Bipolar Junction Transistors (BJTs)

Why do we want transistors, anyway?

In a FET, the "control" is the gate.

In this sense, a photo diode is a "transistor."

Strong field under reverse bias.
No current just because of lack of carriers.
If carriers can be controllably supplied...
There is actually an electrical way to supply carriers to the reverse biased pn junction.

BJTs

Recommended reading:
Müller & Kamins, Device Electronics for Integrated Circuits, pp. 270-294
on short-base pn junctions: pp. 238-239

The E-B np junction is "short-base".
E-B forward biased: diffusion.
Any electron reaching the BC junction will be swept to C by the strong field.
Net recombination rate is \[ \frac{p - p_0}{\tau_p} \]

\( \tau_p \) is the hole lifetime.

Net flow into slice due to diffusion is

\[ -\left( D_p \frac{dp_n}{dx} \bigg|_{x} - D_p \frac{dp_n}{dx} \bigg|_{x+dx} \right) A \]

\[ = + D_p A \frac{d^2 p_n}{dx^2} \, dx \]

\[ \Rightarrow D_p A \frac{d^2 p_n}{dx^2} \, dx = \frac{p_n - p_0}{\tau_p} A \, dx \]

\[ D_p \frac{d^2 p_n}{dx^2} = \frac{p_n - p_0}{\tau_p} \]

\[ \frac{d^2}{dx^2} (p_n - p_{n_0}) = \frac{p_n - p_{n_0}}{D_p \tau_p} \]

\[ p_n (x) - p_{n_0} (x) = \left[ p_n (x_n) - p_{n_0} (x_n) \right] e^{-\frac{x-x_n}{\sqrt{D_p \tau_p}}} \]

Define \( L_p = \sqrt{D_p \tau_p} \)

\[ p_n - p_{n_0} = p_{n_0} \left( e^{\frac{x}{\tau_p}} - 1 \right) e^{-\frac{x-x_n}{L_p}} \]
The hole diffusion current in the n region

\[ J_p = -q D_p \frac{dP_n}{dx} = \frac{q D_p}{\frac{1}{L_p}} (e^{\frac{qV}{kT}} - 1) e^{\frac{qV}{kT}} \]

At \( x = x_n \),

\[ J_p (x_n) = \frac{q D_p}{\frac{1}{L_p}} \left( e^{\frac{qV}{kT}} - 1 \right) \]

Similarly,

\[ J_n (-x_p) = \frac{q D_n}{\frac{1}{L_n}} \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ J = J_p (x_n) + J_n (-x_p) = \frac{q}{2} \left[ \frac{D_p}{\frac{1}{L_p}} \left( \frac{P_n (x_n)}{L_p} \right) + \frac{D_n}{\frac{1}{L_n}} \left( \frac{n_{p_0} (-x_p)}{L_n} \right) \right] \left( e^{\frac{qV}{kT}} - 1 \right) \]

\[ \approx J_s \left( e^{\frac{qV}{kT}} - 1 \right) \approx J_s e^{\frac{qV}{kT}} \]

--- Ideal diode equation ---
These pictures apply to "long base" junctions:

- n neutral region $\gg L_p$
- p $\gg L_n$

No chance to go through w/o recombination.

"Short base" junctions:
- different boundary conditions
- same I-V relation

Read on your own. Did you?

Recommended reading: Muller & Kamins, p.p. 238 – 239

Base width $\ll$ diffusion length
$\Rightarrow$ little chance to recombine
Constant slope, constant current.

\[ J_n = -q D_n \frac{dn_n}{dx} = -q D_n \frac{d}{dx} (n_p - n_n) \]

\[ = q D_n \left( \frac{n_i^2}{N_A} \frac{1}{x_B - x_p} \left( e^{\frac{qV_{BE}}{kT}} - 1 \right) \right) \]

When the short-base junction is the E-B in a BJT,

Define "base charge"

\[ Q_B = q N_A (x_B - x_p), \text{ then} \]

\[ J_n = \frac{q^2 n_i^2 D_n}{Q_B} \left( e^{\frac{qV_{BE}}{kT}} - 1 \right) \]

when \( V_{CE} \) is sufficiently big.

In the case of non-uniform doping.

\[ Q_B = q \int_{x_p}^{x_B} N_A(x) \, dx \]

In the diagram:

- Saturation \((V_C < V_B)\)
- Active \(V_{BE}\)
- Increasing \(V_{CE}\)
Base current & $\beta$.

In the above discussion, $I_C \approx I_E$, $I_B \approx 0$. We get all injected carriers to the collector. $\beta$ controls the injection from $E$, and $C$ gets all the injected $I_E$.

But, some small $I_B$ must be drawn:

1. Base recombination $I_{RB}$
2. B-E junction space-charge region recomb. — not considered here.
3. Hole injection into $E$, $I_{PE}$

$$I_B \approx I_{RB} + I_{PE}$$

$$\beta = \frac{I_C}{I_B} \approx \frac{I_n}{J_{RB} + J_{PE}}$$

(controlled by B-E bias)
\[ J_{rb} = \frac{2}{\tau_n} \int_{x_p}^{x_B} \left[ n_p(x) - n_{p_s}(x) \right] dx \]

\[ = \frac{\frac{2}{\tau_n} n_i^2 (x_a - x_p)}{2 N_A \tau_n} \left( e^{\frac{q V_{BE}}{kT}} - 1 \right) \]

You don't decrease \( J_{rb} \) by increasing \( N_A \).

Why?

You want long minority carrier life time and a narrow base to minimize \( J_{rb} \).

Now let's look at \( J_{PE} \).

For long emitters, \( L_{PE} < \ll W_E \):

\[ I_{PE} = \frac{\frac{q}{N_{DE}} n_i^2 D_{PE}}{L_{PE}} \left( e^{\frac{q V_{BE}}{kT}} - 1 \right) \]

For short emitters, \( L_{PE} \gg W_E \):

\[ I_{PE} = \frac{\frac{q}{N_{DE}} n_i^2 D_{PE}}{W_E} \left( e^{\frac{q V_{BE}}{kT}} - 1 \right) \]

To minimize \( J_{PE} \), you want high \( N_{DE} \), long minority carrier life time in \( E \).
A problem w/ $I_{PE}$: Band gap shrinkage

$$\Delta E_g = -22.5 \text{ meV} \sqrt{\frac{N_D}{10^{18} \text{ cm}^{-3}}} \cdot \frac{300K}{T}$$

But for $N_D > 10^{20} \text{ cm}^{-3}$, $\Delta E_g \approx 0.16 \text{ eV}$

Recall that $E_g \approx 1.1 \text{ eV}$ for Si;

$$n_i \propto e^{-\frac{E_g}{2kT}} \times n_i(E_g) e^{\frac{1}{2kT} \frac{\Delta E_g}{kT}}$$

$$I_{PE} \propto \frac{n_i^2}{N_D} \times \frac{e^{-\frac{E_g}{kT}}}{N_D^2}$$

$$\frac{n_i^2}{N_D} \text{ doesn't decrease w/ increasing } N_D.$$

OK, we want a small $\frac{n_i}{N_D}$

$n_i$ is not fixed, if...
if $E$ is a wider band gap semiconductor

![Diagram of band gap](image)

AlGaAs  GaAs

We don't want the abrupt $\Delta E_c$ & $\Delta E_v$ as we had in the MODFET.

What do we do?
The two most important III–V compound systems are $\text{Al}_{x}\text{Ga}_{1-x}$ and $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ solid solutions\(^{20}\) (Fig. 24). The bandgap against the lattice constant for the III–V binary semiconductors is intermediate ternary or quaternary compounds. To achieve heterostructures with negligible interface traps, the lattices between the two conductors must be closely matched. Using GaAs ($a = 5.6533$ Å) as the substrate, the ternary compound $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can have a lattice mismatch less than 0.1%. Similarly, using InP ($a = 5.8686$ Å) as the substrate, the ternary compound $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ can also have near perfect lattice as indicated by the vertical line in Fig. 24.

Fig. 24  Energy bandgap and lattice constant for two III–V solid solutions. (and Panish, Ref. 20.)