Accurate transit time determination and transfer current parameter extraction

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Outline

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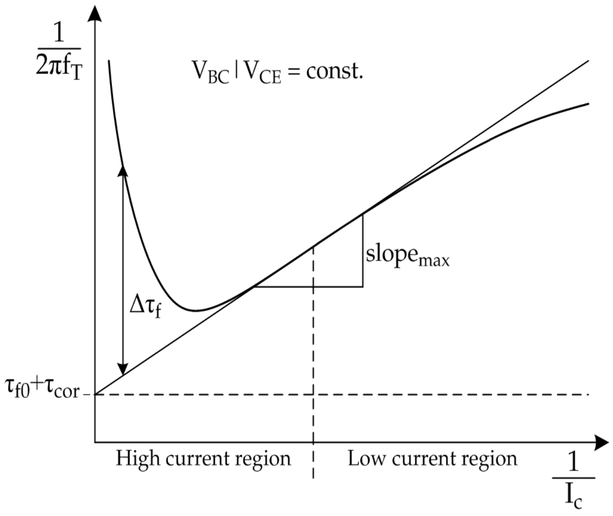
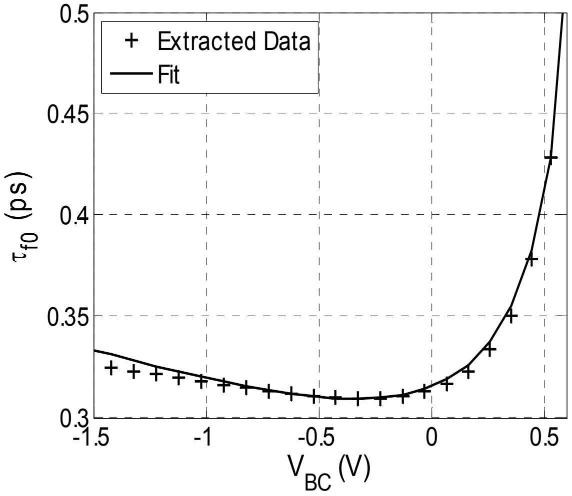
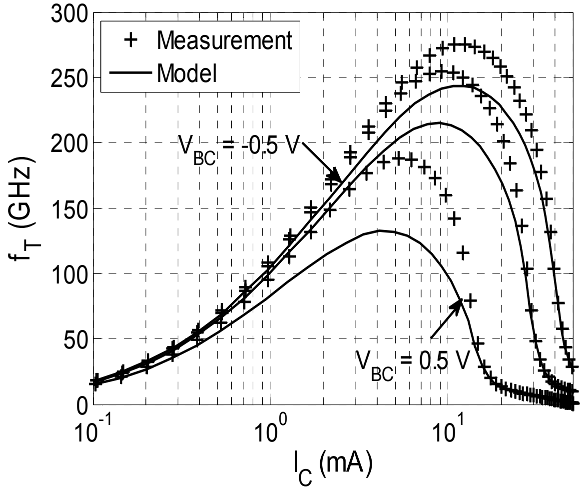
Motivation

- HICUM/L2 is a charge-based model
  - physics-based modeling of charge for accurate description of dynamic transistor behavior
  - charge components are being used also in transfer current formulation via GICCR
- Observation in more advanced technologies: "classical" determination method of transit time from f_T measurement appears to be inaccurate or inconsistent

classical τ_f determination from f_T → τ_f parameter extraction → f_T model playback







=> inaccurate τ_f determination or extraction?

About this presentation ...

- Goal: develop reliable method for
  - transit time determination and model parameter extraction (20 parameters)
  - transfer current model parameter extraction (13 parameters)

- Requirements
  - accurate and consistent
  - include impact of parasitic elements and self-heating
  - allows automation (i.e. avoid manual fine tuning)
  - applicable to all process technology types
  - include new HICUM/L2 v2.31 improvements:
    - Barrier term (essential especially for HBTs)
    - Transfer current formulation

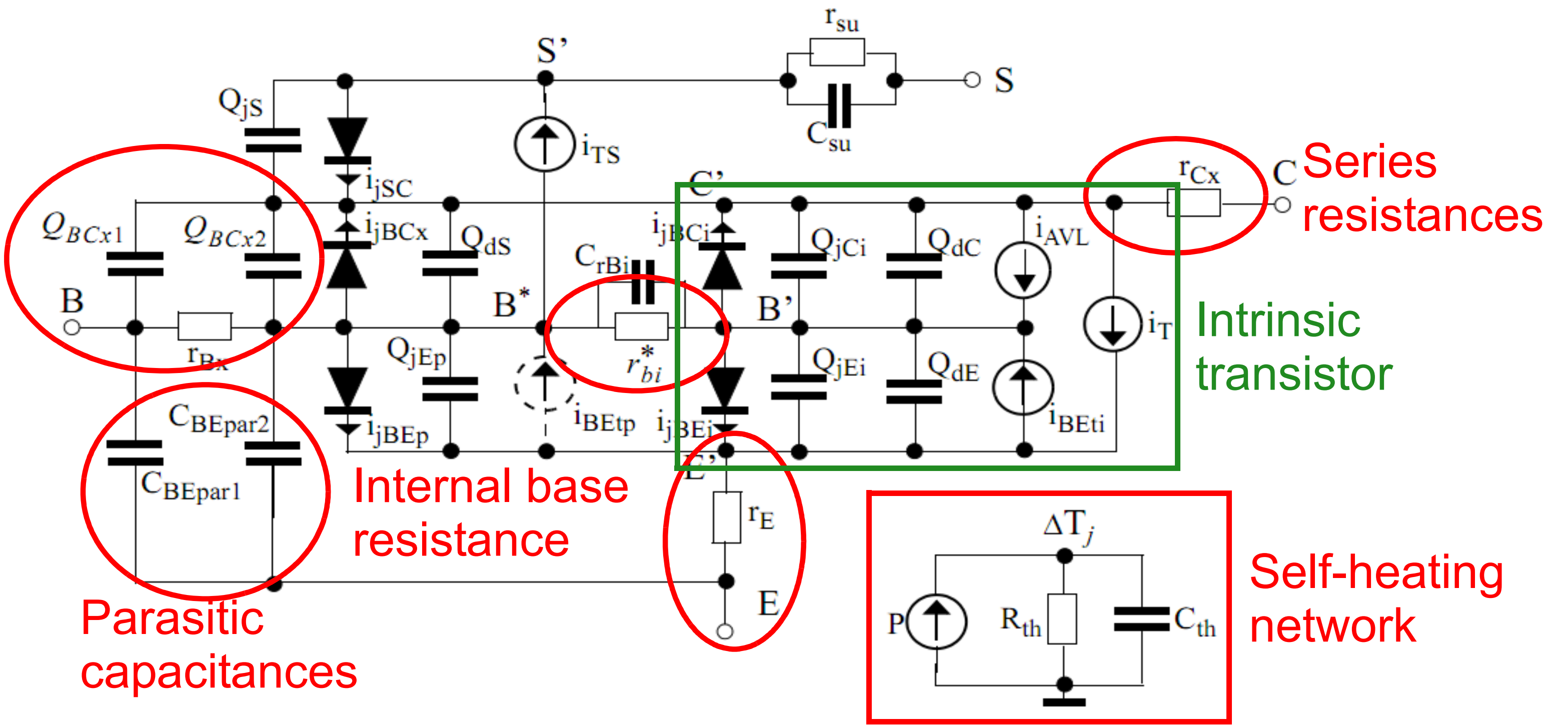
- Verification
  - IHP HBTs with peak (fT, fmax) = (300, 500) GHz

Method overview

- Transit time is associated with the intrinsic transistor portion
- External elements alter Y-parameters of intrinsic transistor
  - in addition: self-heating needs to be included for high current region

=> "De-embedding" of external elements and parasitic effects necessary

HICUM/L2 equivalent circuit



Series resistances

Intrinsic transistor

Internal base resistance

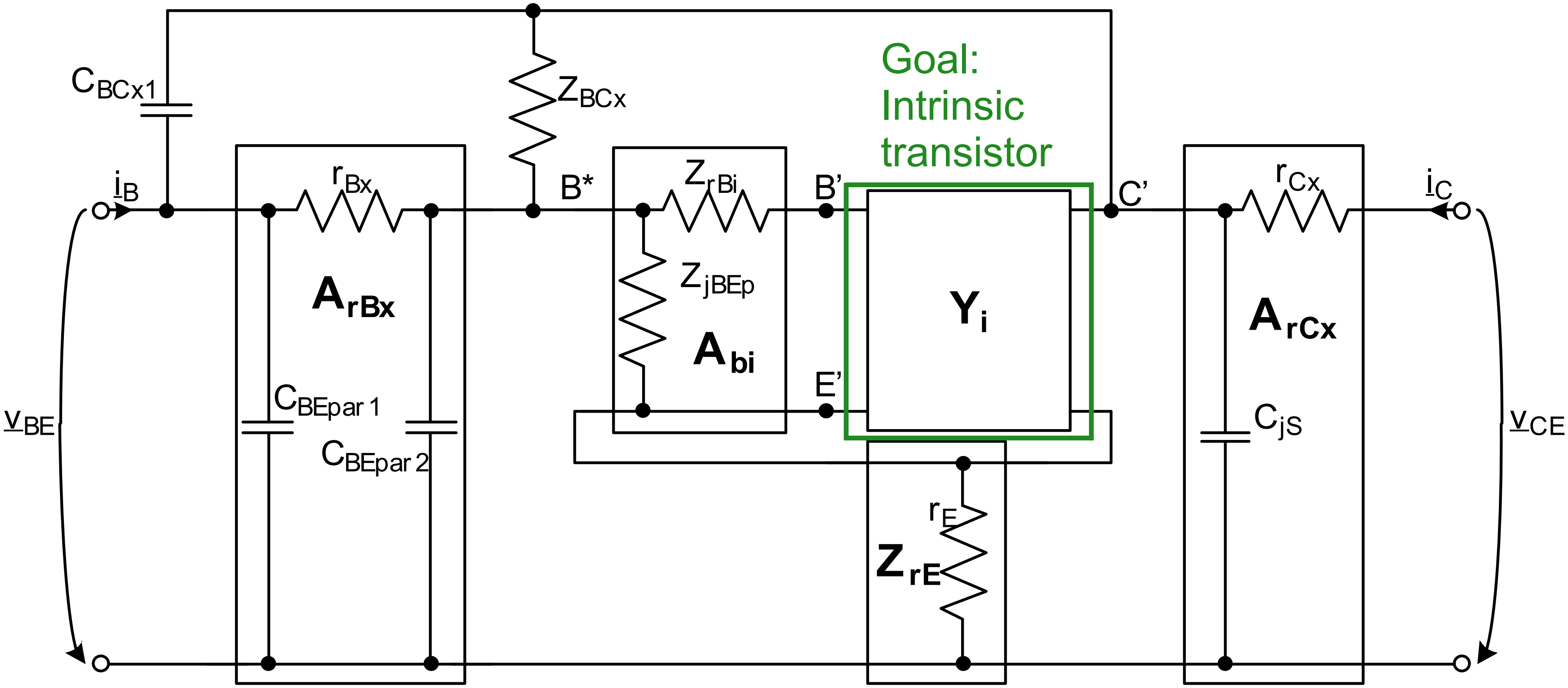
Parasitic capacitances

Self-heating network

De-embedding procedure

Transistor in common-emitter configuration (small-signal EC)

- express each element or physically associated set of elements by sub-two-port

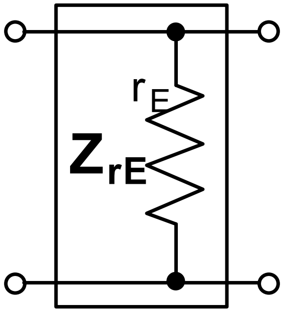


- for sake of simplicity: two-ports of C_{BCx1} and Z_{BCx} are not shown in figure

=> various possibilities, above solution is not unique

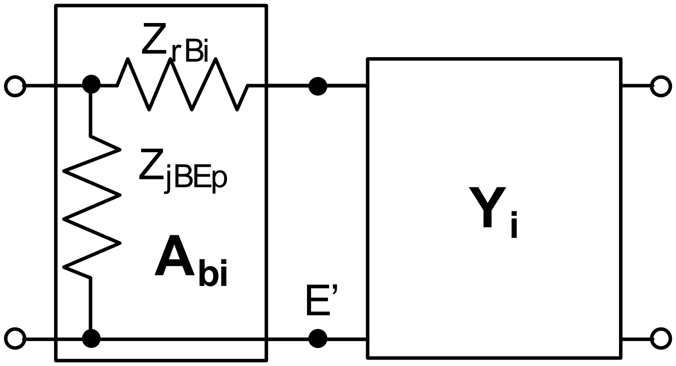
De-embedding procedure

- Calculate two-port parameters of each sub-two-port (example below)
  - choose suitable description for easy calculation (e.g. Y, Z or A parameters)



$$Z_{rE} = \begin{bmatrix} r_E & r_E \\ r_E & r_E \end{bmatrix}$$

- Determine behaviour of total equivalent circuit by means of two-port analysis
  - only simple matrix operations and two-port parameter conversion (e.g. Y → A) are needed



$$A_{tot} = A_{bi} \cdot y2a(Y_i)$$

=> perform step by step operations until two-port is fully reproduced

Flowchart

... steps depend on two-port arrangement of equivalent circuit

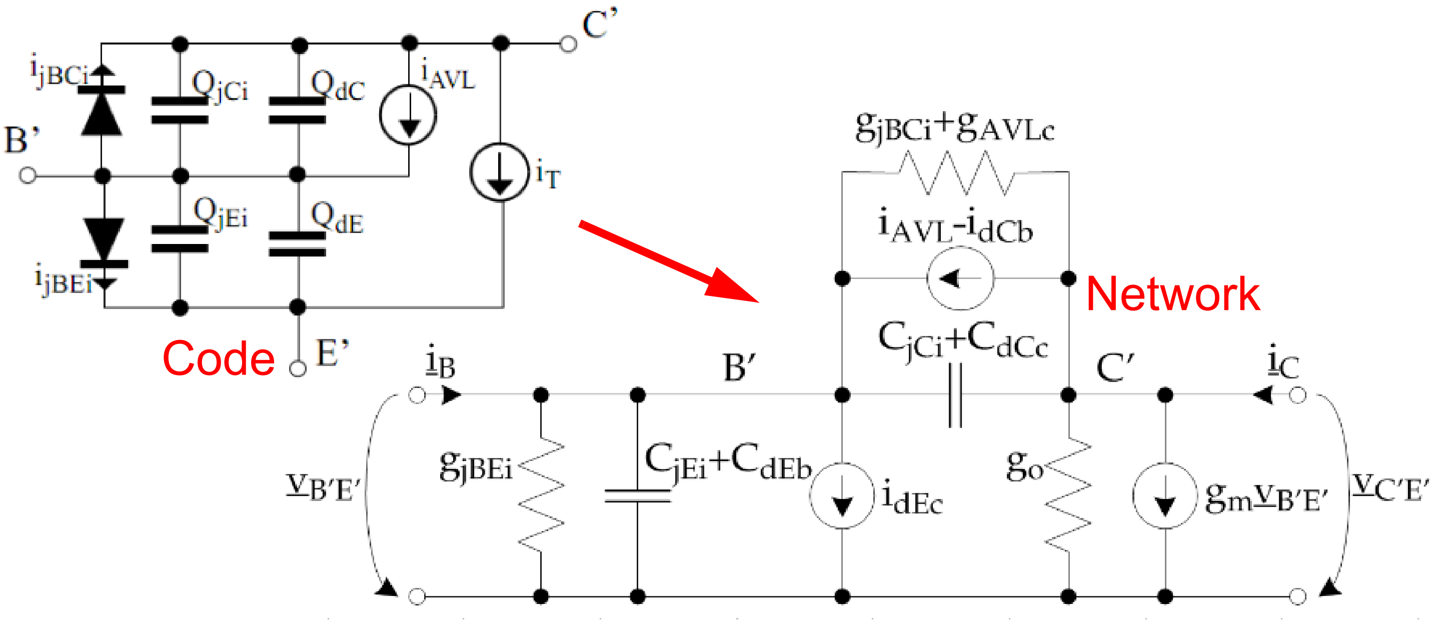
Flow		Main elements
$A_1 = \boxed{A_{bi} * y2a(\boxed{Y_i})}$	Intrinsic transistor	r_{Bi}
$Z_2 = \boxed{Z_{rE} + a2z(A_1)}$	add Z_{BCx}	r_E, C_{BCx2}
$A_3 = \boxed{A_{rBx} * z2a(Z_2)}$	add C_{BCx1}	r_{Bx}, $C_{BEpar1/2}$, C_{BCx1}
$Y_{tot} = \boxed{a2y(A_3 * A_{rCx})}$		r_{Cx}, C_{jS}

- Rearrange equations to calculate Y_i
  - Y_{tot} is known from measurements, parasitic elements are known from beforehand extraction

=> Intrinsic Y-parameters can be obtained!

Intrinsic transistor

- Analysis of the HICUM code shows: complete set of derivatives (small-signal elements) are created due to the implementation in Verilog-A (e.g. d(τ_{f0}) / d(V_{BC}) * I_{Tf})



- Transit time is included within the capacitance C_{dEb}, combining

$$\Im\{y_{i11}+y_{i21}\}/\omega = C_{dEb}+C_{jEi} = \tau_f \cdot g_m + I_{Tf} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}} + C_{jEi}$$

=> sum of y_{i11} and y_{i21} includes τ_f as well as other elements

Fit procedure

- re-arrange equation for fit

$$\tau_{fit} = \frac{\Im\{y_{i11} + y_{i21}\}}{g_m \omega} = \tau_f + \frac{C_{\tau f0} + C_{jEi}}{g_m}$$

with $C_{\tau f0} = I_{Tf} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}}$ and $g_m \approx Re\{y_{i12} + y_{i21}\}$

- equation contains 21 parameters in total

=> Least square fit is likely to fail

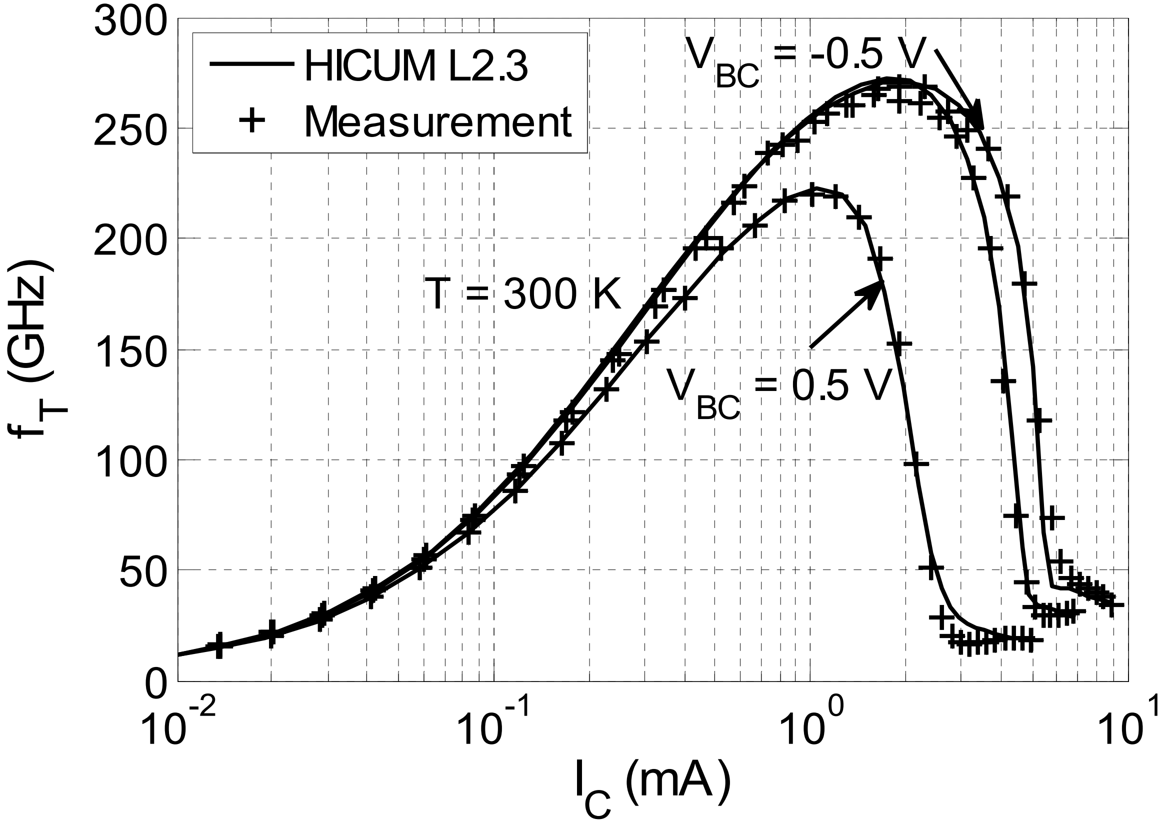
- Split transit time by separating the low- and high-current transit time portion
  - depletion capacitance dominates at low bias
  - high-current transit time portion $\Delta\tau_f$ dominates at high bias

=> apply fit to smaller subsets

=> coupling of subsets is required for final solution

Results

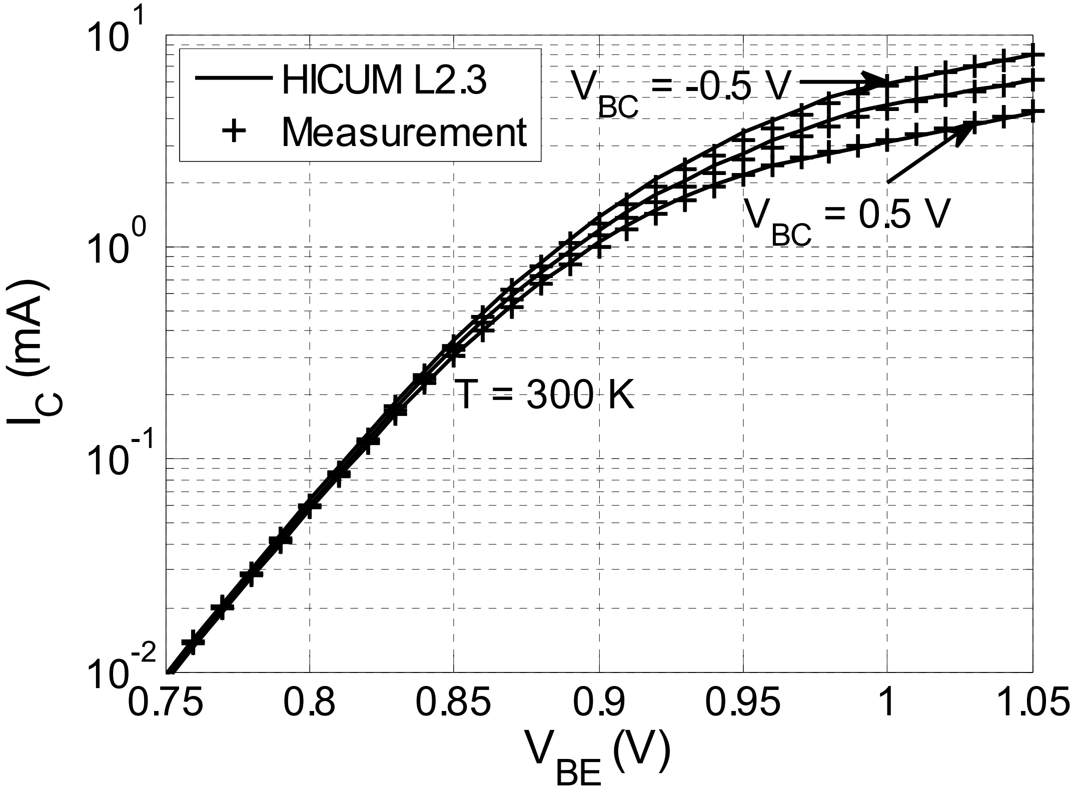
- Transit frequency (SiGe HBT from 130nm IHP process technology)



- New extraction method can provide accuracy similar to a manual procedure
  - High current characteristics is usually even more accurate as self heating is included

Transfer current of high-speed HBT

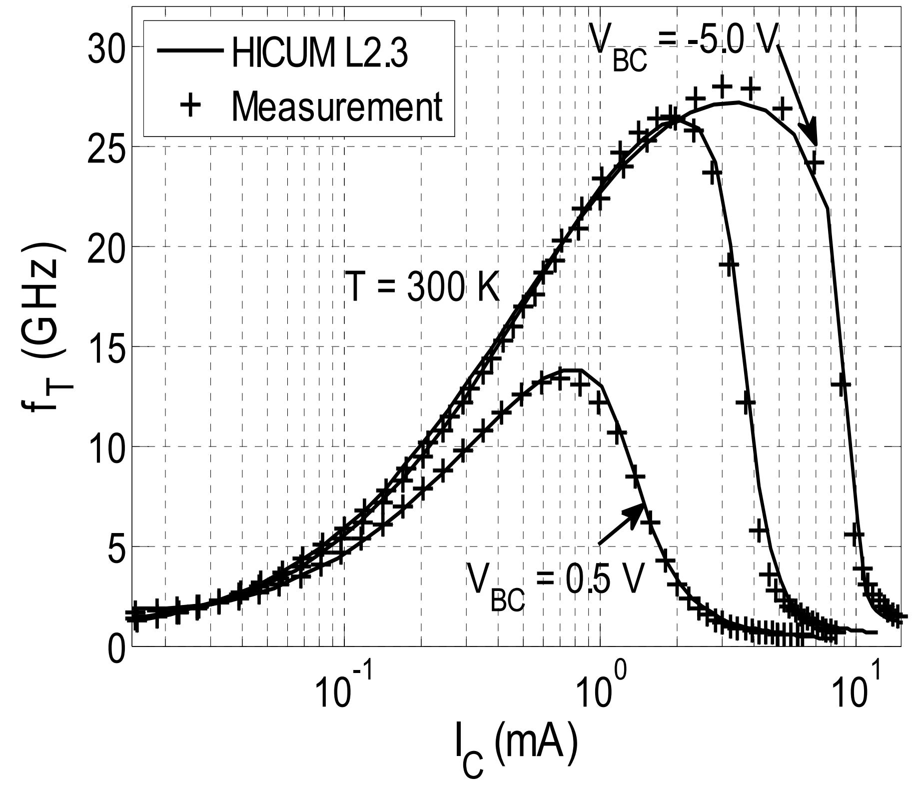
(SiGe HBT from 130nm IHP process technology)



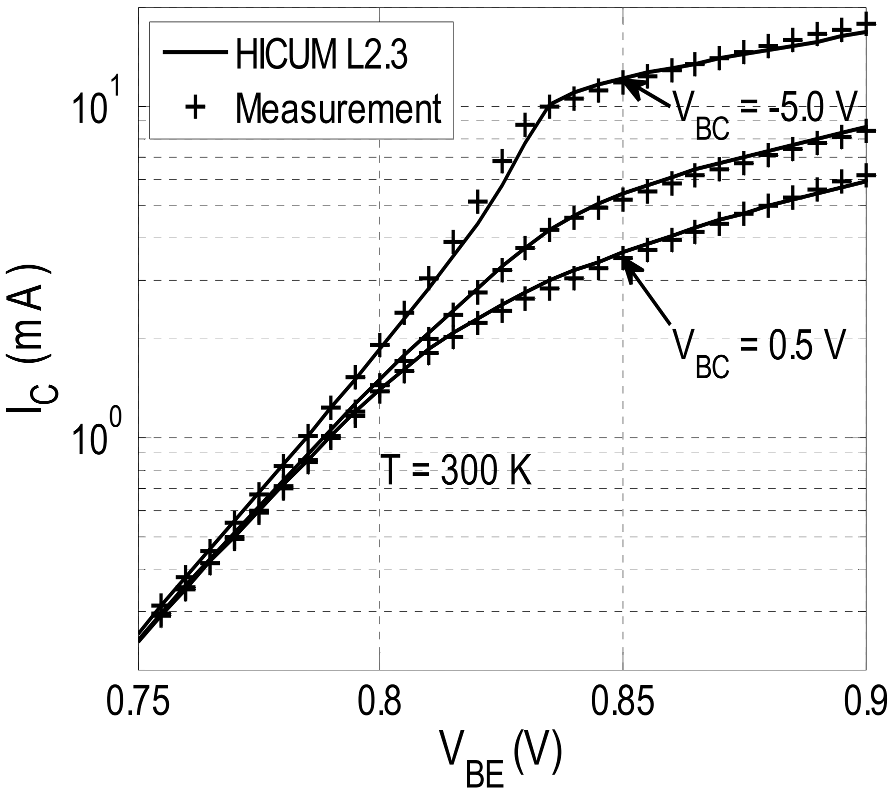
Results are similar to a procedure with time consuming manual fine tuning

High-voltage SiGe HBT (IHP)

Transit frequency



transfer current



=> Extraction also suitable for HV-transistors

Conclusions

- observed discrepancy between measured and modeled transit frequency is due to inconsistent transit time determination from measurements in standard method
  => τ_f cannot be accessed directly using f_T
- problem can be fixed by careful "de-embedding" of intrinsic transistor Y parameters
- method was shown to be consistent and very accurate
  - with extraction fully adapted to HICUM/L2 v2.31
- method was implemented in automated extraction tool
  - adaption to model changes is easy (exchange of equations or transfer function only)
  - still: lot of settings are required to conduct the extraction
- Issues
  - accuracy depends on accuracy of information on several parasitic elements
    especially: handling of internal base resistance is difficult
    => inaccurate settings might render final results useless
  - implementation needs to be changed with each model (eq. or equivalent circuit) change
- method is generally useful for extractions from device simulation and model development