Semiconductor Engineering

:Semiconductor Physics and Devices

Chapter 4. p-n Junction

In Chapter 3

A system of electrons is characterized by a constant Fermi level at thermal equilibrium.

This principle was initially used to deduce the energy-band diagram of a semiconductor having two doping levels.

Systems that are initially not in thermal equilibrium approach equilibrium as electrons move from regions with a higher Fermi level to regions with a lower Fermi level.

The transferred charge causes the buildup of barriers against further electron flow, and the potential drop across these barriers increases to a value that just equalizes the Fermi levels.

These concepts were the foundation for an extensive analysis of metal-semiconductor contacts.

In chapter 4

We consider similar phenomena in a single crystal of semiconductor material containing regions having different dopant concentrations.

The quasi-neutrality approximation is employed in a region of a semiconductor containing a slowly varying dopant concentration, while the depletion approximation is useful in the important case of a semiconductor containing adjacent p- and n-type regions.

We discuss in some detail the transition region at a *pn* junction and the barrier associated with this transition region

We next consider the influence of an applied reverse voltage on the transition region and show that changes in this applied voltage lead to capacitive behavior.

We then extend the concepts to a system containing two different semiconducting materials.

Equilibrium in a semiconductor with a dopant concentration that varies in an arbitrary manner with position

We assume that initially <u>the majority-carrier concentration equals the dopant concentration</u> at every point in the material-a nonequilibrium condition.

A gradient in the mobile carrier concentration leads to <u>diffusion of carriers from regions of higher</u> <u>concentration to regions of lower concentration</u>

As the carriers move from their initial locations, they <u>leave behind uncompensated</u>, <u>oppositely</u> <u>charged dopant ions</u>. This separation of positive and negative charges creates a field that opposes the diffusion flow.

Equilibrium is eventually reached when the tendency of the carriers to diffuse to regions of lower density is exactly balanced by their tendency to move in the opposite direction because of the electric field created by the charge separation.

How the built-in electric field affects the energy-band diagram

Because the system is at thermal equilibrium, the Fermi level is constant throughout the system.

However, the variation of the dopant density and carrier concentration with position causes the separation between the Fermi level and the valenceand conduction-band edges to vary with position.

The separation between the Fermi level and the band edge is less in regions of high carrier density than in regions of lower density, and the intrinsic Fermi level E_i crosses the Fermi level E_f where the net dopant concentration $N_d - N_a$ is zero.



FIGURE 4.1 (a) Net dopant concentration as a function of position in an arbitrarily doped semiconductor. (b) Corresponding energyband diagram versus position, indicating the potential ϕ . Locations a, b, and c are discussed in the text.

Potential

The presence of an electric field can be seen directly from this energy band diagram, as well as from the particle model discussed above.

Since Figure 4.lb represents the energy-band diagram of an electron, the energy of an electron is measured by its distance above the Fermi level on the band diagram.

The separation of the conduction band edge from the Fermi level represents the **potential energy** of an electron while the energy above the conductionband edge represents **kinetic energy**

Because the electric potential Φ at any point is related to the potential energy by the charge -q, the potential can be written

$$\phi_c = -\frac{1}{q}(E_c - E_f) = \frac{1}{q}(E_f - E_c)$$



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Diffusion Current

Drift current

 \rightarrow flows when an electric field is applied and which follows Ohm's law. Ohmic behavior is observed in metals and semiconductors and is probably familiar from direct experience

Additional important component of current in semiconductor

 \rightarrow if a <u>spatial variation of carrier energies or densities</u> exists within the material.



*Diffusion current is generally not an important consideration in metals because metals have very high conductivities

Origin of diffusion current.

The lower conductivity and the possibility of <u>nonuniform densities of carriers</u> <u>and of carrier energies</u> makes diffusion an important process affecting current flow in semiconductors

Diffusion Current

For an electron density that increases with increasing *x*, the gradient is positive, as is the current.

Because electrons to flow from the higher density region at the right to the lower density region at the left and <u>current flows in the direction opposite to that of the electron</u>



Relationship between two important constant (diffusivity & mobility)
→ Related to the carrier transport by diffusion and drift in semicondoctor

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From Chap. 1

From Chap. 1

Diffusion Current

The current due to carrier diffusion is

$$J_n = -qF = qD_n \frac{dn}{dx} \qquad \int \left(\qquad J_p = qF = -qD_p \frac{dp}{dx} \right)$$

→ Diffusion current results from the random thermal motion of carriers in a concentration gradient

When an electric field is applied to a semiconductor with concentration gradient

→ Total current at any point is <u>the sum of the drift and diffusion</u> components

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx} \rightarrow \text{Electron current} \qquad \begin{cases} \text{Drift}: & J_n = qn\mu_n E\\ \text{Diffusion}: & J_n = qD_n \frac{dn}{dx} \end{cases}$$
$$J_p = q\mu_p pE - qD_p \frac{dp}{dx} \rightarrow \text{Hole current} \qquad \begin{cases} \text{Drift}: & J_p = qp\mu_p E\\ \text{Diffusion}: & J_p = -qD_p \frac{dp}{dx} \end{cases}$$
$$\text{Total conduction current} \qquad \end{cases}$$

$$J_{cond} = J_n + J_p$$

Potential

The reference for potential energy is arbitrary, however, and we may shift it from E_c to E_i . Because E_i is usually used for the reference, we will not subscript the symbol Φ for potential which now is written

$$\phi = -\frac{1}{q}(E_i - E_f) = \frac{1}{q}(E_f - E_i)$$

as shown in Figure 4.lb. According to this definition the potential is positive for an <u>n-type semiconductor $(E_f > E_i)$ and negative for <u>p-type material $(E_f < E_i)$.</u></u>



FIGURE 4.1 (a) Net dopant concentration as a function of position in an arbitrarily doped semiconductor. (b) Corresponding energyband diagram versus position, indicating the potential ϕ . Locations a, b, and c are discussed in the text.

Field

Because the electric field is the negative of the spatial gradient of the potential, the field \mathcal{E}_x is found from Equation 4.1.2 to be

$$\phi = -\frac{1}{q}(E_i - E_f) = \frac{1}{q}(E_f - E_i)$$

$$\mathscr{C}_x = -\frac{d\phi}{dx} = \frac{1}{q}\frac{dE_i}{dx}$$

Thus, a spatial variation of the band edges (and the intrinsic Fermi level) implies that a non-zero electric field exists in the semiconductor

<u>At point b</u> of Figure 4.lb, dE_i/dx is negative, and the field is directed toward the left. The resulting force on negatively charged electrons is toward the right; consequently, the field provides a force that opposes the tendency of electrons to diffuse from the high-concentration region at c to the low concentration region at a.



FIGURE 4.1 (a) Net dopant concentration as a function of position in an arbitrarily doped semiconductor. (b) Corresponding energyband diagram versus position, indicating the potential ϕ . Locations a, b, and c are discussed in the text.

Field

The electric field and the graded impurity distribution.

In thermal equilibrium, no current flows at any point in the semiconductor

because thermal equilibrium requires that every process and its inverse are in balance, the electron current and the hole current must each be zero at thermal equilibrium

Total electron current



This expression is applicable both in *n-type* material, where the electrons are majority carriers, and in a *p-type* semiconductor, where they are minority carriers.

drift current diffusion current

When the total electron current is zero, the two terms are exactly balanced.

Because $J_n = 0$, we can solve for the field in terms of the electron concentration and its gradient

for electron current

for hole current

Applied Nanomaterials & Devices LAB. Electronics & Probes by Materials Engineering we can find the mobile carrier concentrations and their gradients, we know the fields in the semiconductor

Field

Considering the relation between the electron density and the position of the band edge (or equivalently the intrinsic Fermi level) with respect to the Fermi level



Field

Relation between the number of carriers at any two points in the material and the energy band structure

the electron density at x_2 is less than that at x_3 because the separation between the conduction-band edge and the Fermi level is greater at x_2 .

Because
$$\mathscr{C}_{x} = -d\phi/dx$$
, (For electron)
 $\mathscr{C}_{x} = -\frac{D_{n}}{\mu_{n}}\frac{1}{n}\frac{dn}{dx} = -\frac{kT}{q}\frac{1}{n}\frac{dn}{dx}$

$$d\phi = \frac{kT}{a}\frac{dn}{n}$$

Integrating this equation between any two points-for example, from x_2 to x_3

$$\phi_3 - \phi_2 = \frac{kT}{q} \ln \frac{n_3}{n_2}$$
 $\xrightarrow{\text{exponential form}}$ $\frac{n_3}{n_2} = \exp\left[\frac{q}{kT}(\phi_3 - \phi_2)\right]$

Applied Nanomaterials & Devices LAB. Electronics & Probes by Materials Engineering The ratio of the carrier densities depends on the potential difference $\phi_B = \phi_3 - \phi_2$ Between the two points



Poisson's Equation

the solution to Poisson's equation is the potential field caused by a given electric charge or mass density distribution

$$\frac{d^2\phi}{dx^2} = -\frac{\rho}{\epsilon_s} = -\frac{q}{\epsilon_s}(p-n+N_d-N_a)$$

Show page 179 for specific calculation

Where, ρ is the space-charge density and the dopant atoms are assumed to be completely ionized.

Poisson's equation can then be rewritten in the form

$$\frac{d^2\phi}{dx^2} = \frac{q}{\epsilon_s} \left(2n_i \sinh \frac{q\,\phi}{kT} + N_a - N_d \right)$$

→ the differential equation for the potential distribution in <u>an arbitrarily doped semiconductor</u>.

we consider two special cases

the dopant concentration varies gradually with position as, for example, the donor distribution within a diffused *n*-type region

abrupt spatial variations of dopant concentration as, for example, in the junction between *p*-type and *n*-type semiconductor regions

Device building block



To build a model for the *pn* junction

- Considering initially separated *n* and p-type semiconductor crystals of the same material
- When these are brought into intimate contact as shown in Figure 4.3b, the large difference in electron concentrations between the two materials causes electrons to flow from the n-type semiconductor into the *p-type* semiconductor and holes to flow from the p-type region into the n-type region.
- As these mobile carriers move into the oppositely doped material, they leave behind uncompensated dopant atoms near the junction, causing an electric field
- The field lines extend from the donor ions on the n-type side of the junction to the acceptor ions on the p-type side (Figure *4.3c*).
- This field creates a potential barrier between the two types of material.
- When equilibrium is reached, the magnitude of the field is such that the tendency of electrons to diffuse from the *n*-*type* region into the p-type region is exactly balanced by the tendency of electrons to drift in the opposite direction under the influence of the built-in field.





Potential barrier



- ▮ ① PN junction이 생성되었다고 가정
- ② 전자와 정공의 농도 차이로 인해서 접합을 향해서 확산
- ③ 전자와 정공이 서로 만나 재결합(recombination)으로 사라짐.
 - ④ 도펀트 이온만 노출되며 공핍영역에 전기장 형성
- ⑤ 도펀트 이온에 의한 전기장방향과 캐리어(전자 또는 정공)에 의한 확산 전류는
 서로 반대
 - ⑥ 확산 전류를 막아서 net current = 0이 될 때까지 전기장 증가
 - ⑦ 확산과 드리프트 간 전류가 평형이 발생하며 그 때, built-in potential 결정

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Junction formation

P-type semiconductor



Semiconductor lattice with acceptor ions and free holes

Acceptor



N-type semiconductor



Semiconductor lattice with donor ions and free electrons





Junction formation : Depletion region



Depletion region : region where free carriers (e, h) are depleted

Junction formation : depletion region (space charge region)



Junction formation : electric field in the space charge region



Junction formation (band diagram)



Equilibrium Fermi level (steady state : without any external excitation)



- → Drift current and diffusion current are canceled each other
- \rightarrow No electron and hole current flow

For hole current at steady state

$$J_{p} = J_{p}(drift) + J_{p}(diffusion) = 0$$

= $q\mu_{p}p\mathcal{E} - qD_{p}\frac{dp}{dx}$
= $q\mu_{p}p\mathcal{E} - qD_{p}\frac{dp}{dx}$
= $q\mu_{p}p\left(\frac{1}{q}\frac{dE_{i}}{dx}\right) - kT\mu_{p}\frac{dp}{dx} = 0$
 $\mathcal{E} = \frac{1}{q}\frac{dE_{i}}{dx} \leftarrow -q\mathcal{E} = -\frac{dE_{i}}{dx}$
 $D_{p} = \left(\frac{kT}{q}\right)\mu_{p}$: Einstein relation

Equilibrium Fermi level (steady state : without any external excitation)

$$J_{p} = \mu_{p} p\left(\frac{dE_{i}}{dx}\right) - kT \mu_{p} \frac{dp}{dx} = 0$$

$$p = n_{i} e^{(E_{i} - E_{F})/kT}$$

$$\frac{dp}{dx} = \left(\frac{1}{kT} \frac{dE_{i}}{dx} - \frac{1}{kT} \frac{dE_{F}}{dx}\right) n_{i} e^{(E_{i} - E_{F})/kT}$$

$$= \left(\frac{1}{kT} \frac{dE_{i}}{dx} - \frac{1}{kT} \frac{dE_{F}}{dx}\right) p$$

$$= \mu_p p\left(\frac{dE_i}{dx}\right) - kT \mu_p p\left(\frac{1}{kT}\frac{dE_i}{dx} - \frac{1}{kT}\frac{dE_F}{dx}\right) = 0$$

$$=\mu_p p \frac{dE_F}{dx} = 0$$
 In the same way, $J_n = \mu_n n \frac{dE_F}{dx} = 0$

 $\frac{dE_F}{dx} = 0$

For the condition of zero net electron and hole current flow, the Fermi level (E_F) should be constant throughout the p-n junction

Poisson's equation : electric field distribution in the junction

 \rightarrow Calculate the electric potential for a given charge distribution.



 \mathcal{E}_{s} : Dielectric permittivity ($\varepsilon_{r}\varepsilon_{0}$) ρ_{s} : Space charge density $\begin{cases} \varepsilon_{\rm r} : \text{ relative permittivity (Si : 11.9)} \\ \varepsilon_0 : \text{ vacuum permittivity} \\ (8.854 \text{ x} 10^{-14} \text{ F/cm}) \end{cases}$

S: Space charge density (sum of the charge carriers and ionized impurity)

→ in the *p*-*n* junction : $\rho_s = q (N_D - N_A + p - n)$

Electrostatic potential (Ψ) and electric field (E) has a relation of ;

$$\mathbf{E} \equiv -\frac{d\Psi}{dx} \quad \Longrightarrow \quad \frac{d\mathbf{E}}{dx} = -\frac{d^2\Psi}{dx^2}$$

$$\frac{d^2\Psi}{dx^2} \equiv -\frac{dE}{dx} = -\frac{\rho_S}{\varepsilon_S} = -\frac{q}{\varepsilon_S}(N_D - N_A + p - n)$$

This equation can be applied to all the region of p-n

: Electrostatic potential (Ψ) and electric field (E) distribution in the *p*-*n* junction.

Built-in potential

 \rightarrow Electrostatic potential difference between the p & n-neutral regions at thermal equilibrium



Built-in potential



• In *n*-type neutral region : $N_A = 0$ and $n \gg p$ $n = n_i e^{(E_F - E_i)/kT} = N_D$

Electrostatic potential of the *n*-neutral region with respect to Fermi level

$$\Psi_n \equiv -\frac{1}{q} (E_i - E_F) \bigg|_{x \ge x_n} = \frac{kT}{q} \ln\left(\frac{N_D}{n_i}\right)$$

Total electrostatic potential difference between the p- and n-side : built-in potential (V_{bi})

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

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

 \Rightarrow As N_A and N_D increases, V_{bi} increases

Current-Voltage(I-V) characteristics of p-n junction



Depletion region (space-charge region)



Applied Nanomaterials & Devices LAB. Electronics & Probes by Materials Engineering In the depletion region : Mobile charges are completely depleted and the mobile charge density is zero.

$$p = n = 0$$

Electrostatic potential in the depletion region

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

$$= -\frac{q}{\varepsilon_{S}}(N_{D} - N_{A}) = \frac{q}{\varepsilon_{S}}(N_{A} - N_{D})$$

- Electrostatic potential in the depletion region varies with parabolic.

- Depends on dopant distribution (profile).

Impurity distribution in depletion region



Abrupt junction: Electric field distribution

Space charge distribution



$$\frac{d^{2}\Psi}{dx^{2}} \equiv -\frac{d\mathbf{E}}{dx} = -\frac{q}{\varepsilon_{S}} (N_{D} - N_{A} + p - n)$$

i) $-x_{p} \leq x < 0$
• Free carriers are totally depleted ($n=p=0$)
• $N_{A} \gg N_{D}$

$$\frac{d^2\Psi}{dx^2} = -\frac{d\mathbf{E}}{dx} = \frac{q}{\varepsilon_S} N_A$$

ii) $\theta < x \leq x_n$

• Free carriers are totally depleted (n=p=0)• $N_D \gg N_A$

$$\frac{d^2\Psi}{dx^2} = -\frac{d\mathbf{E}}{dx} = -\frac{q}{\varepsilon_s}N_D$$

Abrupt junction: Built in potential

Space charge distribution

Total potential variation in the depletion region : built-in potential V_{bi}

Integration of electric field over the depletion region



Abrupt junction: Electric field distribution

i) $-x_p \le x < 0$ $\implies \frac{d^2 \Psi}{dx^2} = -\frac{d\mathcal{E}}{dx} = \frac{q}{\varepsilon_s} N_A$ **Space charge distribution** $\boldsymbol{\mathcal{E}}(x) = \int -\frac{qN_A}{\varepsilon_a} dx = -\frac{qN_A}{\varepsilon_s} x + A \quad \boldsymbol{\boldsymbol{\leftarrow}} \boldsymbol{\mathcal{E}}(-x_p) = 0$ *ii)* $\theta < x \le x_n$ $\Rightarrow \frac{d^2 \Psi}{dx^2} = -\frac{d}{dx} \stackrel{\mathcal{E}}{=} -\frac{qN_D}{c}$ W $\boldsymbol{\mathcal{E}}(x) = \int \frac{qN_D}{\varepsilon_s} dx = \frac{qN_D}{\varepsilon_s} x + B \quad \boldsymbol{\boldsymbol{\mathcal{E}}}(x_n) = 0$ E $x_n \vec{x}$ 0 $=\frac{qN_D}{\varepsilon_S}x-\frac{qN_D}{\varepsilon_S}x_n$ $-\mathcal{E}_m$ $\mathcal{E}_{m} = \frac{qN_{D}}{\varepsilon_{S}} x_{n} = \frac{qN_{A}}{\varepsilon_{S}} x_{p} \Rightarrow \text{Maximum field} \\ \text{at } x = 0 \text{ (junction)}$ Applied Devices LAB.

Abrupt junction: Depletion layer width



One side abrupt junction



Overall space charge neutrality requires;

$$x_p N_A = x_n N_D$$

$$V_{bi} = \frac{\varepsilon_m}{2} (x_p + x_n) = \frac{1}{2} W \varepsilon_m$$

Total depletion layer width (W) as a function of built-in potential

$$W = \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{N_A + N_D}{N_A N_D}\right)} V_{bi} \qquad \begin{array}{c} \varepsilon_s \,, \, V_{bi} \text{ increase} \\ \to \text{ W increases} \end{array}$$

$$W \cong \sqrt{\frac{2\varepsilon_s}{qN_D}V_{bi}}$$

for
$$N_A >> N_D$$

One side abrupt junction p^+ -*n* junction

Abrupt junction: Depletion layer width



One side abrupt junction



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One side abrupt junction p^+ -*n* junction

Abrupt junction: Deriving depletion layer width



$$W = x_p + x_n \implies x_p = W - x_n$$
$$x_p N_A = x_n N_D$$
$$(W - x_n) N_A = x_n N_D$$
$$x_n (N_A + N_D) = W N_A$$
$$x_n = \frac{N_A}{N_A + N_D} W$$

$$V_{bi} = \frac{1}{2} \frac{q}{\varepsilon_S} \frac{N_D N_A}{N_A + N_D} W^2$$

$$\therefore W = \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{N_A + N_D}{N_A N_D}\right) V_{bi}}$$

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