

## 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 **pn** configuration, with the *added condition* that the middle piece (the **base**) is *very thin*. "Very thin" means that the base width  $d_{\text{base}}$  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 **pn** 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  $N_{\text{Acc}}$  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  $N_{\text{Don}}$  in the *n - doped base*.
- The relation between these currents, i.e.  $j_{\text{hole}}/j_{\text{electron}}$ , which we call the **injection ratio**  $\kappa$ , then is given by

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

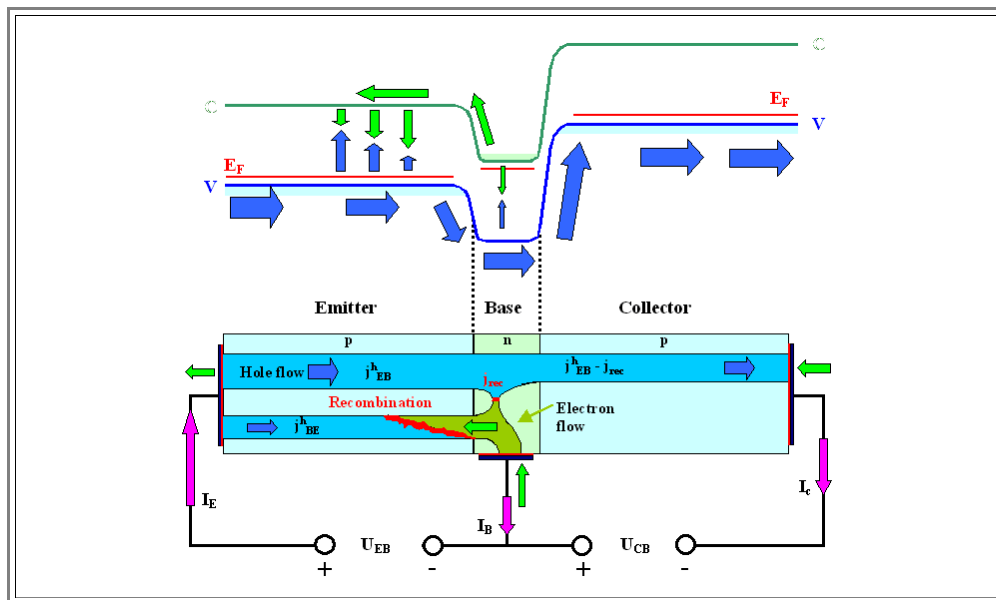
Always assuming that electrons and holes have identical lifetimes and diffusion lengths.

The *injection ratio*  $\kappa$  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

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

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 *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  $\gamma$  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  $j_E = j_{EB}^h + j_B^e$ , while the base current is just the electron component  $j_B^e$ .

This gives us for  $I_E/I_B$  and finally for  $\gamma$ :

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

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

*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

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

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**  $d_{\text{base}}$  which introduces a new quality with respect to device dimensions and device performance.
  - The numerical value of  $d_{\text{base}}$  (or better, the relation  $d_{\text{base}}/L$ ), 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  $\mu\text{m}$**  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  $\mu\text{m}$**  (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