Regional Approach Methods for SiGe HBT compact modeling

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OUTLINE

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- Overview on Regional Approach Methods
- Results and Discussion
- Conclusions

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Introduction

Bipolar transistor main application areas

- high-frequency/high-speed operation

Circuit design constraints

- cost reduction (mask, re-spins..., yield prediction)
- some applications are close to the technology limit $\Rightarrow$ careful circuit optimization

Process development and optimization

- evaluation of charge and delay components within device structure

$\Rightarrow$ **accurate physics-based modeling of charge storage effects**

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Existing methods for analyzing charge storage

analytical solutions

- require strong simplifications of underlying semiconductor equations
- spatial partitioning into neutral region (NR) and space-charge region (SCR) by *definition* of *abrupt boundaries* (***Regional Approach = RA***)

⇒ validity of results is limited to particular spatial and bias region

device simulation

- yields detailed information on carrier and charge distributions
- no limitation of results w.r.t. certain spatial or bias regions
- however: no abrupt boundaries between spatial regions either

desirable:

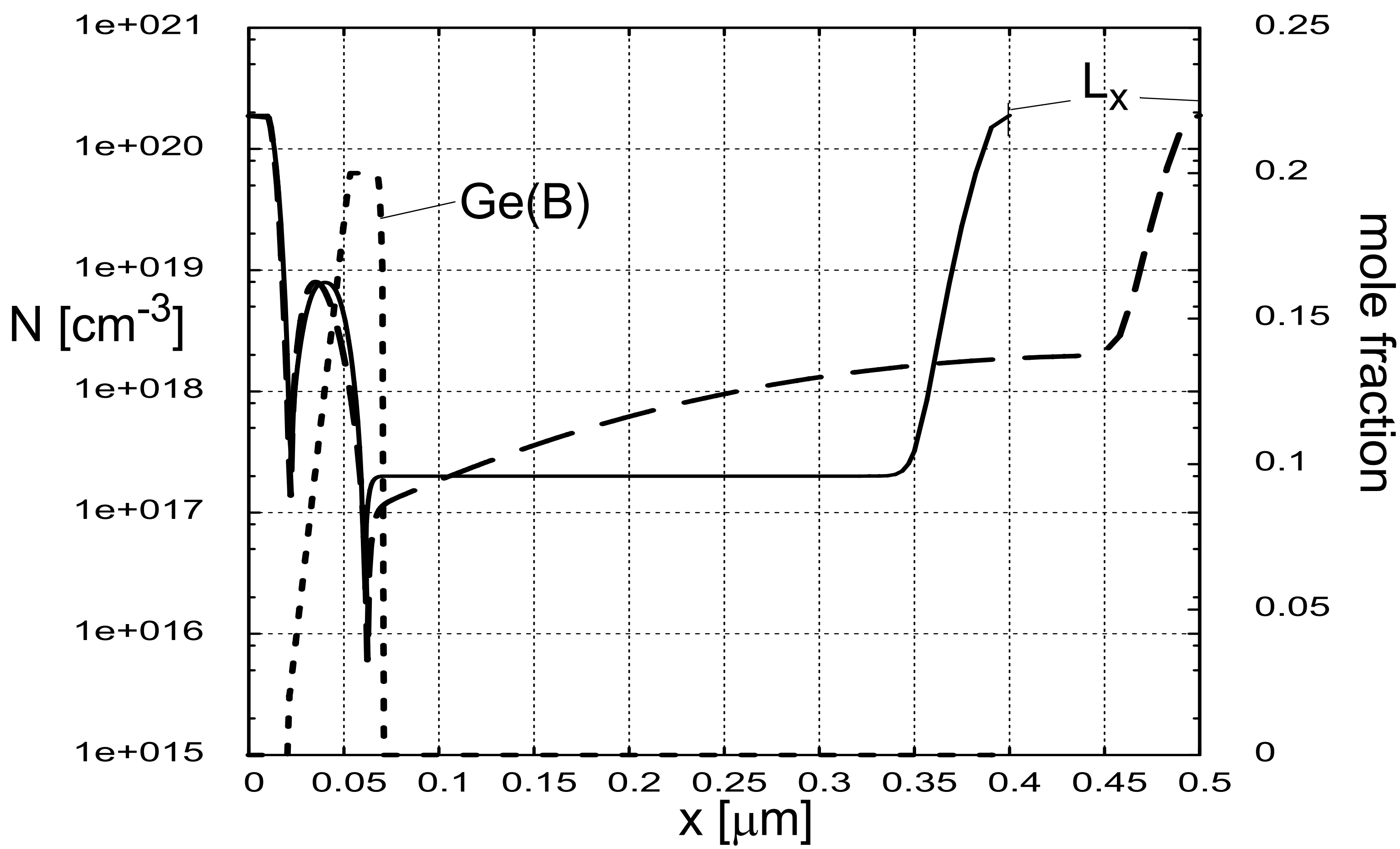
charge storage components from device simulation as reference for analytical modeling

⇒ this work: evaluation of possible RA options for device simulation

Investigated Device Structures

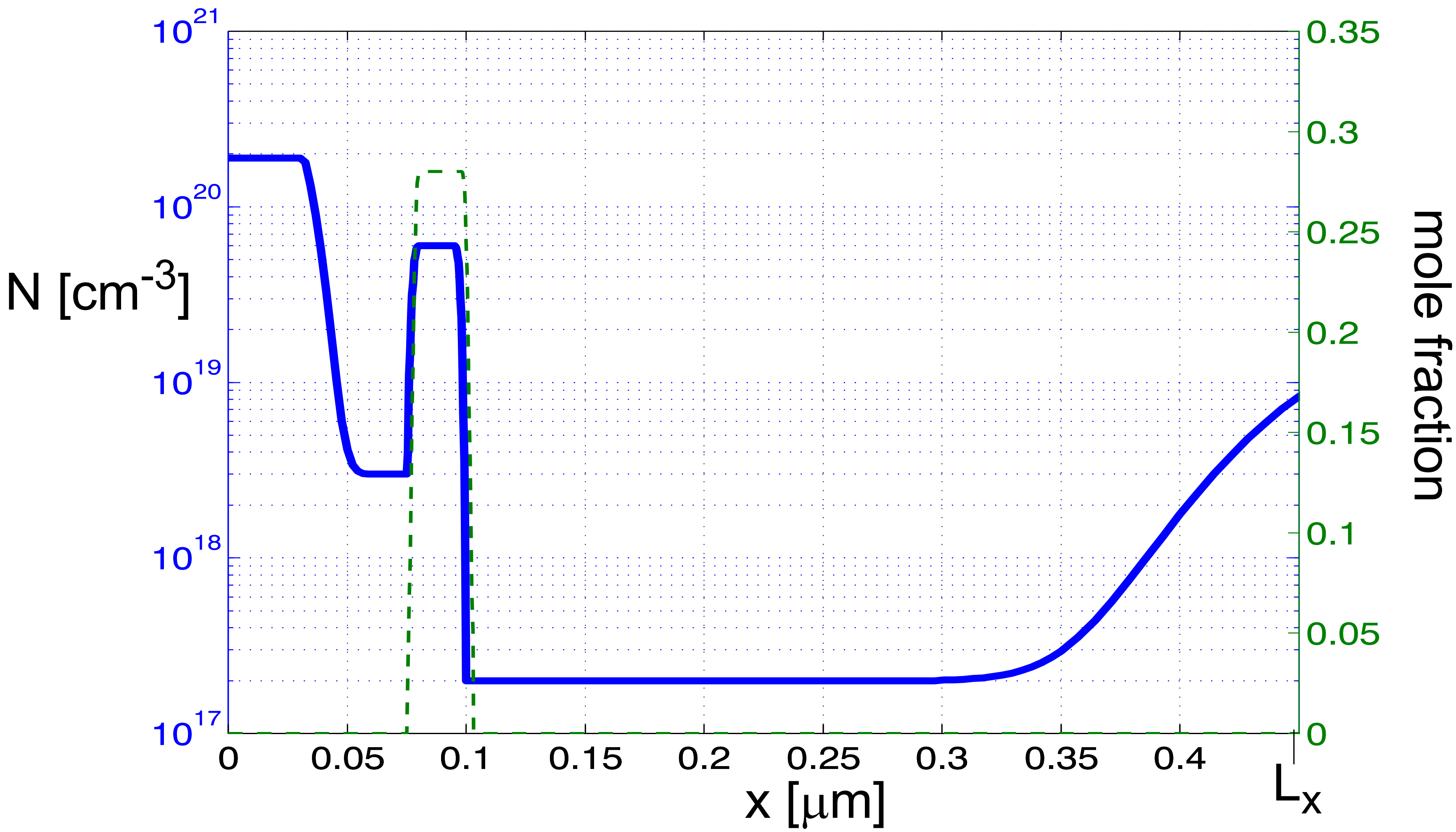
1D device simulation: unit emitter area $A_E = 1\mu m^2$

conventional emitter doping (CED) transistor: high-speed BJT , HBT version



Device Structures

low-emitter concentration (LEC) transistor: high-speed HBT version



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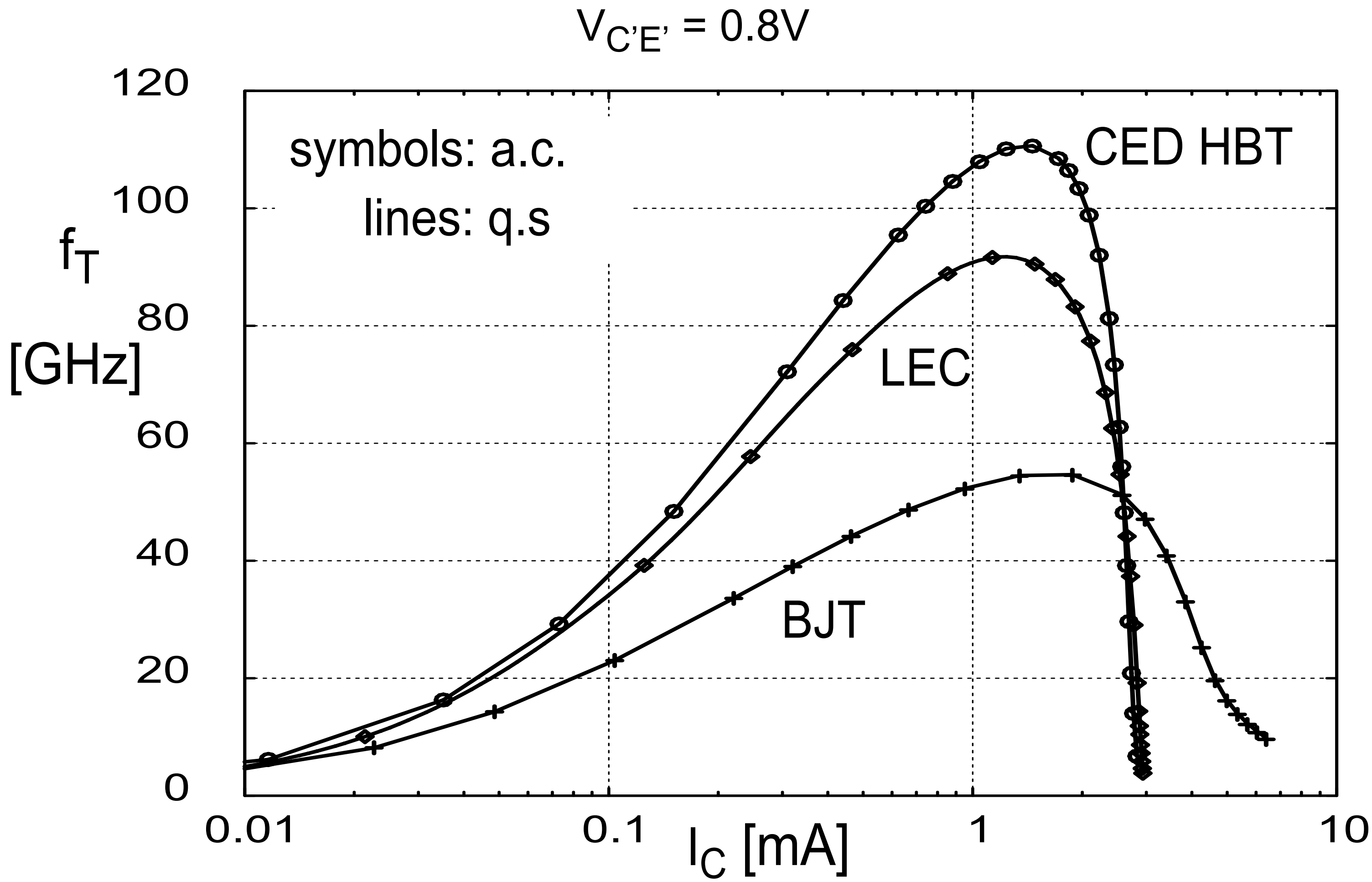
High-frequency performance: transit frequency



- identical results for quasi-static and frequency dependent small-signal calculation

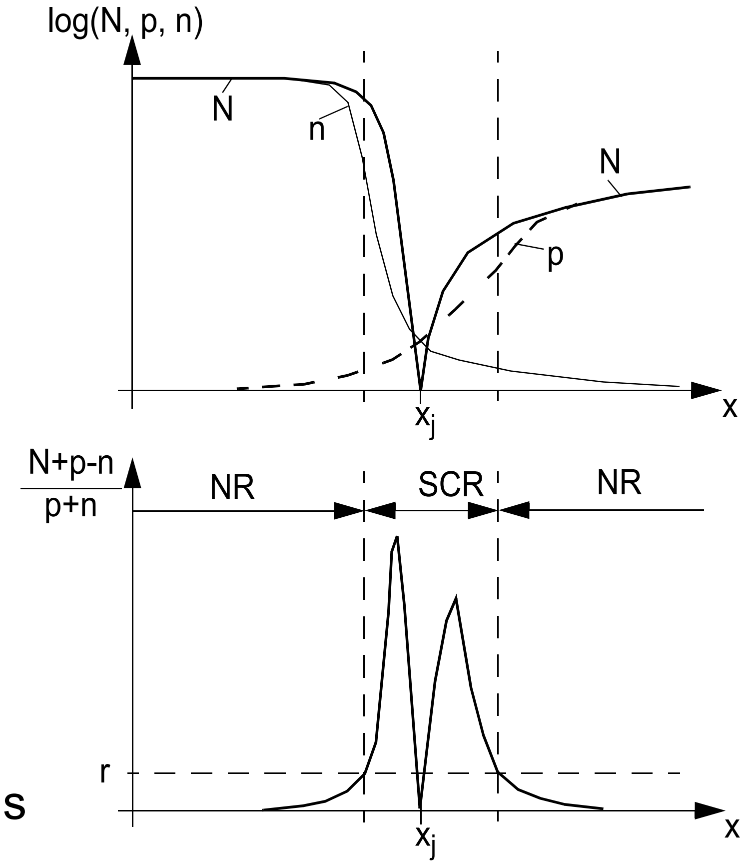
  ⇒ partitioning of transit time based on carrier distribution

Overview on Regional Approach Methods

d.c. method(s)

- determination of NR-SCR boundary is based on static carrier distribution

- classical criterion for detecting point in SCR: majority carrier density < r * doping conc., with r << 1
  - works only for sufficiently low-injection
  - does not work in center region of SCR ($N \rightarrow 0$ but carrier densities remain finite)



- normalized boundary condition:

$$x_r = x\left(\frac{N+p-n}{p+n} \geq r\right) \quad \text{with} \quad r <(<) 1$$

  - works also for high injection
  - search needs to start from neutral region

⇒ designated as DCRA and used for comparisons

problem: missing link to small-signal operation

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Small-signal based regional approaches

- link to small-signal *measurements*
  - via relation between transit frequency and stored hole charge: $\frac{1}{2\pi f_T} = \tau_{ec} = \left.\frac{dQ_p}{dI_C}\right|_{V_{C'E'}}$

  differential hole charge from carrier variation: $dQ_p = qA_E\int_0^{L_x}\partial p\ dx$

- region boundaries detected from *quasi-static* small-signal carrier distribution

- next: comparison of 3 methods

Regional Approach Methods: van den Biesen [6]

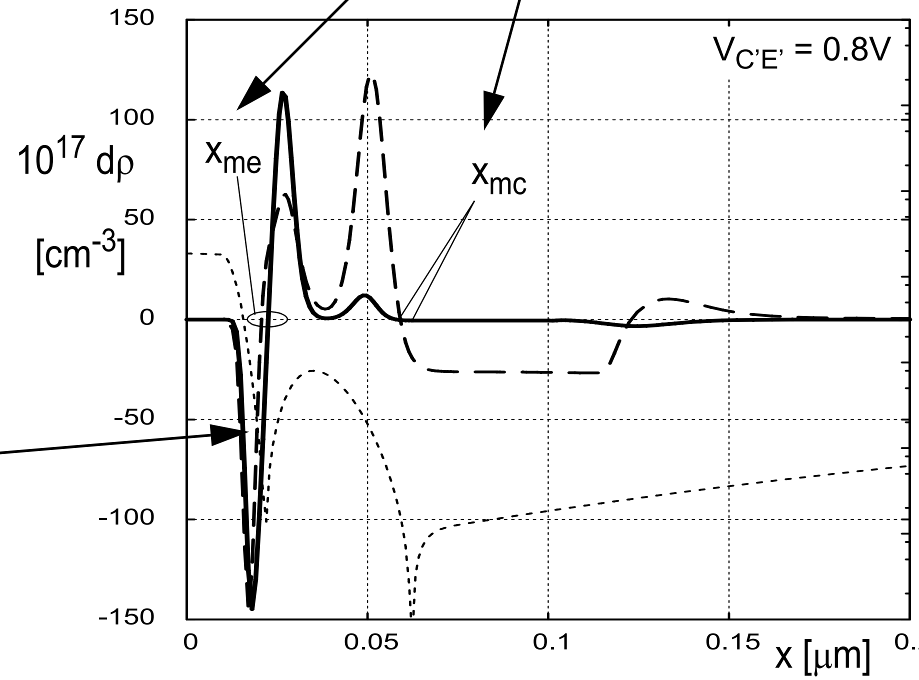
- popular for evaluating device simulation results
- replaces *metallurgical* boundaries by *electrical* boundaries: $x_m = x(dp = dn)$
- storage time partitioning: $\left.\frac{dQ_p}{dI_C}\right|_{V_{C'E'}} \equiv \tau_{ec} = \tau_e^* + \tau_{eb} + \tau_b^* + \tau_{bc} + \tau_c^*$
  - minority carrier storage times, e.g.:

$$\tau_b^* = qA_E \int_{x_{me}}^{x_{mc}} \left.\frac{\partial n}{\partial I_C}\right|_{V_{C'E'}} dx$$

  - depletion region "charging times", e.g.:

$$\tau_{eb} = qA_E \int_0^{x_{me}} \left.\frac{\partial (n-p)}{\partial I_C}\right|_{V_{C'E'}} dx$$

- no separation of NR and SCR



⇒ **not suitable for compact modeling!**

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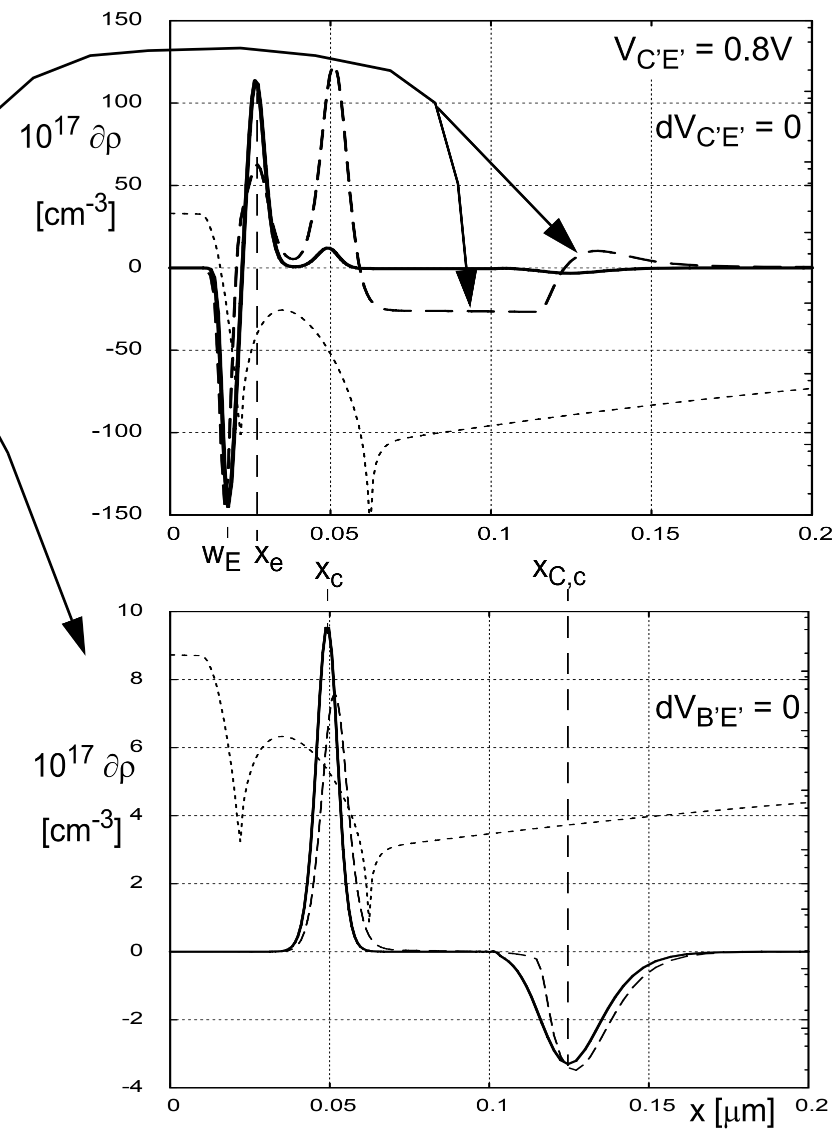
Regional Approach Methods: FRA (1/3)

- region boundaries from peaks of (∂p-∂n)
  - Note: BC SCR boundaries cannot be detected from CE short distribution!
  - need BE short instead
- collector related regions are trickier
  - high-current effects => injection zone
  - Ge drop causes barrier => additional peaks
- SCR edges of BC junction:

$$(x_c, x_{C,c}) = x\left(\left.\frac{\partial\rho}{\partial V_{B'C'}}\right|_{V_{B'E'}} = (max, min)\right)$$

- region widths
  - neutral base: $w_B = min\{x_c, x_{jc}\} - x_e$
  - BC SCR: $w_{BC} = x_{Cc} - x_c$
  - injection width: $w_i = max\{x_c - x_{jc}, 0\}$



Regional Approach Methods: FRA (2/3)

- separation into BE and BC voltage change:

$$dQ_p = \underbrace{\left.\frac{\partial Q_p}{\partial V_{B'E'}}\right|_{V_{C'E'}} dV_{B'E'}}_{dV_{B'E'} = dV_{B'C'}} = \left.\frac{\partial Q_p}{\partial V_{B'E'}}\right|_{V_{B'C'}} dV_{B'E'} + \left.\frac{\partial Q_p}{\partial V_{B'C'}}\right|_{V_{B'E'}} dV_{B'C'}$$

- minorities: $\partial m = \begin{cases} \partial p & , |\partial p| < |\partial n| \\ \partial n & , |\partial n| \le |\partial p| \end{cases}$ $\Rightarrow$ minority charge $dQ_m = qA_E \int_w \partial m dx$

- hole charge partitioning: $dQ_p = dQ_j + dQ_m$

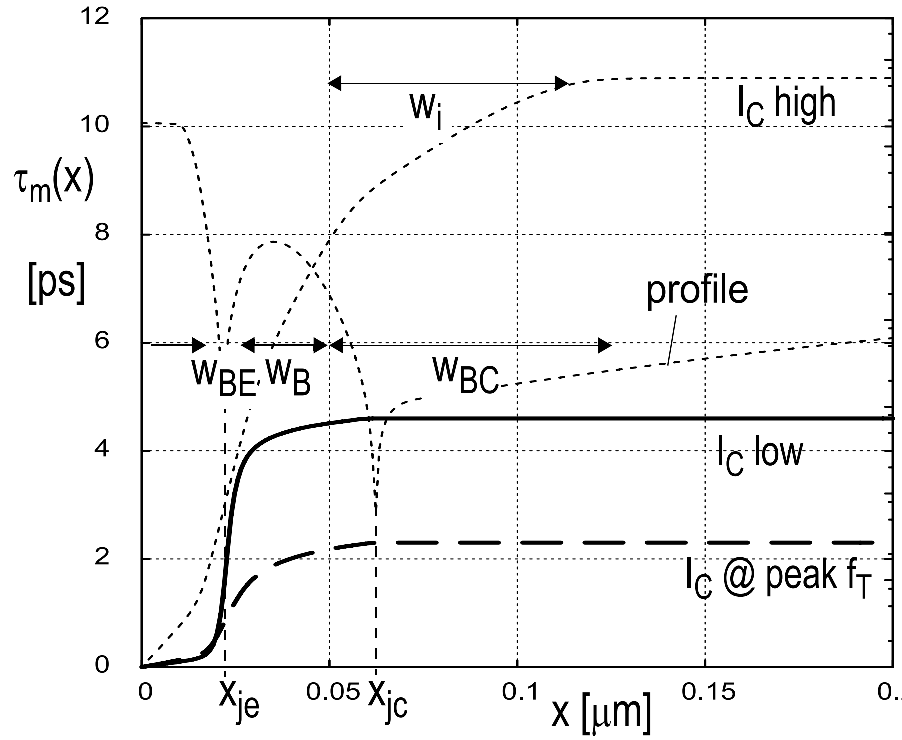
$\Rightarrow$ depletion charge $dQ_j = dQ_p - dQ_m = qA_E \int_{w(\partial p < \partial n)} \partial(n-p) dx$

$\Rightarrow$ consistent with q.s. definition of f_T

Full regional approach (3/3)

- minority carrier storage time components from accumulated storage time:

$$\tau_m(x) = qA_E \int_0^x \left.\frac{\partial m}{\partial I_C}\right|_{V_{C'E'}} d\xi$$



- space-charge modulation in BC SCR:

$$C_{cE} = qA_E \int_{x_{mc}}^{L_x} \left.\frac{\partial(-\rho)}{\partial V_{B'E'}}\right|_{V_{B'C'}} dx$$

= cross-coupled capacitance

- total value: $\tau_f = \tau_m(L_x) + \frac{C_{cE}}{g_{mi}}$

- depletion capacitances:

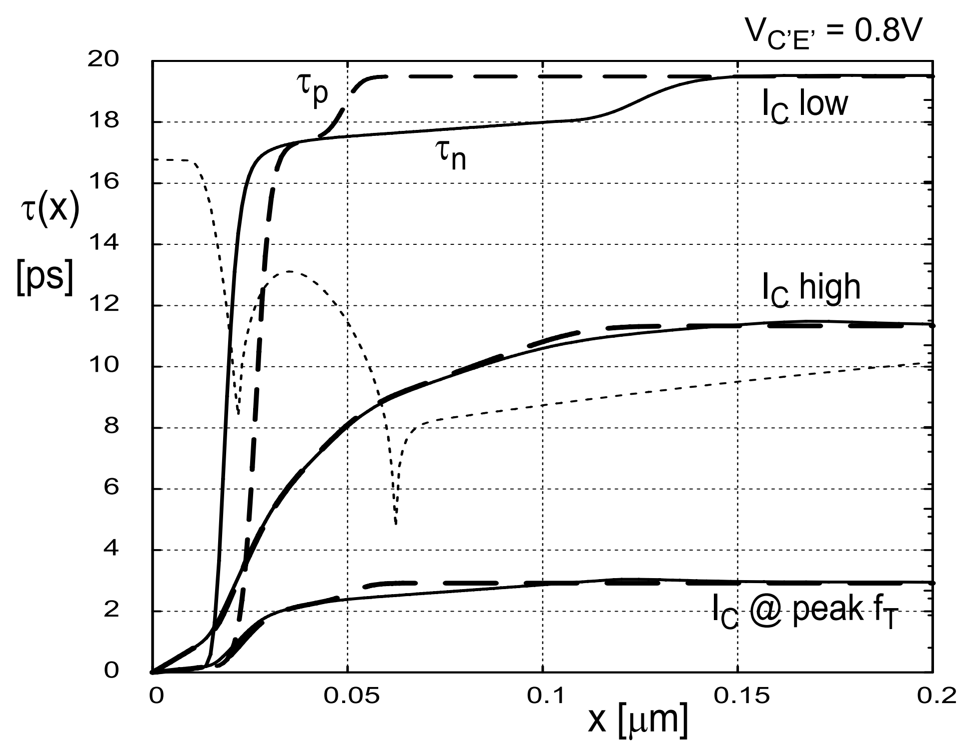
$$C_{jEi} = qA_E \int_0^{x_{me}} \left.\frac{\partial(-\rho)}{\partial V_{B'E'}}\right|_{V_{B'C'}} dx \qquad C_{jCi} = qA_E \int_{x_{mc}}^{L_x} \left.\frac{\partial(-\rho)}{\partial V_{B'C'}}\right|_{V_{B'E'}} dx$$

Regional Approach Methods: DTRA [11]

- proposed for evaluation of device simulation results
- SCR boundary defined as 5% difference between accumulated carrier storage times

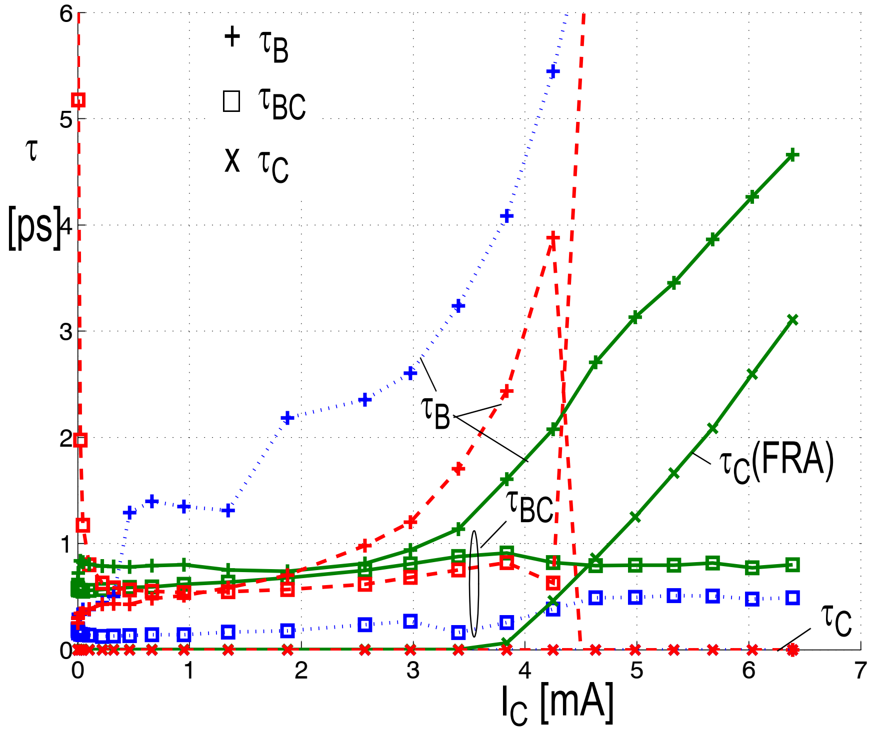
$$\tau_n(x) = qA_E \int_0^x \left.\frac{\partial n}{\partial I_C}\right|_{V_{C'E'}} d\xi \quad , \quad \tau_p(x) = qA_E \int_0^x \left.\frac{\partial p}{\partial I_C}\right|_{V_{C'E'}} d\xi$$

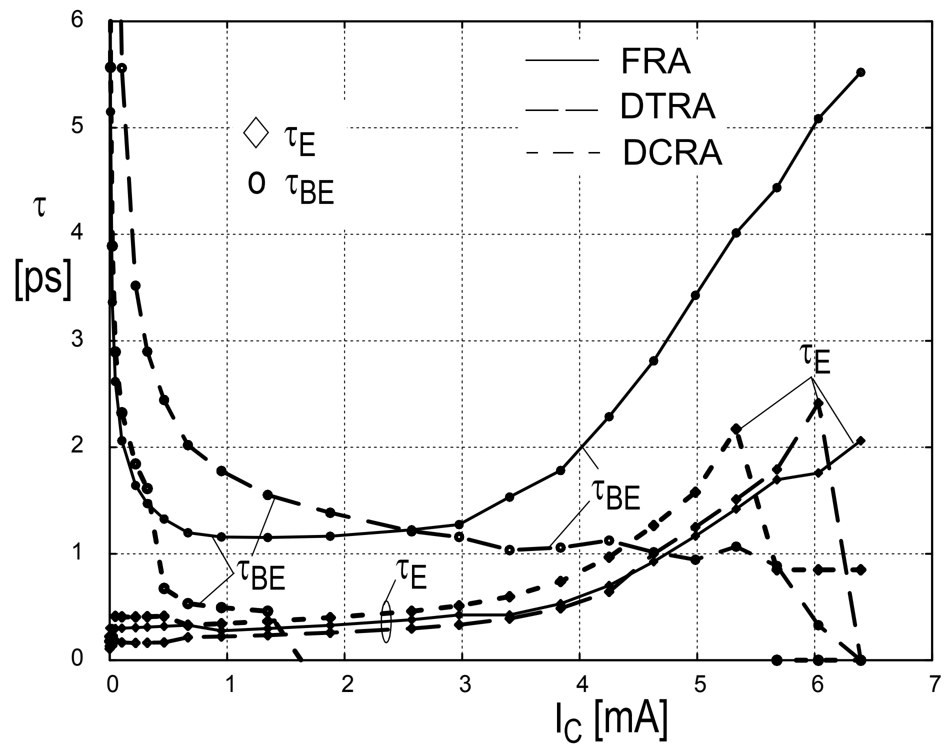
- storage times include depletion charge contributions (C_j/g_m)
- does not allow reliable detection of BC SCR end
- boundary detection difficult at high injection
- correction of $\tau_E \rightarrow (2/3)\tau_E$ based on non-quasi-static operation
  $\Rightarrow$ ignored here



Results and Discussion

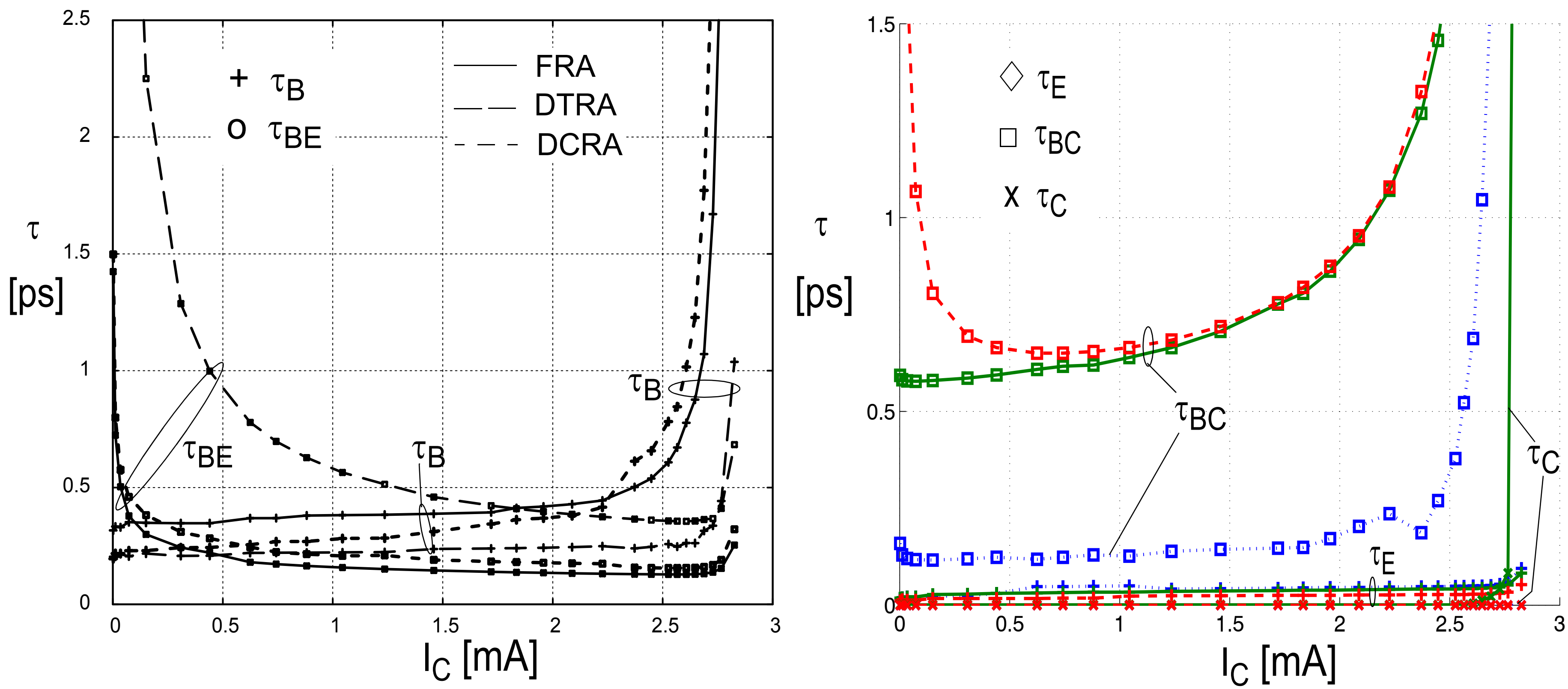
BJT storage time components ($V_{C'E'}$ = 0.8V)





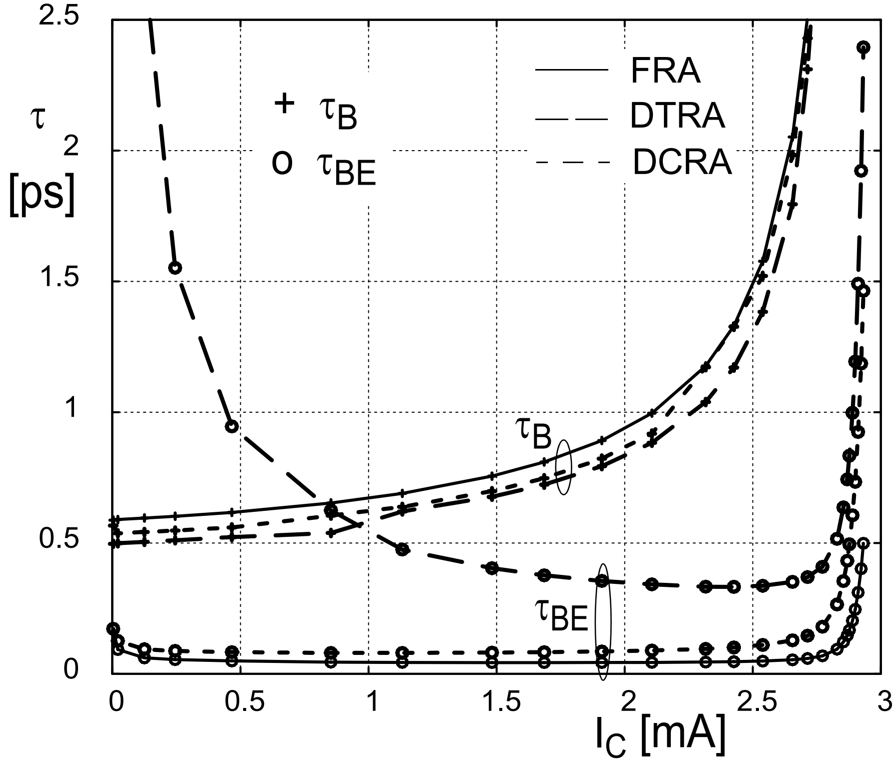
- neutral base: τ_B differs significantly; discontinuous for DTRA due to Kirk effect
- BC SCR: τ_{BC} similar for FRA & DTRA, but too small for DCRA (τ_m only)
- BE SCR: τ_{BE} differs significantly, discontinuous for DCRA (no x_e detection)
- neutral collector: τ_C not detected by DCRA and DTRA

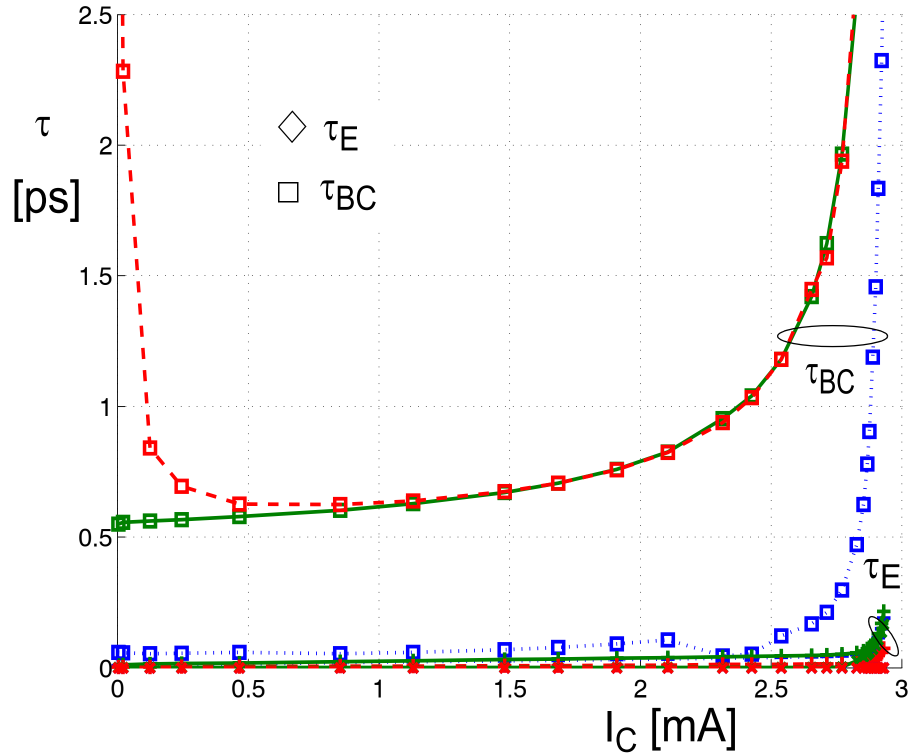
CED HBT storage time components ($V_{C'E'}$ = 0.8V)



- neutral base: τ_B more consistent; DTRA does not detect carrier jam properly
- BC SCR: τ_{BC} similar for FRA & DTRA; difference at low I_C due to C_{jCi}/g_m in DTRA
- BE SCR: τ_{BE} more consistent; DTRA and FRA similar
- neutral collector (τ_C): small injection zone is detected by FRA, not by DTRA, DCRA

LEC HBT storage time components ($V_{C'E'}$ = 0.8V)





- neutral base: τ_B dominates, detected fairly consistently for all methods
- BC SCR: τ_{BC} identical for FRA & DTRA, increase due to barrier
- BE SCR: τ_{BE} similar for DCRA and FRA; DTRA includes C_{jEi}/g_m (low I_C)
- neutral collector (τ_C) and emitter (τ_E): negligible due to barriers

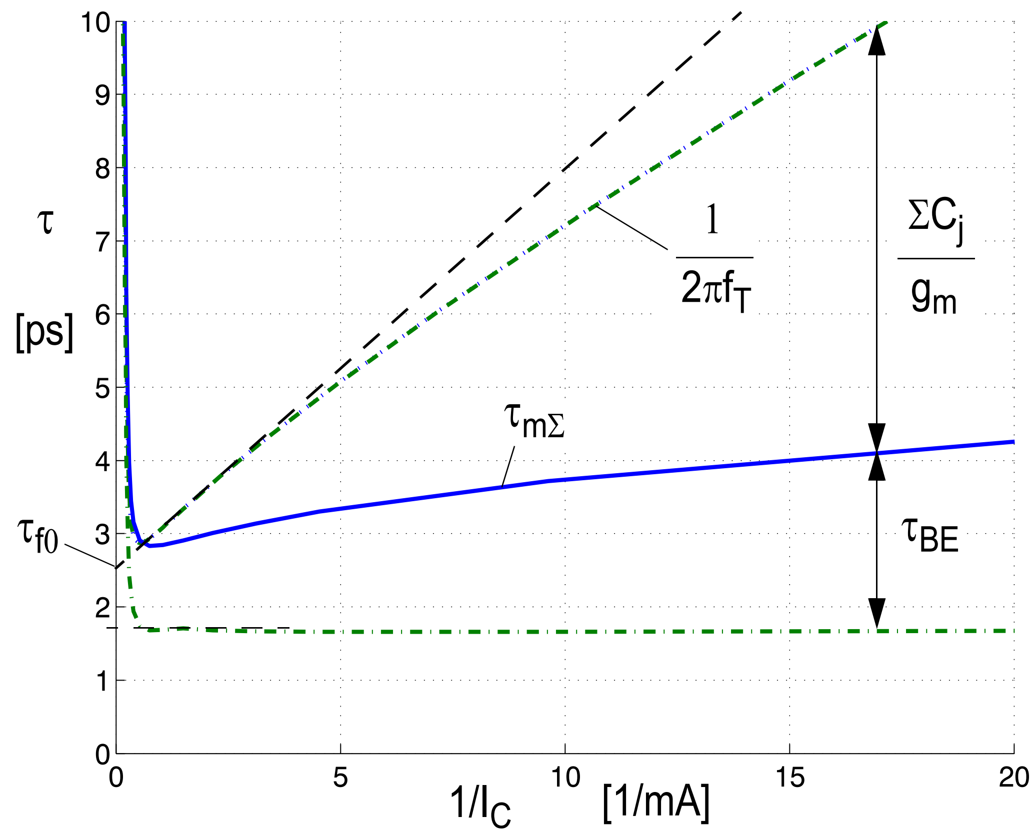
Determination of compact model transit time

Reciprocal f_T and related storage times vs $1/I_C$ for BJT

- standard transit time determination method

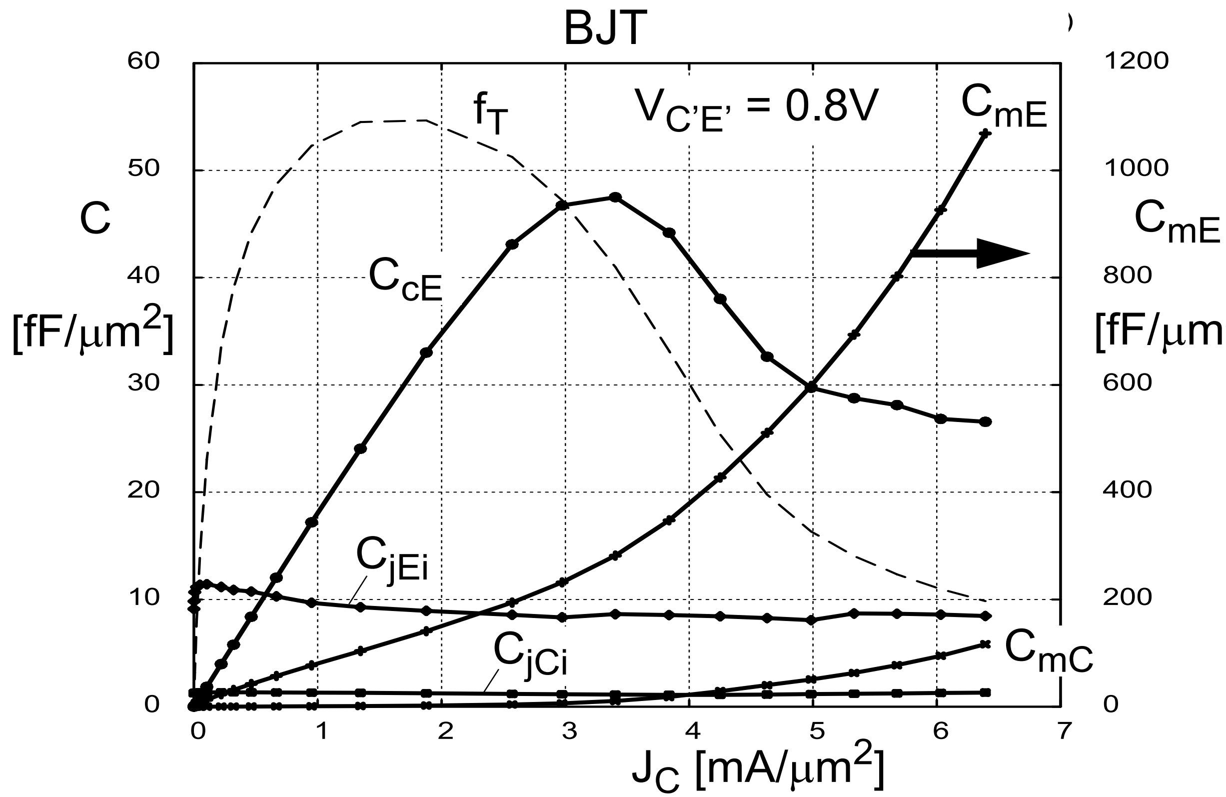
$$\Rightarrow \quad \tau_f = \tau_{f0}(V_{BC}) + \Delta\tau_f(I_T, V_{BC})$$

- slope is usually assumed to be caused by depletion caps
- improved method includes curvature (from V_{BE} dependence of C_{jE})
- in reality: curvature and portion of offset caused by neutral charge in BE SCR



⇒ extracted C_{jE} always includes portion of neutral BE charge

Full regional approach: capacitances



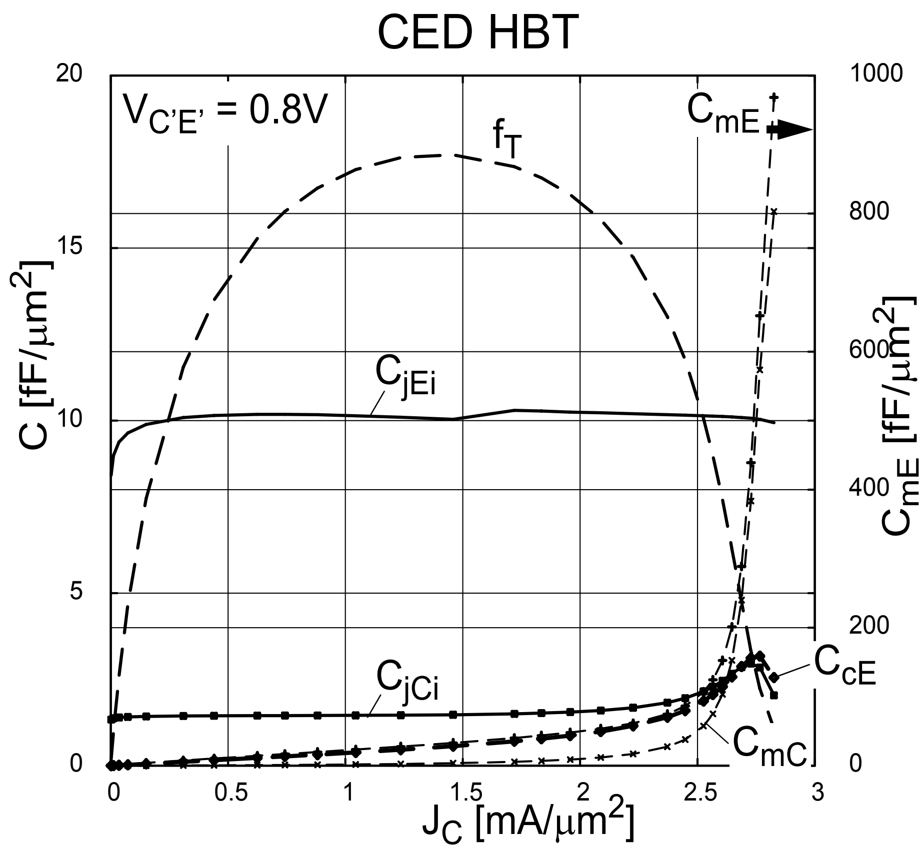
- BC depletion capacitances

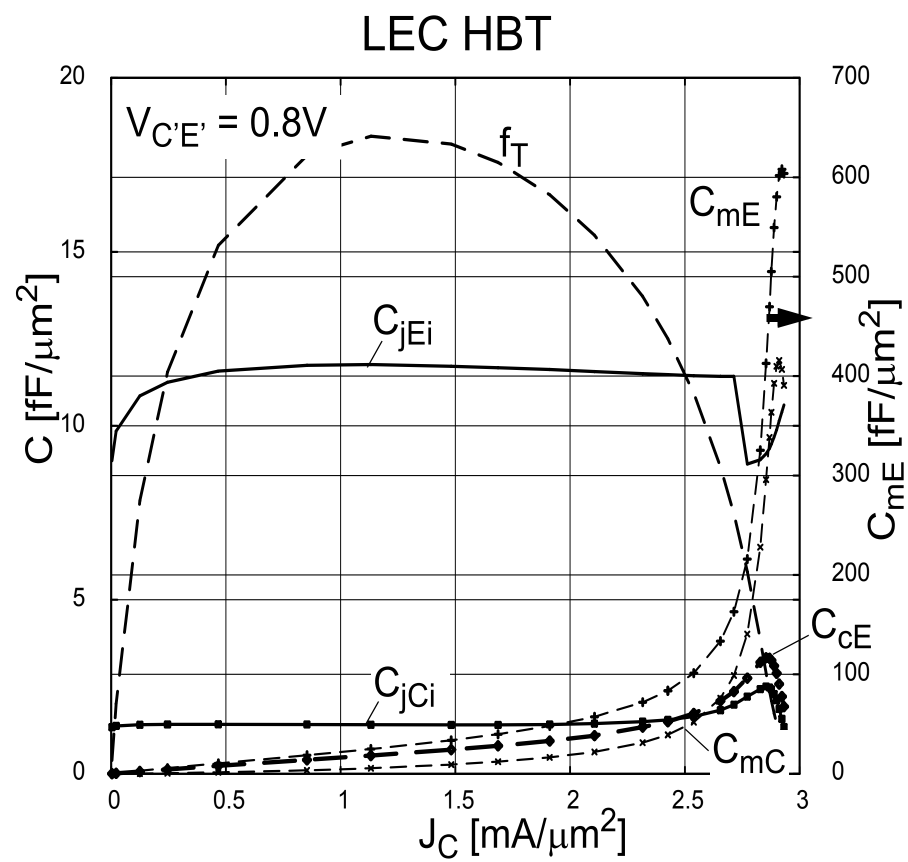
$$C_{jCi} = qA_E\int_{x_{mc}}^{L_x} \frac{\partial\rho}{\partial V_{B'C'}}\bigg|_{V_{B'E'}} dx$$

- cross-coupled BE capacitance

$$C_{cE} = qA_E\int_{x_{mc}}^{L_x} \frac{\partial\rho}{\partial V_{B'E'}}\bigg|_{V_{B'C'}} dx$$

Full regional approach: HBT capacitances





- C_{jEi} dominates before, C_{mE} beyond peak f_T
- stronger C_{mE} increase at high current densities due to barrier effect

Conclusions

- several approaches for regional partitioning in Si-based HBTs have been investigated regarding their suitability for *device simulation and compact modeling* use
- d.c. carrier distribution based methods are unreliable
- small-signal quasi-static carrier distribution based methods:
  - van den Biesen's scheme is not useful for *compact modeling*
  - differential transit time approach (DTRA) is unreliable for BJTs, does not detect boundaries in the collector
  - extended space-charge peak based regional approach (FRA) gives reliable physically reasonable results that can be linked directly to compact model development
- BE depletion charge always contains a portion of neutral charge

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Additional slides

- improved (most recently): $x_{SCR} = \left\{ x: \dfrac{|p - n + \mathrm{sgn}(N)\ G|}{G} \geq r \right\}$ with r = 0.4 ... 0.6
  - works for any discrete point (no search direction required) and all regions of operation
  - r $\in$ (0,1) can be easily adjusted to depletion capacitance value

Full regional approach: results

electron velocity, internal collector resistance

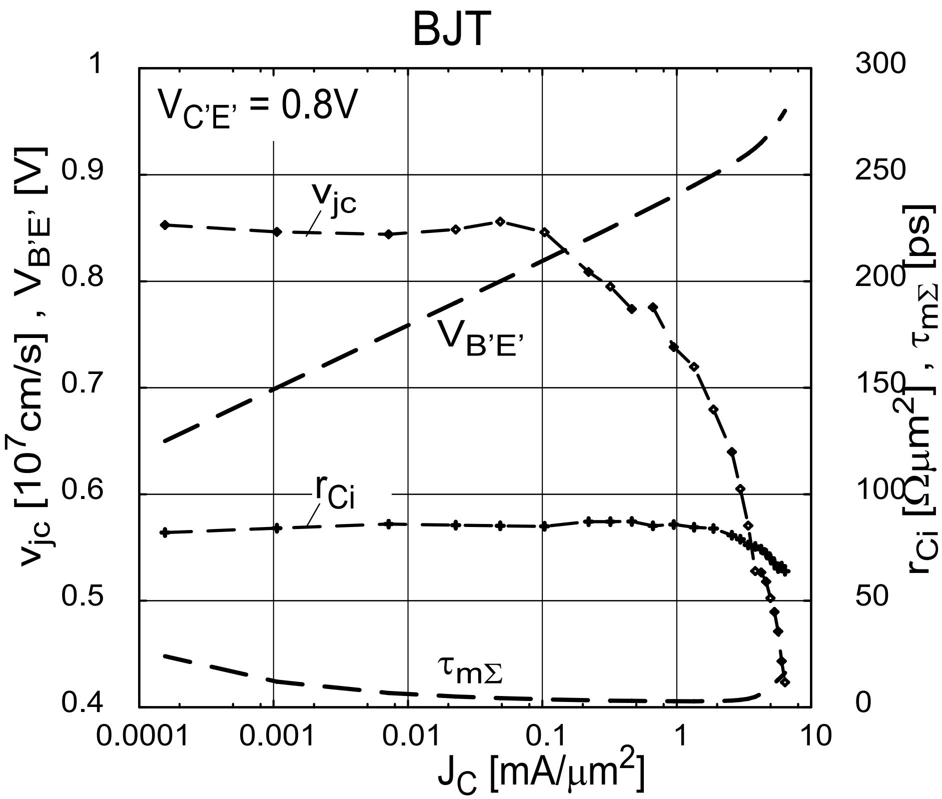
- internal collector resistance:

$$r_{Ci} = A_E^{-1}\int_{x_{bcc}}^{L_x} \frac{1}{q\mu_{nCi}n}dx$$

- carrier velocity:

$$v_{jc} = \frac{w_{BC}}{2(\tau_{BC} - r_{Ci}C_{jCi})}$$

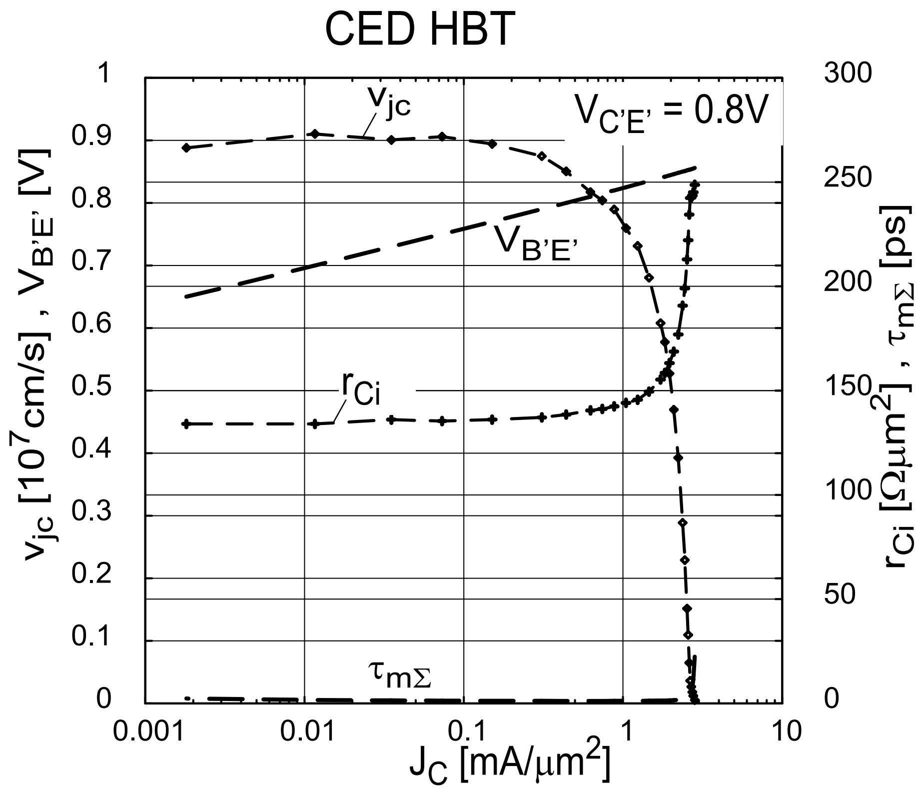
  - τ_{BC} includes collector charge modul.
  - value close to physical ($N_C(x)$!)

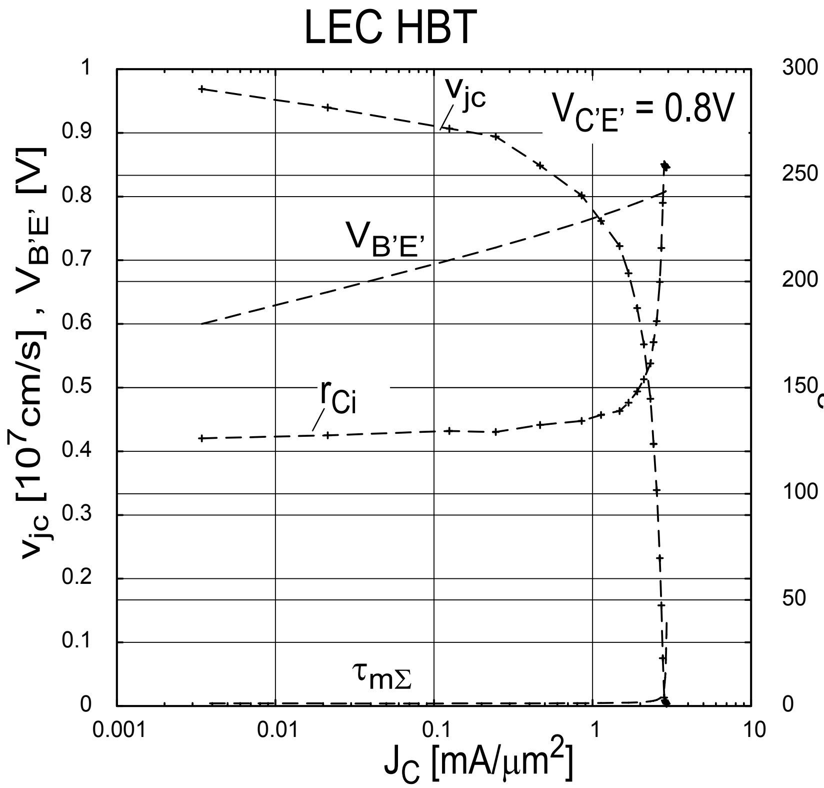


- increasing J_C:
  - w_{BC} increases ($V_c > V_{lim}$) $\Rightarrow$ r_{Ci} decreases
  - E_{jc} decreases $\Rightarrow$ v_{jc} decreases

Full regional approach: results

electron velocity, internal collector resistance

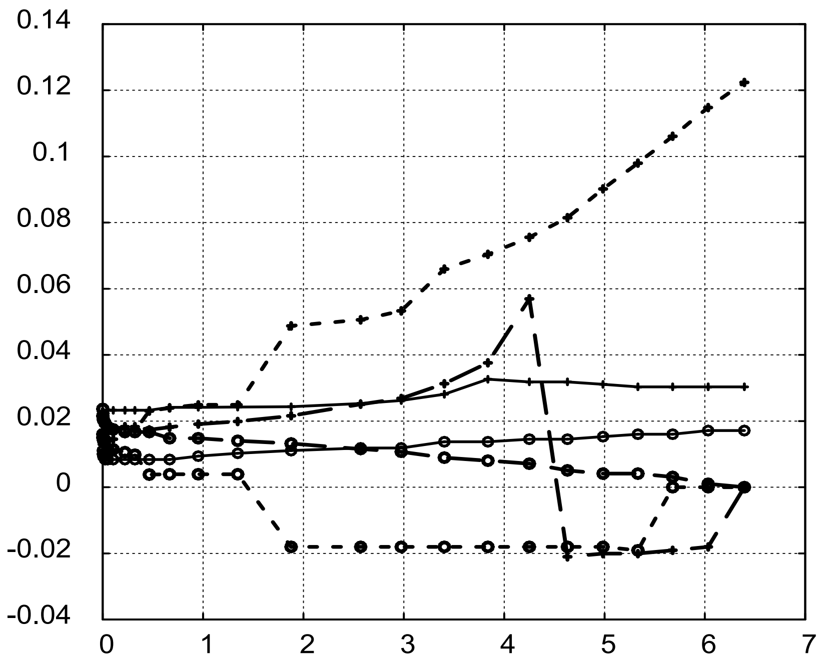


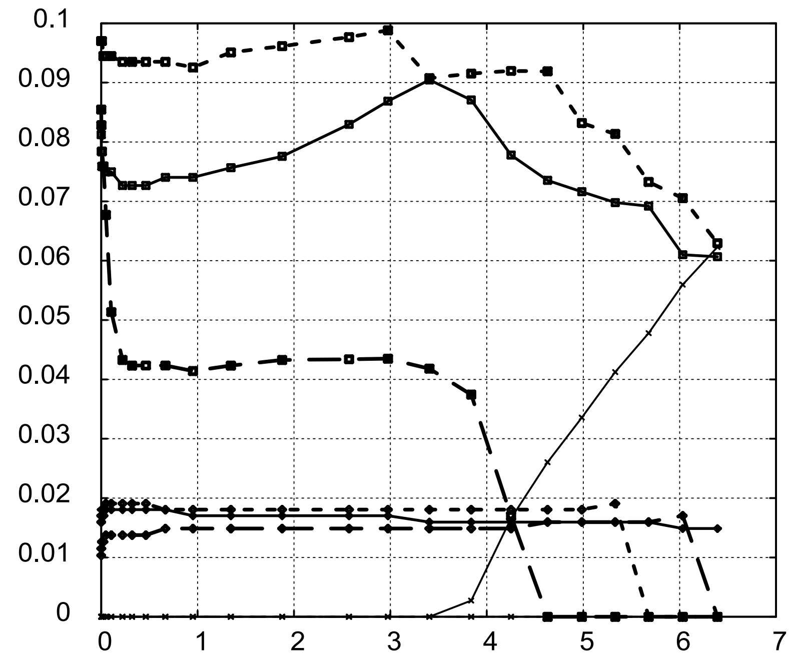


- increasing J_C:
  - w_{BC} decreases ($V_c < V_{lim}$) $\Rightarrow$ r_{Ci} increases
  - E_{jc} decreases $\Rightarrow$ v_{jc} decreases

Full regional approach: bias dependent widths

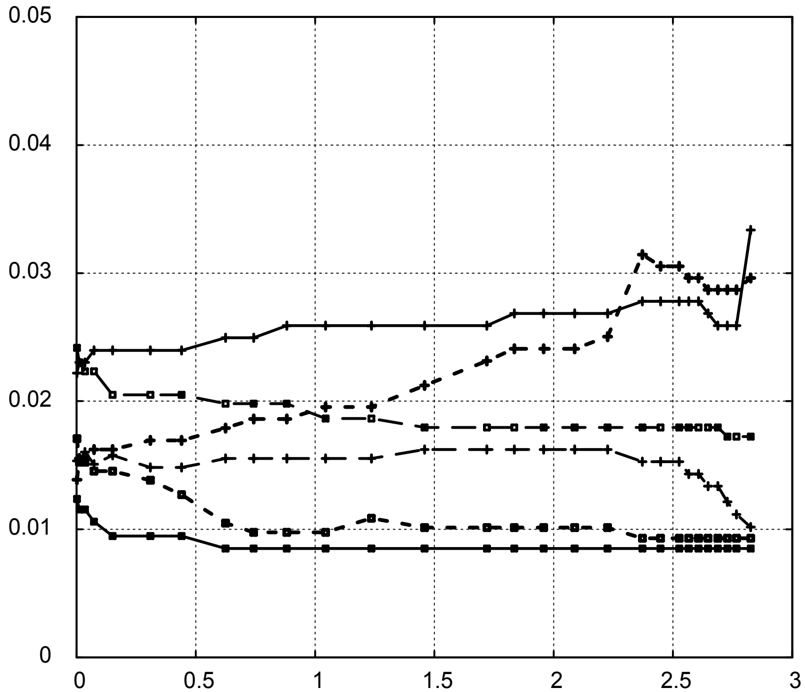
BJT

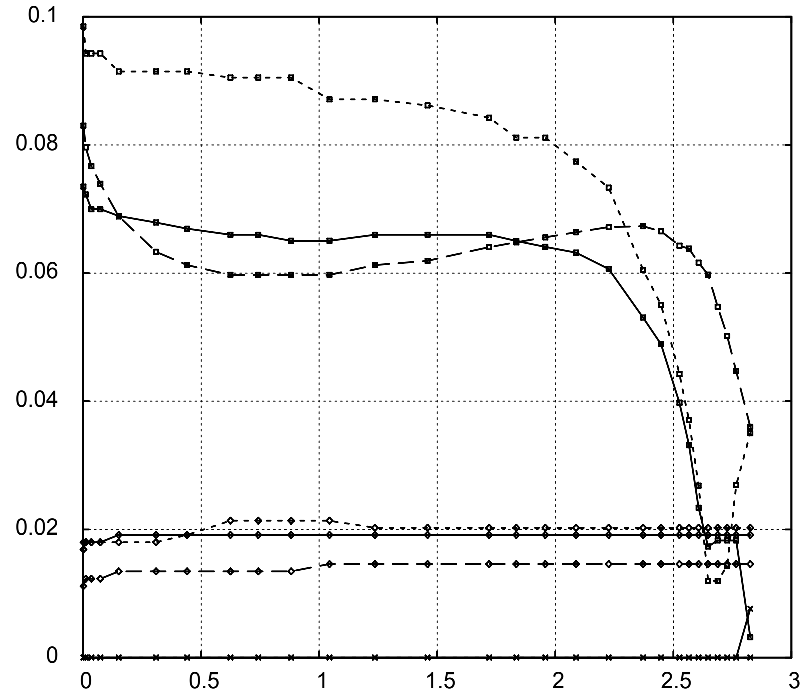




Full regional approach: bias dependent widths

CED transistor





Full regional approach: bias dependent widths

LEC transistor