CMC Meeting

HICUM - Productization and Support Update

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Boston, MA (USA) Oct, 2007
OUTLINE

• HICUM/L2 Support Activities

• HICUM/L0 Support Activities

• Vertical NQS Effects and Implementation
HICUM/L2 Support Activities

fixes and improvements towards v2.23

• testing (changes see previous meeting slides and doc on www):
  • y-parameters (internal transistor) vs. analytical expressions match well with VA Code
  • ST’s comparison of simulator performance see HICUM WS website  => EDA relevant

• Possible to link convergence criterion of I₁ iteration in VA code to simulator current
tol criterion? (same for GMIN and other parameters)
  • example: reltol = $simparam("reltol",1e-6) as suggested by Laurent does not work with OUR
    Spectre version  => need latest simulator versions for support work

• Requests from design houses (using a foundry) regarding model characteristics cannot
be handled without model parameters
  issue: foundry contract prevents design houses from providing parameters

• NQS effects:
  • Bessel polynomial in frequency domain to be implemented with ddt operator due to bias
dependence of τ₁ and τ₂  => see more details later
  • Note: this type of "delay" behavior is common to other devices, too!
    => solution will be of general benefit
  • VA implementation does not converge in Spectre for NQS with RBX=RCX=0 Ohm - cause?
HICUM/L0 Support Activities

Version 1.12

Current L0 version (released March 9, ’07) has been available at
(http://www.iee.et.tu-dresden.de/iee/eb/hic_new/hic_start.html)

• Detailed documentation for HicumL0V1.12 has been released
  • format similar to L2
  • first complete doc for L0 latest version
  • includes complete parameter list, OP list

• Parameter TFH (for high injection correction) has been allowed to take the value 0

• Parameter DT0H (base width modulation) does not have a range limitation anymore;
  i.e. negative values are also allowed
HICUM/L0 Support Activities

=> Version 1.13

Work in response to user requests

• High current region: negative slope in IC(VBE) has been observed (see HICUM WS 2007) for non-physical values of parameter IQFH (in relation to IQF) => high-current correction formulation needs to be investigated

• Improve temperature dependent behavior of IC(VBE) slope (see HICUM WS 2007) caused by T independent emission factor MCf

  => partially development work

  => manpower limited
Vertical NQS Effects and Implementation

- HICUM/L2 v2.1 and lower: implementation via Weil’s approach
- v2.2: attempt to use VA and model compiler
  => implementation via adjunct LCR-type Network (or equivalent network approach)

\[ (i_{qs}, q_{qs}) \]
\[ \frac{d^2 x_{nqs}}{dt^2} + A_1 \frac{dx_{nqs}}{dt} + x_{nqs} = x_{qs}(t) \] \hspace{1cm} (A_1, A_2 generally bias dep.)

**time domain:**

**frequency domain:** compiler creates derivatives due to bias dependent \( \tau_f \)

=> additional elements and disagreement with device simulation (and with theory and previous model versions)

Are VA compiler generated derivatives physically correct?
Example: SiGe HBT delay times

1D device simulation results (peak $f_T = 110$GHz)

- Delay times ($f = 40$) 24-Sep-2007
- NQS ratios ($f = 40$GHz) 24-Sep-2007

$\tau_{Qf}$, $\tau_{IT}$

$\Delta \tau_{IT}$, $\Delta \tau_{Qf}$

$\Delta \tau = \frac{\Delta \tau_{IT}}{\tau_{f}}$

$\Rightarrow$ "delay" times are bias dependent
Device physics and compact model

Time domain solution (e.g., via TICCR)

• 1D diffusion transistor: \( i_{T,nqs}(t) = i_{T,qs}(t) - \alpha \frac{\partial Q_{mB}^{qs}}{\partial t} + \tau \frac{\partial^2 Q_{mB}^{qs}}{\partial t^2} \) (from theory)

  => to be realized in large-signal model (TR simulation)

• at any point in time (bias) during TR simulation:
  => use time "constants" at given time /bias point (or within discrete time interval)

• in the limit of infinitesimally small signals in time domain:
  use time \textit{constant} given by DC bias point

  => transformation to frequency domain contains no derivative of \( \tau \)

• Note: NQS effects are not naturally included in SPICE-like approach
  => higher order terms (e.g. \( \omega^2 \)) require special coding, adjunct networks, etc.

• need implementation that satisfies theory and experimental data:
  => Weil's approach is suitable and has provided accurate results so far
Example: SiGe HBT time domain (TR) analysis

- 1D device simulation at 2.5*I_C(peak f_T): 80GHz with 2.5mV amplitude (small-signal)

- MATLAB model: i_T(t) from discretized solution of \[ A_2 \frac{d^2 i_{nqs}}{dt^2} + A_1 \frac{di_{nqs}}{dt} + i_{nqs} = i_{qs}(t) \]

=) "Weil" approach yields accurate results
Device physics and compact model (2/2)

Frequency domain solution

• 1D drift/diffusion transistor: \( I_{T,\text{nqs}} \approx I_{T,\text{qs}} - (\omega \tau_2)^2 - j\omega \tau_1 \)

=> is valid at any bias point with \( \tau \) at given bias point

=> to be implemented in small-signal model (AC simulation)

• need implementation approach that meets above requirements (related to theory and model formulation):

  => Bessel polynomial is suitable and has provided accurate results so far

  => direct implementation in AC code instead of adjunct network
Example: SiGe HBT frequency domain (AC) analysis

- 1D device simulation at 2.5*IC(peak fT): 80GHz small-signal analysis
- MATLAB model: $I_{T}(\omega)$ from analytical equations and Regional Approach (for C, G)

$\Rightarrow$ delay time at given bias point yields accurate results
Example: SiGe HBT large-signal time domain (TR) analysis

• 1D device simulation: pulse (100GHz slope) with 100mV amplitude

• MATLAB model: \( i_T(t) \) from

\[
A_2 \frac{d^2 i_{nqs}}{dt^2} + A_1 \frac{d i_{nqs}}{dt} + i_{nqs} = i_{qs}(t) \Rightarrow i_C(t) = i_{T,NQS} - \frac{d Q_{jC}}{dt}
\]

\[
\frac{A_2}{2} \frac{d^2 i_{nqs}}{dt^2} + A_1 \frac{d i_{nqs}}{dt} + i_{nqs} = i_{qs}(t) \Rightarrow i_C(t) = i_{T,NQS} - \frac{d Q_{jC}}{dt}
\]

=> "Weil" approach yields accurate large-signal results
VA adjunct network implementation

- Gyrator equivalent of adjunct LCR-type network

\[
\begin{align*}
\text{i}_{T,qs} & \quad \text{C}_1 \quad \text{v}_{C1} \\
\text{v}_{C2} & \quad \text{C}_2 \quad \text{R} \\
\text{v}_{R} & \quad \text{i}_{T,nqs} = \frac{\text{v}_{R}}{\text{R}}
\end{align*}
\]

Coupled equations for traditional implementation with bias-independent \( \tau_f \)

\[
\text{i}_T, qs \frac{d}{dt}(\alpha IT^f \tau \text{v}_1 C_1) - \text{v}_2 C_2 = 0 \quad \text{and} \quad \text{v}_1 C_1 \frac{V_R}{R} \frac{d}{dt}(\alpha IT^f \tau \text{v}_2 C_2) = 0
\]

with \( R = 1 \), \( C_1 = \alpha_f \tau_f \) and \( C_2 = \alpha_f \tau_f / 3 \)

- Represents 2nd order polynomial in frequency and time domain
- Used in VBIC with bias-independent \( \tau_f \)
- For bias-dependent \( \tau_f \)
  
  \( \Rightarrow \) VA compiler generates undesired derivatives in small-signal EC
- Need an implementation that provides no undesired derivatives even with \( \tau_f(V,I) \)
VA adjunct network implementation (2/2)

- proposed implementation with modified expressions for network elements
  
  coupled equations for proposed implementation with bias-dependent $\tau_f$

$$\frac{(i_T, qs - V_{C2})}{\tau_f} = \frac{d}{dt}(\alpha_{IT}V_{C1}) \quad \text{and} \quad \frac{V_{C1} - V_{C2}}{\tau_f} = \frac{d}{dt}\left(\frac{\alpha_{IT}}{3}V_{C2}\right)$$

- "C" elements become bias-independent $\Rightarrow$ no undesired derivatives anymore

- seems to yield desired results
  - division by $\tau_f = 0$ avoided through turning off NQS effects when input of zero value
  - charge conservation issue should be of no consequence for actual model equivalent circuit
  - presently testing

- $i_T, qs/\tau_f$, $V_{C1}$, $V_{C2}$, $R=\tau_f$, $C1=\alpha_{IT}$, $C2=\alpha_{IT}/3$
Results of VA NQS effect implementation (1/3)

HICUM comparison: v2.1(Weil) vs v2.3 (adj. network)

Small-signal frequency-domain simulation: Y11

=> Excellent agreement
Results of VA NQS effect implementation (2/3)

HICUM comparison: v2.1 (Weil) vs v2.3 (adj. network)

Small-signal frequency-domain simulation: Y21

=> excellent agreement

=> "undesired derivative problem" seems to be solved
Results of VA NQS effect implementation (3/3)

HICUM comparison: v2.1 (Weil) vs v2.3 (adj. network)

Large-signal transient simulation (first results)

=> Agreement for QS (reference), but some deviations for NQS case
Conclusions

Weil’s approach and Bessel polynomial ...

- excellent approximations for device theory and circuit applications
- consistent representation in time and frequency domain
  - Note: inverse transformation including bias dependence of $\tau$ would lead to incorrect results in time domain

=> bias dependent delay/phase:

LCR-like adjunct network with bias dependent "C" elements is not a suitable approach for realizing device theory and modeling goals

Solutions:

- modified adjunct network appears to generate correct AC results
- need to do more testing of TR analysis to understand deviations (mostly in base current)
- VA construct for automating implementation of Weil’s approach
  => model remains compatible with older versions