(n) The Potential Variation within a Graded Semiconductor

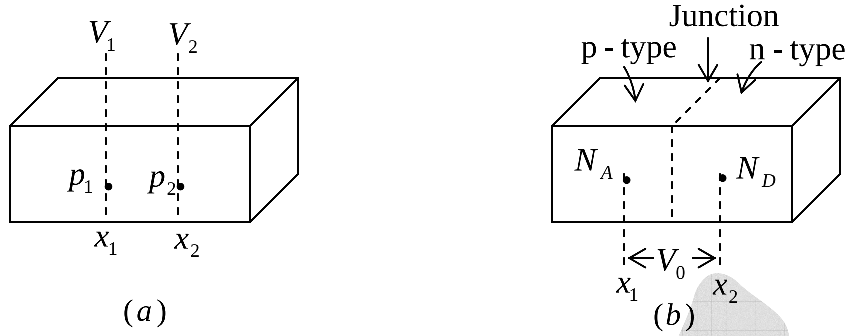

Figure (a): A graded semiconductor: *p(x)* is not constant

(b): One portion is doped with (uniformly) acceptor ions and the other section is doped uniformly with donor ions so that a metallurgical junction is formed.

Consider a semiconductor where the hole concentration *p* is a function of *x*; that is, the doping is non-uniform or graded. Assume a steady-state situation and zero excitation; that is, no carriers are injected into the specimen from any external source. With no excitation there can be no steady movement of charge in the bar, although the carriers possess random motion due to thermal agitation. Hence the total hole current must be zero (also, the total electron current must be zero). Since *p* is not constant, we expect a non-zero hole diffusion current. In order for the total hole current to vanish there must exist a hole drift current which is equal and opposite to the diffusion current. However, conduction current requires an electric field and hence we conclude that, as a result of the non-uniform doping, an electric field is generated within the semiconductor. We shall now find this field and the corresponding potential variation throughout the bar.

Since $J_p = q\mu_p pE - qD_p \frac{dp}{dx} \Rightarrow E = \frac{V_T}{p}\frac{dp}{dx}$ $\quad \because J_p = 0$ and then use $D_p = \mu_p V_T$

If the doping concentration $p(x)$ is known, this equation allows the built in field $E(x)$ to be calculated.

$$\because E = -\frac{dV}{dx} \Rightarrow dV = -V_T \frac{dp}{p}.$$

If this equation is integrated between x_1, where the concentration is p_1 and the potential is V_1 and x_2 where $p = p_2$ and $V = V_2$, the result is: $V_{21} \equiv V_2 - V_1 = V_T \ln \frac{p_1}{p_2}$

Note: The potential difference between two points depends only upon the concentration at these points and is independent of their separation $\left(x_2 - x_1\right)$.

Above equation can be put in the form $p_1 = p_2 e^{V_{21}/V_T}$

This is the Boltzmann relationship of kinetic gas theory.

Starting with $J_n = 0$ and proceeding as above, the Boltzmann equation for electrons is obtained as $n_1 = n_2 e^{-V_{21}/V_T}$. Now $n_1 p_1 = n_2 p_2$.

This equation states that the product np is a constant independent of x, and hence the amount of doping, under thermal equilibrium.

For an intrinsic semiconductor $n = p = n_i$ and hence $np = n_i^2$.

An Open-Circuited Step-graded Junction

Consider the special case indicated in figure (b). The left half of the bar is *p*-type with a constant concentration N_A, whereas the right-half is *n*-type with a uniform density N_D. The dashed plane is a metallurgical $\left(p-n\right)$ junction separating the two sections with different concentrations. This type of doping where the density changes abruptly from p to n type is called step-grading. The step graded junction is located at the plane where the concentration is zero. The above theory indicates that there is built-in potential between these two sections (called the contact difference of potential V_o.)

Thus $V_o = V_{21} = V_T \ln \dfrac{p_{p_o}}{p_{n_o}}$

Because $p_1 = p_{p_o}$ = thermal-equilibrium hole concentration in *p*-side

$p_2 = p_{n_o}$ = thermal equilibrium hole concentration in *n*-side

since $p_{p_o} = N_A$ and $p_{n_o} = \dfrac{n_i^2}{N_D}$ $\Rightarrow$ $\boxed{V_o = V_T \ln \dfrac{N_A N_D}{n_i^2}}$

Summary:

1. In a semiconductor two types of mobile charge carriers are available. The bipolar nature of a semiconductor is to be contrasted with the unipolar property of a metal, which possesses only free electrons.

2. A semiconductor may be fabricated with donor (acceptor) impurities. So it contains mobile charges which are primarily electrons (holes).

3. The intrinsic carrier concentration is a function of temperature. At room temperature, essentially all donors or acceptors are ionized.

4. Current is due to two distinct phenomenons:

(a) Carriers drift in an electric field (this conduction current is also available in metals).

(b) Carriers diffuse if a concentration gradient exists (a phenomenon, which does not take place in metals).

5. Carriers are continuously being generated (due to thermal creation of hole-electron pairs) and are simultaneously disappearing (due to recombination).

6. The fundamental law governing the flow of charges is called the *continuity equation*. It is formulated by considering that charges can neither be created nor destroyed if generation, recombination, drift and diffusion are all taken into account.

7. If the minority carriers are injected into a region containing majority carriers, then usually the injected minority concentration is very small compared with the density of the majority carries. For this low-level injection condition the *minority current is predominantly due to diffusion*; in other words, the minority drift current may be neglected.

8. The total majority-carrier flow is the sum of a drift and diffusion current. The majority conduction current results from a small electric field internally created within the semiconductor because of the injected carriers.

9. The minority-carrier concentration injected into one end of a semiconductor bar decreases exponentially with distance into the specimen (as a result of diffusion and recombination).

10. Across an open-circuited p-n junction there exists a contact difference of potential.