## 5.7. Heterojunction Bipolar Transistors

Heterojunction bipolar transistors are bipolar junction transistors, which are composed of at least two different semiconductors. As a result, the energy bandgap as well as all other material properties can be different in the emitter, base and collector. Moreover, a gradual change also called grading of the material is possible within each region.

Heterojunction bipolar transistors are not just an added complication. On the contrary, the use of heterojunctions provides an additional degree of freedom, which can result in vastly improved devices compared to the homojunction counterparts.
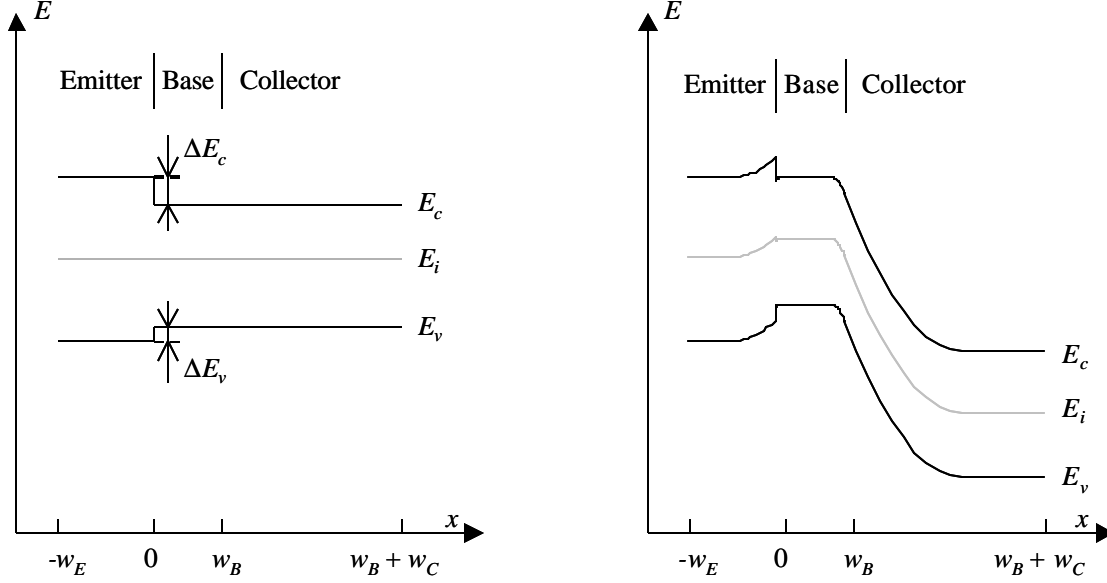


**Figure 5.7.1.** a) Flatband energy band diagram and b) Energy band diagram under forward active bias Variation of the minority-carrier distribution in the base quasi-neutral region due to a variation of the base-collector voltage.

The analysis of the device starts with the calculation of the DC current gain. To this end we recall the equations for the electron and hole current in the base-emitter junction (5.3.1) and (5.3.2), namely:

$$I_{E,n} = qn_{i,B}^2 A_E \left( \frac{D_{n,B}}{N_B w_B'} \right) \left( \exp(\frac{V_{BE}}{V_t}) - 1 \right)$$

(5.7.1)

and

$$I_{E,p} = qn_{i,E}^2 A_E \left( \frac{D_{p,E}}{N_E w_E'} \right) \left( \exp(\frac{V_{BE}}{V_t}) - 1 \right)$$

(5.7.2)

where the fact that the intrinsic carrier density in the emitter, $n_{i,E}$, and base, $n_{i,B}$, are different, is indicated explicitly by the additional subscript.

The emitter efficiency of the transistor is still calculated from the electron current relative to the

total emitter current and equals:

$$\gamma_E \overset{\Delta}{=} \frac{I_{E,n}}{I_{E,p}+I_{E,n}} = \frac{1}{1+\dfrac{D_{p,E}N_B w_B' n_{i,B}^2}{D_{n,B}N_E w_E' n_{i,E}^2}} \qquad (5.7.3)$$

If we now assume that the effective density of states for electrons and holes are the same in the emitter and base, we find that the maximum current gain equals:

$$\beta \cong \frac{D_{n,B}N_E w_E'}{D_{p,E}N_B w_B'}\exp(\frac{\Delta E_g}{kT}), \quad \text{if} \quad \alpha \cong \gamma_E \qquad (5.7.4)$$

Where $\Delta E_g$ is the difference between the bandgap energy in the emitter and the bandgap energy in the base. The current gain depends exponentially on this difference in bandgap energy. As a result one can obtain a very large current gain in a heterojunction bipolar transistor, even if the base doping density, $N_B$, is significantly larger that the emitter doping density, $N_E$. Therefore, the emitter of a typical heterojunction bipolar transistor has a wider bandgap than its base. This difference should be around 0.2 - 0.4 V for optimum performance. A smaller difference provides only a marginal improvement over homojunction devices. A larger difference causes the gain to be strongly temperature dependent, might require exotic material combinations and creates a distinct spike in the energy diagram, which in turn limits the current.

The advantages of HBTs are not restricted to its DC performance. Microwave devices can also be improved dramatically by using an appropriate heterojunction material system. To illustrate this point we now recall the equations for the transit frequency, $f_T$, and the maximum oscillation frequency, $f_{MAX}$:

$$f_T = \frac{1}{2\pi\tau} \qquad (5.7.5)$$

Where the total transit time equals:

$$\tau = \tau_E + \tau_B + \tau_C = \frac{V_t C_{BE}}{I_E} + \frac{w_B'^2}{2D_{n,B}} + \frac{x_{d,BC}}{2v_{sat}} \qquad (5.7.6)$$

and

$$f_{MAX} = \sqrt{\frac{f_T}{2\pi\,R_B C_{BC}}} \qquad (5.7.7)$$

Since a heterojunction transistor can have large current gain, even if the base doping density is higher than the emitter doping density, the base can be much thinner even for the same punchthrough voltage. As a result one can reduce the base transit time without increasing the emitter charging time, while maintaining the same emitter current density. The transit frequency can be further improved by using materials with a higher mobility for the base layer and higher

saturation velocity for the collector layer.

An HBT can be further improved by grading the composition of the base layer such that the bandgap energy of the material is gradually reduced throughout the base as shown in Figure 5.7.2a) and b). The grading causes an electric field, which in turn reduces the transit time as discussed in section 5.5.2 and calculated from equation (5.5.4):

$$t_B = \frac{w_B^{'2}}{2(1+(\frac{E_{bi}}{E_0})^{3/2})D_{n,B}} \quad \text{with} \quad E_{bi} = \frac{E_{g,MAX} - E_{g,MIN}}{qw_B^{'}} \tag{5.7.8}$$

Where $E_{g,MAX}$ and $E_{g,MIN}$ are the maximum and minimum energy bandgap at $x^{'} = 0$ and $x^{'} = x_B^{'}$. A linear variation was assumed in between.



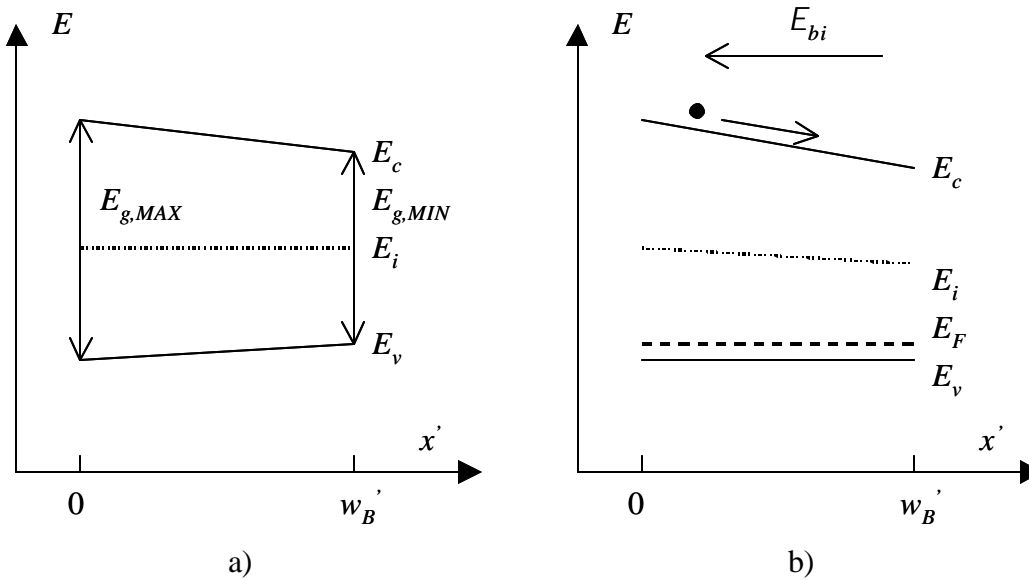a)                                                        b)

**Figure 5.7.2.** a) Energy band diagram of an undoped and composition-graded semiconductor, and b) Energy band diagram of the *p*-type graded base region in a HBT.

The maximum oscillation frequency can also be further improved. The improved transit frequency immediately increases the transit frequency. The higher base doping also provides a lower base resistance and a further improvement of $f_{MAX}$. As in the case of a homojunction BJT, the collector doping can be adjusted to trade off a lower the collector transit time for a lower base-collector capacitance. The fundamental restriction of heterojunction structures still applies, namely that the materials must have a similar lattice constant so that they can be grown without reducing the quality of the material.