BSIM4 and MOS Model 11 benchmarks for MOSFET capacitances

UPDATED PRESENTATION

using new results from STm

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simulation conditions

- **BSIM4**
  - ELDO 5.4_1.1 (Beta version)
  - NMOS default parameters used with XPART=50/50
  - no junction capacitances; no overlap capacitances
  - low frequency sim.: NMOS device: W= 10μm, L= 0.12μm
  - high frequency sim.: NMOS device: W= 10μm, L= 2μm
- **MOS Model 11**
  - no junction capacitances; no overlap capacitances
  - only intrinsic MOS capacitances
  - NQS simulations using channel segmentation (see Scholten et al., IEDM'99)
  - low frequency sim.: NMOS device: W= 10μm, L= 0.18μm
  - high frequency sim.: NMOS device: W= 10μm, L= 2.5μm

simulation conditions

- **ac analysis (low-frequency)**
  - reciprocity
  - drain/source symmetry
  - QS / NQS

  simulations are performed at $V_D=V_S=V_B=0V$ at 1kHz
- **ac analysis (high-frequency)**
  - QS / NQS

  magnitude and phase of admittance parameters Y_{XG} at $V_D=V_S=V_B=0V$ and $V_G=1.2$ or 1.8V from 1MHz to 10GHz
- **transient analysis applying fast voltage ramp to gate**
  - QS / NQS

  currents for voltage ramp of 1V/s applied to gate at $V_D=1.2V$ or 1.8V and $V_S=V_B=0V$

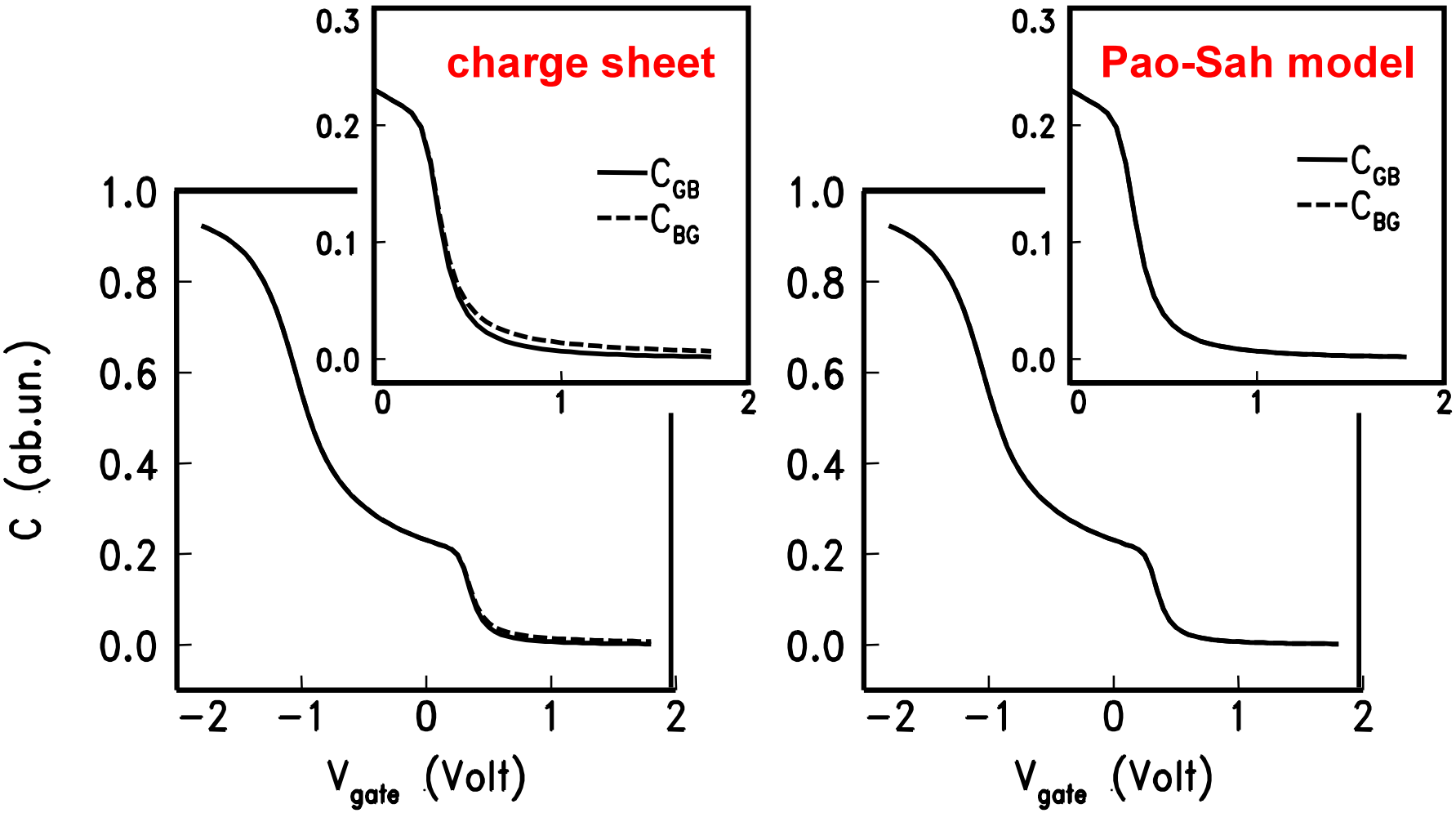
additional remarks

- **MOS Model 11**
  - **dc and ac capacitances are equal!**
- **capacitance definition**
  - **i ≠ j** $C_{ij} = -\frac{\partial Q_i}{\partial V_j}$
  - **i = j** $C_{ij} = \frac{\partial Q_i}{\partial V_j}$
- **$C_{ij} > 0$ holds, except for C_{DS} and C_{SD} !!**
  - **see e.g. eq. (9.2.37j) of "Operation and Modeling of the MOS Transistor", Y. Tsividis, Second Edition, 1999**
  - **checked with Medici simulations**

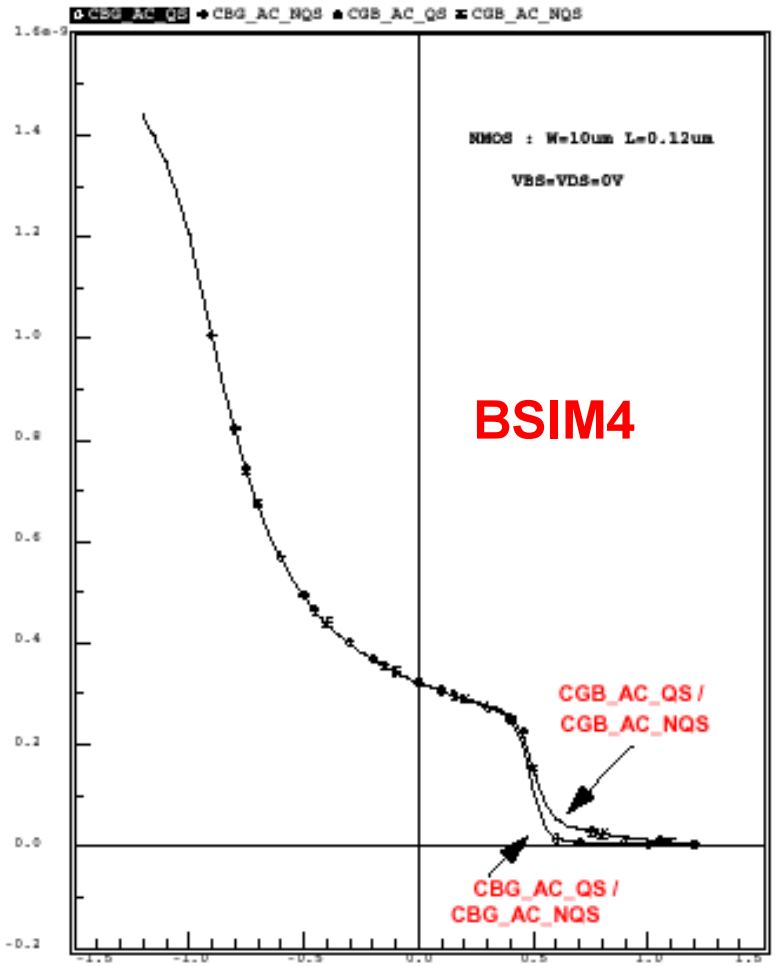
reciprocity

- **at V_{DS}=0 V one has C_{ij}=C_{ji}**
  - **checked with Medici simulations**
  - **investigated for C_{bg}= C_{gb} with 2 surface-potential based compact model formulations**
    - charge sheet
    - Pao-Sah

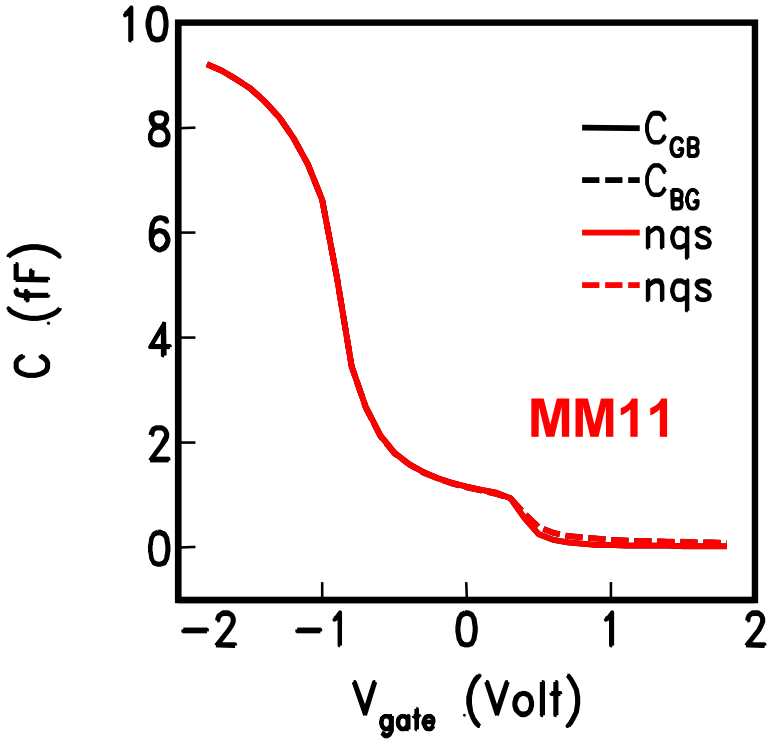
reciprocity: C_{BG}-C_{GB} vs. V_G at V_{DS}=0V



reciprocity: C_{BG}-C_{GB} vs. V_G at V_{DS}=0V

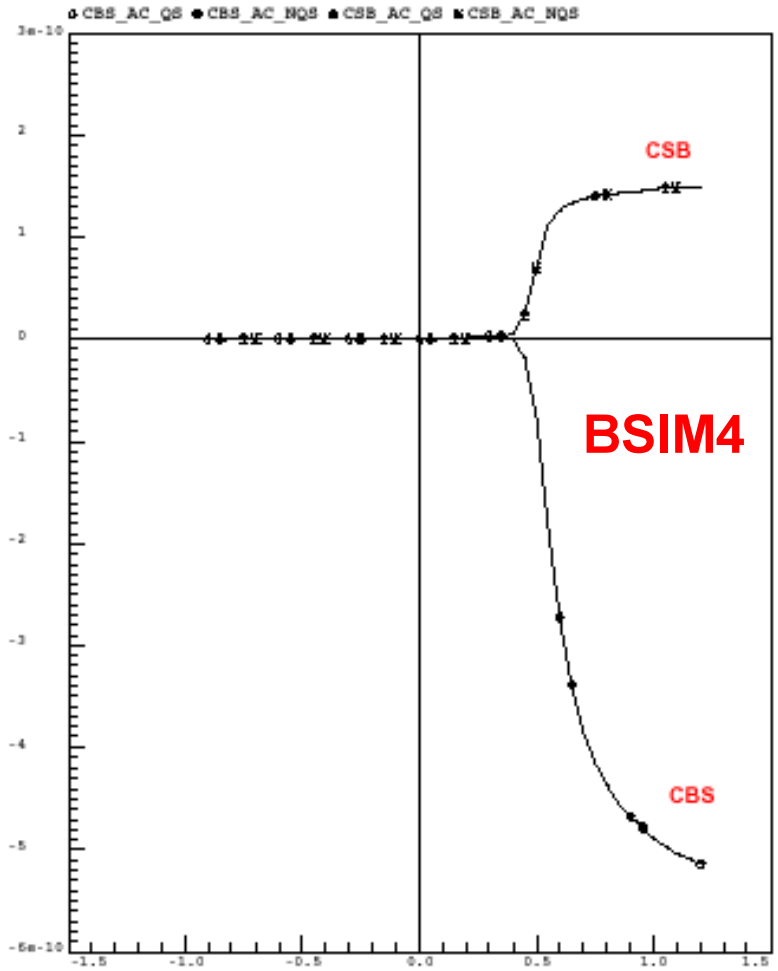


(NQS: ACNQSMOD=1)

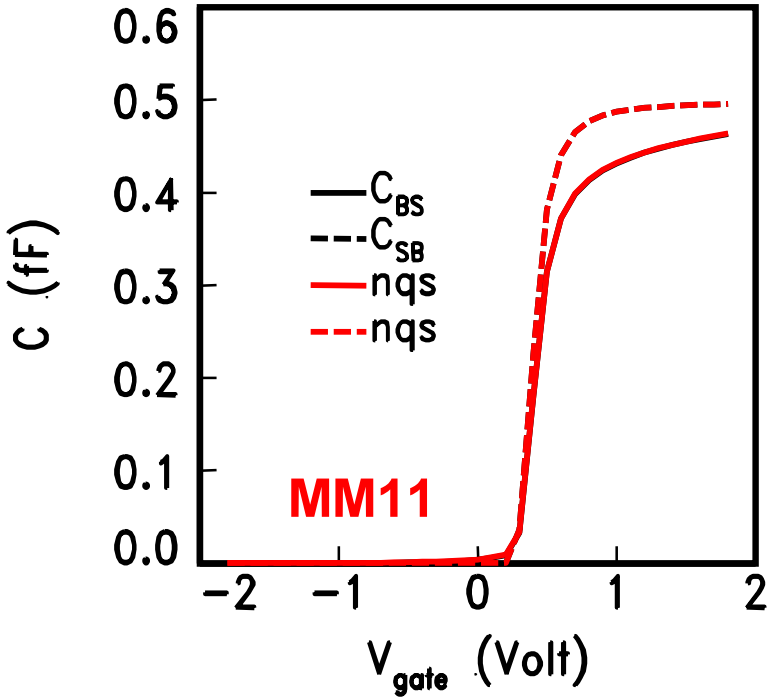


- QS=NQS
- C_{BG} and C_{GB} differ slightly

reciprocity: C_{BS}-C_{SB} vs. V_G at V_{DS}=0V

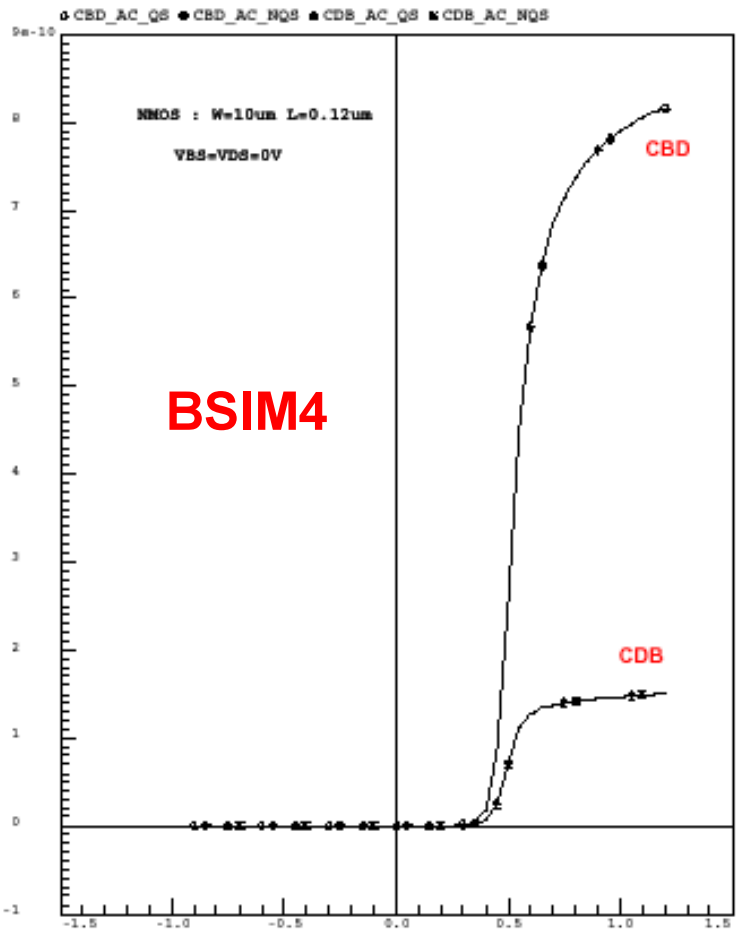


(NQS: ACNQSMOD=1)

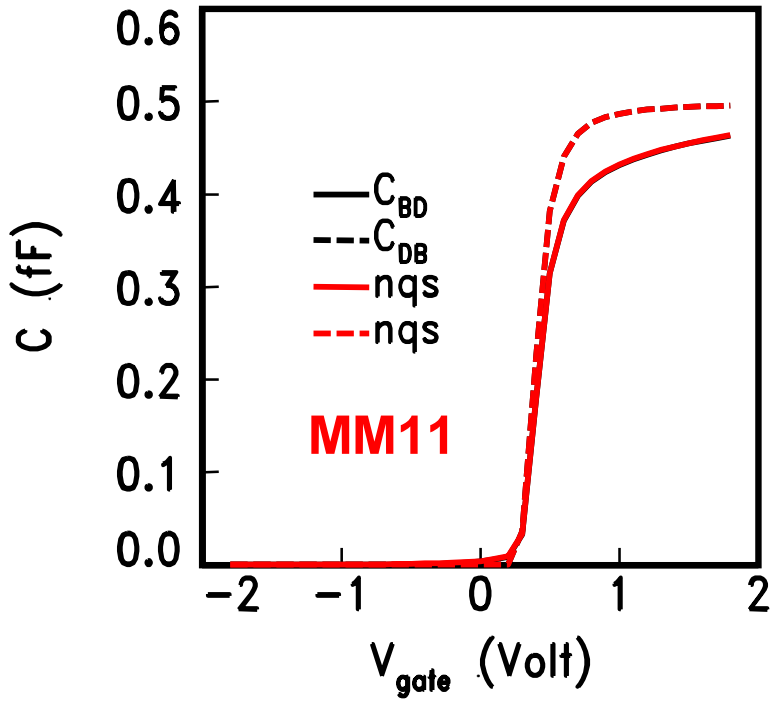


- QS=NQS
- BSIM4: $|C_{BS}|$ and C_{SB} differ factor 4
- BSIM4: C_{BS} is negative!
- MM11: C_{BS} and C_{SB} differ slightly

reciprocity: C_{BD}-C_{DB} vs. V_G at V_{DS}=0V

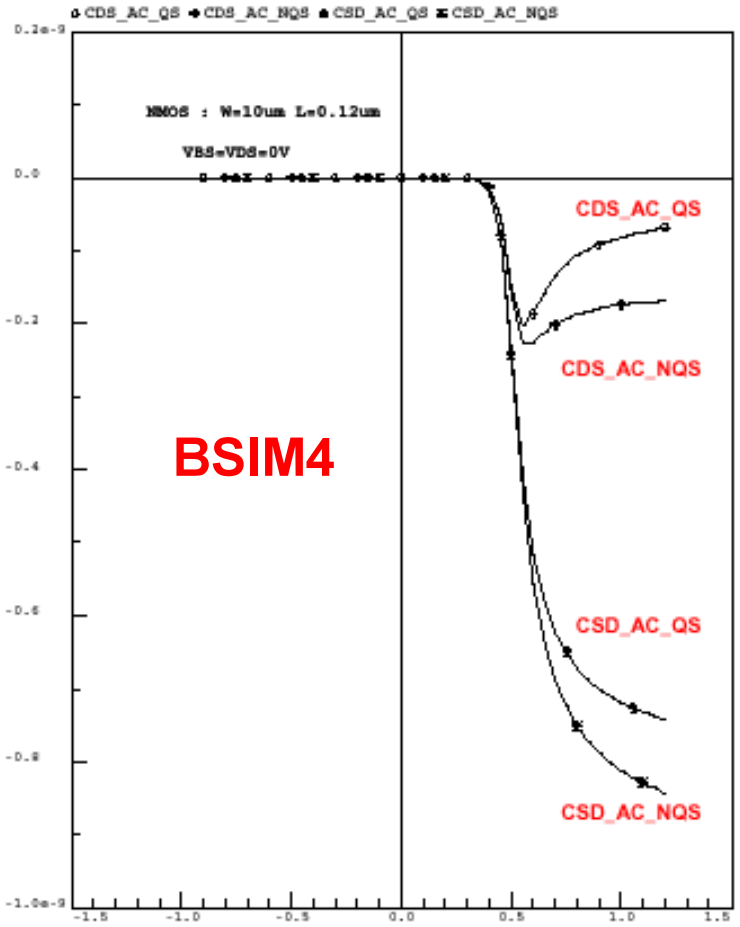


(NQS: ACNQSMOD=1)

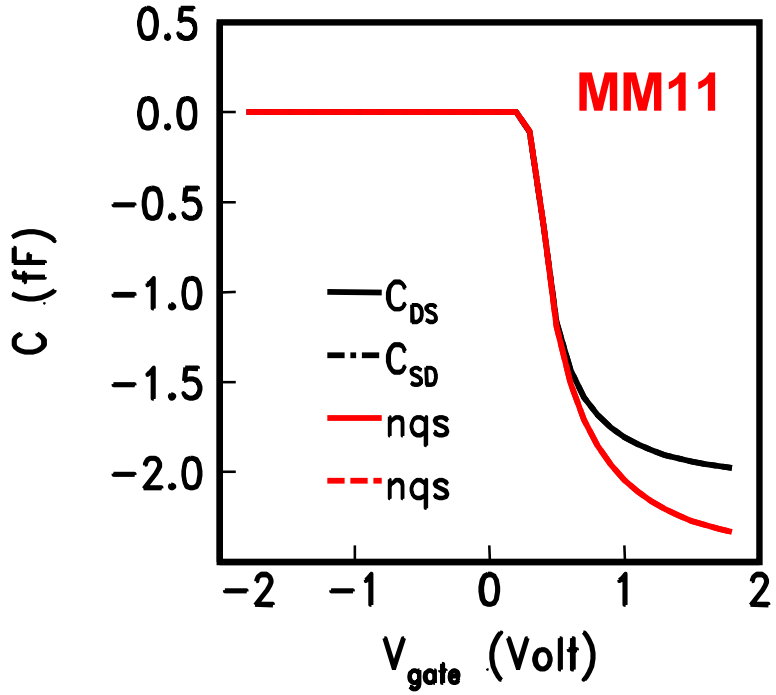


- QS=NQS
- BSIM4: C_{BD} and C_{DB} differ factor 4
- MM11: C_{BD} and C_{DB} differ slightly

reciprocity: C_{DS}-C_{SD} vs. V_G at V_{DS}=0V

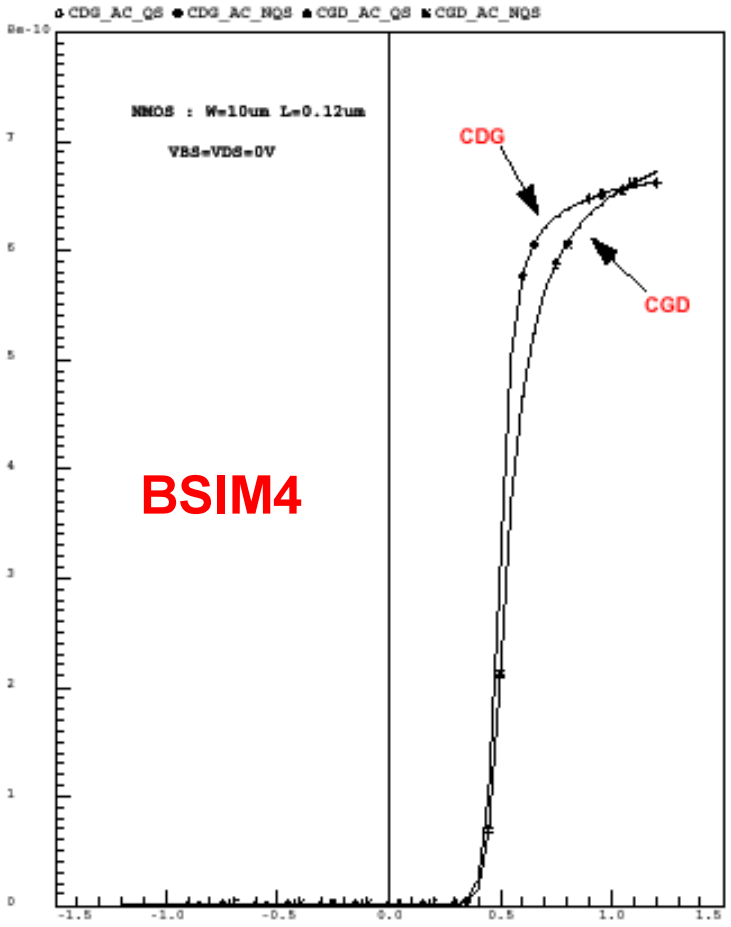


(NQS: ACNQSMOD=1)

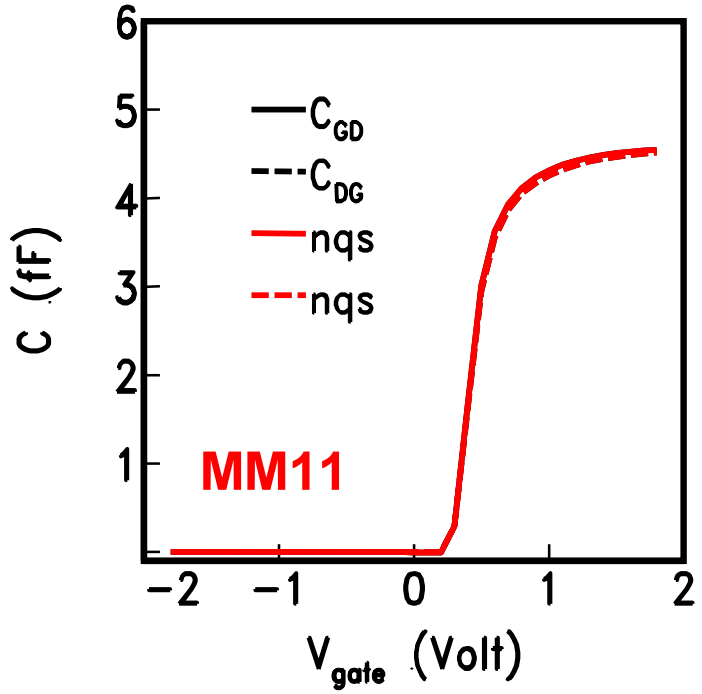


- QS and NQS differ slightly
- BSIM4: C_{DS} and C_{SD} differ factor 4
- MM11: C_{DS} and C_{SD} are equal

reciprocity: C_{DG}-C_{GD} vs. V_G at V_{DS}=0V

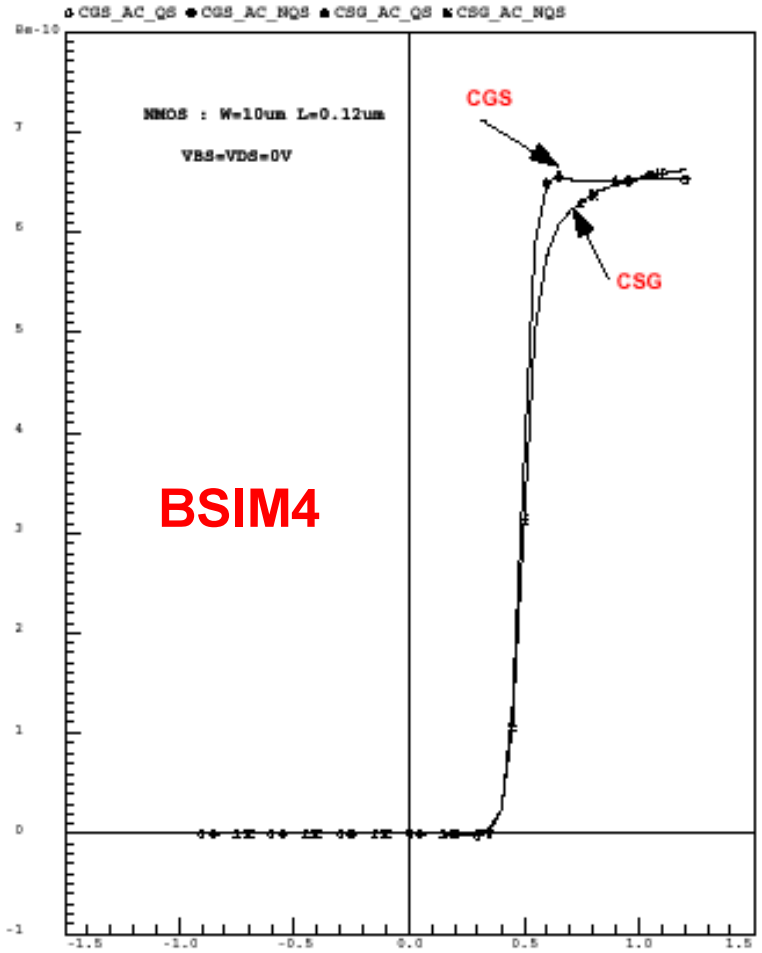


(NQS: ACNQSMOD=1)

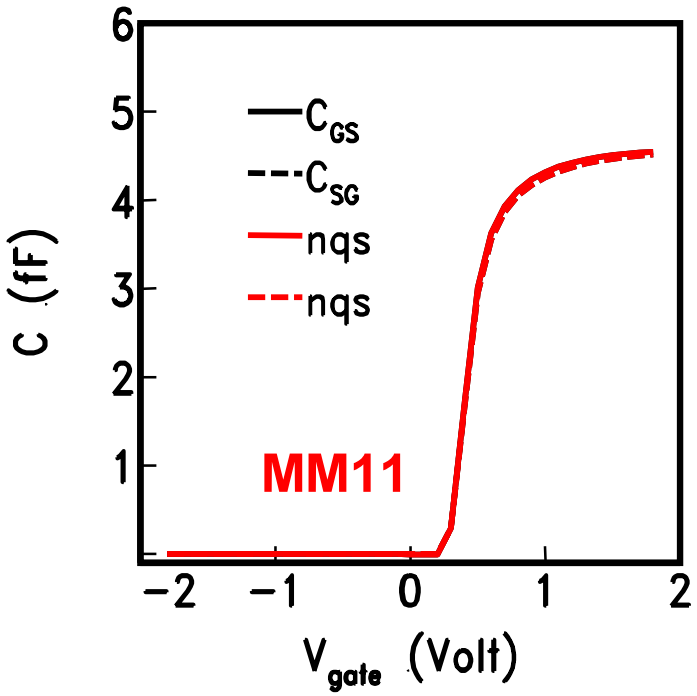


- QS=NQS
- BSIM4: C_{DG} and C_{GD} differ slightly
- MM11: C_{DG} and C_{GD} almost equal

reciprocity: C_{GS}-C_{SG} vs. V_G at V_{DS}=0V



(NQS: ACNQSMOD=1)



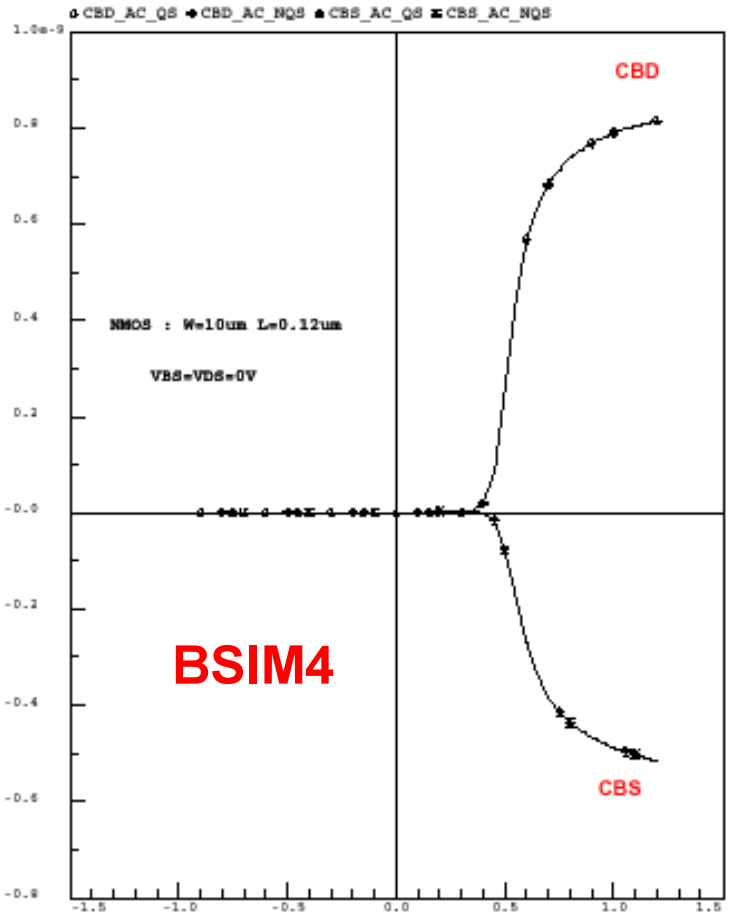
- QS=NQS
- BSIM4: C_{GS} and C_{SG} differ slightly
- MM11: C_{GS} and C_{SG} almost equal

reciprocity: summary

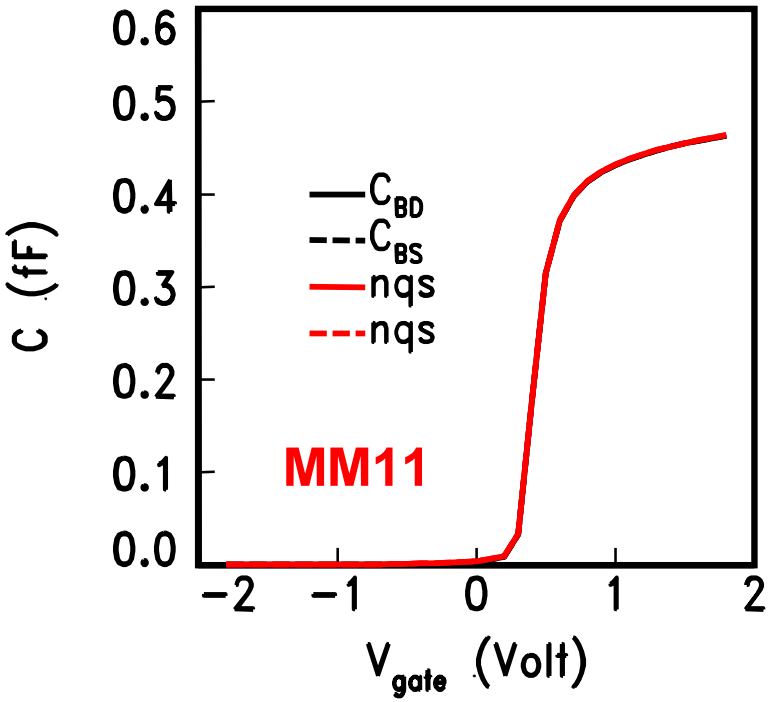
- **BSIM4**
  - **C_{BS} / C_{SB}**
    - **$|C_{BS}|$ and C_{SB} differ factor 4**
    - **C_{BS} is negative**
  - **C_{BD} / C_{DB}**
    - **C_{BD} and C_{DB} differ factor 4**
  - **C_{DS} / C_{SD}**
    - **C_{DS} and C_{SD} differ factor 4**

- **MOS Model 11**
  - **almost perfect reciprocity (better than 0.01 C_{ox})**

symmetry: C_{BD}-C_{BS} vs. V_G at V_{DS}=0V

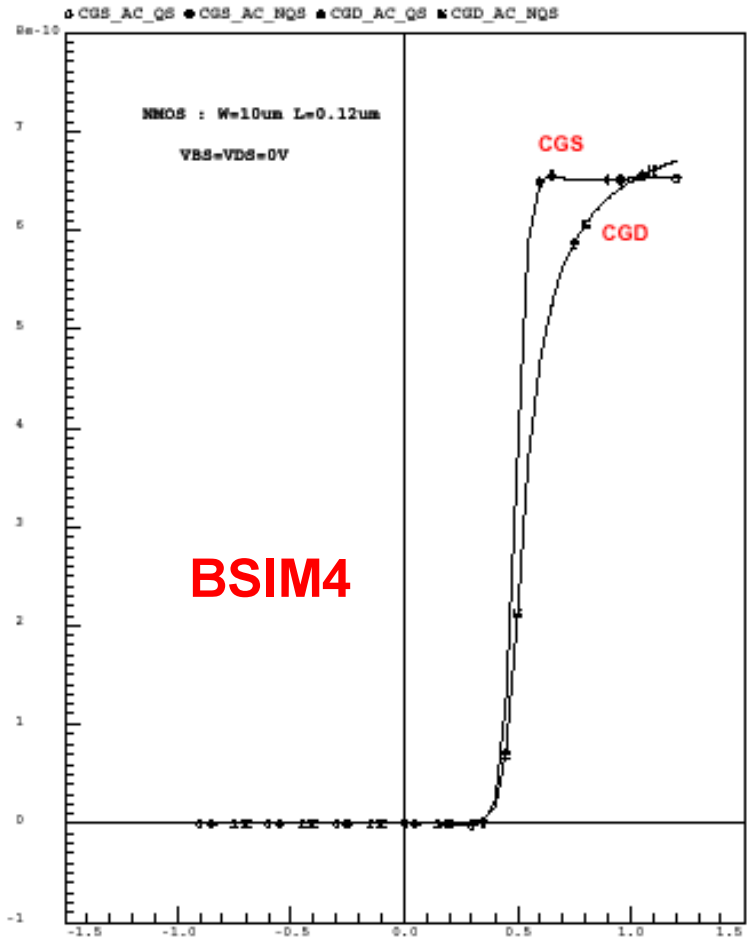


(NQS: ACNQSMOD=1)

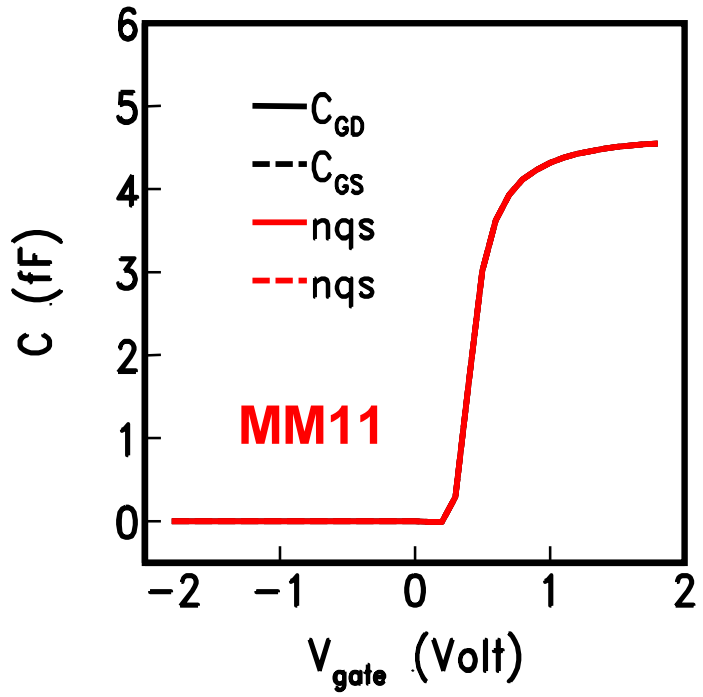


- QS=NQS
- BSIM4: C_{BS} is negative!
- MM11: C_{BD} and C_{BS} are equal

symmetry: C_{GD}-C_{GS} vs. V_G at V_{DS}=0V

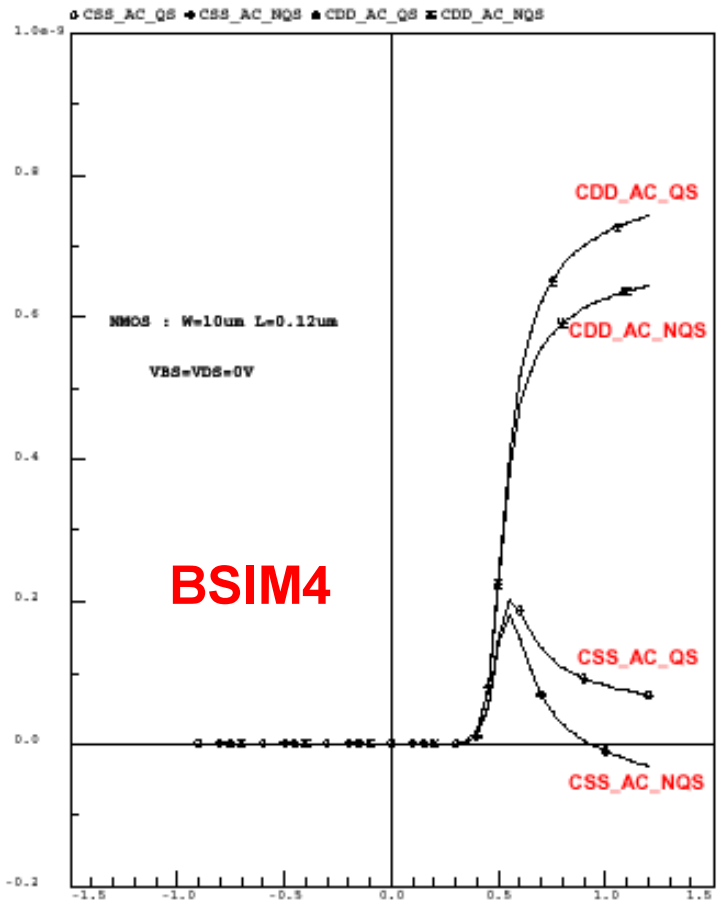


(NQS: ACNQSMOD=1)

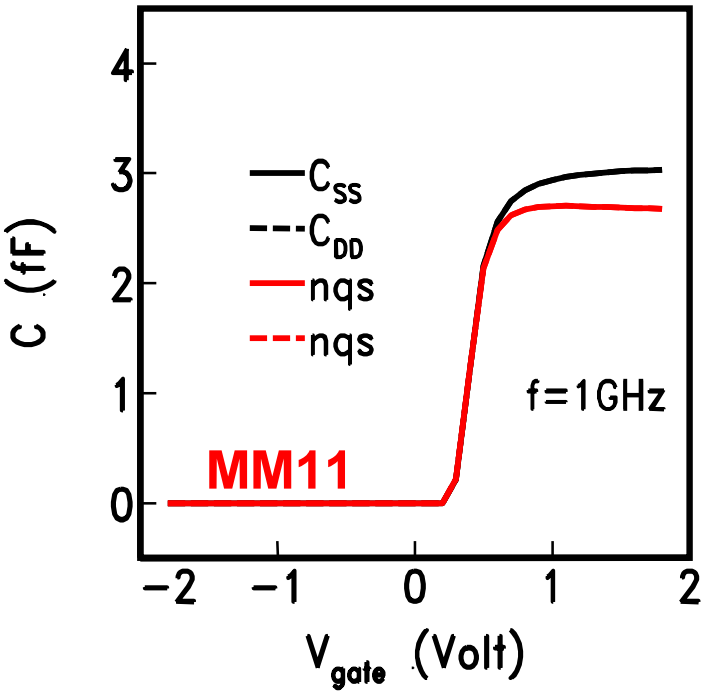


- QS=NQS
- BSIM4: C_{GD} and C_{GS} differ slightly
- MM11: C_{GD} and C_{GS} are equal

symmetry: C_{SS}-C_{DD} vs. V_G at V_{DS}=0V



(NQS: ACNQSMOD=1)

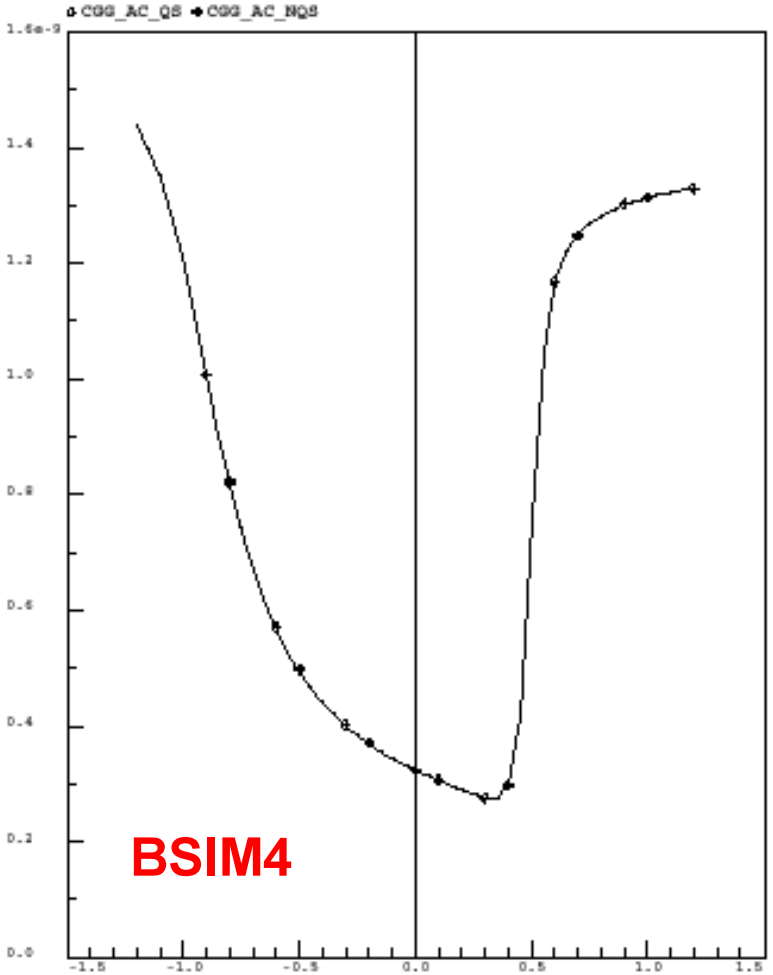


- QS and NQS differ slightly
- BSIM4: C_{SS} and C_{DD} differ factor 4
- MM11: C_{SS} and C_{DD} are equal

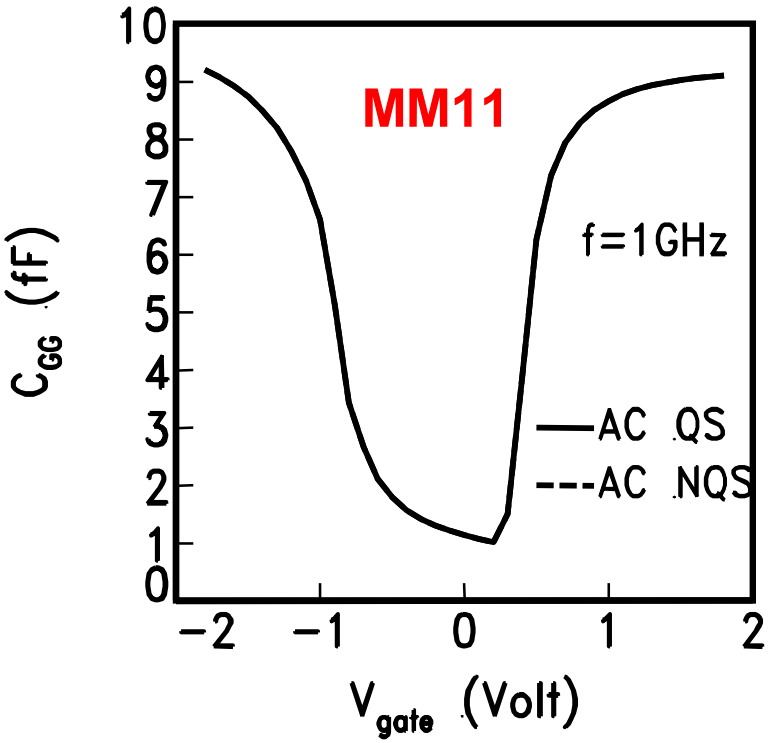
symmetry: summary

- **BSIM4**
  - **C_{BD} / C_{BS}**
    - **C_{BS} is negative**
  - **C_{SS} / C_{DD}**
    - **C_{SS} and C_{DD} differ factor 4**
- **MOS Model 11**
  - **perfect symmetry**

qs / nqs at low frequency: C_{GG} vs. V_G at V_{DS}=0V

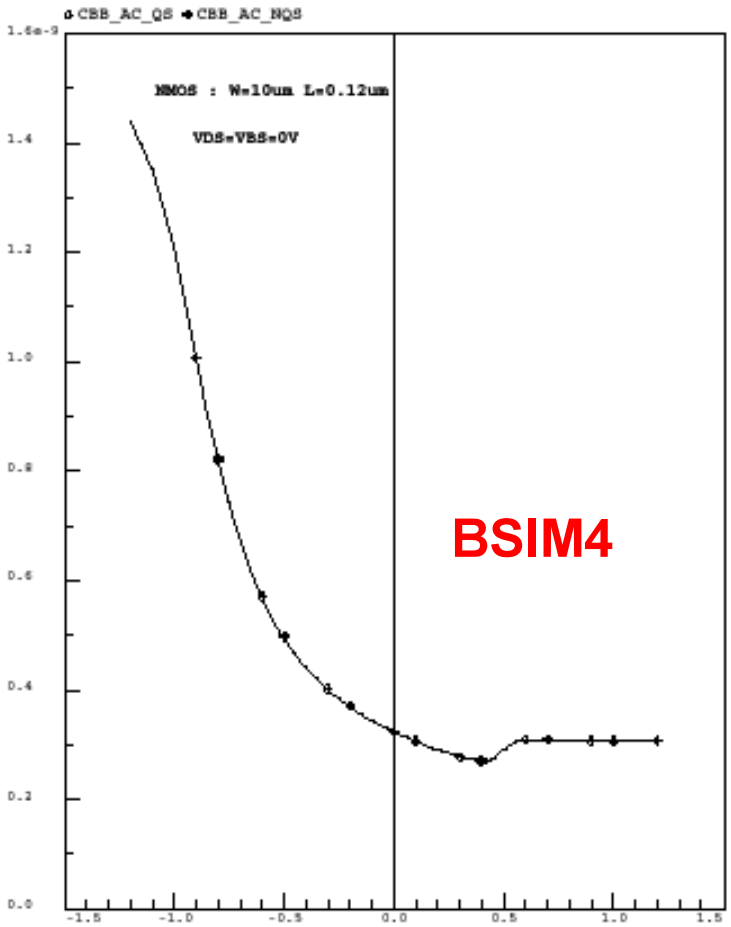


(NQS: ACNQSMOD=1)

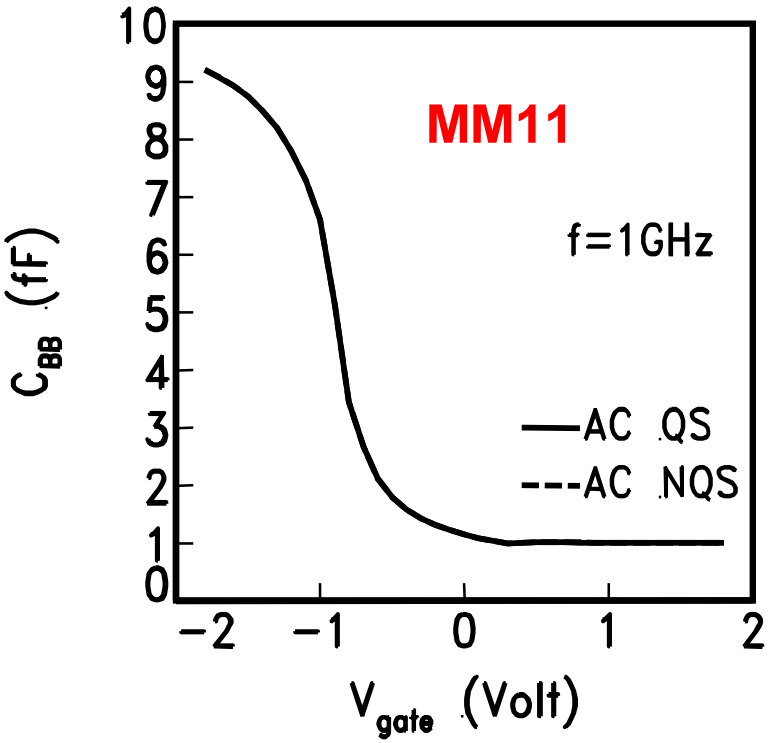


- QS and NQS are equal

qs / nqs at low frequency: C_{BB} vs. V_G at V_{DS}=0V



(NQS: ACNQSMOD=1)



• QS and NQS are equal

comparison QS / NQS at low frequency: summary

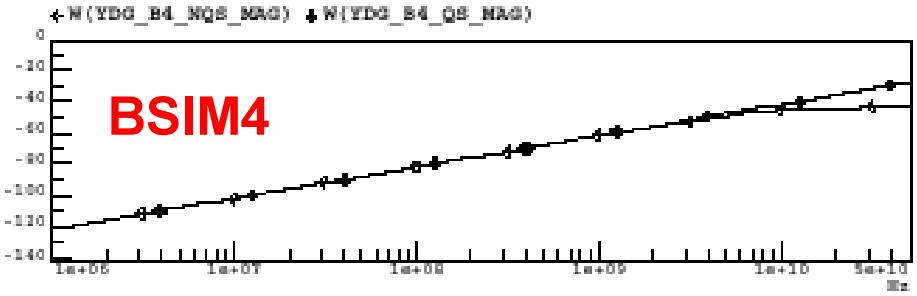
$$C_{ij,\,qs} = C_{ij,\,nqs}\ ?$$

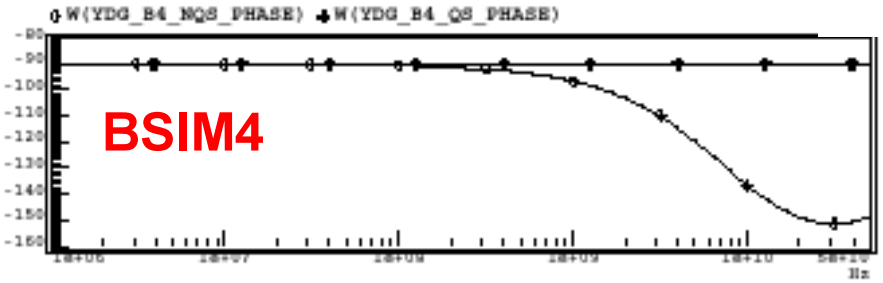
i \ j	G	D	S	B
G	ok	ok	ok	ok
D	ok	no	no	ok
S	ok	no	no	ok
B	ok	ok	ok	ok

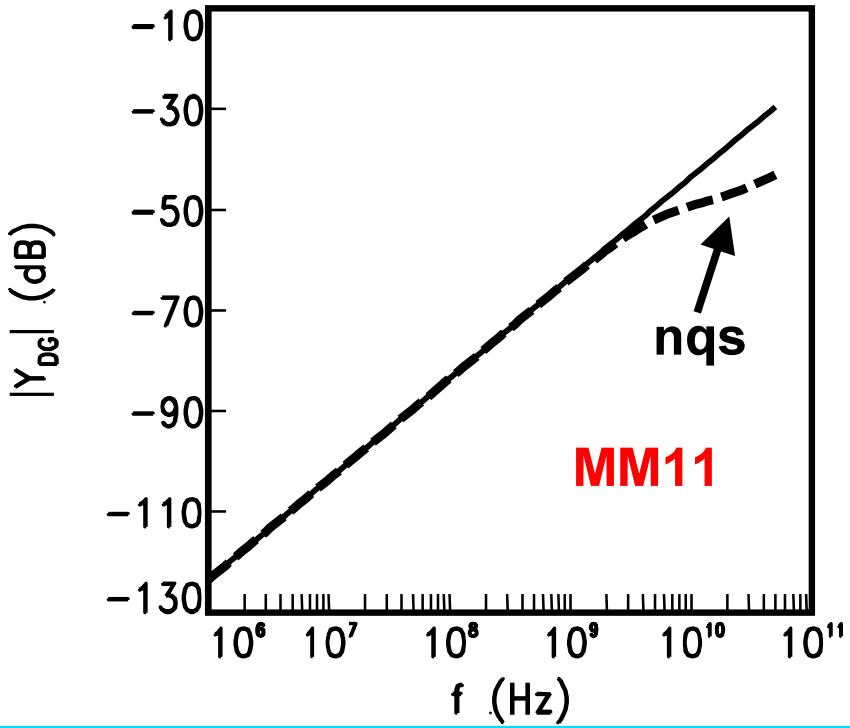
similar results for BSIM4 and MM11

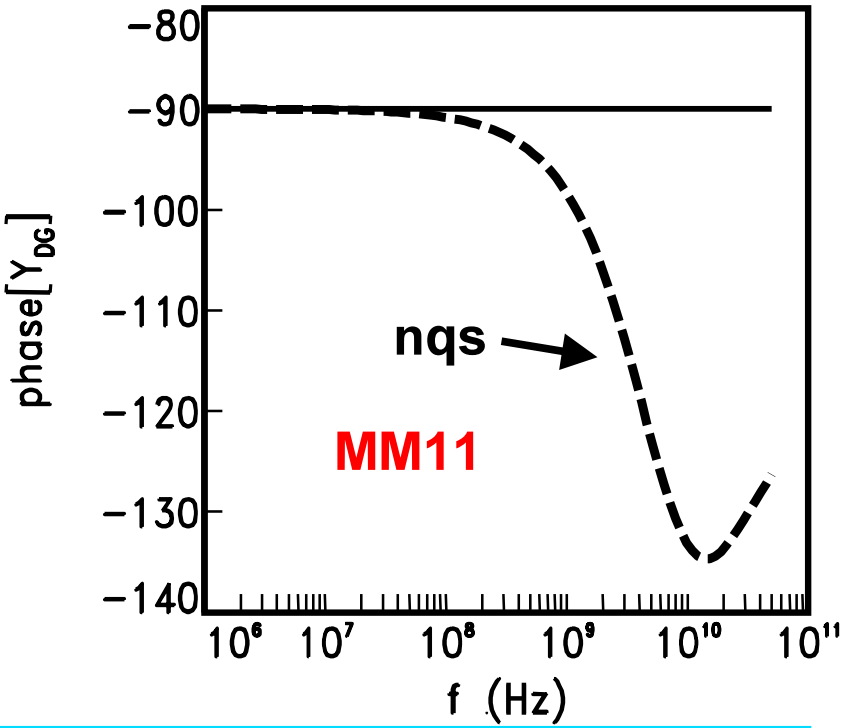
under investigation

qs / nqs at high frequency: Y_{DG} vs. frequency





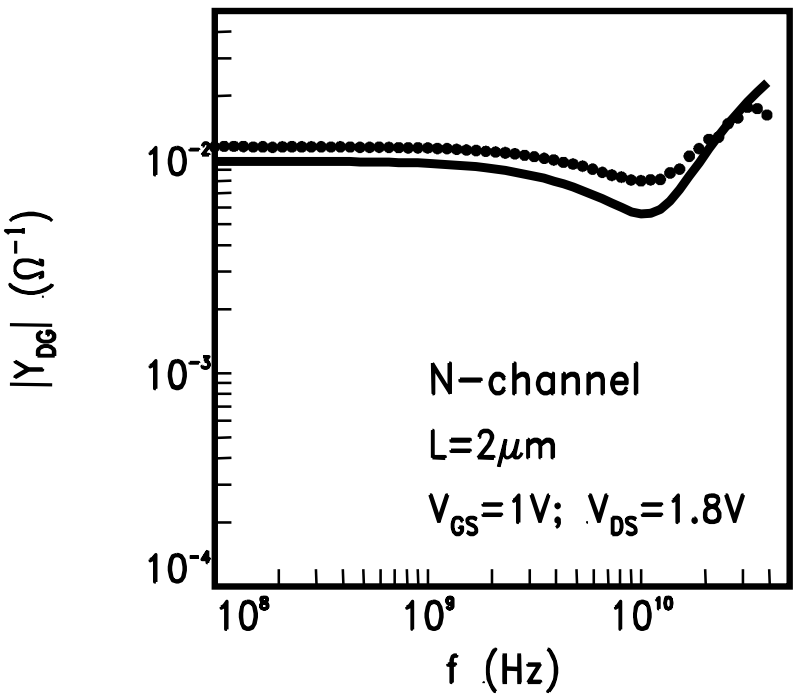


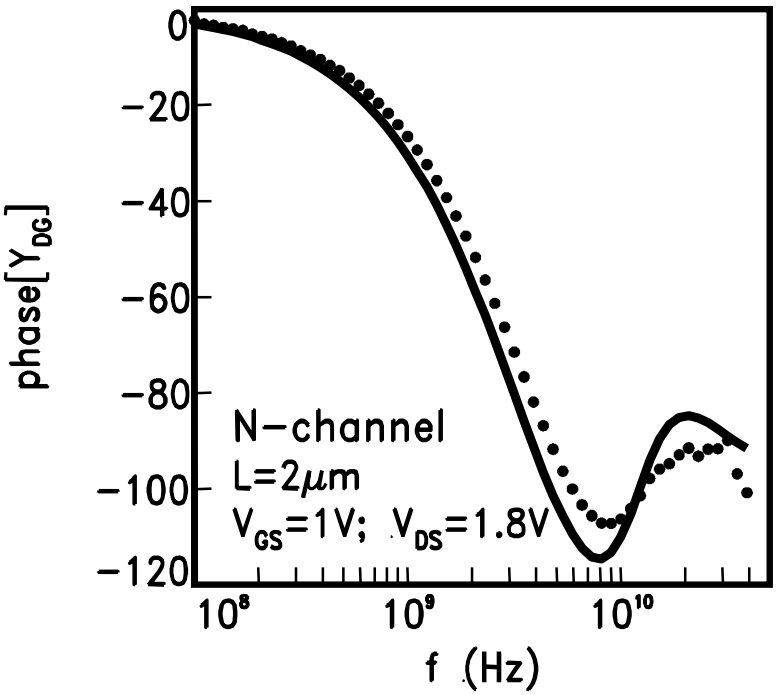


qs / nqs at high frequency: Y_{DG} vs. frequency

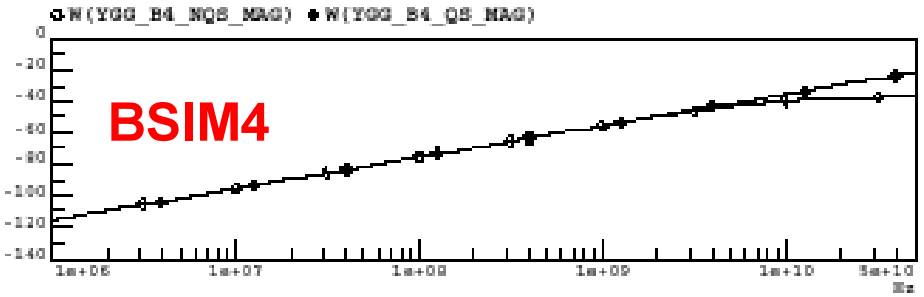
phase check:

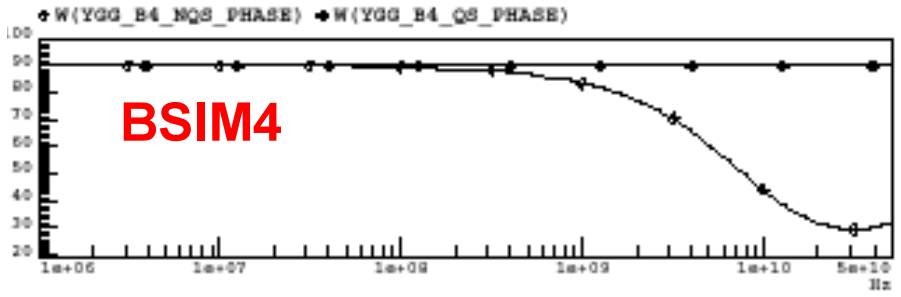
- experimental data
- channel segmentation for MOS Model 9

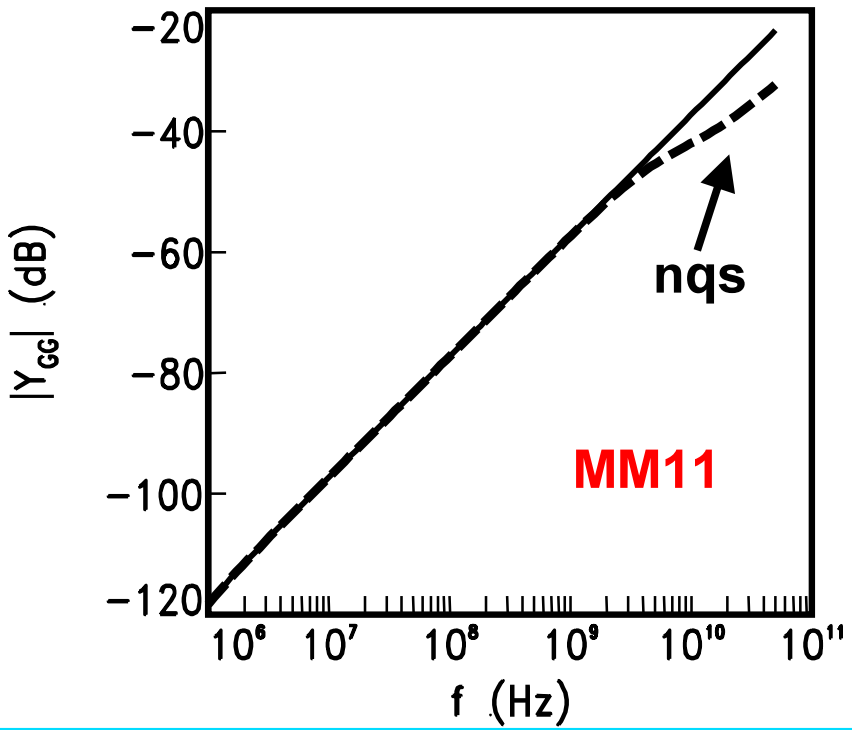


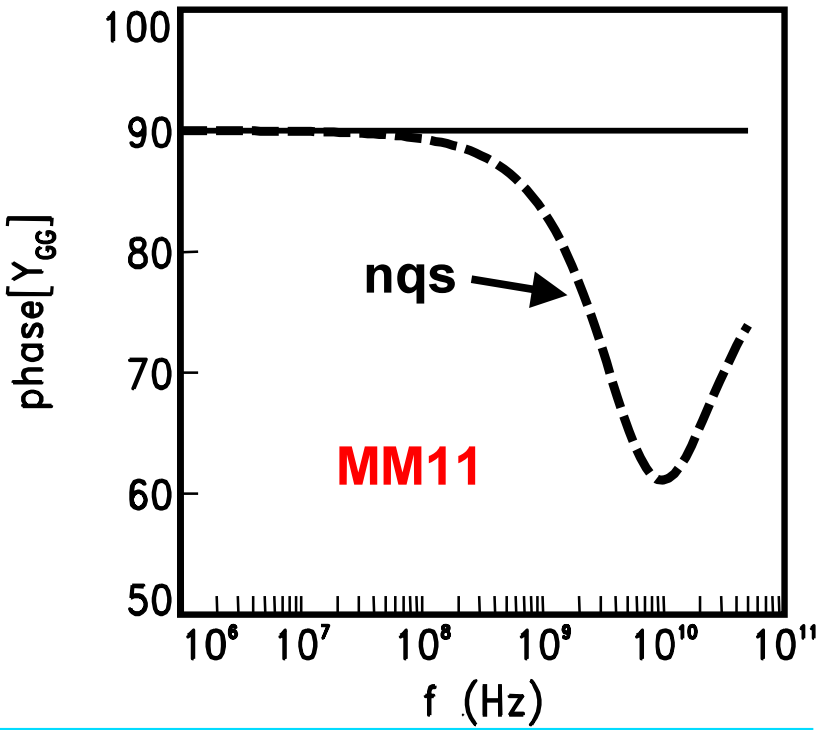


qs / nqs at high frequency: Y_{GG} vs. frequency





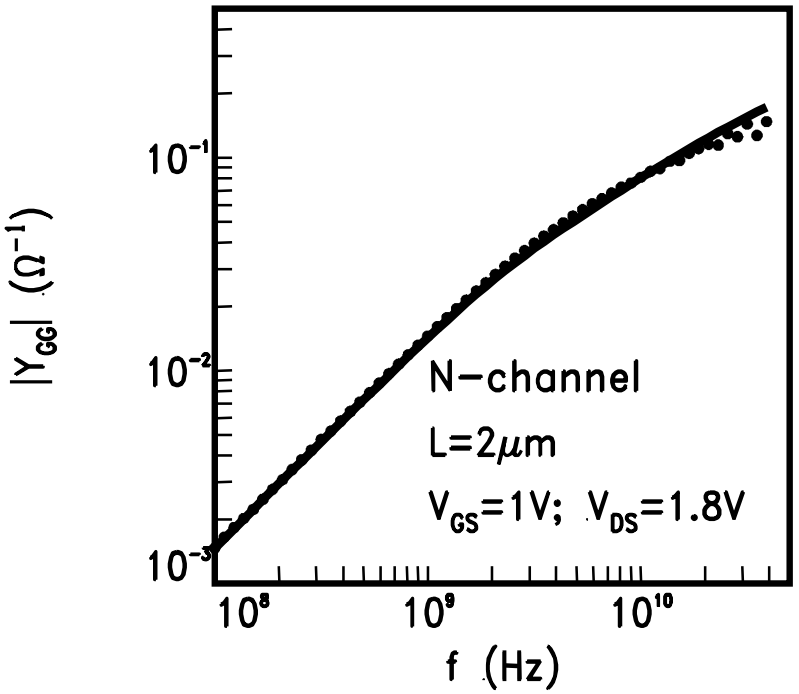


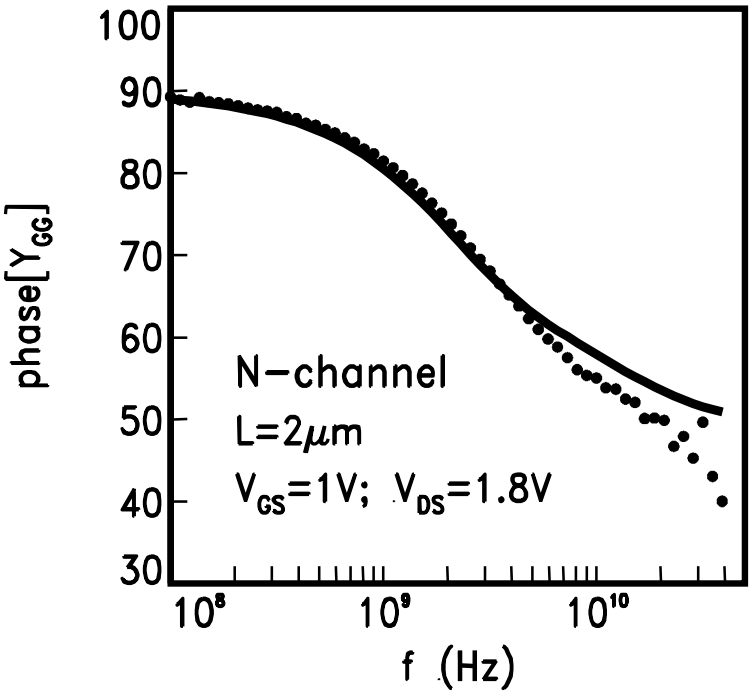


qs / nqs at high frequency: Y_{GG} vs. frequency

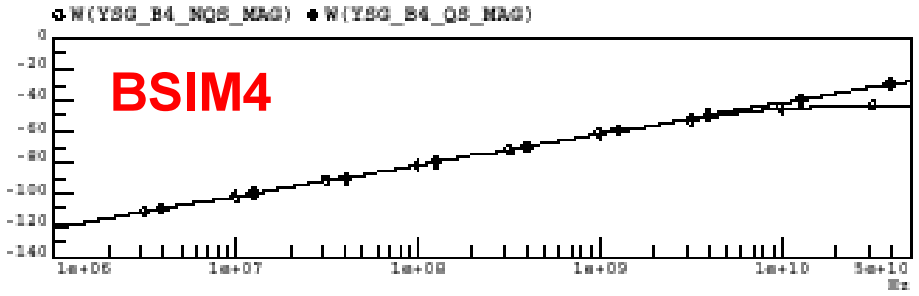
phase check:

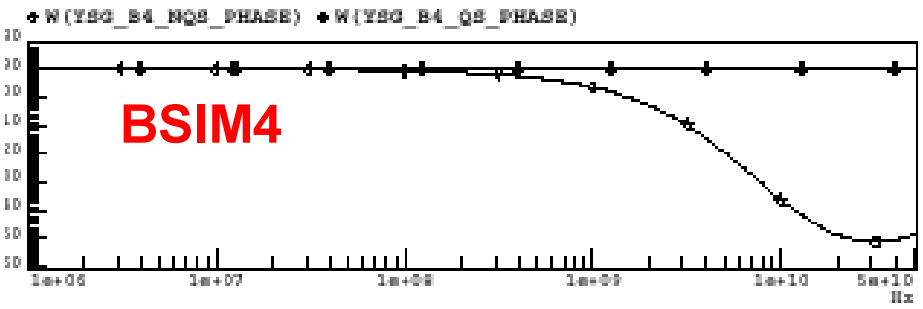
- **experimental data**
- **channel segmentation for MOS Model 9**

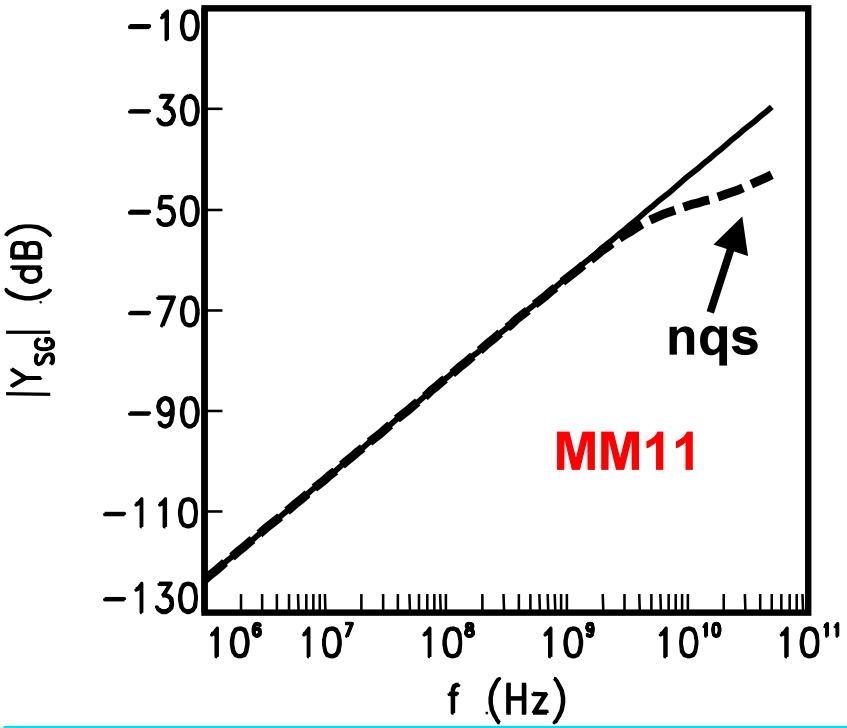


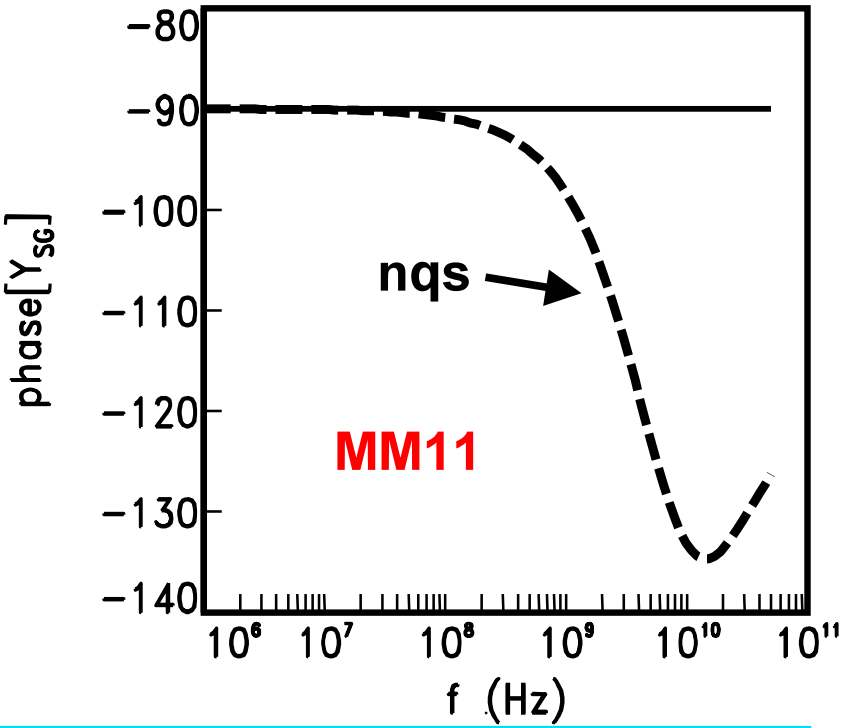


qs / nqs at high frequency: Y_{SG} vs. frequency

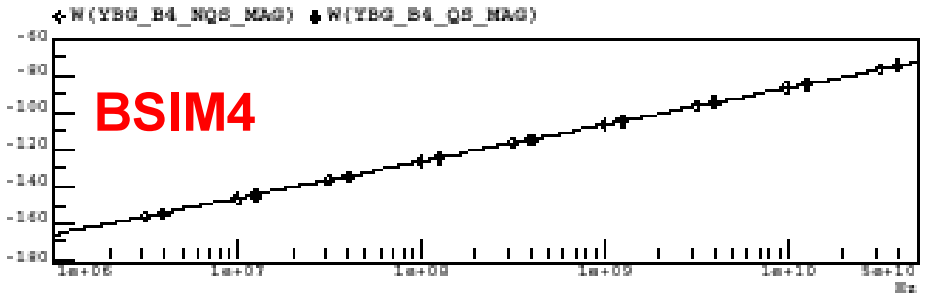


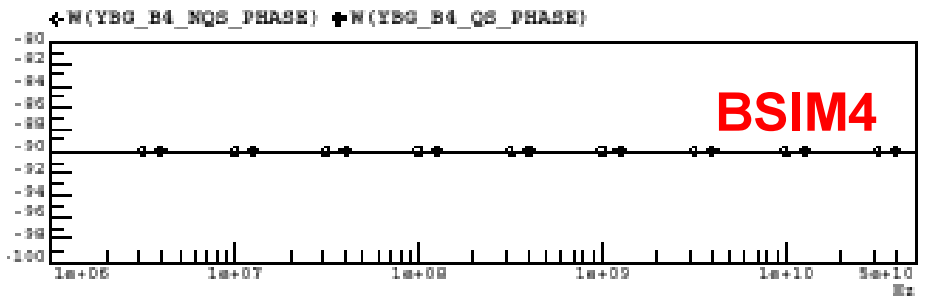


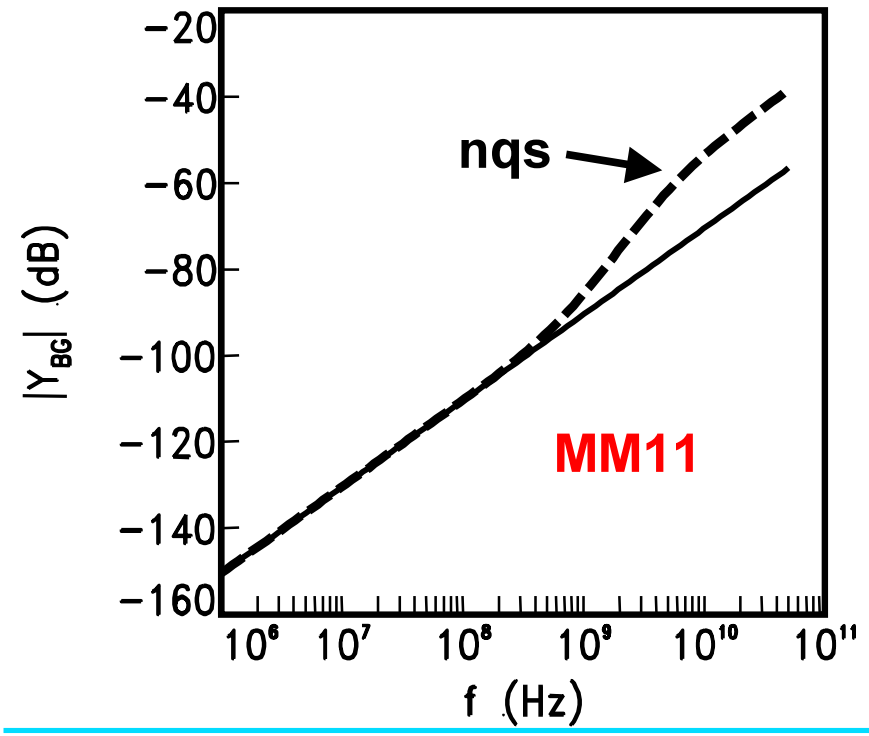


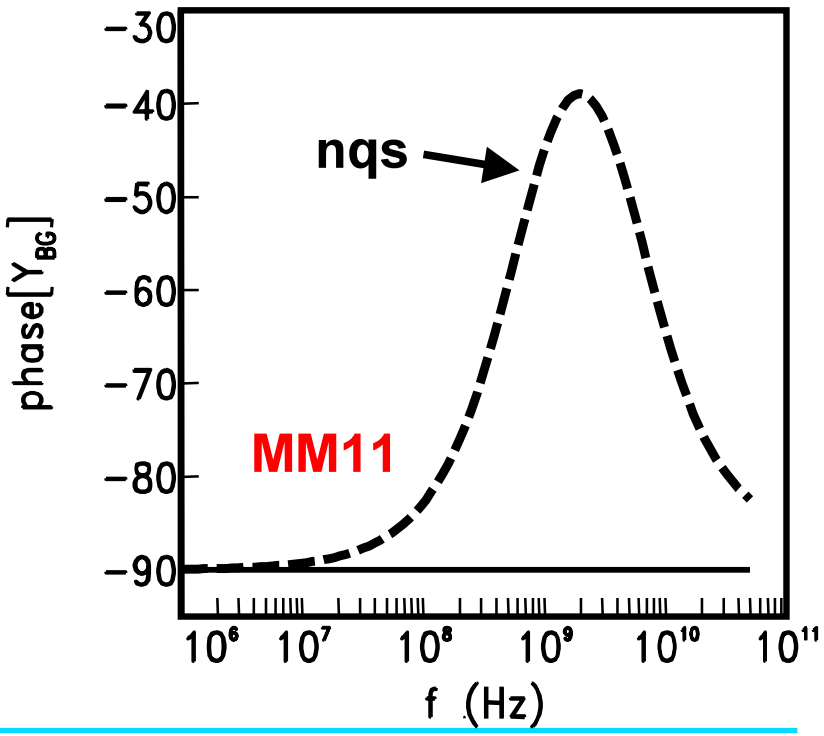


qs / nqs at high frequency: Y_{BG} vs. frequency







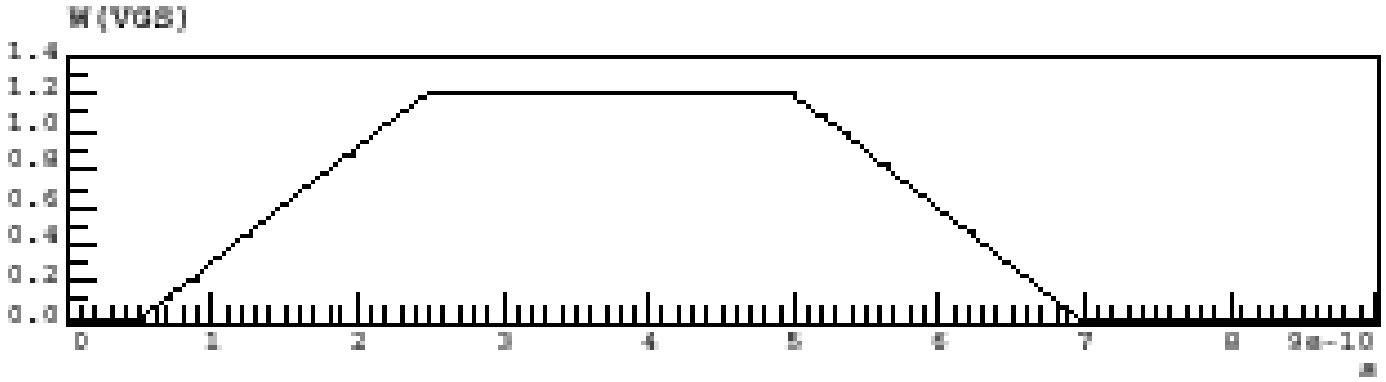


comparison QS / NQS at high frequency: summary

- **BSIM4**
  - **NQS effect on Y_{DG}, Y_{GG} and Y_{SG}**
  - **no NQS effect on Y_{BG}**
- **MOS Model 11**
  - **NQS effect on Y_{DG}, Y_{GG}, Y_{SG} and Y_{BG}**

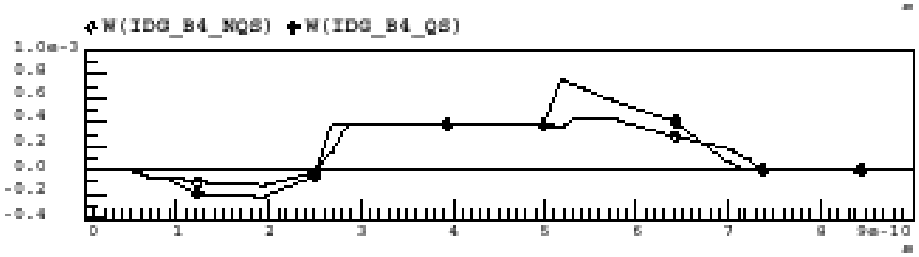
qs / nqs: fast voltage ramp in transient

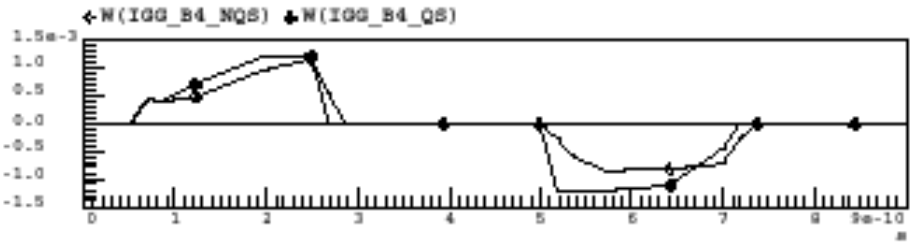
- excitation on the gate

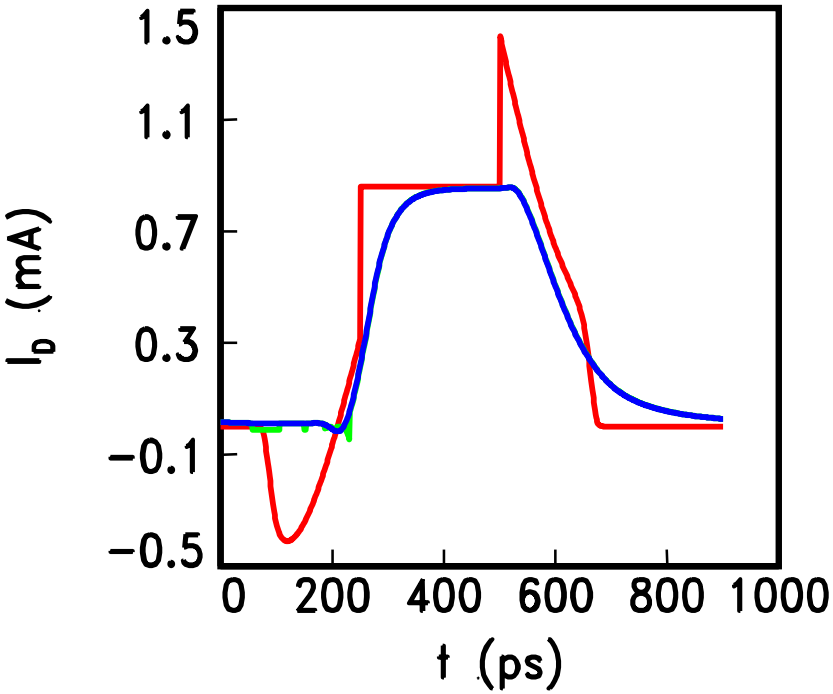


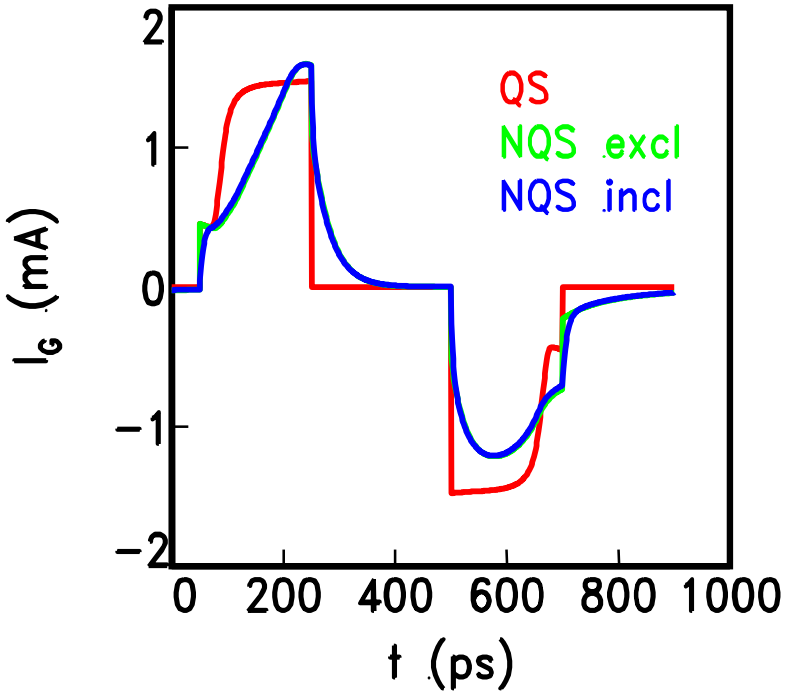
- expected results: smoother waveform in NQS mode
- MOS Model 11 simulations
  - NQS excl: without junction capacitances and bulk resistance
  - NQS incl: with junction capacitances and bulk resistance

qs / nqs: fast voltage ramp in transient

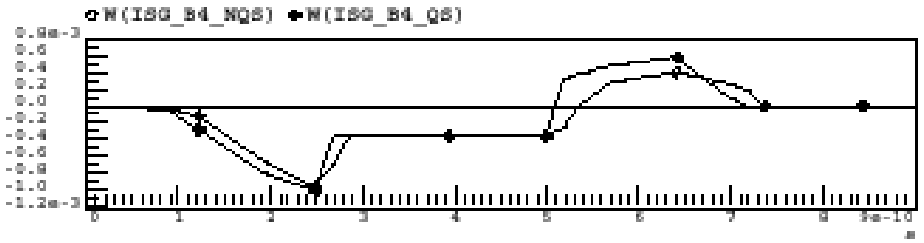


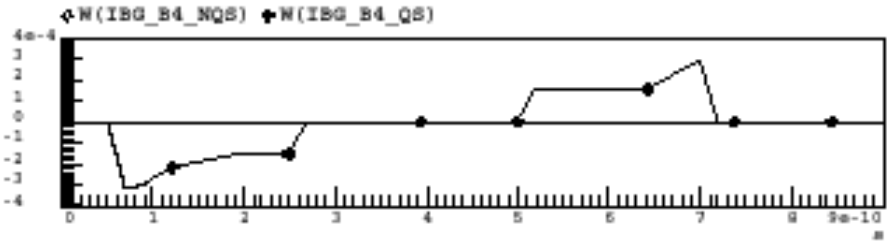


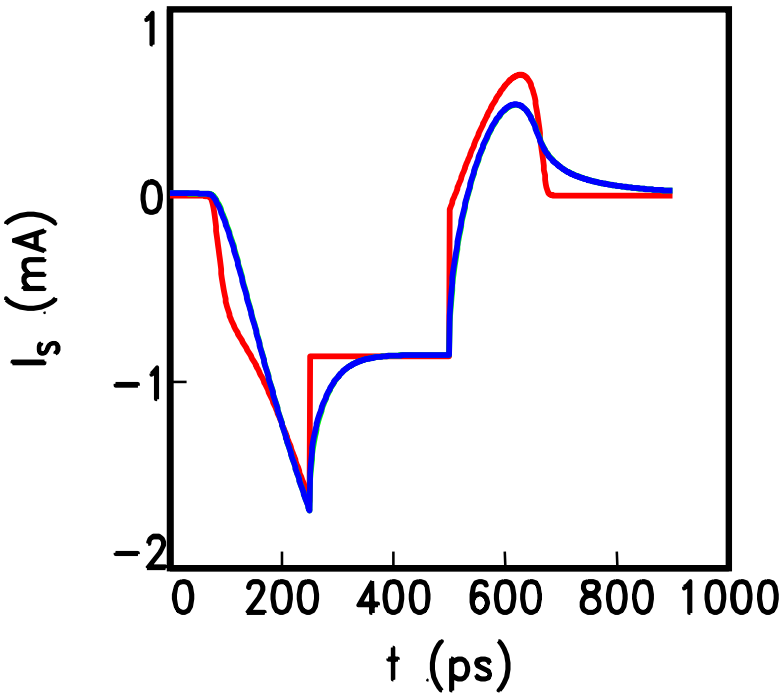


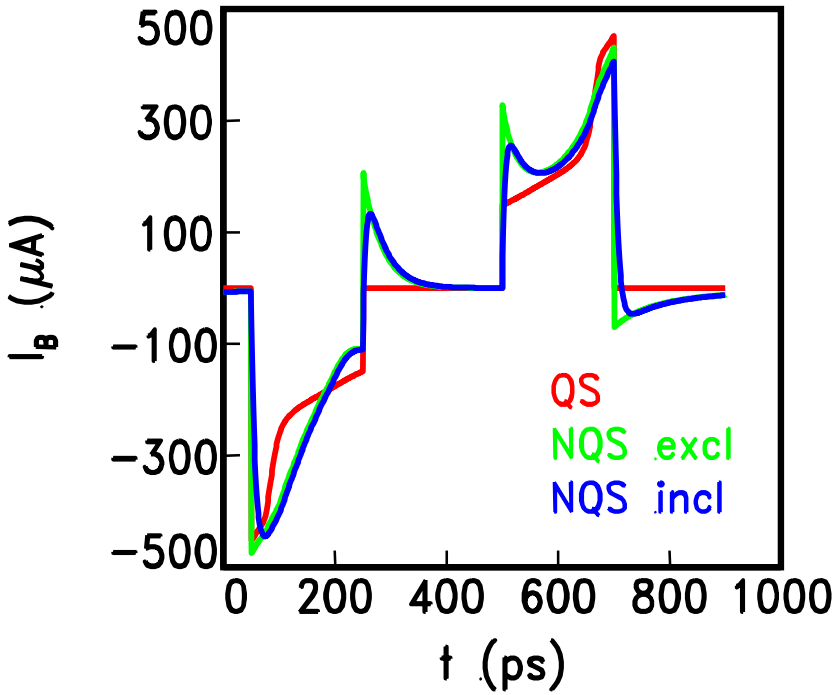


qs / nqs: fast voltage ramp in transient









summary

- reciprocity
  - BSIM4
    - $|C_{BS}|$ and C_{SB} differ factor 4
    - C_{BS} is negative
    - C_{BD} and C_{DB} differ factor 4
    - C_{DS} and C_{SD} differ factor 4
  - MOS Model 11
    - almost perfect reciprocity (better than 0.01 C_{ox})
- symmetry
  - BSIM4
    - C_{BS} is negative
    - C_{DD} and C_{SS} differ factor 4
  - MOS Model 11
    - perfect symmetry

summary (cont'd)

- comparison QS / NQS at low frequency
  - NQS $\neq$ QS for C_{DS}, C_{SD}, C_{SS} and C_{DD}
  - similar results for BSIM4 and MM11
- comparison QS / NQS at high frequency
  - BSIM4
    - NQS effect on Y_{DG}, Y_{GG} and Y_{SG}
    - no NQS effect on Y_{BG}
  - MOS Model 11
    - NQS effect on Y_{DG}, Y_{GG}, Y_{SG} and Y_{BG}