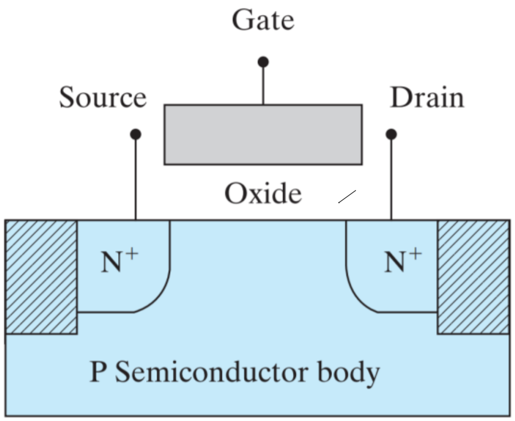
PN junction

EE302

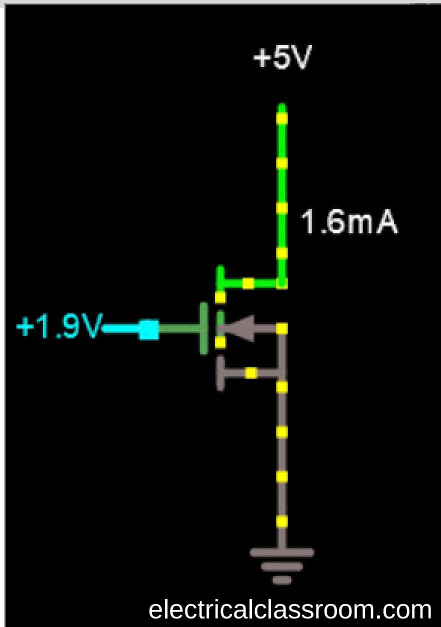
Prof. Sangyoon Han

Fall 2023



References:

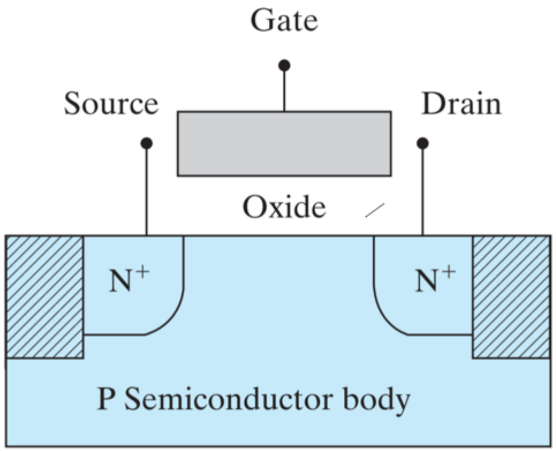
- (R. Pierret) Chapter 5
- (C. Hu) Chapter 4
- Materials from SE393 (Prof. Hongki Kang)



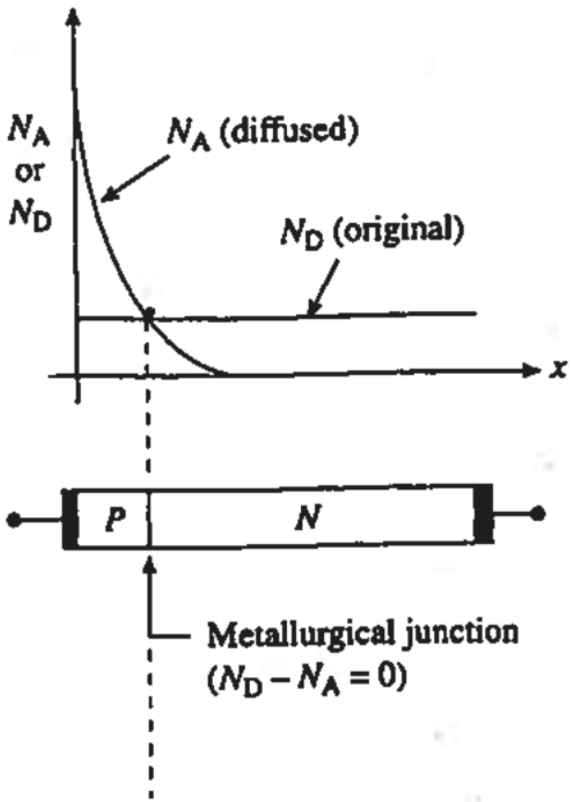
Overview

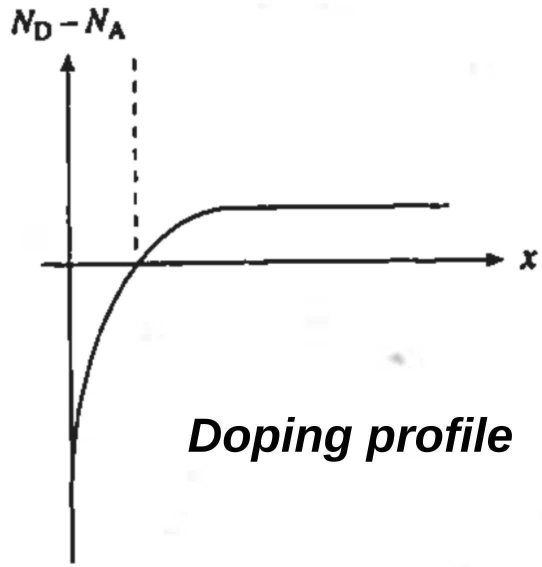
- **PN Junction Diode**
  - **Important device by itself**
  - **Fundamental basis of other devices as well**
    - **BJT, PNPN device**
    - **MS contact (metal-semiconductor), Schottky diode**
    - **MOSFET**
- **Analysis**
  - **Electrostatics**
    - **Charge density, electric field, electrostatic potential**
    - **Under equilibrium conditions**
  - **Steady-state response (d.c.)**
  - **Small-signal response (a.c.)**
  - **Transient response (pulsed)**

Where is PN junction?



Junction Terminology/Idealized Profiles

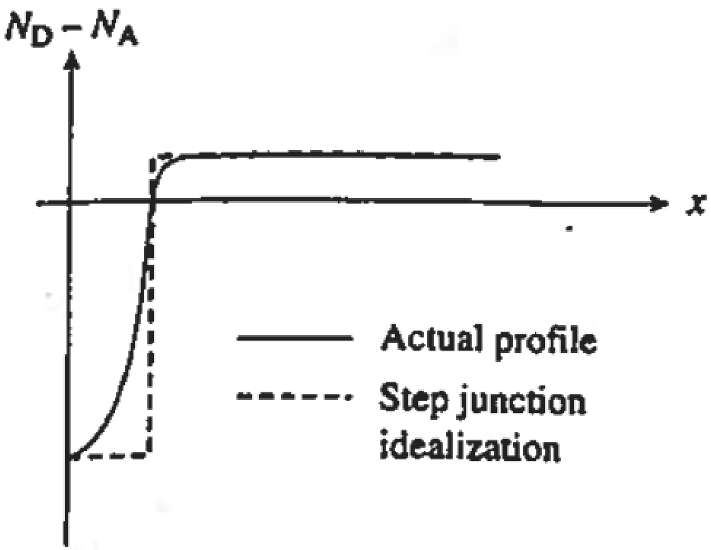




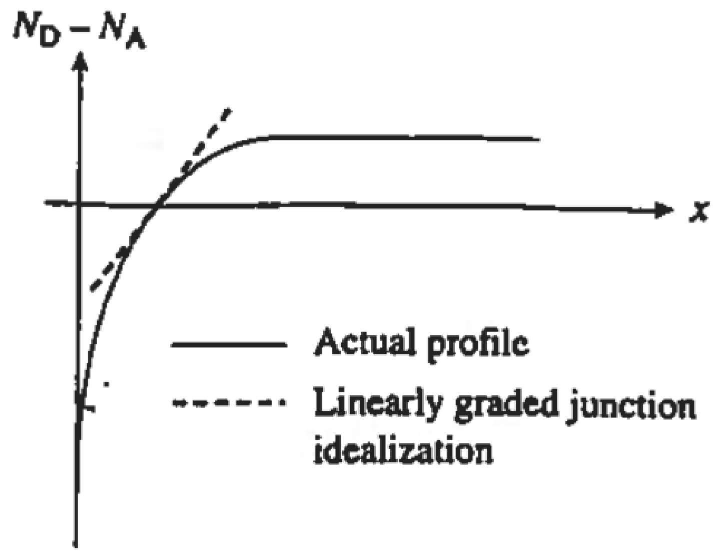
Doping profile

- **Starts with one-type of semiconductor**
- **Diffusion or Ion Implantation**
- **Metallurgical junction**
  - $N_D - N_A = 0$

Junction Terminology/Idealized Profiles



What we mostly use



- **Doping profile near the metallurgical junction**
- **Step junction (ion implantation)**
- **Linearly graded junction (diffusion)**

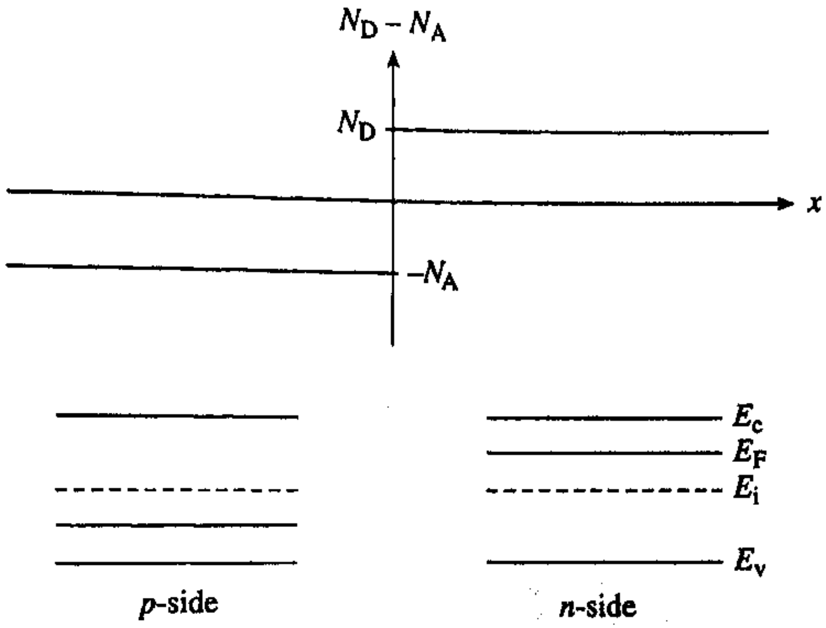
Poisson's Equation

$$\nabla \cdot E = \frac{\rho}{K_s \varepsilon_0}, \qquad \frac{dE}{dx} = \frac{\rho}{K_s \varepsilon_0}$$

- **Poisson's equation**
  - **gives quantitative solutions for the electrostatic variables**
  - **Charge density (ρ)**
    - $\rho = q(p - n + N_D - N_A)$ **(total ionization, charge neutrality)**

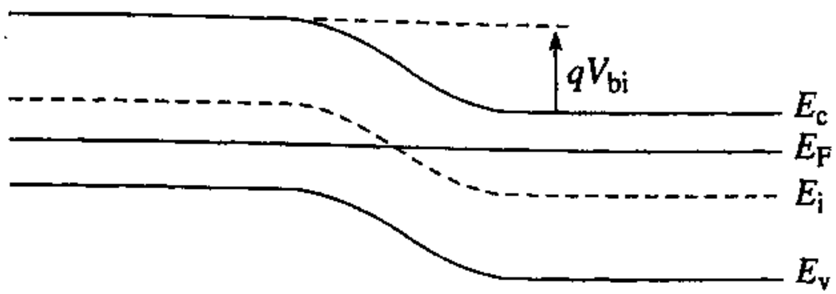
  - **Electric field (E) vs. Charge density (ρ)**

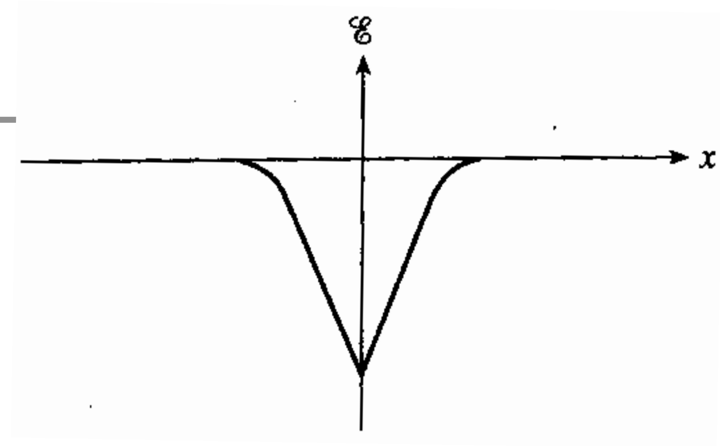
Qualitative Solution

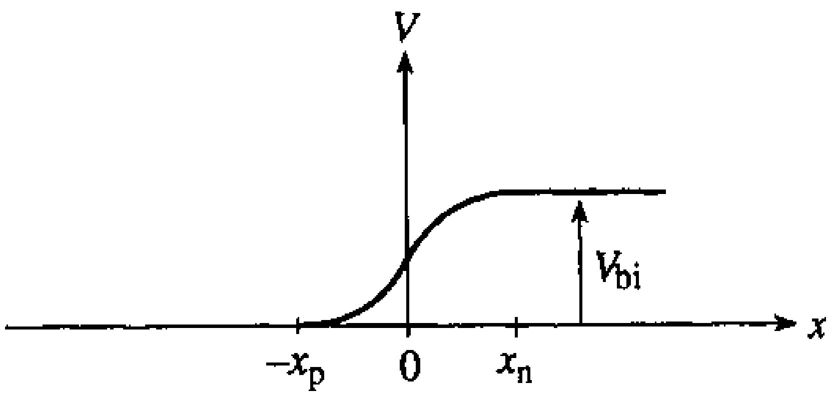


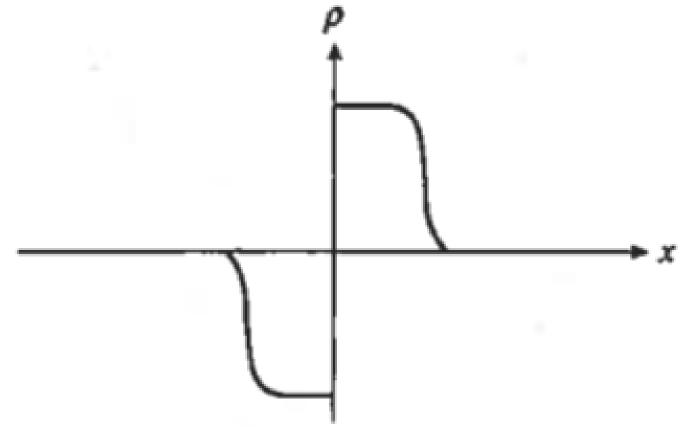
- **Fermi level under equilibrium condition**

Qualitative Solution



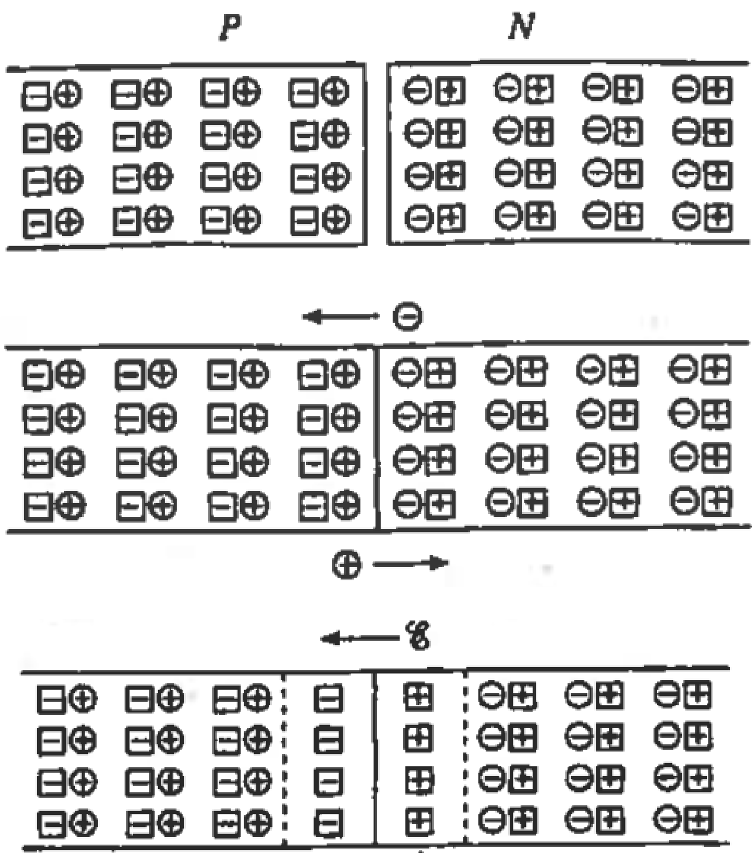


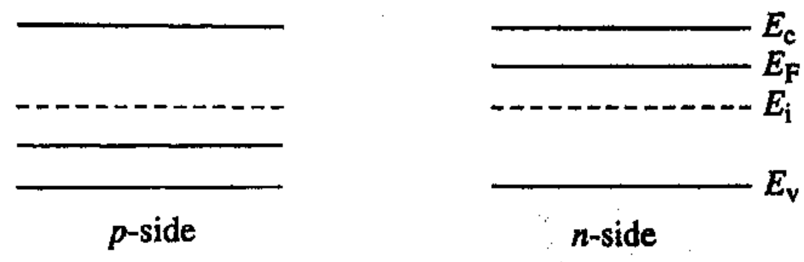




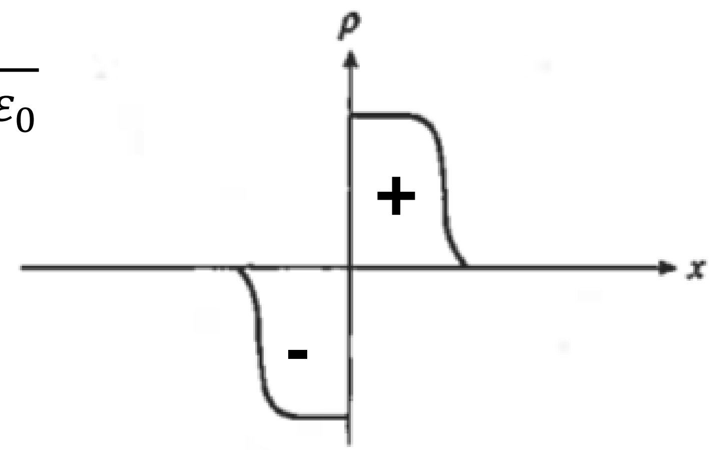
- **Potential, *V*(x)**
- **Electric field *E*(x)**
- **Charge density, $\rho(x)$**
- **Built-in potential, V_{bi}**

Qualitative Solution



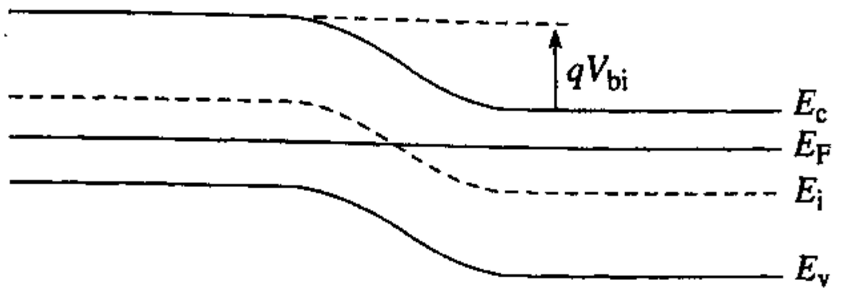


$$\frac{dE}{dx} = \frac{\rho}{K_s \varepsilon_0}$$



- **Diffusion**
- **Space charge region (Depletion region)**

The Built-In Potential (V_{bi})



- **Built-in potential**
  - **Voltage drop across the depletion region in the PN juction under equilibrium (drift + diffusion = 0)**

$$J_N = q\mu_n n\mathscr{E} + qD_N\frac{dn}{dx} = 0$$

$$\mathscr{E} = -\frac{D_N}{\mu_n}\frac{dn/dx}{n} = -\frac{kT}{q}\frac{dn/dx}{n}$$

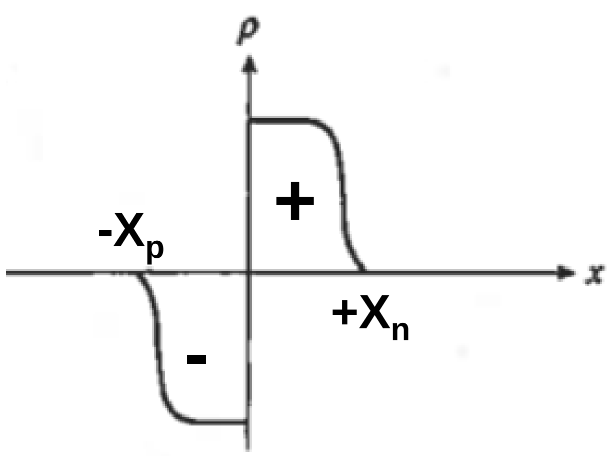
$$\frac{D_n}{\mu_n} = \frac{kT}{q}$$

$$V_{bi} = -\int_{-x_p}^{x_n}\mathscr{E}dx = \frac{kT}{q}\int_{n(-x_p)}^{n(x_n)}\frac{dn}{n} = \frac{kT}{q}\ln\left[\frac{n(x_n)}{n(-x_p)}\right]$$

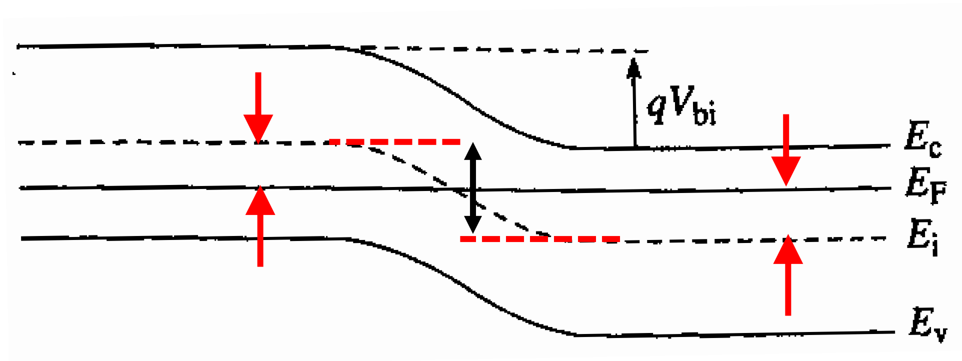
$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$n(x_n) = N_D$$

$$n(-x_p) = \frac{n_i^2}{N_A}$$



The Built-In Potential (V_{bi})



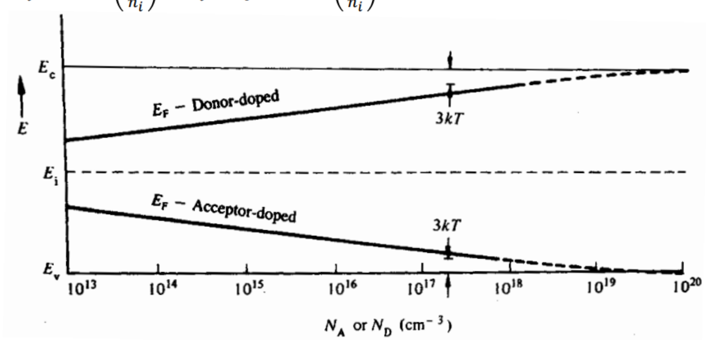
$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

We can calculate the equation in easier way (how?).

Determination of E_F (Fermi Level)

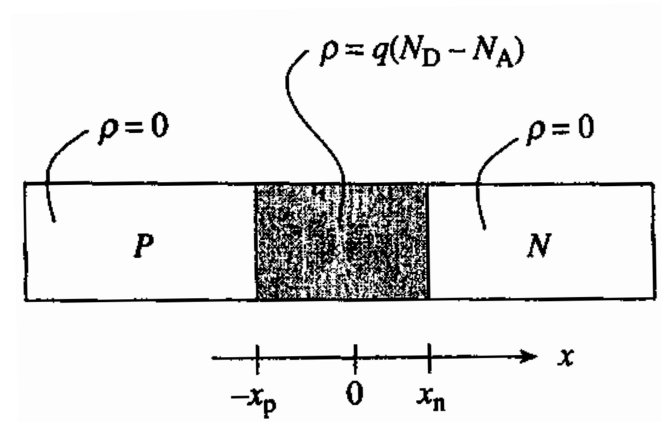
$$n = n_i e^{\frac{E_F - E_i}{kT}}, \qquad p = n_i e^{\frac{E_i - E_F}{kT}}$$

- **Fermi level** in doped semiconductor (nondegenerate, total ionization)
- $E_F - E_i = kT \ln\left(\frac{n}{n_i}\right) = -kTln\left(\frac{p}{n_i}\right)$
- $E_F - E_i = kT \ln\left(\frac{N_D}{n_i}\right)$, $E_i - E_F = kTln\left(\frac{N_A}{n_i}\right)$



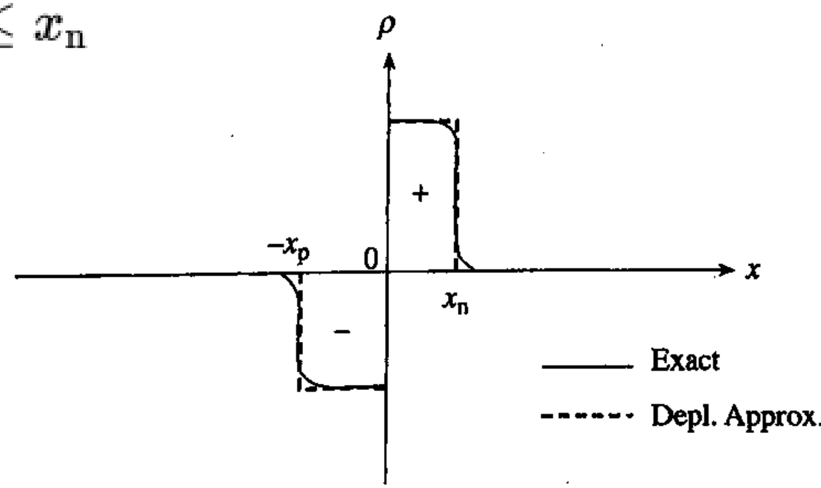
The Depletion Approximation

- **Depletion Approximation**
  1. **Carrier concentrations (*n*, *p*) in $-x_p \ll x \ll +x_n$ is much smaller than the net doping concentrations ($n, p \ll N_D, N_A$)**
  2. **Charge density outside the depletion region is zero.**
     ($\rho = 0$, $-x_p \geq x;\ +x_n \leq x$)

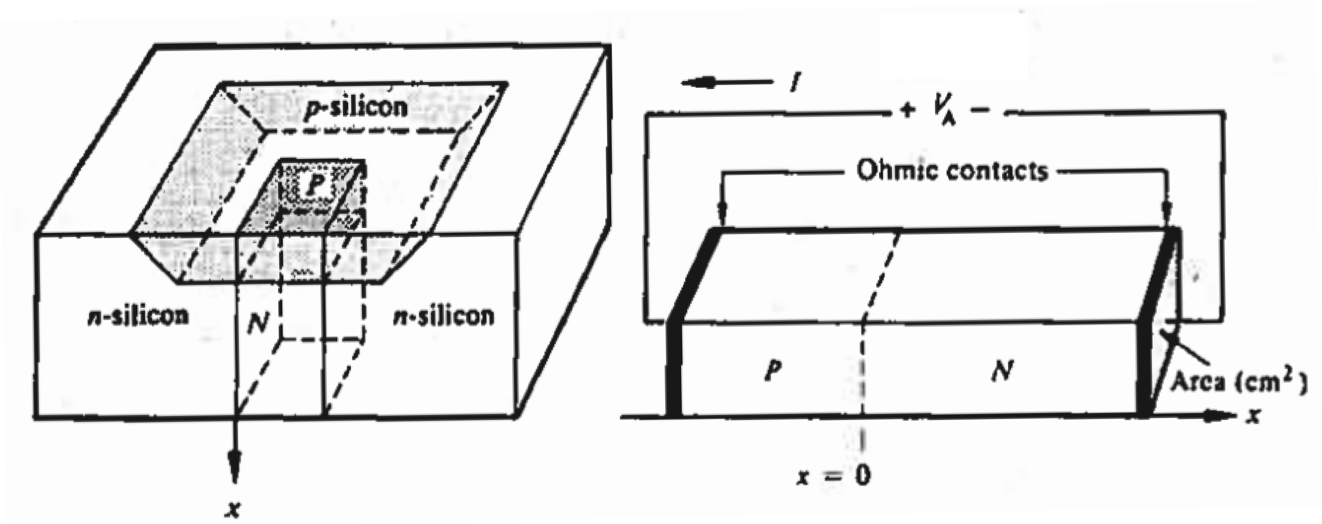


$$\frac{d\boldsymbol{E}}{d\boldsymbol{x}} = \frac{\boldsymbol{q}}{\boldsymbol{K_S \epsilon_0}}(\boldsymbol{p} - \boldsymbol{n} + \boldsymbol{N_D} - \boldsymbol{N_A})$$

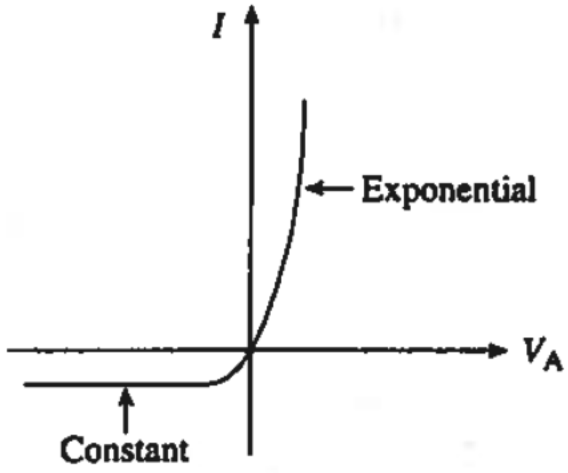
$$\frac{dE}{dx} \cong \begin{cases} \frac{q}{K_s \varepsilon_0}(N_\mathrm{D} - N_\mathrm{A}) & \ldots -x_\mathrm{p} \leq x \leq x_\mathrm{n} \\ 0 \quad \ldots x \leq -x_\mathrm{p} & \text{and } x \geq x_\mathrm{n} \end{cases}$$



Quantitative Electrostatic Relationships



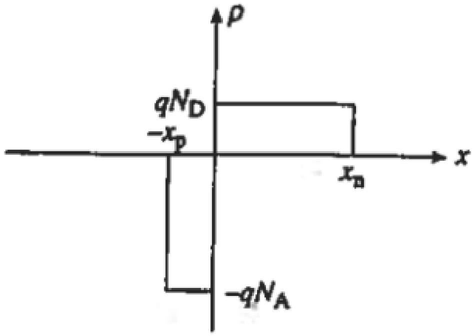
- **PN junction diode**
- **Rectifier**
- **Applied voltage, V_A**
- **Ohmic contacts**
  - **Ideally zero resistance, zero voltage drop**



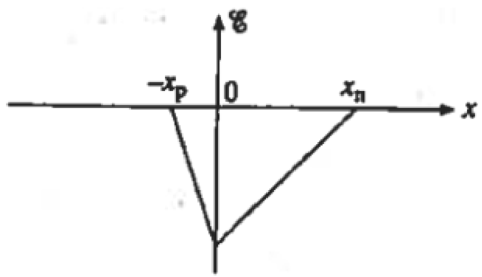
1. Charge density (ρ), Electric field (E(x))

$$\rho = \begin{cases} -qN_A & \ldots -x_p \le x \le 0 \\ qN_D & \ldots 0 \le x \le x_n \\ 0 & \ldots x \le -x_p \text{ and } x \ge x_n \end{cases}$$

$$\frac{dE}{dx} = \frac{\rho}{K_s \varepsilon_0}$$



$$\frac{dE}{dx} = \begin{cases} -qN_A/K_S\varepsilon_0 & \ldots -x_p \le x \le 0 \\ qN_D/K_s\varepsilon_0 & \ldots x \le x \le x_n \\ 0 & \ldots x \le -x_p \text{ and } x \ge x_n \end{cases}$$



$$\int_0^{E(x)} dE = -\int_{-x_p}^{x} \frac{qN_A}{K_s\varepsilon_0} dx \qquad \int_{E(x)}^{0} dE' = \int_{x}^{x_n} \frac{qN_D}{K_S\varepsilon_0} dx'$$

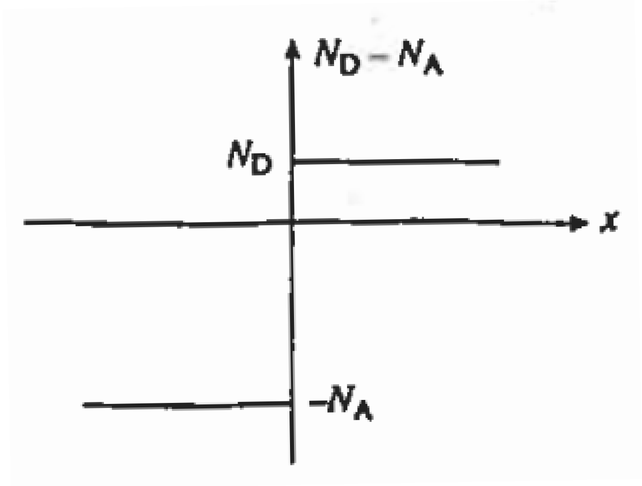
$$E(x) = -\frac{qN_A}{K_s\varepsilon_0}(x_p + x) \quad \ldots -x_p \le x \le 0$$

$$E(x) = -\frac{qN_D}{K_S\varepsilon_0}(x_n - x) \quad \ldots 0 \le x \le x_n$$

$$E(0^-) = E(0^+)$$

$$N_A x_p = N_D x_n$$

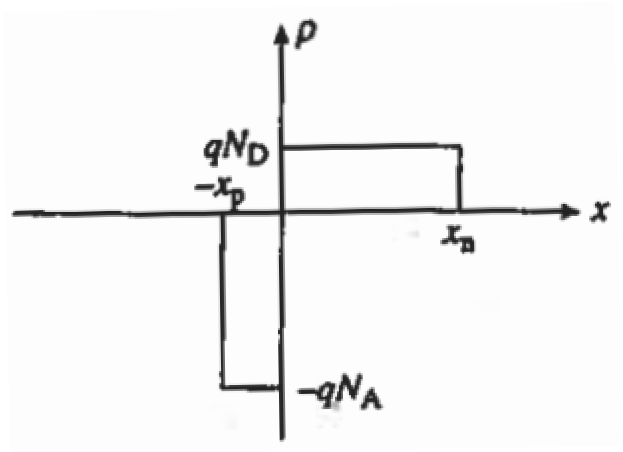
1. Charge density (ρ), Electric field (E(x))

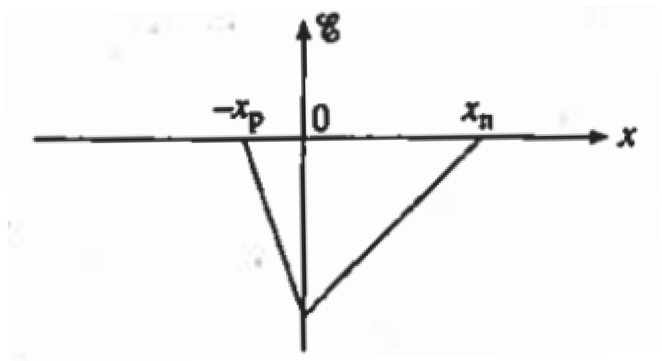


$$E(x) = -\frac{qN_A}{K_s\varepsilon_0}(x_p + x) \quad \ldots -x_p \le x \le 0$$

$$E(x) = -\frac{qN_D}{K_S\varepsilon_0}(x_n - x) \quad \ldots 0 \le x \le x_n$$

$$N_A x_p = N_D x_n$$





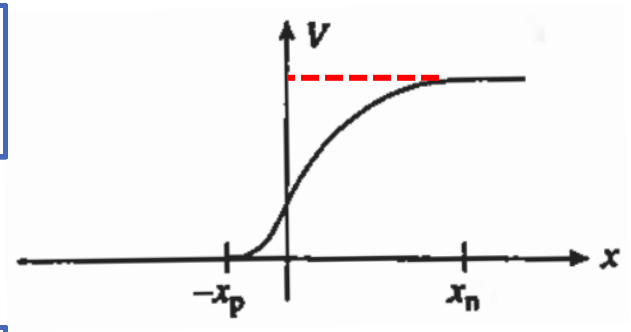
2. Potential (V)

$$\mathscr{E} = -dV/dx$$

$$\frac{dV}{dx} = \begin{cases} \frac{qN_A}{K_S\varepsilon_0}(x_p + x) & \ldots, -x_p \le x \le 0 \\ \frac{qN_D}{K_S\varepsilon_0}(x_n - x) & \ldots 0 \le x \le x_n \end{cases}$$

$$\int_0^{V(x)} dV' = \int_{-x_p}^{x} \frac{qN_A}{K_S\varepsilon_0}(x_p + x')dx'$$

$$V(x) = \frac{qN_A}{2K_S\varepsilon_0}(x_p + x)^2 \quad \ldots \quad -x_p \le x \le 0$$



$$\int_{V(x)}^{V_{bi}} dV' = \int_{x}^{x_n} \frac{qN_D}{K_S\varepsilon_0}(x_n - x')dx'$$

$$V(x) = V_{bi} - \frac{qN_D}{2K_S\varepsilon_0}(x_n - x)^2 \quad \ldots . 0 \le x \le x_n$$

3. Depletion region boundary ($+x_n, -x_p$)

$$V(0^-) = V(0^+)$$

$$N_A x_p = N_D x_n$$

$$V(0^-) = \frac{qN_A}{2K_S\varepsilon_0}\left(x_p + 0^-\right)^2 = V_{bi} - \frac{qN_D}{2K_S\varepsilon_0}\left(x_n - 0^+\right)^2 = V(0^+)$$

$$x_n = \left[\frac{2K_s\varepsilon_0}{q}\frac{N_A}{N_D(N_A+N_D)}V_{bi}\right]^{1/2}$$

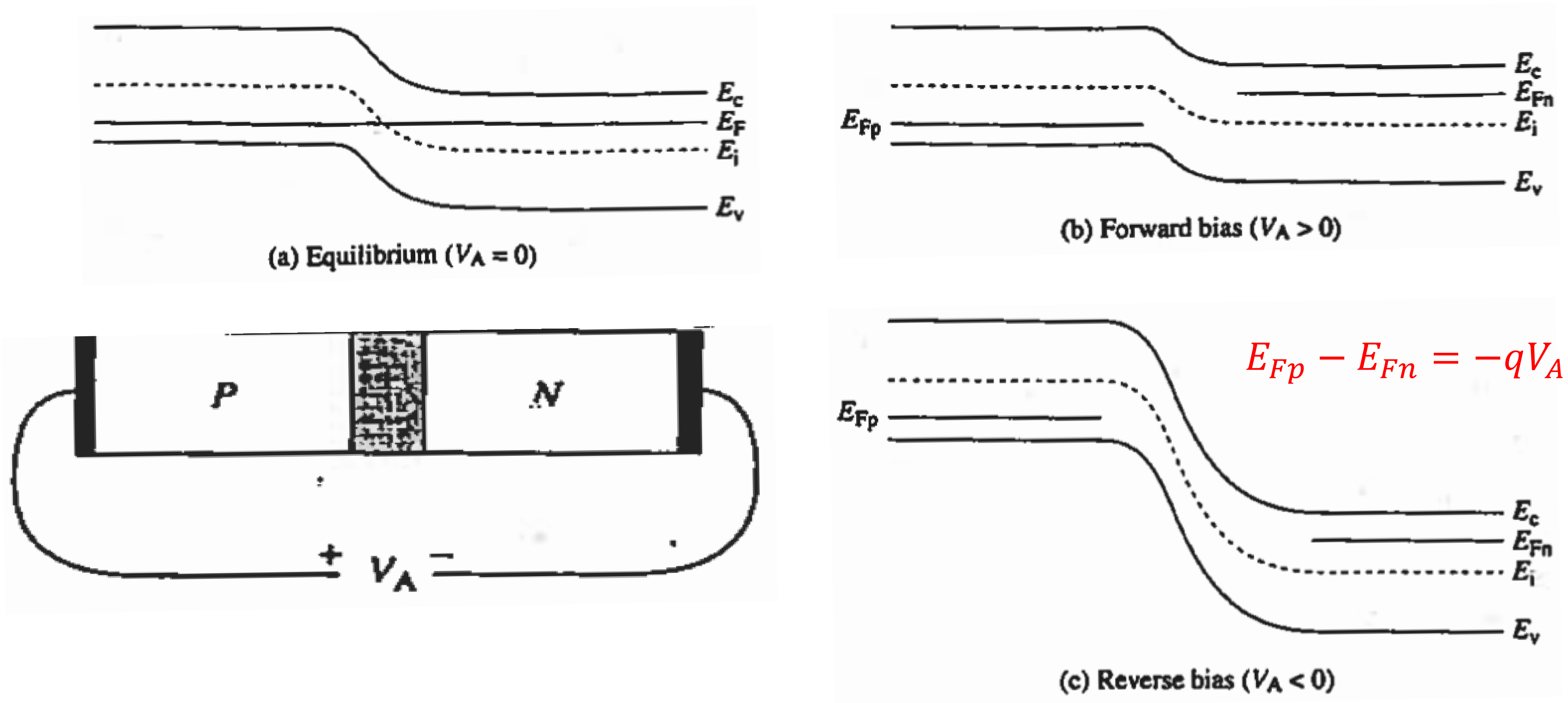
$$x_p = \frac{N_D x_n}{N_A} = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}V_{bi}\right]^{1/2}$$

Depletion width (W)

$$W = x_n + x_p = \left[\frac{2K_s\varepsilon_0}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)V_{bi}\right]^{1/2}$$

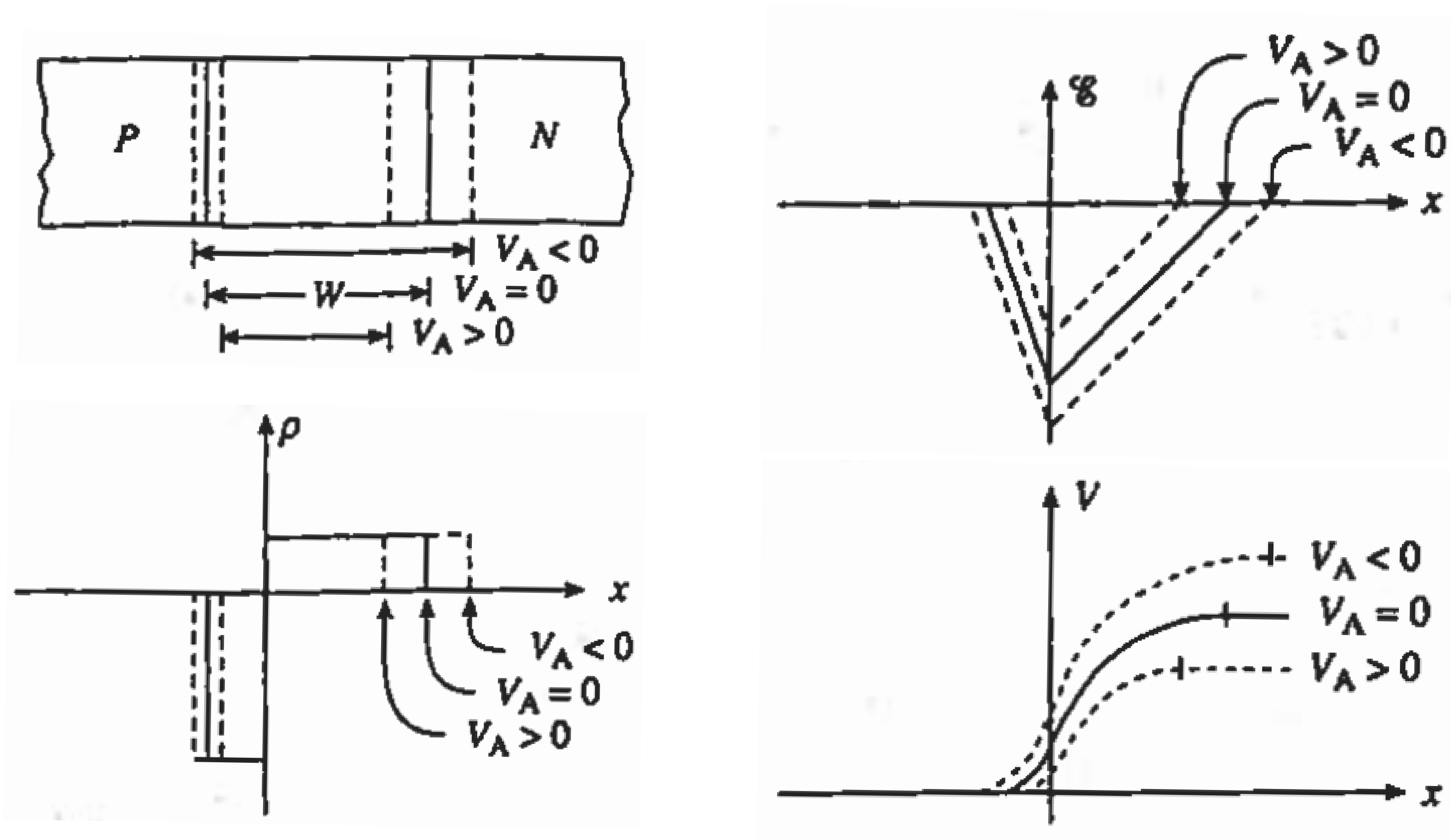
Examination/Extrapolation of Results

Quasi-Fermi levels



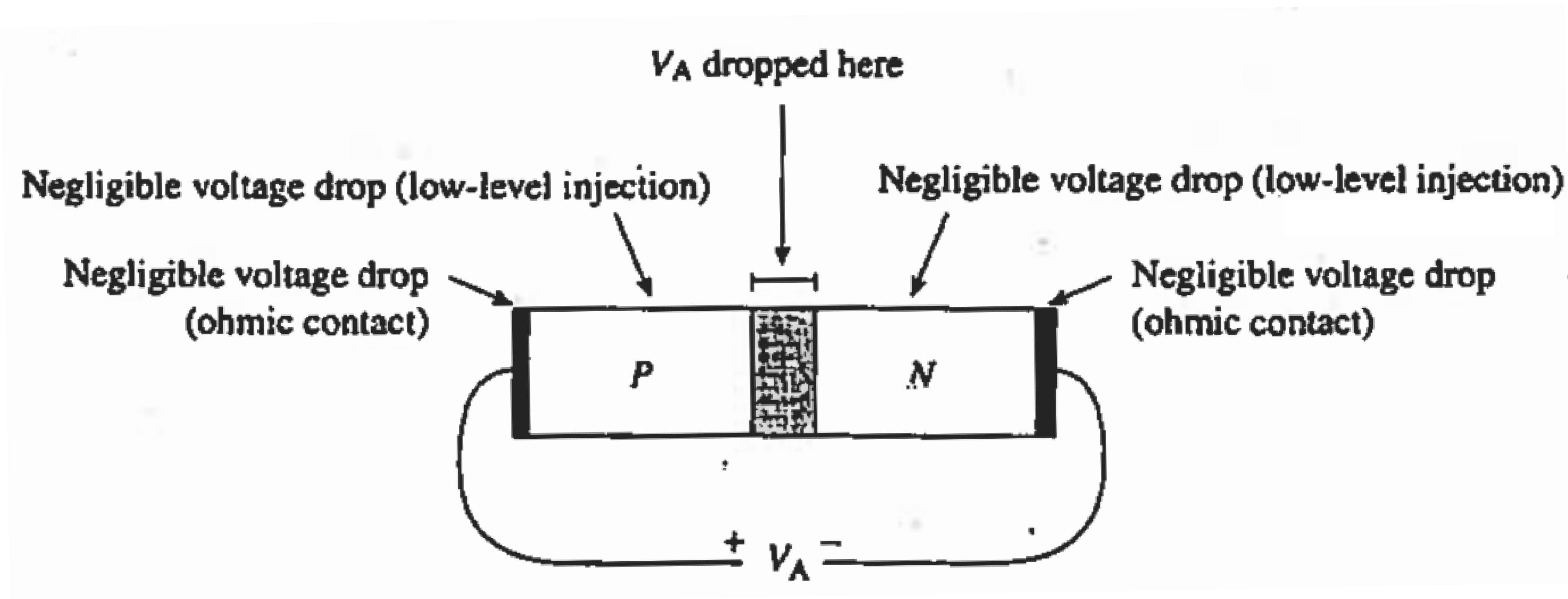
- **Why does n-type energy level increase with positive bias on p-type?**
- **What would happen if V_A keep increases (i.e., >V_{bi})?**

Examination/Extrapolation of Results



- **Charge density / Depletion width**
- **Electric field**
- **Potential barrier**

Step Junction with $V_A \neq 0$ (solving for $\rho, E, V, +x_n, -x_p$)



- **Low level injection**
  - ***Δn*, *Δp* << N_D, N_A**
- **Most of voltage drop across the depletion region**
- **With $V_A \neq 0$, V_{bi} changes.**
  - **$V_A \neq 0$, $V_{bi} \Rightarrow V_{bi} - V_A$**

Step Junction with $V_A \neq 0$ (solving for $\rho, E, V, +x_n, -x_p$)

- **Electric field equations are unchanged.**
  - **x_p, x_n will be different**
- **Potential equations ($V_{bi} \Rightarrow V_{bi} - V_A$)**

$$V(x) = \frac{qN_A}{2K_S\varepsilon_0}(x_p + x)^2 \quad \ldots \quad -x_p \leq x \leq 0$$

$$V(x) = V_{bi} - \frac{qN_D}{2K_S\varepsilon_0}(x_n - x)^2 \quad \ldots .0 \leq x \leq x_n$$

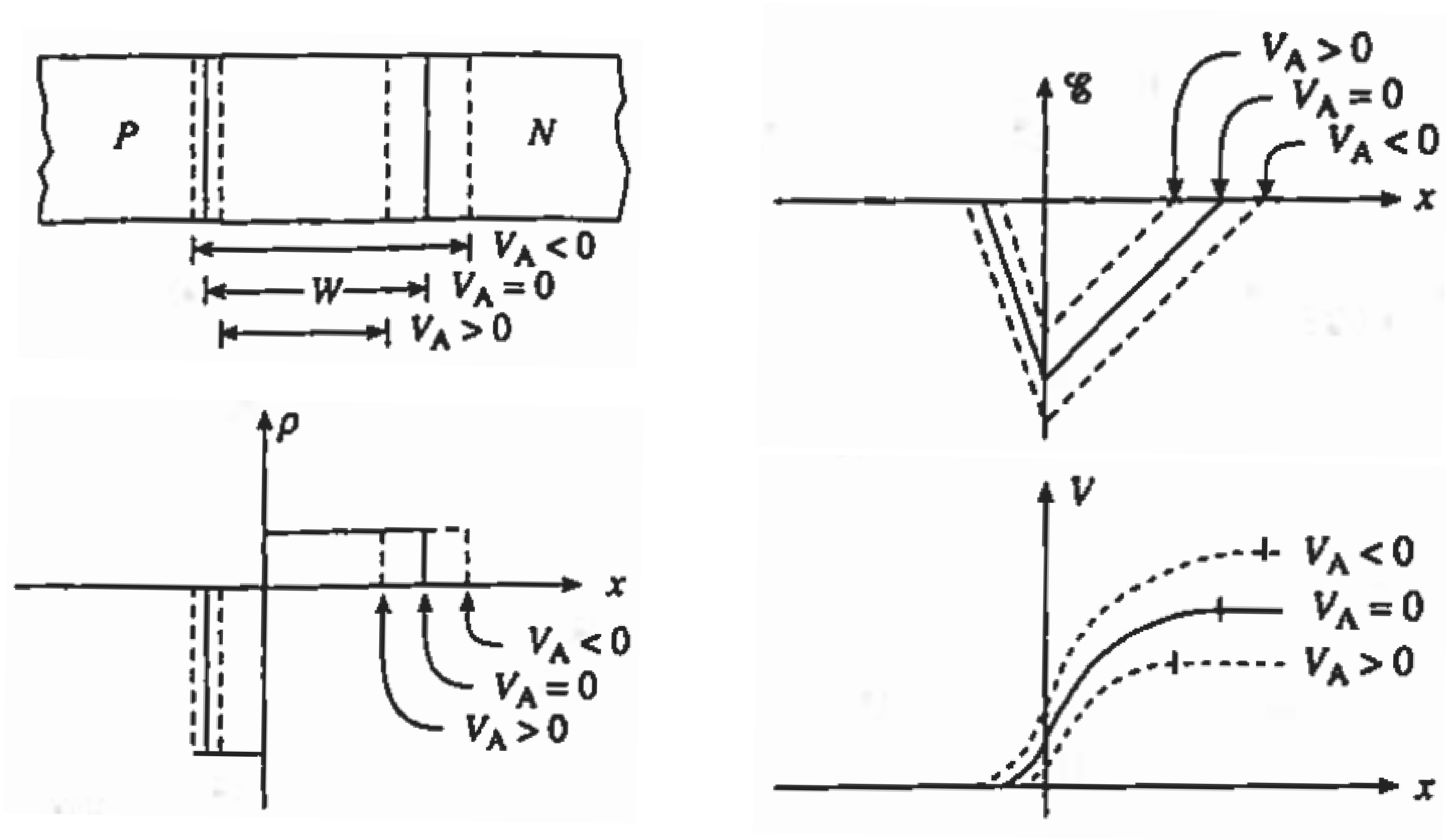
V_{bi} ⇓ $V_{bi} - V_A$

- **Depletion region width**

$$x_n = \left[\frac{2K_s\varepsilon_0}{q}\frac{N_A}{N_D(N_A+N_D)}(V_{bi} - V_A)\right]^{1/2} \quad x_p = \left[\frac{2K_S\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}(V_{bi} - V_A)\right]^{1/2}$$

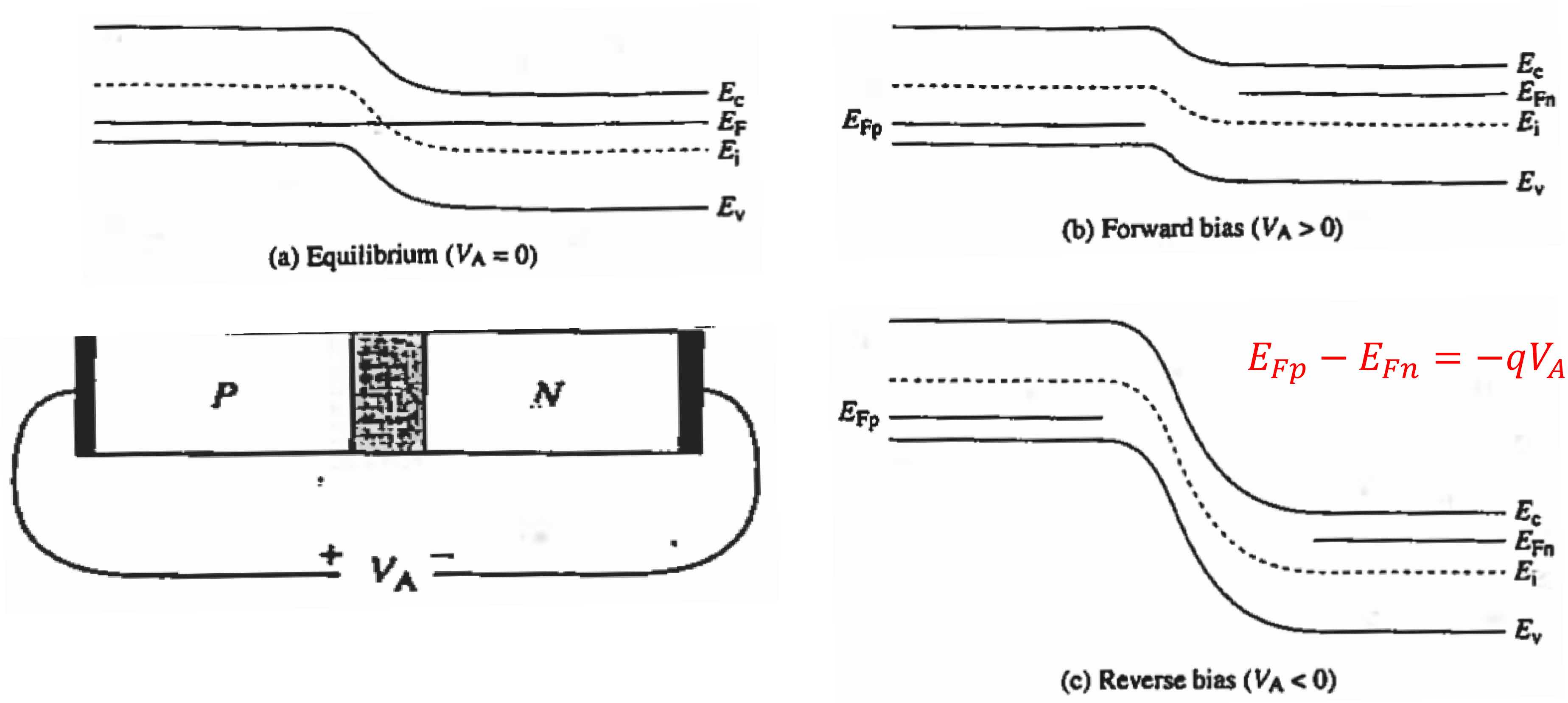
$$W = x_n + x_p = \left[\frac{2K_s\varepsilon_0}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)(V_{bi} - V_A)\right]^{1/2}$$

Examination/Extrapolation of Results



- **Charge density / Depletion width**
- **Electric field**
- **Potential barrier**

Quasi-Fermi levels



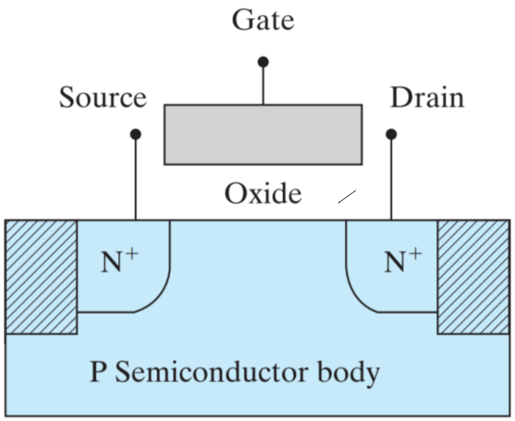
$$E_{Fp} - E_{Fn} = -qV_A$$

- **Why does n-type energy level increase with positive bias on p-type?**
- **What would happen if V_A keep increases (i.e., >V_{bi})?**

Summary

- **Qualitative, and Quantitiative analysis of PN junction**
- **Balancing of Diffusion and Drift**
- **Band bending at the junction**
- **Depletion region (or space charge region)**
- **The effect of applied bias on the band bending**
- **Electrostatic parameters**
  - **Poisson equation**
- **This analysis will be the basis of most of electronic devices.**

PN junction
Diode I-V Characteristics



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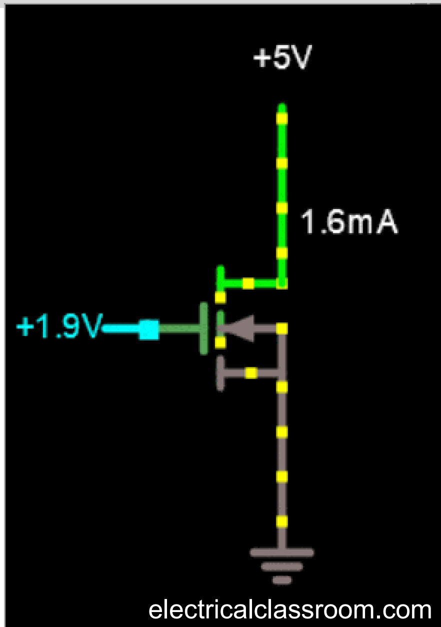
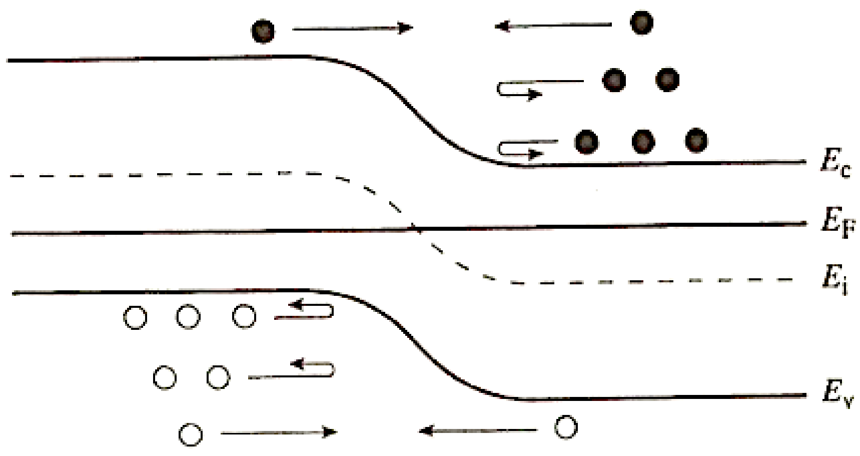


Overview

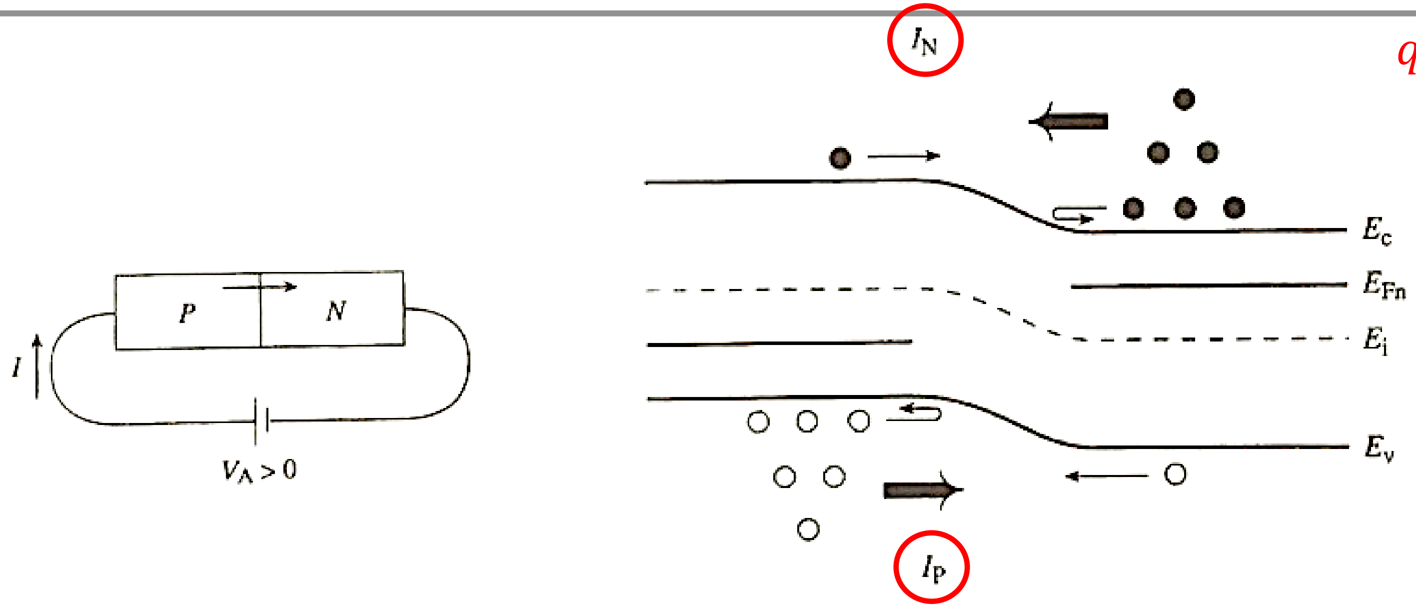
- **Steady-state response modeling of the *pn* junction diode**
- **Ideal diode**
  - **Qualitative analysis**
  - **Quantitative analysis**
- **Non-ideal diode characteristics**

Qualitative Derivation



- **Under equilibrium ($V_A = 0$)**
  - **Balance of drift & diffusion for both e^- and h^+**
  - **Net current?**

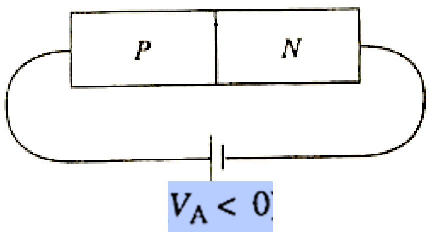
Qualitative Derivation

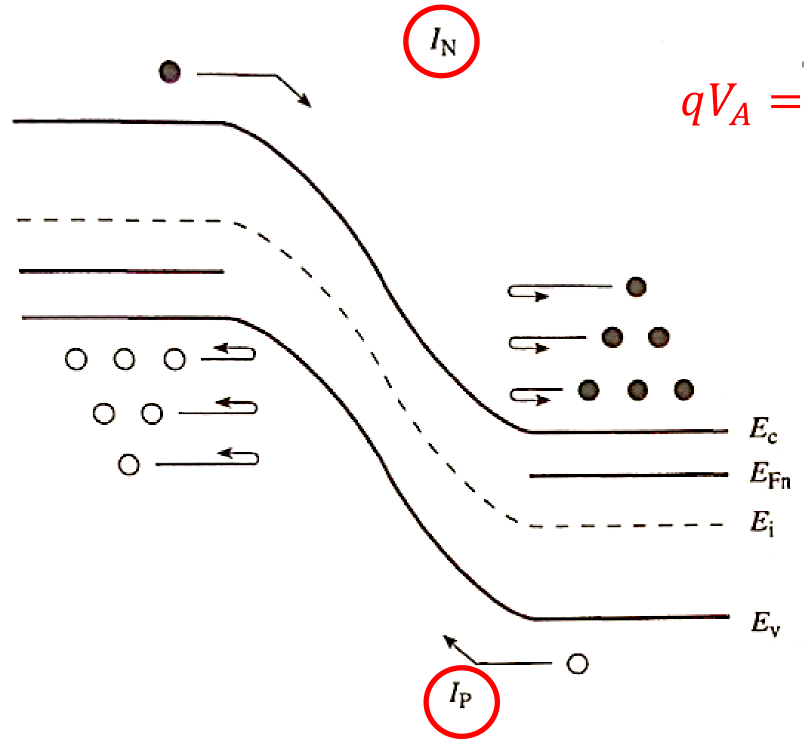


$qV_A = E_{Fn} - E_{Fp}$

- **Forward biased ($V_A > 0$)**
  - **Quasi-Fermi level locations**
  - **Drift vs. Diffusion**
  - **Majority carriers vs. Minority carriers**
  - **Direction of net current for e^- and h^+?**
  - **Net current?**

Qualitative Derivation

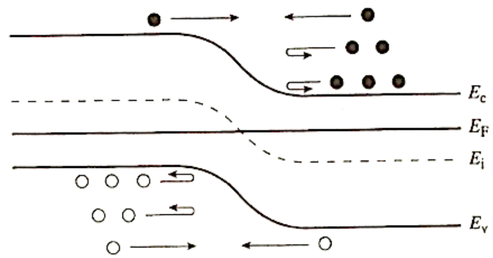


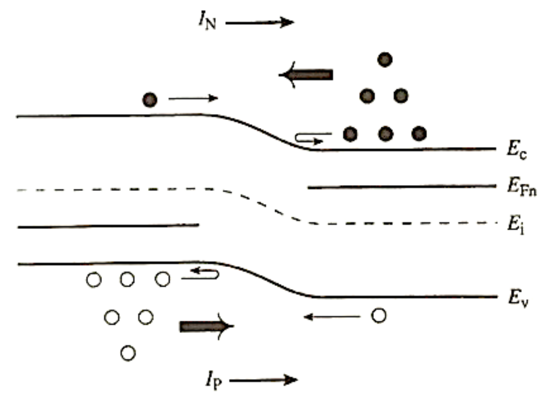


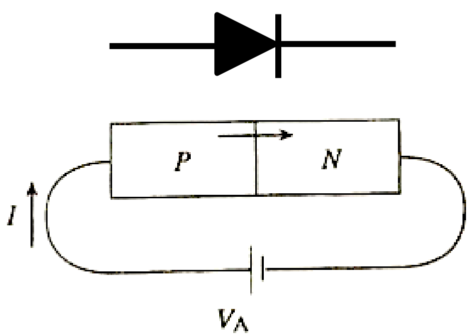
$$qV_A = E_{Fn} - E_{Fp}$$

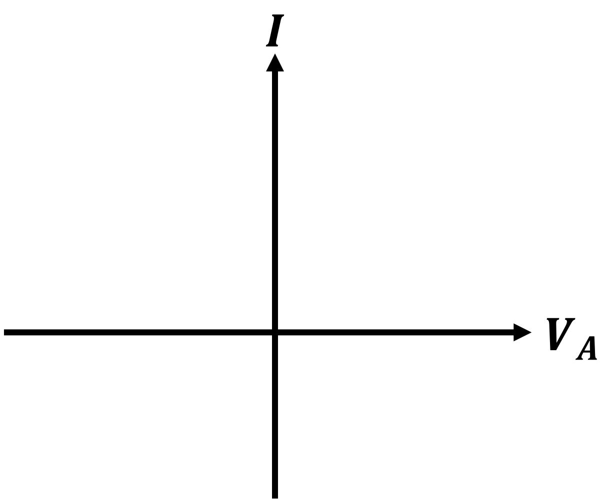
- **Reverse biased ($V_A < 0$)**
  - **Quasi-Fermi level locations**
  - **Drift vs. Diffusion**
  - **Majority carriers vs. Minority carriers**
  - **Direction of net current for e^- and h^+?**
  - **Net current?**

Qualitative Derivation









- **How would diode current (I) changes in response to applied bias (V_A)?**

Qualitative Derivation

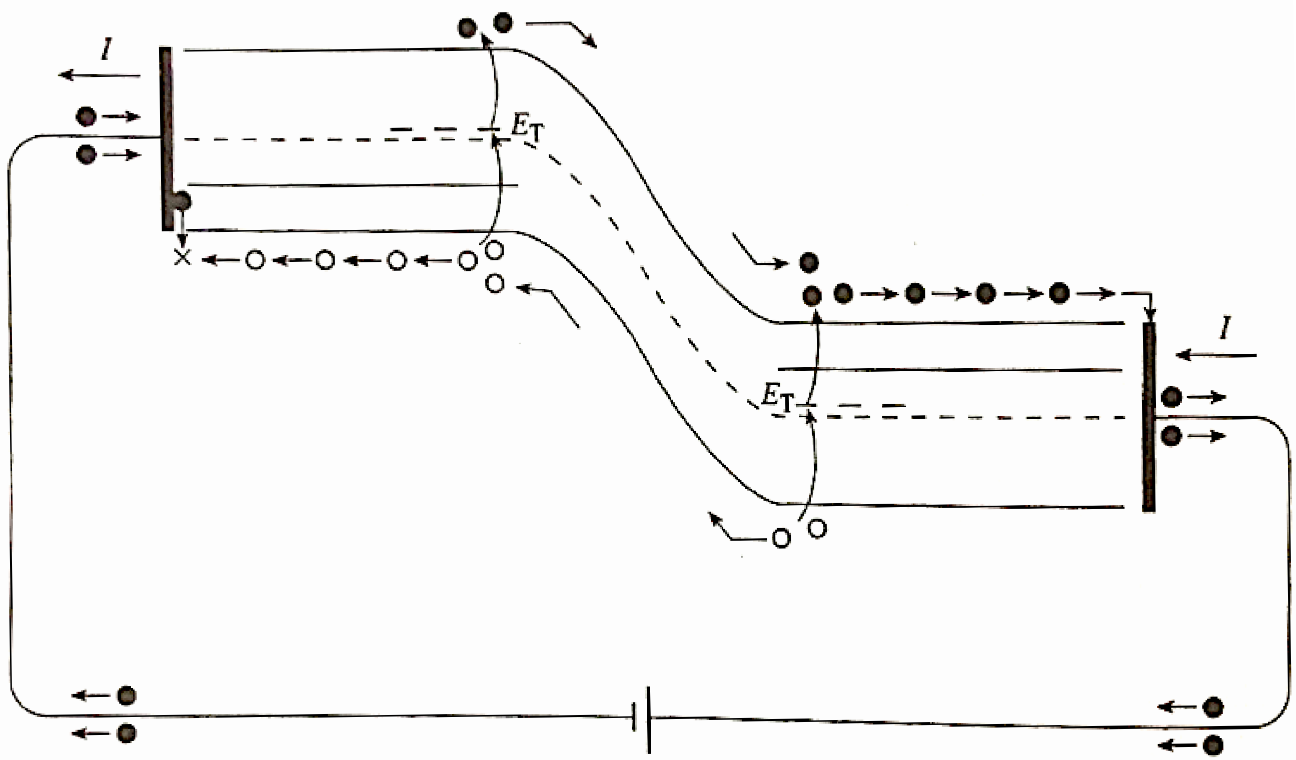


Figure 6.2 Composite energy-band/circuit diagram providing an overall view of carrier activity inside a reverse-biased *pn* junction diode. The capacitor-like plates at the outer ends of the energy band diagram schematically represent the ohmic contacts to the diode.

- **Beyond the depletion region**
- **R–G in Quasi-Neutral regions**