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a leap ahead

“Removing the Internal Iteration Loop from Hicup/L2”

9th Hicup Workshop at the University of Applied
Sciences Würzburg, Germany, 23. October 2009

a leap ahead

in Device Characterization and Modeling

Outline

- recall and summarize present I_T formulation
- weighted charge components
- implicit nonlinear $I_{Tf}=f(Q_{pT}(I_{Tf}))$ dependence, NR iteration
- concept: assume $I_{Tf}=f(Q_{pT}(I_{Tp}))$ AND constrain $I_{Tf}=I_{Tp}$
- realization of the scheme in the model equivalent circuit
- nonlinear problem merged in MNA circuit solution
- results and summary

Transfer current formulation

The transfer current splits to forward and reverse components

$$i_T = i_{Tf} - i_{Tr}$$

with

$$i_{Tf} = \frac{c_{10} \exp\left(\frac{v_{B'E'}}{m_{cf} \cdot V_T}\right)}{Q_{pT}} \quad i_{Tr} = \frac{c_{10} \exp\left(\frac{v_{B'C'}}{V_T}\right)}{Q_{pT}}$$

In fact obsolete spreading formula is preserved for compatibility

$$i_T = \frac{c_{10} \left[\left(1 + \frac{i_{Tf1}}{ich}\right) \cdot \exp\left(\frac{v_{B'E'}}{m_{cf} \cdot V_T}\right) - \exp\left(\frac{v_{B'C'}}{V_T}\right) \right]}{Q_{pT}(i_T)} \quad \text{with} \quad i_{Tf1} = \frac{c_{10}}{Q_{pT}(i_T)} \exp\left(\frac{v_{B'E'}}{m_{cf} V_T}\right)$$

The weighted charge Q_{pT} nonlinearly depends on i_T as opposed to more conservative models where a linear dependence allows for a quadratic solution

Componets of the weighted charge

$$Q_{pT} = Q_{pT,low} + Q_{r,T} + Q_{f,T} \Leftarrow Q_{pT,j} + Q_{r,T} + Q_{f,T} \quad (Q_{pT,low} == Q_{pT,j \text{ limited}})$$

Fixed (or junction related) charge:

$$Q_{pT,j} = qp0 + hjei \cdot Q_{jEi} + hjeci \cdot Q_{jCi}$$

Reverse charge:

$$Q_{r,T} = tr \cdot i_{Tr}$$

Weighted hole charge:

$$Q_{f,T} = Q_{f0} + hfe \cdot \Delta Q_{Ef} + \Delta Q_{Bf} + hfc \cdot \Delta Q_{Cf}$$

The 2nd, 3rd and 4th Δ prefixed terms are the emitter and the additional base and collector charges respectively

Charge dependences

Manual	VA code	Comment	Dependence
Q_{f0}	N.A. (part of Q_f)	Low current minority charge ($tf0 \cdot itf$)	vbici, itf
Q_{pT_j}	Q_0	Fixed (or junction related) charge (Early term)	vbiei, vbici
Q_f	Q_f	Mobile hole (actual) charge	vbici, vciei, itf
Q_{fT}	Q_fT	Weighted hole charge for transfer current, part of	vbici, vciei, itf
ΔQ_{Ef}	QfE (FFd_ QfE)	Emitter charge	vciei, itf
ΔQ_{Bf}	Q_bf (FFd_ QfB)	Add'l base charge	vciei, itf
ΔQ_{Cf}	QfC (FFQ_ fC)	Add'l coll. charge	vciei, itf
Q_{Cf} N.A.	$QfCT$ (FFQ_ cT)	Add'l coll. charge with current spreading	vciei, itf

All but one charge components incorporate the forward transfer current, all but one nonlinearly. Explicit solution is not possible.

NR solution for the weighted charge

$Q_{pT}(i_{Tf})$ is a common variable in i_{Tf} and i_{Tr} thus it is solved for.

Newton-Raphson (NR) scheme:
$$x^{(k+1)} = x^{(k)} - \frac{y^{(k)}}{(y^{(k)})'}$$

The error function is the charge difference between the steps

$$y^{(k+1)} = dQ^{(k+1)} = Q_{pT}^{(k+1)} - Q_{pT}^{(k)}$$

The iteration is performed by

$$Q_{pT}^{(k+1)} = Q_{pT}^{(k)} - \frac{dQ^{(k)}}{dQ^{(k)'}}$$

with the initial value:

$$Q_{pT}^{(1)} = \frac{Q_{pT,low}}{2} + \sqrt{\left(\frac{Q_{pT,low}}{2}\right)^2 + c_{10} \cdot \left[t_{f0} \cdot \exp\left(\frac{V_{B'E'}}{mcf \cdot V_T}\right) + tr \cdot \exp\left(\frac{V_{B'C'}}{V_T}\right) \right]} \quad (1)$$

Comments

- loop terminates at $\text{reitol}=1\text{e-}5$ or at achieving 200 steps
- loop iterations multiply by the #of network solution cycles
- $\text{reitol}=1\text{e-}5$ holds also when network is still far from solution
- HL2 is the single recent model having an internal loop

Former attempts to get rid of the internal iterations led to L0 variants all compromising model performance

The solution proposed next preserves perfect HL2 model equivalence while speeding up operation

Concept

1. New system variable i_{Tp} for controlling the weighted charge

$$Q_{pT}(i_{Tf}) \text{ becomes } Q_{pT}(i_{Tp})$$

2. Auxiliary condition for constraining

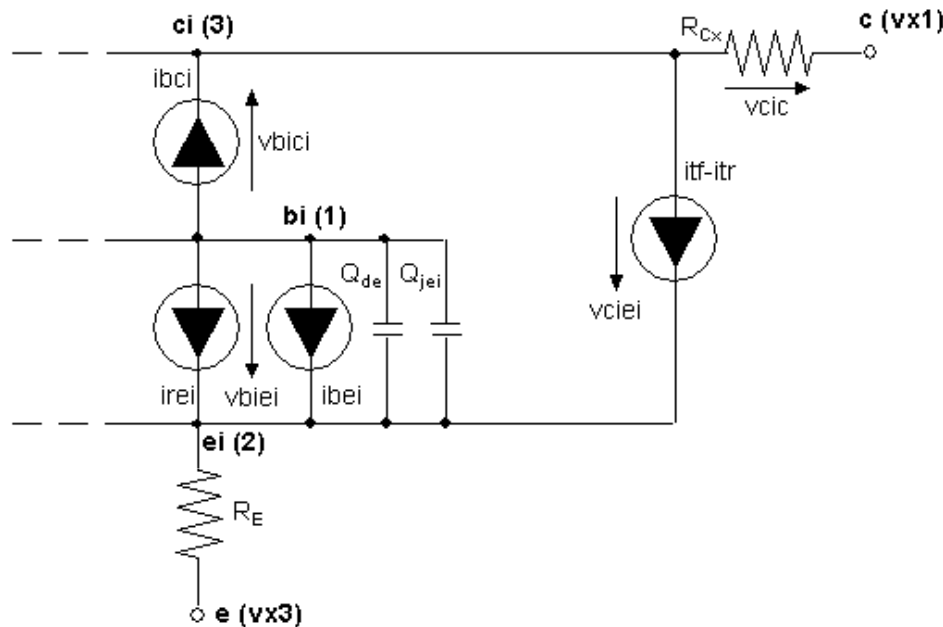
$$i_{Tf} = i_{Tp}$$

3. Construct SCKT for the realization of conditions 1. and 2.

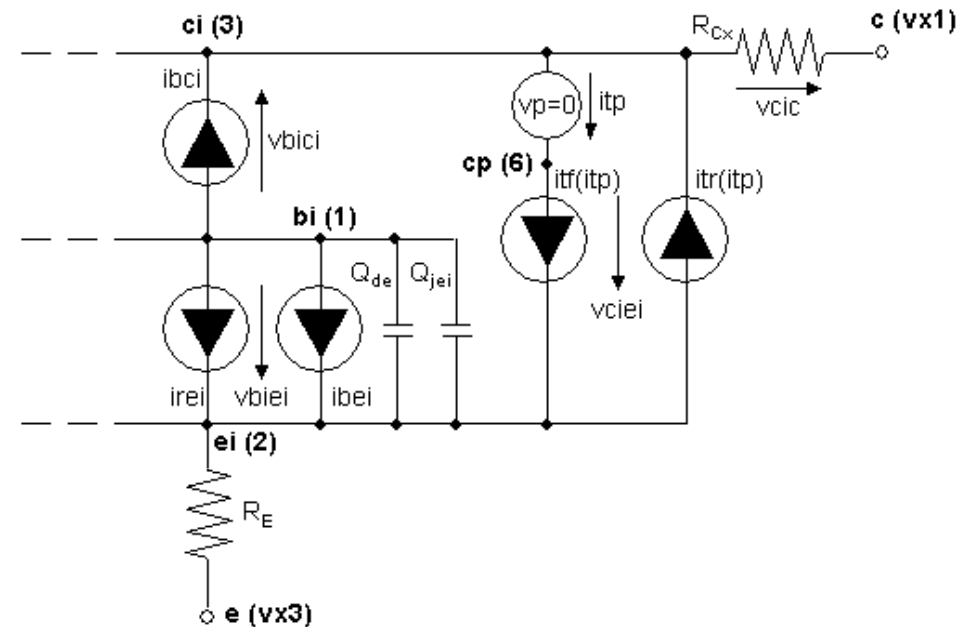
4. Let the simulator solve the SCKT with the whole model

With the model solution found the nonlinear i_T problem gets automatically satisfied w/o any internal loops

Embedding the SCKT in the model equivalent



present eq. circuit detail



proposed eq. circuit detail

itp is the current of the voltage source $v_p=0$. Both itf and itr depends on itp through the charge $Q_{pT}(itp)$. Network solver guarantees $itp=itf$ in node cp

Solution for Q_{pT}

A closer look reveals that Q_{pT} is implicit

$$Q_{pT} = Q_{pT,low} + Q_{f,T}(itp) + Q_{r,T} = Q_{pT,low} + Q_{f,T}(itp) + tr \cdot itr = Q_{pT,low} + Q_{f,T}(itp) + \frac{tr \cdot c_{10}}{Q_{pT}} \exp\left(\frac{v_{B'C'}}{V_T}\right)$$

This can be solved for Q_{pT}

$$Q_{pT}(itp) = \frac{Q_{pTlow} + Q_{fT}(itp)}{2} + \sqrt{\left(\frac{Q_{pTlow} + Q_{fT}(itp)}{2}\right)^2 + tr \cdot c_{10} \cdot \exp\left(\frac{v_{B'C'}}{V_T}\right)}$$

Providing

$$I_{_Tf1} = \frac{c_{10}}{Q_{pT}(itp)} \exp\left(\frac{v_{B'E'}}{mcf \cdot V_T}\right)$$

$$itf = I_{_Tf1} \cdot \left(1 + \frac{I_{_Tf1}}{ich}\right)$$

$$itr = \frac{tr \cdot c_{10}}{Q_{pT}(itp)} \exp\left(\frac{v_{B'C'}}{V_T}\right)$$

If simulator supports „INITIAL CURRENT” use (1) on slide#6

$$I_{_Tf1}^{(1)} = \frac{c_{10}}{Q_{pT}^{(1)}} \exp\left(\frac{v_{B'E'}}{mcf \cdot V_T}\right) \quad itp_{ini} = I_{_Tf1}^{(1)} \cdot \left(1 + \frac{I_{_Tf1}^{(1)}}{ich}\right) \quad itf_{ini} = itp_{ini} \quad itr_{ini} = \frac{tr \cdot c_{10}}{Q_{pT}^{(1)}} \exp\left(\frac{v_{B'C'}}{V_T}\right)$$

Results and Summary

- scheme was implemented in the Matlab environment of HWS07
- speed improvements ranged from 1.49 (hicumL2V2p23_c) to 2.11 (hicumL2V2p23_c_ccs) on IB forced forward output tests
- both DC and AC simulations returned present model in rms=1e-5
- convergence enhancement techniques of professional simulators automatically apply resulting in further possible speed improvement
- potential competitive disadvantage of HL2 claimed for double-cycling eliminated at the cost of one additional node
- new #node=6 is still below #node=7 of VBIC and Mextram_v504.7
- relative merits of L0 variants shrink to marginal