3.4.2 Bipolar Transistors

Basic Concept and Operation

We are not particularly interested in **bipolar transistors** and therefore will treat them only cursory.

- Essentially, we have two junctions diodes switched in series (sharing one doped piece of **Si**), i.e. a **npn** or a **pnp** configuration, with the *added condition* that the middle piece (the **base**) is *very thin*. "Very thin" means that the base width d_{base} is much smaller than the diffusion length L.

The other two doped regions are called the **emitter** and the **collector**.

- For transistor operation, we switch the emitter - base (**EB)** diode in forward direction, and the base - collector (**BC**) diode in reverse direction as shown below.
- This will give us a large forward current and a small reverse current - which we will simply neglect at present - in the **EB** diode, exactly as described for diodes . What happens in the **BC** diode is more complicated and constitutes the principle of the transistor.
- In other words, in a **pnp** transistor, we are injecting a lot of holes into the base from the emitter side and a lot of electrons into the emitter from the base side; and vice versa in a **npn**- transistor. Lets look at the two **EB** current components more closely transistor:

For the *hole* forward current, we have in the simplest approximation (ideal diode, no reverse current; no **SCR** contribution):

$$j_{hole}(U) = \frac{e \cdot L \cdot n_i^2}{\tau \cdot N_{Acc}} \cdot \exp - \frac{e \cdot U}{kT}$$

- and the relevant quantities refer to the *hole* properties in the ***n** - doped base* and the doping level N_{Acc} in the ***p** - doped emitter*. For the electron forward current we have accordingly:

$$j_{electron}(U) = \frac{e \cdot L \cdot n_i^2}{\tau \cdot N_{Don}} \cdot \exp - \frac{e \cdot U}{kT}$$

- and the relevant quantities refer to the *electron* properties in the ***p** - doped emitter* and the doping level N_{Don} in the ***n** - doped base*.
- The relation between these currents, i.e. $j_{hole}/j_{electron}$, which we call the **injection ratio** κ, then is given by

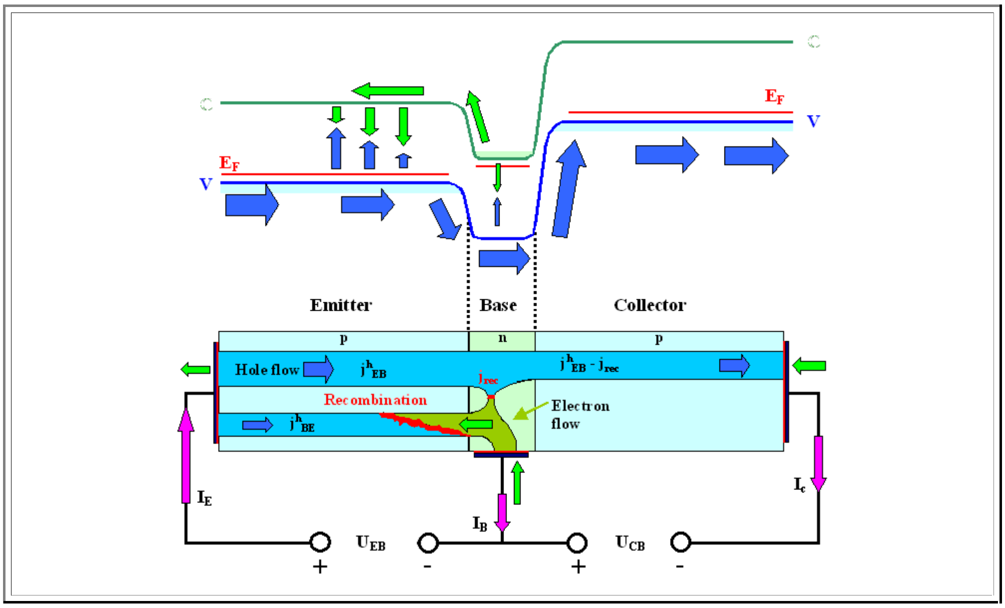
$$\kappa = \frac{\dfrac{L_h}{\tau_h \cdot N_{Ac}}}{\dfrac{L_e}{\tau_e \cdot N_{Don}}} = \frac{N_{Ac}}{N_{Don}}$$

- Always assuming that electrons and holes have identical lifetimes and diffusion lengths.

The *injection ratio* κ is a prime quantity. We will encounter it again when we discuss for optoelectronic devices!

For only one diode, that would be all. But we have a second diode right after the first one. The holes injected into the base from the emitter, will diffuse around in the base and long before the die a natural death by recombination, they will have reached the other side of the base

- There they encounter the electrical field of the base-collector **SCR** which will sweep them rapidly towards the collector region where they become majority carriers. In other words, we have a large hole component in the reverse current of the **BC** diode (and the normal small electron component which we neglect).
- A band diagram and the flow of carriers is shown schematically below in a band diagram and a current and carrier flow diagram.



- Lets discuss the various currents going from left to right.
  - At the *emitter contact*, we have two hole currents, $j_{EB}{}^{h}$ and $j_{BE}{}^{h}$ that are converted to electron currents that carry a negative charge away form the emitter. The technical current (mauve arrows) flows in the opposite direction by convention.
- For the *base current* two major components are important:
  - **1.** An electron current $j_B{}^{e}$, directly taken from the *base contact*, most of which is injected into the emitter. The electrons are minority carriers there and recombine within a distance L with holes, causing the small hole current component shown at the emitter contact.
  - **2.** An internal recombination current j_{rec} caused by the few holes injected into the base from the emitter that recombine in the base region with electrons, and which reduces $j_B{}^{e}$ somewhat. This gives us

$$j_{BE}{}^{h} \;=\; j_B{}^{e} \;-\; j_{rec}$$

  - Since all holes would recombine within L, we may approximate the fraction recombining in the base by

$$j_{rec} \;=\; j_{EB}{}^{h} \cdot \frac{d_{base}}{L}$$

- Last, the current at the *collector contact* is the *hole* current $j_{EB}{}^{h} - j_{rec}$ which will be converted into an electron current at the contact.
- The external terminal *currents* I_E,I_B, and I_C thus are related by the simple equation

$$I_E \;=\; I_B \;+\; I_C$$

- A bipolar transistor, as we know, is a *current amplifier*. In black box terms this means that a small current at the the *input* causes a large current at the *output* .
  - The input current is I_B , the output current I_C. This gives us a current amplification factor γ of

$$\gamma = \frac{I_C}{I_B} = \frac{I_E}{I_B} - 1$$

  - Lets neglect the small recombination current in the base for a minute. The emitter current (density) then is simply the total current through a **pn**-junction, i.e. in the terminology from the picture $j_E = j_{BE}{}^{h} + j_B{}^{e}$, while the base current is just the electron component $j_B{}^{e}$.
  - This gives us for I_E/I_B and finally for γ:

$$\frac{I_E}{I_B} = \frac{j_{BE}^{h} + j_B^{e}}{j_B^{e}} = \kappa + 1$$

$$\gamma = \frac{I_E}{I_B} - 1 = \kappa + 1 - 1 = \kappa = \frac{N_{Ac}}{N_{Don}}$$

- *Now this is really easy*! We will obtain a large current amplification (easily **100** or more), if we use a lightly doped base and a heavily doped emitter. And since we can use large base - collector voltages, we can get heavy power amplification, too.
    - Making better approximations is not difficult either. Allowing somewhat different properties of electrons and holes and a finite recombination current in the base, we get

$$\gamma = \frac{\dfrac{L_h}{\tau_h \cdot N_{Ac}}}{\dfrac{L_e}{\tau_e \cdot N_{Don}}} \cdot \left(1 - \frac{d_{base}}{L}\right) \approx \frac{N_{Don}}{N_{DAc}} \cdot \left(1 - \frac{d_{base}}{L}\right)$$

    - The approximation again is for identical life times and diffusion lengths.
- Obviously, you want to make the base width d_{base} small, *and* keep L large.

Real Bipolar Transistors

- Real bipolar transistors, especially the very small ones in integrated circuits, are complicated affairs; for a quick glance on how they are made and what the **pnp** or or **npn** part looks like, use the link.
- Otherwise, everything mentioned in the context of real diodes applies to bipolar transistors just as well. And there are, of course, some special topics, too.
    - But we will *not* discuss this any further, except to point out that the "small device" topic introduced for a simple p-n-junction now becomes a new quality:
    - Besides the length of the emitter and collector part which are influencing currents in the way discussed, we now have the **width of the base region** d_{base} which introduces a new quality with respect to device dimensions and device performance.
    - The numerical value of d_{base} (or better, the relation d_{base}/L), does not just change the device properties somewhat, but is the *crucial* parameter that brings the device into existence. A transistor with a base width of several **100 µm** simply is not a transistor, neither are two individual diodes soldered together.
- The immediate and unavoidable consequence is that at this point of making semiconductor devices, *we have to make things real small*.
    - Microtechnology - typical lengths around or below **1 µm** (at least in one dimension) - is mandatory. There are no big transistors in more than two dimensions.
    - Understanding *microscopic* properties of materials (demanding quantum theory, statistical thermodynamics, and so on) becomes mandatory. *Materials Science and Engineering was born*.