VE 320 Summer 2019

Introduction to Semiconductor Devices

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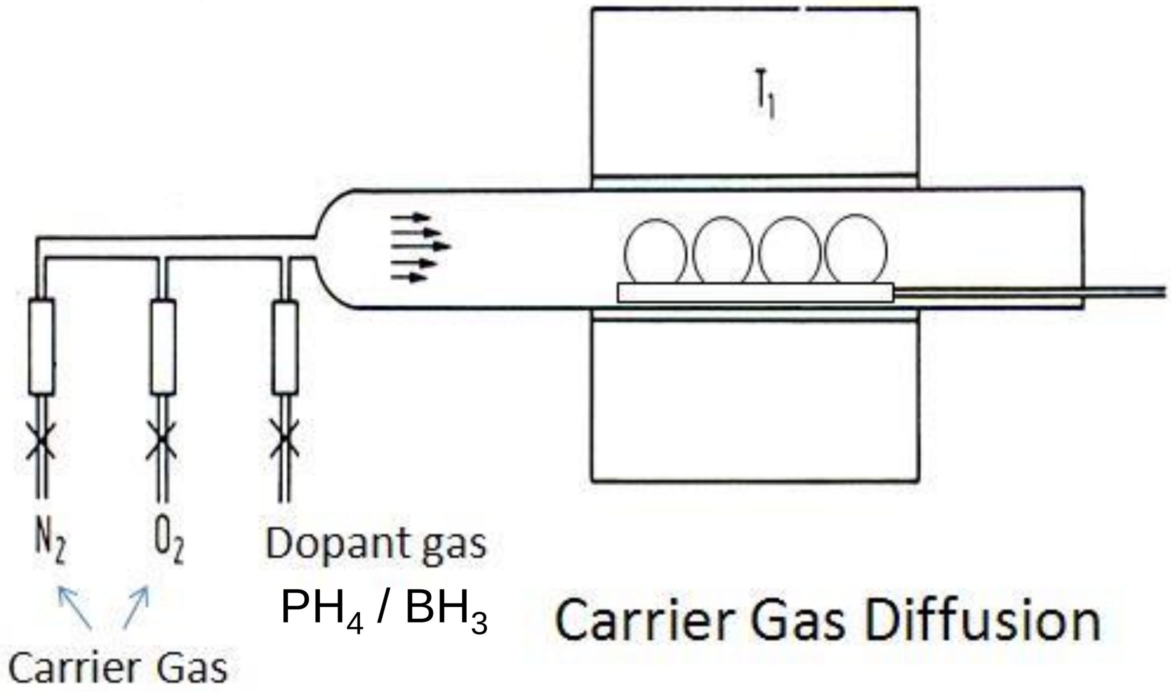
Lecture 7

pn Junction
(Chapter 7)

PN junction formation

- Doping by Thermal Diffusion

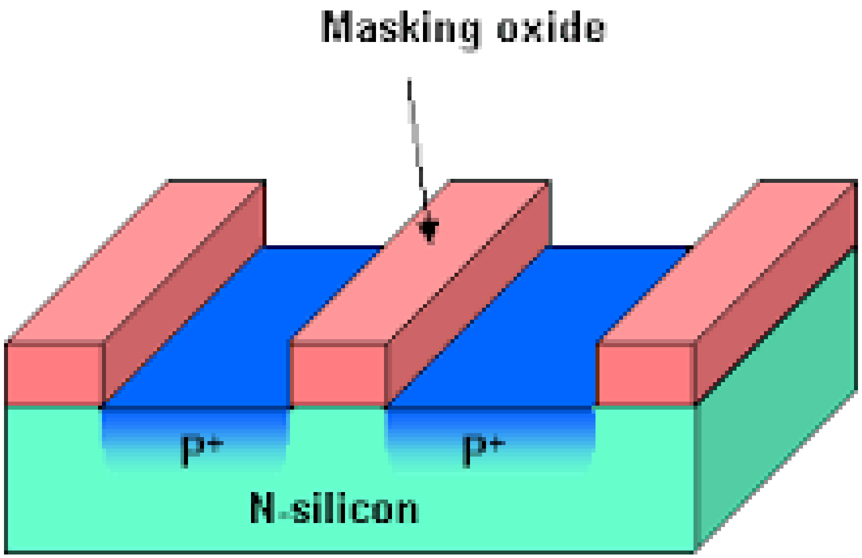


PN junction formation

- Doping by Thermal Diffusion

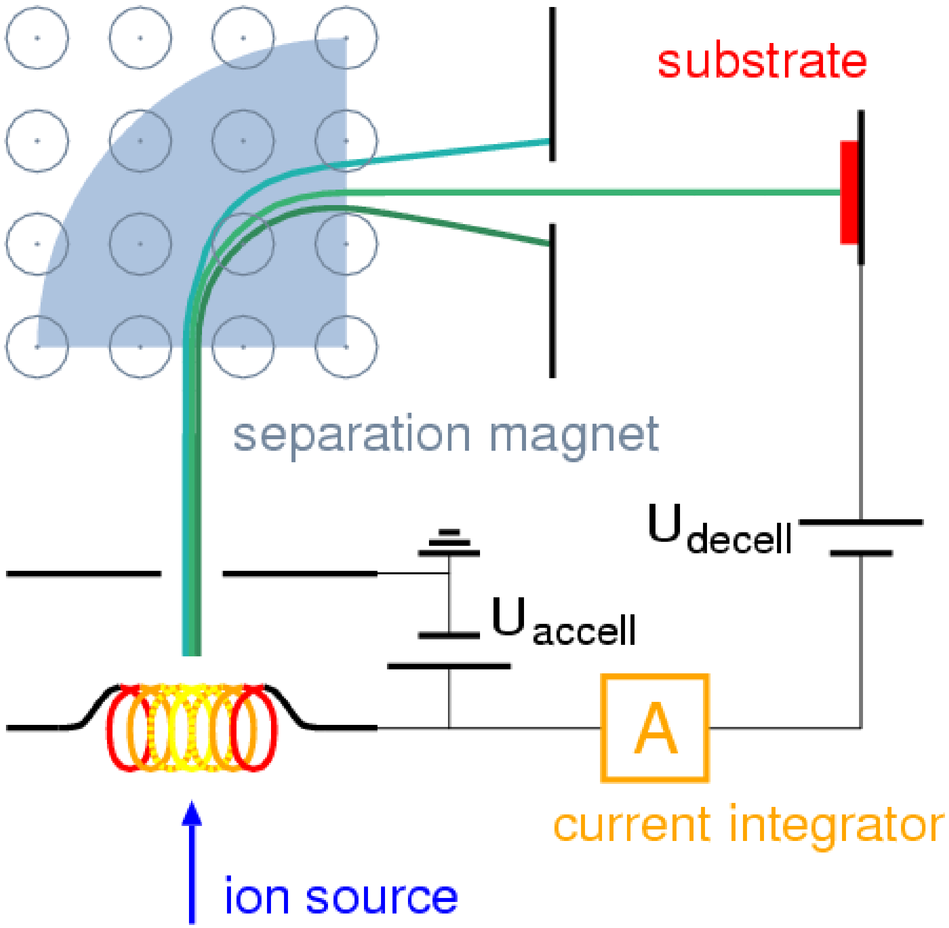
PN junction formation

- Doping by Thermal Diffusion



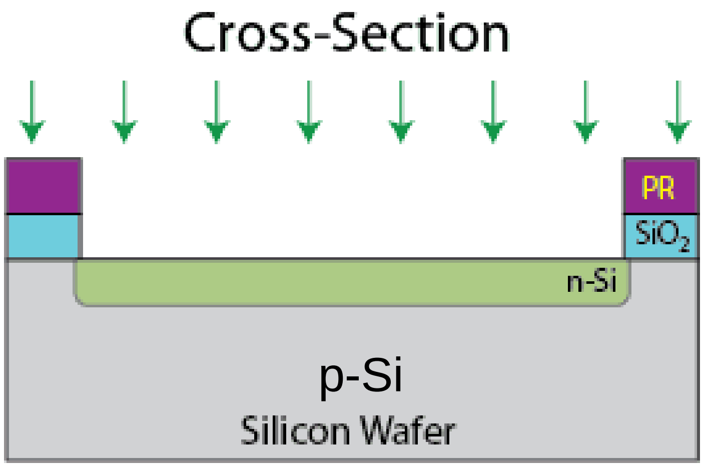
PN junction formation

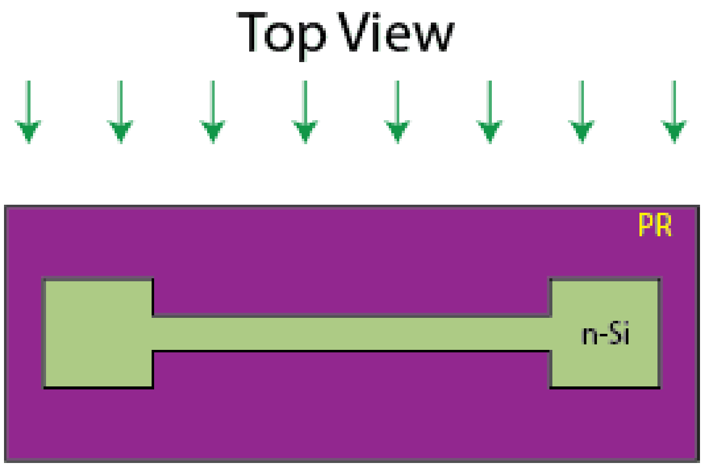
- Doping by Ion Implantation



PN junction formation

- Doping by Ion Implantation

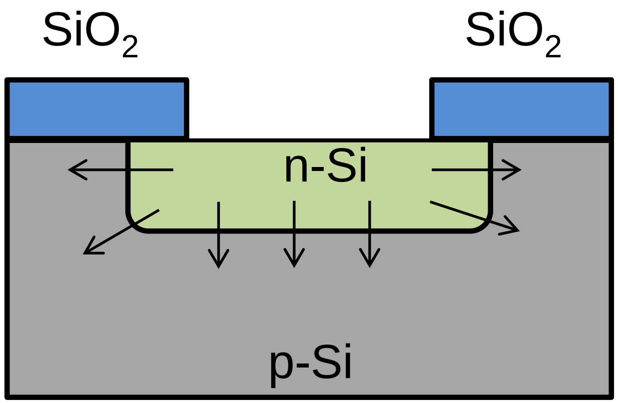




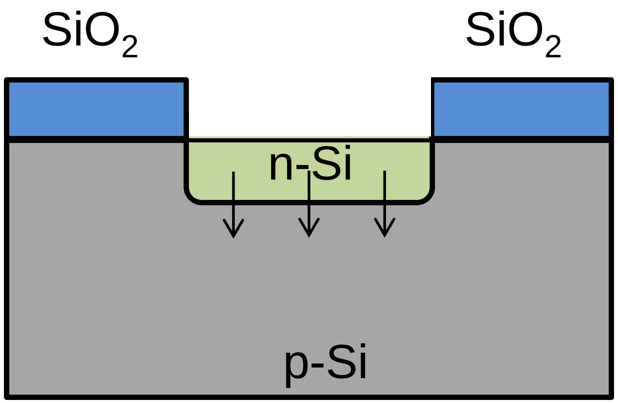
Followed by rapid thermal annealing:
- chemically activate dopants
- not cause physical diffusion

PN junction formation

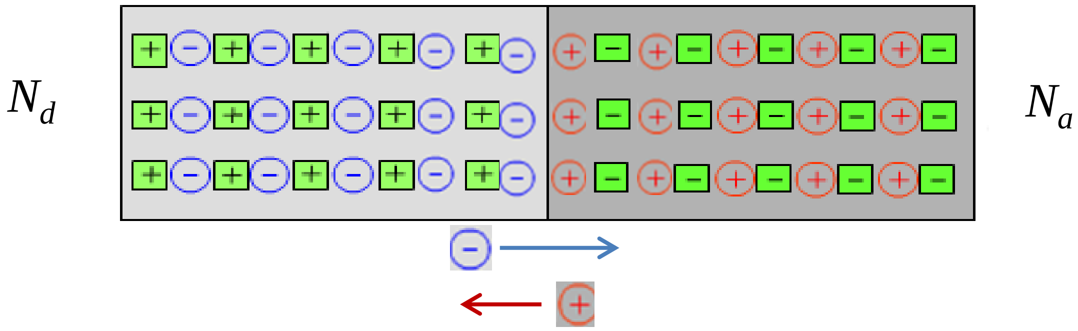
- Doping by Thermal Diffusion



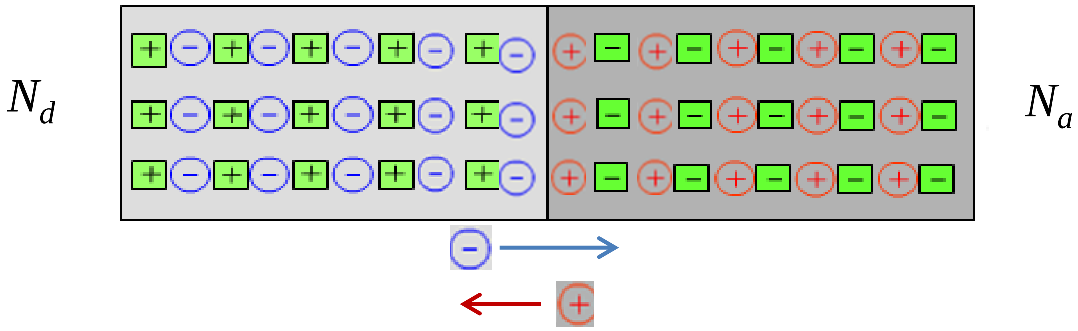
- Doping by Ion Implantation

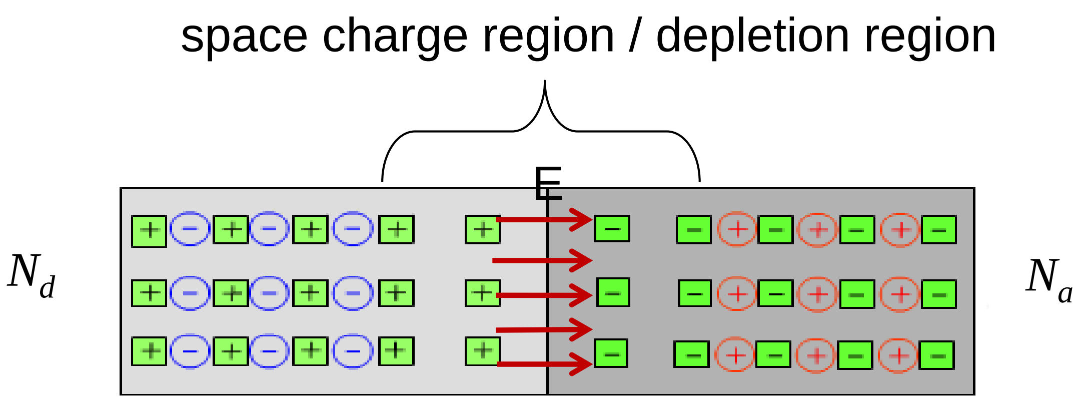


PN junction electrostatics

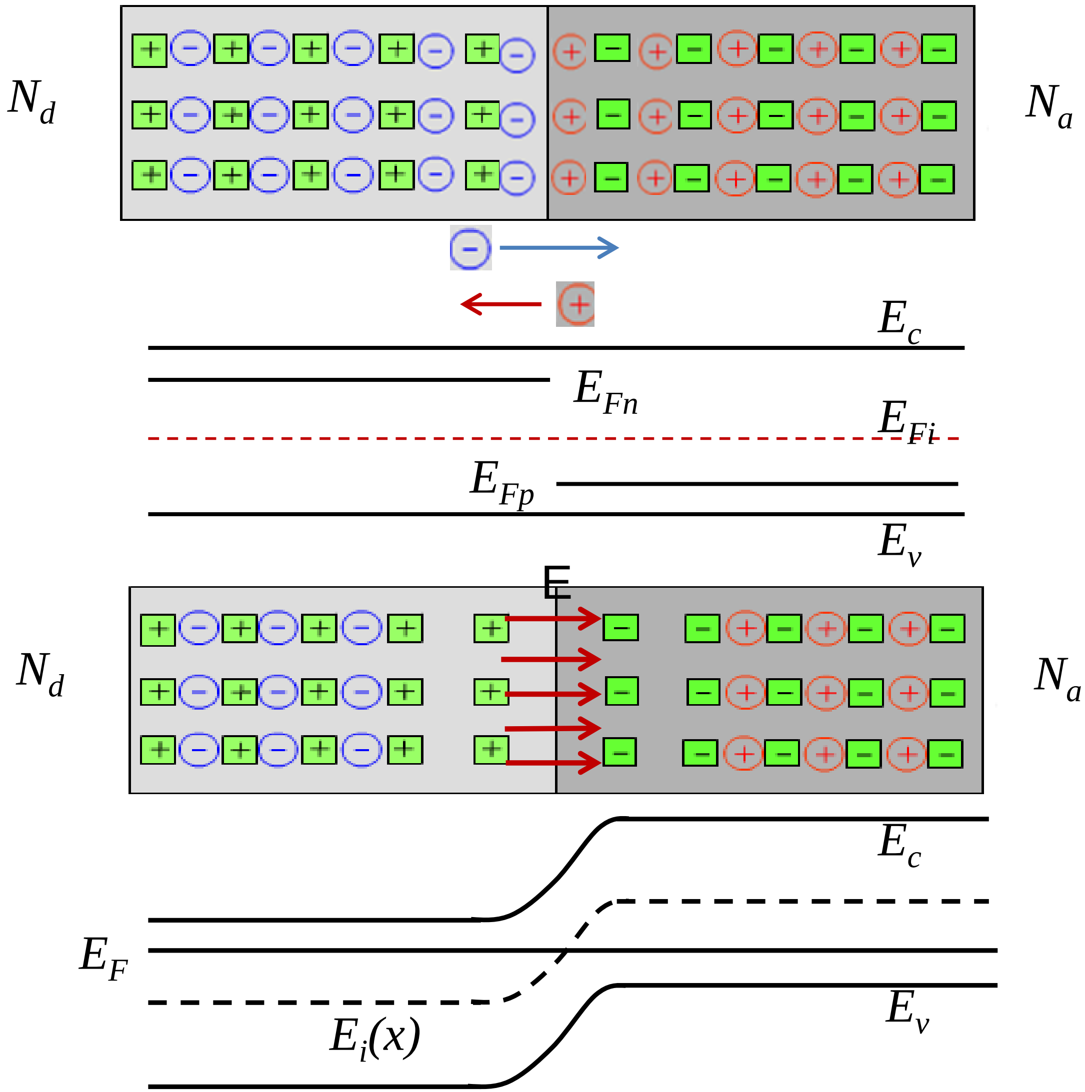


PN junction electrostatics





PN junction electrostatics



PN junction electrostatics

- Built-in Potential

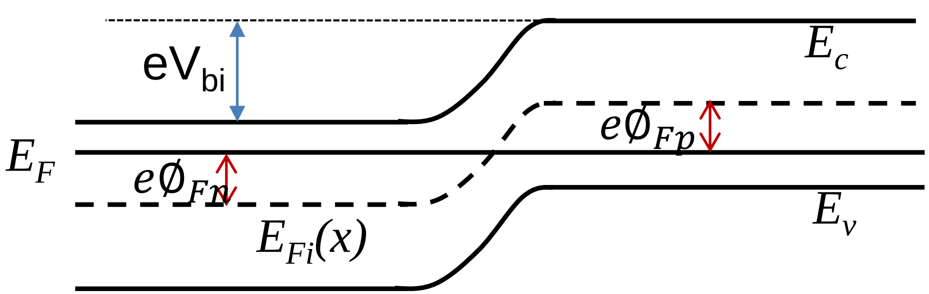
Assume complete ionization

$$n_0 = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right) = n_i \exp\left(\frac{e\emptyset_{Fn}}{kT}\right) \longrightarrow \phi_{Fn} = \frac{-kT}{e}\ln\left(\frac{N_d}{n_i}\right)$$

$$p_0 = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right) = n_i \exp\left(\frac{e\emptyset_{Fp}}{kT}\right) \longrightarrow \phi_{Fp} = +\frac{kT}{e}\ln\left(\frac{N_a}{n_i}\right)$$

$$\Rightarrow V_{bi} = |\emptyset_{Fn}| + |\emptyset_{Fp}| = kTln\left(\frac{N_a}{n_i}\right) + kTln\left(\frac{N_d}{n_i}\right) = kTln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$Example:\ N_a = 10^{17}cm^{-3}, N_d = 10^{17}cm^{-3}, \Rightarrow\ V_{bi} = 0.026 * \ln\left(\frac{10^{17}10^{17}}{10^{20}}\right) = 0.84eV$$

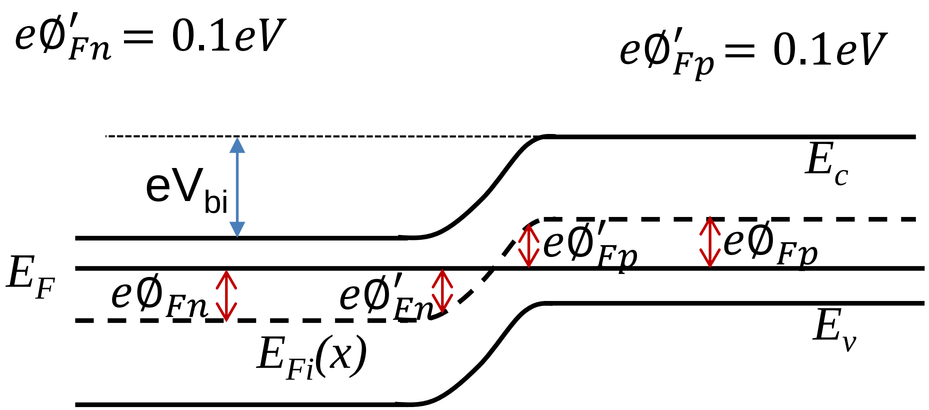


PN junction electrostatics

- Charge carrier distribution

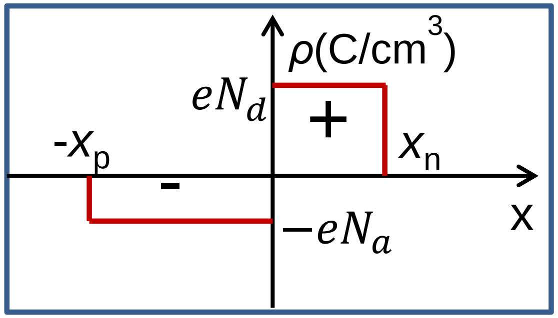
$$n = n_i \exp\left(\frac{E_F - E_{Fi}(x)}{kT}\right) = N_d exp\left(\frac{0.1eV}{0.026eV}\right) \approx \frac{N_d}{50}$$

$$p = n_i \exp\left(\frac{E_{Fi}(x) - E_F}{kT}\right) = N_a exp\left(\frac{0.1eV}{0.026eV}\right) \approx \frac{N_a}{50}$$



PN junction electrostatics

- Potential function: Poisson's equation



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

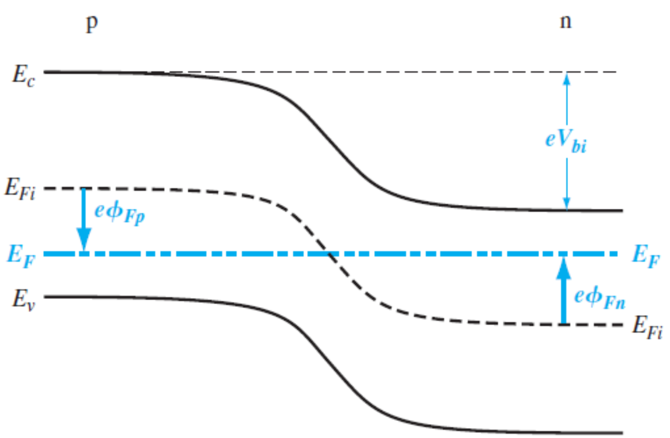
$\rho(x)$: volume charge density

$$= -\frac{e}{\varepsilon}[N_d\ (x) - N_a\ (x) + p(x) - n(x)]$$

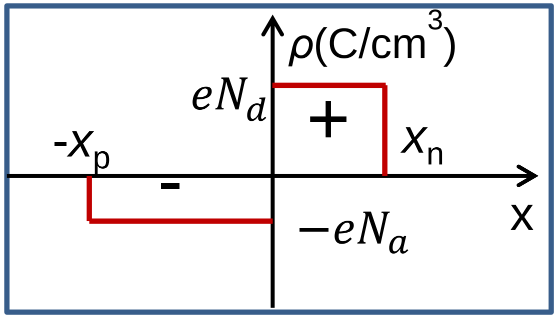
Depletion region: no mobile charge $n=p=0$

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

$$\rho(x) = eN_d \qquad 0 < x < x_n$$



PN junction electrostatics



- Potential function: Poisson's equation

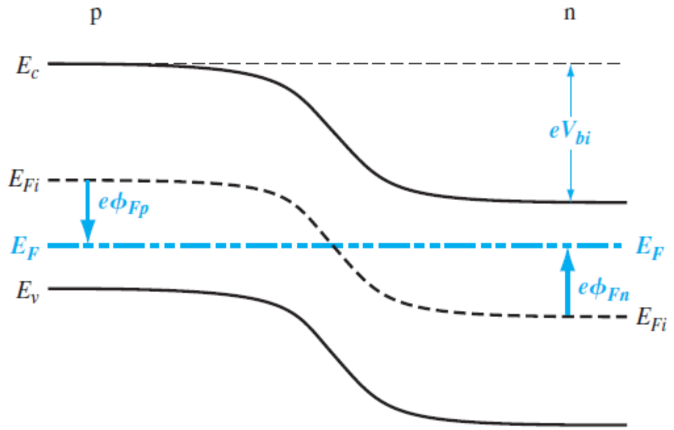
$$\frac{d^2\emptyset(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon} = -\frac{dE(x)}{dx}$$

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

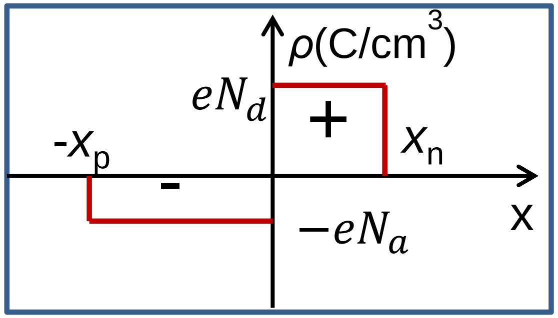
Electric field in the p region (in the depletion region): integration

$$\mathrm{E} = \int \frac{\rho(x)}{\epsilon_s}\,dx = -\int \frac{eN_a}{\epsilon_s}\,dx = \frac{-eN_a}{\epsilon_s}x + C_1$$

$\mathrm{E} = 0$ at $x = -x_p$ So $\mathrm{E} = \dfrac{-eN_a}{\epsilon_s}(x + x_p) \qquad -x_p \le x \le 0$



PN junction electrostatics



- Potential function: Poisson's equation

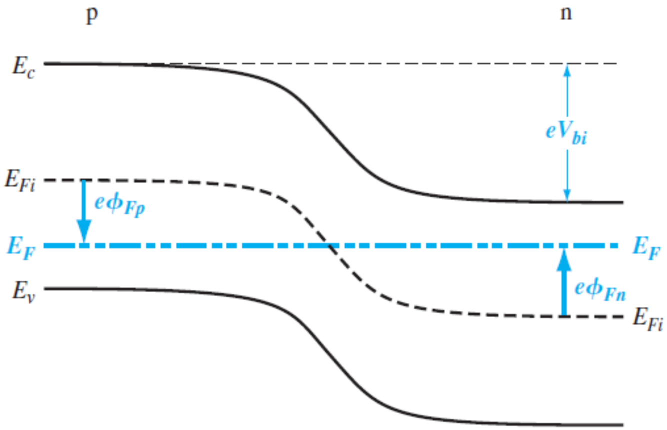
$$\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon} = -\frac{dE(x)}{dx}$$

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

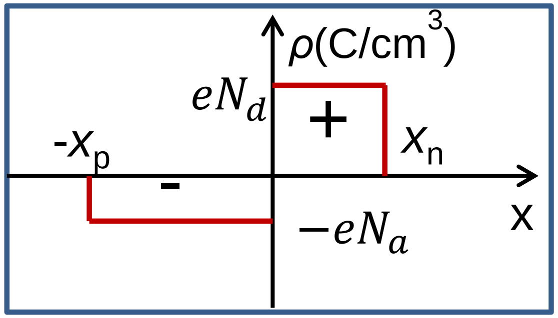
Electric field in the n region: integration

$$\mathrm{E} = \int \frac{(eN_d)}{\epsilon_s}\,dx = \frac{eN_d}{\epsilon_s}x + C_2$$

$\mathrm{E} = 0$ at $x = x_n$ So $\mathrm{E} = \dfrac{-eN_d}{\epsilon_s}(x_n - x) \qquad 0 \le x \le x_n$



PN junction electrostatics



- Potential function: Poisson's equation

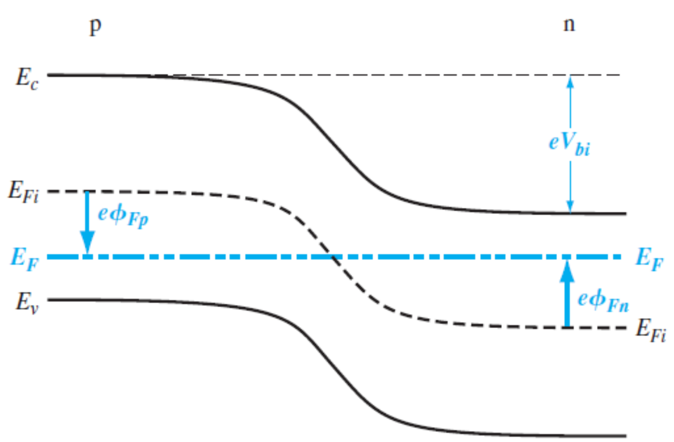
$$\frac{d^2\emptyset(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon} = -\frac{dE(x)}{dx}$$

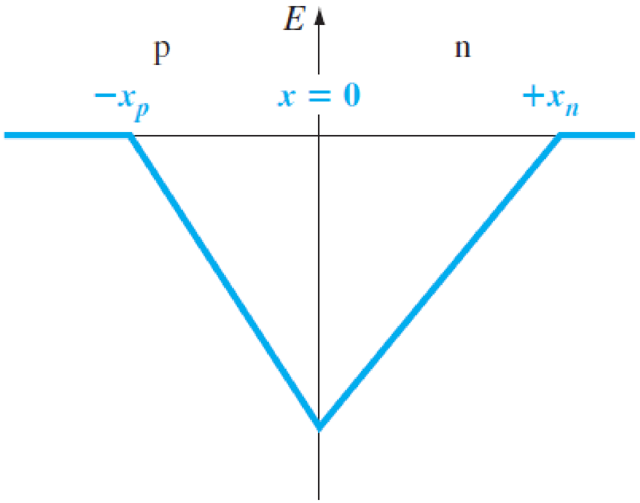
$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

Electric field at x=0: continuous

$$N_a x_p = N_d x_n$$

the number of negative charges per unit area in the p region is equal to the number of positive charges per unit area in the n region





PN junction electrostatics

Potential: integrate electric field

In the p region (in the depletion region)

$$\phi(x) = -\int \mathrm{E}(x)dx = \int \frac{eN_a}{\epsilon_s}(x + x_p)dx$$

$$\phi(x) = \frac{eN_a}{\epsilon_s}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_1'$$

Only potential difference is important, so set potential=0 at $x=x_p$

$$C_1' = \frac{eN_a}{2\epsilon_s}x_p^2$$

$$\phi(x) = \frac{eN_a}{2\epsilon_s}(x + x_p)^2 \qquad (-x_p \le x \le 0)$$

In the n region

$$\phi(x) = \int \frac{eN_d}{\epsilon_s}(x_n - x)dx = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + C_2'$$

Potential is continuous at $x=0$

$$C_2' = \frac{eN_a}{2\epsilon_s}x_p^2$$

$$\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + \frac{eN_a}{2\epsilon_s}x_p^2 \qquad (0 \le x \le x_n)$$

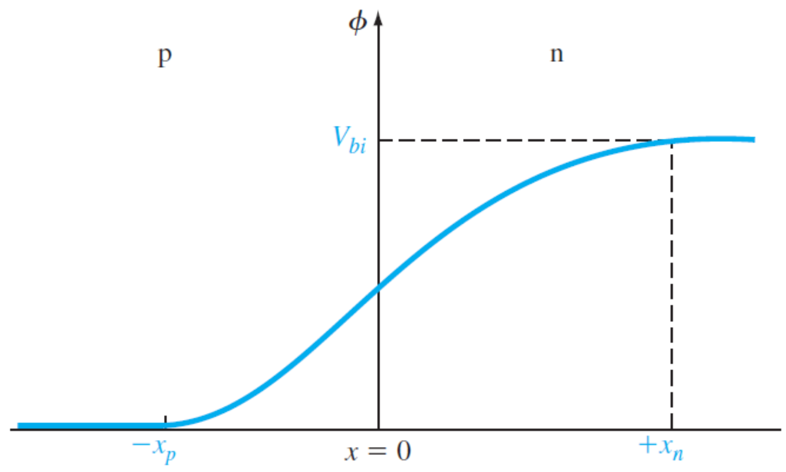
PN junction electrostatics

Potential: quadratic function of distance

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

Potential energy

$$E = -e\phi$$



PN junction electrostatics

Preciously we have $N_a x_p = N_d x_n$ → $x_p = \frac{N_d x_n}{N_a}$

From $V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$

We have
$$x_n = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

Space charge width, or the width of the depletion region, extending into the n-type region for the case of zero applied voltage

$$x_p = \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_d}{N_a}\right]\left[\frac{1}{N_a + N_d}\right]\right\}^{1/2}$$

In the p-type region

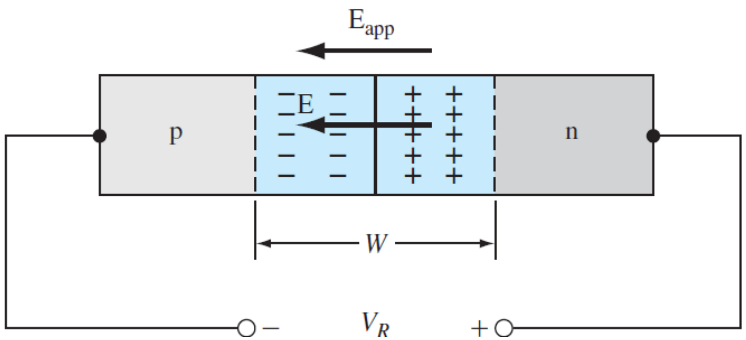
Total depletion or space charge width

$$W = x_n + x_p$$

$$= \left\{\frac{2\epsilon_s V_{bi}}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

PN junction electrostatics

- Reverse applied bias: Fermi energy no longer constant

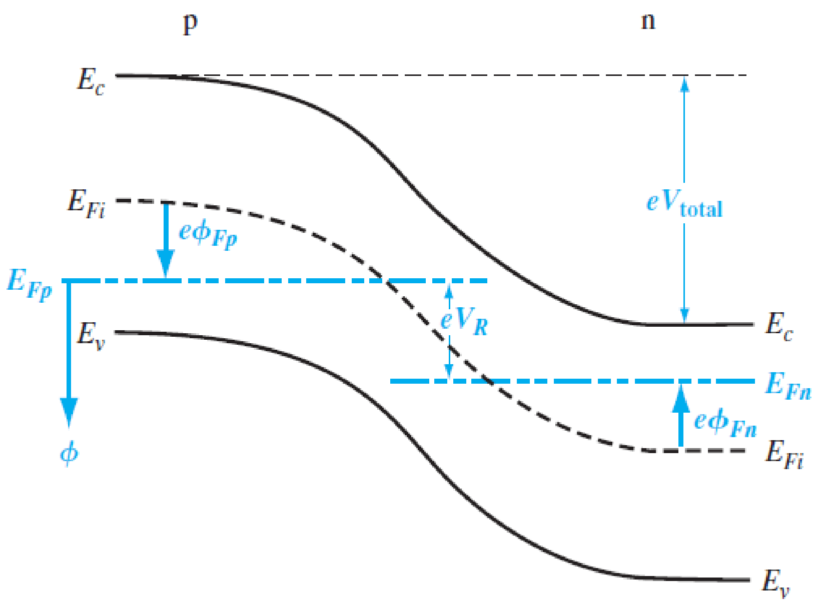


$$V_{\text{total}} = |\phi_{Fn}| + |\phi_{Fp}| + V_R$$
$$= V_{bi} + V_R$$

No longer thermal equilibrium

PN junction electrostatics

- <u>Reverse applied bias: Fermi energy no longer constant</u>



Space charge region: electric field increase
impurity concentration not changed → Space charge width *W* increases

$$W = \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$

PN junction electrostatics

- Reversed applied bias: Fermi energy no longer constant

Electric field:

$$\mathrm{E} = \frac{-eN_a}{\epsilon_s}(x + x_p) \qquad -x_p \leq x \leq 0$$

$$\mathrm{E} = \frac{-eN_d}{\epsilon_s}(x_n - x) \qquad 0 \leq x \leq x_n$$

Maximum electric field: x=0, metallurgical junction

$$\mathrm{E}_{\max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-eN_a x_p}{\epsilon_s}$$

$$\mathrm{E}_{\max} = -\left\{\frac{2e(V_{bi} + V_R)}{\epsilon_s}\left(\frac{N_a N_d}{N_a + N_d}\right)\right\}^{1/2}$$

$$W = \left\{\frac{2\epsilon_s(V_{bi} + V_R)}{e}\left[\frac{N_a + N_d}{N_a N_d}\right]\right\}^{1/2}$$

$$\mathrm{E}_{\max} = \frac{-2(V_{bi} + V_R)}{W}$$

PN junction electrostatics

- Junction capacitance

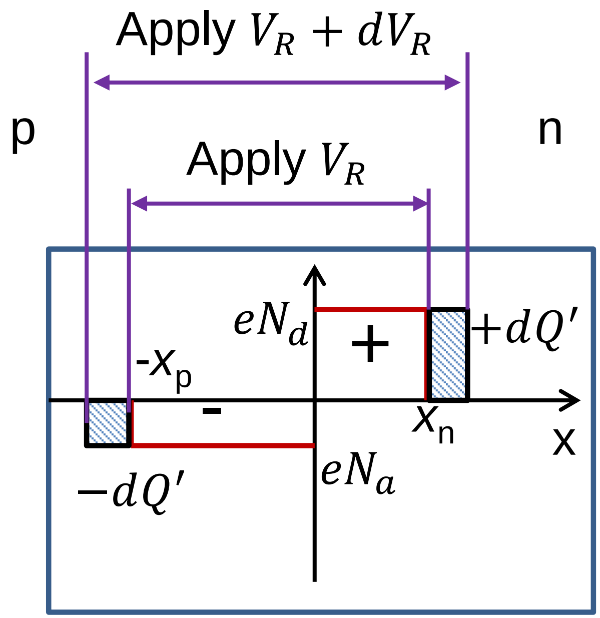
$$C' = \frac{dQ'}{dV_R}$$

$$dQ' = eN_d\,dx_n = eN_a\,dx_p$$

$$x_n = \left\{\frac{2\epsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{1/2}$$

$$C' = \frac{dQ'}{dV_R} = eN_d\frac{dx_n}{dV_R}$$

$$C' = \left\{\frac{e\epsilon_s N_a N_d}{2(V_{bi}+V_R)(N_a+N_d)}\right\}^{1/2}$$



Depletion layer capacitance

pn Junction with reverse bias

- One-sided junction:

If $N_a >> N_d$, the junction is a p$^+$n junction

$$W \approx \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{eN_d} \right\}^{1/2}$$

$$x_p \ll x_n \qquad W \approx x_n$$

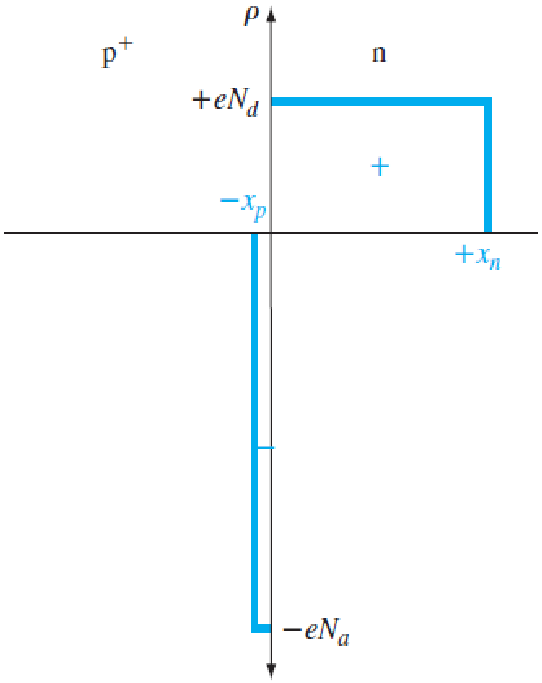
Almost the entire space charge layer extends into the low-doped region of the junction.

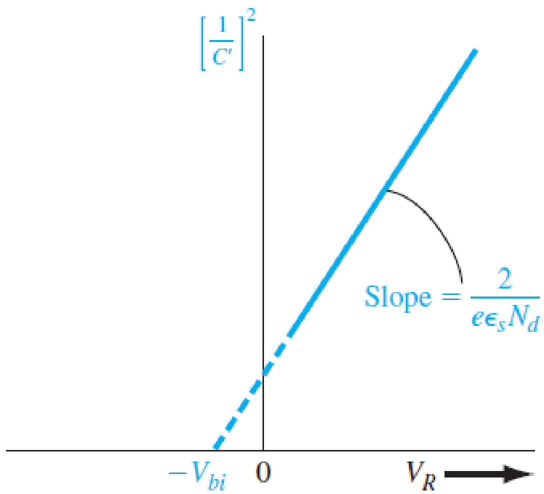
$$C' \approx \left\{ \frac{e\epsilon_s N_d}{2(V_{bi} + V_R)} \right\}^{1/2}$$

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

Assume: uniform doping in both semiconductor regions, the abrupt junction approximation, and a planar junction.

V_{bi} and N_d can be determined





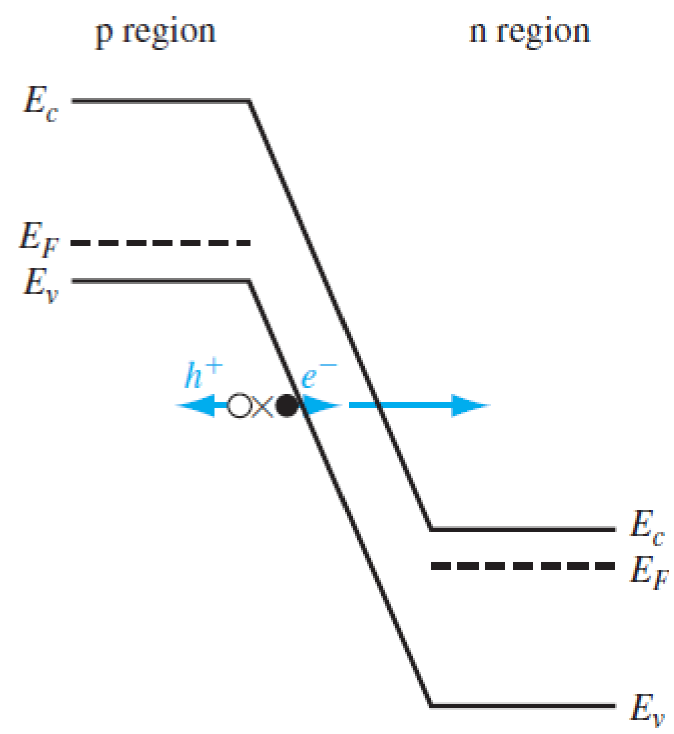
pn Junction breakdown

- Reverse bias: breakdown at large voltage

Zener effect and the avalanche effect

Zener breakdown: tunneling mechanism.

- In highly doped pn junctions
- Conduction and valence bands on opposite sides of the junction are sufficiently close during reverse bias
- Electrons may “tunnel” directly from the valence band on the p side into the conduction band on the n side.



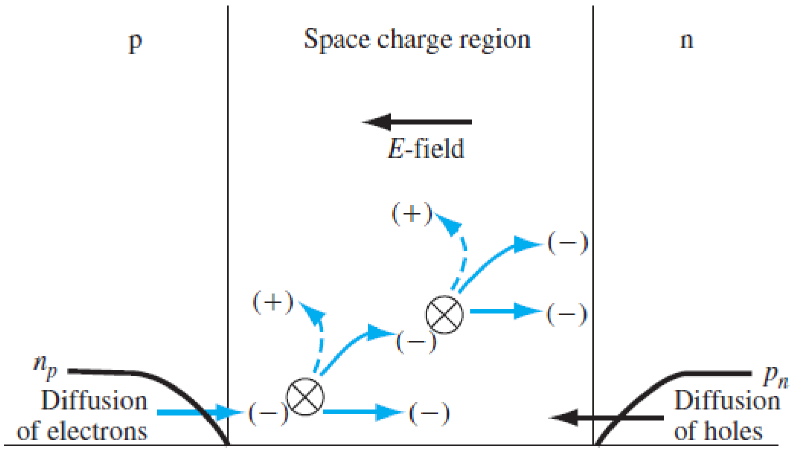
pn Junction breakdown

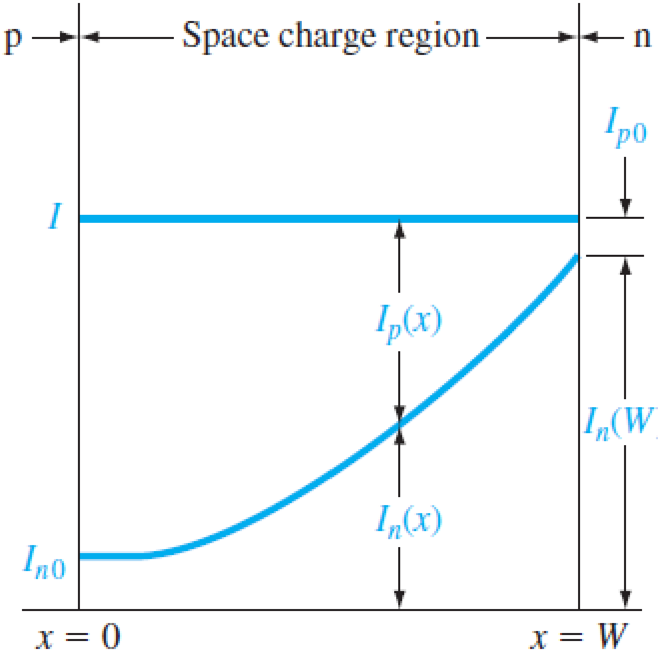
- Reverse bias: breakdown at large voltage

Zener effect and the avalanche effect

Avalanche breakdown: collision, dominant mechanism

- Electrons and/or holes, moving across the space charge region, acquire sufficient energy from the electric field to create New electron–hole pairs by colliding with atomic electrons within the depletion region
- Electrons and holes move in opposite directions due to the electric field and thereby create a reverse-biased current
- Avalanche: the newly generated electrons and/or holes may acquire sufficient energy to ionize other atoms-> more and more





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- Reverse bias: breakdown at large voltage

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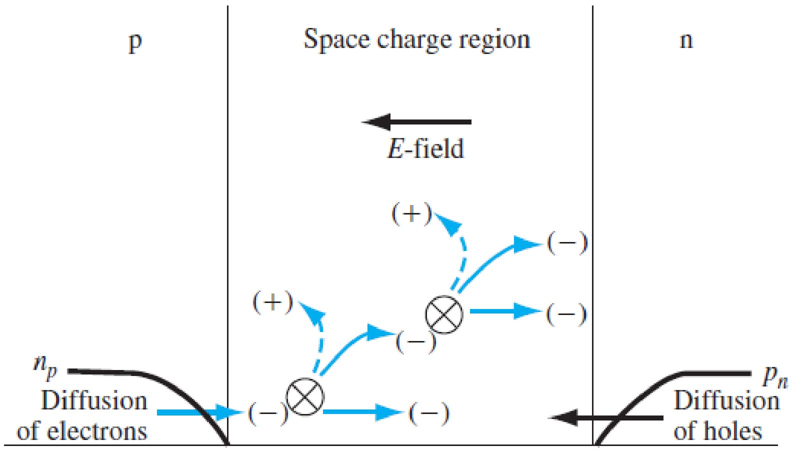
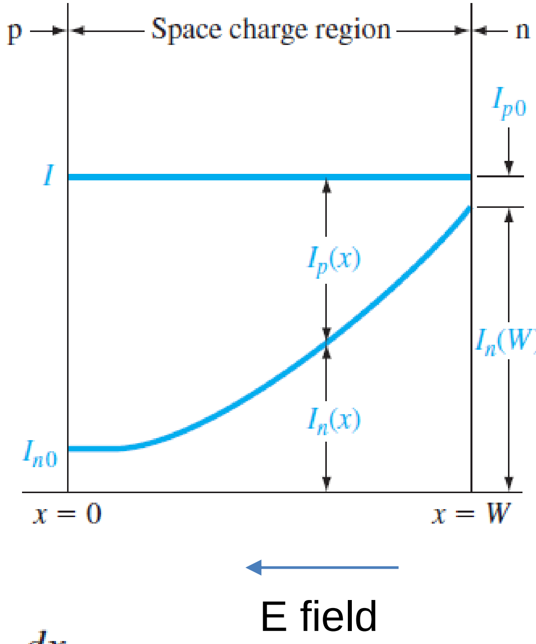
Avalanche breakdown: collision, dominant mechanism



pn Junction breakdown



Avalanche breakdown:
Reverse-biased electron current I_{n0} enters the depletion region at x = 0,
At x=W, $$I_n(W) = M_n I_{n0}$$

where M_n is a multiplication factor
Hole current: large at x=0
Total current: constant through the pn junction
Incremental electron current $dI_n(x) = I_n(x)\alpha_n\, dx + I_p(x)\alpha_p\, dx$
α_n and α_p are the ionization rates, or the number of electron-hole pairs generated per unit length
Total current is a constant $I = I_n(x) + I_p(x)$

$$\frac{dI_n(x)}{dx} + (\alpha_p - \alpha_n)I_n(x) = \alpha_p I$$

Assume electron and hole ionization rates are equal $\alpha_n = \alpha_p \equiv \alpha$

Integrate: $$I_n(W) - I_n(0) = I \int_0^W \alpha\, dx$$

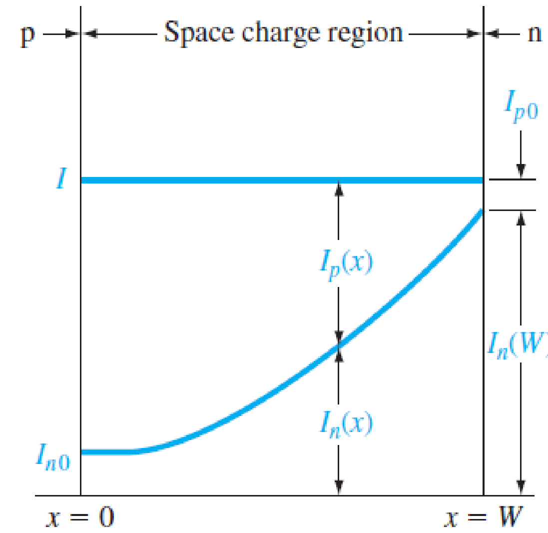
pn Junction breakdown

Avalanche breakdown:

$$\frac{M_n I_{n0} - I_n(0)}{I} = \int_0^W \alpha\, dx$$

Since $M_n I_{n0} \approx I$ and since $I_n(0) = I_{n0}$

$$1 - \frac{1}{M_n} = \int_0^W \alpha\, dx$$



Avalanche breakdown: M_n->∞ $\int_0^W \alpha dx = 1$

For one-sided p⁺n junction: $$\mathrm{E}_{max} = \frac{eN_d\, x_n}{\epsilon_s}$$

Depletion width: $$x_n \approx \left\{\frac{2\epsilon_s V_R}{e} \cdot \frac{1}{N_d}\right\}^{1/2}$$

Breakdown voltage: $$V_B = \frac{\epsilon_s \mathrm{E}_{crit}^2}{2eN_B}$$