ECE 111

PN Junction

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Objective

Selected areas covered in this lecture:

- **band diagram**
- **pn-junction**
- **depletion region**
- **depletion width**
- **built-in potential**
- **biased junction**

P-N Junctions - Introduction

Charter member of the family of **all the solid state devices.**

Basic theory of operation of p-n junctions **is essential to the understanding of all the other devices.**

Many of these devices also contain parasitic p-n junctions. It is essential to understand how these parasitic junctions affect the performance of the main device.

What are p-n junctions?

In part I of this course we focused on **semiconductors** which are **either n-type or p-type**. Now we will study the behavior of samples that are doped with different type of impurities in different parts of the sample.

P-N Junction formation technology

There are three main methods of formation of p-n junctions:

- **Diffusion**

  Start with an n-type wafer. Diffuse a p-type impurity at a high temperature. Or start with a p-type wafer and diffuse an n-type impurity. In both cases a p-n junction is formed near the surface of the wafer. Typical junction depths are a few microns.

- **Ion implantation**

  Start with an n-type wafer and shoot ions of a p-type impurity. Ion energies typically 50 - 200 KeV. Alternatively, implant ions of an n-type impurity into a p-type substrate.

- **Epitaxy**

  Start with an n-type wafer. Deposit a thin layer of p-type Si epitaxially (single crystal Si).

The first two techniques are extensively used in Si technology. Epitaxial junctions are more common in GaAs technology.

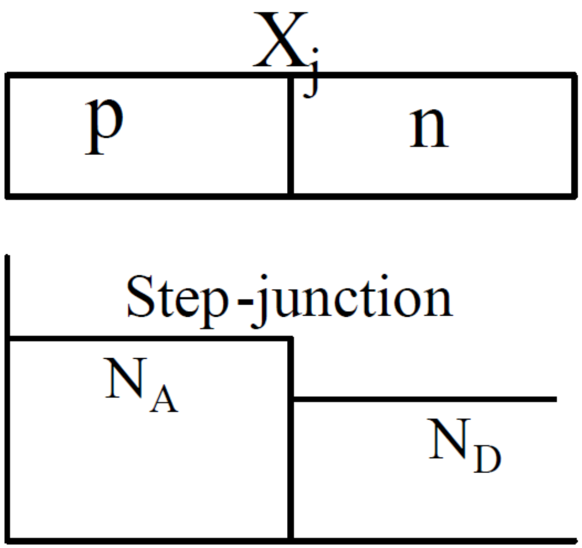
Step junction versus linearly graded junction

Step junction:

If the conductivity type changes **abruptly** at some plane, then the junction is called a **step junction or abrupt junction**. **Epitaxial method** results in abrupt junctions. The plane $x = x_j$ at which the conductivity type changes is called the junction-plane or the metallurgical junction.

$X<X_j$, $N_A > N_D$ (usually N_D on the p-side is very small)

$X> X_j$, $N_D > N_A$ (usually N_A n-side is very small)



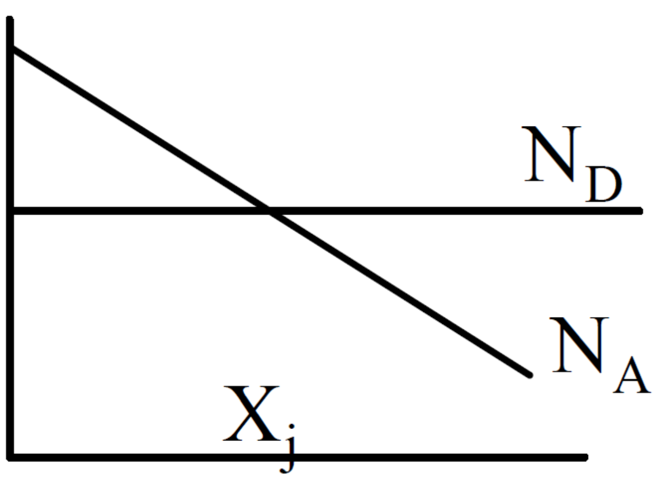
Linearly graded junctions:

Diffused junctions are generally linearly graded junctions. The plane $X=X_j$ at which $N_D = N_A$ is called the junction plane.

» For $x < X_j$, $N_A > N_D$ (p-type)
» For $x > X_j$, $N_D > N_A$ (n-type)
» At $X=X_j$, $n= p= n_i$. Hole concentration ($p= N_A-N_D$)

increases linearly to the left of X_j. Electron ($n= N_D-N_A$) concentration increases linearly to the right of X_j

Linearly graded junction

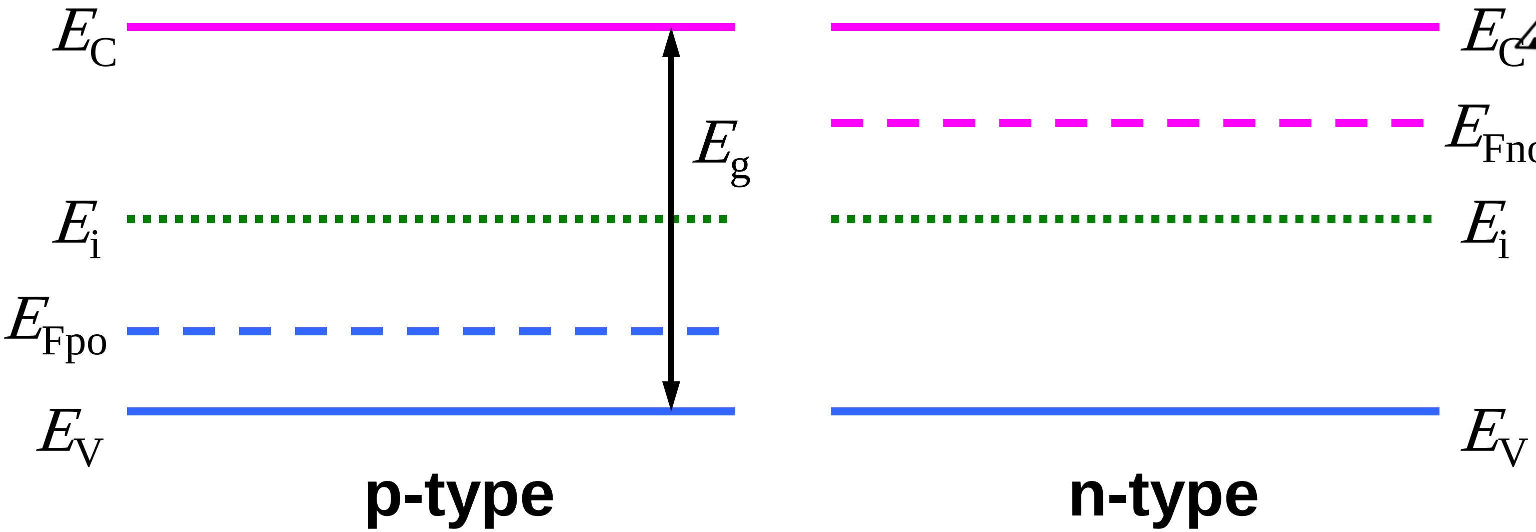


pn-junction in thermal equilibrium

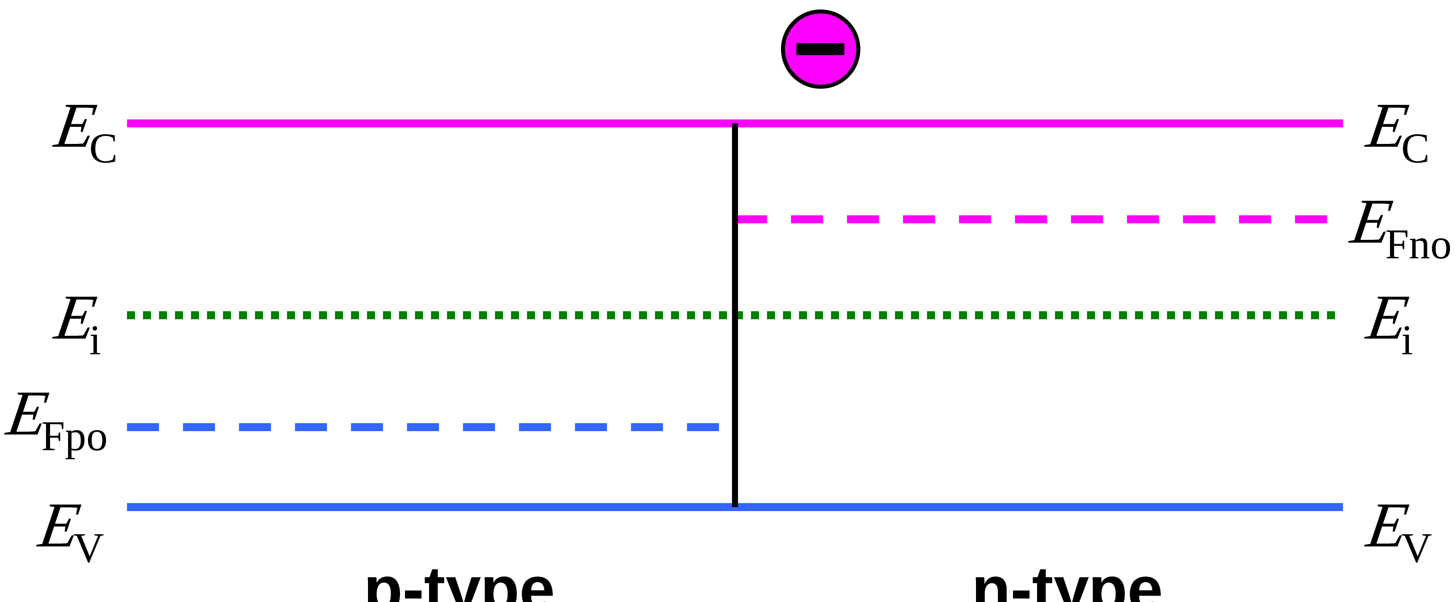
abrupt junction

p-type	n-type
N_A	N_D

before connection



connection

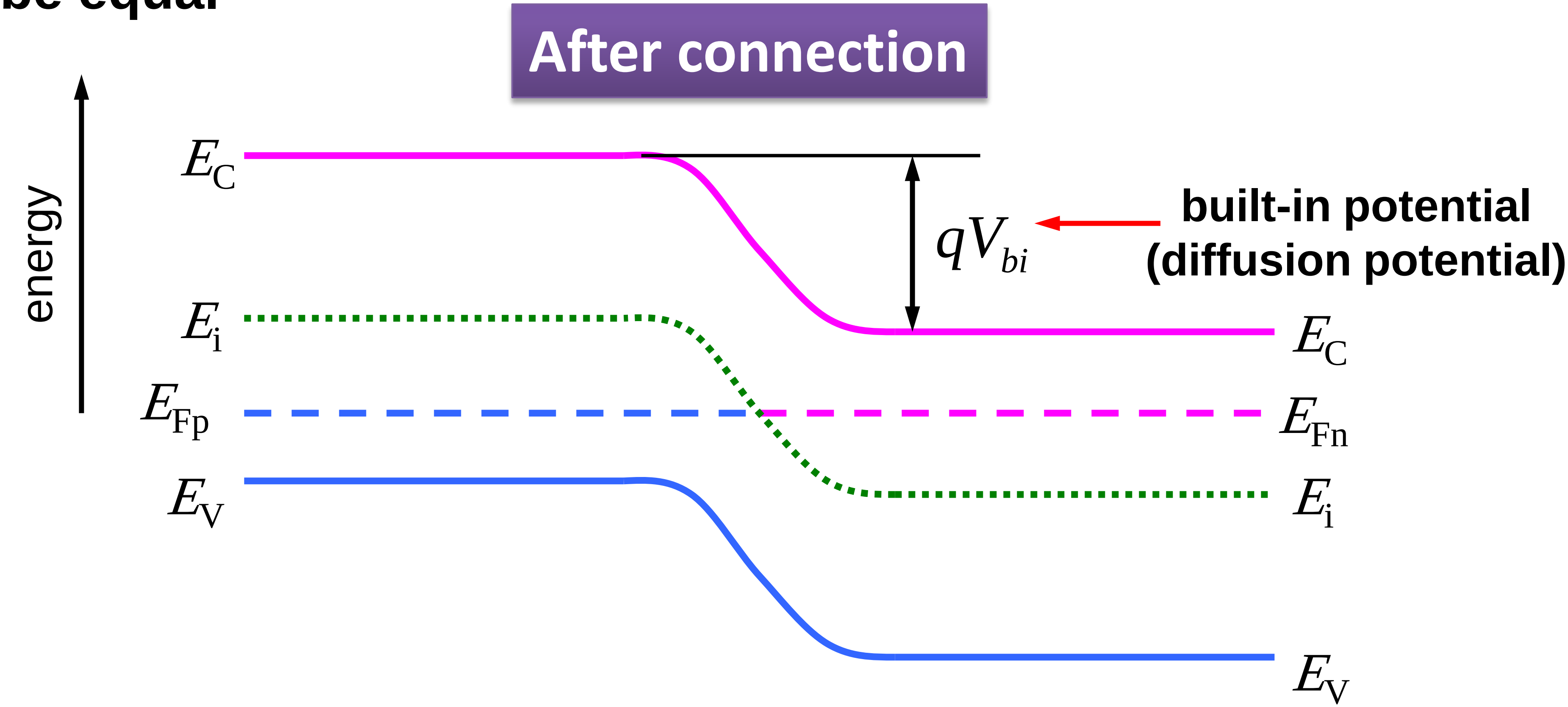


requirement of thermal equilibrium

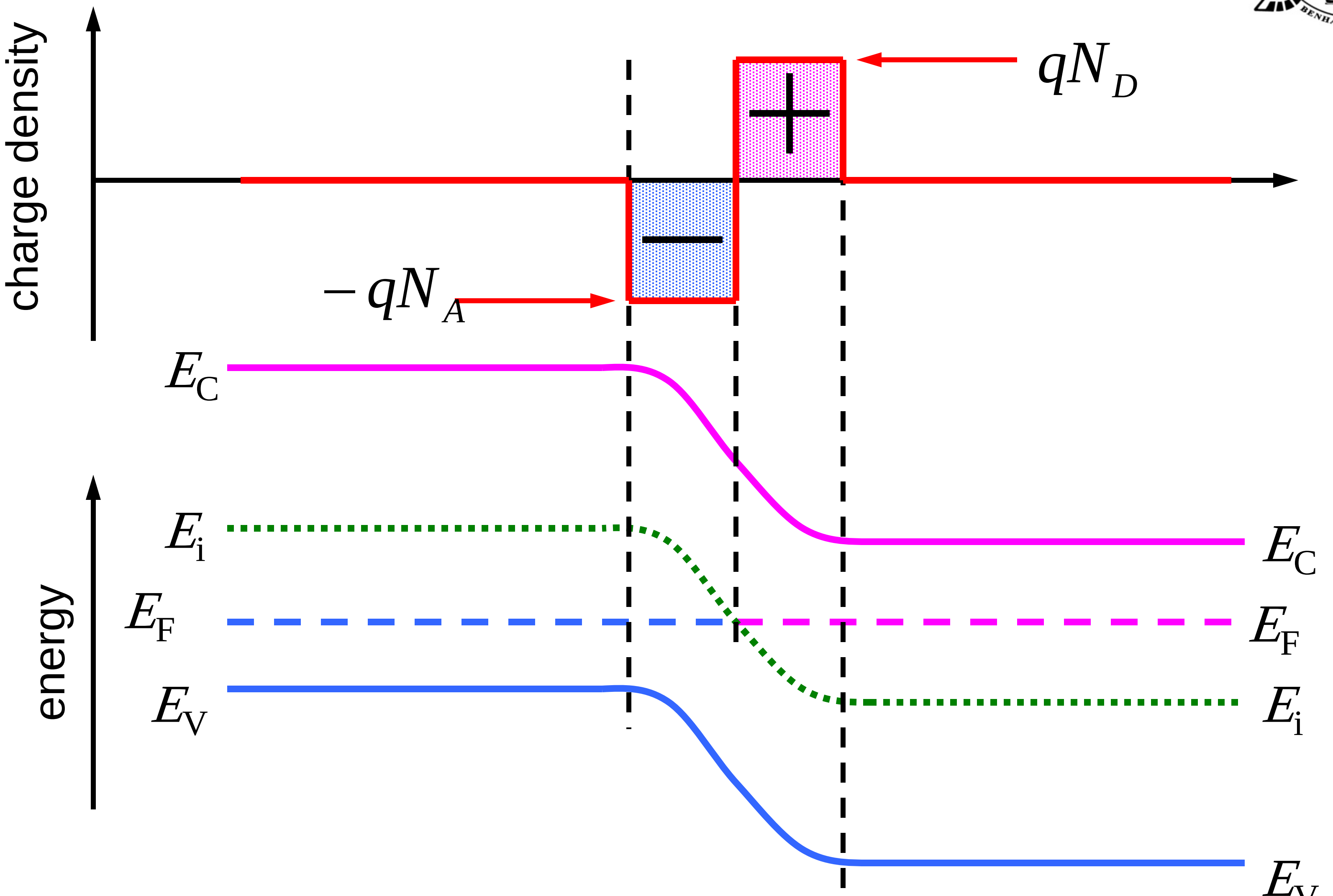
for thermal equilibrium $\boxed{\frac{dE_F}{dx} = 0}$

consequence:

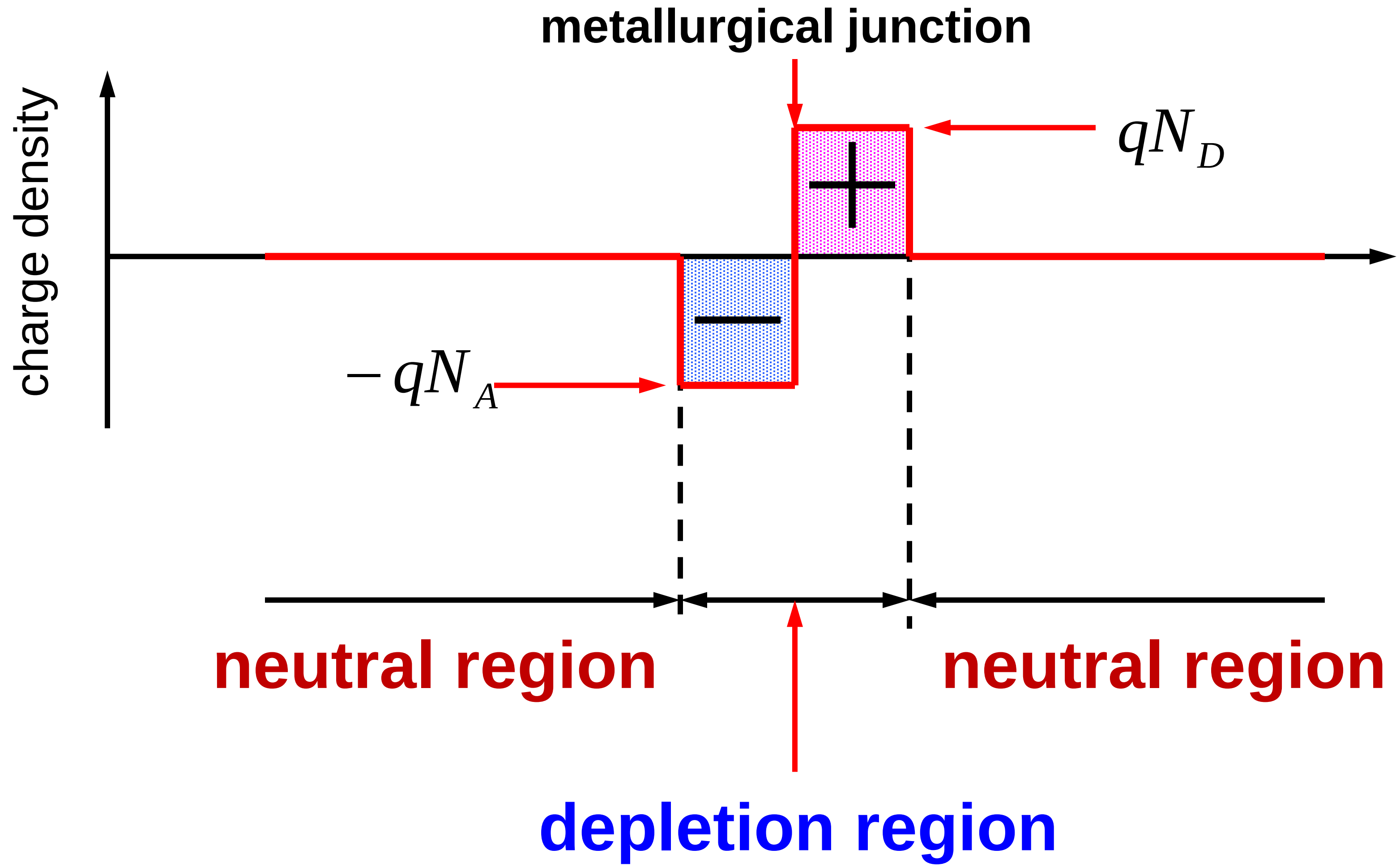
the Fermi levels in the p- and n-type semiconductors must be equal



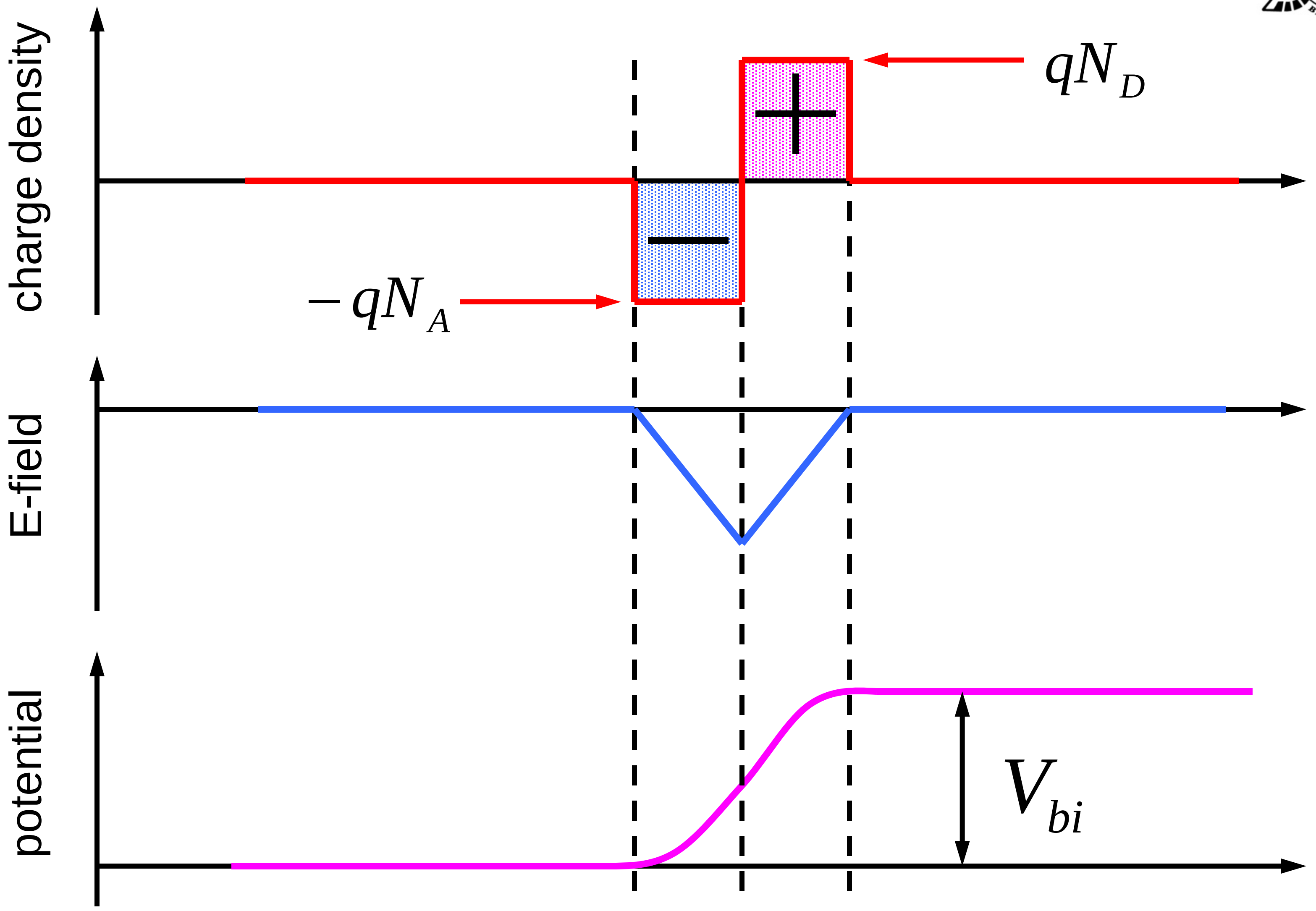
depletion region



depletion region



depletion region



Thermal equilibrium condition

At equilibrium condition the drift current due to the electric field must exactly cancel the diffusion current due to the concentration gradient

$$J_n = q\mu_n n\mathbf{E} + qD_n \frac{dn}{dx} = 0$$

$$J_p = q\mu_p p\mathbf{E} - qD_p \frac{dp}{dx} = 0$$

1D Poisson's equation:

$$\frac{d^2\psi(x)}{dx^2} = -\frac{d\mathbf{E}(x)}{dx} = -\frac{\rho_s(x)}{\varepsilon} =$$

$$= -\frac{q}{\varepsilon}\left[N_D(x) - N_A(x) + p(x) - n(x)\right]$$

ψ - electrostatical potential

ρ - space charge density

ε_s - semiconductor permittivity

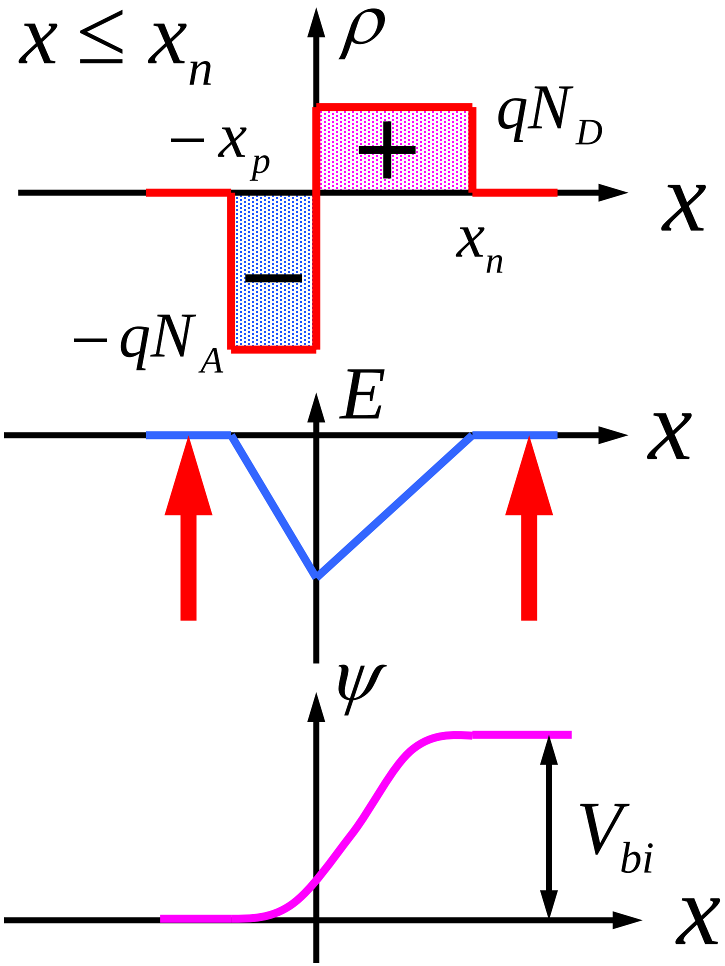
Poisson's equation for abrupt junction

$$\frac{d^2\psi(x)}{dx^2} = -\frac{d\mathbf{E}(x)}{dx} = -\frac{qN_A}{\varepsilon} \quad \textbf{for} \quad -x_p \le x < 0$$

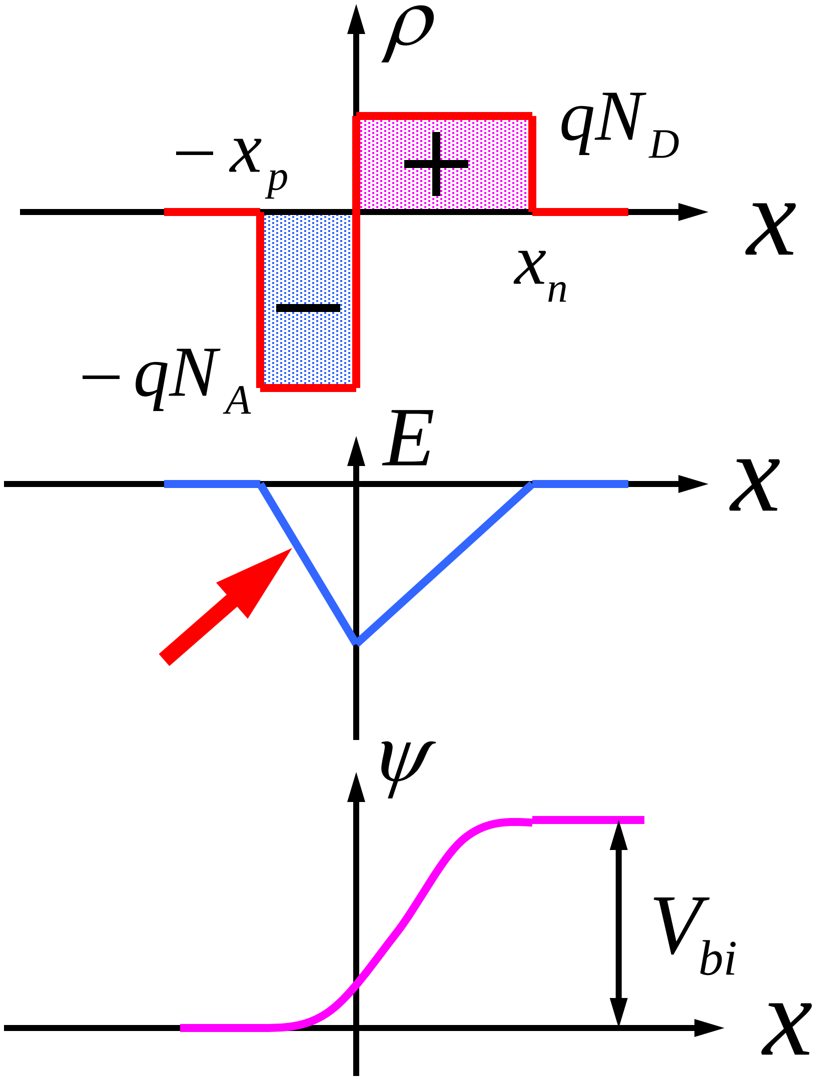
$$\frac{d^2\psi(x)}{dx^2} = -\frac{d\mathbf{E}(x)}{dx} = \frac{qN_D}{\varepsilon} \quad \textbf{for} \quad 0 < x \le x_n$$

junction potential

$$\frac{d\mathbf{E}(x)}{dx} = 0$$



electric field distribution



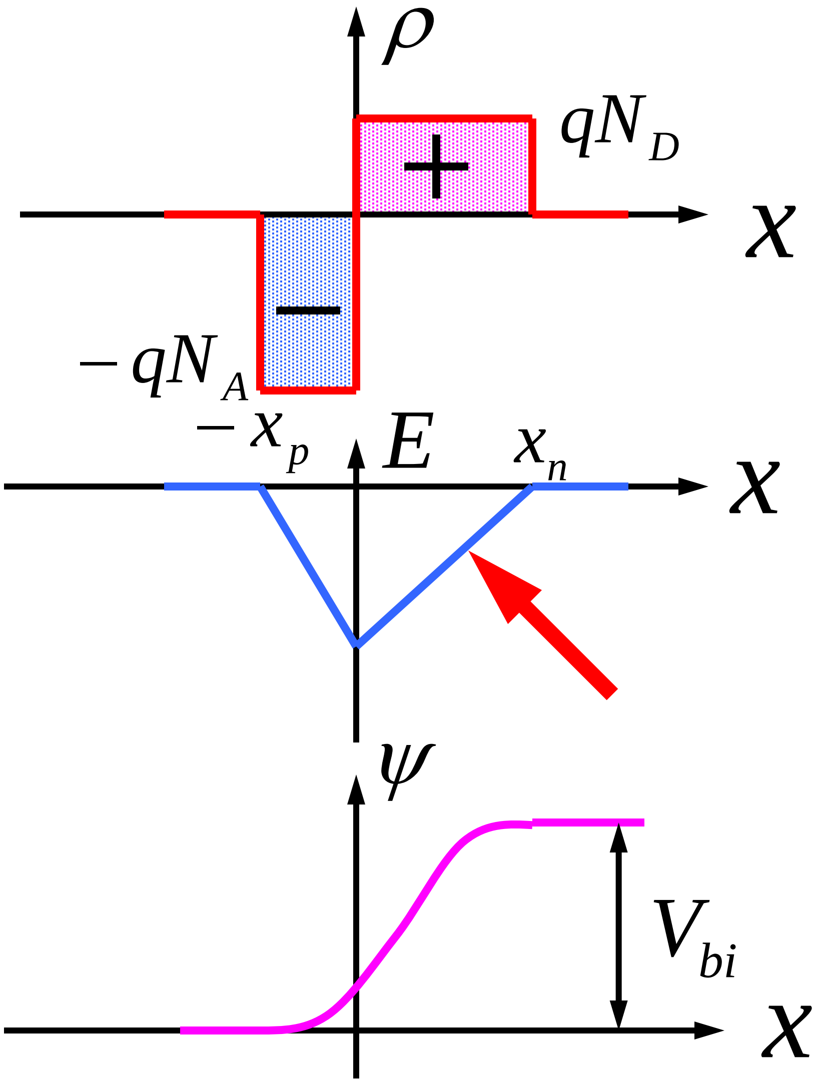
$$\frac{d\mathbf{E}(x)}{dx} = \frac{-qN_A}{\varepsilon}$$

$$\mathbf{E}(x) = -\frac{qN_A}{\varepsilon}x + \mathbf{E}_1$$

$$\mathbf{E}_1 = -\frac{qN_A}{\varepsilon}x_p$$

$$\boxed{\mathbf{E}(x) = -\frac{qN_A}{\varepsilon}\left(x + x_p\right)}$$

electric field distribution



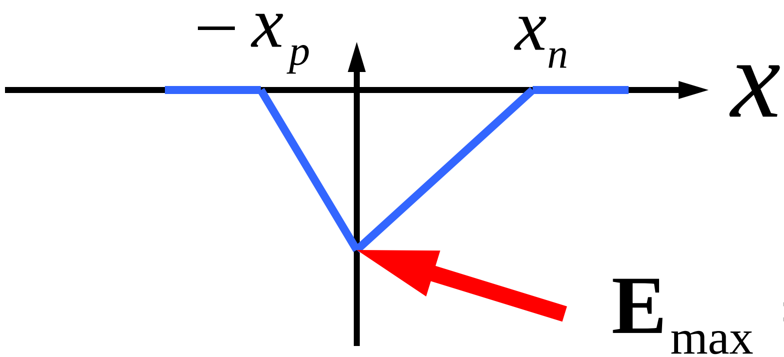
$$\frac{d\mathbf{E}(x)}{dx} = \frac{qN_D}{\varepsilon}$$

$$\mathbf{E}(x) = \frac{qN_D}{\varepsilon} x + \mathbf{E}_2$$

$$\mathbf{E}_2 = -\frac{qN_D}{\varepsilon} x_n$$

$$\mathbf{E}(x) = \frac{qN_D}{\varepsilon}\left(x - x_n\right)$$

maximum electric field



$$\mathbf{E}_{\max} = \mathbf{E}(0) = -\frac{qN_A}{\varepsilon}x_p = -\frac{qN_D}{\varepsilon}x_n$$

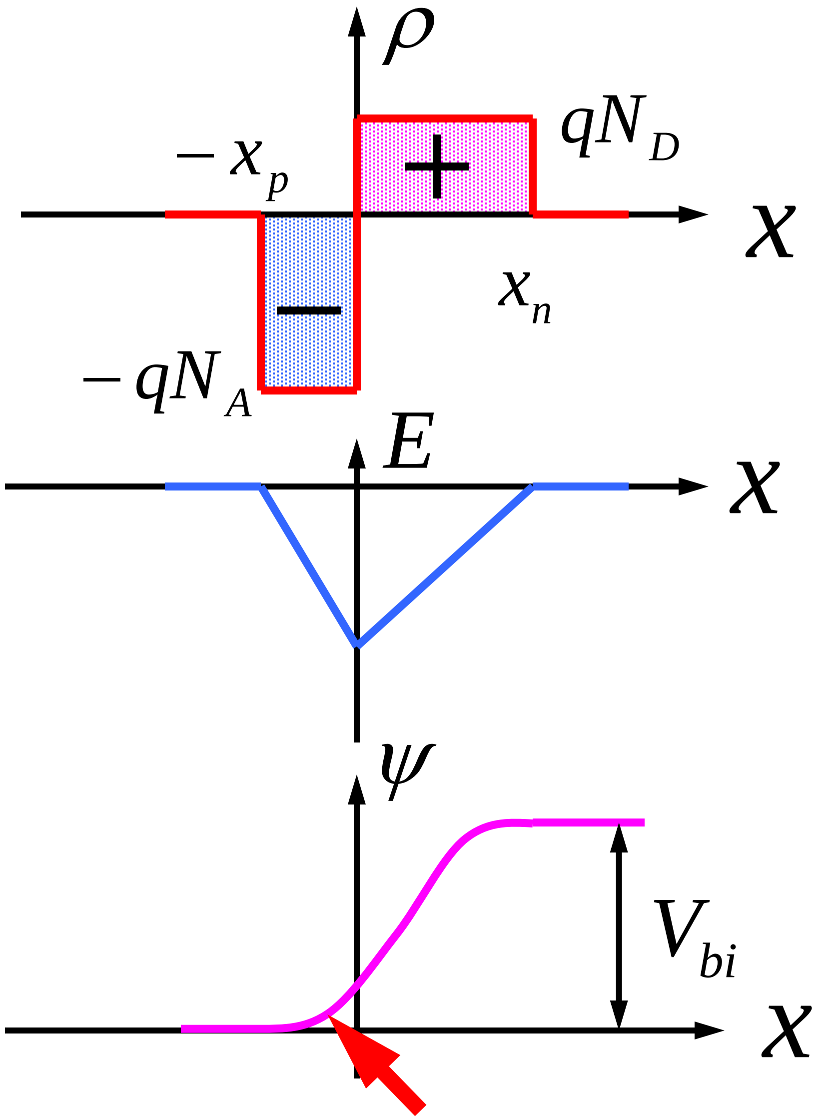
consequence: $$\boxed{N_A x_p = N_D x_p}$$

potential distribution

$$\mathbf{E}(x) = -\frac{d\psi(s)}{dx}$$

$$\psi(s) = -\int \mathbf{E}(x)dx$$

potential distribution $-x_p < x < 0$



$$\psi(x) = \int \frac{qN_A}{\varepsilon}\left(x + x_p\right)dx$$

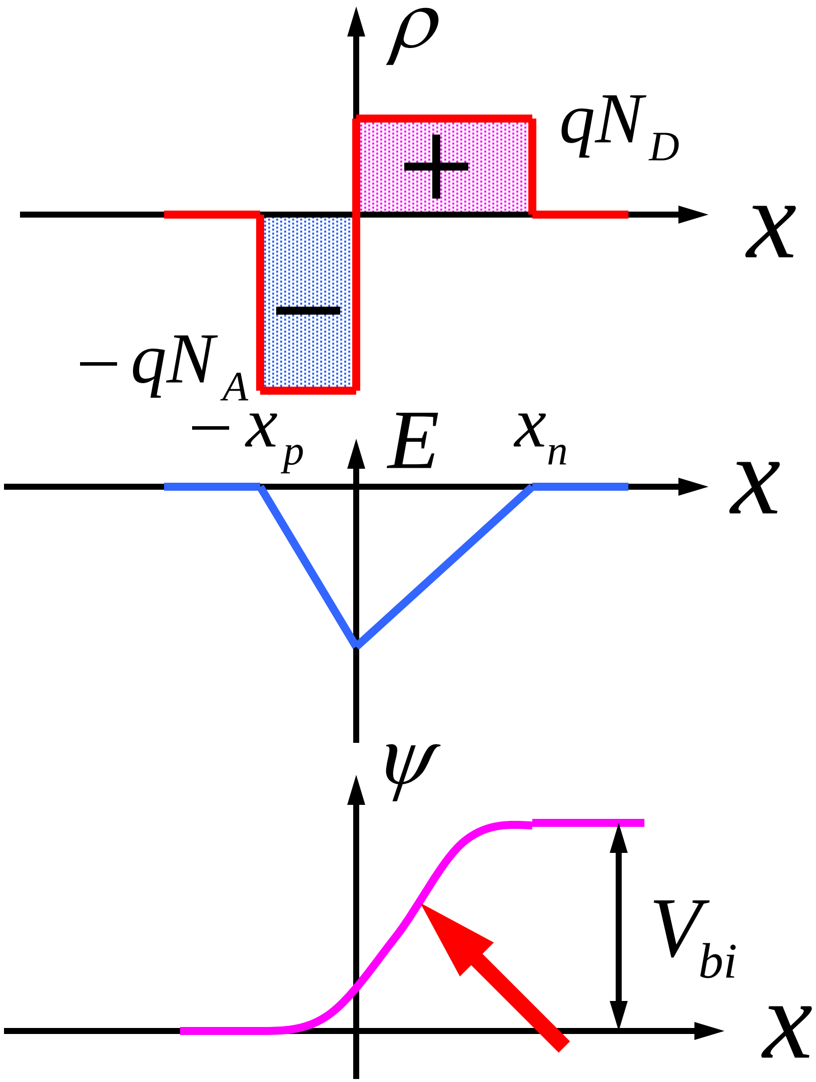
$$= \frac{qN_A}{\varepsilon}\left(\frac{x^2}{2} + x_p x\right) + \psi_1$$

with $\psi(-x_p) = 0$

$$\psi_1 = \frac{qN_A}{\varepsilon}\frac{x_p^2}{2}$$

$$\boxed{\psi(x) = \frac{qN_A}{2\varepsilon}\left(x_p + x\right)^2}$$

potential distribution $0 < x < x_n$



$$\psi(x) = \int \frac{qN_D}{\varepsilon}(x_n + x)dx$$

$$= \frac{qN_D}{\varepsilon}\left(x_n x - \frac{x^2}{2}\right) + \psi_2$$

with $\psi(x_n) = V_{bi}$

$$\psi_2 = V_{bi} - \frac{qN_D}{\varepsilon}\frac{x_n^{\ 2}}{2}$$

$$\boxed{\psi(x) = V_{bi} - \frac{qN_D}{2\varepsilon}(x_n - x)^2}$$

built-in potential

for $x = 0$ both expressions

$$\psi(x) = V_{bi} - \frac{qN_D}{2\varepsilon}(x_n - x)^2 \qquad \psi(x) = \frac{qN_A}{2\varepsilon}(x_p + x)^2$$

must give the same value:

$$\psi(0) = V_{bi} - \frac{qN_D}{2\varepsilon} x_n{}^2 = \frac{qN_A}{2\varepsilon} x_p{}^2$$

$$\boxed{V_{bi} = \frac{q}{2\varepsilon}\left(N_D x_n{}^2 + N_A x_p{}^2\right)}$$

depletion width

$$\boxed{x_d \equiv x_n + x_p}$$

$$V_{bi} = \frac{q}{2\varepsilon}\left(N_D x_n{}^2 + N_A x_p{}^2\right) \qquad N_A x_p = N_D x_n$$

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

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

$$x_n = \sqrt{\frac{2\varepsilon}{q}\frac{N_A}{N_D N_A + N_D{}^2} V_{bi}} \qquad x_p = \sqrt{\frac{2\varepsilon}{q}\frac{N_D}{N_D N_A + N_A{}^2} V_{bi}}$$

depletion width

$$x_n = \sqrt{\frac{2\varepsilon}{q}\frac{N_A}{N_D N_A + N_D{}^2}V_{bi}} \qquad x_p = \sqrt{\frac{2\varepsilon}{q}\frac{N_D}{N_D N_A + N_A{}^2}V_{bi}}$$

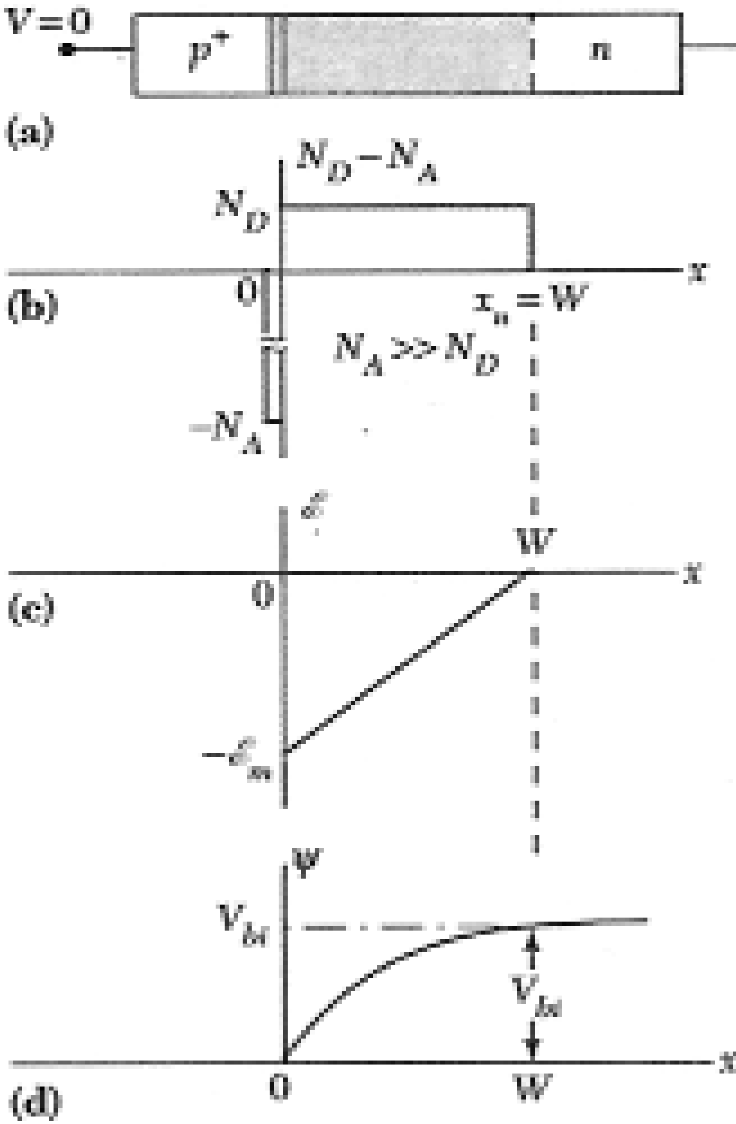
$$x_d{}^2 = \left(x_n + x_p\right)^2 = \frac{2\varepsilon}{q}\frac{N_A}{N_D N_A + N_D{}^2}V_{bi} + \frac{2\varepsilon}{q}\frac{N_D}{N_A N_D + N_A{}^2}V_{bi}$$

$$+2\cdot\sqrt{\frac{2\varepsilon}{q}\frac{N_A}{N_D N_A + N_D{}^2}V_{bi}}\cdot\sqrt{\frac{2\varepsilon}{q}\frac{N_D}{N_A N_D + N_A{}^2}V_{bi}} =$$

$$\frac{2\varepsilon}{q}V_{bi}\frac{N_A{}^2 + 2N_D N_A + N_D{}^2}{\left(N_A + N_D\right)N_D N_A} = \frac{2\varepsilon}{q}\frac{\left(N_A + N_D\right)}{N_D N_A}V_{bi}$$

$$\boxed{x_d = \sqrt{\frac{2\varepsilon}{q}\frac{\left(N_A + N_D\right)}{N_D N_A}V_{bi}}}$$

one-side abrupt junction



$$x_d = \sqrt{\frac{2\varepsilon}{q}\frac{\left(N_A + N_D\right)}{N_D N_A}V_{bi}}$$

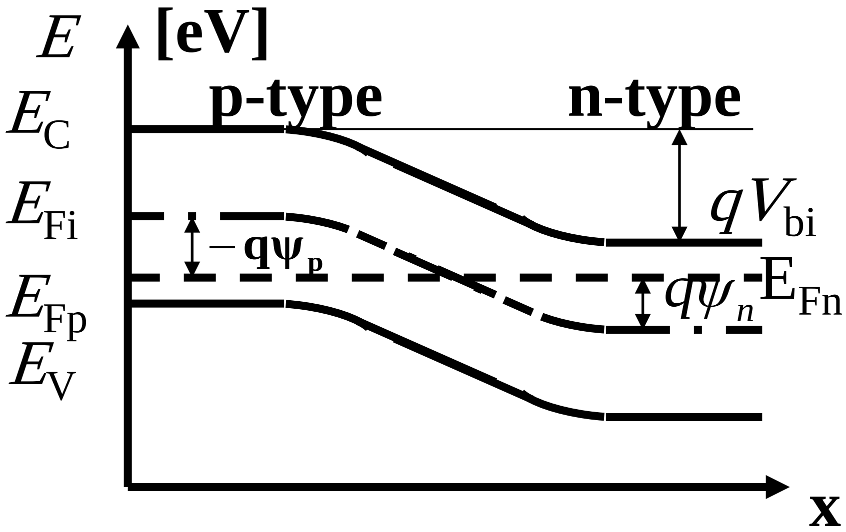
if $\quad x_p << x_n$

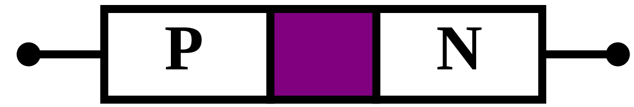
$$x_d \cong x_n = \sqrt{\frac{2\varepsilon V_{bi}}{qN_D}}$$

potential vs. carrier concentration

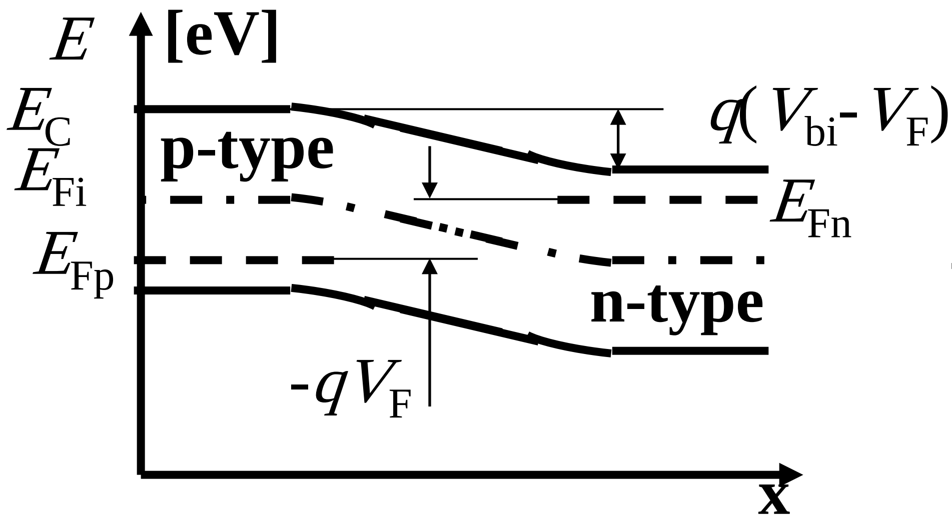
The derivation will be done in the lecture:

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

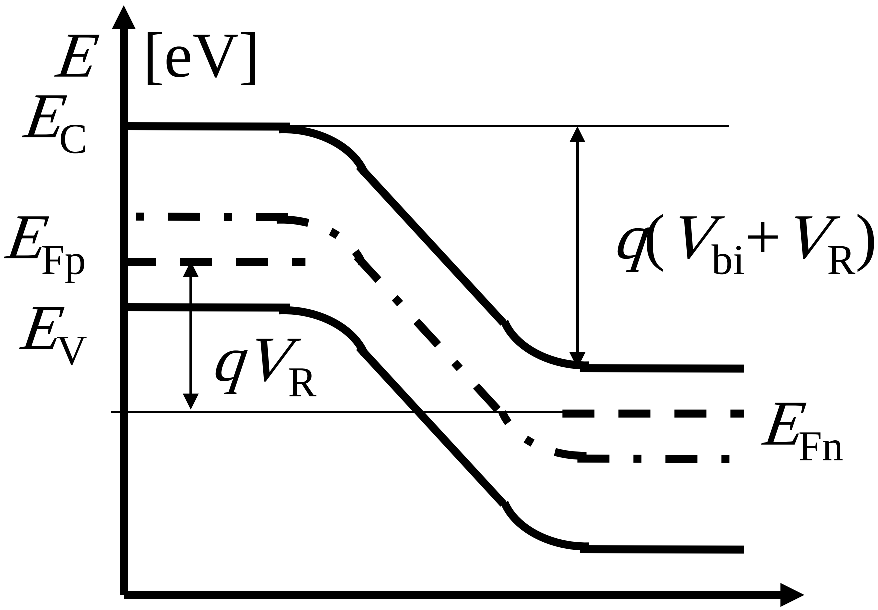




unbiased junction



forward-biased junction



reverse-biased junction

generalized depletion layer width

$$\boxed{x_d = \sqrt{\frac{2\varepsilon\left(V_{bi} - V\right)}{qN_B}}}$$

N_B – lightly doped bulk concentration

V - **positive for FB**, **negative for RB**