NQS effects and their implementation

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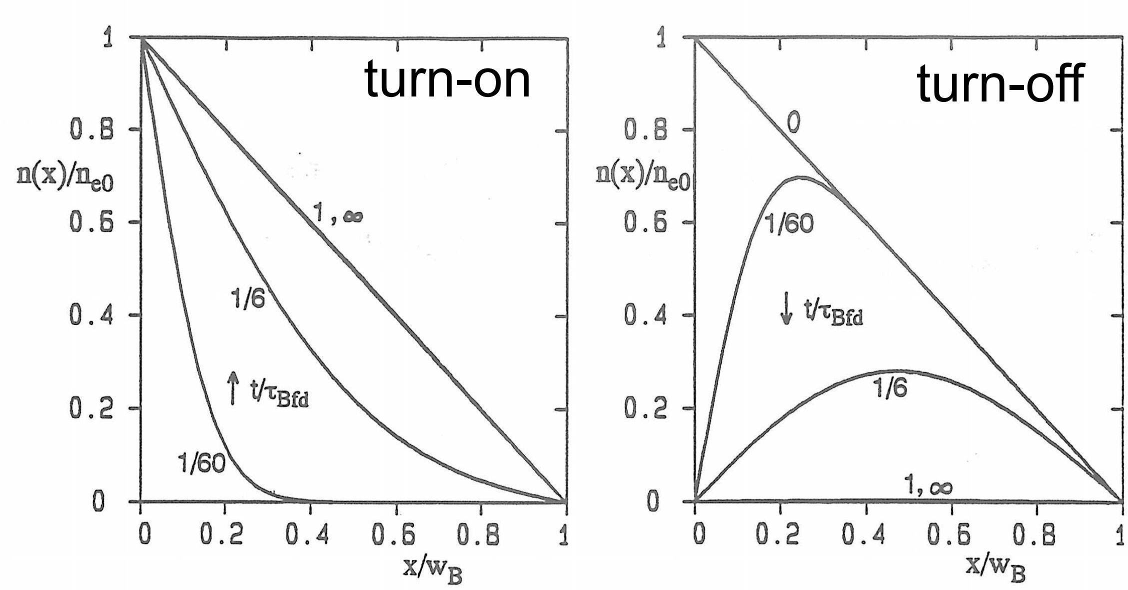
OUTLINE

- Vertical non-quasi-static (NQS) effects: device physics
- Vertical NQS effects: compact modeling
- Vertical NQS effects: implementation
- Implementation in VA-based releases
- Results of NQS effect implementation
- Summary

Vertical non-quasi-static (NQS) effects: device physics

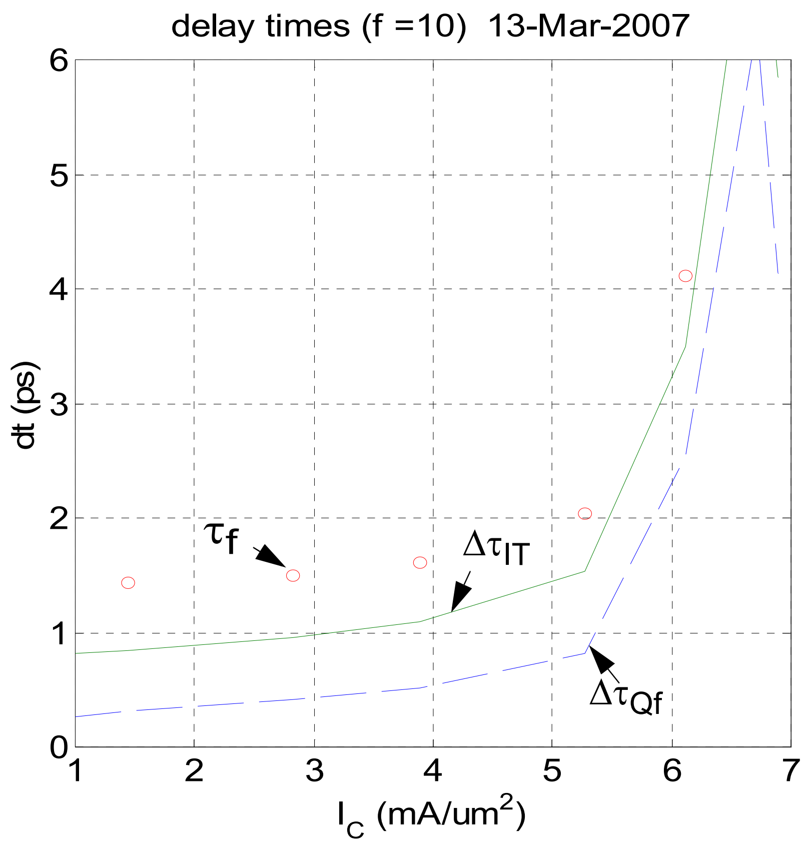
- at high-speed switching or high frequencies (h.f.) => "delayed" reaction to BE voltage change:
  - charge Q_f <u>*and*</u>
  - transfer current I_T
- visible for intrinsic transistor at about $f_T/5$

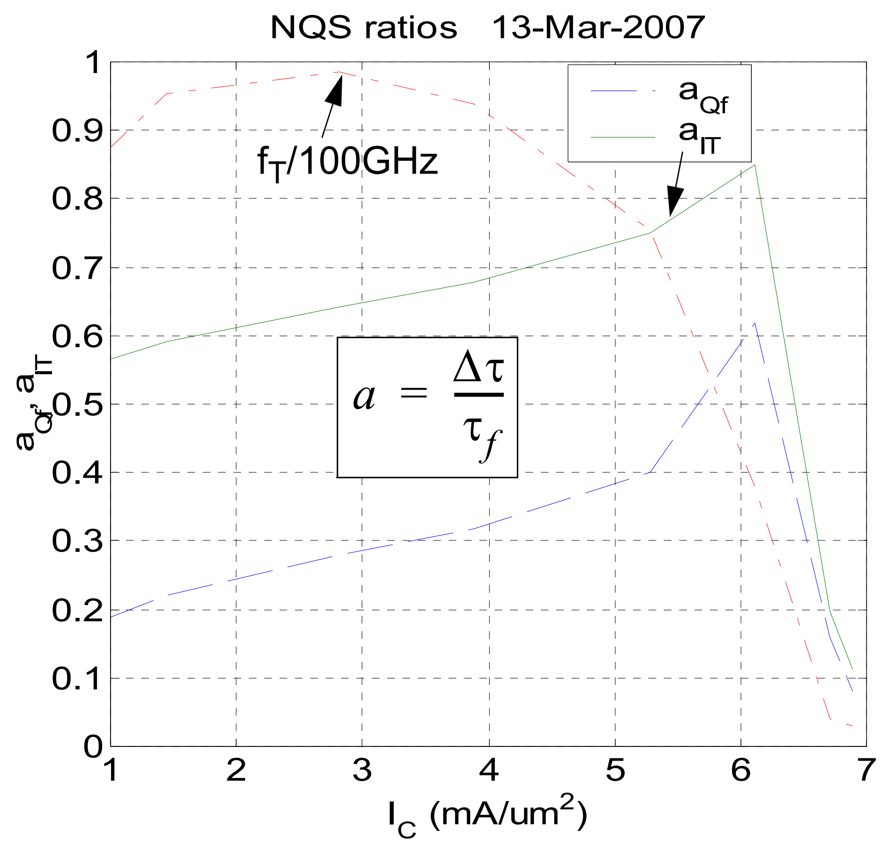


- often found: "delay approach $\exp(-j\omega\tau_d)$" for the transconductance => *small-signal based only* and no theoretical basis
- often found: charge delay ignored => incorrect current gain phase shift
- exact solution from continuity & transport equation is available but not in closed form; also, no compact generic solution for ***large-signal nonlinear*** case

SiGe HBT example

1D device simulation results





=> "delay" times are bias dependent

Vertical NQS effects: compact modeling

- frequency domain solution is truncated after first or second frequency term:

$$\underline{X}_{nqs} \approx X_{qs} - (\omega\tau_2)^2 - j\omega\tau_1 \quad (X = I_T,\ Q_f)$$

=> valid at each bias point!

- time domain solution (TICCR)
  - allows to construct arbitrarily accurate NQS description (in theory)
  - usually QS carrier distribution assumed (known in time and frequency domain)
    => partitioned-charge based (PCB) approach

$$i_C(t) = i_{T,qs} - \gamma_t \frac{\partial q_f(t)}{\partial t} - \frac{\partial q_{jC}(t)}{\partial t}$$ => additional time delay in collector current

$$i_B(t) = i_{B,qs} + \frac{\partial q_{jE}(t)}{\partial t} + \frac{\partial q_{jC}(t)}{\partial t} + \frac{\partial q_f(t)}{\partial t}$$ => no additional time delay in charge

  - theoretical evaluation yields ***small-signal*** solution identical to classical g_m

Vertical NQS effects: implementation

existing HICUM/L2 v2.1

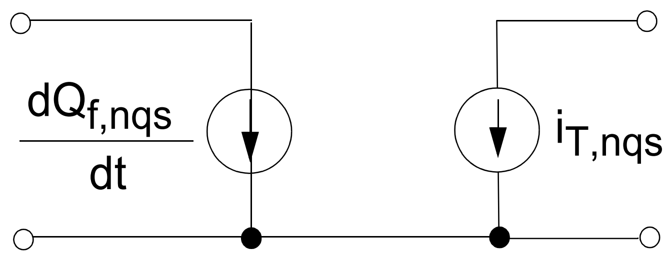
- takes into account charge *and* collector current NQS effect (ALIT, ALQF)
  => correct description of both ***current gain*** and ***g_m***

- uses Weil's approach: Bessel polynomial in frequency domain is transformed to 2nd-order differential equation in time domain

$$\underline{X}_{nqs} \approx X_{qs} - (\omega\tau_2)^2 - j\omega\tau_1 \cong \frac{X_{qs}}{1 + A_1 s + A_2 s^2} \quad \circ\!\!-\!\!\bullet \quad A_2 \frac{d^2 x_{nqs}}{dt^2} + A_1 \frac{dx_{nqs}}{dt} + x_{nqs} = x_{qs}(t)$$

- explicit form and consistent in time domain and frequency domain

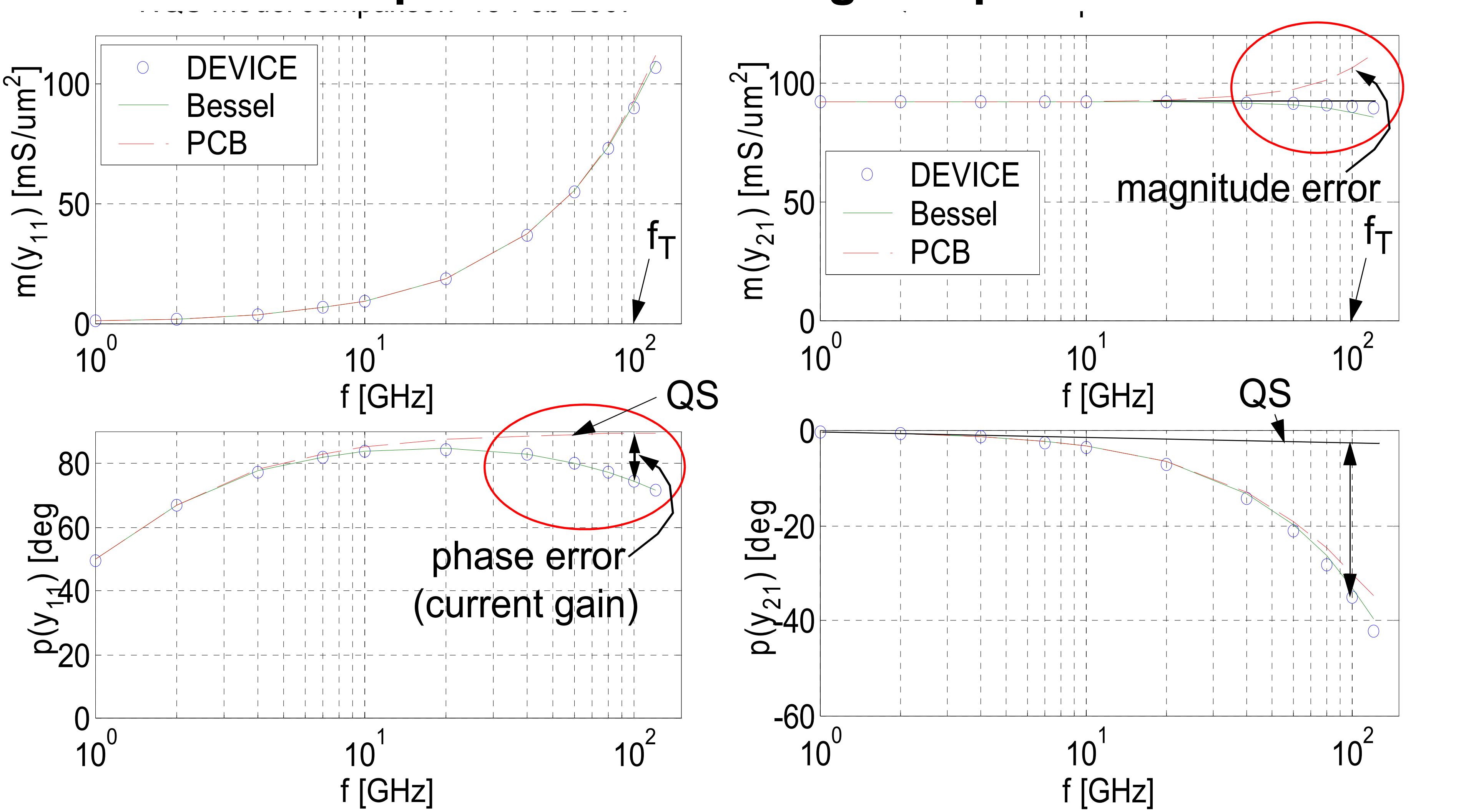
- no change in equivalent circuit



Note: simple low-pass is sufficient for charge

- Weil's approach has worked very well so far AND has indicated design errors in several known cases!!

Comparison of small-signal options



- error depends on bias and frequency (increases with current density, f)

Implementation in existing VA code

HICUM/L2 v2.21 and v2.22

- First VA-based release (without VA code for NQS effects)

- VA does not (yet?) allow to use Weil's approach directly
  => assumption: already existing Weil's code will be taken over from v2.1

- Note1: remember EDA vendor comments about VA compiler issues:
  "... need *handcrafting* in any way to optimize computational performance ..."

- Note2: release procedure seemed to be acceptable to EDA vendors (and according to existing Q&A release guidelines)

Issue:

- completely VA-based model code incl. NQS effect implementation

Implementation in VA-based releases

... and assuming new release requirement

Option1: C code only release

- generate C code from compiler
- handcraft features that are not available (yet) in VA compilers
  => code is valid for ONE specific simulator only!
- further optimization by EDA vendor

=> back to square1: simulator dependent code release

Option 2: VA code only release

- simulator independent code release (dependence is shifted to VA compiler)
- not all necessary features available (yet) in compiler: Weil’s approach, ...

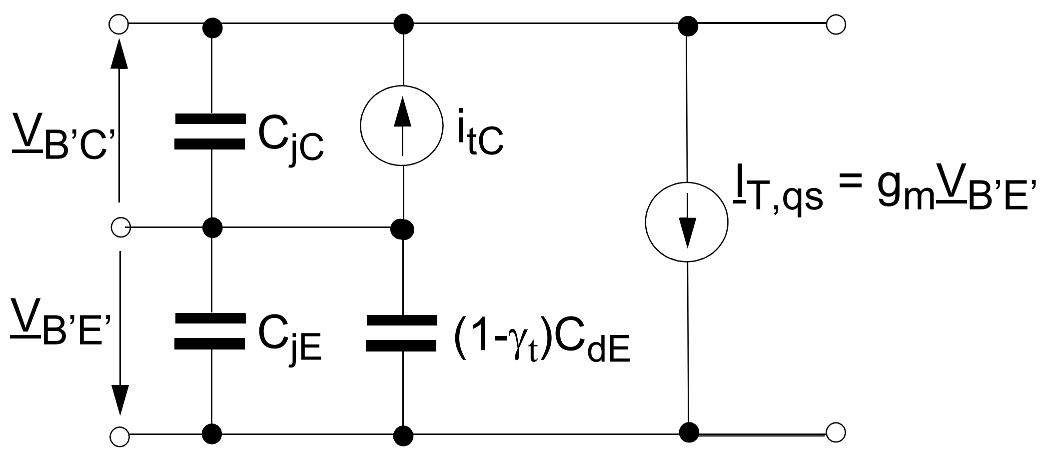
=> need other options for implementing NQS effects unless **VA construct** is made available for Weil’s approach

Implementation: VA-suitable methods (1/5)

partitioned-charge based (PCB) approach (transcapacitance)

- only phase of I_T, g_m => incorrect magnitude of y_{21} and phase of y_{11}
- diffusion charge Q_f(bias,T) and associated capacitance C_{dE}(bias,T)

=> undesired derivatives in small-signal EC are Newton/compiler artifact



assumption: γ_t = const(bias,t)

"trans"-charge: $Q_{tC} = \gamma_t Q_f(v_{B'E'}, v_{B'C})$

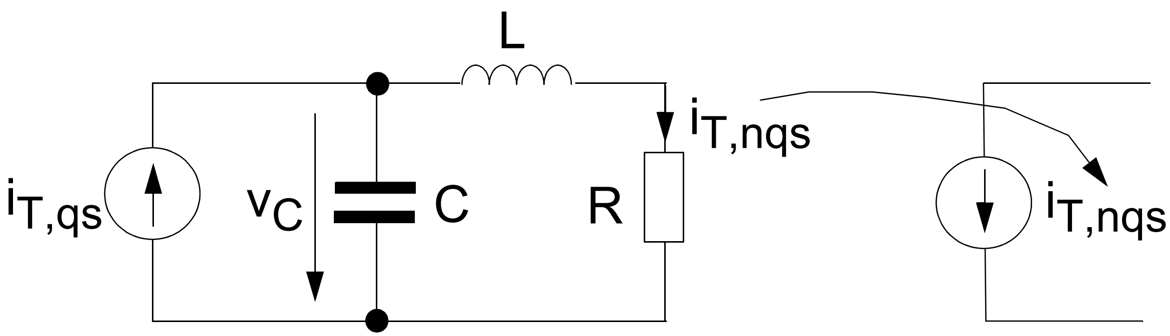
large-signal current: $i_{tC} = \dfrac{dQ_{tC}}{dt}$

small-signal current:

$$di_{tC} = \underbrace{\frac{dQ_{tC}}{dV_{B'E'}} \frac{dv_{B'E'}}{dt}}_{= \gamma_t C_{dE}} + \underbrace{\frac{dQ_{tC}}{dV_{B'C'}} \frac{dv_{B'C'}}{dt}}_{\text{undesired}}$$

Implementation options (2/5)

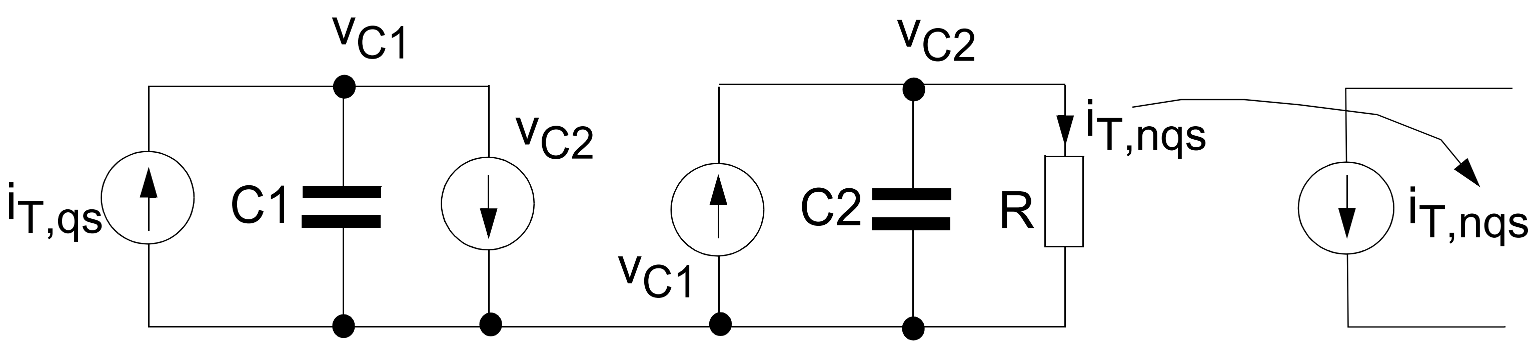
adjunct LCR network (or gyrator equivalent)



$C = C(v_{B'E'}, v_{B'C})$

$L = L(v_{B'E'}, v_{B'C})$

$R = 1\Omega$

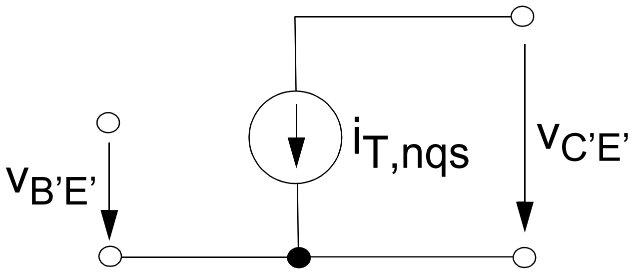


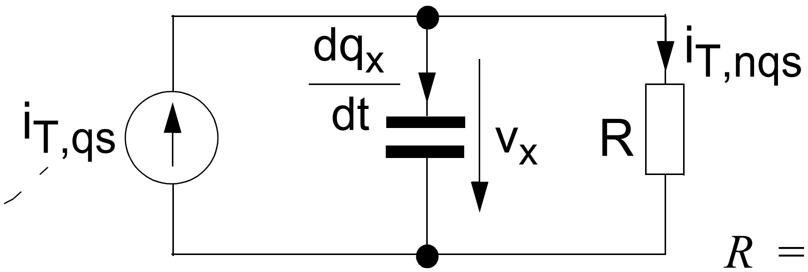
- represents 2nd-order polynomial **<u>exactly</u>** in time- **<u>and</u>** -frequency domain
- used (e.g. VBIC) so far for I_T, g_m only, but with *<u>(bias,T) independent</u>* delay time
- need to (i) make values (bias,T) dependent, (ii) add charge-related adjunct network

=> VA compiler generates undesired derivatives in s-s EC

NQS adjunct networks: implementation issues (3/5)

Example: simple NQS model for large-signal (time domain) transfer current





$$R = 1\Omega$$

$$i_{T,qs}(v_{B'E'}, v_{C'E'}) \qquad q_x = C(i_{T,qs})v_x \quad \text{with} \quad C(i_{T,qs}) = a_{IT}\tau_f(i_{T,qs})$$

generated small-signal elements ...

$$g_m = \frac{di_{T,qs}}{dv_{B'E'}} \qquad g_o = \frac{di_{T,qs}}{dv_{C'E'}}$$

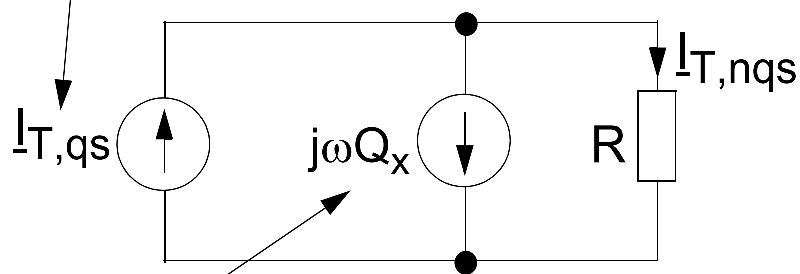
$$C = \frac{dq_x}{dv_x}$$

$$C_{xe} = \frac{dq_x}{dv_{B'E'}} = V_x\frac{dC}{dv_{B'E'}} = a_{IT}g_m\frac{d\tau_f}{di_{T,qs}}$$

$$C_{xc} = \frac{dq_x}{dv_{C'E'}} = V_x\frac{dC}{dv_{C'E'}} = a_{IT}g_o\frac{d\tau_f}{di_{T,qs}}$$

... and associated equivalent circuit

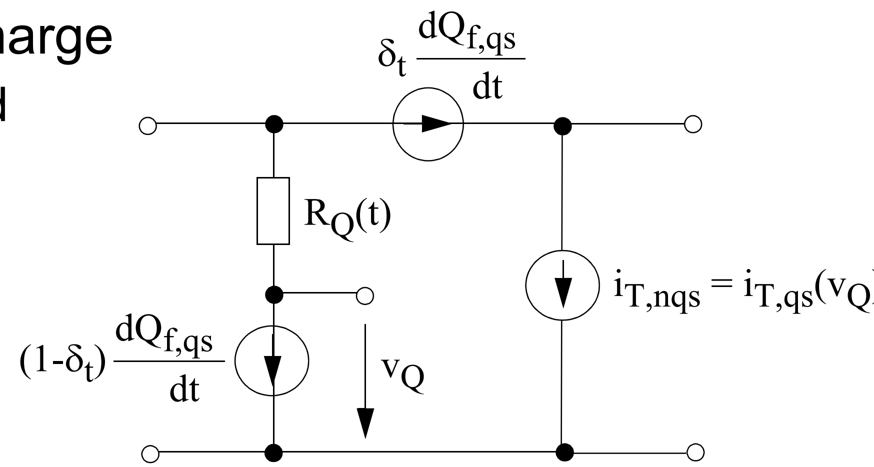
$$\Delta i_{T,qs} = g_m\Delta v_{B'E'} + \underbrace{g_o\Delta v_{C'E'}}_{\text{undesired for NQS}}$$



$$\Delta q_x = C\Delta v_x + \underbrace{C_{xe}\Delta v_{B'E'} + C_{xc}\Delta v_{C'E'}}_{\text{undesired}}$$

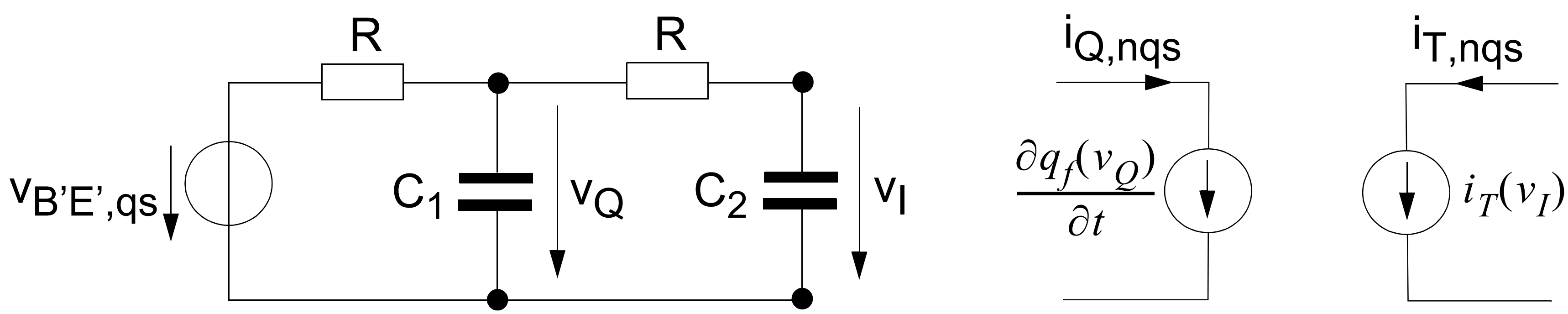
Implementation options (4/5)

- RC network instead of QS diffusion charge
  - so far used only for small-signal EC and (bias,T) independent delay time
  - R_Q is frequency dependent (ω^2)!!
  - adds permanent additional internal node



=> not practically feasible

- delay controlling voltage (delayed electron quasi-fermi-potential)
  - with different time constants for Q_f and I_T
  - cascaded low-pass



=> never tested in BJT/HBT models => physical approach?

Implementation options (5/5)

- base region discretization (collocation method)
  - generates permanent nodes
    => unacceptable increase in simulation time, especially if effect is not desired
  - note: base region is not the only relevant region with charge
  - additional issues
    - structural information (often considered as IP by foundries)
    - more or less significant "reformulation" of other model equations

=> not an attractive option

- keep delay times bias independent
  - incompatible to previous version 2.1 and implemented 2.2 versions

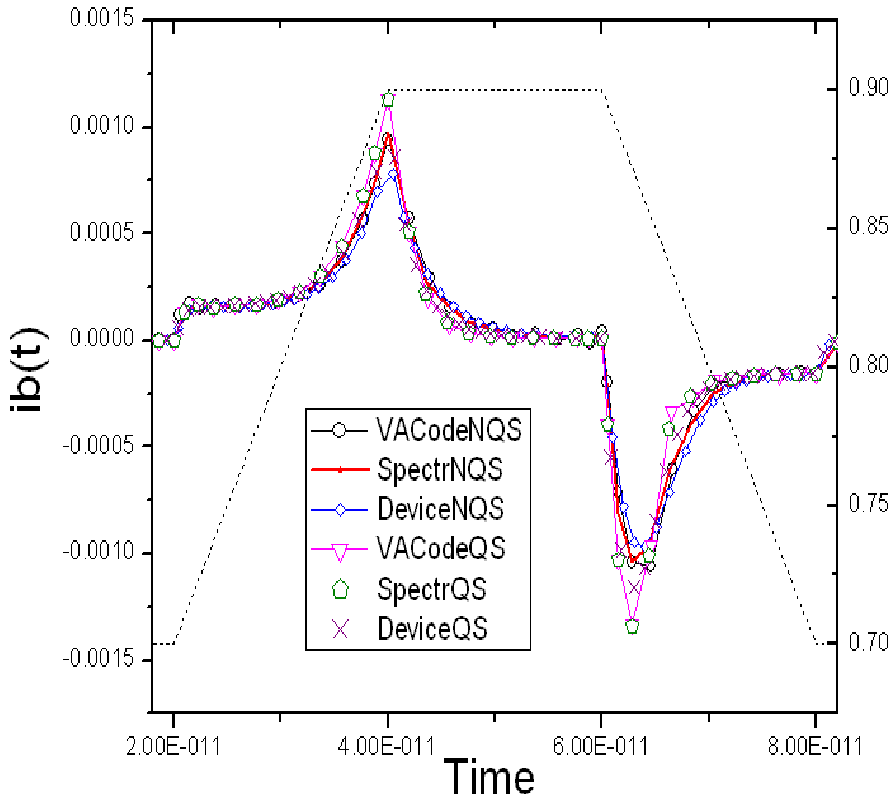
=> intermediate solution

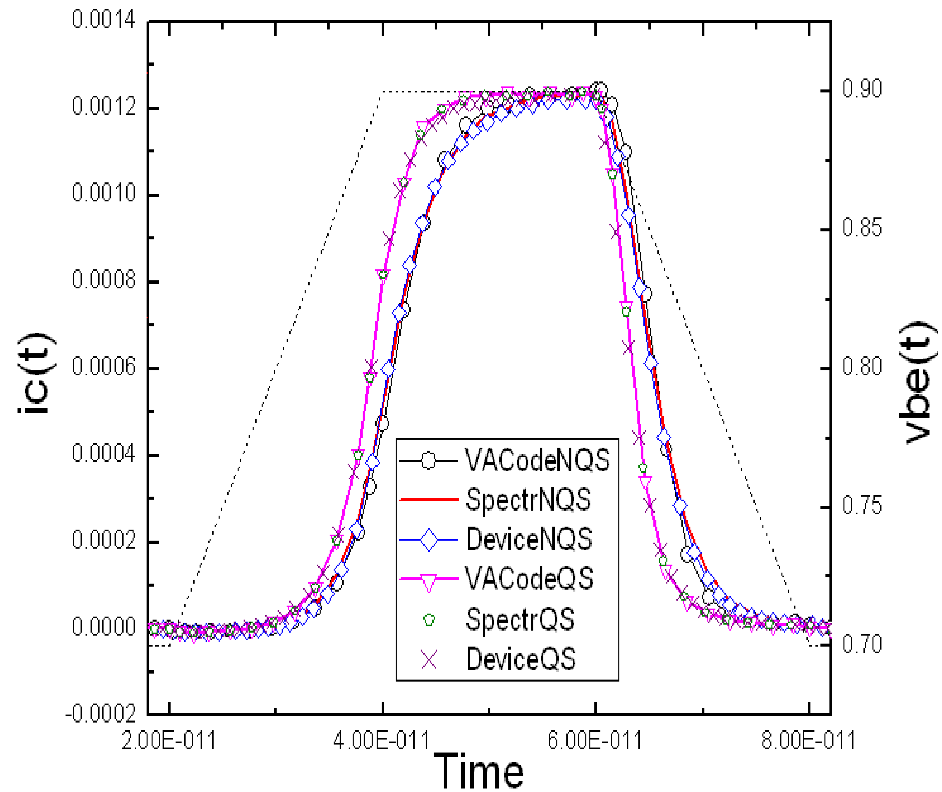
- omit NQS effects
  => incompatibility to previous versions (e.g. HICUM v2.1)
  => h.f. design impact

Results of NQS effect implementation

HICUM comparison: v2.1(Weil) vs. v2.2 (adj. netw.)

Large-signal transient simulation (first results)

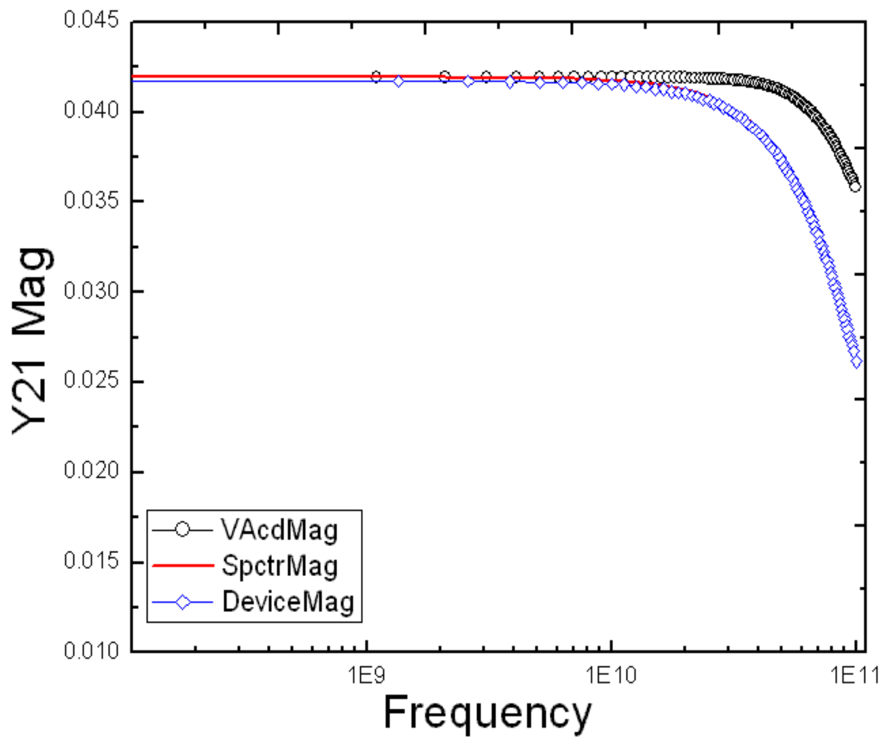


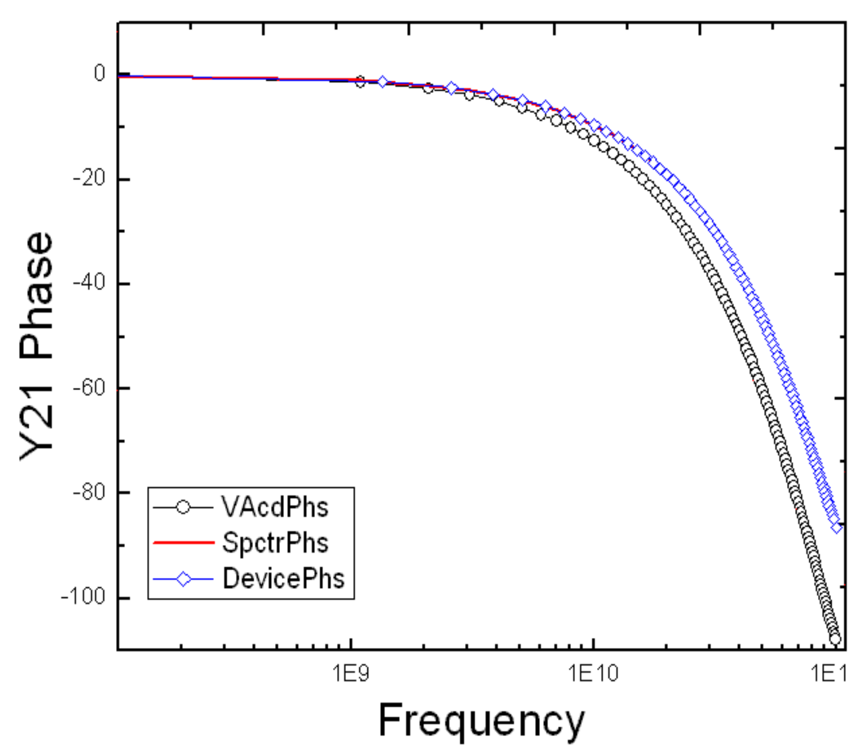


=> acceptable agreement

HICUM comparison: v2.1(Weil) vs. v2.2 (adj. netw.)

Small-signal frequency-domain simulation: Y21



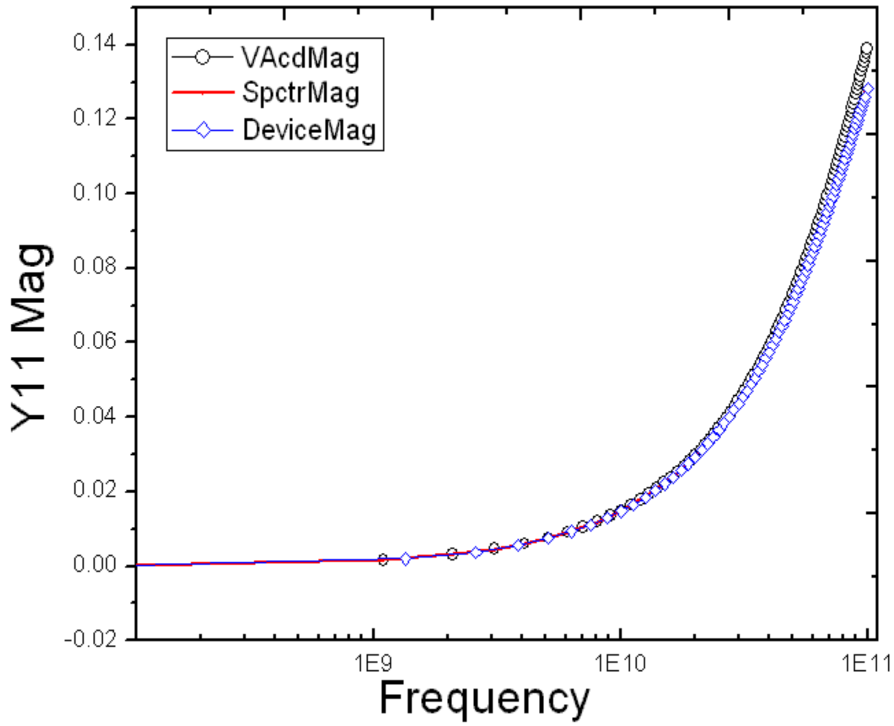


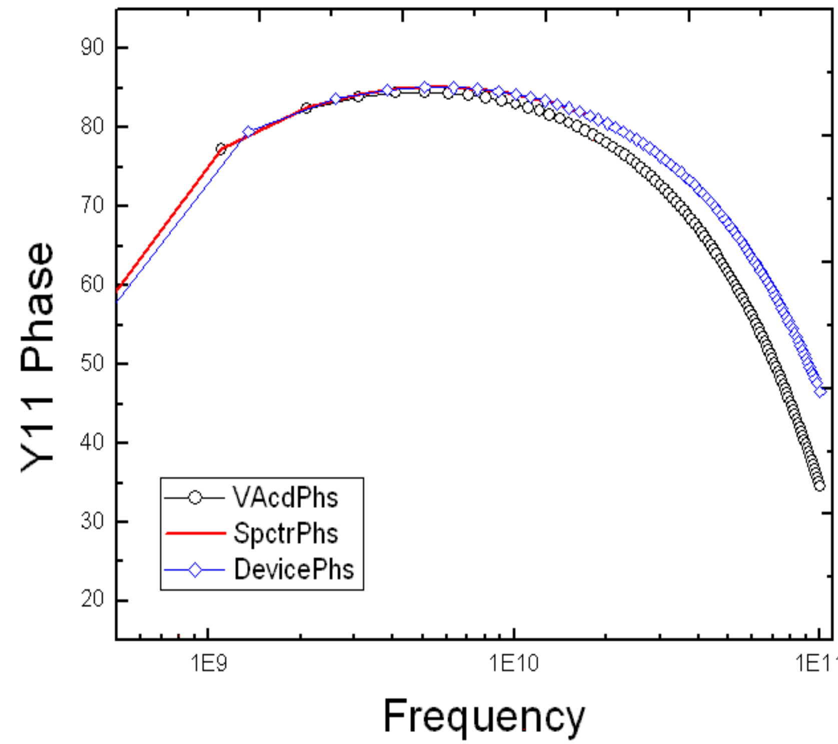
- Weil's approach implementations agree (v2.1 in SPECTRE and DEVICE)
- VA (adj. netw.) deviates from Weil's approach implementation

=> derivative issue?

HICUM comparison: v2.1(Weil) vs. v2.2 (adj. netw.)

Small-signal frequency-domain simulation: Y11





- similar results as for y21
- results with bias **<u>independent</u>** transit and delay times are identical for all implementations

Summary

HICUM/L2 v2.23: will proceed with release

- EDA vendors: use existing simulator-specific NQS code (Weil’s approach)
- joint effort with Agilent:
  define VA language construct for automated generation of "Weil-code"

VA-based NQS effect implementation

- only "LCR"-approach is sufficiently similar to Weil’s approach
  => presently implemented
- first version is available and under test
- can simplify charge-related adjunct network to 1st-order low-pass
- need to clarify small-signal parameter deviation of VA code
- run-time comparison desirable (VA compiled model vs. built-in Weil code)
- further theoretical investigations needed