EEE105 - Electronic Devices
Lecture 14

Photodiodes

(CAL: photopn)

In a photodetector we wish to convert a light signal into an electrical signal, which we can then use in some manner. There are many photodetector types that can be made in semiconductors. One is a photoconductor, where we use a piece of intrinsic (or nearly intrinsic) semiconductor material. When light is shone upon it excess holes and electrons are created. Hence the conductivity of the material increases. In this situation the resistance measured will drop according to the amount of light being absorbed by the sample.

A diode can also be used to detect a light signal. In this case the diode is normally reverse biased. When light is shone on the sample the photons can be absorbed, creating electron-hole pairs.

Let us first consider the situation where the electron and hole are created in the depletion region of a reverse biased diode. In the depletion region there is an electric field. This electric field acts to prevent majority carrier electrons moving to the p-type material, and vice-versa. The field will therefore accelerate the free electron into the n-type material and the hole into the p-type material, this electron and hole will consequently appear at the terminals of the device. This means that if we create electron-hole pairs in the depletion region they will give a current in the device.

If the electron-hole pair is created in the p- or n-type material, we need to consider what happens to the minority carrier. So let us consider the p-type material. The electron will start diffusing in the p-type material, usually towards the depletion region. If the electron recombines in the p-type material then it Is lost and there will be no contribution to the current flow in the device. If, however, it reaches the depletion region it will be swept by the field into the n-type material, where it becomes a majority carrier, and will appear as current in the device.

The current generated by light being absorbed creating electron-hole pairs is called a photocurrent.

Note that there is also a built-in potential in the device even at zero bias. This means that current can be induced to flow in the p-n junction if we apply light to it. This is the principle of a ***solar-cell.***

Diode Depletion Width

(CAL: pn(n) ,pn(o), pn(p))

Similarity with a capacitor:

There are many types of transistor that can be made in semiconducting materials. These allow the control of a relatively large current, using either a small current, or a voltage.

In the Junction Field Effect Transistor (JFET) the device relies upon control of the depletion region thickness (or depletion width) for its operation. Thus before moving on to discuss transistors fully we need to discuss how the depletion width varies in a semiconductor p-n junction.

Now from before we can draw:

Now in the region of width $d_p = d_1$

We have: $\rho_p = -qN_a$ coulombs/volume

Now in the region of width $d_n = d_2$

We have: coulombs/volume $\rho_n = -qN_d$

Outside of the region given by $d_j = d_p + d_n$ the material must be neutral. As we are in equilibrium then the space charge densities must balance. (that is the charge on either side of the junction must be the same):

$qN_a d_1 = qN_d d_2$ which gives us by simple rearrangement: $\frac{d_1}{d_2} = \frac{N_d}{N_a}$.

This means that the depletion region thickness is inversely proportional to the doping concentration.

The E-field in the depletion region can be characterised using Poisson's Equation: $\frac{dE}{dx} = \frac{\rho}{\varepsilon}$

Where

Now we know that outside the region given by d_j, the material is neutral and there is no field.

If we consider field lines then the strength of the electric field can be given by the density of field lines at any point along the x-axis, given that it is a one-dimensional problem. We can draw these field lines between the charges as shown in the picture:

Clearly the maximum density of field lines will occur at the junction, meaning that the field will have the largest value (ignoring the sign) at that point. Hence the field variation can be drawn as in the figure to the right:

From Poisson's Equation the slope of the line describing the variation of the field in the depletion region on the p-type side of the junction will be:

$$\frac{dE}{dx} = -\frac{N_a q}{\varepsilon}$$

and similarly in the depletion region on the n-type side of the junction we will have:

$$\frac{dE}{dx} = \frac{N_d q}{\varepsilon}$$

Now as the value of dE/dx is a constant hence, $E = const \cdot x$ (or a straight line of constant slope –as shown)

Now for the p-type side (where $-d_1 \le x \le 0$) we have $\frac{dE}{dx} = -\frac{N_a q}{\varepsilon}$

Hence $$E(x) = \int -\frac{N_a q}{\varepsilon} dx = -\frac{N_a q x}{\varepsilon} + C$$

Now we have a boundary condition that E=0 at x=-d_1

Therefore $\frac{N_a q d_1}{\varepsilon} + C = 0$ and hence $C = -\frac{N_a q d_1}{\varepsilon}$

Thus we can write $E(x) = -\frac{N_a q (x + d_1)}{\varepsilon}$

Similarly for the region given by $0 \le x \le d_2$ we will have $E(x) = \frac{N_a q(x - d_2)}{\varepsilon}$

Now the maximum value of the field will occur at *x*=0: $E(0) = -\frac{N_d q d_2}{\varepsilon} = -\frac{N_a q d_1}{\varepsilon}$

The built-in potential V_0 is given by: $V_0 = -\int_{-d_1}^{d_2} E(x)dx$

Rather than integrating this let us remember what an integration represents:

Using this approach:

$$V_0 = \tfrac{1}{2} \cdot d_1 \cdot \frac{N_a q d_1}{\varepsilon} + \tfrac{1}{2} \cdot d_2 \cdot \frac{N_d q d_2}{\varepsilon} = \frac{N_a q d_1^2}{2\varepsilon} + \frac{N_d q d_2^2}{2\varepsilon} = \frac{q\left(N_a d_1^2 + N_d d_2^2\right)}{2\varepsilon}$$

Now to simplify this let us look at the situation where the doping is much heavier on one side of the junction than the other (for example where $N_a >> N_d$). In this situation the depletion region will be much thinner on one side of the junction than the other (if $N_a >> N_d$ then we will have $d_1 << d_2$). In this case the equation above can be reduced to:

$$V_0 = \frac{q N_d d_2^2}{2\varepsilon} \qquad \text{which we can write as } d_j \approx d_n = d_2 = \left(\frac{2\varepsilon_0 \varepsilon_r V_0}{q N_d}\right)^{1/2}$$

For the case where we have a p^+-n junction.

Under Bias:

As before in this equation we can modify for the case where we apply forward or reverse bias:

In forward bias instead of V_0 we should use

In reverse bias instead of V_0 we should use

Thus from the above we can see that under forward bias the depletion region will decrease in thickness, and in many forward bias conditions we can ignore its existence.

In reverse bias clearly the depletion width increases with increasing reverse bias voltage, and at large values of reverse bias we can assume: $V >> V_0$ and hence we get the relationship that $d_j \propto V^{1/2}$ for a p^+-n junction.

Diode Junction Capacitance

(CAL: pn(q))

Now as we said at the earlier in this lecture the depletion region is an insulating region (or the dielectric) in a parallel plate capacitor.

Therefore we can write that the capacitance of the p-n junction is: $C_j = \frac{\varepsilon A}{d_j}$.

Substituting for d_j gives: $C_j = \left(\frac{q\varepsilon N_d}{2V_j}\right)^{1/2} \cdot A$ for a p^+-n junction

Where $V_j = V_0 + V$ or $V_j = V_0 - V$ depending on the bias applied to the junction.

Note: $V_j \sim V$ and $C_j \sim V^{-1/2}$ for large reverse bias.

Note that this device can be used as a variable capacitor!

Key Points to Remember:

1. If light is absorbed by a reverse biased p-n junction then a photo-current can be induced
    a. This is the basis of a photodiode
    b. For the carriers to contribute to the current at least one of them must be swept into the opposite side of the junction by the depletion region field.
2. A photo-current can also be induced at zero-bias giving the basis of a solar cell.
3. The depletion region width of a diode depends on the doping
4. The depletion region will mainly be on the lower doped side of a p-n junction.
5. The depletion region will be reduced under forward bias and increase under reverse bias
    a. Under high reverse bias the width will increase in proportion to the square root of the applied voltage
6. The depletion region can be used as the dielectric of a capacitor
    a. Changing the reverse bias can change the capacitance.