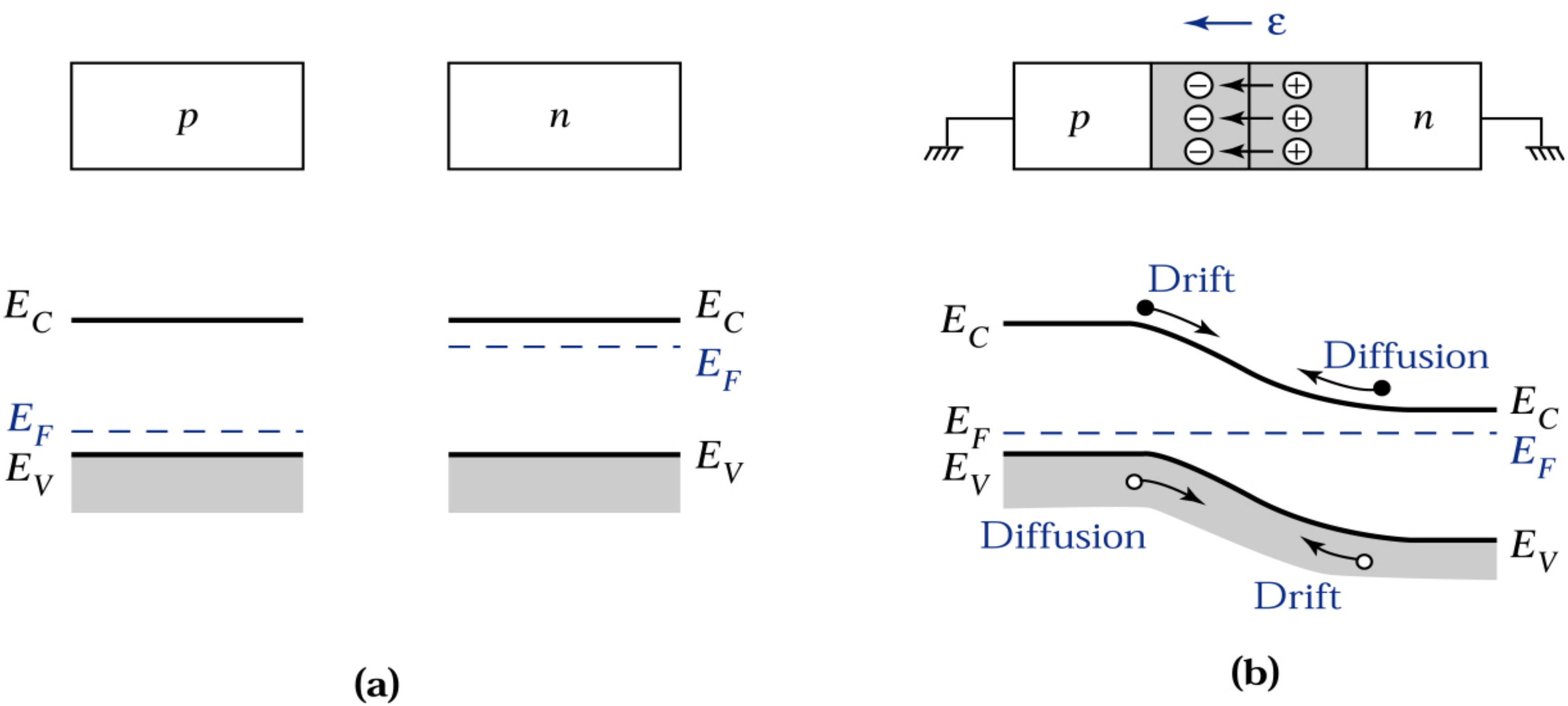
Figure 4.4. (*a*) Uniformly doped *p*-type and *n*-type semiconductors before the junction is formed. (*b*) The electric field in the depletion region and the energy band diagram of a *p*-*n* junction in thermal equilibrium.



Band Diagram

- Fermi Level close to valence band for p.
- Fermi level close to conduction band for n.
- P type contains of majority of holes and fewer electron.
- N type contains of majority of electron and fewer holes.
- When the are join together there are large gradient at the junction cause carrier diffusion.

Band Diagram

- Hole from p-side diffuse into n- side and electron form n-side diffuse into p-side.
- As the hole leaves there are some negative acceptor are fixed in semiconductor.
- Similarly there are some uncompensated positive donor ions as electron leave the n side.

Band Diagram

- As a result a negative space charge region forms near the p-side of the junction and a positive charge forms near the n-side.
- This creates electric field is directed from positive charge towards the negative charge.
- The electric field is in the direction of opposite of the diffusion current.

Band Diagram

- From the diagram we can see that the hole diffusion current moves form left to right and hole drift current moves from right to left.

Equilibrium Fermi Level

- At thermal equilibrium in steady state at given temperature without any external excitation, the individual electron and hole current flowing across the junction is eventually zero.

$$J_P = J_P(drift) + J_P(diffusion)$$

$$= q\mu_p p\varepsilon - qD_p \frac{dp}{dx}$$

$$= q\mu pp\left(\frac{1}{q}\frac{dE_i}{dx}\right) - kT\mu p\frac{dp}{dx} = 0$$

Equilibrium Fermi Level

$$p = n_i e^{\left(\frac{E_i - E_F}{kT}\right)}$$

$$\frac{dp}{dx} = \frac{p}{kT}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)$$

$$J_P = \mu_P P \frac{dE_F}{dx} = 0$$

$$J_n = \mu_n n \frac{dE_F}{dx} = 0$$

Equilibrium Fermi Level

- Thus for the condition of zero net electron and hole current the fermi level must be constant.
- The constant Fermi level required at thermal equilibrium results in unique space charge distribution at the junction.

Equilibrium Fermi Level

- Poisson Equation

$$\frac{d^2\Psi}{dx^2} \equiv -\frac{\rho}{\varepsilon_s}(N_D - N_A + p - n)$$

- Poisson equation equal to zero at the far away region.

$$\frac{d^2\Psi}{dx^2} \equiv 0$$

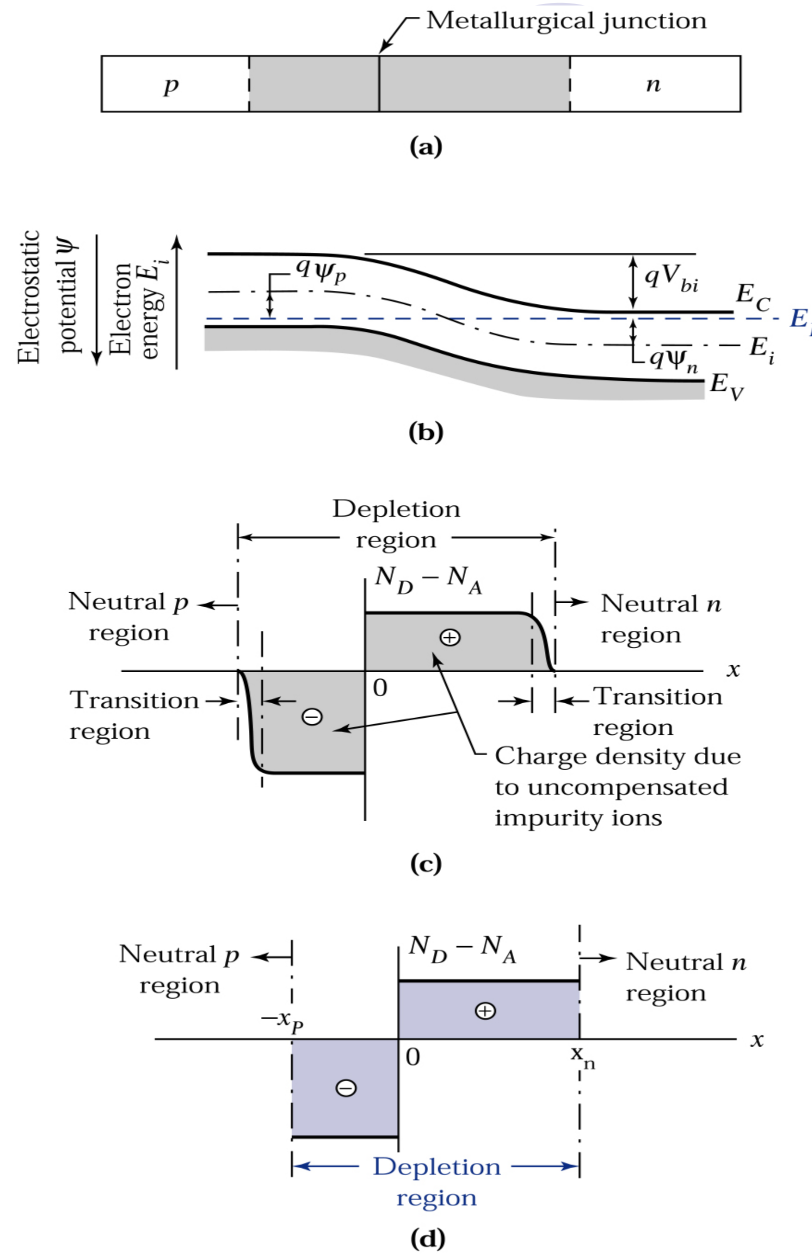
Equilibrium Fermi Level

- P-type N_D=0 and p>>n

$$\Psi_P = -\frac{kT}{q}\ln\left(\frac{N_A}{ni}\right)$$

$$\Psi_n = \frac{kT}{q}\ln\left(\frac{N_D}{ni}\right)$$

Figure 4.5. (*a*) A *p-n* junction with abrupt doping changes at the metallurgical junction. (*b*) Energy band diagram of an abrupt junction at thermal equilibrium. (*c*) Space charge distribution. (*d*) Rectangular approximation of the space charge distribution.



Equilibrium Fermi Level

- The total electrostatic potential difference between the p-side and n-side neutral regions at thermal equilibrium is called built-in potential V_{BI}.

$$V_{bi} = \Psi_n - \Psi_P = \frac{kT}{q} \ln\left(\frac{N_A N_D}{ni^2} \right)$$

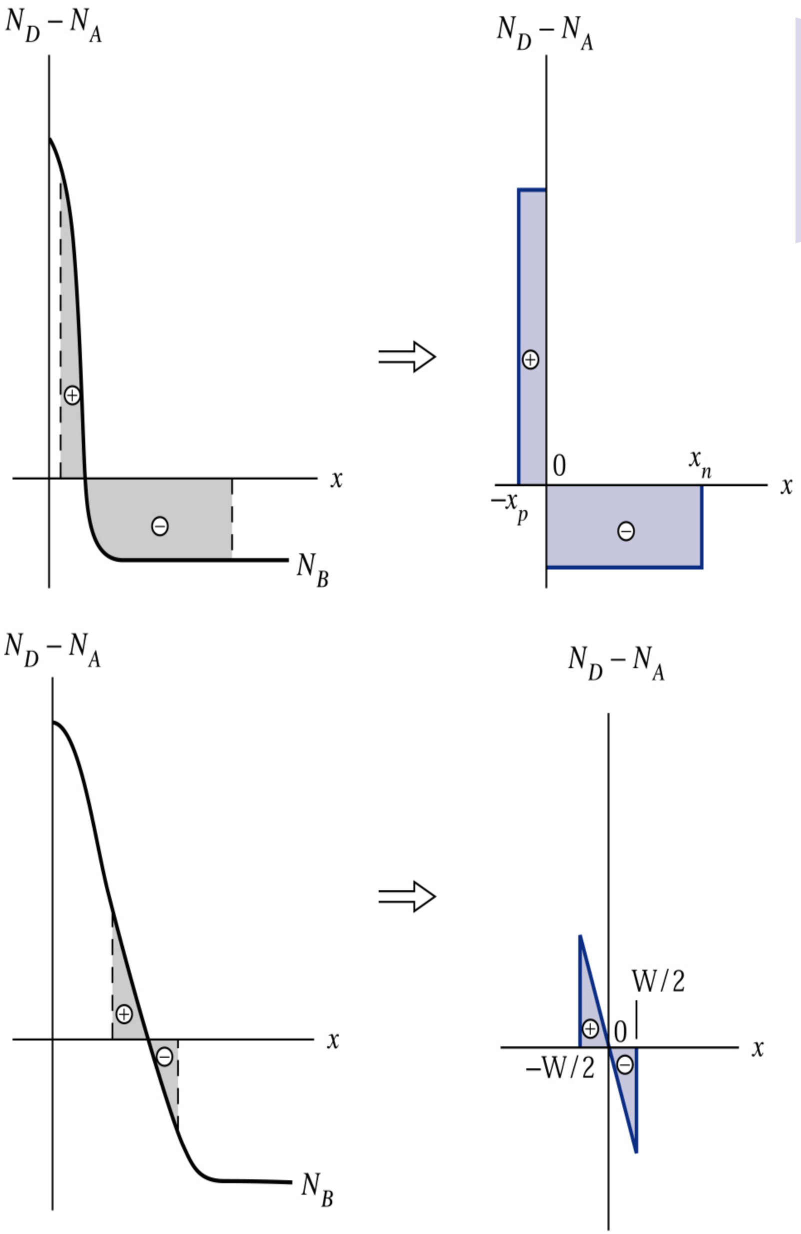
Space Charge

- From neutral to depletion region.
- Space charge impurity is partially compensated by mobile carriers.
- Typical p-n junction for silicon and gallium arsenide the width of each transition region is small compare width the width of depletion region.
- Therefore we neglect the transition region and represent the depletion region by square.

Depletion Region

- Consider 2 cases
- The abrupt junction.
- Linearly graded junction

Figure 4.7.
Approximate doping profiles.
(a) Abrupt junction.
(b) Linearly graded junction.



Depletion Region

- Abrupt junction p-n junction formed by shallow diffusion and low energy ion implantation.
- For deep diffusion or high energy ion implantation the impurity profile may be approximate by linearly graded junction.

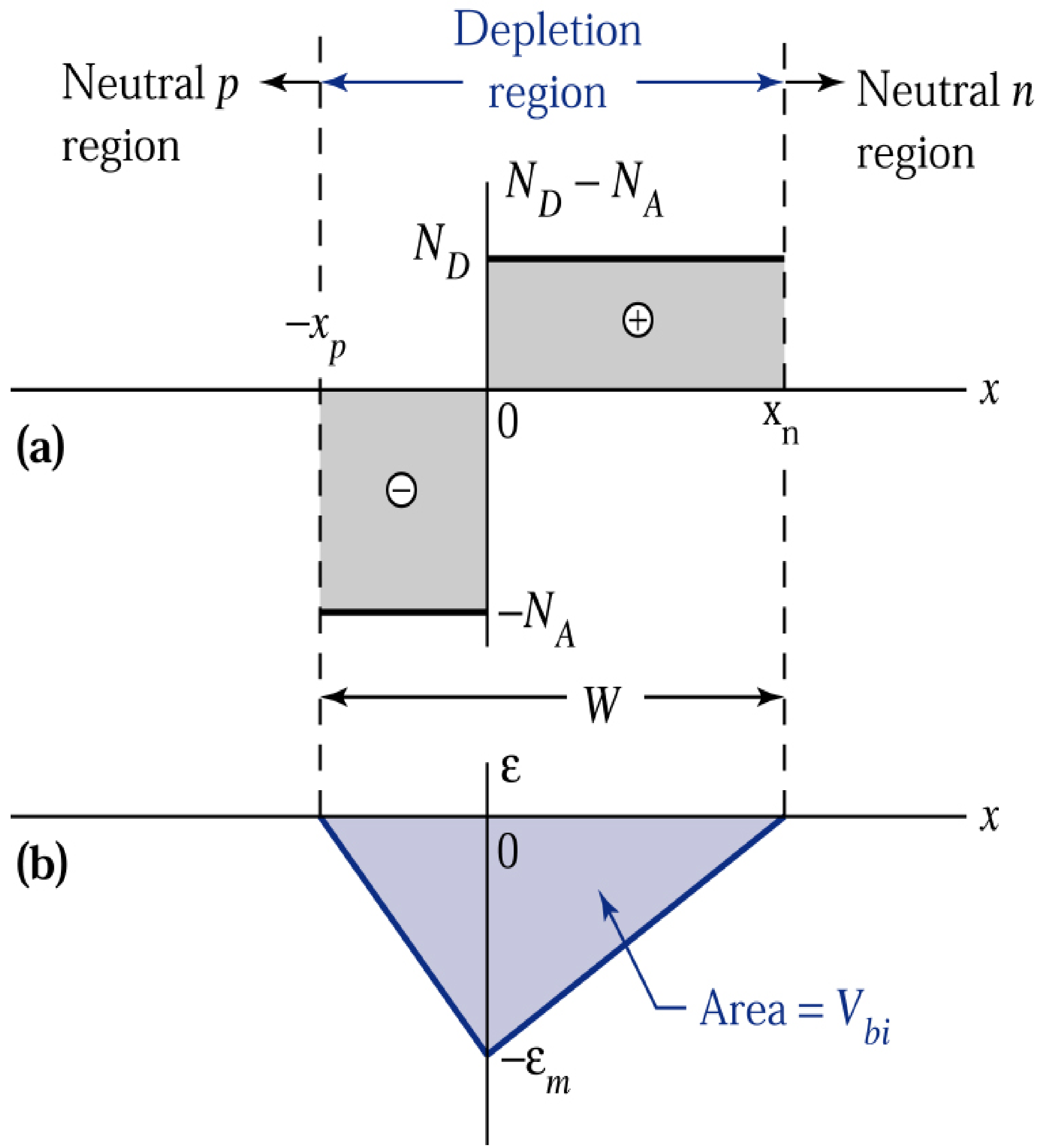
Abrupt Junction

In the depletion region free carriers are totally depleted meaning there is no carriers.

This simplifies Poisson to:

$$\frac{d^2\Psi}{dx^2} = \frac{q}{\varepsilon_s} N_A \qquad \frac{d^2\Psi}{dx^2} = -\frac{q}{\varepsilon_s} N_D$$

Figure 4.8.
(*a*) Space charge distribution in the depletion region at thermal equilibrium. (*b*) Electric-field distribution. The shaded area corresponds to the built-in potential.



Abrupt Junction

- The overall charge neutrality of semiconductor requires total space charge equal negative and positive.

$$N_A x_P = N_D x_n$$

- Total depletion width W= $x_p + x_n$

Abrupt junction

- Electric field :

$$\varepsilon(x) = -\frac{d\Psi}{dx} = -\frac{qN_A(x + x_p)}{\varepsilon_s}$$

$$\varepsilon(x) = \frac{qN_D}{\varepsilon_s}(x - x_n)$$

- At depletion region

Abrupt Junction

- Electric field is maximum at x=0
- Therefore integrating over depletion region give built in potential
- $$V_{bi} = \frac{1}{2}\varepsilon_m W$$
  $$W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_{bi}}$$