4.2.1 Influence of Collector Doping on HBT Performance

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Introduction:
The figures of merit for high frequency performance are the cut-off frequency $f_T$ and the maximum frequency of oscillation $f_{\text{max}}$ [1].

$$\frac{1}{2\pi \cdot f_T} = \tau_{\text{base}} + \tau_{\text{collector}} + C_{\mu} \frac{kT}{q I_e} + C_m \left( \frac{kT}{q I_c} + R_n + R_{\text{coll}} \right)$$

$$f_{\text{max}} \approx \sqrt{\frac{f_T}{8\pi \cdot R_{\text{BB}} C_{BC}}}$$

As it is depicted in equation (1), the cut-off frequency is limited by the transition times, which are mostly influenced by the vertical dimension of the HBT structure. The maximum oscillation frequency is additionally affected by the parasitic capacitances and resistances, which can be controlled by lateral scaling of the devices.

Briefly, $f_T$ can be improved by epitaxy and processing and while the layout mainly improves $f_{\text{max}}$.

By decreasing the base and collector thickness, the transit frequency $f_T$ can be improved but at the same time $f_{\text{max}}$ may be affected adversely.

In this work, we have investigated the effect of collector doping on the improvement of $f_T$. At a high collector current density ($J_c > q N_{dc} v_{\text{sat}}$), the electron density entering the base collector depletion region exceeds the doping level and this changes the electric field profile at the junction. This will cause an increase of hole injection from base to collector and so increasing base width. The extended base width results in increased base transit time and also degraded current gain. This high current density effect is the well-known Kirk Effect [2,3]. Doping of the collector ($N_C$) may push the Kirk current density to higher levels.

Experiment:

The structures are grown by LP-MOVPE (Low Pressure-Metal Organic Vapour Phase Epitaxy) (Aixtron 200) on (001) $\pm 0.5^\circ$ oriented semi insulating (001) InP (Fe) substrate. Three samples were used for this investigation. Sample A, Sample B, and Sample C have the same layer structure as depicted in table 1, but the collector doping differs. The collector doping is nid (A) (non-intentionally doped), $5 \times 10^{16}$ cm$^{-3}$ (B), $5 \times 10^{17}$ cm$^{-3}$ (C), respectively. These samples are processed in parallel, to eliminate any deviation that may occur by environmental effect during processing.

Device fabrication is carried out by conventional wet chemical etching based on phosphoric acid ($H_3PO_4$) for InGaAs and InGaAsP layers, and hydrochloric acid for InP containing layers. The emitter, base and collector layers are defined by optical lithography. The Ti/Pt/Au contact metal system is used for emitter and collector contacts. The self-aligned base metallization is deposited as
Pt/Ti/Pt/Au. Air bridges are used for the connections to the measurement pads. SEM (Scanning Electron microscope) micrograph of one of the realized HBTs is shown in Figure 1.

![SEM picture of HBT with nominal $A_E = 2 \times 10 \mu m^2$](image)

**Figure 1. SEM picture of HBT with nominal $A_E = 2 \times 10 \mu m^2$**

**Results**

The DC characteristics of the DHBTs were measured by an HP4515B parameter analyzer.

![Common Emitter Output Characteristics for Sample A, B and C](image)

**Figure 2. Common Emitter Output Characteristics for Sample A, B and C**

In figure 2 common emitter output characteristic for sample A, B and C are shown. The DC current gain is ~70 for all three samples at $I_B = 200 \mu A$. The breakdown voltage has decreased by increasing collector doping. ($BV_{CESampleA} = 5.5V$, $BV_{CESampleB} = 4.5V$, $BV_{CESampleC} = 3V$)

High frequency measurements using an HP8510C network analyser, have been performed. For these measurements on devices with $A_E = 2 \times 10 \mu m^2$. Sample A, B and C have shown transit frequency ($f_t$) of 100GHz, 120GHz and 165GHz, respectively.
The calculation of Kirk current density is given in equation 3.

\[
J_{Kirk} = (1 + \frac{V_{cb} + \phi_{cb}}{V_2 + \phi_{cb}})qN_C v_{sat}
\]  

(3)

where:

- \(\phi_{cb}\): Base collector junction potential
- \(V_2\): Applied base-collector bias that totally depletes collector layer when \(J_C=0\)
- \(N_C\): Collector doping
- \(v_{sat}\): Saturation velocity

Calculated Kirk current densities \((J_{Kirk})\) are as follows;

- \(J_{Kirk,A}=0.9\,\text{mA/µm}^2\), \(J_{Kirk,B}=2.5\,\text{mA/µm}^2\), \(J_{Kirk,C}=6.5\,\text{mA/µm}^2\). These values fit really nice with the values measured.

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**Figure 3.** \(f_T\) vs. Current density
Figure 4. Compromise for collector doping to $J_{Kirk}$ and breakdown voltage

The effect of collector doping on the $J_{Kirk}$ and collector emitter breakdown voltage can be seen at the same time. The measured Kirk current densities show good agreement with the calculated values.

**Conclusion**

The Kirk effect has been experimentally observed in DHBTs with varied collector doping densities. It has been found out that doping the collector can reduce this effect. This will lead to better RF performance. On the other hand, the collector doping decreases the breakdown voltage. The experimental results are compared with the theoretical calculations and good agreement has been achieved.

**References**

