Heterojunctions

- Heterojunctions
- Heterojunction bipolar transistor
  - SiGe
  - GaAs

Definitions

<table>
<thead>
<tr>
<th>Element</th>
<th>Electron affinity, $\chi$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge, germanium</td>
<td>4.13</td>
</tr>
<tr>
<td>Si, silicon</td>
<td>4.01</td>
</tr>
<tr>
<td>GaAs, gallium arsenide</td>
<td>4.07</td>
</tr>
<tr>
<td>AlAs, aluminium arsenide</td>
<td>3.5</td>
</tr>
</tbody>
</table>
**Definitions**

- Straddling:
  - $E_{c1}$
  - $E_{v1}$

- Staggered:
  - $E_{c1}$
  - $E_{v1}$

- Broken gap:
  - $E_{c1}$
  - $E_{v1}$

**Band diagram**

- Vacuum level

- $e\phi_m$ to $E_{cm}$

- $e\chi_m$ to $E_{cm}$

- $e\phi_p$ to $E_{cp}$

- $e\chi_p$ to $E_{cp}$

- $\Delta E_C$ between $E_{cm}$ and $E_{cm}$

- $\Delta E_V$ between $E_{cp}$ and $E_{vcp}$
\[ \Delta E_c = e(\chi_n - \chi_P) \]

\[ \Delta E_c + \Delta E_v = E_{gP} - E_{gn} = \Delta E_g \]
**Electrostatics**

**Poisson equation:**

\[
\frac{d^2 \phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho}{\varepsilon}
\]

**Electric field becomes:**

\[
E_n = \frac{eN_{dn}}{\varepsilon_n} (x_n + x)
\]

\[
E_P = \frac{eN_{up}}{\varepsilon_P} (x_p - x)
\]

**Boundary condition**

\[
E_n(x < -x_n) = E_p(x > x_p) = 0
\]

\[
eV_{nl} = \phi_{xl} - \phi_{nl} = \left[ e\chi_p + E_{pP} - (E_{FP} - E_{VP}) \right] - \left[ e\chi_n + E_{gn} - (E_{Fn} - E_{vn}) \right]
= \ldots
= \Delta E_v + kT \ln \left( \frac{p_{n0}}{p_{n0}} \cdot \frac{N_{vn}}{N_{vp}} \right)
\]
**Electrostatics**

Electric flux density continuous across junction:

\[ \varepsilon_n E_n(x = 0) = \varepsilon_p E_p(x = 0) \Rightarrow N_{dn} x_n = N_{ap} x_p \]

Subsequent integration of electric field gives built-in voltage:

\[ V_{bi} = V_{bip} + V_{biP} = \frac{e N_{dn} x_n^2}{2 \varepsilon_n} + \frac{e N_{ap} x_p^2}{2 \varepsilon_p} \]

... and for the depletion region width:

\[ W = x_n + x_p = \sqrt{\frac{2 \varepsilon_a \varepsilon_p (N_{dn} + N_{ap})^2 V_{bi}}{e N_{dn} N_{ap} (\varepsilon_n N_{dn} + \varepsilon_p N_{ap})}} \]
Band diagram n-N junction with grading

Current behaviour in heterojunctions

Characteristics of the junctions between the different materials:
- High recombination/generation rate.
- There is a potential barrier, $\varphi_{b0}$.

At metal-semiconductor junction:
- Metal is infinite good conductor

In a p-n junction: drift-diffusion model

Metal-semiconductor: how many electrons can overcome the potential barrier
Differences with homojunctions:

- Barrier height not the same for electrons and holes
- One band (in this case the conduction band) similar to a rectifying metal-semiconductor junction
- (Effective mass different on either side junction)

Current-voltage relation

General current-voltage relation: 

\[ J = J_S \left[ \exp \left( \frac{eV_a}{kT} \right) - 1 \right] \]

For a rectifying metal-semiconductor junction

\[ J_S = A^* T^2 \exp \left( - \frac{e\phi_{BS}}{kT} \right), \quad \text{with:} \quad A^* = \frac{4\pi m^*_h k^2}{\hbar^3} \]

...and a p-n junction:

\[ J_S = \frac{eD_n n_{p0}}{L_n} + \frac{eD_p P_{n0}}{L_p} \]
Minority carrier concentration in the base

Study transport equation (no electric field, no generation, and static equilibrium):

\[ D_B \frac{\partial^2 (\delta n_B(x))}{\partial x^2} - \frac{\delta n_B(x)}{\tau_{B0}} = 0 \]

Solve this differential equation with the correct boundary conditions (!)

\[ n_{B0} \left\{ \exp \left( \frac{eV_{BE}}{kT} \right) - 1 \right\} \sinh \left( \frac{x_B - x}{L_B} \right) - \sinh \left( \frac{x}{L_B} \right) \]

\[ \sinh \left( \frac{x_B}{L_B} \right) \]

\[ \approx n_{B0} \left\{ \exp \left( \frac{eV_{BE}}{kT} \right) - 1 \right\} (x_B - x) \]

\[ n_{B0} \left\{ \exp \left( \frac{eV_{BE}}{kT} \right) - 1 \right\} \left( x_B - x - \frac{x_B}{L_B} \right) \]
Small-signal common base current gain

\[ \alpha = \frac{\frac{J_{nE}}{J_{nE} + J_{pE}}}{\gamma} \frac{J_{nE}}{J_{nE} + J_{pE}} \frac{J_{nE} + J_{pE}}{J_{nE} + J_{R} + J_{pE}}\]

- Emitter injection efficiency factor, \( \gamma \): ratio electron diffusion current / total diffusion current
- Base transport factor, \( \alpha_T \): determines the efficiency of charge transport across the base, in other words is a measure for the recombination losses in the base
- Recombination factor, \( \delta \): measure for the quality of the emitter-base junction and gives an indication about the recombination
Band diagram SiGe HBT
Current gain

Common-emitter current gain: \[ \beta_0 \equiv \frac{\alpha_0}{1 - \alpha_0} = \frac{\gamma \alpha_t \delta}{1 - \gamma \alpha_t \delta} \approx \frac{\gamma}{1 - \gamma} \]

Substituting for \( \gamma \): \[ \beta = \frac{1}{D_E \frac{p_{E0}}{B_D n_{B0}} \frac{x_B}{x_E}} \approx \frac{n_{B0}}{p_{E0}} \]

For the thermal equilibrium carrier concentrations we have:

\[ p_{E0} = \frac{n_{i,E}^2}{N_{C,E} N_{V,E}} \exp\left(-\frac{E_{i,E}}{kT}\right) \]

\[ n_{B0} = \frac{n_{i,B}^2}{N_{C,B} N_{V,B}} \exp\left(-\frac{E_{i,B}}{kT}\right) \]
Current gain

\[ \beta_0 \sim \frac{N_E}{N_B} \exp \left( \frac{E_{g,E} - E_{g,B}}{kT} \right) = \frac{N_E}{N_B} \exp \left( \frac{\Delta E_g}{kT} \right) \]

Current gain increases exponentially with band gap difference

⇒ Larger current gain allows higher base doping

⇒ Higher base doping allows narrow base width

⇒ Narrow base width implies a faster device