

PN junction

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April 20 2012

Abstract

In this laboratory we examined some of the most important characteristics of PN junctions. These include the depletion width, the junction capacitance, and the built-in voltage.

List of symbols

V_T	thermal voltage	V
V_R	reverse-bias voltage	V
V_{bi}	built-in voltage	V
k	Boltzmann's constant	JK^{-1}
T	absolute temperature	K
C	junction capacitance	F
ϵ_s	dielectric permittivity of the semiconductor material	F cm^{-1}
q	electron charge	C
Q_j	junction space-charge	C
n_i	intrinsic carrier concentration	cm^{-3}
N_a	acceptor concentration	cm^{-3}
N_d	donor concentration	cm^{-3}
W	depletion or space-charge width	μm , cm or m

1 Introduction

A PN junction, in its simplest manifestation, is simply a diode. On this basis alone it is worth understanding its behaviour. It also forms the basis of more complex devices, however — including LEDs, lasers, thyristors, and so on. This fact makes a careful study of the PN junction all the more worthwhile.

1.1 Abrupt PN junction

In this laboratory we assumed an idealized PN junction with uniform concentration of doping elements on either side of the junction — and a step change in concentration at the junction itself. This is sometimes referred to as an abrupt PN junction.

1.2 Why are these parameters important?

1.2.1 Junction capacitance

The capacitance of the junction is important as it determines the frequency characteristics of the device (e.g. diode, transistor, etc.). It may be desirable to use the device at very high frequencies, for example, in which case the time constant — and hence the capacitance — of the junction should be as low as feasible. Applications in which this might be relevant include analog-to-digital converters in software-defined radio or other communications devices.

1.2.2 Built-in voltage

Built-in voltage is an important consideration in certain applications. Silicon is the cheapest semiconductor material, but its relatively high threshold voltage renders it unsuitable for certain purposes. Germanium, for example, has a lower built-in voltage than silicon, and was preferred over silicon in radio receivers for a long time. Schottky diodes have an even lower threshold voltage than germanium, and are used in applications such as switched mode power supplies where such characteristics are desirable.

2 Junction characteristics

2.1 Built-in voltage

The built-in voltage, V_{bi} , depends on the carrier concentrations N_a and N_d , and the temperature T . Notably, it does *not* depend on the geometry (thickness, height, area) of the junction. Quantitatively,

$$V_{bi} = V_T \ln \left(\frac{N_d N_a}{n_i^2} \right), \quad (1)$$

where

$$V_T = \frac{kT}{q} \quad (2)$$

is the thermal voltage.

2.1.1 Example — Germanium

Consider a PN junction created on a germanium substrate. Let the doping concentrations be $N_a = 10^{16}\text{cm}^{-3}$ and $N_d = 10^{16}\text{cm}^{-3}$. If the intrinsic carrier concentration of germanium is $2.4 \times 10^{13}\text{cm}^{-3}$, determine the built-in voltage for the junction. Assume an ambient temperature of 300 K. (Expected value: $V_{bi} \approx 0.3\text{V}$.)

$$\begin{aligned}
 V_{bi} &= V_T \ln \frac{N_a N_d}{n_i^2} \\
 &= (25.9\text{mV}) \ln \frac{10^{16} \cdot 10^{16}\text{cm}^{-6}}{(2.4 \cdot 10^{13}\text{cm}^{-3})^2} \\
 &= (25.9\text{mV}) \ln \frac{1 \cdot 10^{32}\text{cm}^{-6}}{5.76 \cdot 10^{26}\text{cm}^{-6}} \\
 &= (25.9\text{mV}) \ln(.174 \cdot 10^6) \\
 &= (25.9\text{mV})(12.067) \\
 &= 313\text{mV} \\
 &\boxed{V_{bi} = .313\text{V}}
 \end{aligned}$$

2.2 Space charge

The space charge — unlike the built-in voltage — does depend on the geometry of the junction. The charge is

$$Q_n = qN_d x_n A. \quad (3)$$

2.3 Depletion width

2.3.1 What is the space-charge region?

The space-charge region is simply that region around the PN junction in which there is a net charge. An isolated P- or N-type extrinsic semiconductor will be electrically neutral. When P- and N-type semiconductor exist side-by-side, however, charge carriers from one type diffuse across the junction to the other. Consider a PN junction under zero reverse-bias, for example. Even with no external bias applied, there is a diffusion of electrons and holes across the junction.

2.3.2 Parameters affecting the depletion width

The depletion-width is a function of the built-in voltage, the carrier concentration, and the permittivity of the semiconductor material. Quantitatively,

$$W = \left[\frac{2\epsilon_s V_{bi}}{q} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2}. \quad (4)$$

The distances the space charge region extends into the N and P regions are

$$x_n = W \cdot \frac{N_d}{N_a + N_d} \quad (5)$$

$$x_p = W \cdot \frac{N_a}{N_a + N_d}. \quad (6)$$

Note, also, that the total depletion width is simply

$$W = x_n + x_p. \quad (7)$$

2.4 Capacitance

The junction capacitance is inversely proportional to the depletion width. Is it determined most simply by using the formula

$$C = \frac{\epsilon_s}{W}. \quad (8)$$

3 Example — A silicon junction

Consider a PN junction formed on a silicon substrate with doping concentrations: $N_a = 10^{16} \text{cm}^{-3}$ and $N_d = 10^{16} \text{cm}^{-3}$. Assuming that the cross-sectional area of the junction is 2500mm^2 , calculate (i) the built-in potential of the junction, (ii) the width of the depletion region, (iii) the charge stored on either side of the junction, and (iv) the capacitance of the junction. (Assume $T = 300\text{K}$.)

3.1 Solution

The built-in voltage is

$$\begin{aligned} V_{bi} &= V_T \ln \left(\frac{N_a N_d}{n_i^2} \right) \\ &= (25\text{mV}) \ln \left(\frac{10^{32} \text{cm}^{-6}}{2.25 \cdot 10^{20} \text{cm}^{-6}} \right) \\ &= (25\text{mV}) \ln(.444 \cdot 10^{12}) \\ &= (25\text{mV})(26.82) \\ &= 670\text{mV}. \end{aligned}$$

$V_{bi} = .67\text{V}$

The width of the depletion region is

$$\begin{aligned} W &= \left[\frac{2\epsilon_s V_{bi}}{e} \left(\frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \\ &= \left[\frac{2(1.04 \cdot 10^{-12} \text{F cm}^{-1})(0.67\text{V})}{1.6 \cdot 10^{-19} \text{C}} \left(\frac{2 \cdot 10^{16} \text{cm}^{-3}}{10^{32} \text{cm}^{-6}} \right) \right]^{1/2} \end{aligned}$$

$$\begin{aligned}
&= \left[\frac{1.394 \cdot 10^{-12} \text{cm}^{-1}}{1.6 \cdot 10^{-19}} (2 \cdot 10^{-16} \text{cm}^3) \right]^{1/2} \\
&\quad [8.71 \cdot 10^6 \cdot 2 \cdot 10^{-16} \text{cm}^2]^{1/2} \\
&\quad = \sqrt{17.42 \cdot 10^{-10} \text{cm}} \\
&\quad = 4.174 \cdot 10^{-5} \text{cm} \\
&= 4.174 \cdot 10^{-7} \text{m} = .417 \cdot 10^{-6} \text{m}. \\
&\quad \boxed{W = .417 \mu\text{m}}
\end{aligned}$$

The distance the space charge region extends into the p region is

$$\begin{aligned}
x_p &= W \cdot \frac{N_a}{N_a + N_d} \\
&= (.417 \mu\text{m}) \cdot \frac{1}{2} \\
&\approx .209 \mu\text{m}.
\end{aligned}$$

$$\boxed{x_p = x_n \approx .209 \mu\text{m} = 209 \text{nm}}$$

To determine the total space charge, we use equation 3.

$$\begin{aligned}
Q_j &= qN_d x_n A \\
&= (1.6 \cdot 10^{-19} \text{C})(10^{16} \text{cm}^{-3})(209 \cdot 10^{-7} \text{cm})(.25 \text{cm}^2) \\
&= 8.36 \cdot 10^{-9} \text{C}.
\end{aligned}$$

$$\boxed{Q_j = Q_n = Q_p = 8.36 \cdot 10^{-9} \text{C}}$$

Finally, the capacitance of the junction is

$$\begin{aligned}
C &= \frac{\epsilon_s}{W} \\
&= \frac{1.04 \cdot 10^{-12} \text{F cm}^{-1}}{.417 \cdot 10^{-4} \text{cm}} \\
&= 24.9 \text{nF}.
\end{aligned}$$

$$\boxed{C = 24.9 \text{nF}}$$

4 Simulation

Figure 1 shows the results of various simulations in MATLAB. The depletion region is denoted by the color white. It can be noted (Figures 1a and 1b) that the depletion width increases according to the reverse voltage, V_R .

The width of the depletion region also depends on the doping concentration. Compare Figures 1a and 1d, for example. While the reverse voltage is 0 V in both cases, the depletion width in the latter is much smaller. This is due to the much higher doping concentrations in Figure 1d. The basis for this disparity can be understood from equation 4.

Finally, as indicated in equation 8, the capacitance of the junction is inversely proportional to the depletion width (Figures 1c and 1d).

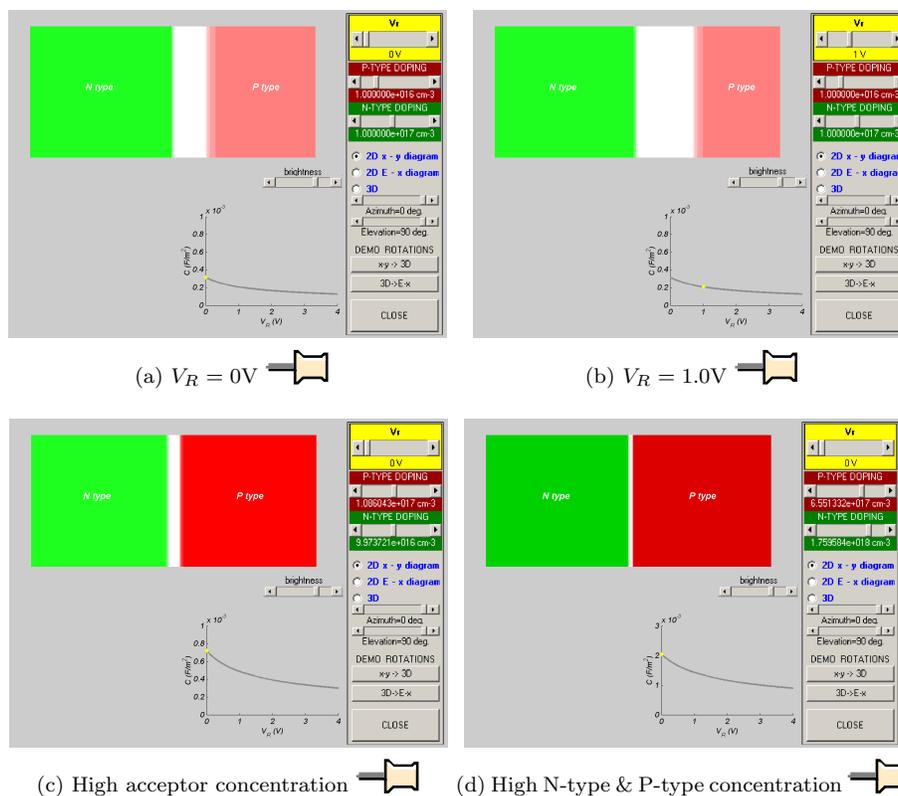


Figure 1: Simulation of a PN junction in MATLAB

5 Conclusion

5.1 Summary

We have demonstrated that the most important characteristics of PN junctions can be determined once we know the doping concentrations and certain parameters of the semiconductor material itself. The values calculated for the built-in voltage of both silicon and germanium were close to those expected.

In so doing we have gained a brief initial insight into the sort of design processes that are carried out in the semiconductor industry.

5.2 Computer simulation

In this laboratory the calculations were relatively simple and the use of computer simulation was not vital. Nonetheless, computer simulation is invaluable in the design of more complex semiconductor devices. Hence it is useful to be

acquainted with the relevant software. For the purposes of this exercise we used MATLAB but more specialised tools are available also. Simulation prior to fabrication can significantly reduce the risk of error and shortcomings in the design.