Diodes & BJTs

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Solution:

$$n_H = n_h = \frac{n_i^2}{N_D} = \frac{(1.45\times10^{10})^2}{10^{14}} = 2.10\times10^6 \text{cm}^{-3}$$

When doped this way, the probability of finding free *electrons* e^-'s is higher than that of finding *holes* h^+'s. So E_F in N-type material is closer to the conduction band in Fig. 2 than to the valence band. Since the probability of finding charge carriers drops exponentially away from E_F and the band gap is free of carriers, n_E peaks at the edge of the conduction band and decreases exponentially above E_C. Although to a lower extent, n_H similarly peaks at the edge of the valence band (where electrons are more likely to break free) and decreases exponentially below E_V.

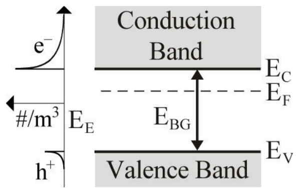

Fig. 2. Band diagram of N-type semiconductors.

B. P Type

Acceptor atoms produce the opposite effect. Electrons in the outermost orbit of acceptor atoms are so tightly bound in doped semiconductors that they are in the valence band. This outer orbit is incomplete, however, with electron vacancies or holes h^+'s. Since these impurities are more likely to "accept" than donate electrons, engineers say material doped with acceptor atoms is positive or *P type*. The material is nevertheless electrically neutral because the intrinsic and dopant atoms that comprise it are neutral.

With more holes in the valence band, the probability that thermionic electrons in the conduction band recombine is higher, so n_E and n_H are

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Example 2: Find n_H and n_E outside the depletion region at 27° C for a PN junction doped with $10^{17}/cm^3$ acceptor atoms and $10^{14}/cm^3$ donor atoms.

Solution:

$$n_{H(P)} \approx N_A = 10^{17} cm^{-3}$$

$$n_{E(P)} \approx n_{e(P)} = \frac{n_i^{\ 2}}{N_A} = \frac{(1.45 \times 10^{10})^2}{10^{17}} = 2.10 \times 10^3 cm^{-3}$$

$$n_{H(N)} \approx n_{h(N)} = \frac{n_i^{\ 2}}{N_D} = \frac{(1.45 \times 10^{10})^2}{10^{14}} = 2.10 \times 10^6 cm^{-3}$$

$$n_{E(N)} \approx N_D = 10^{14} cm^{-3}$$

Note: $n_{E(P)}$'s $n_{e(P)}$ is lower than $n_{H(N)}$'s $n_{h(N)}$ because the P side is more heavily doped than the N side, so more thermionic electrons recombine.

D. Depletion Width

More densely populated regions require less space to neutralize incoming carriers. So depletion distances from the junction are shorter when doping concentrations are higher. Total *depletion width* d_W is therefore shorter when N_A and N_D are higher:

$$d_W = d_P + d_N \propto \sqrt{\frac{1}{N_A} + \frac{1}{N_D}} \ . \qquad (6)$$

Opposing doping concentrations across PN junctions are usually vastly different. In such cases, the highly doped region diffuses more carriers than the lightly doped side. With more incoming carriers and less neutralizing agents, depletion distance in the lightly doped side is far breakdown. So since i_D is high and negative in breakdown, i_D in Fig. 14 skyrockets down near $-V_{BD}$, saturates to $-I_S$ in reverse bias, increases exponentially with v_D in forward bias, and skyrockets up near V_{BI}.

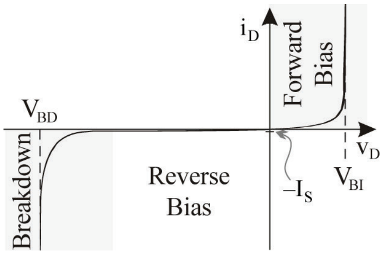

Fig. 14. Diode's Current–voltage translation.

The diode is practically a short in breakdown and at V_{BI} and an open circuit otherwise. This is why engineers often use them as on–off switches. When used this way, the diode switch closes and drops close to V_{BI} with forward current and opens whenever current reverses.

C. Dynamic Response

<u>Small Variations</u>: Shifting the operating point of a diode requires charge. Raising the barrier voltage, for example, repels recombined carriers back to their home regions. The number of carriers that diffuse across the junction also decreases. Moving these carriers changes the charge concentration across the junction.

This requires time because i_D carries a finite amount of charge per second. So the current and charge needed Δi_D and Δq_D to vary the voltage Δv_D dictate the response time Δt_R of the diode. *Junction capacitance* C_J, which is the charge held across the junction with one volt, relates these parameters:

$$C_J = \frac{\Delta q_D}{\Delta v_D} = \frac{\Delta i_D \Delta t_R}{\Delta v_D} = C_{DEP} + C_{DIF} . \qquad (12)$$

Depletion capacitance C_{DEP} is the component that the depletion region holds. *Diffusion capacitance* C_{DIF} is the diffusion charge held in transit.

hot-carrier diodes are also common appellations because diffusing electrons carry more energy than electrons in the metal.

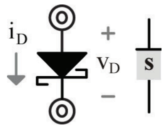

Fig. 20. Schottky (metal–semiconductor) diode symbol.

B. I–V Translation

i_D rises so much when v_D reaches V_{BI} that the junction practically shorts, like Fig. 14 shows. Reinforcing the barrier with a negative v_D induces so little i_R that the device opens like a switch. When the reverse voltage is high enough, however, the junction breaks down and shorts to conduct substantial i_R. So this diode behaves very much like the PN diode.

This diode, however, normally diffuses fewer carriers with zero bias than the PN junction. So the V_{BI} that these diffusing electrons establish is usually lower, about 150–300 mV. With a lower barrier, more thermionic electrons cross when v_D reverses, so I_S is also higher. Since diffusing electrons in the metal do not recombine like they would in a P region, the non-ideality factor is closer to one.

C. Dynamic Response

Carriers that diffuse away and vanish from the depletion region ionize the junction. Since the barrier voltage $V_{BI} – v_D$ keeps more carriers from diffusing, reducing v_D reduces the number of carriers that vanish and the charge they establish. Depletion capacitance C_{DEP} therefore holds less charge when v_D falls and reverses, like in the PN diode. C_{DEP} also scales with doping concentration because more carriers diffuse when carrier density is higher.

Unlike PN diodes, however, forward-bias electrons do not traverse a P region before reaching a metallic contact. So they do not require forward transit time τ_F to feed i_D. This means that the process of the junctions diffuse away into the N regions. So the depletion regions effectively squeeze the base.

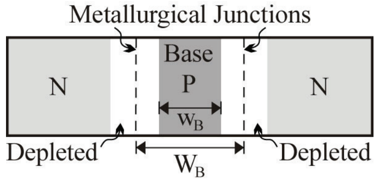

Fig. 23. NPN BJT structure.

A. Active

Bias: With a short base, the BJT *activates* when one diode forward-biases and the other diode reverses. In Fig. 24, the *base voltage* v_B forward-biases the junction on the left with respect to v_E and reverse-biases the junction on the right with respect to v_C. So v_C is greater than v_B, which is in turn greater than v_E. As a result, the barrier voltage and depletion region on the left decrease and the counterparts on the right increase.

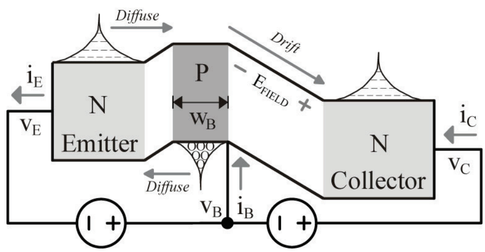

Fig. 24. Band diagram of NPN when activated.

Electrostatics: Electrons and holes therefore diffuse across the junction on the left. w_B is so short that almost all diffused electrons reach the opposite end of the base without recombining. Since v_C is greater than v_B, v_C pulls these base electrons across the depletion region into the N region on the right.

This way, the N region on the left "emits" the electrons that the N region on the right "collects". And as this happens, the P base injects