

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

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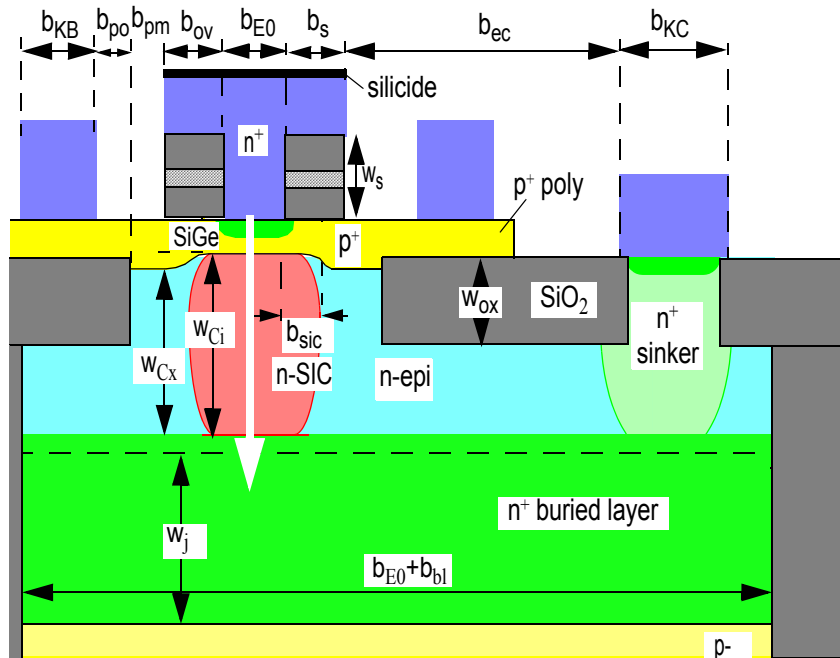
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Introduction

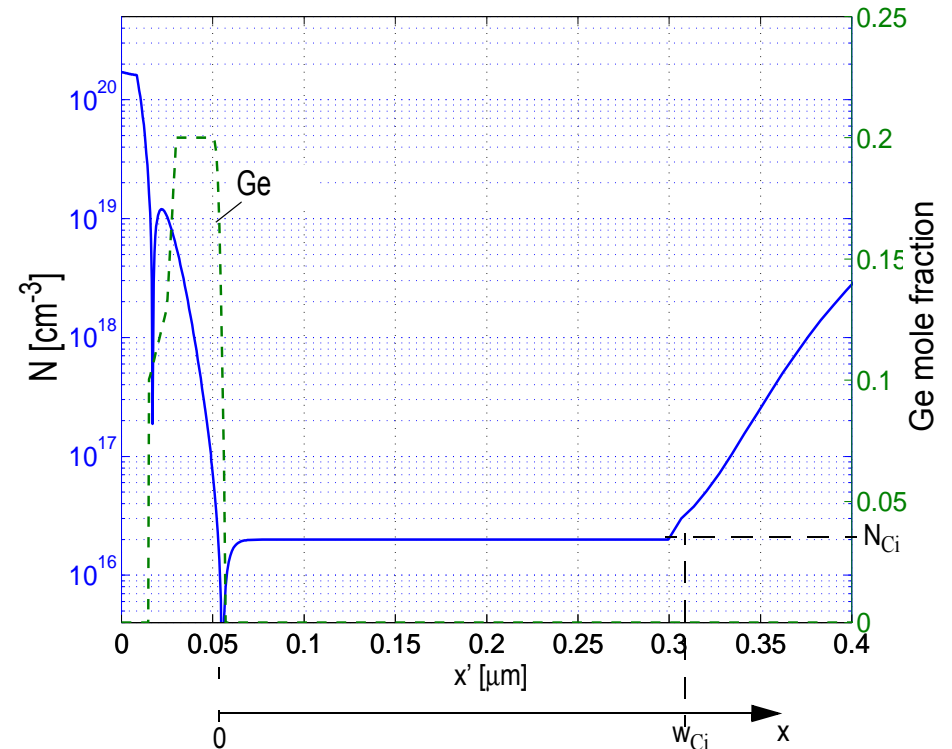
- Applications of bipolar transistors: high-frequency/high-speed operation
 - Bluetooth, 802.11, WLAN (e.g. 60GHz), UWB (impulse) radio, Free Space Optics, OC 192/768...
- Design requirements to reduce cost (mask, fab...): accurate compact models for SiGe HBTs
 - presently: covered by advanced models 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



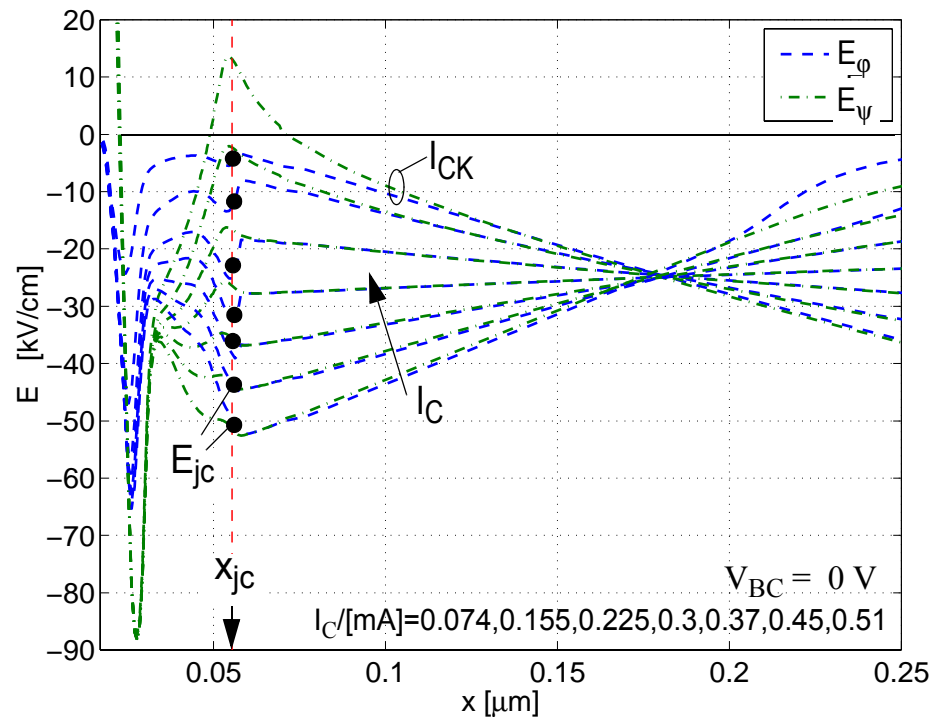
vertical doping profile (1D) under emitter



- 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:

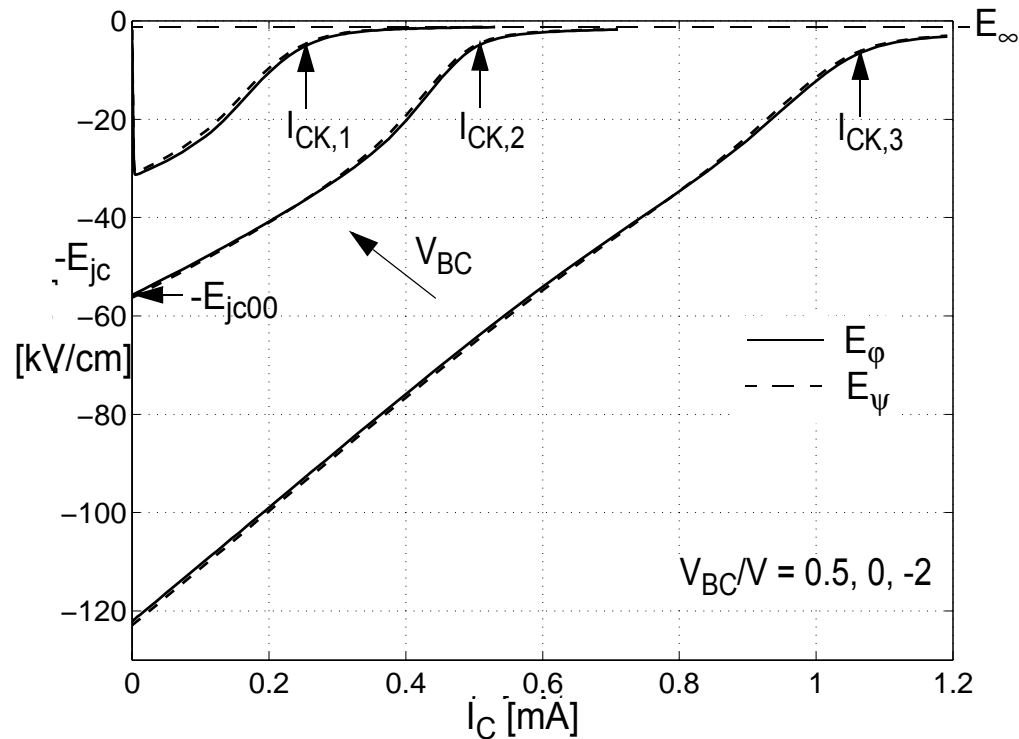
$$J_n = q\mu_n n E_{\phi} = q\mu_n V_T \frac{dn}{dx} + q\mu_n n E_{\psi}$$

\Rightarrow use E_{ϕ} and not E_{ψ} for modeling

definition: $E_{jc} = -E_{\phi}(x_{jc}) \Rightarrow$ 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 (ΔV_{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: $N_{Ci}(x) = \text{const}$, $v_n = v_s \Rightarrow$ integration of Poisson equation yields for

low voltages (partial depletion)

high voltages (full depletion)

$$E_{jc} = E_{wc} + \sqrt{\frac{2qN_{Ci}}{\epsilon}} \sqrt{\left(1 - \frac{I_{Tf}}{I_{lim}}\right) (v_{ceff} - E_{wc}w_{Ci})}$$

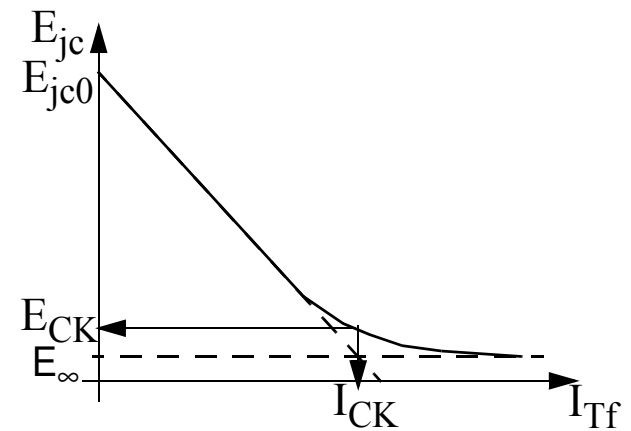
with $E_{wc} = \rho_{Ci} \frac{I_{Tf}}{A_E} = \frac{I_{Tf}}{qA_E \mu_{nCi}(E_{wc}) N_{Ci}}$

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

with $V_{PT0} = \frac{qN_{Ci}}{2\epsilon} w_{Ci}^2$

- issues with above equations:
 - limited validity range: $v_{ceff} > E_{wc}w_{Ci}$ (@ low voltages); $I_{Tf} = I_C < I_{lim} = qN_{Ci}v_sA_E$ (@ 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
 - smoothing function depends on key "parameters" E_{jc0} , I_{CK} , E_∞



Modeling the bias dependent field at the BC junction

comparison between device simulation and analytical equation

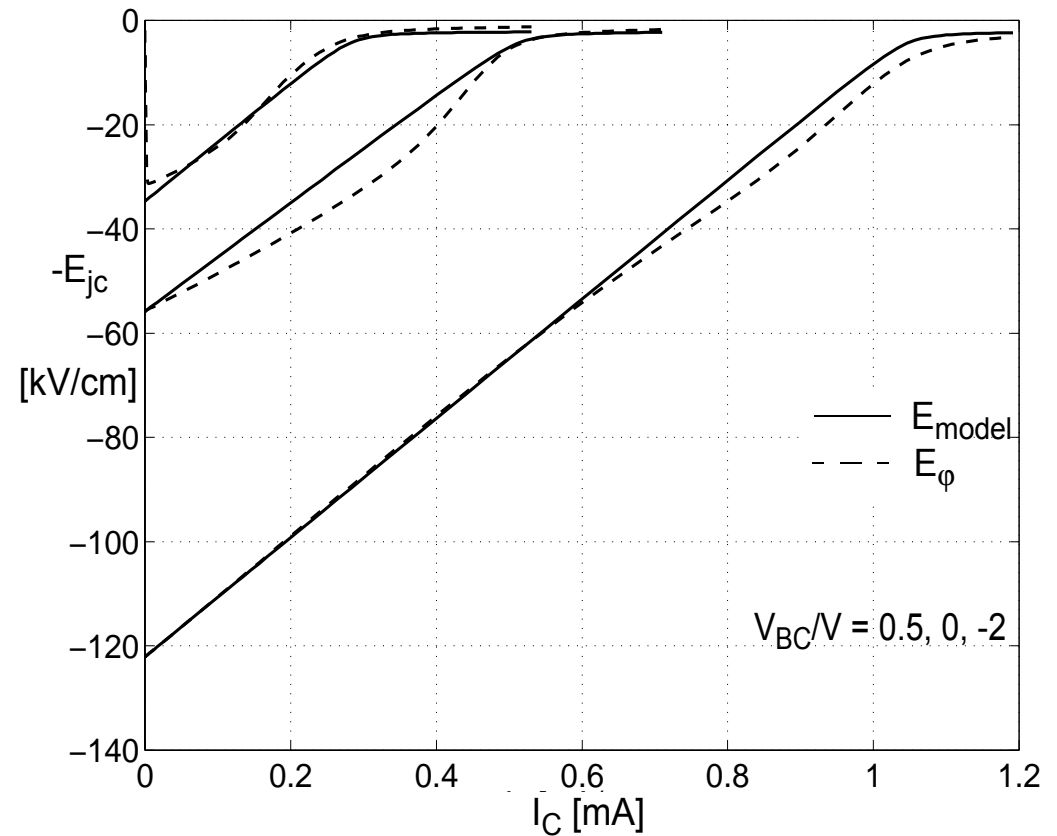
- model equation: $E_{jc} = E_{\infty} + f_e E_{lim}$

with

$$f_e(V_{BC}, I_{Tf}) = \frac{e_j + \sqrt{e_j^2 + g_{jc} \frac{E_{CK}}{E_{lim}}}}{2},$$

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

- parameter: g_{jc} (all other parameters are already available in HICUM)
- deviation at low V_{BC} : missing square root dependence



⇒ 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):

$$dQ_{BC}(V_{BC}, I_{Tf}) = C_{jCi} dV_{BC} + \tau_{BC} dI_{Tf}$$

- BC depletion capacitance is a function of voltage and current

$$C_{jCi}(V_{BC}, I_{Tf}) = \left. \frac{\partial Q_{BC}}{\partial V_{BC}} \right|_{I_{Tf}}$$

- relation to electric field via Gauss' law:

$$Q_{BC}(V_{BC}, I_{Tf}) = \epsilon E_{jc}(V_{BC}, I_{Tf})$$

- 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)

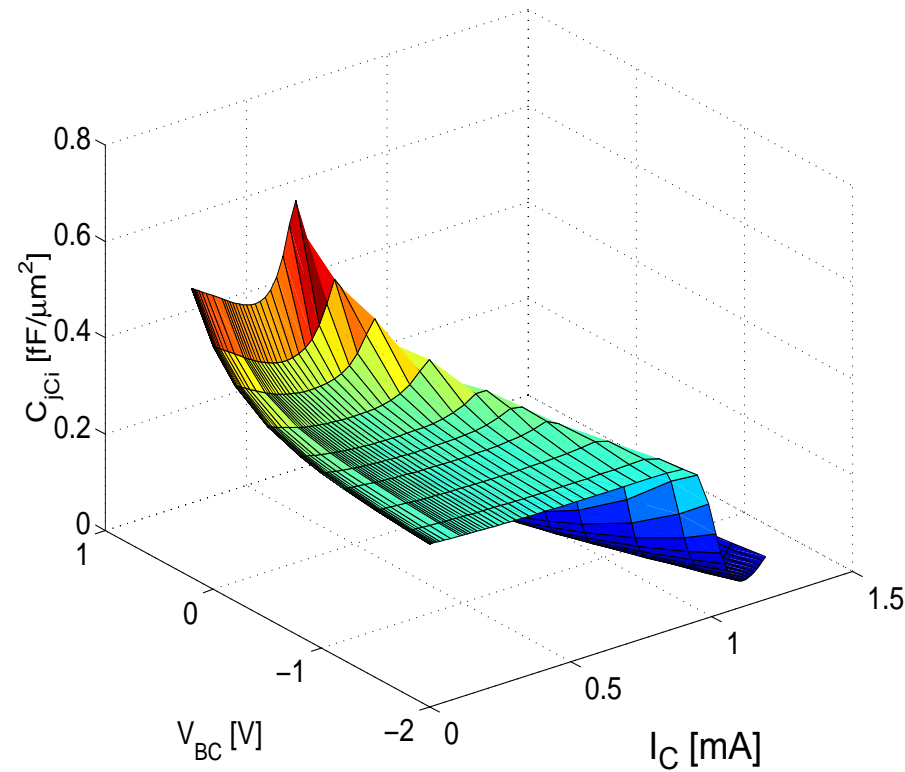
$$\Rightarrow \text{roughly approximated by } \Delta V_{pd} = V_{lim} \frac{I_{Tf}}{I_{lim}} \left(1 + \frac{I_{Tf}}{I_{lim}} \right)$$

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

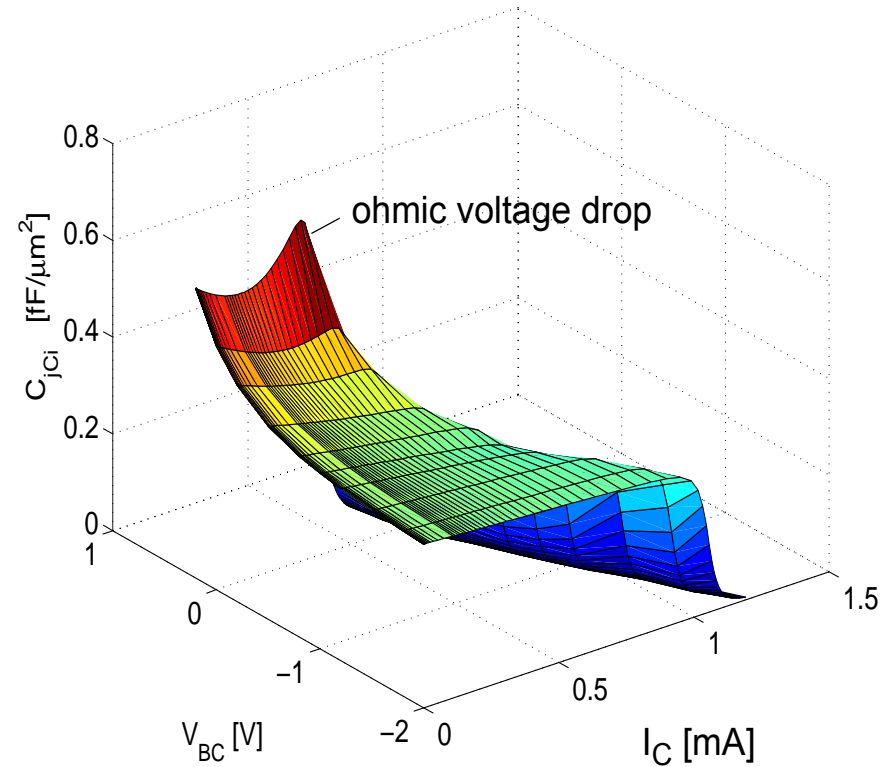
$$\Rightarrow \text{retains explicit formulation}$$

Current and voltage dependent results: comparison

device simulation



analytical equation

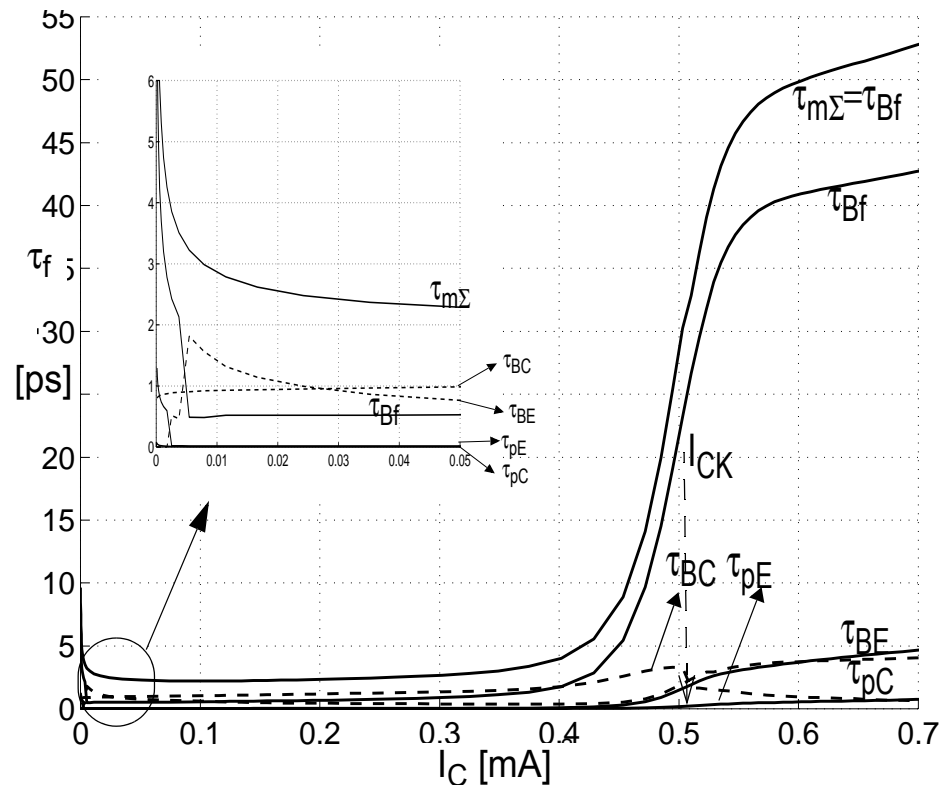


- very accurate voltage dependence (by "design") at zero current
- differences in current dependence caused by inaccuracy of E_{jc} formulation

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) τ_{BC} , (2) τ_{Bf} , (3) τ_{BE}
- high current region:
 - mainly τ_{Bf} dominated (BC barrier !)
- Note: relative importance differs for
 - high-speed device (smaller τ_{BC})
 - Si BJTs (τ_{pC} large at high I_{Tf})
 - GaAs HBTs (τ_{BC} dominated at low I_{Tf})

- impact of E_{jc} (bias) mainly on τ_{Bf} , τ_{BC}

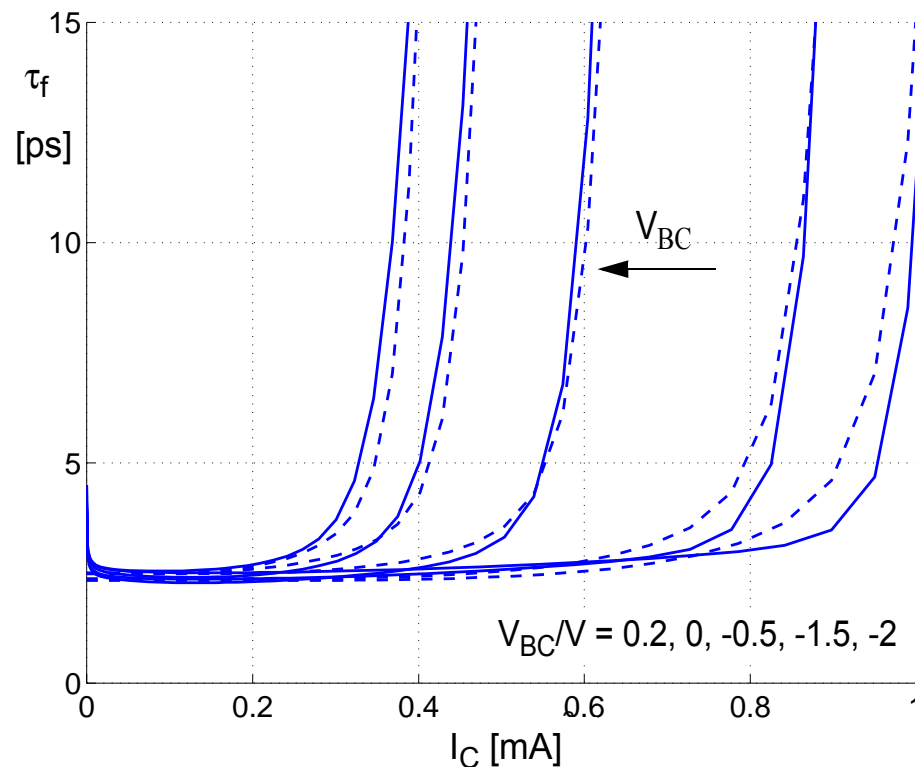
- τ_{BC} defined by incremental BC charge expression: $\tau_{BC}(V_{BC}, I_{Tf}) = \left. \frac{\partial Q_{BC}}{\partial I_{Tf}} \right|_{V_{BC}}$
- τ_{Bf} model: extension of existing HICUM equation

Modeling the transit time

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

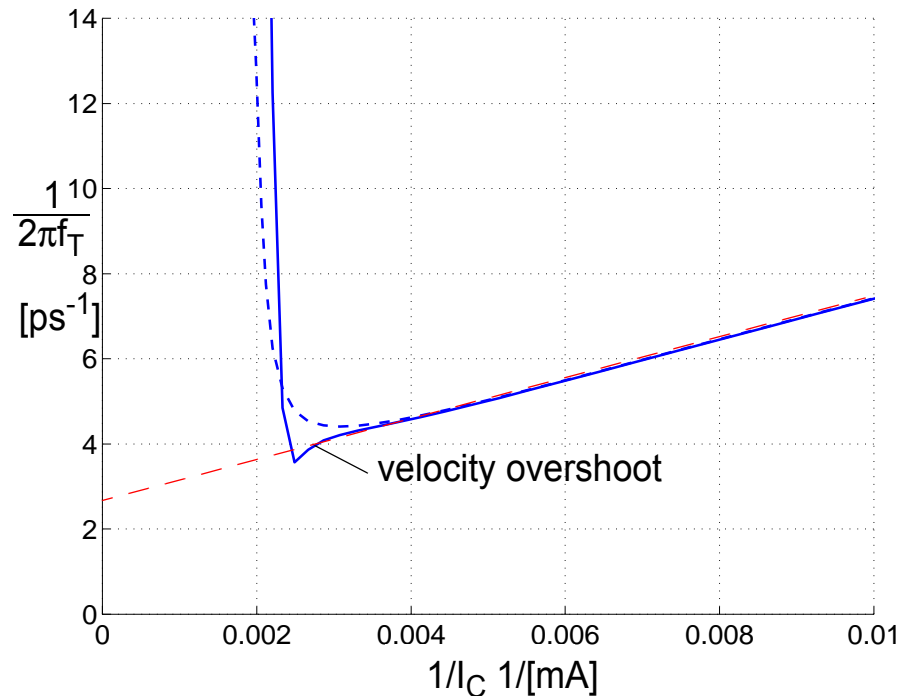
with $f_u(u)$ given in the proceedings b_{hc} as new model parameter, and $g_u = 1$ (holes), 2 (electrons)

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



- 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

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

(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_{jc} 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

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