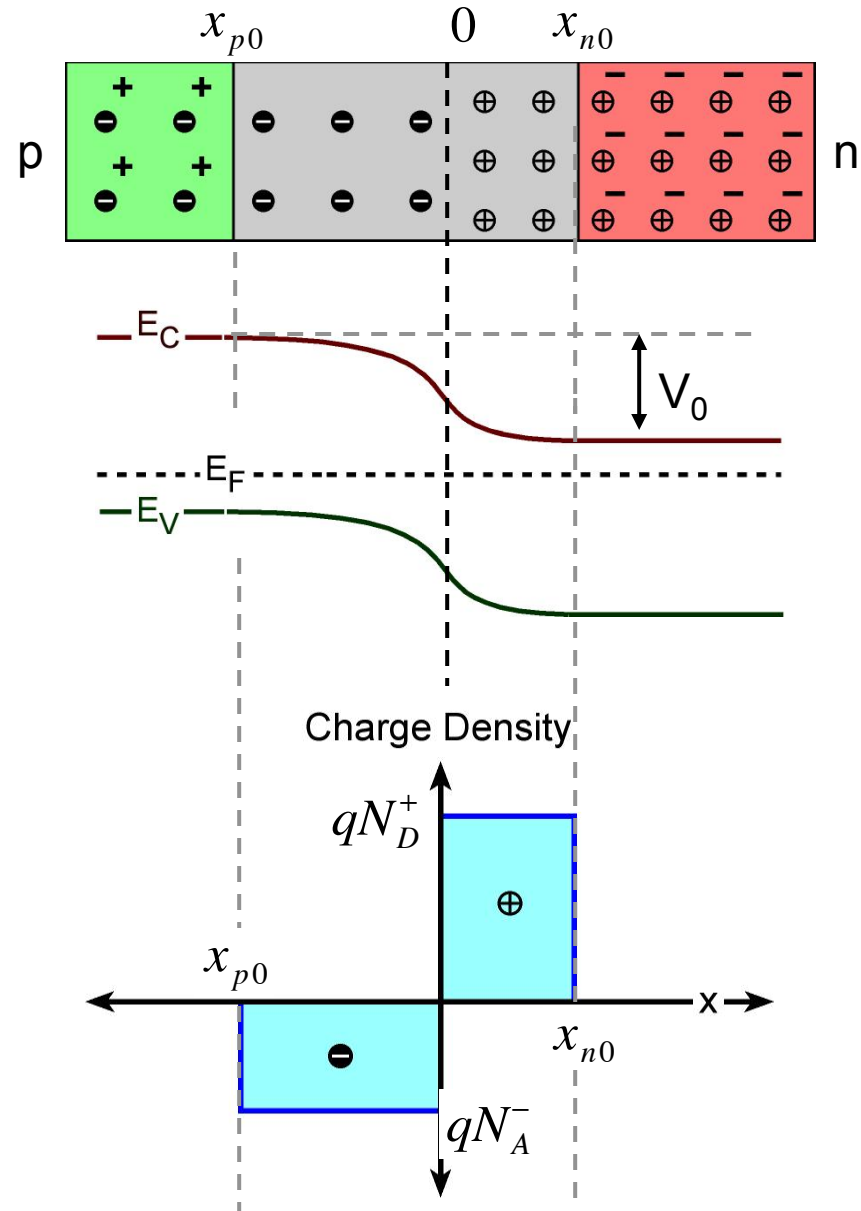


► Consider $N_D > N_A \dots$
 ... we must uncover
 equal amount of Q on
 each side, higher
 doping = less volume
 needed to obtain Q

$$\underbrace{qA \times x_{p0} N_A}_{Q_{total, p}} = \underbrace{x_{n0} N_D \times qA}_{Q_{total, n}}$$

$A = \text{cross-sectional area}$

- Why $x_n < x_p$?
- What if $N_A = N_D$?
- What if $N_A \gg N_D$?



► Change in E field is dependent on charge density

.... Poisson's Equation

$$\frac{dE(x)}{dx} = \frac{q}{\epsilon} (p - n + N_D^+ - N_A^-)$$

Makes sense! Want to change E-field rapidly? Need closer spaced charges to do so (charge density).

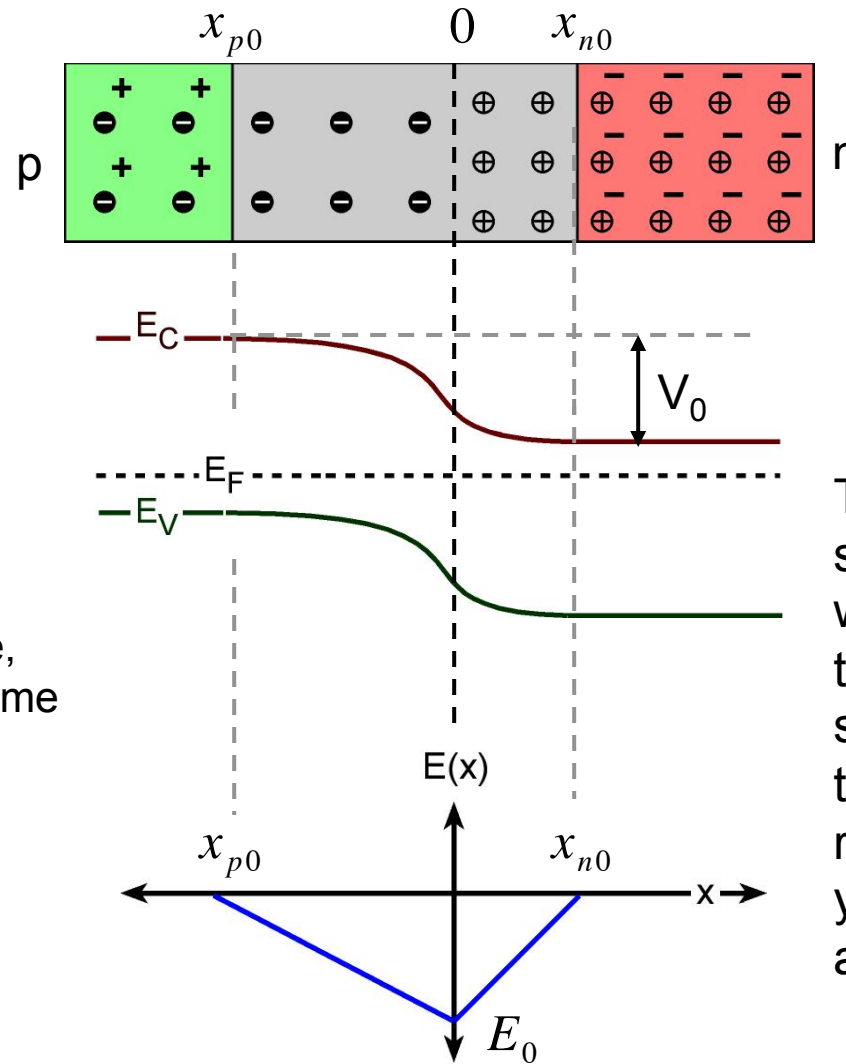
(1) Assume $E=E_0$ at $x=0$ (max value, why?). (2) At x_{p0} and x_{n0} I can assume $E=0$. How can you tell?

► P-side

$$\int_0^{E_0} dE = -\frac{q}{\epsilon} N_A \int_{-x_{p0}}^0 dx$$

► N-side (same integ. direction)

$$\int_{E_0}^0 dE = \frac{q}{\epsilon} N_D \int_0^{-x_{n0}} dx$$



► Cool!!! This now shows me why I have the changing slopes across the depletion region, can you see why also?

$$E_0 = -\frac{q}{\epsilon} N_D x_{n0} = -\frac{q}{\epsilon} N_A x_{p0}$$

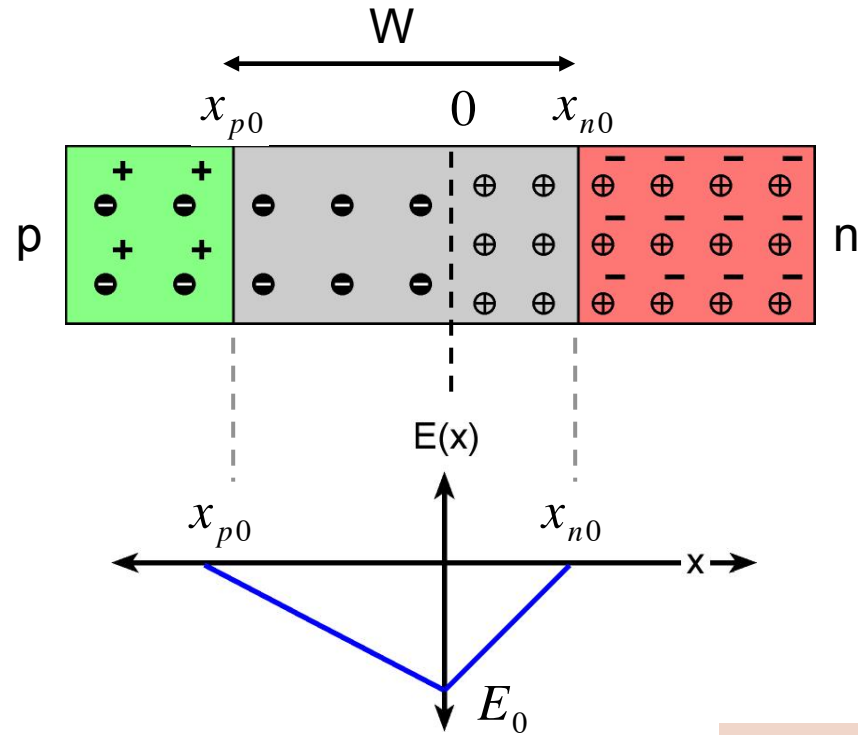
► Simple relations to get dimensions...

➔ $E(x) = -\frac{dV(x)}{dx}$

➔ $-V_0 = \int_{-x_{p0}}^{x_{n0}} E(x) dx$

➔ $V_0 = \frac{1}{2} E_0 W$ (V/cm*cm)
 ½ of a square...

$W = x_{n0} + x_{p0} \longleftrightarrow x_{n0} N_D = x_{p0} N_A$



$$W = \sqrt{\frac{2\epsilon kT}{q^2} \left(\ln \frac{N_A N_D}{n_i^2} \right) \left(\frac{1}{N_A} + \frac{1}{N_D} \right)}$$

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

$$x_{n0} = \frac{W N_a}{N_a + N_d}$$

► Want an example W?

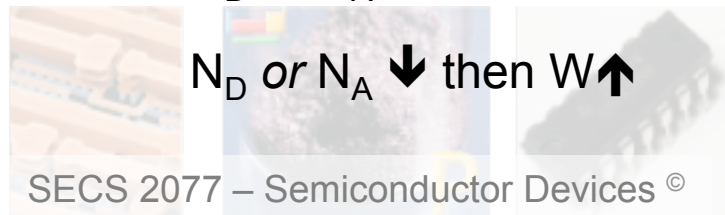
Ex 5-2, for $N_a=10^{18}$, and $N_d=5 \times 10^{15}$, $W=0.5 \mu m$.

N_D or N_A ↑ then W ↓

x ↑ when doping ↓ on side of x

N_D or N_A ↓ then W ↑

x ↓ when doping ↑ on side of x



From Pierret 5.3

%Vbi Computation (p+/n and n+/p Si junctions corresponding to VA = 0.5V, 0.0V, and -10V
 %The Vbi relationship employed is $V_{bi} = (E_G/2q) + (kT/q) \ln(N_B/n_i)$ where NB is the impurity concentration on the lightly doped side.

%Constants and Parameters

T=300; % Temperature in Kelvin
 k=8.617e-5; % Boltzmann constant (eV/K)
 e0=8.85e-14; % permittivity of free space (F/cm)
 q=1.602e-19; % charge of an electron (coul)
 KS=11.8; % dielectric constant of Si at 300K
 ni=1e10; % intrinsic carrier conc. in Si (cm^-3)
 EG=1.12; % band gap of Silicon (eV)

%Choose variable values

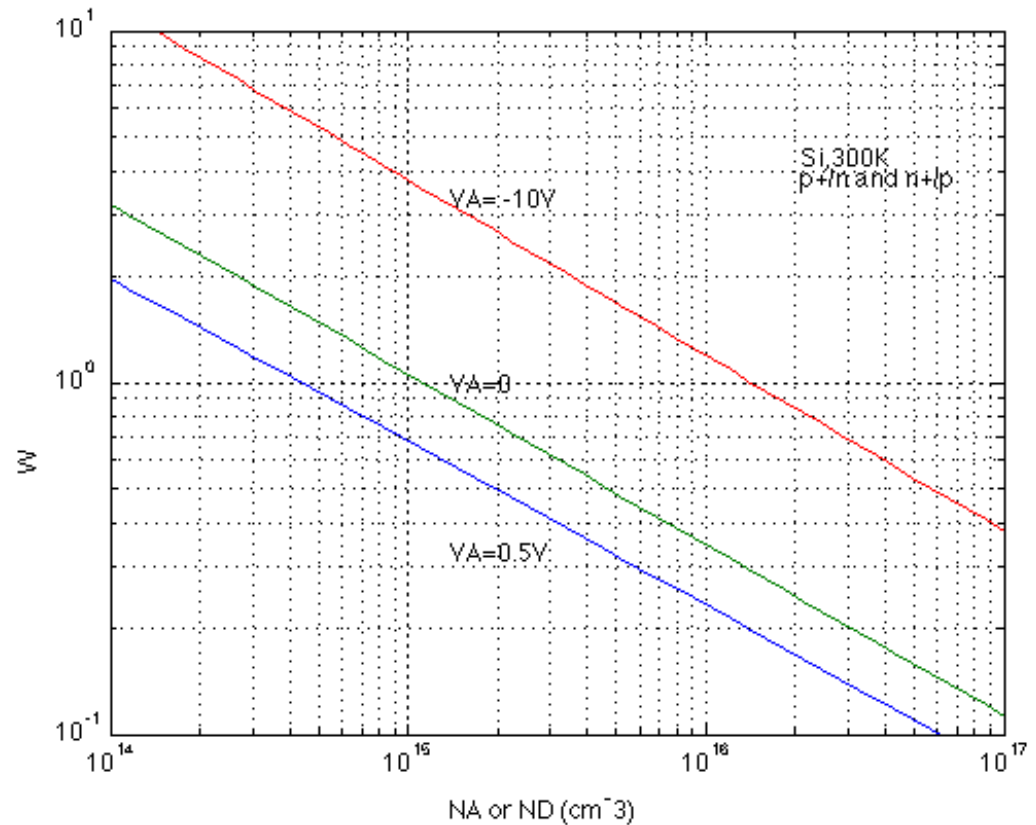
NB=logspace(14,17); % doping ranges from 1e14 to 1e17
 VA=[0.5 0 -10]; % VA values set

%Depletion width calculation

Vbi=EG/2+k*T.*log(NB./ni);
 W(1,:)=1.0e4*sqrt(2*KS*e0/q.*(Vbi-VA(1))./NB);
 W(2,:)=1.0e4*sqrt(2*KS*e0/q.*(Vbi-VA(2))./NB);
 W(3,:)=1.0e4*sqrt(2*KS*e0/q.*(Vbi-VA(3))./NB);

%Plot

Close
 loglog(NB, W, '-')
 axis([1.0e14 1.0e17 1.0e-1 1.0e1])
 Grid



```
xlabel('NA or ND (cm^-3)')
ylabel('W (micrometers)')
set(gca,'DefaultTextUnits','normalized')
text(.38,.26,'VA=0.5V')
text(.38,.50,'VA=0')
text(.38,.76,'VA= -10V')
text(.77,.82,'Si,300K')
text(.77,.79,'p+/n and n+/p')
```

▶ Bring p and n semiconductors together, what happens first What happens second? **S3**

▶ Is there a balance? What causes the balance? **S5**

▶ What current components are there at thermal equilibrium? Do they balance? **S5**

▶ When I see bent bands, what does that mean? What does that mean for e's and h's? **S11**

▶ Why do the bands curve the way they do inside the depletion region? **S11**

▶ Where is my contact potential? How and why does it change with doping? **S7**

▶ Where is my depletion width? How and why does it change with doping? **S12**

