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

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Outline

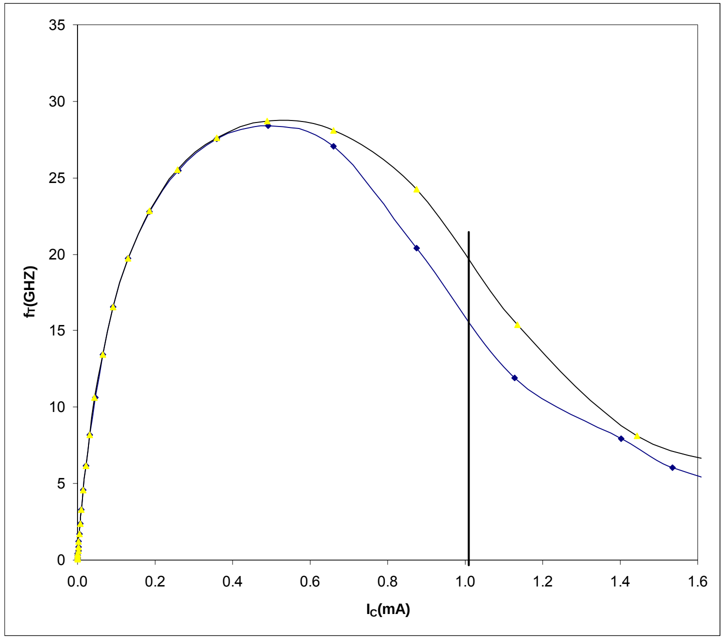
- Introduction
- Barrier effect @ high current
- SiGe and breakdown voltage
- Retrograde Ge profile
- Results
- Discussion and outlook

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)

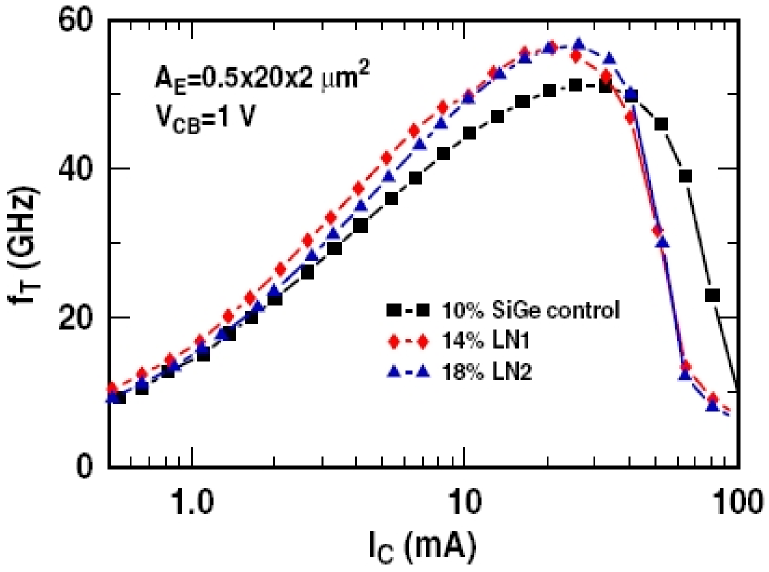
- Figure of merit: $f_T(I_C)$ shape

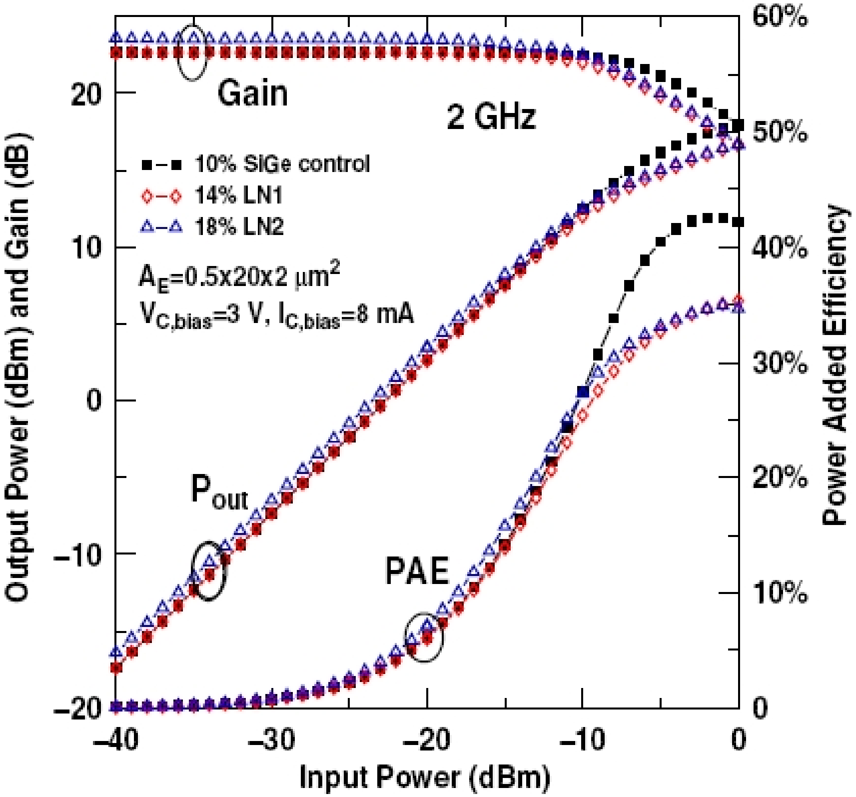


- The upper curve is preferable
  - I_C=1mA: f_{T1}=15GHz, f_{T2}=20GHZ
  - 33% improvement

Introduction (3/4)

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





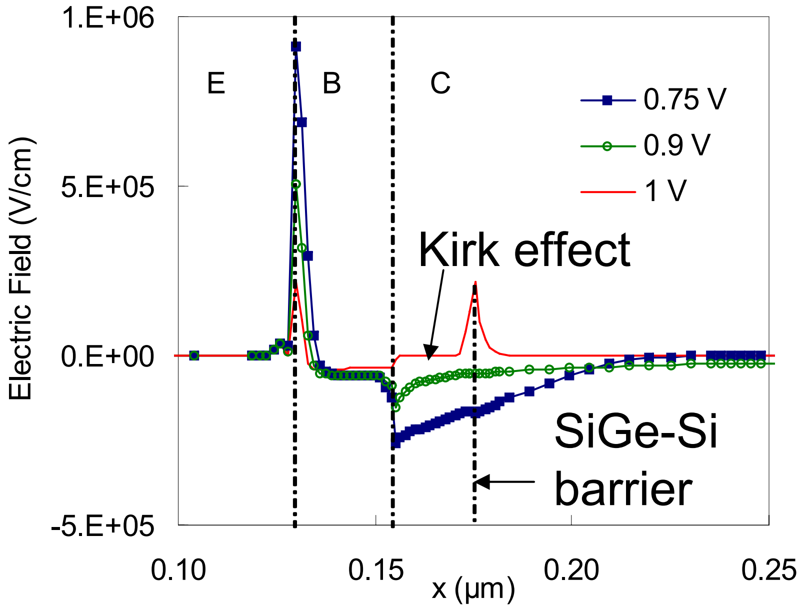
From: Pan et al, BCTM 2004

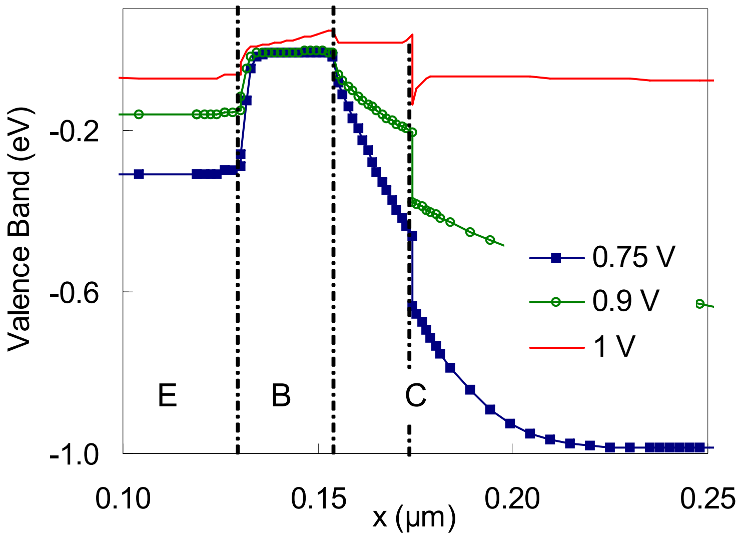
Introduction (4/4)

- 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



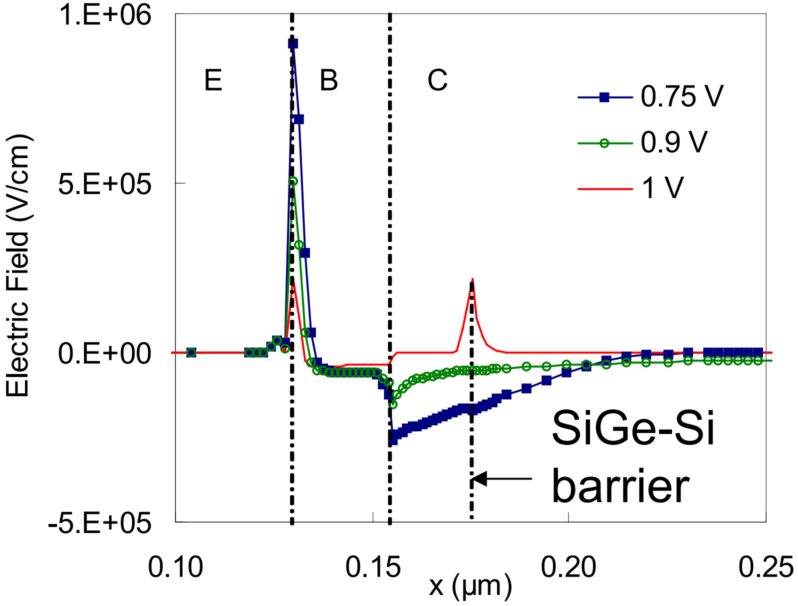


Here: Abrupt SiGe-Si barrier

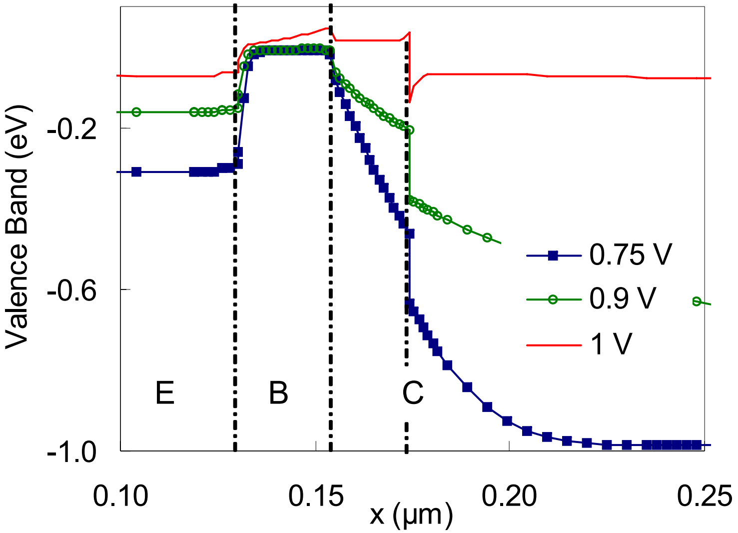
Barrier effect (1/3)

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

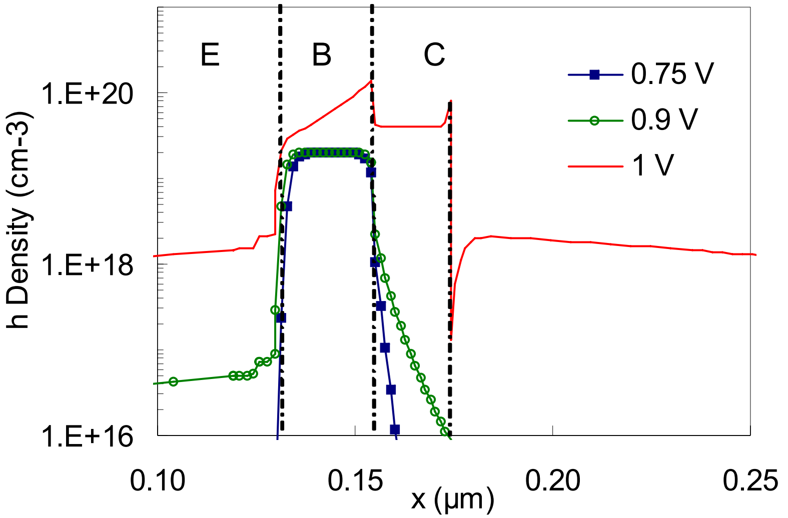


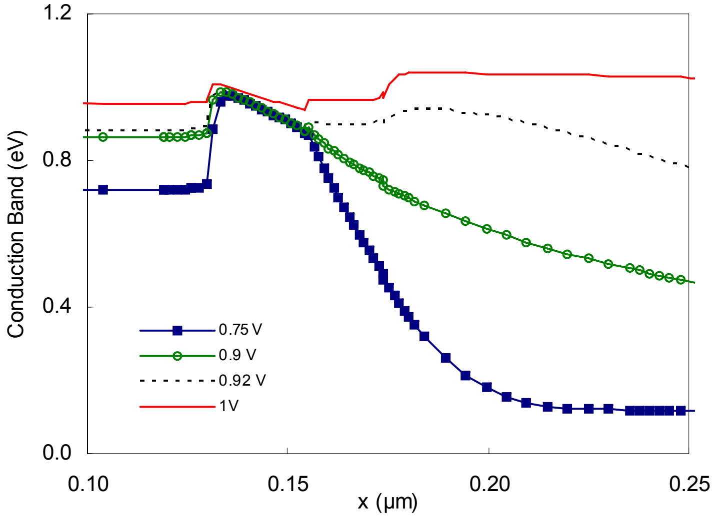
SiGe-Si barrier



Barrier effect (2/3)

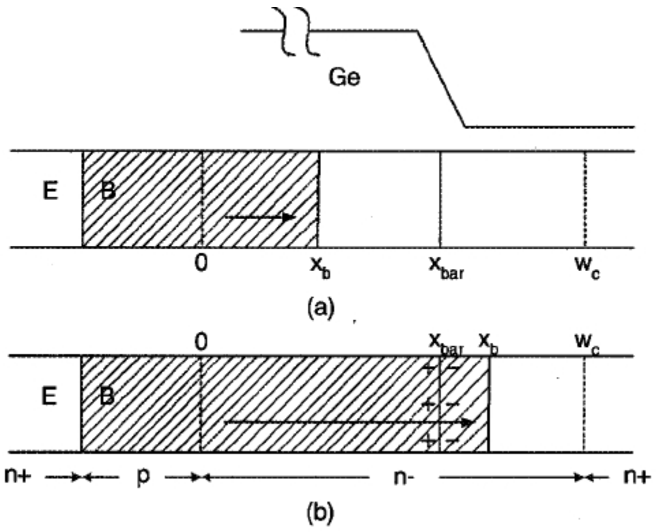
- The hole pile-up that occurs at the heterointerface induces a conduction band barrier that opposes the electron flow into the collector
- This causes an increase in the stored base charge that results in the sudden decrease of both f_T and f_{max}





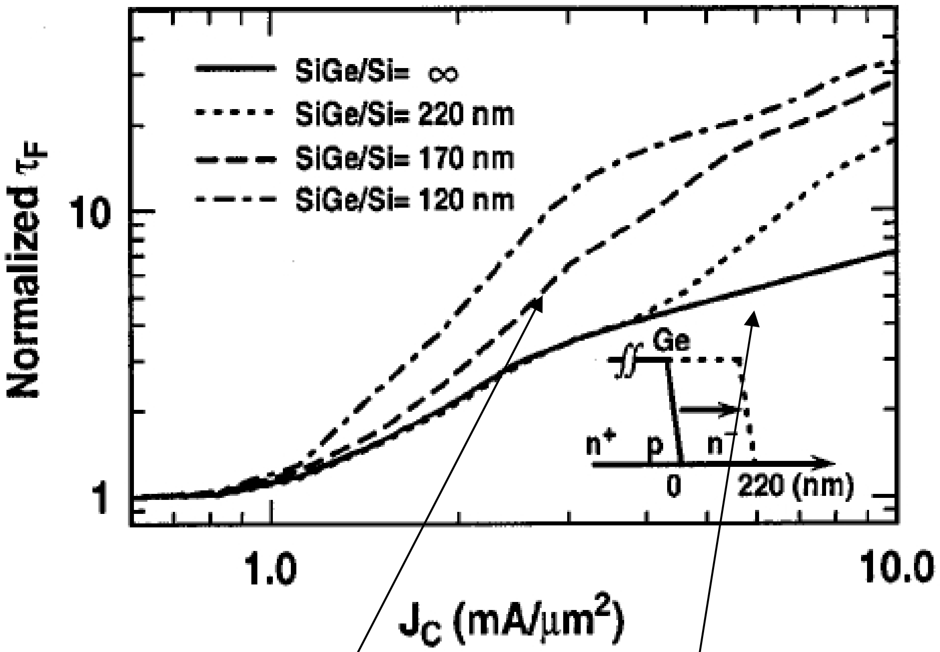
Barrier effect (3/3)

- Transit time



Abrupt SiGe-Si barrier with different barrier distance

From Jiang et al, IEEE-ED, 2002

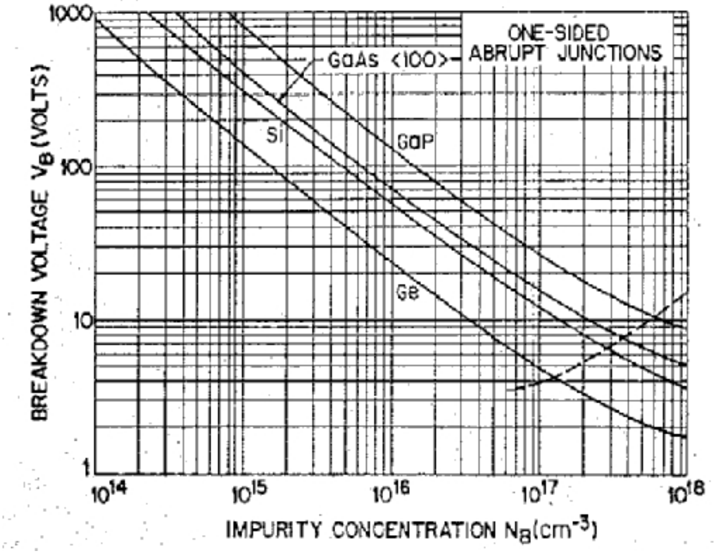


Kirk effect

Barrier effect

Only SiGe collector ?

- SiGe and breakdown voltage



From Sze, “Physic of semiconductor devices”, John Wiley

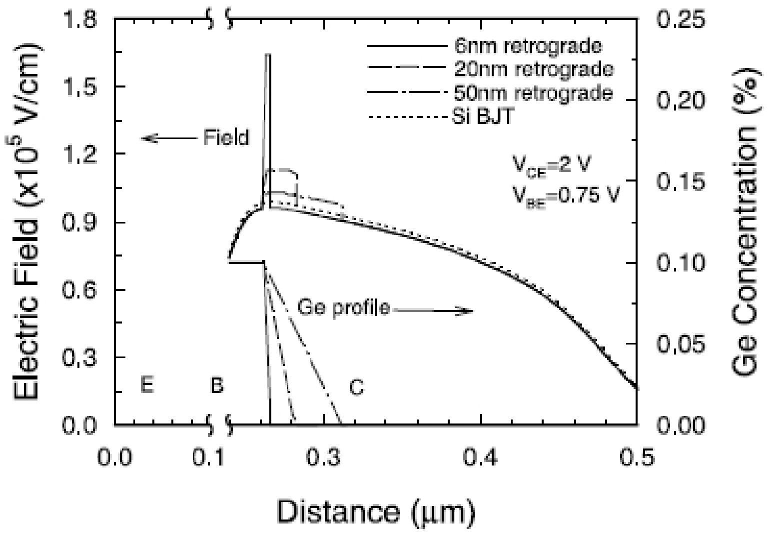
$$E_{SiGe} = E_{Si} - \Delta E(y)$$
$$\Delta E(y) = 0.74\ y\ (eV)$$
$$y : Ge\ content$$

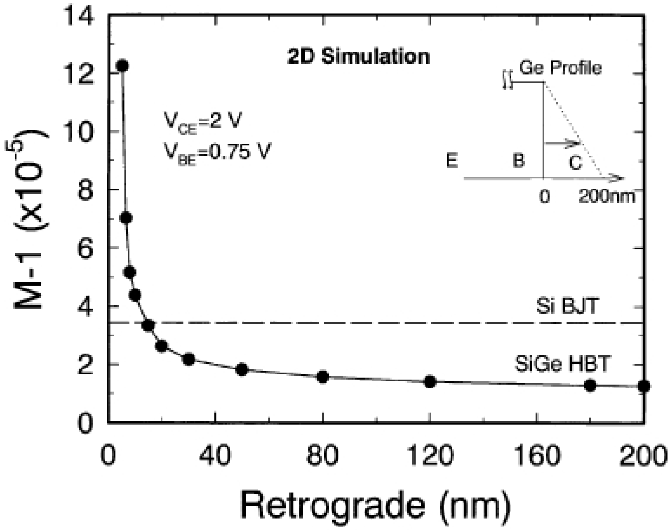
From People et al, Appl. Phys. Lett, 1986

- 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



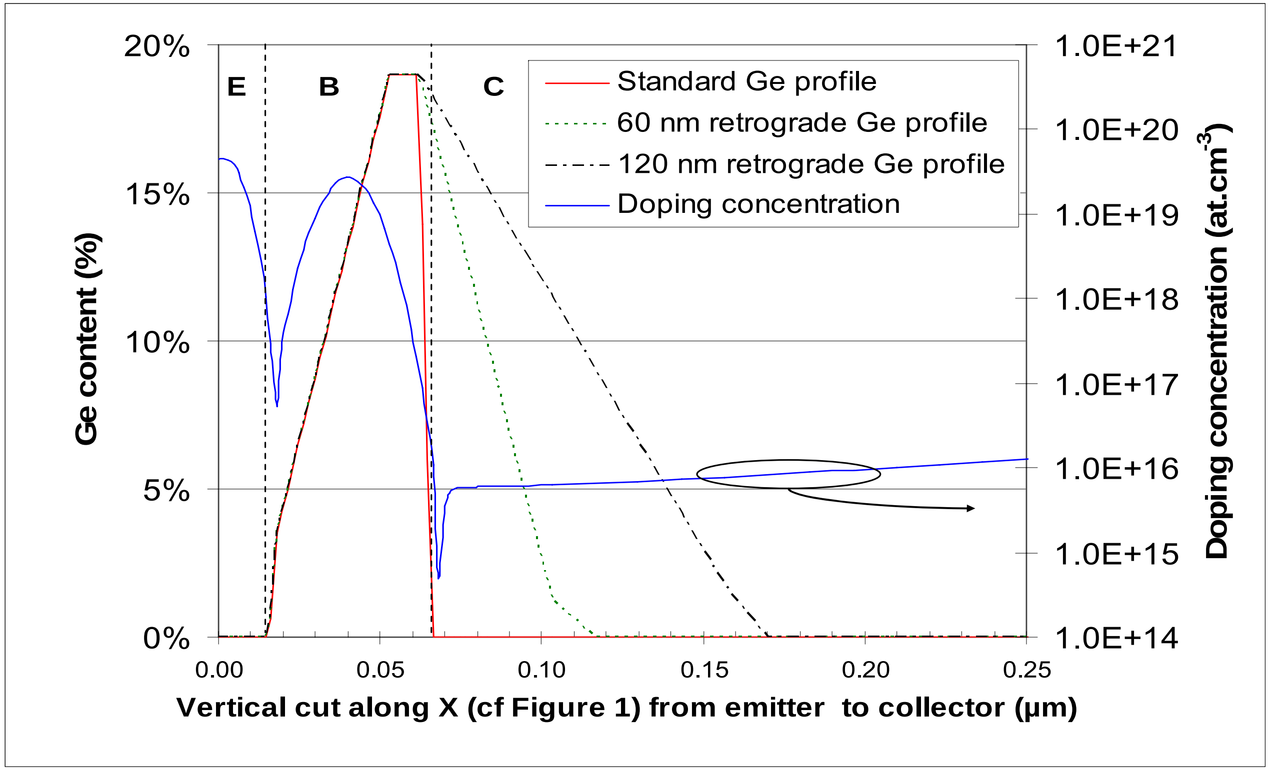


  - The Ge retrograde field E_r depends on the retrograde distance D_r
  - Increasing D_r reduces E_r and hence M-1

From: G. Zhang et al. / Solid-State Electronics 46 (2002) 655–659

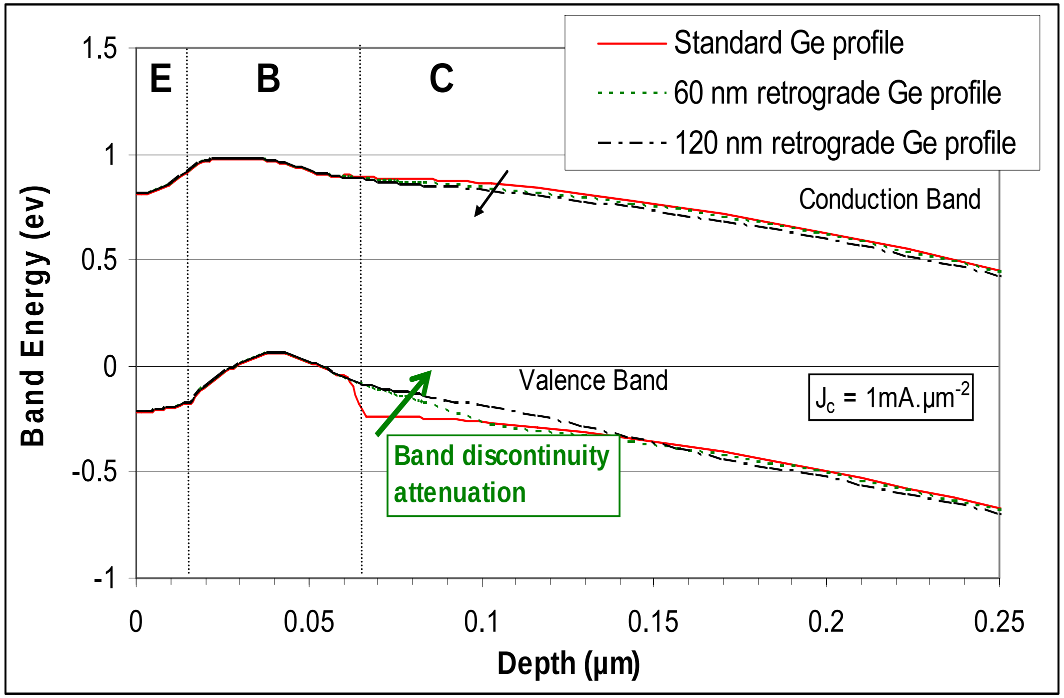
Retrograde profile

- Ge content and doping concentration



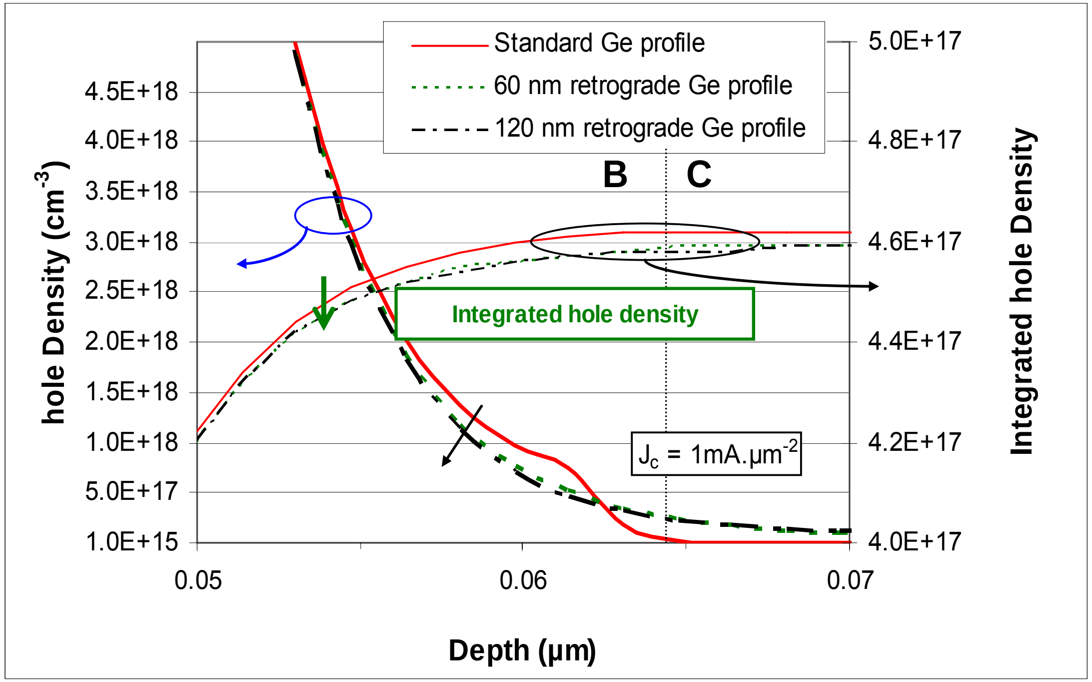
TCAD simulation results (1/3)

- Band energy diagram



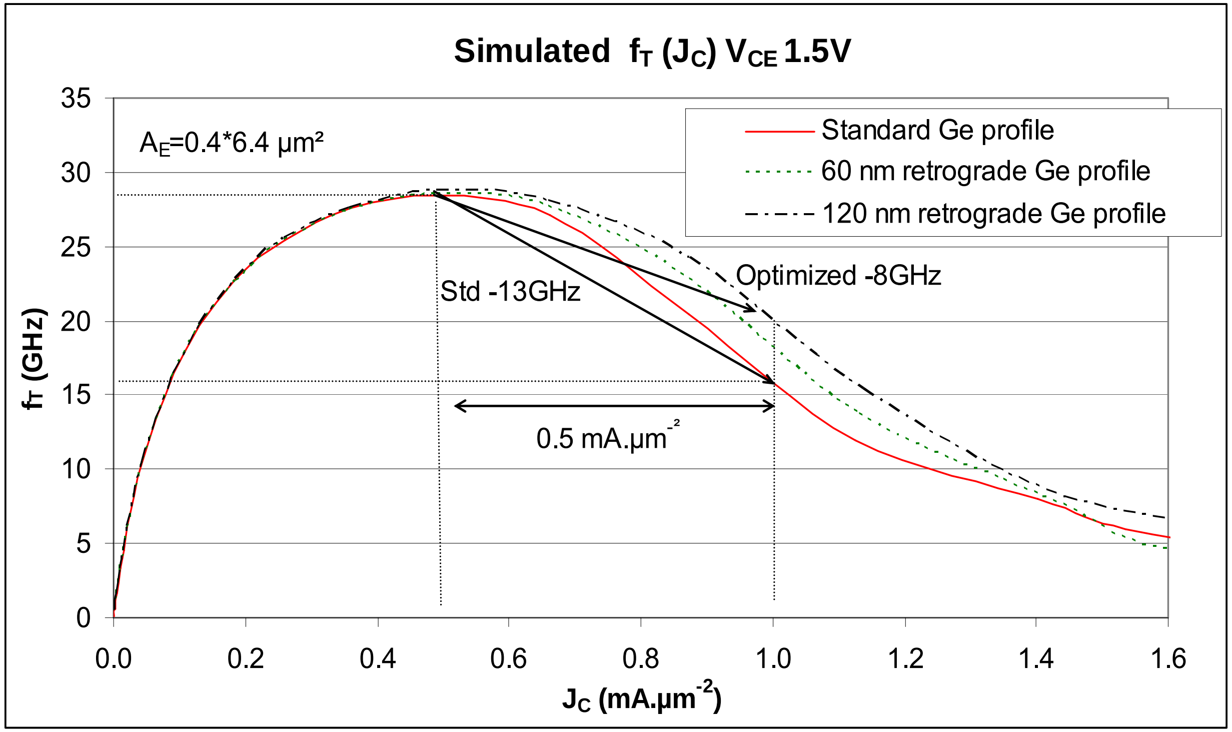
TCAD simulation results (2/3)

- Hole density



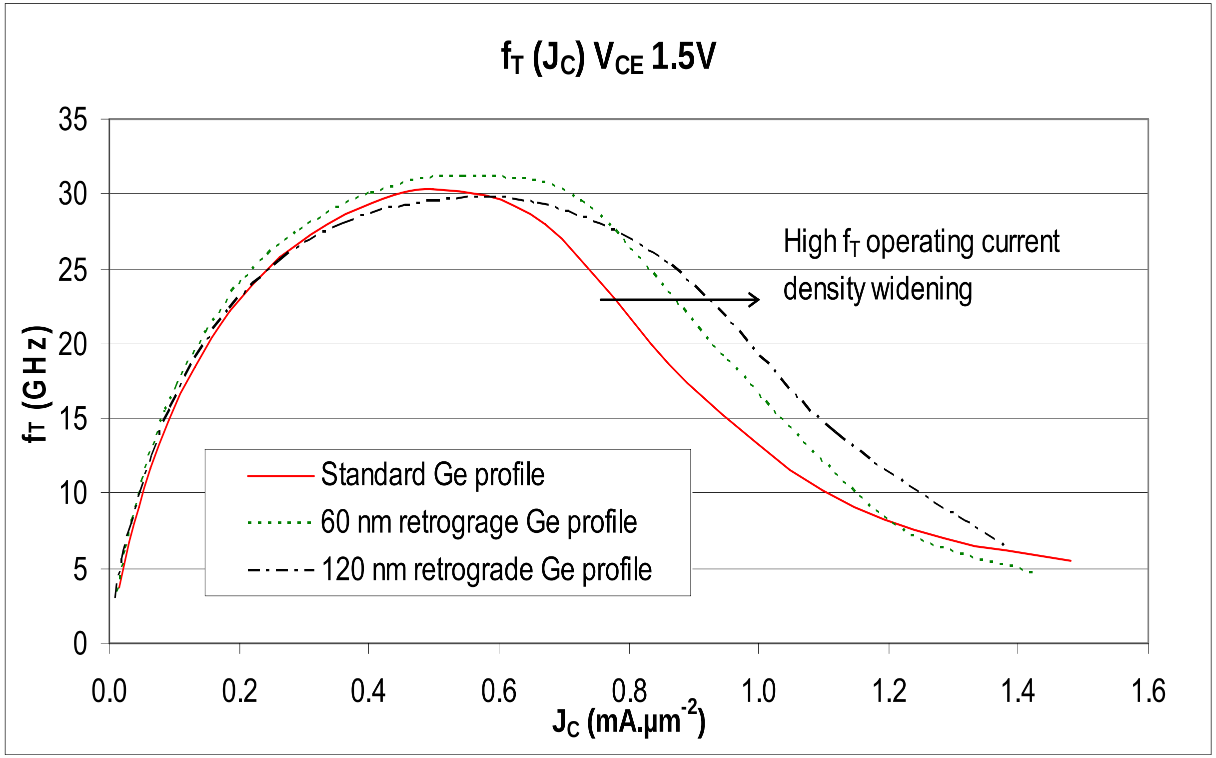
TCAD simulation results (3/3)

- Transit frequency



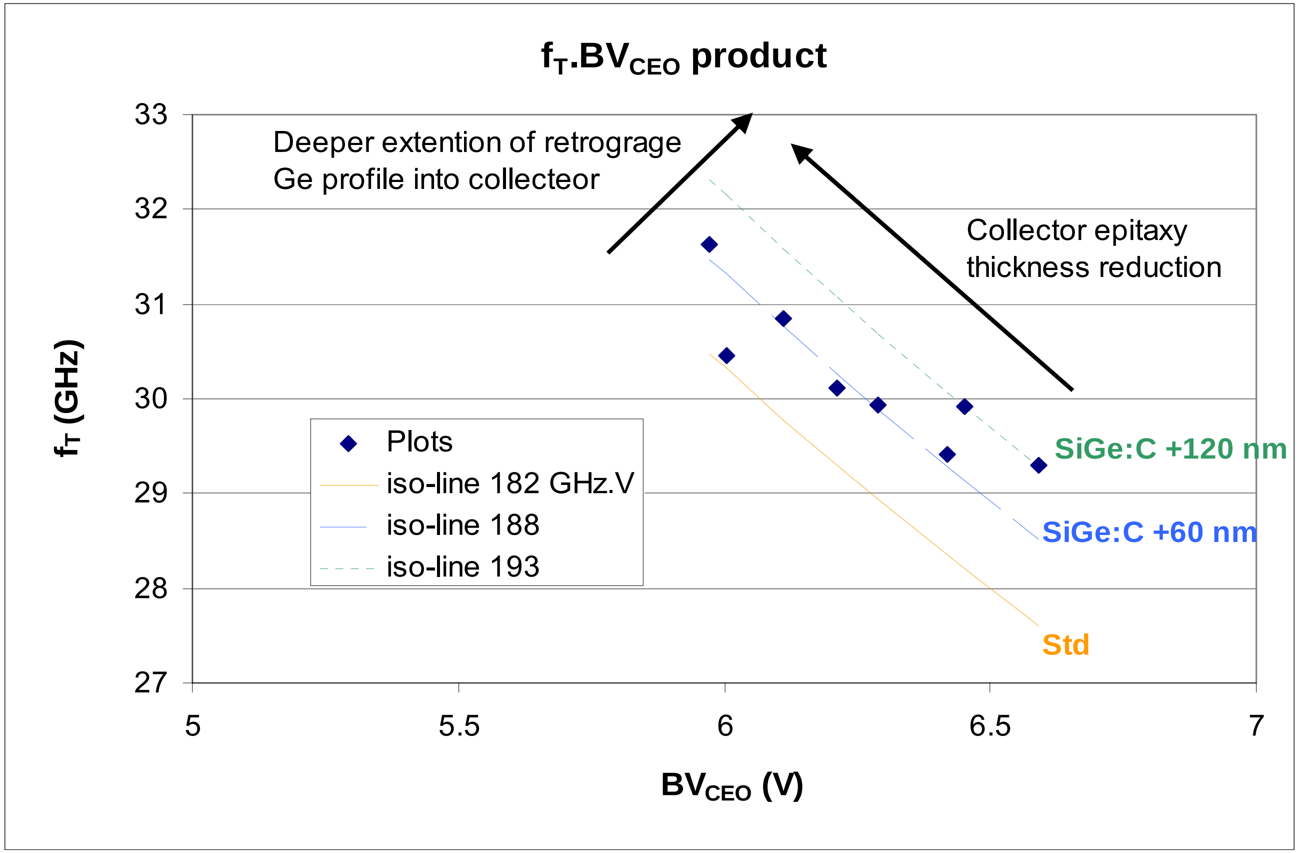
Measurement results (1/2)

- Transit frequency



Measurement results (2/2)

- f_T-BV_{CE0} product



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

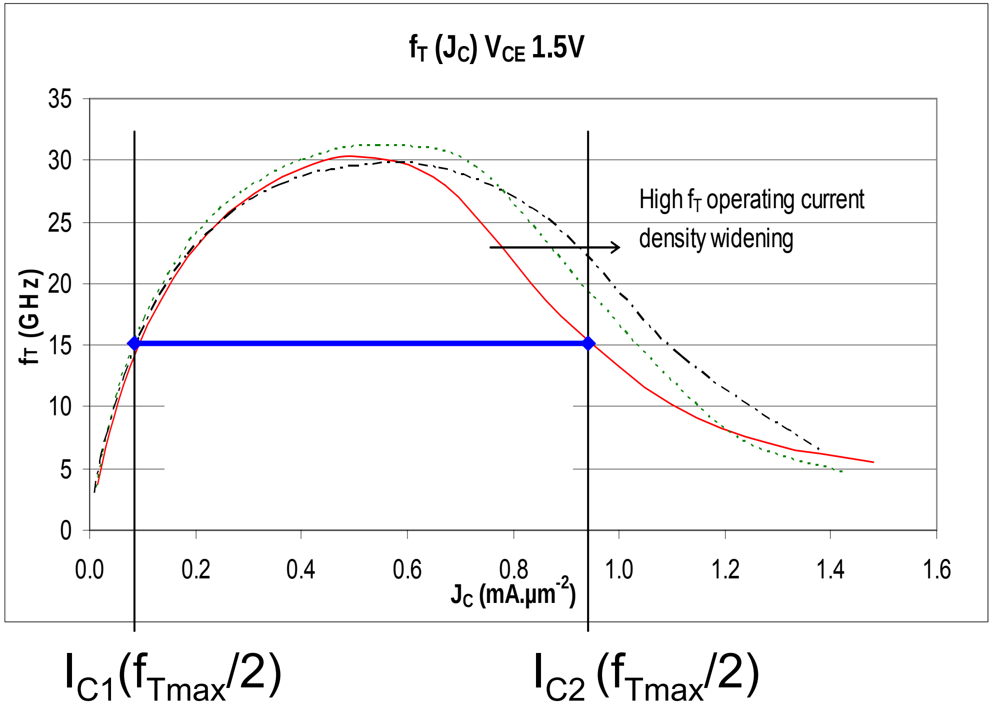
Outlook (1/2)

- New figure of merit to characterize the wider current range with suitable f_T
- Half f_T current range

$$\Delta I_C\Big|_{f_{T\max}/2} = I_{C2}\left(f_{T_{\max}}/2\right) - I_{C1}\left(f_{T_{\max}}/2\right)$$

- Normalized half f_T current range

$$\frac{\Delta I_C\Big|_{f_{T\max}/2}}{I_{C1}\left(f_{T_{\max}}/2\right)} = I_{C2}\left(f_{T_{\max}}/2\right) - I_{C1}\left(f_{T_{\max}}/2\right)$$



Outlook (2/2)

- Half f_T current range

	Standard Ge profile	60 nm retrograde Ge profile	120 nm retrograde Ge profile
Half f_T current range	0.86mA	0.94mA	0.99mA
Normalized half f_T current range	9.25	10.13 Increase of ≈10%	10.62 Increase of ≈15%

- The devices with optimized profile exhibit improved f_{Tmax} and wider f_T operating current density range
- Best for PA applications