

5. General Aspects of Silicon Technology

5.0 Required Reading

5.0.1 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):

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

- 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:

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

- 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. $j_{\text{hole}}/j_{\text{electron}}$, which we call the **injection ratio** κ , then is given by

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

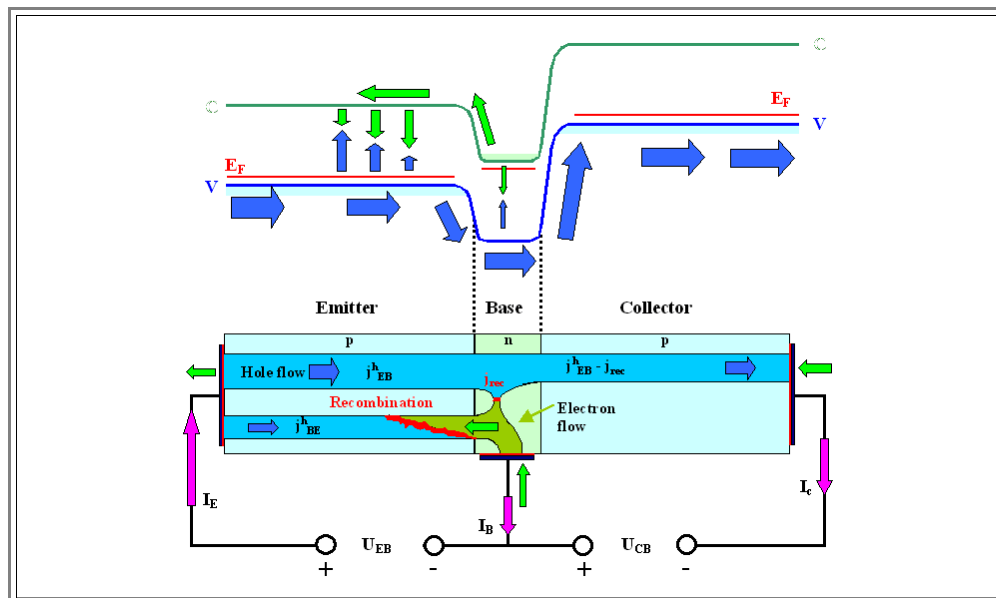
- Always assuming that electrons and holes have identical lifetimes and diffusion lengths.

The **injection ratio** κ is a prime quantity. We will encounter it again when we discuss optoelectronic devices! (in a separate lecture course).

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

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

Last, the current at the **collector contact** is the **hole** current $j_{\text{EB}}^{\text{h}} - j_{\text{rec}}$ which will be converted into an **electron** current at the contact.

The external terminal **currents** $I_{\text{E}}, I_{\text{B}}$, and I_{C} thus are related by the simple equation

$$I_{\text{E}} = I_{\text{B}} + I_{\text{C}}$$

A bipolar transistor, as we know, is a **current amplifier**. In black box terms this means that a small current at 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

$$\gamma = \frac{I_{\text{C}}}{I_{\text{B}}} = \frac{I_{\text{E}}}{I_{\text{B}}} - 1$$

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 $j_{\text{E}} = j_{\text{BE}}^{\text{h}} + j_{\text{B}}^{\text{e}}$, while the base current is just the electron component j_{B}^{e} .

This gives us for $I_{\text{E}}/I_{\text{B}}$ and finally for γ :

$$\frac{I_{\text{E}}}{I_{\text{B}}} = \frac{j_{\text{BE}}^{\text{h}} + j_{\text{B}}^{\text{e}}}{j_{\text{B}}^{\text{e}}} = \kappa + 1$$

$$\gamma = \frac{I_{\text{E}}}{I_{\text{B}}} - 1 = \kappa + 1 - 1 = \kappa = \frac{N_{\text{Ac}}}{N_{\text{Don}}}$$

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

$$\gamma = \frac{\frac{L_{\text{h}}}{\tau_{\text{h}} \cdot N_{\text{Ac}}}}{\frac{L_{\text{e}}}{\tau_{\text{e}} \cdot N_{\text{Don}}}} \cdot \left(1 - \frac{d_{\text{base}}}{L} \right) \approx \frac{N_{\text{Don}}}{N_{\text{Ac}}} \cdot \left(1 - \frac{d_{\text{base}}}{L} \right)$$

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*.

Questionnaire

Multiple Choice questions to 5.0.1