Investigation of Ge content in the BC transition region with respect to transit frequency

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Outline

• Introduction
• Barrier effect @ high current
• SiGe and breakdown voltage
• Retrograde Ge profile
• Results
• Discussion and outlook
Introduction (1/4)

• High Power HBT
  – E.g. for hand-set application
  – Huge market: 1 Billion of hand-sets sold in 2007
  – Output power stage in SiGe

• Figure of merits
  – $f_T$
  – $BV_{CE0}$, $BV_{CB0}$
  – PAE
  – $P_{1dB}$
Introduction (2/4)

- Figure of merit: $f_T(I_C)$ shape

- The upper curve is preferable
  - $I_C=1\text{mA}$: $f_{T1}=15\text{GHz}$, $f_{T2}=20\text{GHz}$
  - 33% improvement
Introduction (3/4)

- $f_T(I_C)$ and PAE and power gain
  - 3 different devices
  - 3 Ge content

From: Pan et al, BCTM 2004

![Graph showing $f_T(I_C)$ and PAE performance for different Ge contents.](image)
Introduction (4/4)

- Why does $f_T$ drop?
  - the neutral-base charge, which dominates the transit time at high current density
  - two dominant high-injection effects
    - conventional Kirk effect
    - heterojunction barrier effect
Conventional Kirk effect

• Before floating the barrier

Here: Abrupt SiGe-Si barrier
Barrier effect (1/3)

Valence band barrier

- The transition from a narrow gap SiGe base layer to the larger bandgap Si collector layer introduces a valence band offset at the heterointerface.
- Since this barrier is masked by the band bending in the collector-base (CB) depletion region during low-injection operation, it has negligible effect on the device characteristics.
- At high-injection, the collapse of original CB electric field at the heterointerface reveals the barrier which opposes the hole injection into the collector.
Barrier effect (2/3)

- The hole pile-up that occurs at the heterointerface induces a conduction band barrier that opposes the electron flow into the collector.
- This causes an increase in the stored base charge that results in the sudden decrease of both $f_T$ and $f_{max}$. 

![Graph showing density and conduction band for different voltages](image)
Barrier effect (3/3)

- Transit time

Abrupt SiGe-Si barrier with different barrier distance

From Jiang et al., IEEE-ED, 2002
Only SiGe collector?

- SiGe and breakdown voltage

From People et al, Appl. Phys. Lett, 1986

\[
E_{SiGe} = E_{Si} - \Delta E(y)
\]

\[
\Delta E(y) = 0.74 \ y \ (eV)
\]

\[y : Ge \ content\]

From Sze, "Physic of semiconductor devices", John Wiley

- The SiGe profile has to be optimized:
- Tradeoff between breakdown and barrier effect
- Thick SiGe layer: relaxing risk
Retrograde Ge profile

- **E-field and multiplication factor**
  - Varying Ge content produces an change in the valence band
  - This change creates a heterojunction-induced electric field

  The Ge retrograde field $E_r$ depends on the retrograde distance $D_r$
  - Increasing $D_r$ reduces $E_r$ and hence $M-1$

Retrograde profile

- Ge content and doping concentration
TCAD simulation results (1/3)

• Band energy diagram

![Band Energy Diagram](image)

- Conduction Band
- Valence Band

- Standard Ge profile
- 60 nm retrograde Ge profile
- 120 nm retrograde Ge profile

- Band discontinuity attenuation

- $J_c = 1 \text{mA.µm}^{-2}$
TCAD simulation results (2/3)

• Hole density

![Graph showing hole density as a function of depth for different profiles, with integrated hole density marked and Jc = 1mA.µm⁻²]
TCAD simulation results (3/3)

- Transit frequency

![Simulated $f_T$ ($J_C$) $V_{CE}$ 1.5V chart]

- Standard Ge profile
- 60 nm retrograde Ge profile
- 120 nm retrograde Ge profile

- $A_e=0.4*6.4 \, \mu m^2$
- $0.5 \, mA.\mu m^{-2}$
Measurement results (1/2)

• Transit frequency

![Graph showing transit frequency (f_T) vs. operating current density (J_C) for different Ge profiles. The graph compares Standard Ge profile, 60 nm retrograde Ge profile, and 120 nm retrograde Ge profile. The operating voltage is 1.5V. There is a peak in f_T at a specific J_C value for each profile, with a note on high f_T operating current density widening.]
Measurement results (2/2)

• $f_T \cdot \text{BV}_{CEO}$ product

![Graph showing $f_T \cdot \text{BV}_{CEO}$ product with iso-lines and various thickness reductions.]

- Collector epitaxy thickness reduction
- Deeper extension of retrograde Ge profile into collector

Plots:
- SiGe:C +120 nm
- SiGe:C +60 nm
- Std
Conclusion

- Barrier effect analysis
- Tradeoff between SiGe and $BV_{CE0}$
- Ge retrograde profile in the collector
  - Device simulation
  - high injection operation
  - $f_T$ performance
  - confirmed by measurements
Outlook (1/2)

- New figure of merit to characterize the wider current range with suitable \( f_T \)

- Half \( f_T \) current range

\[
\Delta I_C \bigg|_{f_T \text{ max/2}} = I_{C2}(f_{T_{\text{max}}}/2) - I_{C1}(f_{T_{\text{max}}}/2)
\]

- Normalized half \( f_T \) current range

\[
\frac{\Delta I_C}{I_{C1}(f_{T_{\text{max}}}/2)} = I_{C2}(f_{T_{\text{max}}}/2) - I_{C1}(f_{T_{\text{max}}}/2)
\]
Outlook (2/2)

- **Half $f_T$ current range**

<table>
<thead>
<tr>
<th></th>
<th>Standard Ge profile</th>
<th>60 nm retrograde Ge profile</th>
<th>120 nm retrograde Ge profile</th>
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</thead>
<tbody>
<tr>
<td>Half $f_T$ current range</td>
<td>0.86 mA</td>
<td>0.94 mA</td>
<td>0.99 mA</td>
</tr>
<tr>
<td>Normalized half $f_T$ current range</td>
<td>9.25</td>
<td>10.13 (Increase of ≈10%)</td>
<td>10.62 (Increase of ≈15%)</td>
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- The devices with optimized profile exhibit improved $f_{T_{max}}$ and wider $f_T$ operating current density range
- Best for PA applications