Modeling of charge and collector field in silicon-based bipolar transistors

H. Tran and M. Schroter
Chair for Electron Devices and Integrated Circuits
University of Technology Dresden, Germany
mschroter@ieee.org
http://www.iee.et.tu-dresden.de/iee/eb/eb_homee.html

Workshop on Compact Modeling, Boston, March 2004
Contents

• Introduction
• Investigated process technology
• Modeling the electric field
• Base-collector charge and depletion capacitance
• Transit time
• Modeling velocity overshoot
• Conclusions
Introduction

• Applications of bipolar transistors: high-frequency/high-speed operation
  • Bluetooth, 802.11, WLAN (e.g. 60GHz), UWB (impulse) radio, Free Space Optics, OC 192/768...

• Design requirements to reduce cost (mask, fab...): accurate compact models for SiGe HBTs
  • presently: covered by advanced models such as HICUM, MEXTRAM, VBIC
  • future: increasing importance of accurate non-linear modeling, non-local effects ...

⇒ purpose of this work: physics-based model concept for future technologies

• Transistor operation is strongly determined by ("epi"-)collector region
  ⇒ key variable: "electric" field E in the BC region

• Also: \(E(V_{BC},I_C)\) is linked to BC capacitance, transit time, avalanche effect
  ⇒ makes modeling of E very attractive

... however: so far no analytical description available that is suitable for compact modeling
Investigated process technology

- schematic cross-section of SiGe HBT
- vertical doping profile (1D) under emitter

- profile corresponds to high-voltage (or power) transistor version in respective process
- peak $f_T \approx 35\text{GHz} @ V_{BC} = 0\text{V}$
- "conventional" doping profile to develop fundamental relations, then apply to other profiles
- 1D device simulation: unit emitter area $A_E = 1\text{ mA}/\mu\text{m}^2$
Modeling the electric field

spatial dependence of the electric field at $V_{CE} = \text{const}$ and $I_C$ as parameter

- base-collector junction located at $x_{jc}$
- "electric" field curves for
  $$E_{\psi} = -\frac{d\psi}{dx} \quad \text{and} \quad E_{\phi} = -\frac{d\phi_n}{dx}$$
- low currents: typical "triangular" shape
- $E(x_{jc})$ and slope decrease with $I_C$
- beyond critical current $I_{CK}$:
  $E_{\psi}(x_{jc}) < 0$ due to barrier (caused by Ge)
  while $E_{\phi}(x_{jc})$ remains $> 0$
- electron current density:
  $$J_n = q \mu_n n E_{\phi} = q \mu_n V_T \frac{dn}{dx} + q \mu_n n E_{\psi}$$
  $$\Rightarrow \text{use } E_{\phi} \text{ and not } E_{\psi} \text{ for modeling}$$

definition: $E_{jc} = -E_{\phi}(x_{jc}) \Rightarrow \text{focus from here on}$
Bias dependence of the electric field

current dependent field $E_{jc}$ at $V_{BC} = \text{const}$

- $E_{jc}$ drops with current
- linear at high voltages
- curvature at low voltages ($\Delta V_{pd}$)
- levelling off beyond $I_{CK}(V_{BC})$
- $I_{CK}(V_{BC})$ indicates onset of high-current effects and $f_T$ drop (still applies also to SiGe HBTs)
- minimum value at high currents:

$$E_\infty = \frac{2V_T}{w_{Ci}}$$

- definitions:
  - effective BC voltage: $v_{ceff} = V_{DCi} - V_{BC}$
  - field at zero BC voltage and zero current: $E_{jc00} = E_{jc}(V_{BC} = 0, I_C = 0)$
  - field at zero BC voltage and nonzero current: $E_{jc0} = E_{jc}(V_{BC}, I_C = 0)$
Modeling the bias dependent field at the BC junction

- main assumptions: \( N_{Ci}(x) = \text{const} \), \( v_n = v_s \) ⇒ integration of Poisson equation yields for
  
  low voltages (partial depletion)

  \[
  E_{jc} = E_{wc} + \sqrt{2qN_{Ci} \over \varepsilon} \sqrt{(1 - {I_{Tf} \over I_{lim}})(v_{ceff} - E_{wc}w_{Ci})}
  \]

  with \( E_{wc} = \rho_{Ci} {I_{Tf} \over A_E} = {I_{Tf} \over qA_E \mu_n C_i (E_{wc}) N_{Ci}} \)

  high voltages (full depletion)

  \[
  E_{jc} = {v_{ceff} + V_{PT0}(1 - {I_{Tf} / I_{lim}}) \over w_{Ci}}
  \]

  with \( V_{PT0} = {qN_{Ci}w_{Ci}^{2} \over 2\varepsilon} \)

- issues with above equations:
  
  - limited validity range: \( v_{ceff} > E_{wc}w_{Ci} \) (@ low voltages); \( I_{Tf} = I_C < I_{lim} = qN_{Ci}v_s A_E \) (@ high voltages)
  
  - difficult to extend numerically stable beyond \( I_{lim} \) (and \( I_{CK} \)) into high-current range

- proposed approach here:
  
  - linear \( I_{Tf} \) dependence at low current
  
  - level off toward high currents \{ smooth in between \}
  
  - smoothing function depends on key "parameters" \( E_{jc0}, I_{CK}, E_{\infty} \)
Modeling the bias dependent field at the BC junction

comparison between device simulation and analytical equation

- model equation: \( E_{jc} = E_{\infty} + f_e E_{lim} \)

  \[ f_e(V_{BC}, I_Tf) = \frac{e_j + \sqrt{e_j^2 + g_{jc} E_{CK}}}{2} \]

  \[ e_j = \frac{(E_{jc0} - E_{\infty}) - (E_{jc0} - E_{CK}) I_{Tf}}{I_{CK} E_{lim}} \]

- parameter: \( g_{jc} \) (all other parameters are already available in HICUM)

- deviation at low \( V_{BC} \): missing square root dependence

  \( \Rightarrow \) impact on model variables: see next slides
Base-collector charge and depletion capacitance

• incremental charge in BC region for quasi-static operation (path independent integral):

\[ dQ_{BC}(V_{BC}, I_{Tf}) = C_jC_i dV_{BC} + \tau_{BC} dI_{Tf} \]

• BC depletion capacitance is a function of voltage and current

\[ C_{jCi}(V_{BC}, I_{Tf}) = \frac{\partial Q_{BC}}{\partial V_{BC}} \bigg|_{I_{Tf}} \]

• relation to electric field via Gauss’ law:

\[ Q_{BC}(V_{BC}, I_{Tf}) = \varepsilon E_{jc}(V_{BC}, I_{Tf}) \]

• model accuracy is maintained by describing \( E_{jc0} \) through measurable \( C_{jCi}(V_{BC},0) \)

• current dependence: include voltage drop across non-depleted collector (ohmic region)

\[ \Rightarrow \text{roughly approximated by } \Delta V_{pd} = V_{lim} \frac{I_{Tf}}{I_{lim}} \left( 1 + \frac{I_{Tf}}{I_{lim}} \right) \]

\[ \Rightarrow \text{replace } V_{BC} \text{ by } V_{BC} + \Delta V_{pd} \]

\[ \Rightarrow \text{retains explicit formulation} \]
**Current and voltage dependent results: comparison**

- very accurate voltage dependence (by "design") at zero current
- differences in current dependence caused by inaccuracy of $E_{jc}$ formulation

overall: explicit formulation with reasonable accuracy and simplicity
Transit time

represents minority charge storage in the whole transistor: \( \tau_f = \tau_{pE} + \tau_{BE} + \tau_{Bf} + \tau_{BC} + \tau_{pC} \)

- relative importance of components in SiGe HBT depends on current density
- low current region:
  - (1) \( \tau_{BC} \), (2) \( \tau_{Bf} \), (3) \( \tau_{BE} \)
- high current region:
  - mainly \( \tau_{Bf} \) dominated (BC barrier !)
- Note: relative importance differs for
  - high-speed device (smaller \( \tau_{BC} \))
  - Si BJTs (\( \tau_{pC} \) large at high \( I_{TF} \))
  - GaAs HBTS (\( \tau_{BC} \) dominated at low \( I_{TF} \))

- impact of \( E_{jc}\) (bias) mainly on \( \tau_{Bf} \), \( \tau_{BC} \)
  - \( \tau_{BC} \) defined by incremental BC charge expression:
    \( \tau_{BC}(V_{BC}, I_{TF}) = \frac{\partial Q_{BC}}{\partial I_{TF}} \bigg|_{V_{BC}} \)
Modeling the transit time

extended HICUM base component: $\Delta \tau_{Bfv} = \tau_{Bfv} f_u \left[ 1 - \left( 1 - \left( \frac{v_n}{v_{sn}} \right)^{\gamma_u} \right) \frac{I_{Tf} du}{u \, dI_{Tf}} \right] \exp(-b_{hc} u)$

with $f_u(u)$ given in the proceedings $b_{hc}$ as new model parameter, and $g_u = 1$ (holes), 2 (electrons)

- both transit time formulations depend on the normalized field $u = \frac{E_{jc}(V_{BC}, I_{Tf})}{E_{lim}}$

- comparison between device simulation and analytical equation:
  - good agreement over
    - wide voltage range
    - wide current density range
  - compatible with already existing HICUM formulation
  - physics-based

- comment on parameter determination
  - can use most extraction procedures already existing for HICUM
  - $b_{hc}$: see [2] in Proceedings or from fit
Modeling velocity overshoot

- observation: certain III-V HBTs show "spike" in transit frequency around peak
- cause: scattering of high-energy electrons from the lower to the upper valley
- issues:
  - determination of transit time using standard method (cf. Fig.)
  - modeling of "low-current" transit time

- approach: use $E_{jc}$ as first-order approximation in standard velocity equation

$$v_n = v_{sn} \frac{(v_{\text{max}}/v_{sn})u + u^4}{1 + u^4} \quad \text{with} \quad u = \frac{E_{jc}(V_{BC}, I_{Tf})}{E_{lim}}$$

(feedback of faster carriers on field neglected)
Conclusions

• A first version of a compact analytical formulation of the electric field in the collector has been presented

• Analytical field model has been applied to describe the
  • voltage and current dependence of the base-collector depletion capacitance
  • base-collector and neutral base transit time at high current densities
  • velocity overshoot in the BC depletion region

  ⇒ sufficiently simple approximations suitable for compact modeling

• Simple and rough approximation for $E_{je}$ so far; possibly need more accurate expression
  • development depends on further investigations of other transistor designs / technologies
  • equation formulation restricted to reasonable complexity, need to be able to extract parameters

Acknowledgments

• financial support from
  • German Ministry of Research and Technology (SFB358)
  • Atmel Germany, Heilbronn