Automated Transit Time and Transfer Current Extraction

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Outline

- Introduction & motivation
- Method overview
- Extraction procedure ($\tau_f$)
- Extraction procedure ($I_T$)
- Results
- Conclusion
Introduction

• Classical approach for transit time ($\tau_f$) extraction yields inaccurate results
  • perform example extraction (e.g. [1]) based on simulation data

Classical method:
extrapolate $\tau_{f_0}$ data from $f_T$ vs. $1/I_C$

\[
\frac{1}{2\pi f_T} \quad V_{BC} \mid V_{CE} = \text{const} \\
\Delta \tau_f \quad \text{slope}_{\text{max}} \\
\tau_{f_0} \quad \frac{1}{I_C}
\]

Introduction

- Classical approach for transit time ($\tau_f$) extraction yields inaccurate results
  - perform example extraction (e.g. [1]) based on simulation data

\[ \frac{1}{2\pi f_T} \]

\[ V_{BC} \parallel V_{CE} = \text{const} \]

\[ \Delta \tau_f \]

\[ \tau_{f0} \]

\[ 1 \]

\[ I_C (mA) \]

\[ f_T (GHz) \]

\[ 0 \]

\[ 10^{-1} \]

\[ 10^0 \]

\[ 10^1 \]

\[ 10^2 \]

\[ V_{BC} \]

\[ V_{CE} \]

\[ \text{slopemax} \]

\[ \text{reference} \]

\[ \text{extraction} \]

=> discrepancy caused by inaccurate $\tau_f$ determination
Motivation

• Accuracy
  • classical approach for transit time ($\tau_f$) extraction yields inaccurate results

• Handle complexity
  • large number of involved HICUM parameters: 33 in total
  • self-heating (SH), base current ($I_B$) and $\tau_f$ affect transfer current ($I_T$) at high current densities

• Flexibility
  • approach in [2] is a closed-form analytical system
  • model related adjustments are meant to be easy

• Automation
  • optimum condition: “One-click” extraction

Method overview

• Transit time is associated with intrinsic transistor
  • external elements influence extraction process
  => Deembedding of external elements necessary

• Small-signal common-emitter equiv. circuit of HICUM
  • substrate transistor, -diode and -network, NQS deactivated
  => negligible for forward active region & medium frequencies
Deembedding procedure

• Express suitable sets of elements by sub-two-port
  => various options for arranging two-ports

![Diagram]

• Further details on deembedding

Extraction procedure ($\tau_f$)

• Result of deembedding & internal transistor analysis

\[
\tau_{\text{fit}} = \frac{\Im \{y_{i11} + y_{i21}\}}{g_m \omega} = \tau_f + \frac{C_{\tau f_0}(\tau_{f_0}) + C_{jE_i}}{g_m}
\]

with \( C_{\tau f_0} = I_{Tf} \frac{\partial \tau_{f_0}}{\partial V_{B'C'}} \) and \( g_m \equiv \text{Re}\{y_{i21}\}, \quad I_{Tf} \equiv I_C \)

• Equation contains 21 parameters in total

  => least square fit is likely to fail

• Proposed solution
  • split up \( \tau_f \) into distinct regions

  => apply fit to smaller parameter-subsets

  => couple subsets (loop) for final solution
Self heating

- Strongly affects high current region (extr. of $I_{CK} \& I_C$)
  - calculate internal device temperature

$$I_C V_{C'E'}(T) R_{th}(T) - T + T_0 = 0$$

with $V_{C'E'}(T) = V_{CE} - I_C r_{Cx}(T) - I_E r_E(T)$

$=>$ Solve implicit equation w.r.t. $T$

Required preextracted parameters
- $r_{Cx}$, $r_{th}$ & $r_E$
- corresponding temp. coeff.

$=>$ Include SH by considering $T_j$ in every extraction step
Master equation

- Handling the master equation

\[ \tau_{fit} = \tau_f + \frac{C_{\tau f0}(\tau_{f0}) + C_{jEi}}{g_m} \] => key to successful extraction

- Result of deembedding process: \( \tau_{fit} \)

three distinct regions

- 1: \( C_{jEi} / g_m \) dom.
- 2: \( \tau_{f0} \) dom.
- 3: \( \Delta \tau_f \) dom.

=> extraction split up should be possible

=> run loop over regions for interaction
Region 1 of $\tau_{\text{fit}}$

- R1 can be used to extract parameters for $C_{jEi}$
  - rearrange master equation for capacitance

\[
C_{jEi} = (\tau_{\text{fit}} - \tau_f)g_m - C_{\tau f_0}(\tau_{f_0})
\]

First iteration
- $\tau_f$ & $C_{\tau f_0}$ unknown
  => set to Zero

Global loop
- insert $\tau_f$ & $C_{\tau f_0}$
  => allows parameter interaction

- Usual measurement range: $V_{BE} > 0.7$ V
  - allows to tune $a_{jEi}$ & $(V_{DEi})$
- All parameters for $C_{jEi}$ can be adjusted for TCAD data
Region 2 of $\tau_{\text{fit}}$

- $R2$ is influenced by $C_{jEi}$ & $\Delta \tau_f$!
  - how to select appropriate data for $\tau_{f0}$?
    $=>$ select lhs of $\min(\tau_{\text{fit}})$

- Rearrange master equation

$$
\tau_{f0} = \tau_{\text{fit}} - \frac{C_{jEi}}{g_m} - \frac{C_{\tau f0}}{g_m} - \Delta \tau_f
$$

without SH

$=>$ SH can already be observed for $\tau_{f0}$ extraction

with SH
Region 3 of $\tau_{\text{fit}}$

- Rearrange master equation for $\Delta \tau_f$

\[
\Delta \tau_f = \tau_{\text{fit}} - C_{jE_i}/g_m - C_{\tau f_0}/g_m - \tau_{f_0}
\]

- How to extract the critical current?
  - obtain starting values first: e.g. standard method of [1]

- Extracted values for $I_{CKi}$ correspond to $V_{CEi}$
  => delivers first parameter set for further evaluation
Critical current

• Further improvements possible?
  • for negligible SH: $\Delta \tau_f(I_C/I_{CK})$ curves must superimpose

  ![Graph showing $\Delta \tau_f(I_C/I_{CK})$ curves and point of inflection]

  - method
  - result

  $\Delta \tau_f$ vs. $I_C/I_{CK}$
  - point of inflection
  - $e_1$, $e_2$
  - mean
  - $V_{BC} = V_1$
  - $V_{BC} = V_2$

• Advantages
  • no need for inception point, good medium current accuracy
  • amount of selected data increases

• But: might involve some errors in high current region due to SH
Extraction result for $\tau_{fit}$

- Final step of $\Delta \tau_f$ extraction
  - previous step provides parameters sufficient for optimization
  - run optimization on $\Delta \tau_f(I_{CK}, \tau_{hcs}, \tau_{ef0})$ directly

- Repeat steps for region 1 - 3
  - allow for parameter interaction ($C_{jEi} \leftrightarrow \tau_{f0} \leftrightarrow \Delta \tau_f$)

$\Rightarrow \tau_{fit}$ is reproduced
Extraction procedure ($I_T$)

- Low current description in HICUM

\[ I_{Tf} = \frac{c_{10}}{Q_p + h_{jEi}(V_{BEi})Q_{jEi}} \exp\left(\frac{V_{BEi}}{V_T}\right) \]

- Standard extraction of $c_{10}$ & $h_{jEi}$

\[ \frac{\exp\left(\frac{V_{BEi}}{V_T}\right)}{I_C} = \frac{Q_p}{c_{10}} + \frac{h_{jEi}(V_{BEi})Q_{jEi}}{c_{10}} \]

Did extraction work?

- not enough information to assess extraction result

=> check $g_{m,norm}$
Normalized transconductance \((g_{m,\text{norm}})\)

- **Definition**
  \[
  g_{m,\text{norm}} = V_T \frac{g_{m}}{I_C} \quad \text{and} \quad \frac{\partial}{\partial V_{\text{BE}i}} \ln(I_C) = \frac{1}{I_C} \frac{\partial I_C}{\partial V_{\text{BE}i}} = \frac{g_{m}}{I_C}
  \]

- **Maximum value**
  \[
  g_{m,\text{ideal}} = \frac{I_C}{V_T} \implies g_{m,\text{norm},\text{max}} = 1
  \]

**Benefit**
- larger sensitivity on change of \(h_{\text{JE}i}\) than standard method

\(\implies\) use for optimization of \(a_{h_{\text{JE}i}}\)
Extraction of high current weight factors

• Issue with calculating $h_{FE}$, $h_{FC}$
  • transit time depends on $I_T$ and vice versa

• Usual approach
  • $I_T = I_{C,\text{meas}}$ assumed for calculating $\tau_f$
  • but especially in the high current range: small errors cannot be avoided

=> leads to inconsistent determination of $h_f$ and wrong results

• Tedious approach
  • solve simplified HICUM transfer current equation
    • keep initially calculated internal voltages
    • keep initially calculated internal temperature
  • solve transfer current equation w.r.t. $Q(\tau_f)$

=> consistent data for $\tau_f$ & $I_T$
Transfer current result

• Overview of characteristics

Used extraction approach
- standard method for $c_{10}$ & $h_{jEi}$
- optimize $a_{jEi}$ on $g_{m,norm}$
=> loop for consistency

=> strategy is confirmed working
Results: ST BiCMOS9MW

transit frequency

\[ V_{BC} = [0.5, 0, -0.5] \text{ V} \]

=> excellent agreement for whole bias range & temperatures

Results: ST BiCMOS9MW

\[ V_{BC} = [0.5, 0, -0.5] \text{ V} \]

=> results are similar to those obtained from time consuming manual fine tuning

Results: TCAD (1D HD-simulation)

Transit time

Transfer current

$V_{BC} = [0.5, 0.3, 0, -0.3, -0.5] \text{ V}$

$\Rightarrow$ method suitable for automated extraction from device simulation
Conclusion

• Standard determination method for $\tau_f$ insufficient
  
  => $\tau_f$ cannot be accessed directly using $f_T$

• Problem can be solved by careful "deembedding" down to intrinsic transistor Y-parameters and an advanced extraction strategy
  
  • consistent model representation necessary (HICUM/L2 here)
  • self heating included for all bias points

• Method was shown to be consistent and accurate
  
  • extraction fully adapted to HICUM/L2 v2.32
  • method also suitable for other models
  • Method is very useful for automated extractions from device simulations

• Method implemented in Matlab based tool
  
  • batch & GUI mode available
Thank you for your attention!
\[ C_{dEb} = \left. \frac{dQ_f}{dV_{B'E'}} \right|_{V_{C'E'}} = \frac{\partial Q_f}{\partial I_{Tf}} \cdot \frac{\partial I_{Tf}}{\partial V_{B'E'}} + \frac{\partial Q_f}{\partial \tau_{f0}} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}} + \frac{\partial Q_f}{\partial I_{CK}} \cdot \frac{\partial I_{CK}}{\partial V_{B'E'}} \]
\[ = \tau_f \cdot S_{fb} + I_{Tf} \cdot \frac{\partial \tau_{f0}}{\partial V_{B'C'}} + 0 \]

- Special term is visible in all frequency ranges [5], about 1% of \( tf \) at low currents
- Term is caused by implementation in Verilog-A and physically correct

GUI interface