Basic Bipolar Transistor

For the purpose of this basic module, we simply take the contents of the "Bipolar Transistor" module from the *Semiconductor Hyperscript*.

- There you will always find the newest version; the module is reproduced below.

- It is about as basic as it can be - just assuming that you know the *basics about pn-junctions*.

- If you remember **pn**-junctions diodes only vaguely (or not at all), turn to the diode parts of the Semiconductor Hyperscripts and check the links from there.

If you understand German; this link will bring you to the relevant parts of the Hyperscript "Einführung in die Materialwissenschaft **II**"

Bipolar Transistors: Basic Concept and Operation

We are not very 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:

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.

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 they 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.
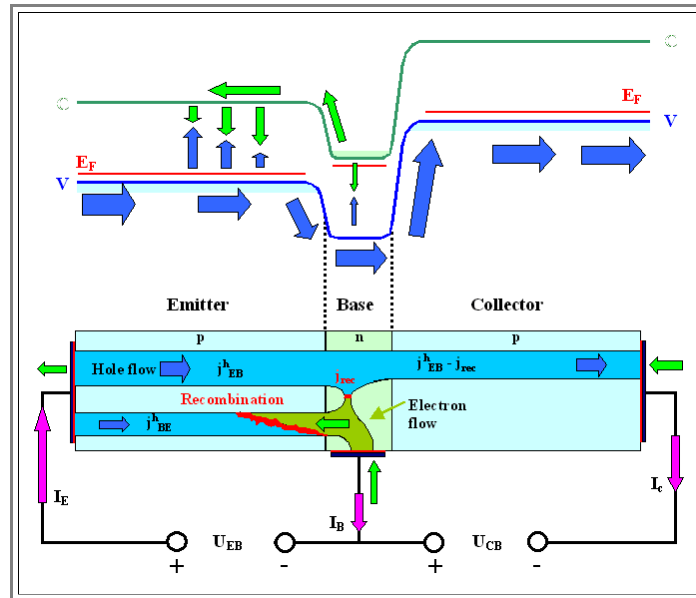
Let's discuss the various currents going from left to right.

- 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 from 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

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

- 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 **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*.