

Chapter 3. PN junction as a basic building block

Chapter 3. PN junction: Basic building block

- 3-1. PN junction in equilibrium
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 - Tunneling
 - Avalanche Breakdown

Objective

To review the PN junction as a basic building block . Special emphasis will be given to generation current components of the reverse biased PN junction. The understanding of the reverse bias leakage current flow mechanism is imperatively important in understanding the MOS IV characteristics and the breakdown mechanism of semiconductor devices.

3-1. PN junction in equilibrium

- Homojunction and Heterojunction
- Depletion approximation

PN junction is the basic building block of the semiconductor devices and integrated circuits. PN junction provides,

- current control according to the voltage across the junction, (PN diode)
- device to device isolation in the integrated circuits, (junction isolation)

- amplifying and switching function if two and more junctions are properly positioned,(BJT and other devices),
- the potential energy well formed by the junction provides the capability of storing charges,(image sensor) and so on.

Even though the electrical, thermal and optical properties can be predicted and understood by the numerical modeling based on the 'semiconductor equations' studied in chapter 2, the analytical modeling is helpful since it provides many physical concepts and intuitions.

are not covered assuming student have background equivalent to undergraduate "semiconductor device theory". However, understanding of PN junction current flow mechanism(especially the reverse bias current) is so important in understanding the MOS current, I will quickly summarize the PN junction reverse bias current.

A. regional approach

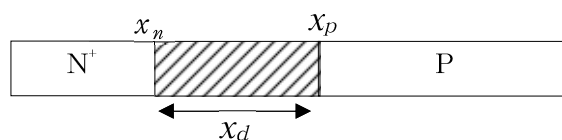


Fig. 3.1. N⁺P junction arbitrary voltage in applied

- Consider N⁺P junction in Fig. 1. PN junction is divided by three regions, N⁺ neutral region, depletion region and neutral P region. The width of the depletion region, x_d , can be approximated by,

$$x_d = \sqrt{2\epsilon_s \frac{V_{bi} + V_R}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)}$$

where V_R is the reverse bias voltage.

If one sided abrupt junction with $N_d \gg N_a$, x_d is simply

$$x_d = \sqrt{2\epsilon_s \frac{V_{bi} + V_R}{qN_a}}.$$

- The above situation can be best understood by combining two pictures; the energy band diagram and the electric field profile.

The potential applied across the junction and associated electric field can be depicted under the depletion approximation as;

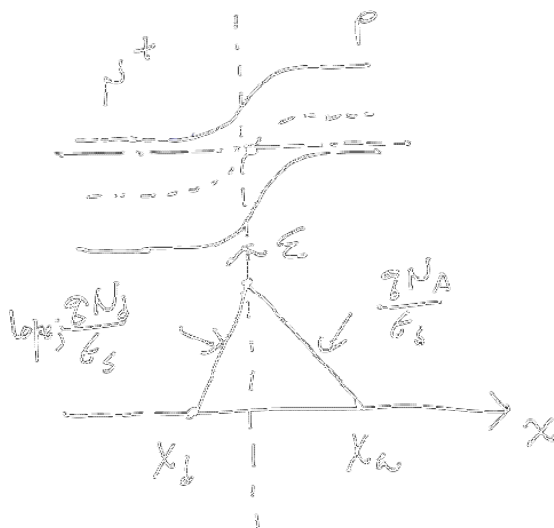


Fig. 3.2. Pictorial representation of the PN junction.

- In the picture above, the area under the electric field profile is the 'total potential difference between two neutral regions' which is $V = V_{bi} + V_A$ where V_A is the applied voltage (+ if reverse , - if forward)

B. Homojunction and Inhomogeneous junction

- Thanks to many CVD technologies, it is possible to form a PN junction between different material having different E_g , W and χ (electron affinity). The major motivation is to be able to control the injection efficiency for carriers from different region(material), to form a deeper potential well for optical applications.

3-2. PN junction in Non equilibrium

A. Homojunction case

- Under forward and reverse bias

- Shockley's junction law states that, at the edge of the depletion region, the minority carrier concentrations can be written as,

$$n_p(0) = n_{p0} e^{-V_R/V_t},$$

$$p_n(0) = p_{n0} e^{-V_R/V_t}.$$

Another way of looking this situation is that the Quasi Fermi level of the majority carrier is constant across the depletion region(so current is negligible).

- Current continuity equation in the neutral region.

Current continuity condition for electron in the neutral P region can be written as,

$$\frac{dn}{dt} = -\nabla \cdot F_n + U \quad (1)$$

where

$$U = CN_t \frac{np - n_i^2}{n + p + 2n_i \cosh \frac{E_t - E_i}{k_B T}}. \quad (2)$$

In the steady state condition, neglecting E field in the neutral region, eq. (1) becomes,

$$0 = D_n \frac{d^2 n_p}{dx^2} + (n_p - n_0)/\tau_n$$

where $\tau_n =$.

Then $n_p(x) = n_{po}(1 - e^{-x/L_n})$ so that flux for electron at $x = x_p$ is

$$F_n(0) = -D_n \left. \frac{dn_p}{dx} \right|_{x_p} = D_n \frac{n_{po}}{L_n}.$$

In the same way, F_p at $x = x_n$ can be written as,

$$F_p = -D_p \frac{dp}{dx} = D_p \frac{p_{no}}{L_p},$$

where $L_n = \sqrt{\tau_n D_n}$ and $L_p = \sqrt{\tau_p D_p}$.

- Current component in the depletion region.

In the region, there are no minority carrier life time defined, so that it is difficult to express the current continuity equation for minority carriers. However, the generation rate in the region can be written as,

$$-U = +CN_t \frac{n_i}{2} \quad \text{with } E_t = E_i,$$

so that total generation rate of electrons and holes in the depletion region is $-\int U dx = CN_t \frac{n_i}{2} x_d$.

- Total leakage current due to thermal generation

Then total leakage current measured at the terminal is simply sum of the total generation components of each region, i.e.,

$$I_{leakage} = A_D \left\{ F_n(x_p) + F_p(x_n) + \int U dx \right\}$$

where A_D is the area of the diode.

Notice that

$\int U dx \gg F_n(x_p) \gg F_p(x_n)$, however, F_n , F_p components increase with temperature increases.

$$\int U dx = \frac{n_i}{2\tau_i} x_d$$

$$F_n = \frac{D_n}{L_n} n_{po} = \frac{L_n}{\tau_n} \frac{n_i^2}{N_a}$$

$$F_p = \frac{L_p}{\tau_p} \frac{n_i^2}{N_D}$$

Notice the temperature dependence mostly comes from n_i .

B. Inhomojunction case

- Under forward and reverse bias

- (1) Current-voltage characteristic

The band diagram of a p+-N heterojunction diode at a zero bias condition ($V=0$) and at a forward bias condition ($V>0$) are shown in Fig. 3-3.

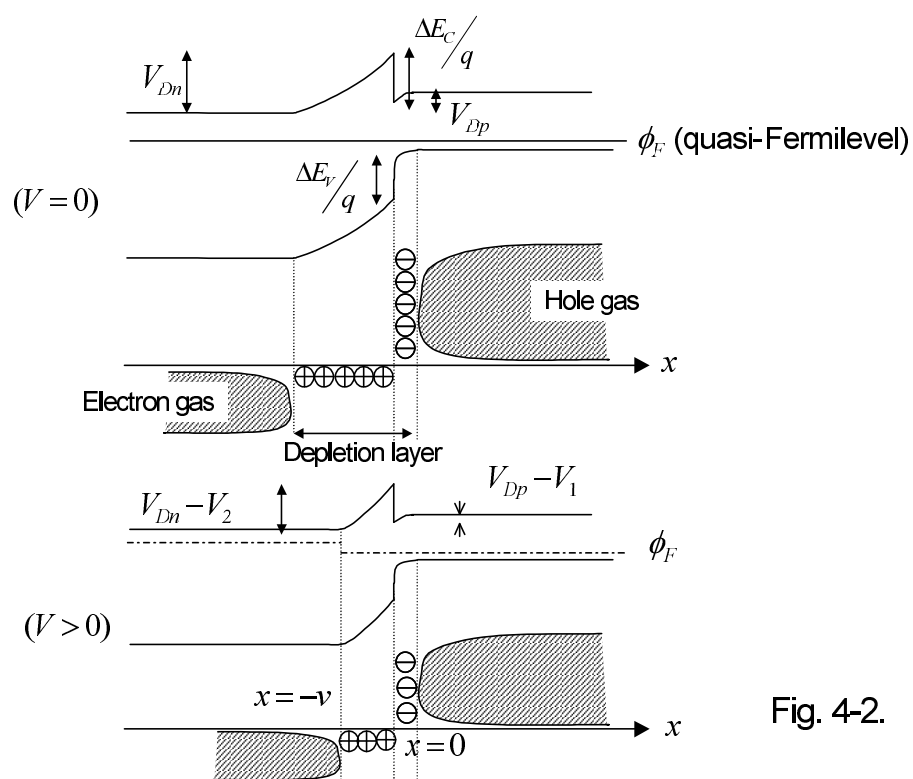


Fig. 4-2.

Fig. 3.3

The built-in potential V_D is supported by the p-layer and N-layer :

$$V_{Dp} = \frac{V_D}{K},$$

(1)

$$V_{Dn} = V_D \left(1 - \frac{1}{K}\right),$$

(2)

where

$$K = 1 + \frac{\varepsilon_1(N_{A1}^- - N_{D1}^+)}{\varepsilon_2(N_{D2}^+ - N_{A2}^-)} \quad (3)$$

In a p⁺-N diode, $\varepsilon_1 > \varepsilon_2$ and $N_{A1}^- - N_{D1}^+ \gg N_{D2}^+ - N_{A2}^-$ so that $K \gg 1$. Consequently, the built-in potential V_D is mainly supported in the N-layer, i.e. $V_{Dn} \simeq V_D$ and $V_{Dp} \simeq 0$. The transmitted electron flux from the N-layer to the p-layer across the potential barrier height V_{Dn} should be equal to the transmitted electron flux from the p-layer to the N-layer across the potential barrier $\Delta E_c/q$, because there is no net at $V=0$.

When a forward bias ($V>0$) is applied, only the potential barrier seen by the electrons in the N-layer decrease to $V_{Dn} - V_2 \simeq V_D - V$. The electron density at the edge of the depletion layer ($x=0$) is given by

$$n_p = X n_{N0} e^{-\frac{V_D - V}{V_T}} = n_{p0} e^{\frac{V}{V_T}}, \quad (4)$$

where

$$n_{p0} = X n_{N0} e^{-\frac{V_D}{V_T}}, \quad (5)$$

is the thermal equilibrium electron density in the p+-layer. X is the transmission coefficient of an electron at the heterojunction interface and n_{p0} is the thermal equilibrium electron density in the N-layer.

The excess electron density (4.5) at $x=0$ diffused towards $x=W$, where a p-side metal contact is located. The distribution of the excess electron density obeys

$$\frac{\partial}{\partial t} n(x, t) = -\frac{n(x, t) - n_{p0}}{\tau_n} - \frac{1}{q} \frac{\partial}{\partial x} i_n(x, t), \quad (6)$$

where the carried by only a diffusion component

$$i_n(x, t) = -qD_n \frac{\partial}{\partial x} n(x, t) \quad (7)$$

Solving (6) and (7) with the boundary conditions,

$$n_p = \begin{cases} n_{p0} e^{\frac{V}{V_T}} & \text{at } t=0 \\ n_{p0} & \text{at } x \gg L_n \end{cases} \quad (8)$$

the steady state solution for $n(x)$ is now given by

$$n(x) = n_{p0} + (n_p - n_{p0}) e^{-x/L_n} \quad (9)$$

The junction current density is determined by the diffusion current (7) at $x=0$:

$$i \equiv i_n(x=0) = \frac{qD_n}{L_n}(n_p - n_{p0}) = \frac{qD_n n_{p0}}{L_n} (e^{\frac{V}{V_T}} - 1) \quad (10)$$

The total current $I=Ai$ versus the junction voltage V is plotted in Fig. 3-4.

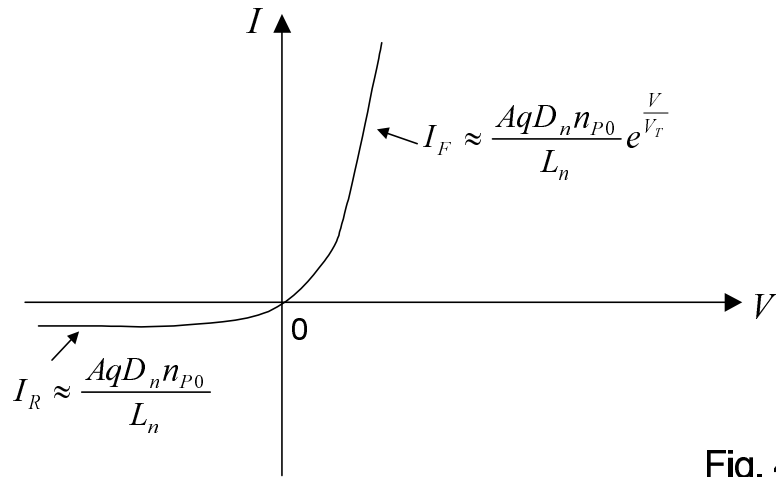


Fig. 4-3.

Fig. 3.4

The differential resistance R_d is defined by $(\frac{dI}{dV})^{-1}$ is given by differentiation of (10) w.r.t. V under a forward bias condition. The diffusion capacitance C_d of the diode is calculated

$$\begin{aligned}
C_d &\equiv A \frac{d}{dV} [q \int_0^\infty [n(x) - n_{p0}] dx] \\
&= \frac{AqL_n n_{p0}}{V_T} e^{\frac{V}{V_T}} \simeq \frac{I}{V_T} \tau_n
\end{aligned}$$

(11)

Here $L_n^2 = D_n \tau_n$ is need. The RC time constant characterized by the differential resistance R_d and the diffusion capacitance C_d is equal to the electron lifetime τ_n as it should be.