PN junction

(I) Fundamentals (this lecture)

(II) Fabrication (after midterm test)

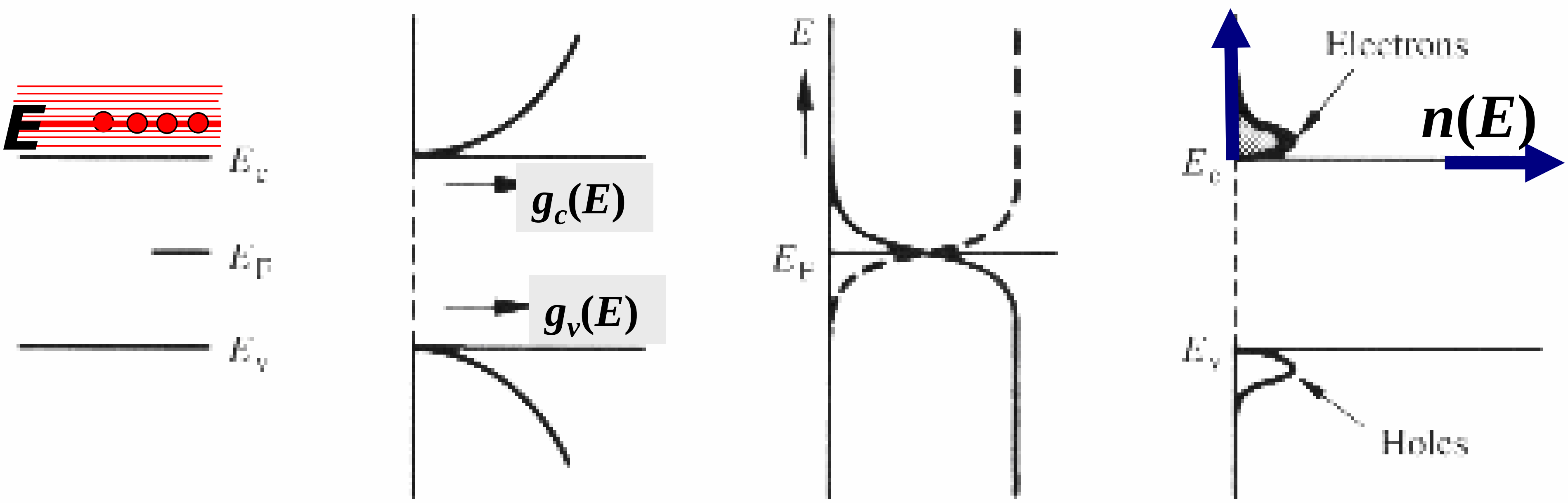
Reading: Chapter 3.1 & 4.0

**Material developed
by Prof. C. Z. Zhao**

Last lecture: Distribution of Electrons

- Obtain $n(E)$ by multiplying $g_c(E)$ and $f(E)$

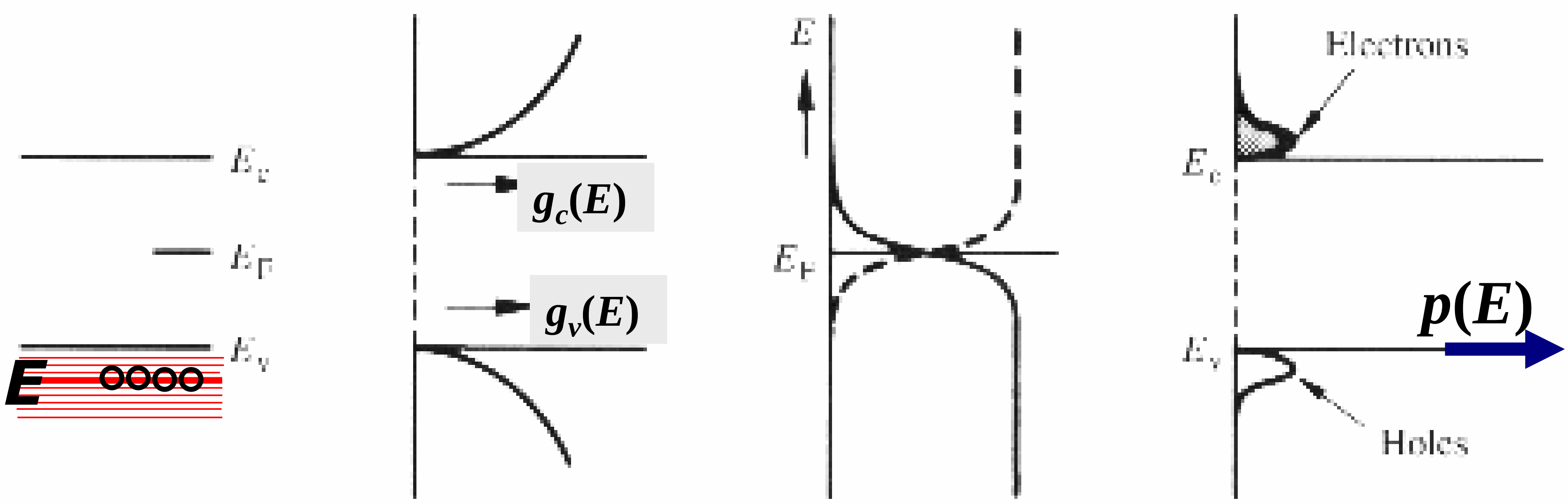
Energy band diagram | Density of States | Probability of occupancy | Carrier distribution



Last lecture: Distribution of Holes

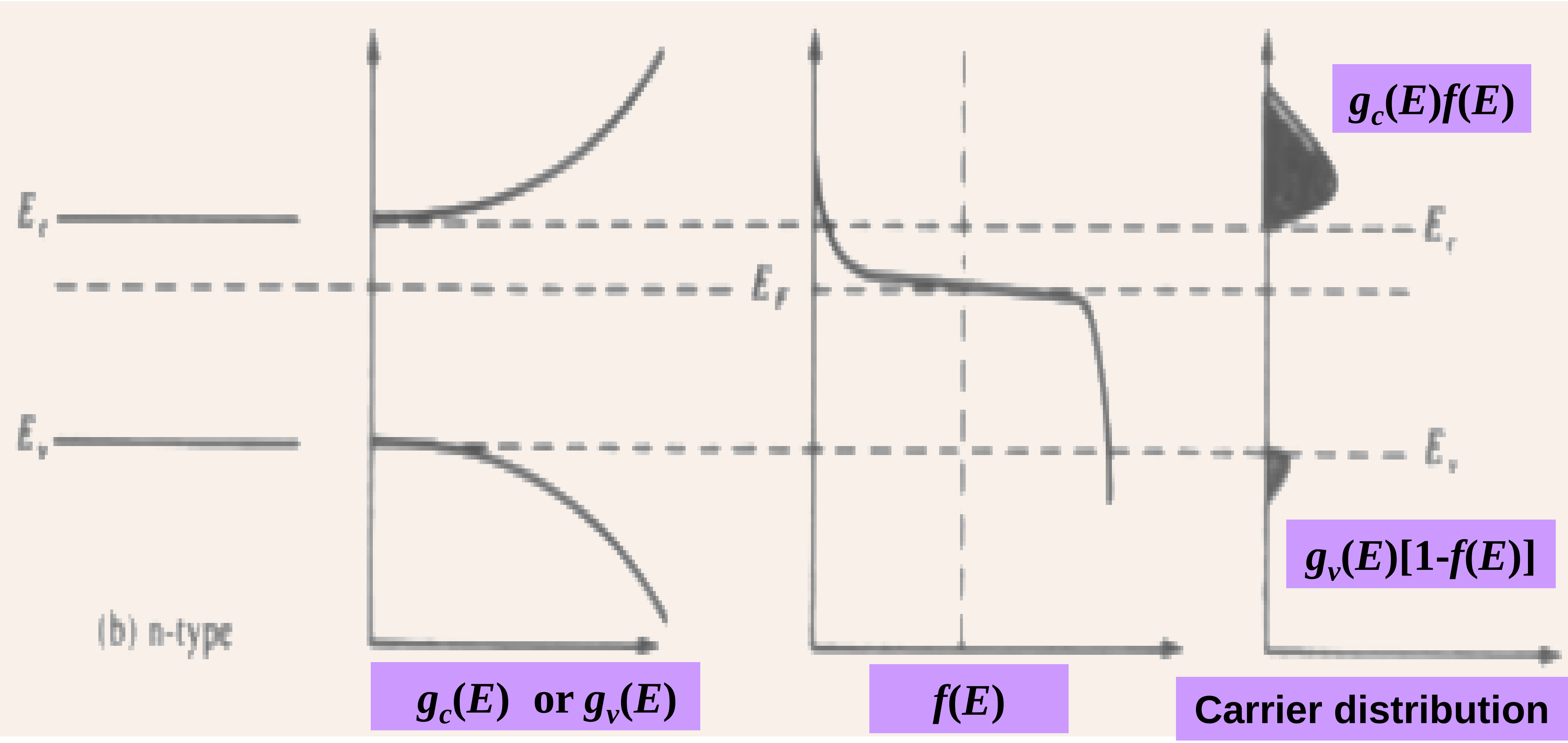
- Obtain $p(E)$ by multiplying $g_v(E)$ and $1\text{-}f(E)$

Energy band diagram | **Density of States** | **Probability of occupancy** | **Carrier distribution**

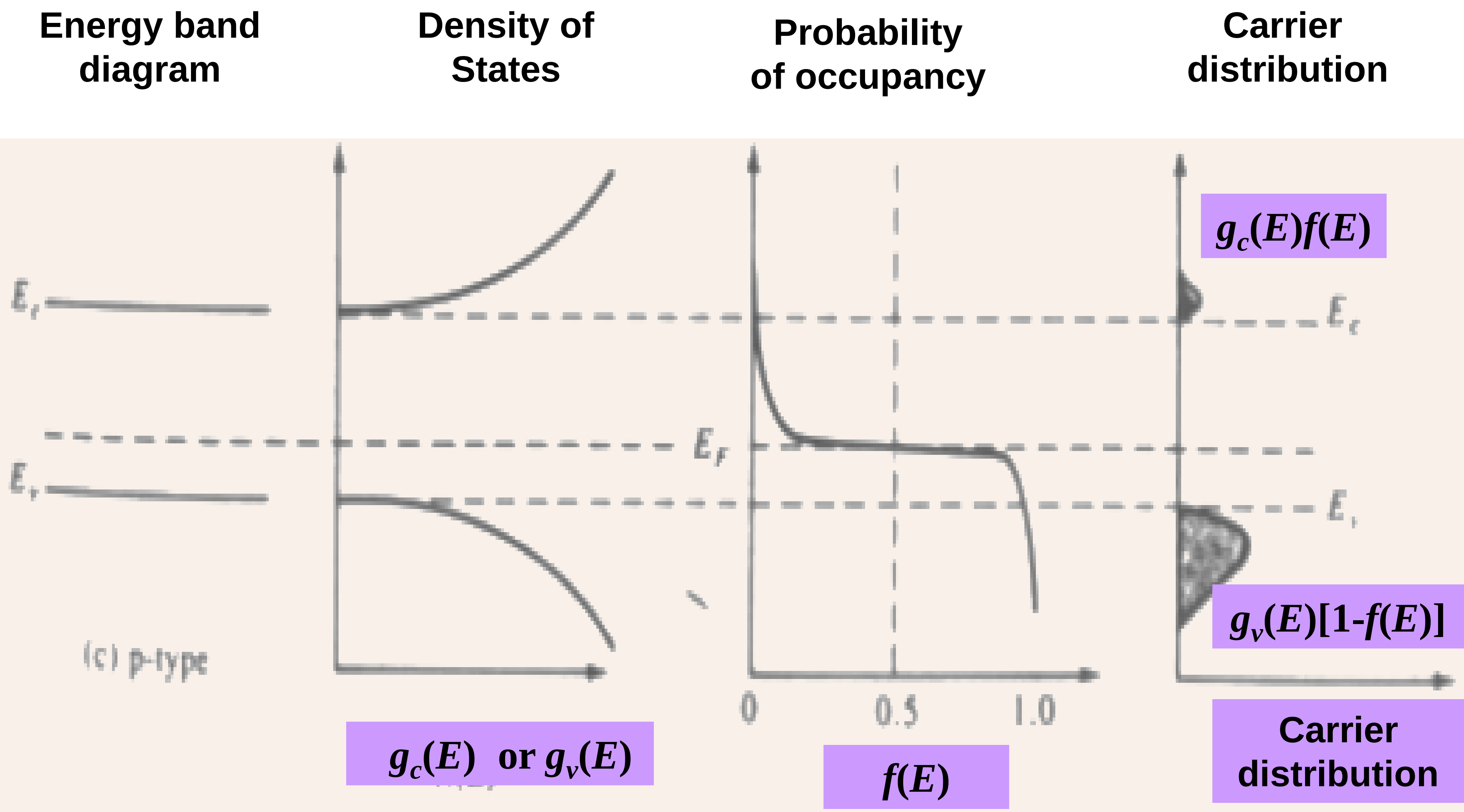


N-type Material

Energy band diagram | **Density of States** | **Probability of occupancy** | **Carrier distribution**



P-type Material



Last lecture: the **total** current

- The total current flowing in a semiconductor is the sum of **drift current** and **diffusion current**:

$$\boxed{J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff}}$$

$$J_{p,drift} = qp\mu_p E, \qquad J_{n,drift} = qn\mu_n E$$

$$J_{p,diff} = -qD_p \frac{dp}{dx}, \quad J_{n,diff} = qD_n \frac{dn}{dx}$$

The Einstein Relation

- The characteristic constants for drift and diffusion are related:

$D_n = \frac{kT}{q}\mu_n$

$D_p = \frac{kT}{q}\mu_p$

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}} \simeq 26\ \text{mV}$$

at $T = 300K$

- Note that $\frac{kT}{q} \cong 26\text{mV}$ at room temperature (**300K**)

  - This is often referred to as the **"thermal voltage"**.

PN junction – (I)

OUTLINE

- Formation of depletion region (DR)
- Built-in potential of DR
- Distribution of electric field and electric potential in DR
- Effect of applied voltage on DR
- Depletion capacitance of DR*

Reference Reading

- **Chapter 3.1 (page 92-116)**

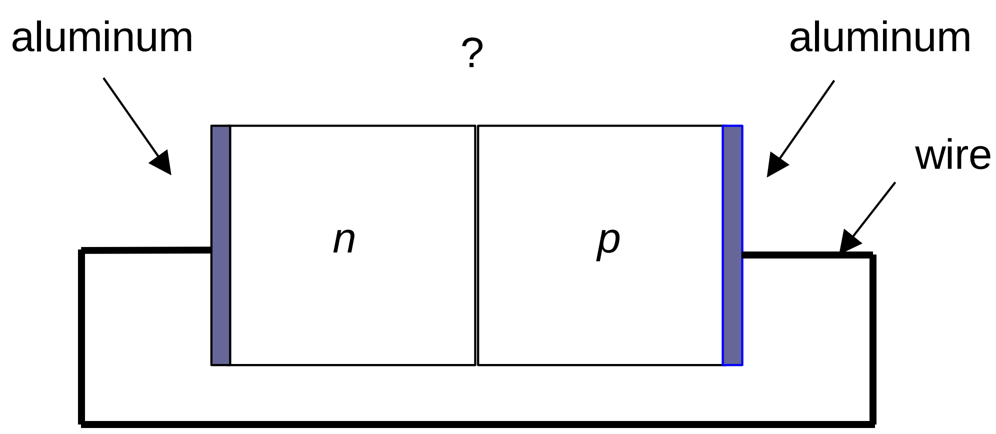
Junctions of n- and p-type Regions

p-n junctions form the essential basis of all semiconductor devices.

A silicon chip may have 10^8 to 10^9 p-n junctions today.

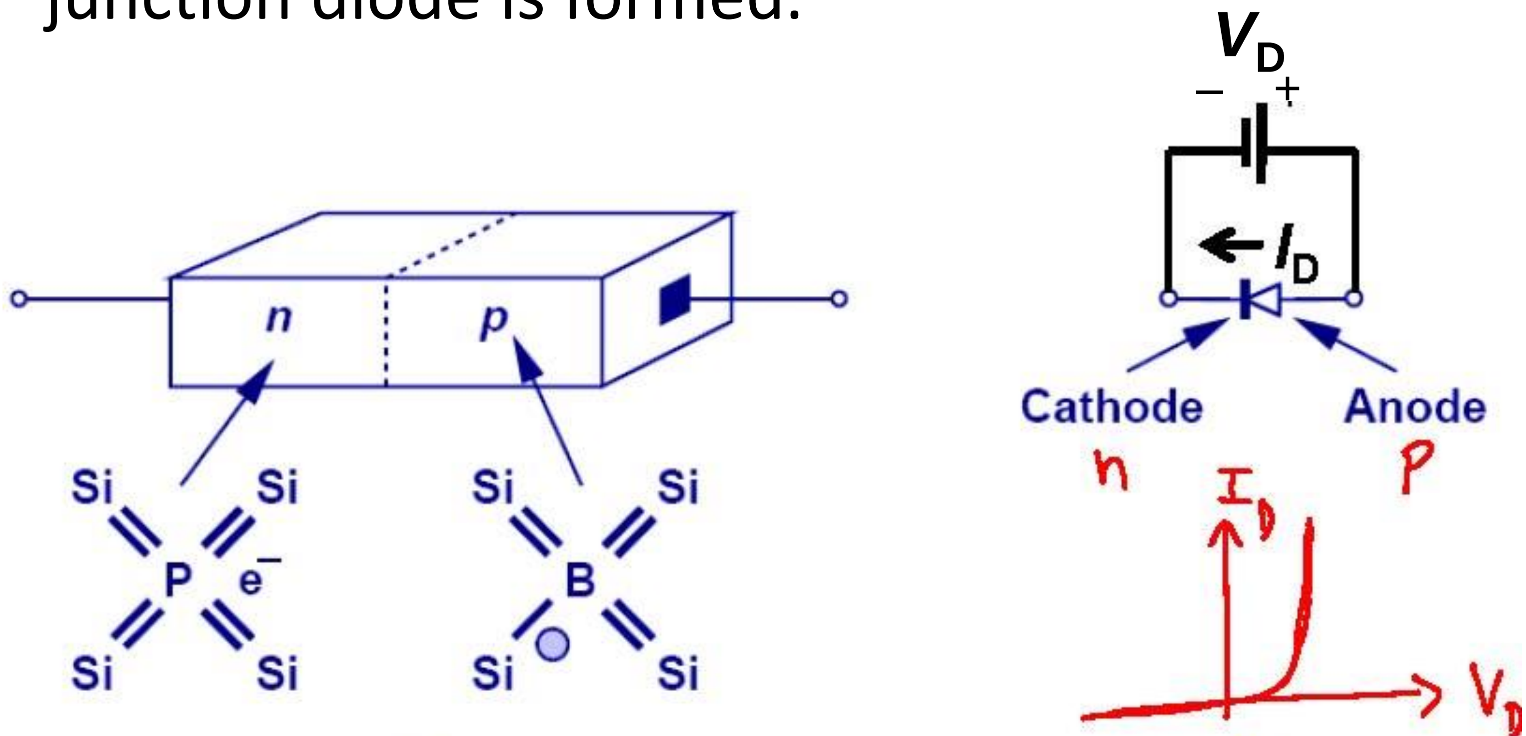
What happens to the electrons and holes if

***n* and *p* regions are brought into contact ?**



The PN Junction Diode

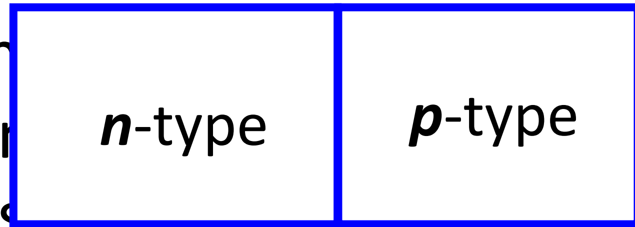
- When a P-type semiconductor region and an N-type semiconductor region are in contact, a PN junction diode is formed.

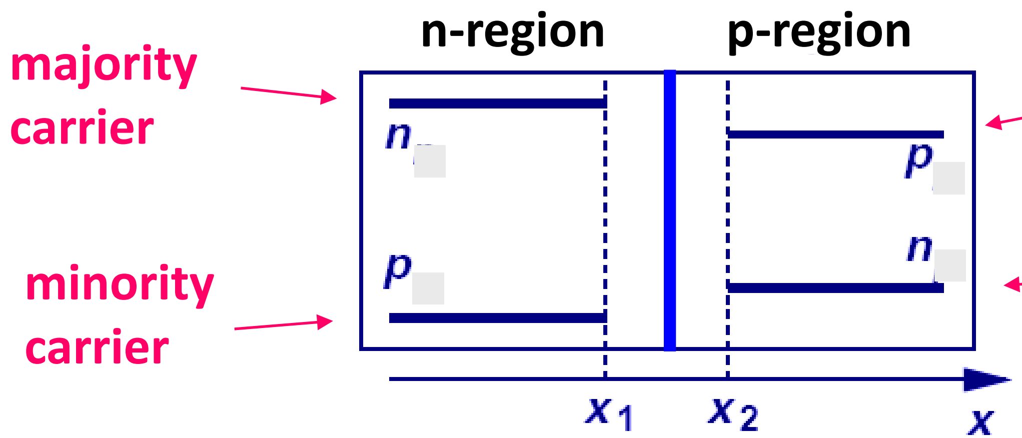


(a) (b)

Carrier concentration distribution in thermal equilibrium

- Because of th … and electron concentration … e junction, carriers diffuse across the junction:





Notation:

$n_n \equiv$ electron concentration on N-type side (cm^{-3}) $\approx N_D$

$p_n \equiv$ hole concentration on N-type side (cm^{-3}) $\approx n_i^2/N_D$

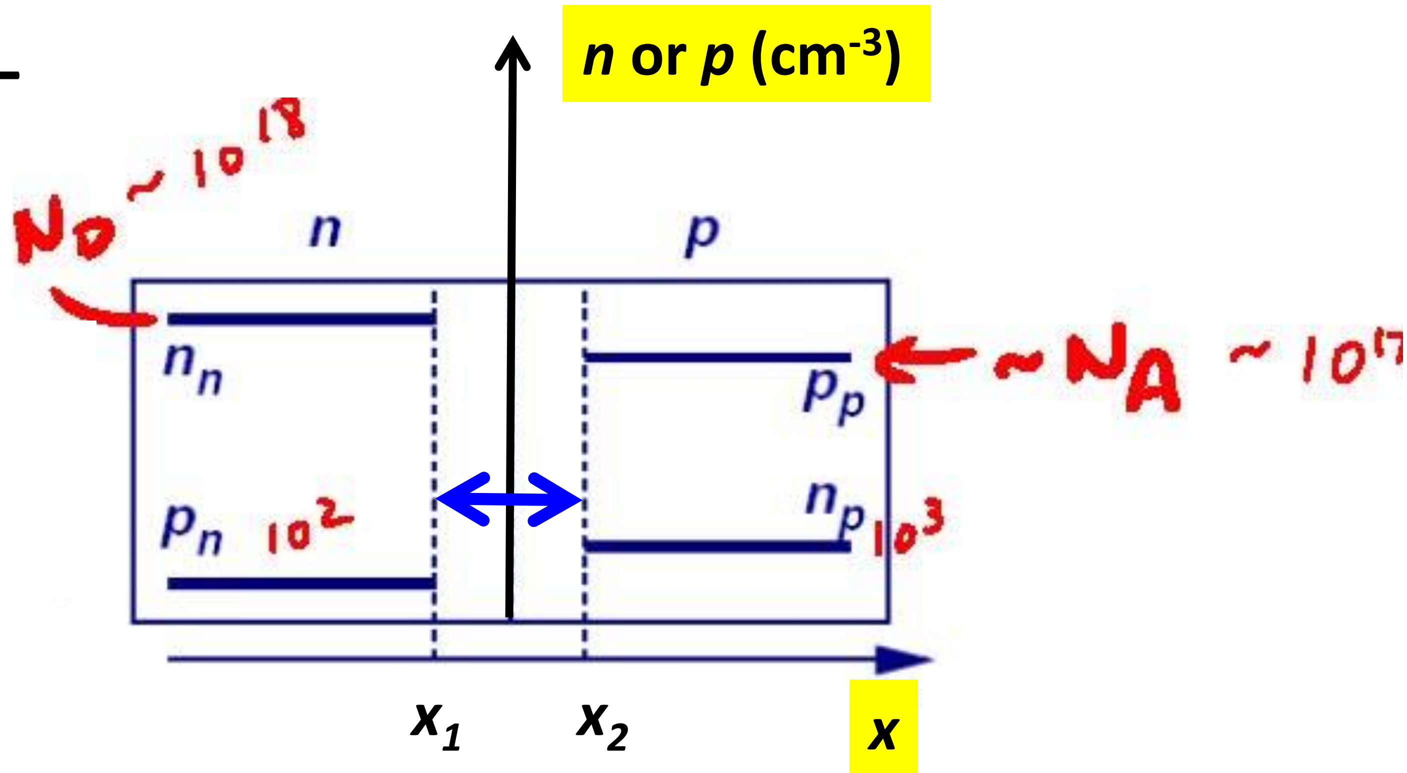
$p_p \equiv$ hole concentration on P-type side (cm^{-3}) $\approx N_A$

$n_p \equiv$ electron concentration on P-type side (cm^{-3}) $\approx n_i^2/N_A$

T=300K

Log scale

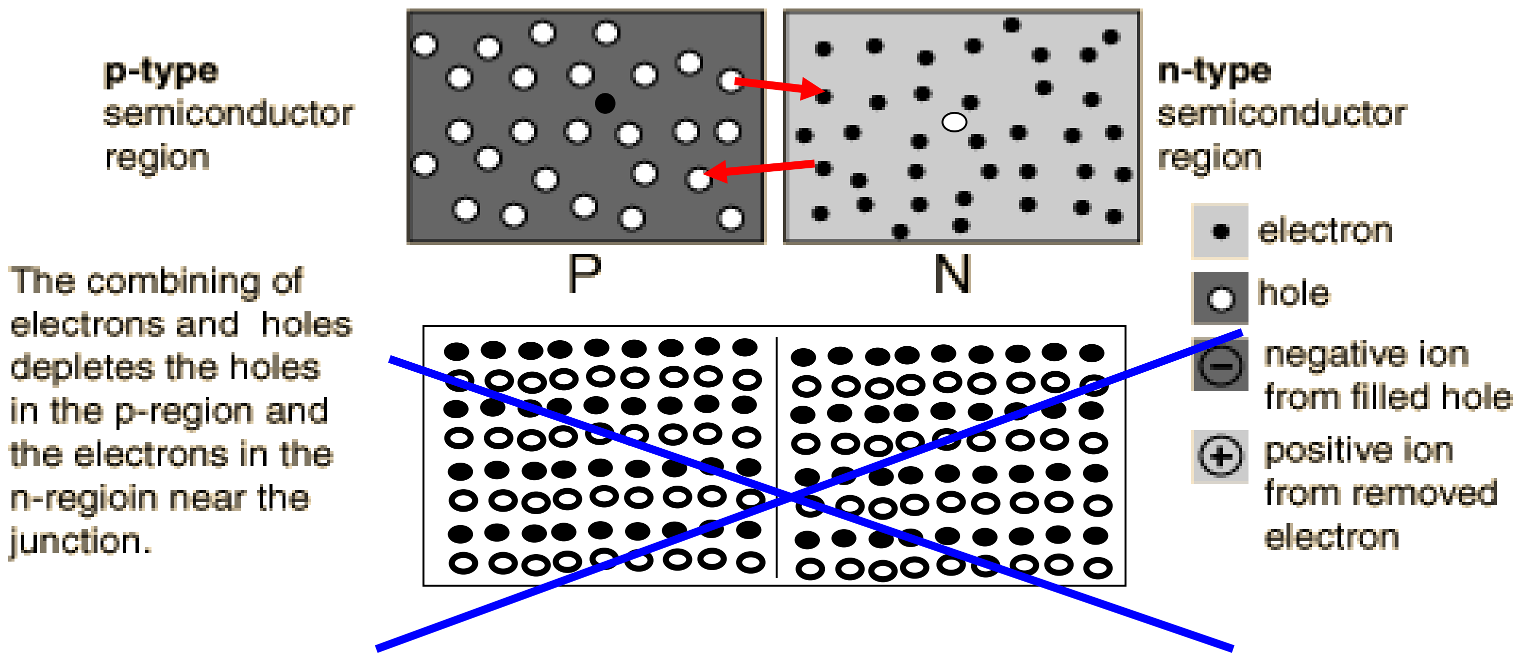
At RT



Carrier Depletion Region
载流子耗尽区

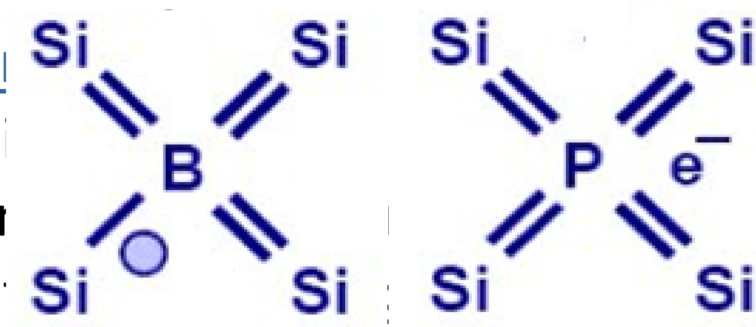
Carrier Diffusion across the Junction

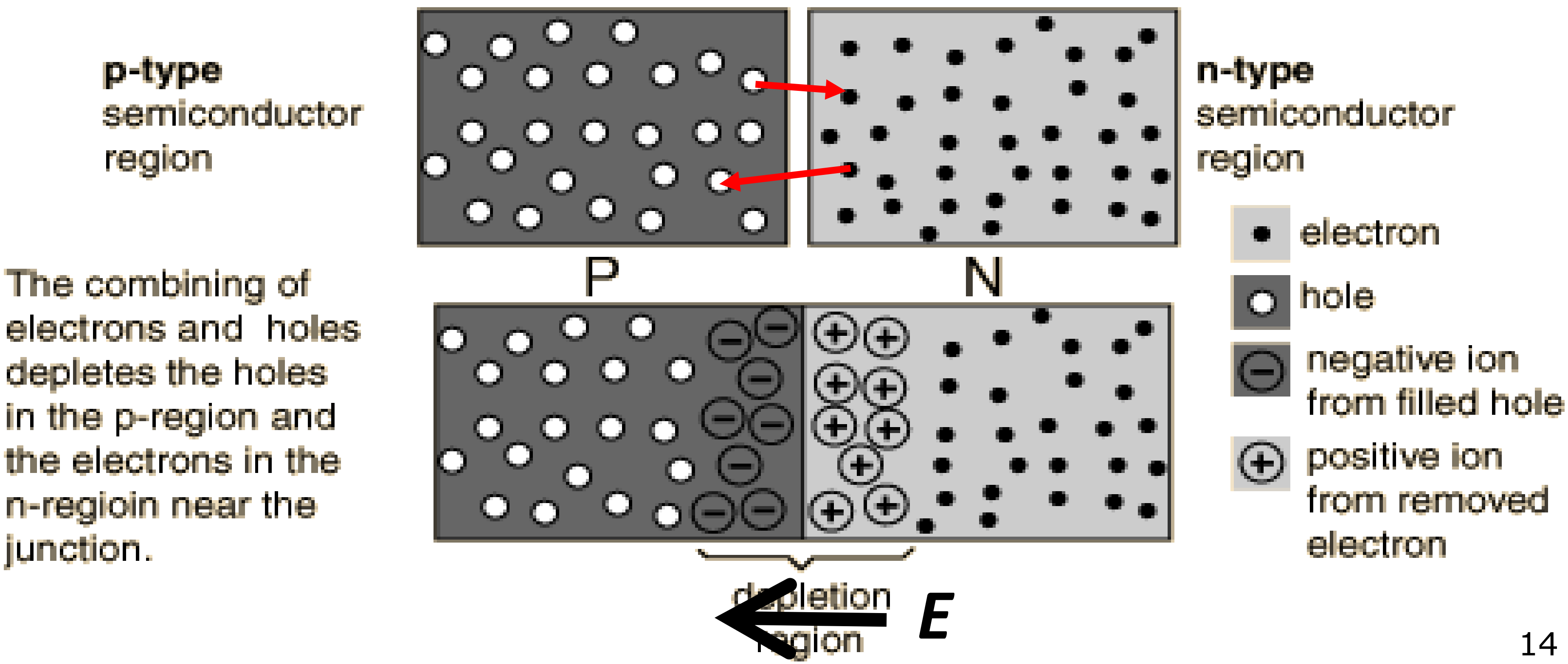
$p_p >> n_p$ $\quad$ $n_n >> p_n$



Carrier **Diffusion** across the Junction

When a p-n ju free electrons in
the n-region di combine with
holes to form r leave behind
positive ions a

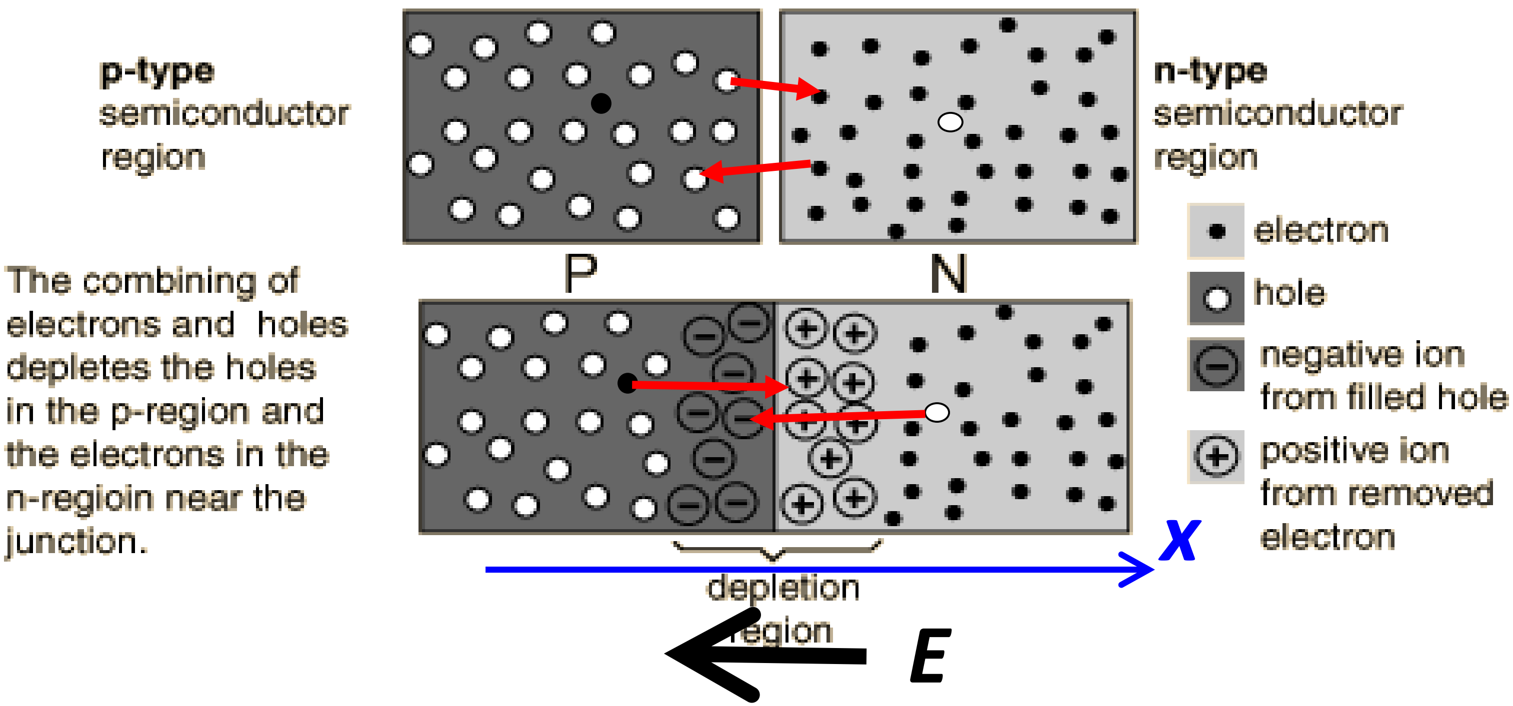




Carrier Drift across the Junction

- Because charge density ≠ 0 in the depletion region, an electric field exists, hence there is drift current.

Thermal equilibrium: balance between drift and diffusion



$\overrightarrow{J_p^{diff}}$

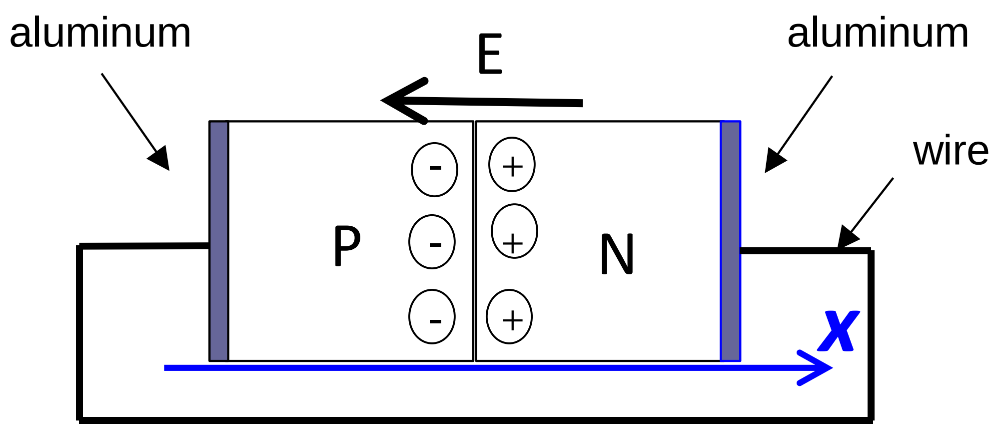
$\overleftarrow{J_p^{drift}}$

$\overrightarrow{J_n^{diff}}$

$\overleftarrow{J_n^{drift}}$

Carrier Drift across the Junction

Thermal equilibrium: balance between drift and diffusion



$$\left.\begin{array}{l} \xrightarrow{J_p^{diff}} \\ \xleftarrow{J_p^{drift}} \end{array}\right\} J_p = 0$$

$$\left.\begin{array}{l} \xrightarrow{J_n^{diff}} \\ \xleftarrow{J_n^{drift}} \end{array}\right\} J_n = 0$$

$J = 0$ @ every x

PN junction – (I)

OUTLINE

- The formation of depletion region
- **Built-in potential (two methods for V_{bi})**
- Distribution of electric field and electric potential
- Effect of Applied Voltage
- Depletion capacitance

Reference Reading

- **Chapter 3.1 (Page 92-116)**

PN Junction in Equilibrium

- In equilibrium, the drift and diffusion components of current are balanced; therefore the net current flowing across the junction is zero.

$$\boxed{J_{p,drift} + J_{p,diff} = 0}$$

$$J_{n,drift} + J_{n,diff} = 0$$

$$J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff} = 0$$

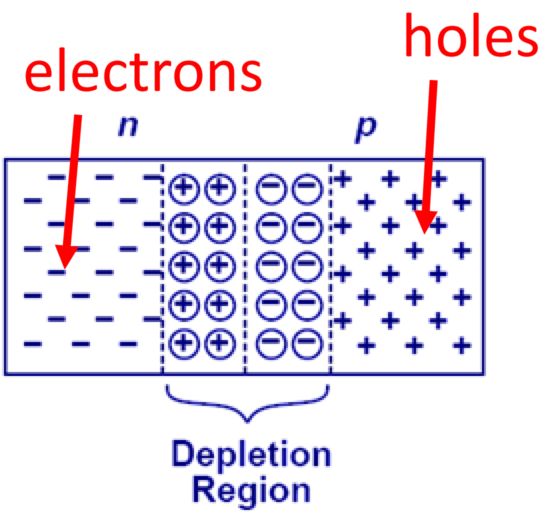
$$J_{p,drift} = qp\mu_p E, \qquad J_{n,drift} = qn\mu_n E$$

$$J_{p,diff} = -qD_p \frac{dp}{dx}, \qquad J_{n,diff} = qD_n \frac{dn}{dx}$$

Built-in Potential, V_{bi}

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

- Because of the electric field in the depletion region, there exists a potential drop across the junction:



$$qp\mu_p E = qD_p \frac{dp}{dx} \quad \Rightarrow \quad p\mu_p\left(-\frac{dV}{dx}\right) = D_p \frac{dp}{dx}$$

$$\Rightarrow \quad -\mu_p \int_{x_1}^{x_2} dV = D_p \int_{p_n}^{p_p} \frac{dp}{p}$$

$$\Rightarrow \quad V(x_1) - V(x_2) = \boxed{\frac{D_p}{\mu_p}} \ln \frac{p_p}{p_n} = \boxed{\frac{kT}{q}} \ln \frac{N_A}{\left(n_i^2 / N_D\right)}$$

$$\boxed{V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2} = V_{bi}}$$

(Unit: Volts)

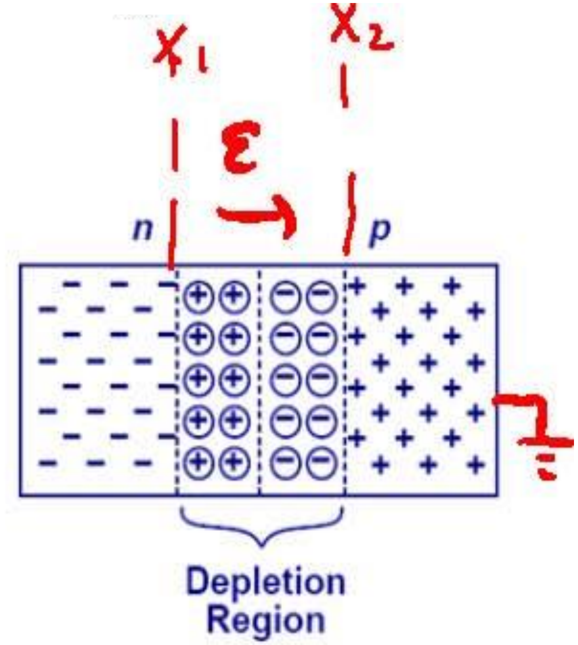
(at RT)

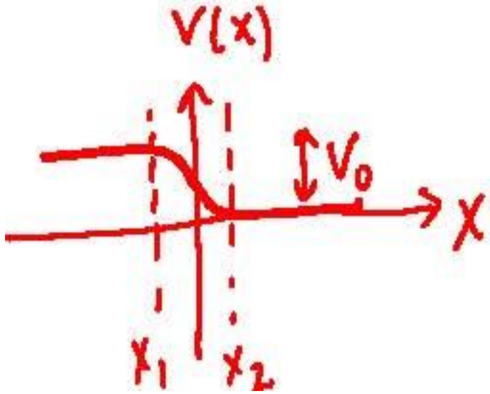
drift Diffusion

$$qp\mu_p E = qD_p \frac{dp}{dx} \quad \Rightarrow \quad p\mu_p\left(-\frac{dV}{dx}\right) = D_p \frac{dp}{dx}$$

$$\Rightarrow \quad -\mu_p \int_{x_1}^{x_2} dV = D_p \int_{p_n}^{p_p} \frac{dp}{p}$$

$$\Rightarrow \quad V(x_1) - V(x_2) = \frac{D_p}{\mu_p} \ln \frac{p_p}{p_n} = \frac{kT}{q} \ln \frac{N_A}{\left(n_i^2 / N_D\right)}$$





$$\boxed{V_0 = \overbrace{\frac{kT}{q}}^{26\text{mV}} \ln \frac{N_A N_D}{n_i^2}}$$

(Unit: Volts)

Built-In Potential Example

HW6

- Estimate the built-in potential for PN junction below.
  - Note that

N	P
$N_D = 10^{18}$ cm^{-3}	$N_A = 10^{15}$ cm^{-3}

$V_0 \lesssim 1V$ for a Si PN junction

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_D N_A}{n_i^2}\right) = \frac{kT}{q}\ln\left(\frac{10^{18}\,10^{15}}{10^{20}}\right) = \frac{kT}{q}\ln\left(10^{13}\right)$$

$$= 13 \cdot \frac{kT}{q}\ln(10) = 13 \cdot 0.06\,V$$

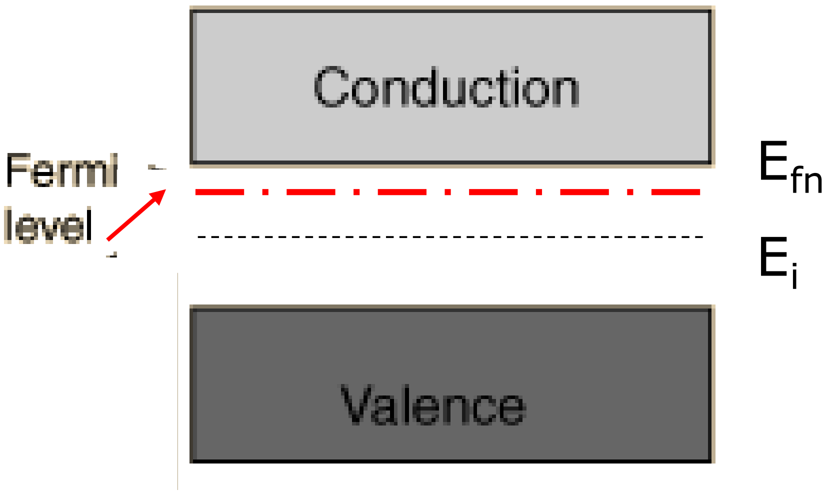
$$= 0.78\,V$$

$$\frac{kT}{q}\ln(10) \cong 26\text{mV} \times 2.3 \cong 60\text{mV}, \quad \text{at RT}$$

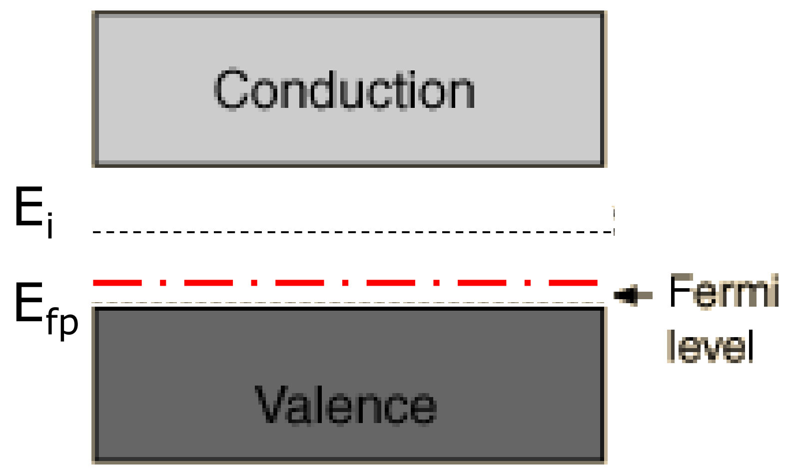
$$\boxed{V_0 = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^{\,2}}}$$

Energy bands of n- and p- type

n-type



p-type



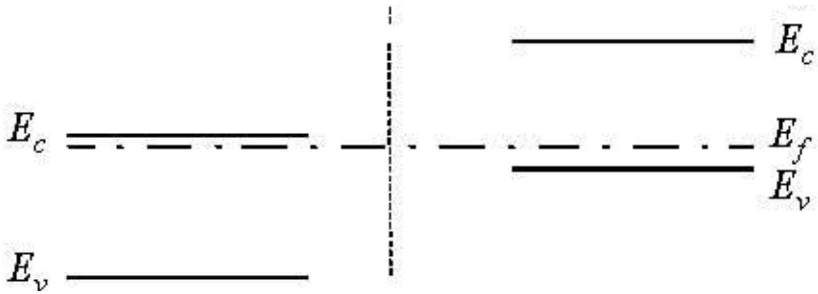
- If n-type and p-type are in the same thermal equilibrium system, **they have the same Fermi level**.

Energy Band Diagram and Depletion Layer

(a)

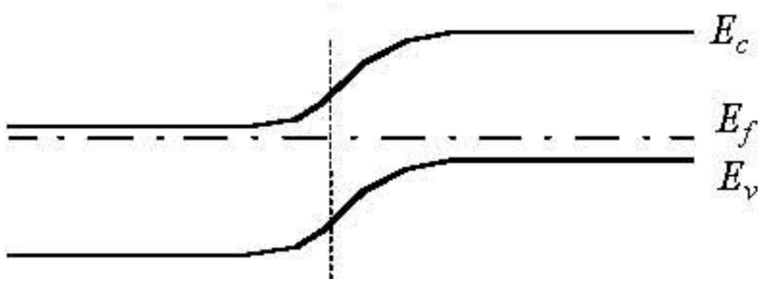
Energy Band Diagram and Depletion Layer

(b)



Energy Band Diagram and Depletion Layer

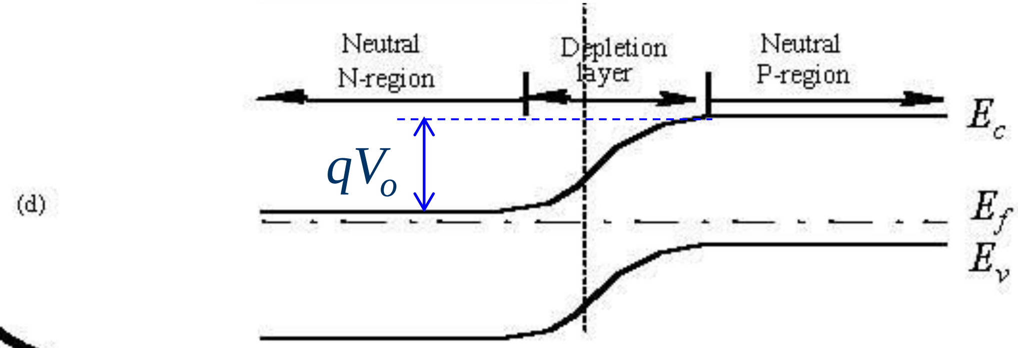
(c)



Energy Band Diagram and Depletion Layer

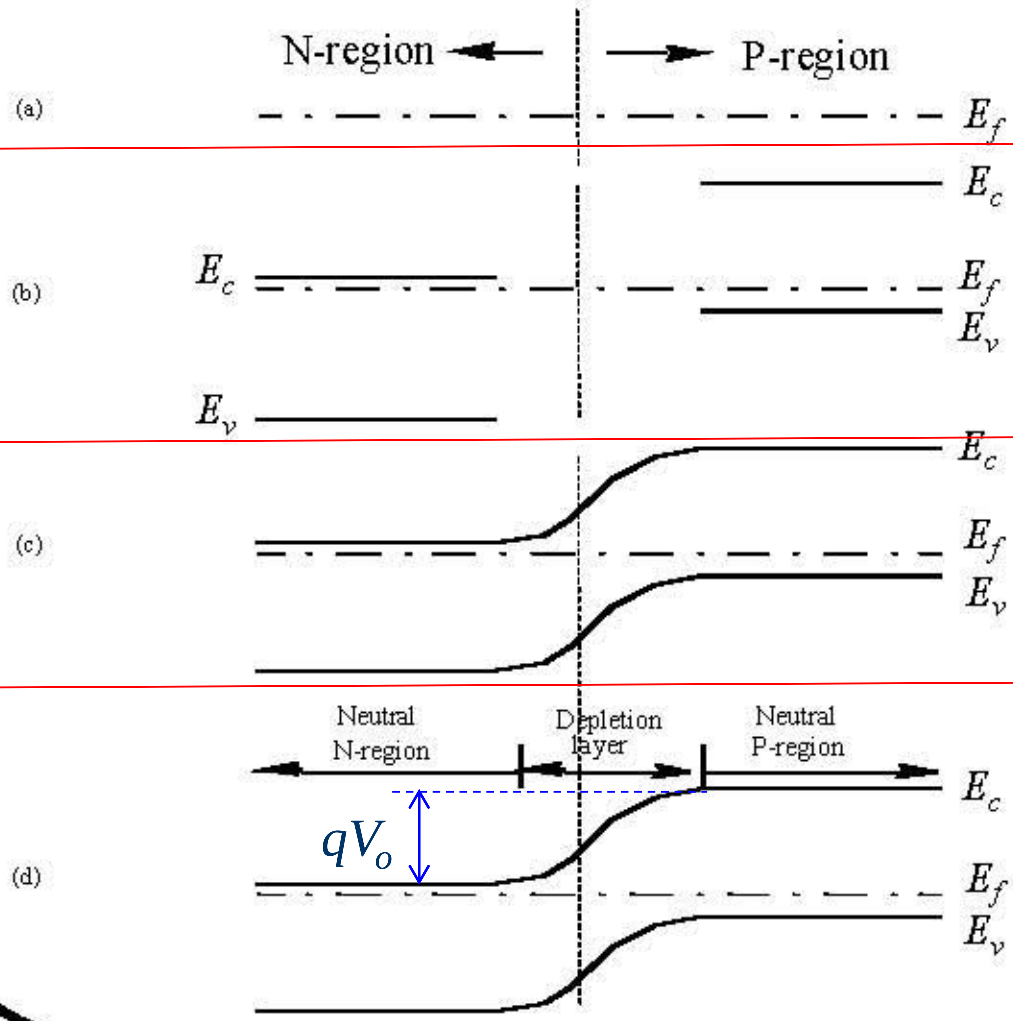
$$n = N_D = N_C \exp\left(\frac{E_{fn} - E_{Cn}}{kT}\right)$$

$$p = N_A = N_V \exp\left(\frac{E_{Vp} - E_{fp}}{kT}\right)$$



$$\boxed{V_o = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2}}$$

Energy Band Diagram and Depletion Layer



$$n = N_D = N_C \exp\left(\frac{E_{fn} - E_C}{kT}\right)$$

$$p = N_A = N_V \exp\left(\frac{E_V - E_{fp}}{kT}\right)$$

HW7

$$V_o = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^{2}}$$

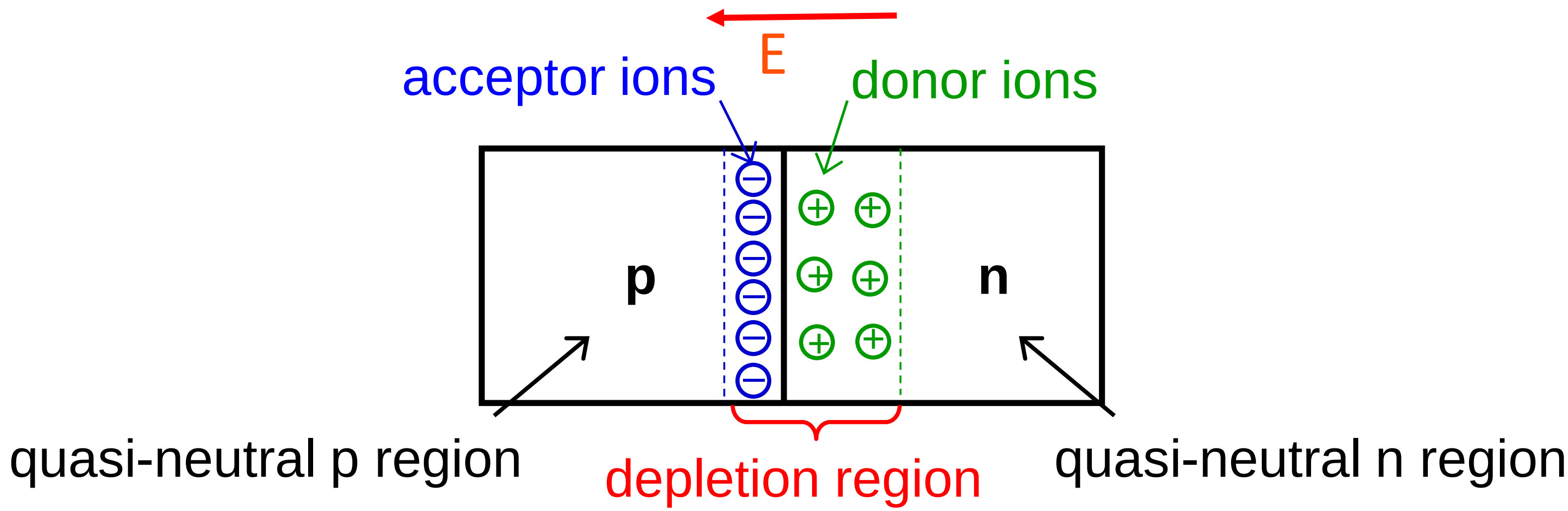
PN junction – (I)

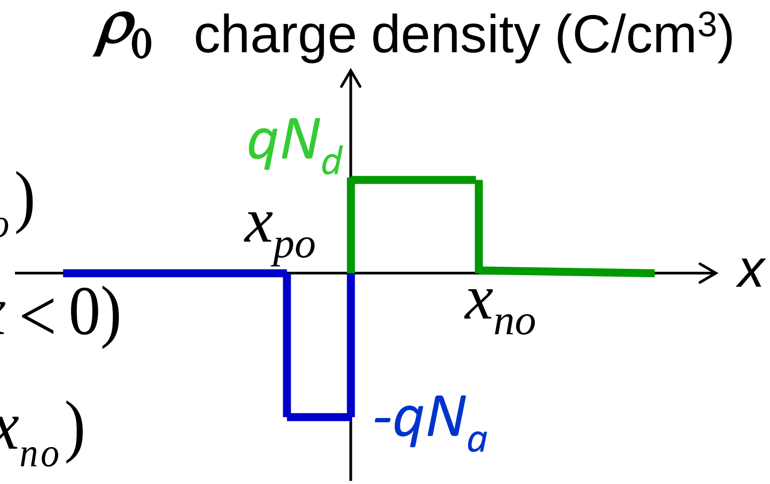
OUTLINE

- The formation of depletion region
- Built-in potential
- **Distribution of electric field and electric potential**
- Effect of Applied Voltage
- Depletion capacitance

Depletion Approximation

Charge is stored in the depletion region.





$$\rho_0(x) = \begin{cases} 0 & (x < -x_{po}) \\ -qN_a & (-x_{po} < x < 0) \\ qN_d & (0 < x < x_{no}) \\ 0 & (x_{no} < x) \end{cases}$$

$$N_d \equiv N_D$$

$$N_a \equiv N_A$$

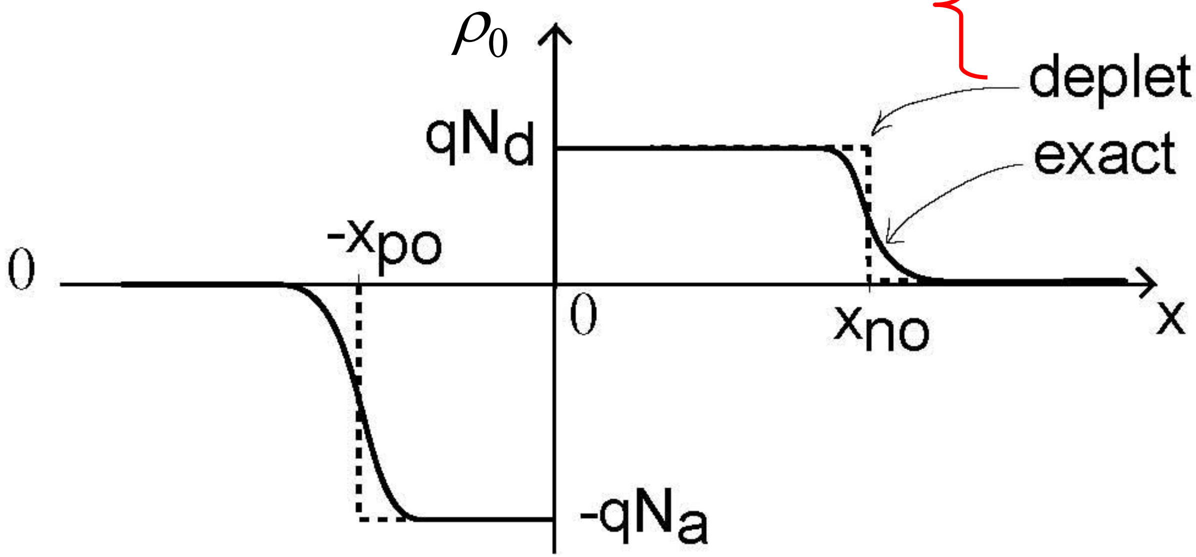
Depletion Approximation

SL

$$
\begin{aligned}
\rho_0(x) &= 0 & x < -x_{po} \\
&= -qN_a & -x_{po} < x < 0 \\
&= qN_d & 0 < x < x_{no} \\
&= 0 & x_{no} < x
\end{aligned}
$$

Depletion approx.:

n=0, p=0 in depletion layer



Two Governing Laws

$$E = -\frac{dV}{dx} \quad or \quad E = -\frac{d\phi}{dx}$$

Gauss's Law describes the relationship of charge (density) and electric field.

$$\oint_S \vec{E} \cdot d\vec{A} = \frac{1}{\varepsilon} \int_V \rho dV = \frac{Q_{encl}}{\varepsilon}$$

$\boldsymbol{\varepsilon = \varepsilon_S}$

$$\boxed{\frac{dE}{dx} = \frac{\rho}{\varepsilon}}$$

$$\boxed{E(x) - E(x_0) = \frac{1}{\varepsilon} \int_{x_0}^{x} \rho(x) dx}$$

Poisson's Equation describes the relationship between electric field distribution and electric potential

$$\boxed{\frac{d^2\phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\varepsilon}}$$

$$\boxed{\phi(x) - \phi(x_0) = \int_{x_0}^{x} -E(x) dx}$$

Depletion Approximation 1 (Electric field)

$$E_0(x) - E_0(x_0) = \frac{1}{\varepsilon_{Si}} \int_{x_0}^{x} \rho_0(x)\,dx$$

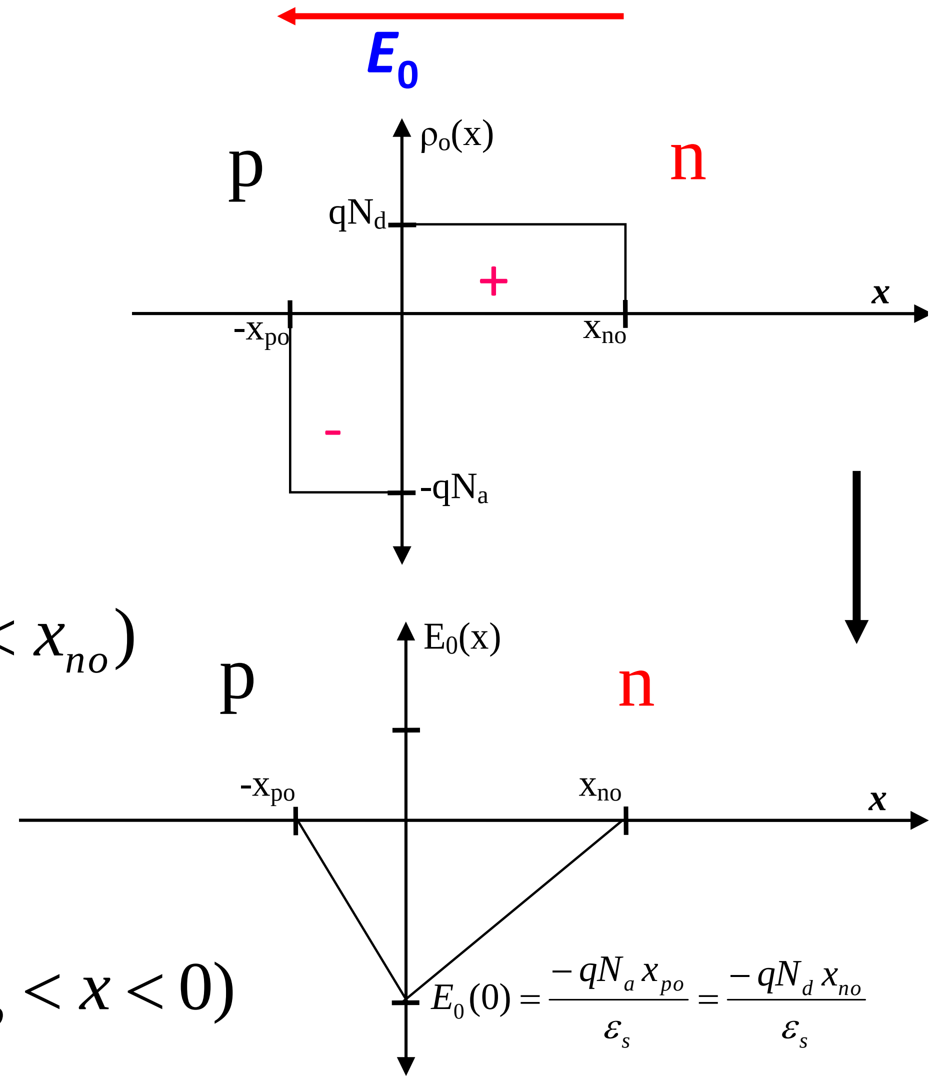
n Side:

$$E_0(x) - E_0(x_{n0}) = \frac{1}{\varepsilon_{Si}} \int_{x_{n0}}^{x} qN_d\,dx$$

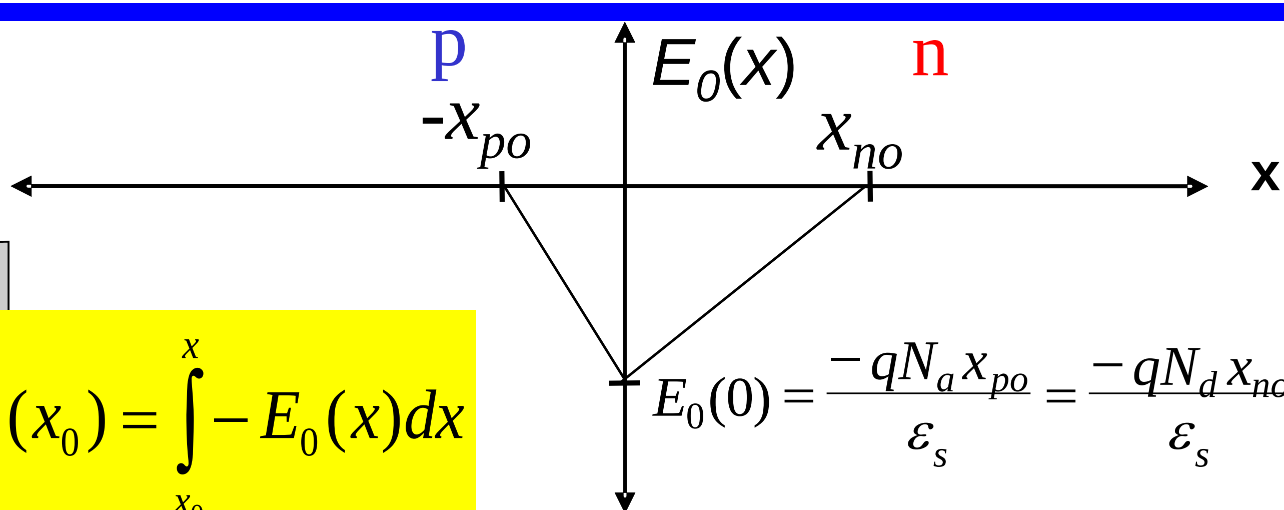
$$E_0(x) = \frac{qN_d}{\varepsilon_{Si}}(x - x_{no}) \qquad (0 < x < x_{no})$$

p Side:

$$E_0(x) = \frac{-qN_a}{\varepsilon_s}(x + x_{po}) \qquad (-x_{po} < x < 0)$$



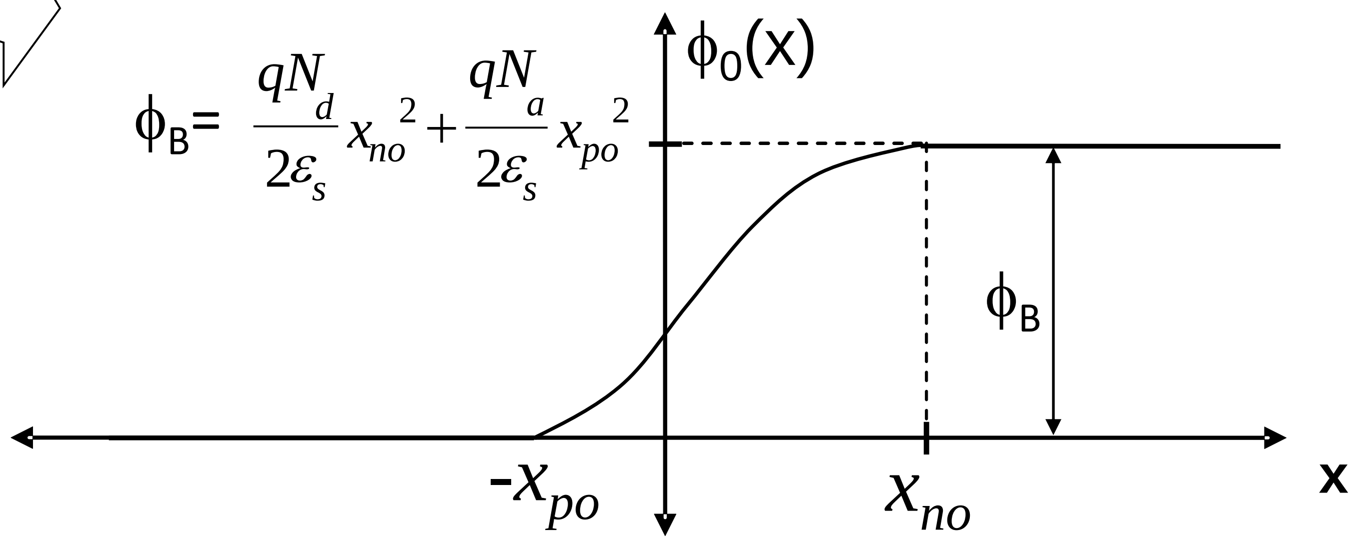
Depletion Approximation 2 (Electrostatic potential)



$$E_0(0)=\frac{-qN_a x_{po}}{\varepsilon_s}=\frac{-qN_d x_{no}}{\varepsilon_s}$$

$$\phi_0(x)-\phi_0(x_0)=\int_{x_0}^{x}-E_0(x)dx$$

$$\phi_B=\frac{qN_d}{2\varepsilon_s}x_{no}^{\ 2}+\frac{qN_a}{2\varepsilon_s}x_{po}^{\ 2}$$



Depletion Approximation 3

$$\phi_0(x) = \int_{-x_{po}}^{x} -E_0(x)dx + \underline{\phi_0(-x_{po})} = \int_{-x_{po}}^{x} \frac{qN_a}{\varepsilon_s}(x + x_{po})dx \underline{+0}$$

$$\rightarrow \quad \phi_0(x) = \frac{qN_a}{2\varepsilon_s}(x + x_{po})^2 \qquad (-x_{po} < x < 0)$$

$$\phi_0(x) = \int_{0}^{x} -E_0(x)dx + \underline{\phi_0(0)} = \int_{0}^{x} -\frac{qN_d}{\varepsilon_s}(x - x_{no})dx + \underline{\frac{qN_a}{2\varepsilon_s}(0 + x_{po})^2}$$

$$\rightarrow \quad \phi_0(x) = \frac{qN_d}{2\varepsilon_s}x(2x_{no} - x)^2 + \frac{qN_a}{2\varepsilon_s}x_{po}{}^2 \qquad (0 < x < x_{no})$$

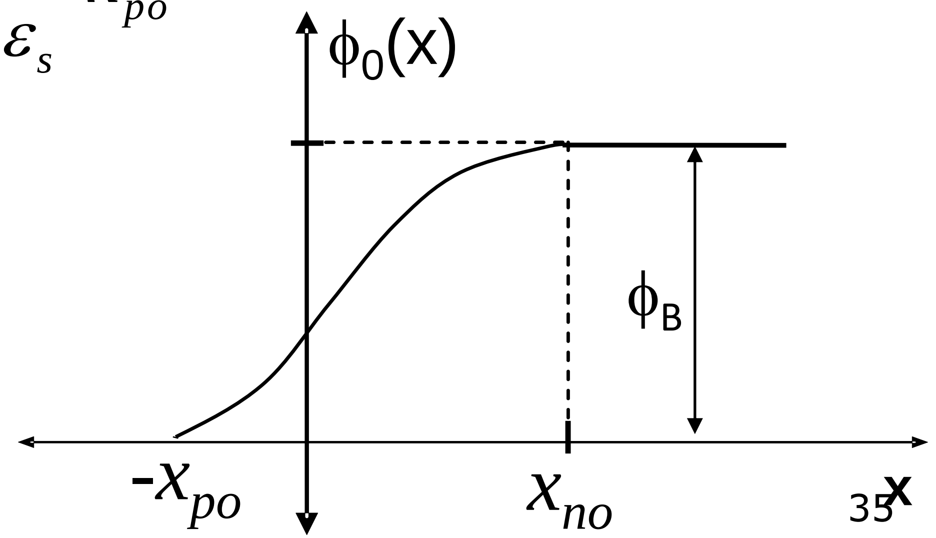
Built-in Potential, ϕ_B

$$\phi_0(x) = \frac{qN_a}{2\varepsilon_s}(x + x_{po})^2 \qquad (-x_{po} < x < 0)$$

$$\phi_0(x) = \frac{qN_d}{2\varepsilon_s}x(2x_{no} - x)^2 + \frac{qN_a}{2\varepsilon_s}x_{po}{}^2 \qquad (0 < x < x_{no})$$

At $x = x_{no}$

$$\phi_0 = \phi_B = \frac{qN_d}{2\varepsilon_s}x_{no}^2 + \frac{qN_a}{2\varepsilon_s}x_{po}^2$$



$$\phi_B = V_{bi} = \frac{kT}{q}\ln\frac{N_d N_a}{n_i^2}$$

Barrier, 势垒

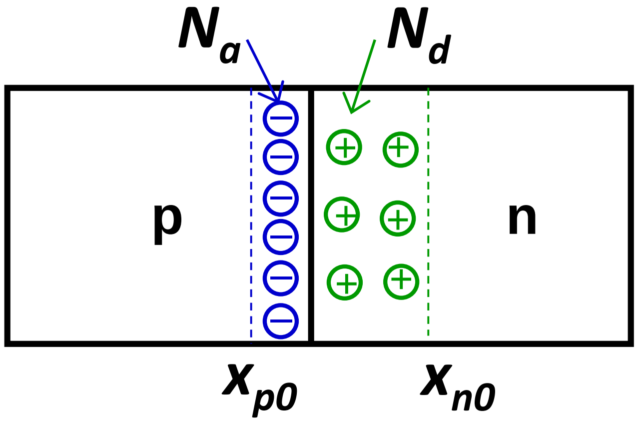
Still don't know x_{no} and x_{po}

1. Require overall charge neutrality:

$$qN_a x_{po} = qN_d x_{no}$$

2. Require $\phi(x)$ continuous at $x = 0$:

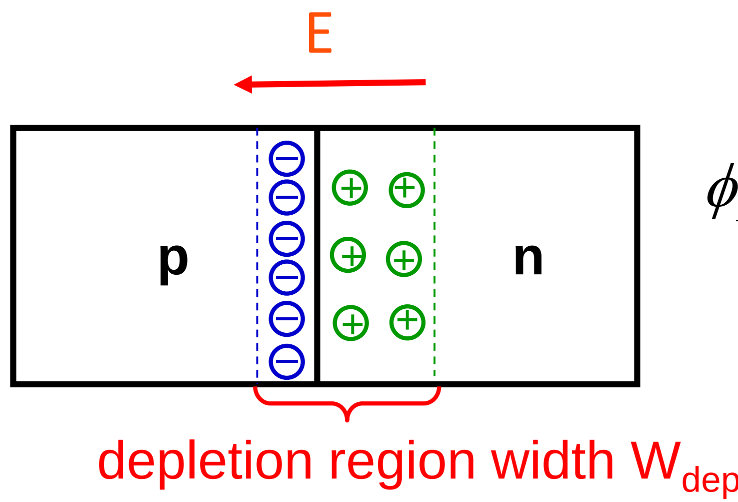
$$\phi_B = \frac{qN_d}{2\varepsilon_s} x_{no}^2 + \frac{qN_a}{2\varepsilon_s} x_{po}^2$$



Two equations with two unknowns. Solution:

$$x_{n0} = \sqrt{\frac{2\varepsilon_s \phi_B N_a}{q(N_a + N_d)N_d}} \qquad x_{p0} = \sqrt{\frac{2\varepsilon_s \phi_B N_d}{q(N_a + N_d)N_a}}$$

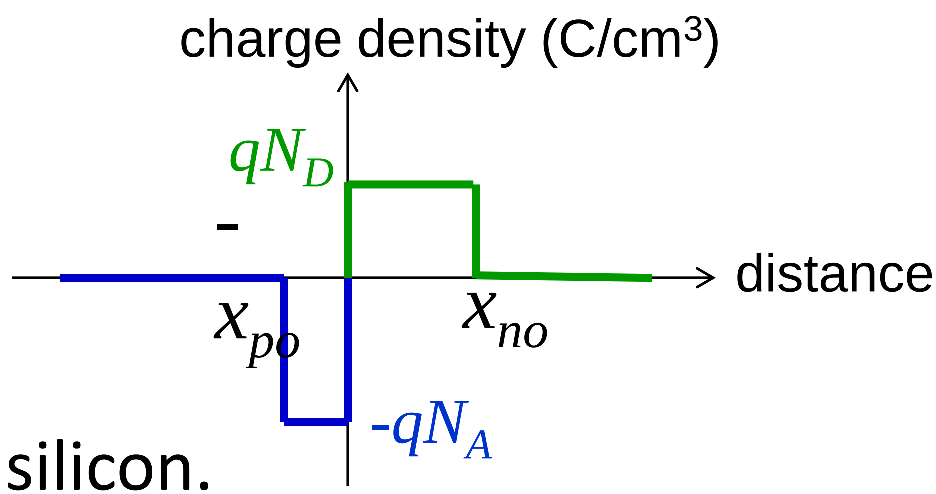
Depletion Region Width W_{dep}



$$\phi_B = \frac{kT}{q}\ln\frac{N_D N_A}{n_i^2}$$

$$\varepsilon_{Si} = \varepsilon_{r,Si}\varepsilon_0$$

$$W_{dep} = x_{po} + x_{no} = \sqrt{\frac{2\varepsilon_{Si}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\phi_B}$$



$$\varepsilon_{Si} \approx 10^{-12}\ \text{F/cm}$$

is the permittivity of silicon.

PN junction – (I)

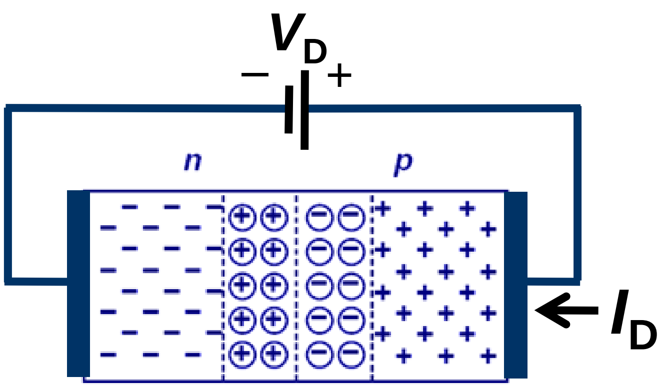
<u>OUTLINE</u>

- The formation of depletion region
- Built-in potential
- Distribution of electric field and electric potential
- **Effect of Applied Voltage**
- Depletion capacitance

Effect of Applied Voltage

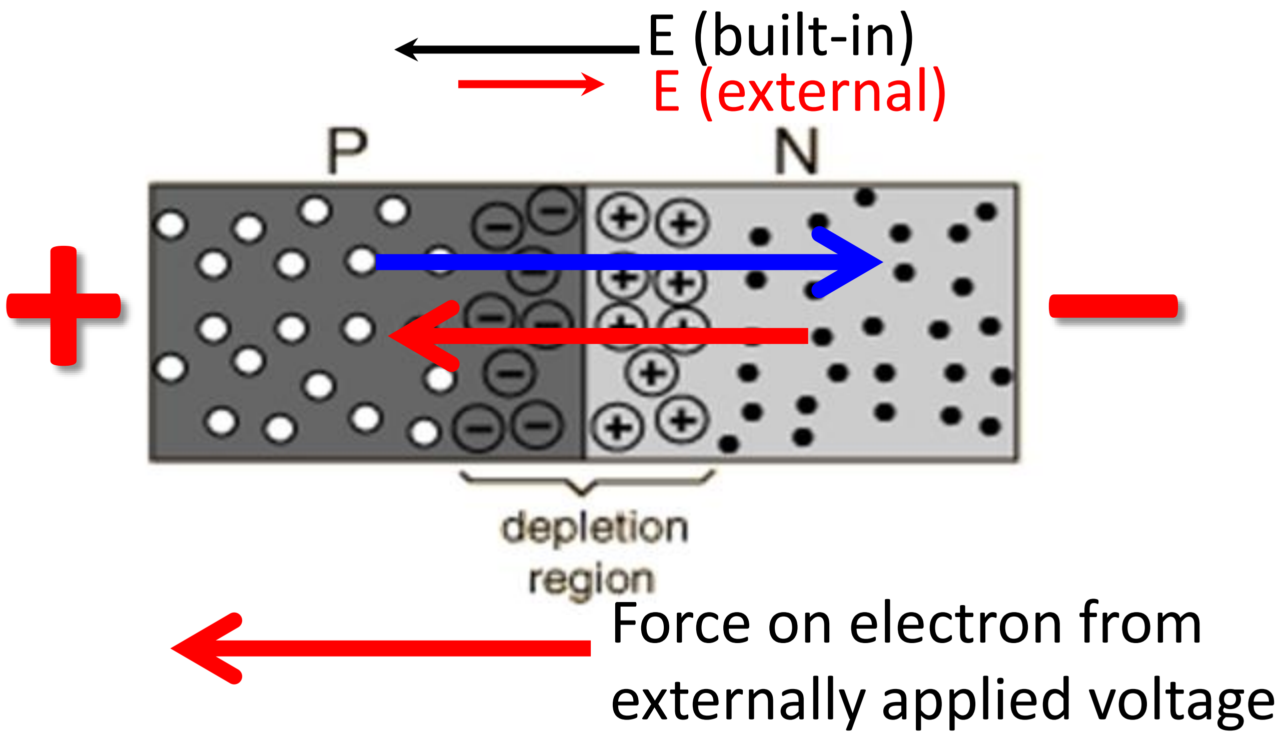
- The quasi-neutral N-type and P-type regions have low resistivity, whereas the depletion region has high resistivity.
  - Thus, when an **external voltage V_D** is applied across the ***diode***, almost all of this voltage **is dropped across the depletion region**. (Think of a voltage divider circuit.)
- If $V_D < 0$ (***reverse bias, or V_R***), the potential barrier to carrier diffusion is increased by the applied voltage.
- If $V_D > 0$ (***forward bias, or V_F***), the potential barrier to carrier diffusion is reduced by the applied voltage.

$$V_D = \begin{cases} V_R & (V_D < 0) \\ V_F & (V_D > 0) \end{cases}$$



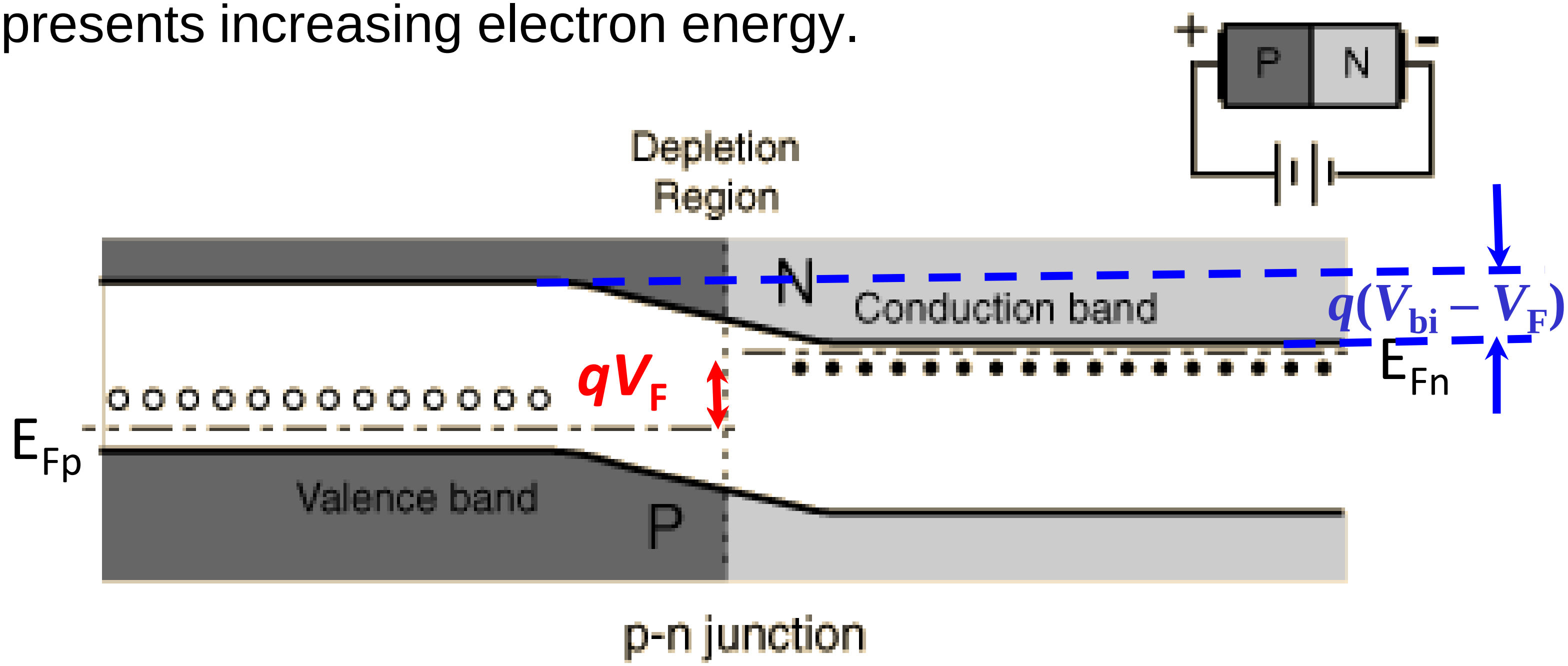
+Bias effect on electrons in depletion zone

- Forward bias
- An applied voltage in the forward direction as indicated assists electrons in overcoming the coulomb barrier of the space charge in depletion region. Electrons will flow with very small resistance in the forward direction.



+Bias effect on electrons in depletion zone

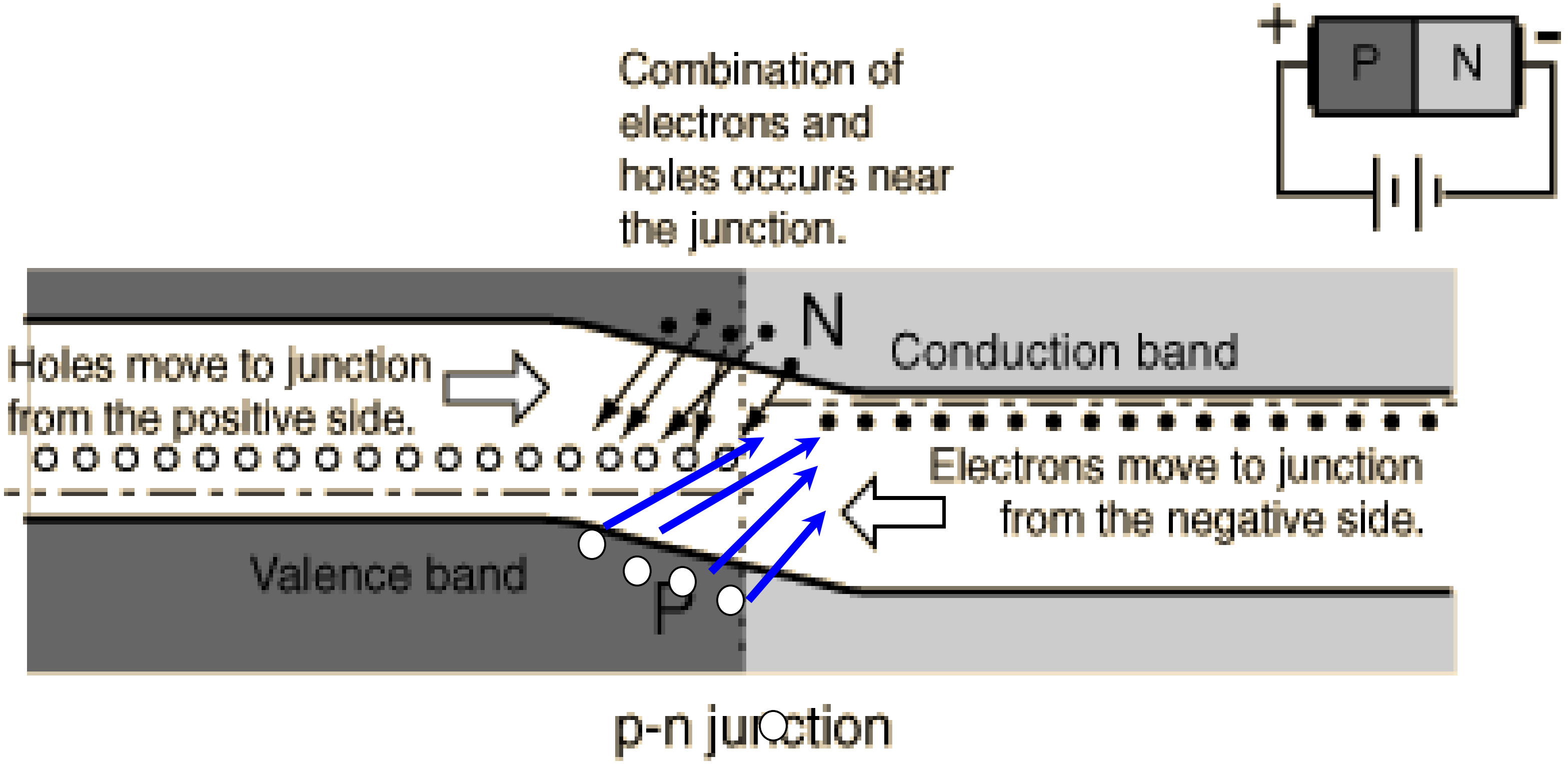
To forward bias the p-n junction, the p side is made more positive, so that it is "downhill" for electron motion across the junction. An electron can move across the junction and fill a vacancy or "hole" near the junction. It can then move from vacancy to vacancy leftward toward the positive terminal, which could be described as the hole moving right. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.



Forward Biased Conduction

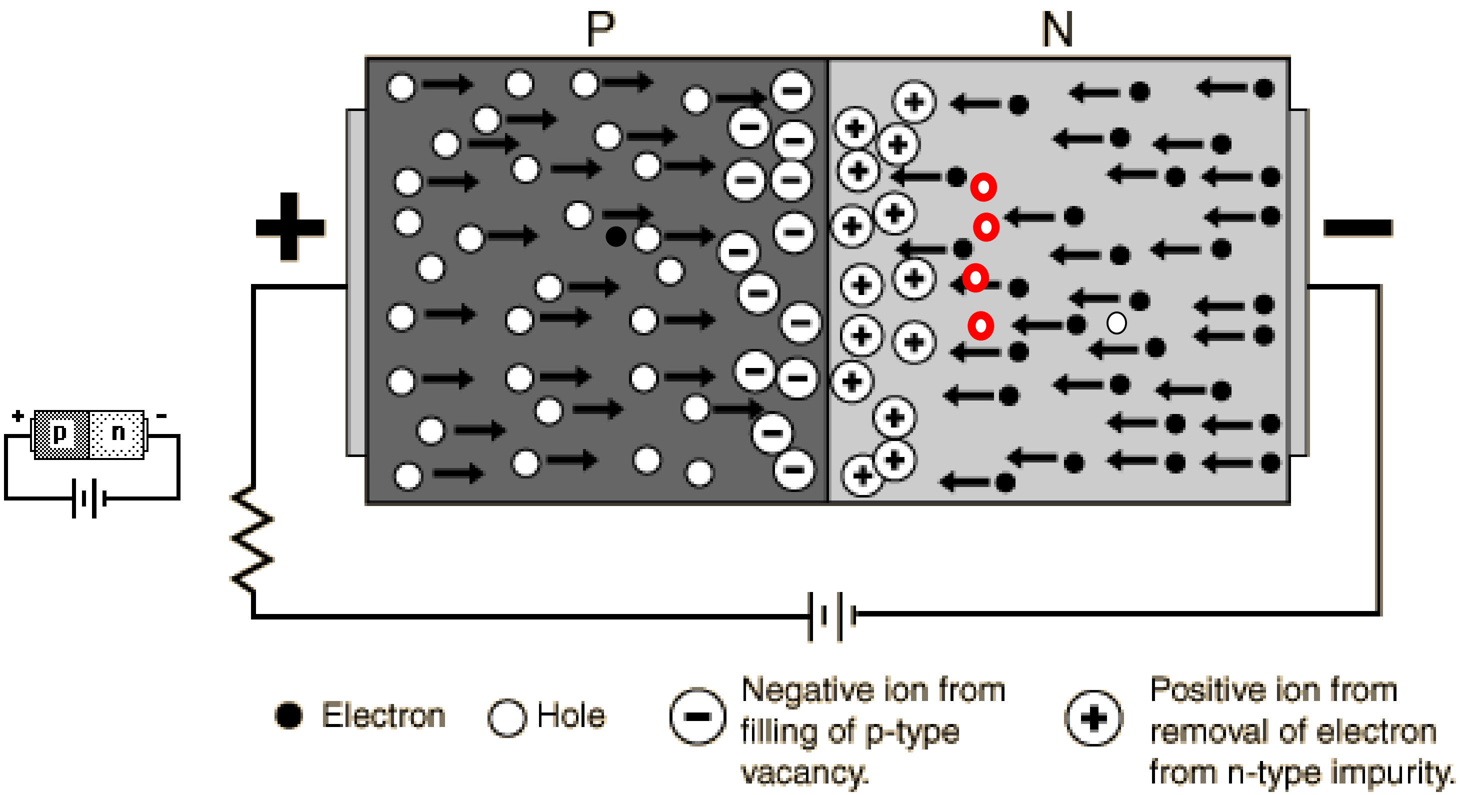
SL

When the p-n junction is forward biased, the electrons in the n-type material which have been elevated to the conduction band and which have diffused across the junction find themselves at a higher energy than the holes in the p-type material. They readily combine with those holes, making possible a continuous forward current through the junction.



Forward Biased Conduction

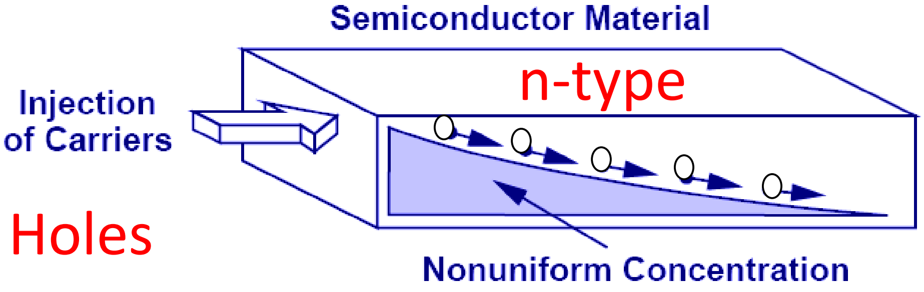
The forward current in a p-n junction when it is forward-biased (illustrated below) involves electrons from the n-type material moving leftward across the junction and combining with holes in the p-type material. Electrons can then proceed further leftward by jumping from hole to hole, so the holes can be said to be moving to the right in this process.



Carrier Diffusion

PL

- Due to thermally induced random motion, mobile particles tend to move from a region of high concentration to a region of low concentration.
  - Analogy: ink droplet in water
- Current flow due to mobile charge diffusion is proportional to the carrier <u>concentration gradient</u>.
  - The proportionality constant is the ***diffusion constant***.

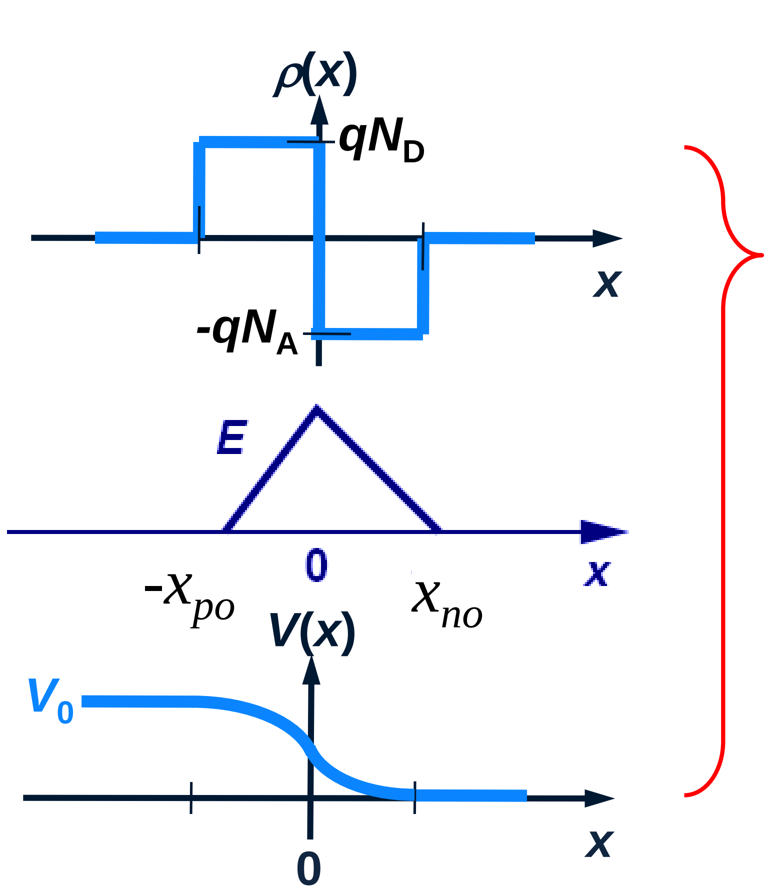


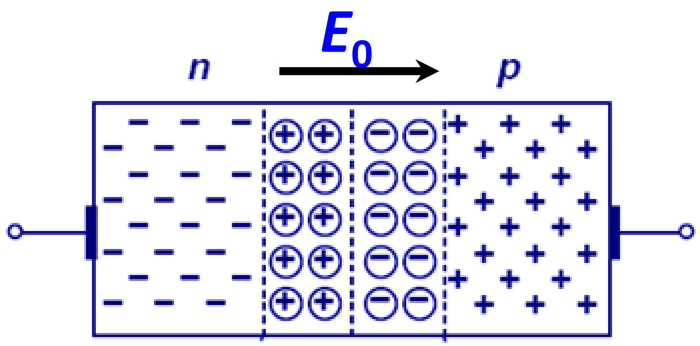
$$J_p = -qD_p \frac{dp}{dx}$$

<u>Notation</u>:
$D_p \equiv$ hole diffusion constant (cm^2/s)

PN Junction under Forward Bias

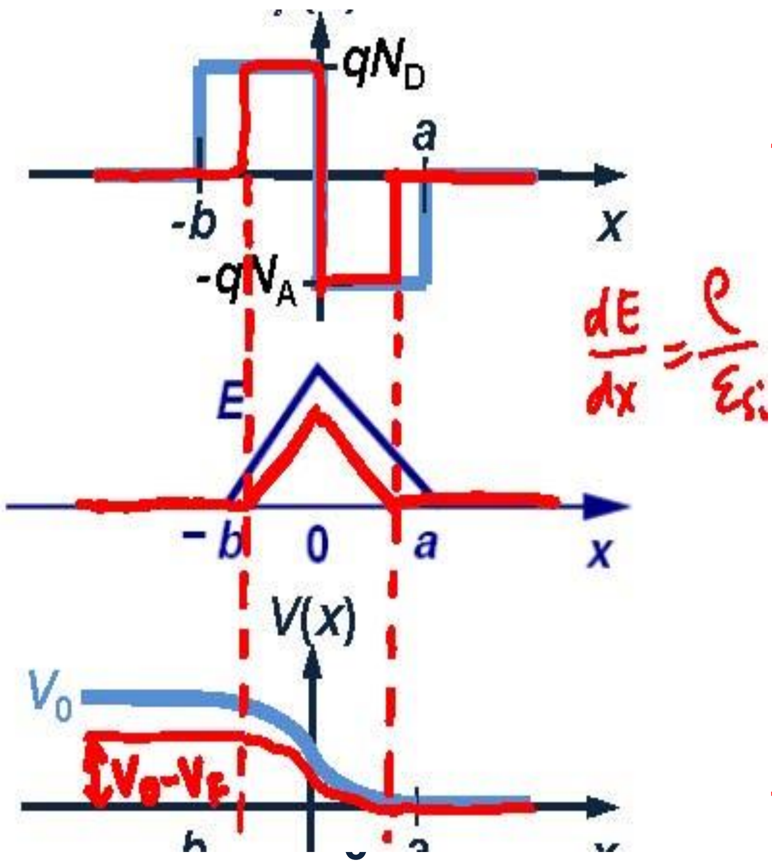
- A forward bias decreases the potential drop across the junction. As a result, the magnitude of the electric field decreases and the width of the depletion region narrows.

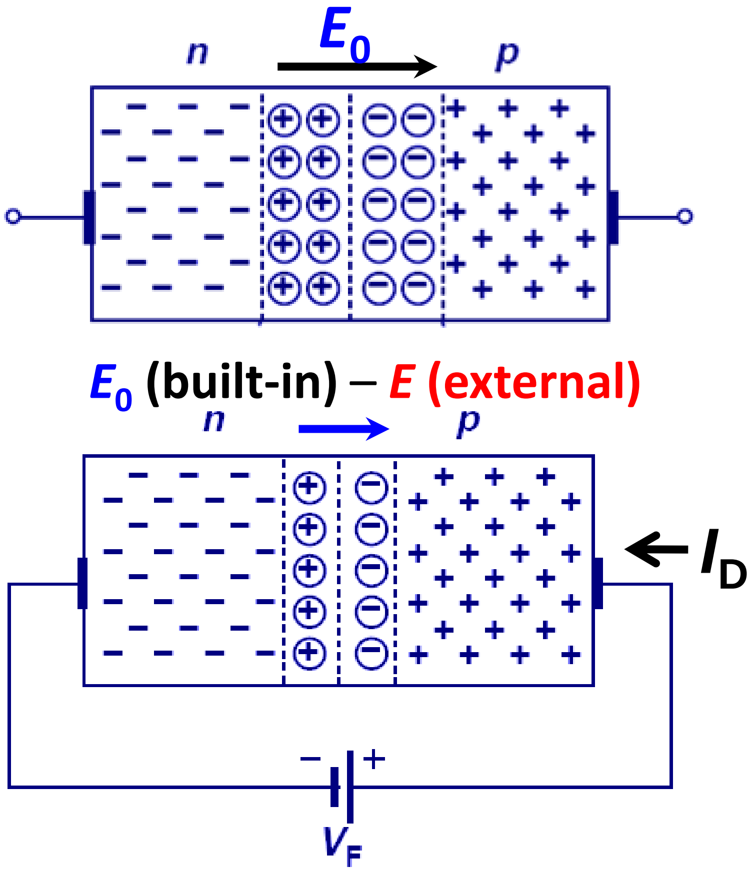




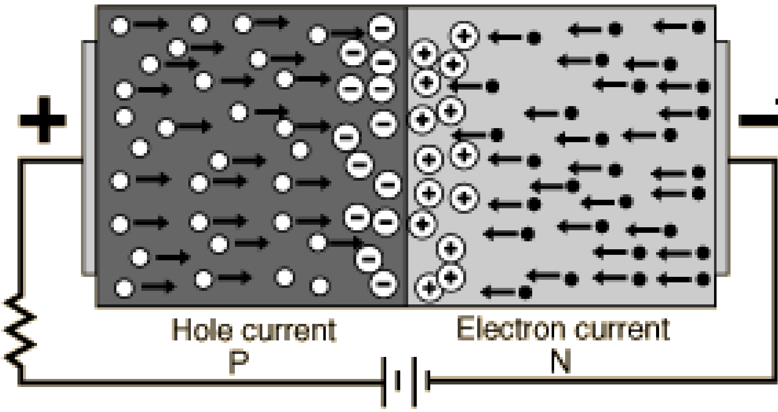
PN Junction under Forward Bias

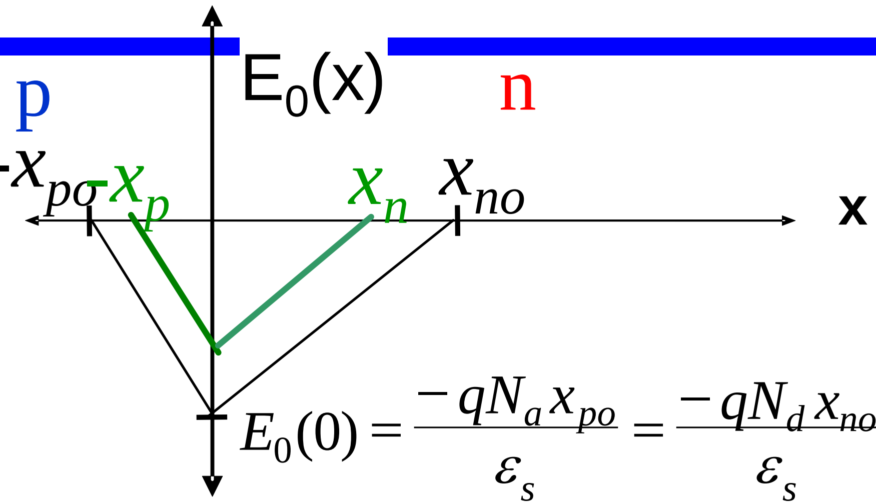
- A forward bias decreases the potential drop across the junction. As a result, the magnitude of the electric field decreases and the width of the depletion region narrows.





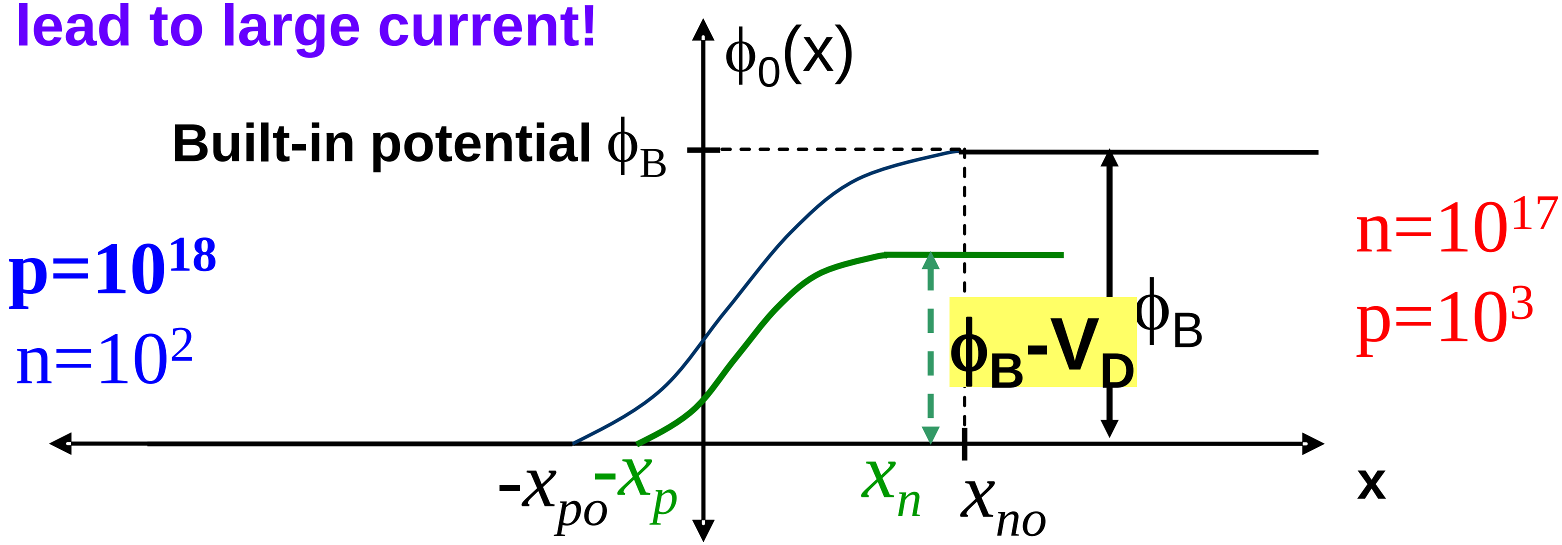
Depletion Approx. – with V_D>0 forward bias





$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Lower barrier and large hole (electron) density at the right places lead to large current!



Depletion Region Width W_{dep}

At V_D=0

$$W_{dep} = x_{po} + x_{no} = \sqrt{\frac{2\varepsilon_{Si}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\phi_B}$$

At V_D>0

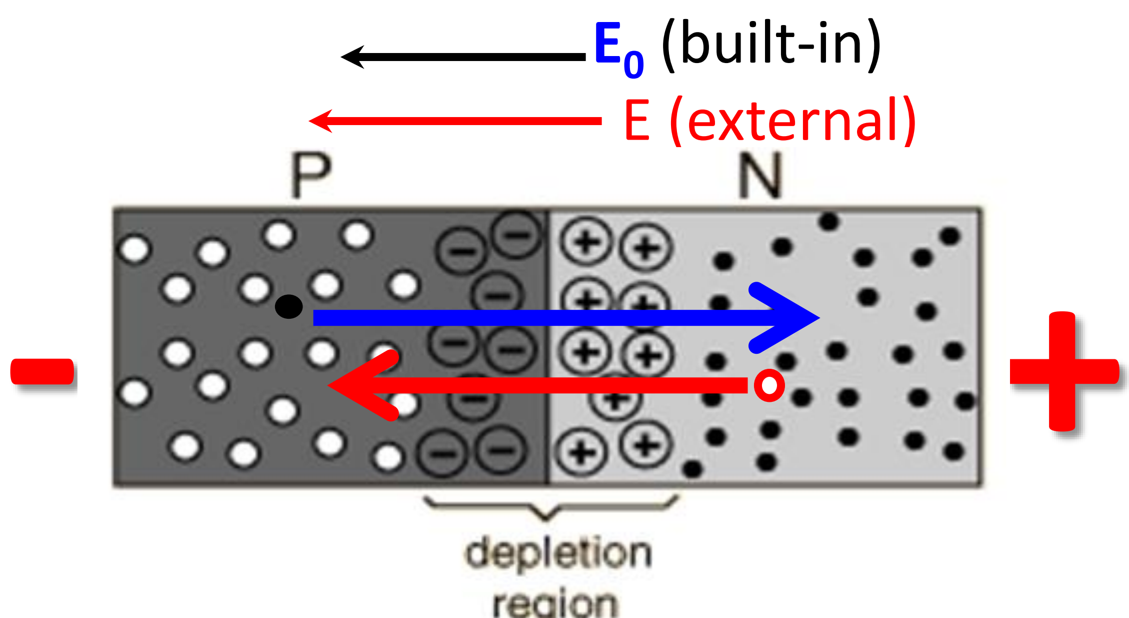
$$W_{dep} = x_p + x_n = \sqrt{\frac{2\varepsilon_{Si}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(\phi_B - V_D)}$$

- The width of the depletion region is a function of the bias voltage, and is dependent on N_A and N_D.

-Bias effect on electrons in depletion zone

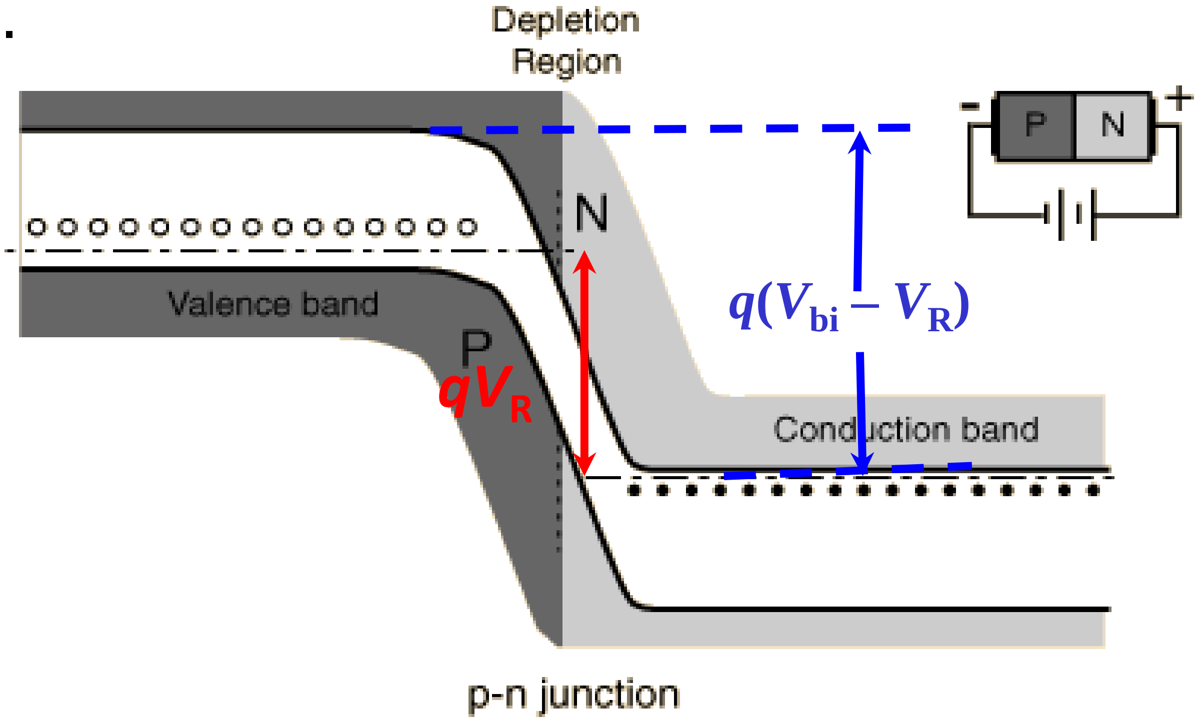
Reverse bias

An applied voltage with the indicated polarity further impedes the flow of electrons across the junction. For conduction in the device, electrons from the N region must move to the junction and combine with holes in the P region. A reverse voltage drives the electrons away from the junction, preventing conduction.



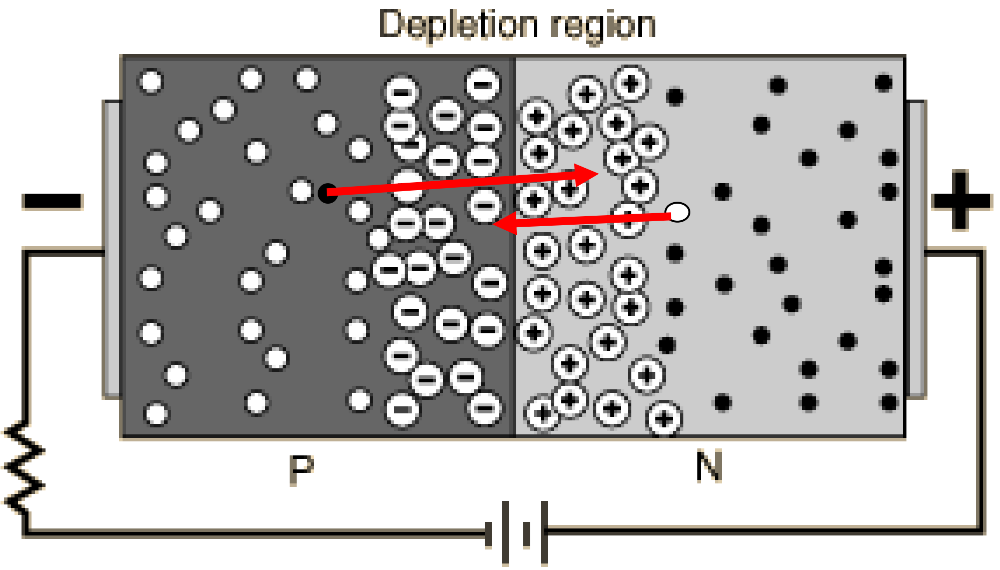
Bias effect on electrons in depletion zone

- To reverse-bias the p-n junction, the p side is made more negative, making it "uphill" for electrons moving across the junction. The conduction direction for electrons in the diagram is right to left, and the upward direction represents increasing electron energy.



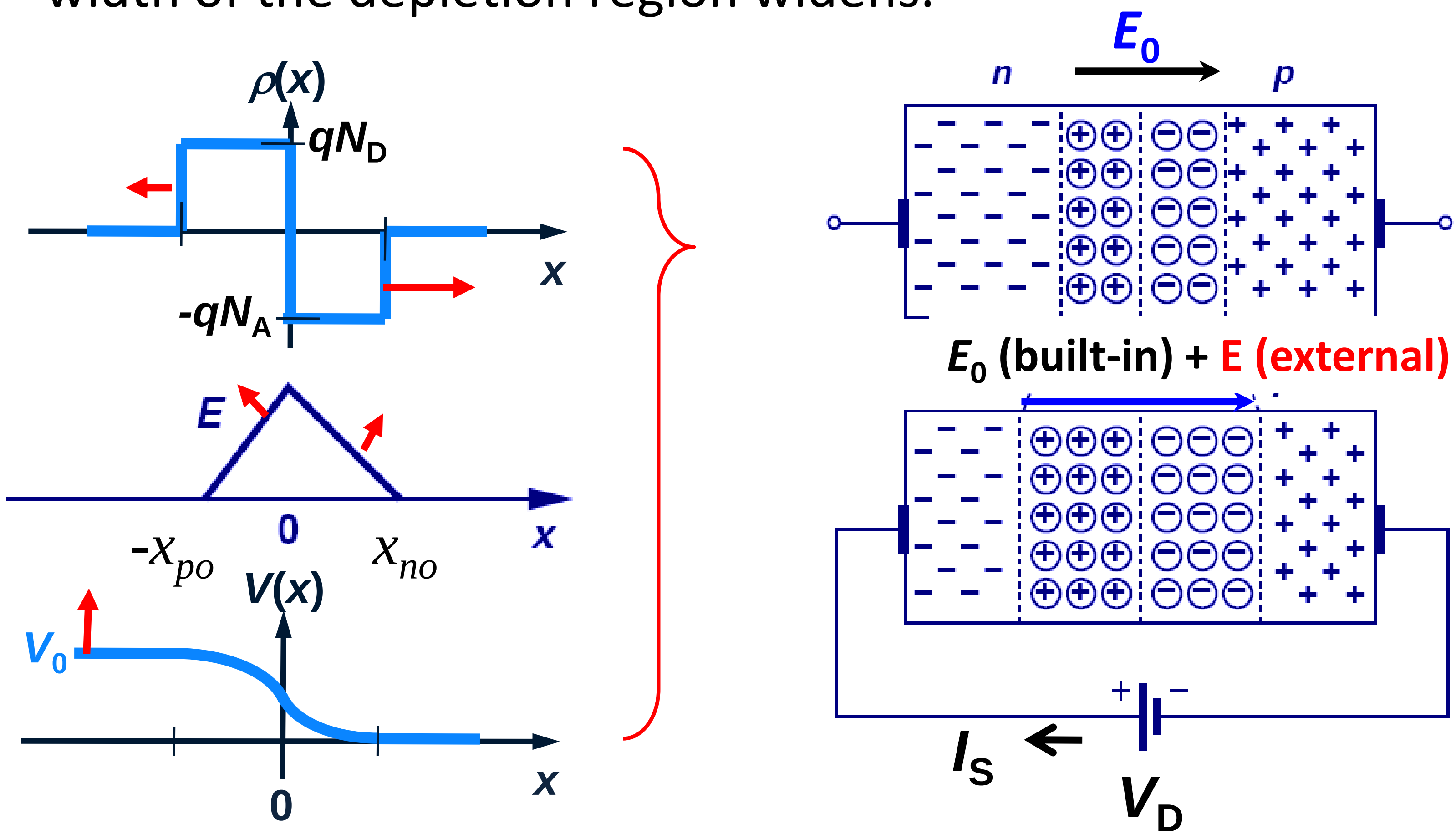
Reverse Biased P-N Junction

The application of a reverse voltage to the p-n junction will cause a transient current to flow as both electrons and holes are pulled away from the junction. When the potential formed by the widened depletion layer equals the applied voltage, the current will cease except for the small thermal current.

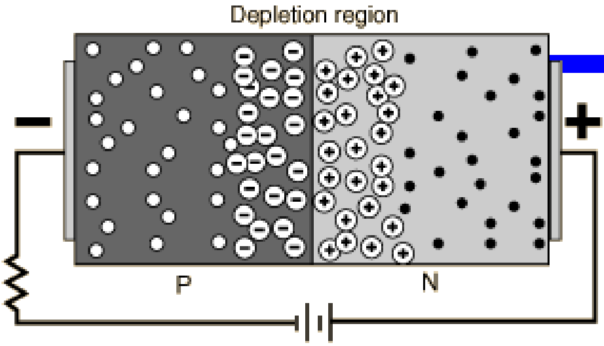


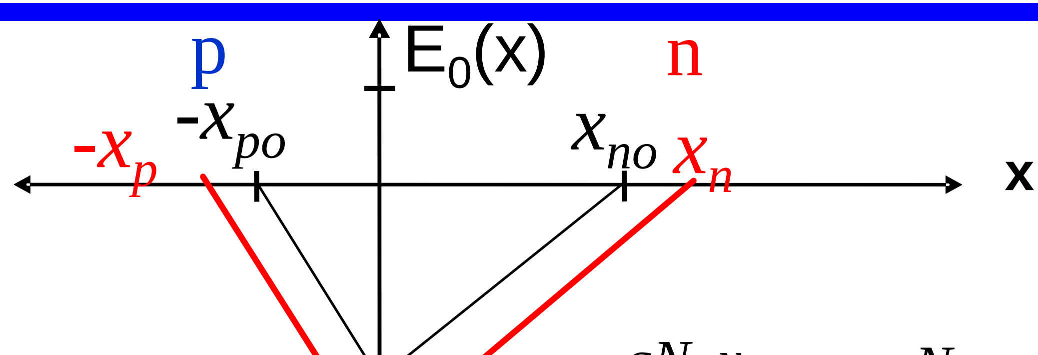
PN Junction under Reverse Bias

- A revers bias increases the potential drop across the junction. As a result, the magnitude of the electric field increases and the width of the depletion region widens.



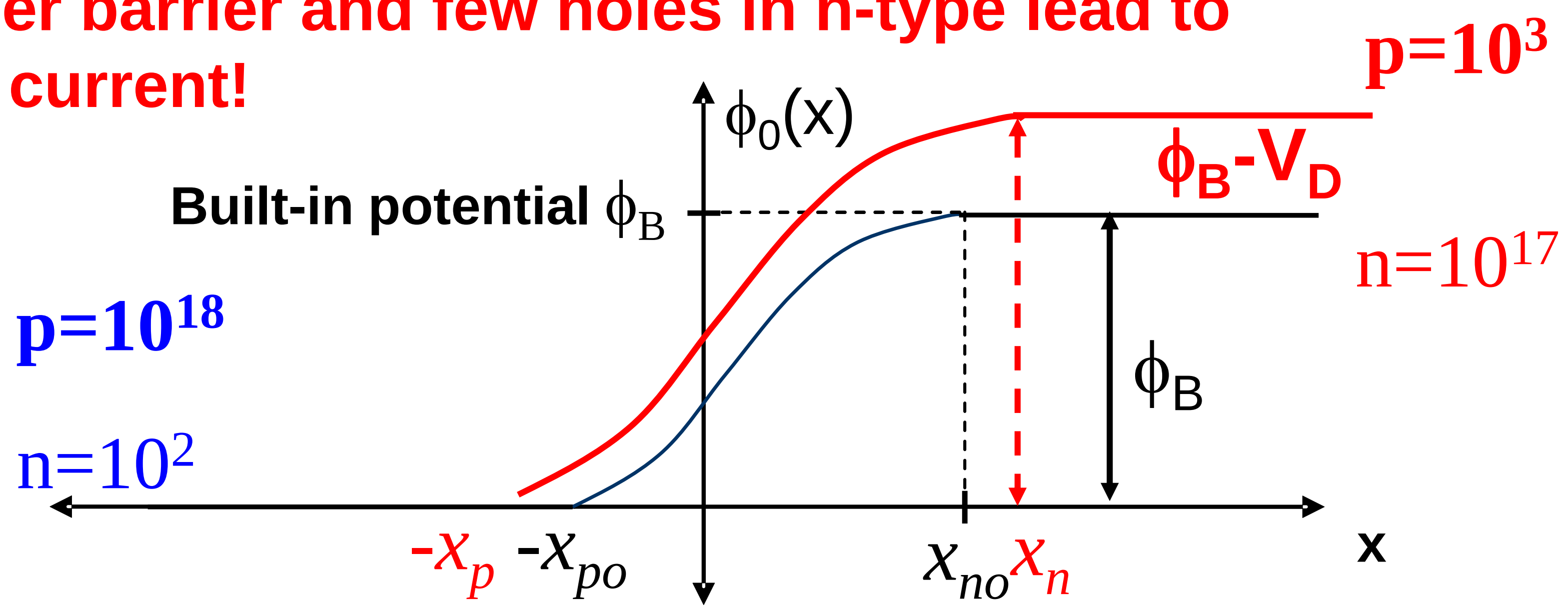
Depletion Approx. – with V_D<0 reverse bias





$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Higher barrier and few holes in n-type lead to little current!



Depletion Region Width W_{dep}

At V_D=0

$$W_{dep} = x_{po} + x_{no} = \sqrt{\frac{2\varepsilon_{Si}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)\phi_B}$$

At V_D<0

$$W_{dep} = x_p + x_n = \sqrt{\frac{2\varepsilon_{Si}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(\phi_B - V_D)}$$

- The width of the depletion region is a function of the bias voltage, and is dependent on $\boldsymbol{N_A}$ and $\boldsymbol{N_D}$.
- If one side is much more heavily doped than the other (which is commonly the case), then this can be simplified:

$$W_{dep} \cong \sqrt{\frac{2\varepsilon_{Si}}{qN}(\phi_B - V_D)}$$

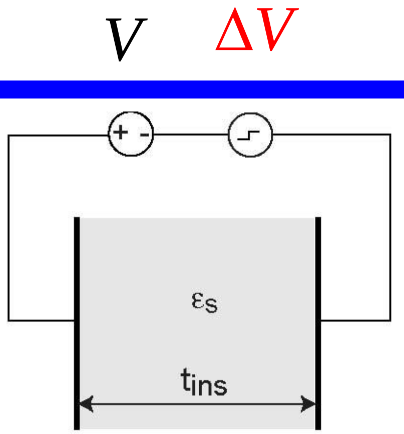
where *N* is the doping concentration on the more lightly doped side.

PN junction – (I)

OUTLINE

- The formation of depletion region
- Build-in potential
- Distribution of electric field and electric potential
- Effect of Applied Voltage
- **Depletion capacitance**

parallel-plate capacitor:



- Capacitance **<u>per unit area</u>**:

Apply *small signal* on top of bias:

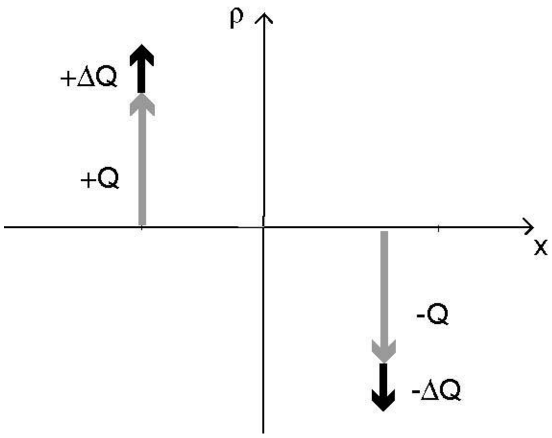
$C=\varepsilon_s/t_{ins}$

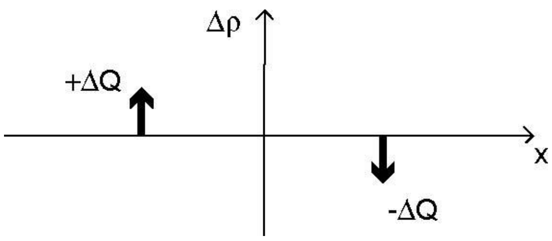
C = Q/V

$\varepsilon_s=\varepsilon_{r,s}\varepsilon_0$

$\varepsilon_{r's}$ is the relative dielectric constant of insulators.

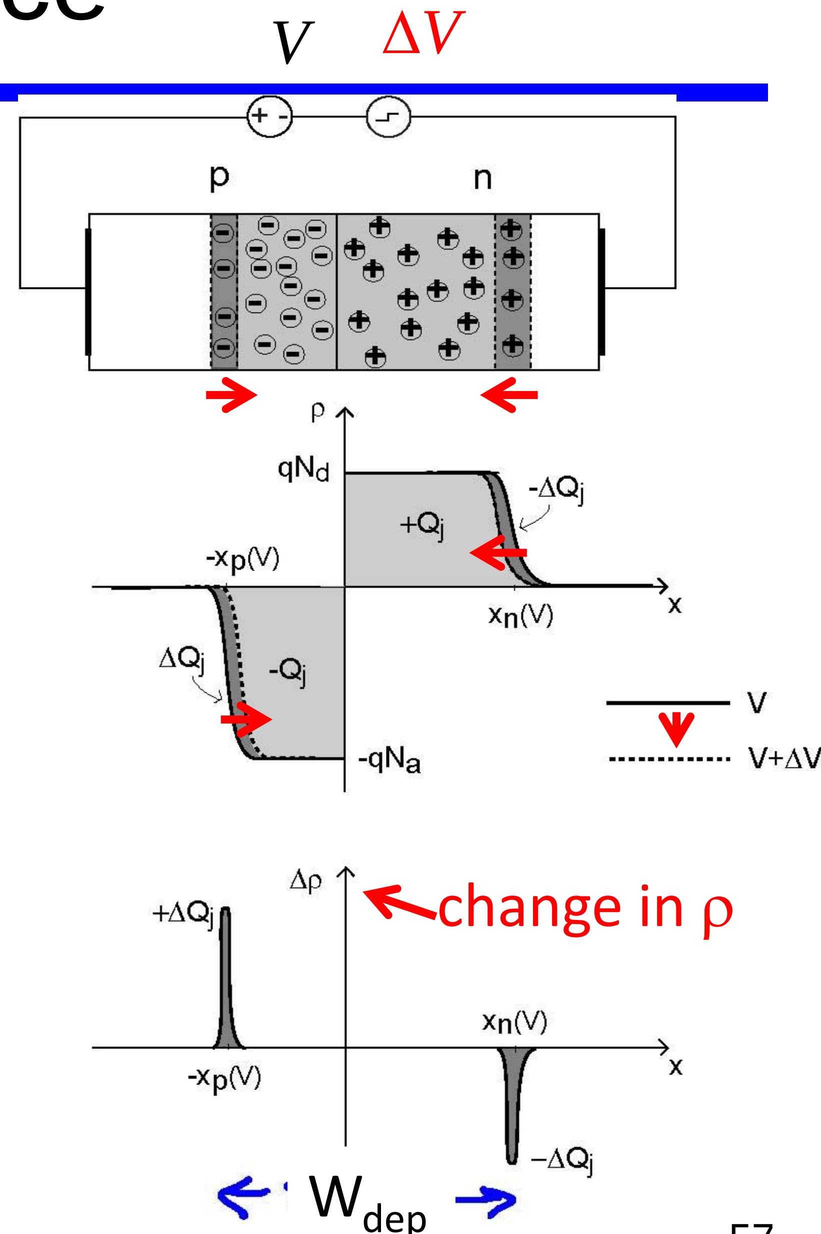
ε_0 is the permittivity of free space.





Depletion capacitance

Apply *small signal* on top of bias:



Change in ΔV across diode causes:

change of ΔQ_j at $-x_p$

change of $-\Delta Q_j$ at x_n

$$\boldsymbol{V >> |\Delta V|}$$

$$\boldsymbol{W_{dep} >> \Delta W_{dep}}$$

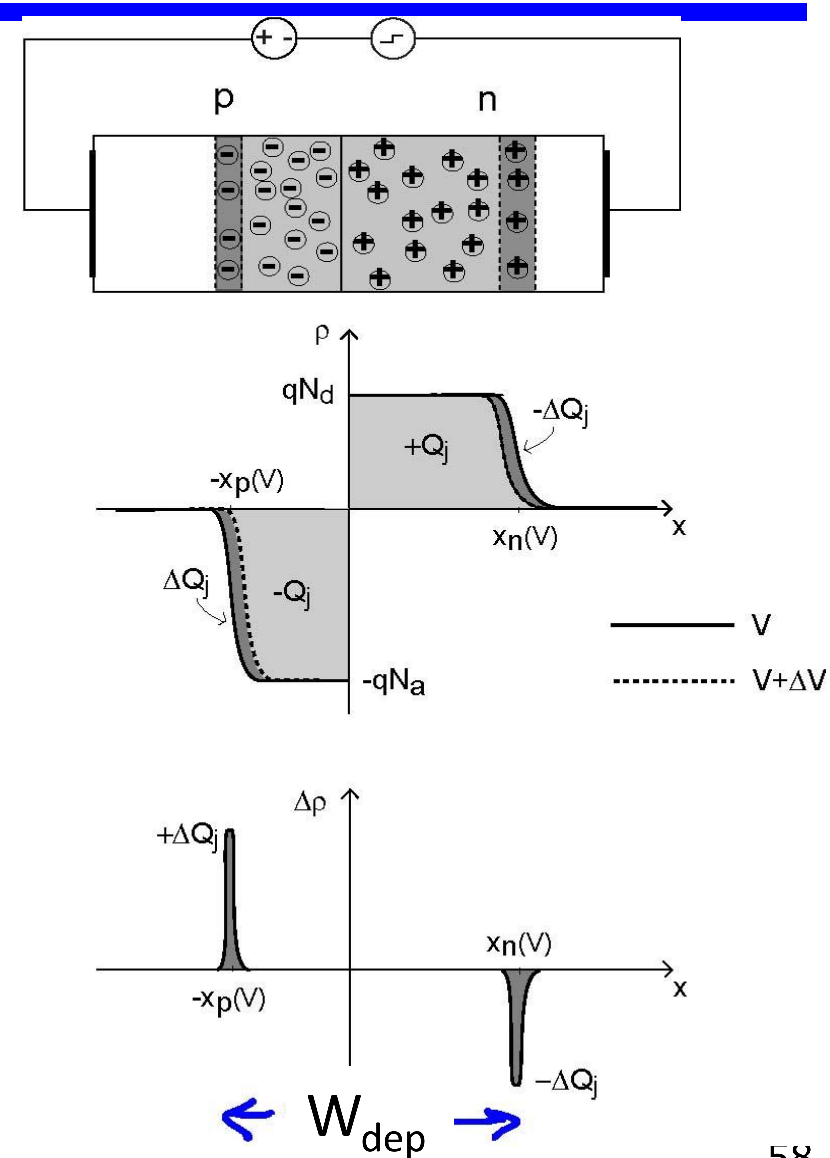
Depletion capacitance per unit area (depletion approx.)

- In analogy, in pn junction:

$$C_j(V) = \frac{\varepsilon_S}{W_{dep}(V)}$$

$$C_j(V) = \frac{\varepsilon_S}{W_{dep}(V)} = \sqrt{\frac{q\varepsilon_s N_a N_d}{2(\phi_B - V)(N_a + N_d)}} = \frac{C_{jo}}{\sqrt{1 - V/\phi_B}}$$

$$C_{j0} = \sqrt{\frac{\varepsilon_{si} q}{2} \frac{N_a N_d}{N_a + N_d} \frac{1}{\phi_B}}$$



Alternative view of capacitance: depletion charge

- Within depletion approximation:
- Cj is slope of Qj vs.V characteristics:

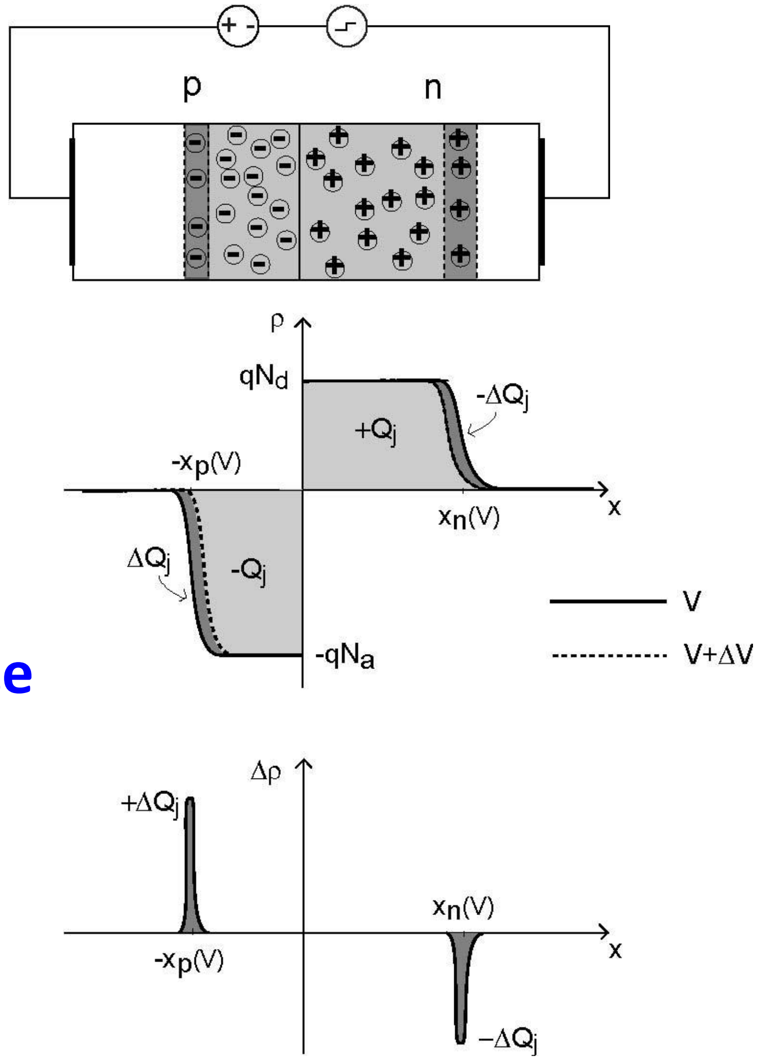
$$C_j(V)=\sqrt{\frac{q\varepsilon_s N_a N_d}{2(N_a+N_d)(\phi_B-V)}}=C_{jo}/\sqrt{1-\frac{V}{\phi_B}}$$

$$\boxed{C_j=\frac{dQ_j}{dV}}$$

***

Differential capacitance

$$\cancel{C_j=\frac{Q_j}{V}}$$



Summary-1

- A depletion region (in which ***n*** and ***p*** are each much smaller than the net dopant concentration) is formed at the junction between p- and n-type regions
  - A built-in potential barrier (voltage drop) exists across the depletion region, opposing carrier diffusion (due to a concentration gradient) across the junction:
    $$\phi_0 = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$
    - At equilibrium (V_D=0), no net current flows across the junction
  - Width of depletion region $$W_j \cong \sqrt{\frac{2\varepsilon_{Si}}{qN}(\phi_0 - V_D)}$$
    - decreases with increasing forward bias (p-type region biased at higher potential than n-type region)
    - increases with increasing reverse bias (n-type region biased at higher potential than p-type region)
    $$C_j = \frac{A_D \varepsilon_{Si}}{W_j}$$
  - Charge stored in depletion region → capacitance

Summary-2

Current flowing in a semiconductor is comprised of drift and diffusion components: $J_{tot} = qp\mu_p E + qn\mu_n E + qD_n \frac{dn}{dx} - qD_p \frac{dp}{dx}$

A region depleted of mobile charge exists at the junction between P-type and N-type materials.

- A built-in potential drop (V_0) across this region is established by the charge density profile; it opposes diffusion of carriers across the junction. A reverse bias voltage serves to enhance the potential drop across the depletion region, resulting in very little (drift) current flowing across the junction.
- The width of the depletion region (W_{dep}) is a function of the bias voltage (V_D).

$$W_{dep} = \sqrt{\frac{2\varepsilon_{si}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V_D)} \qquad V_0 = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

One of Prof Zhao's researches, Background

- Optical communications: λ=1.3 ~ 1.55μm.

  Si is transparent (the band-edge wavelength of 1.12μm)

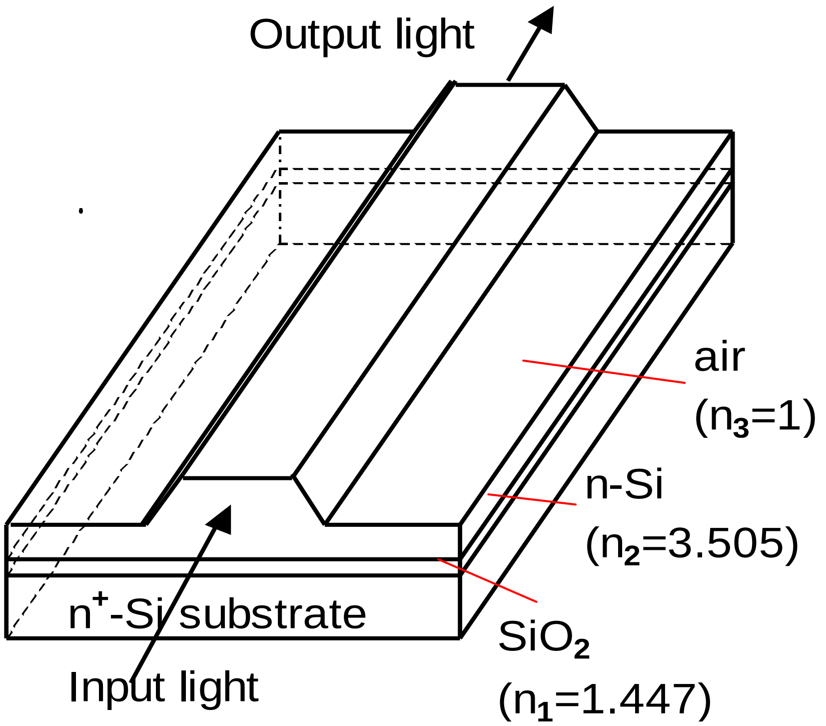
- Electro-optic integration at the wafer level.

  Si technology is well developed (the backbone of IC chip)

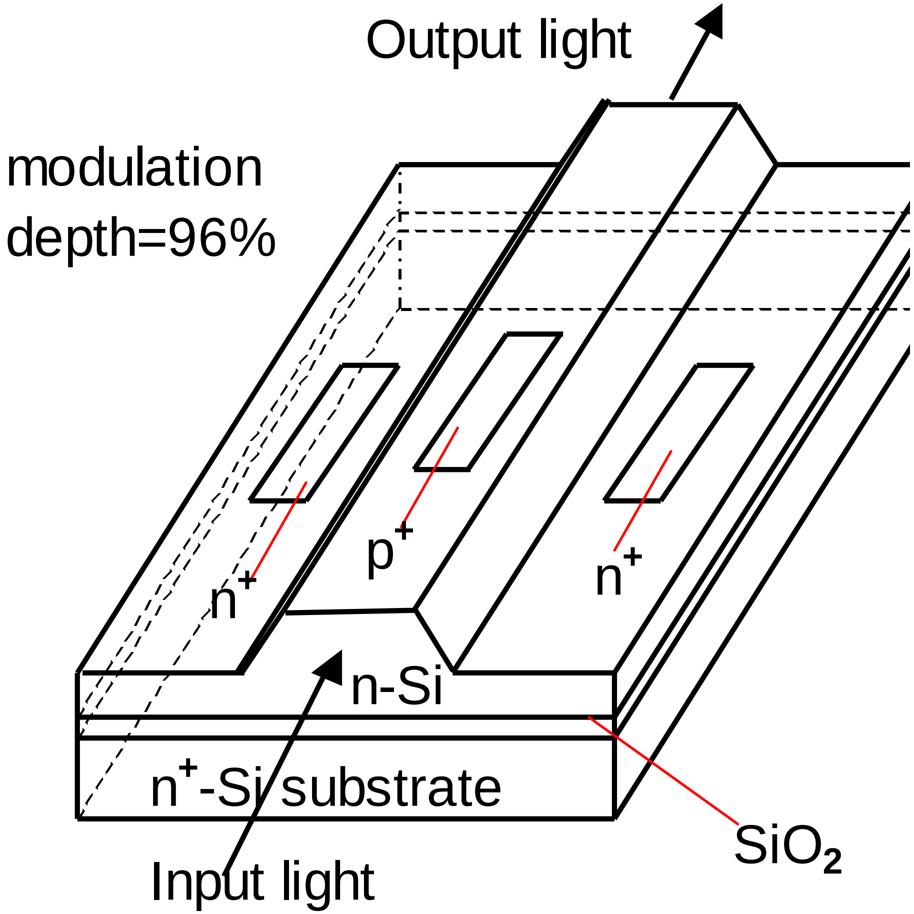
- Essential components in integrated optics

  Optical waveguide --- interconnection

  Optical switch --- cell (like MOSFET in IC)

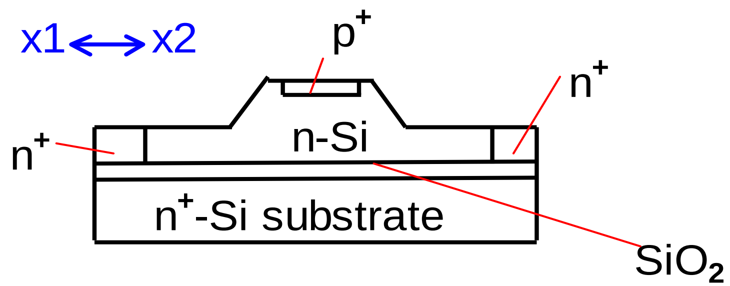


Optical waveguide modulator



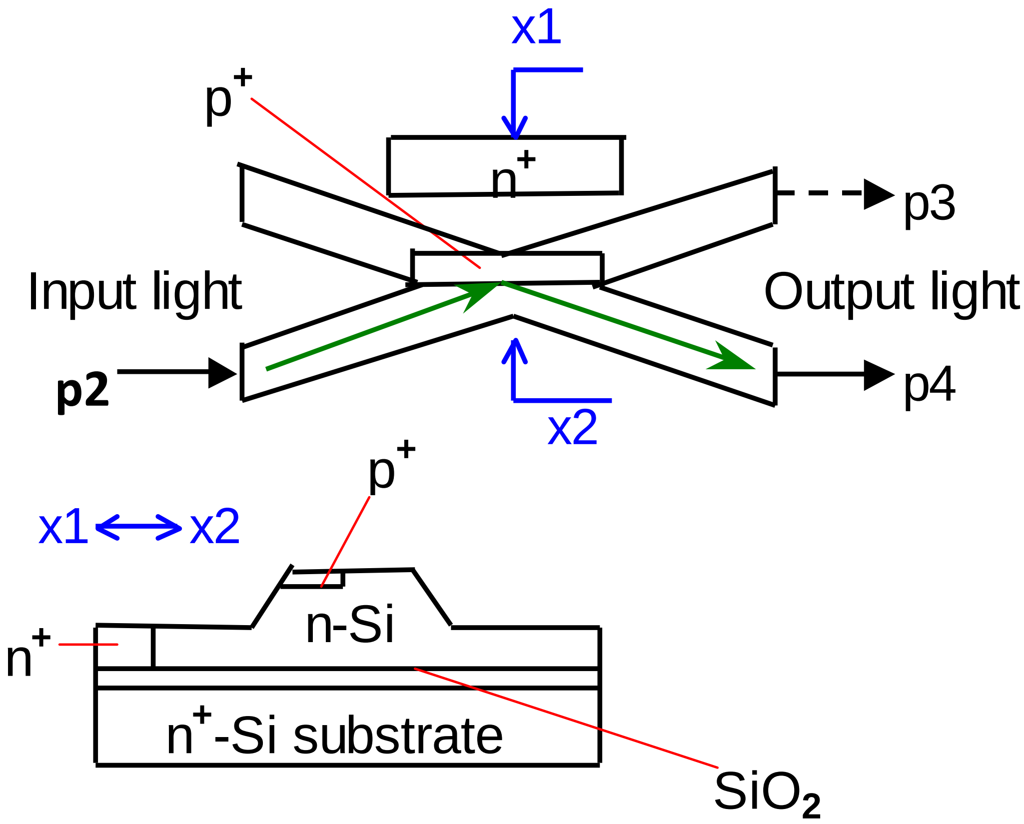
Single waveguide modulator:

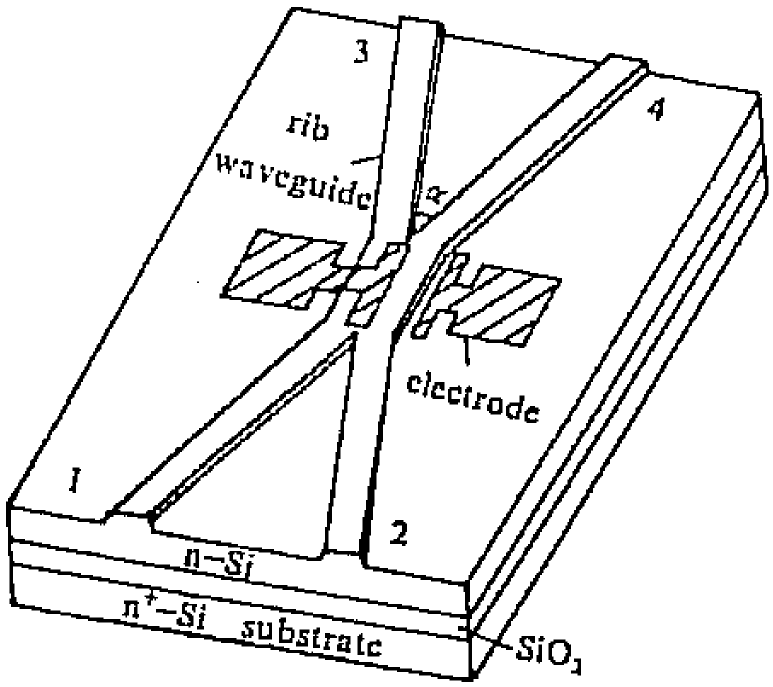
Waveguide-vanishing effect based on free carrier plasma dispersion



Total internal reflection switch

A reflection region is formed once holes inject.





HW7

Electron and hole concentrations

PL

$$n = N_C \exp\left[\frac{-(E_C - E_F)}{kT}\right]$$

$$p = N_V \exp\left[\frac{-(E_F - E_V)}{kT}\right]$$

$$n \cdot p = n_i^2$$

+

$$n_i = N_C \exp\left[\frac{-(E_C - E_i)}{kT}\right]$$

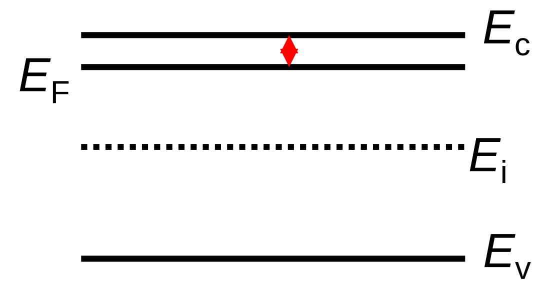
$$n_i = N_V \exp\left[\frac{-(E_i - E_V)}{kT}\right]$$

$$n = n_i \exp\left[\frac{(E_F - E_i)}{kT}\right]$$

$$p = n_i \exp\left[\frac{-(E_F - E_i)}{kT}\right]$$

At RT

***n* = *N*$_D$**



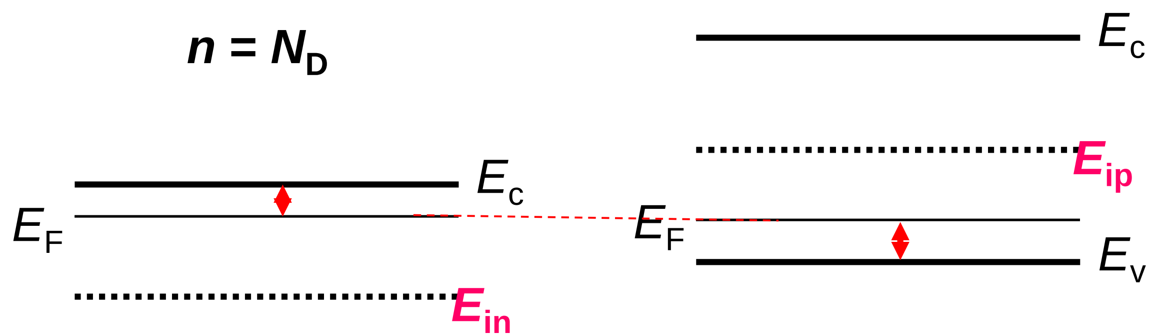
HW7

Electron and hole concentrations

$$n = n_i \exp\left[\frac{(E_F - E_i)}{kT}\right], \qquad p = n_i \exp\left[\frac{-(E_F - E_i)}{kT}\right]$$

$p = N_A$

$n = N_D$



$$N_A = p = n_i \exp\left[\frac{-(E_F - E_{ip})}{kT}\right]$$

$$N_D = n = n_i \exp\left[\frac{(E_F - E_{in})}{kT}\right]$$

$$qV_0 = E_{ip} - E_{in} \Rightarrow V_0 = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2}$$