Introduction to and overview of Mextram

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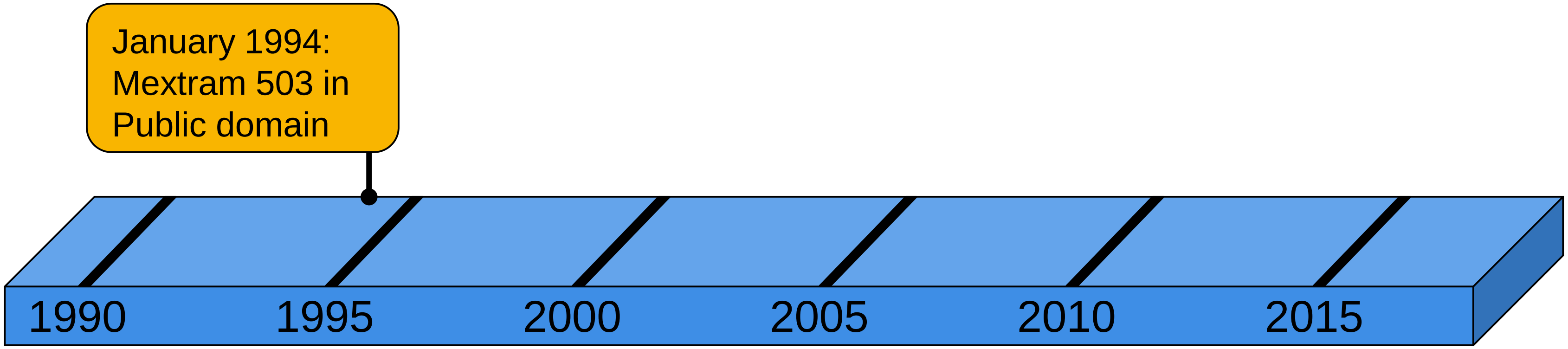
SECURE CONNECTIONS
FOR A SMARTER WORLD

Contents

- History Mextram
- Equivalent circuit Mextram
- Parameter extraction: procedure & results
- Overview Mextram documentation and Mextram related publications
- Summary

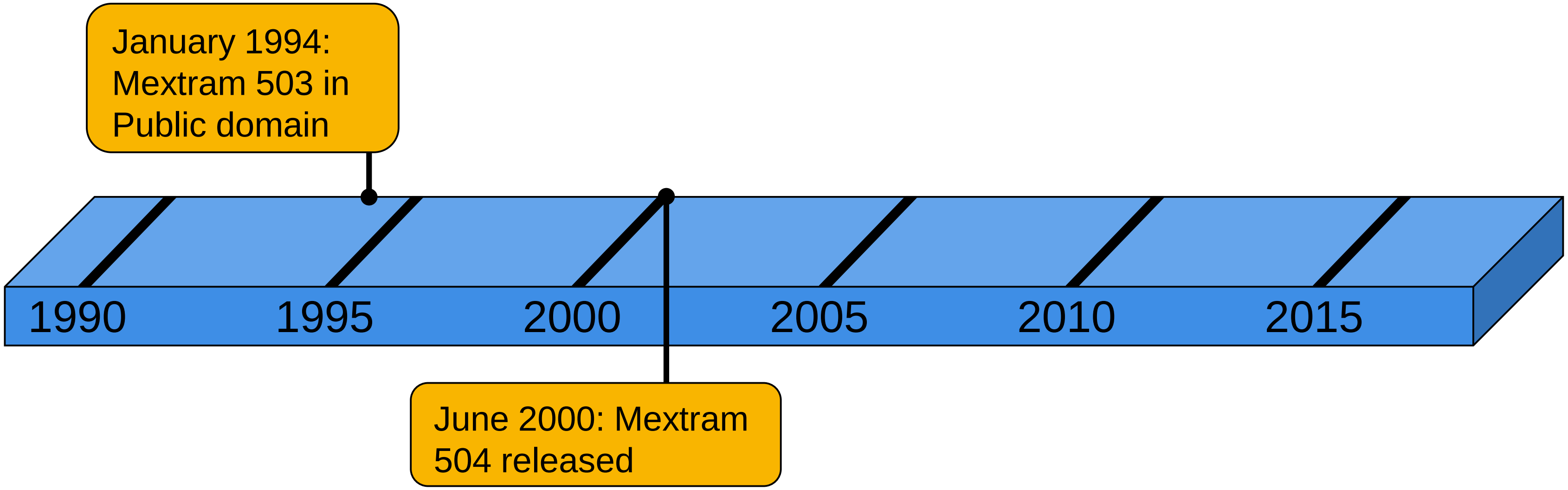
History Mextram (I)



January 1994: Mextram 503 in Public domain

- January 1994 – Release of Mextram level 503.1
- June 1995 – Release of Mextram level 503.2
  - Improved description of Early voltage
  - Improved description of cut-off frequency
  - Parameter compatible with level 503.1

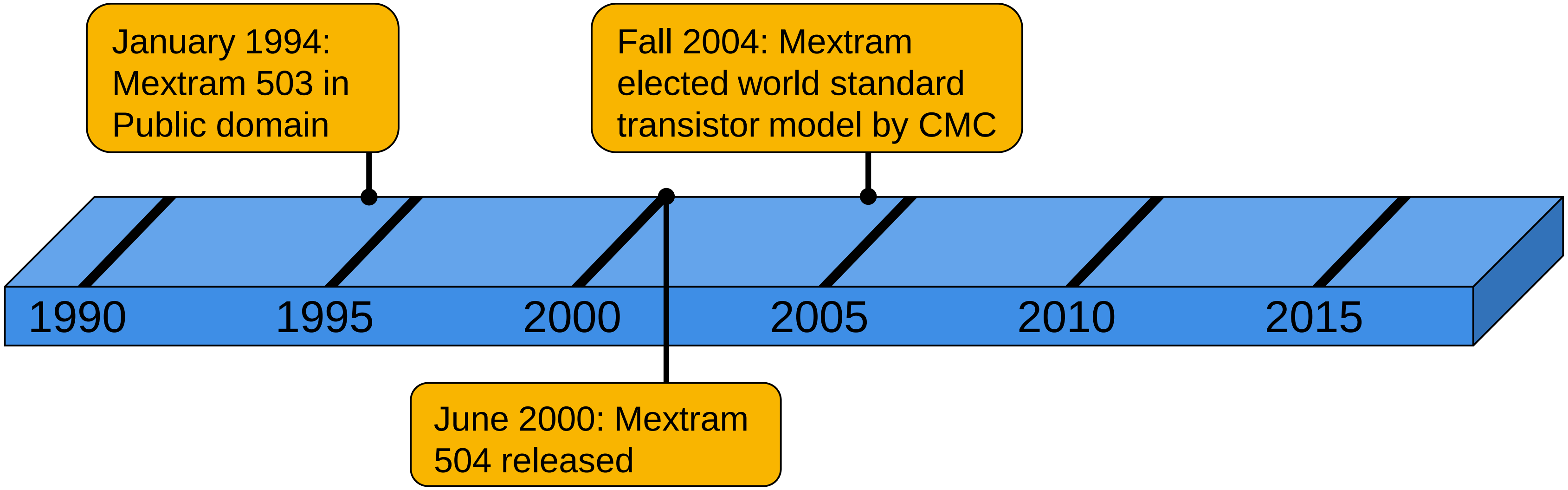
History Mextram (II)


January 1994: Mextram 503 in Public domain

June 2000: Mextram 504 released

- June 2000 - Release of Mextram level 504 (preliminary version)
  - Complete review of the model
- April 2001 - Release of Mextram level 504
  - Small fixes
    - Parameter R_{TH} and C_{TH} added to MULT-scaling
    - Expression for α in operating point information fixed
  - Changes w.r.t. June 2000 version:
    - Addition of overlap capacitances C_{BEO} and C_{BCO}
    - Change in temperature scaling of diffusion voltages
    - Change in neutral base recombination current
    - Addition of numerical examples with self-heating
- September 2001 - Mextram level 504.1
  - Lower bound on RTH is now 0^{O}C/W
  - Small changes in F_{ex} and Q_{B1B2} to enhance robustness

History Mextram (III)



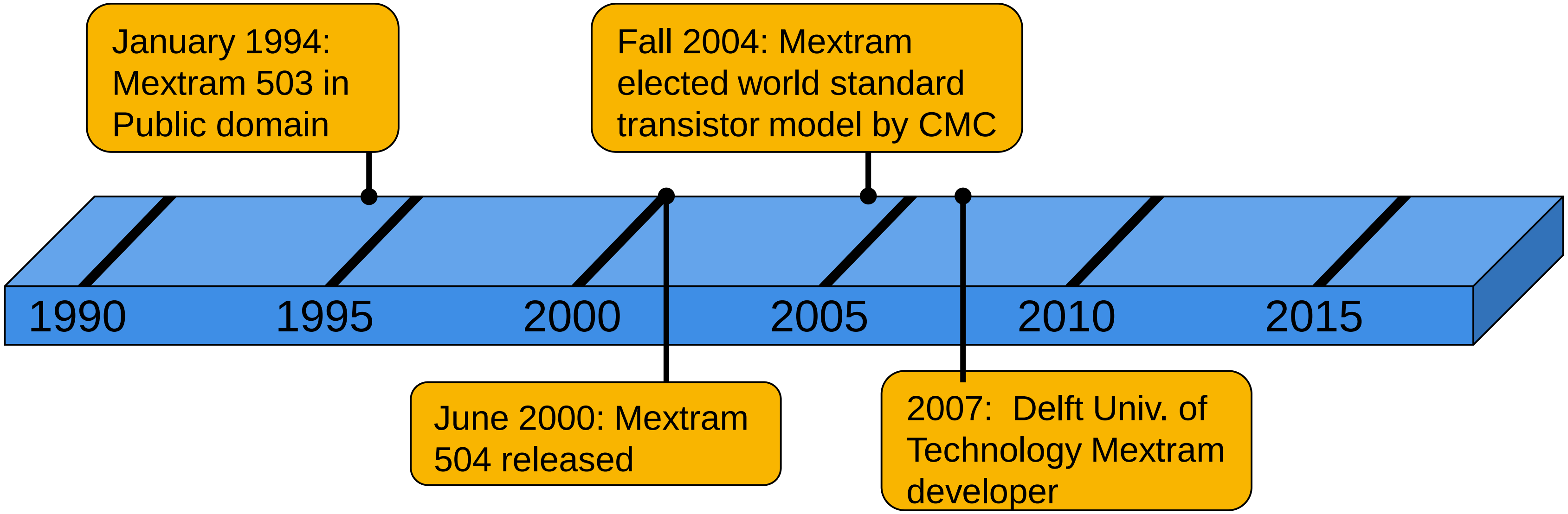
January 1994: Mextram 503 in Public domain

Fall 2004: Mextram elected world standard transistor model by CMC

June 2000: Mextram 504 released

- March 2002 - Changes in implementation for increased numerical stability
  - Numerical stability increased of x_i/W_{epi} at small V_{C1C2}
  - Numerical stability increased of p_0^*
- December 2002 - Minor changes in documentation not in model
- October 2003 - Release of Mextram 504.3
  - MULT moved in list of parameters
  - Lower clipping value T_{ref} changed to $-273^{O}C$
  - Added I_C, I_B, β_{DC} to operating point information
- April 2004 - Release of Mextram 504.4
  - Noise of collector epilayer has been removed

History Mextram (IV)



January 1994: Mextram 503 in Public domain

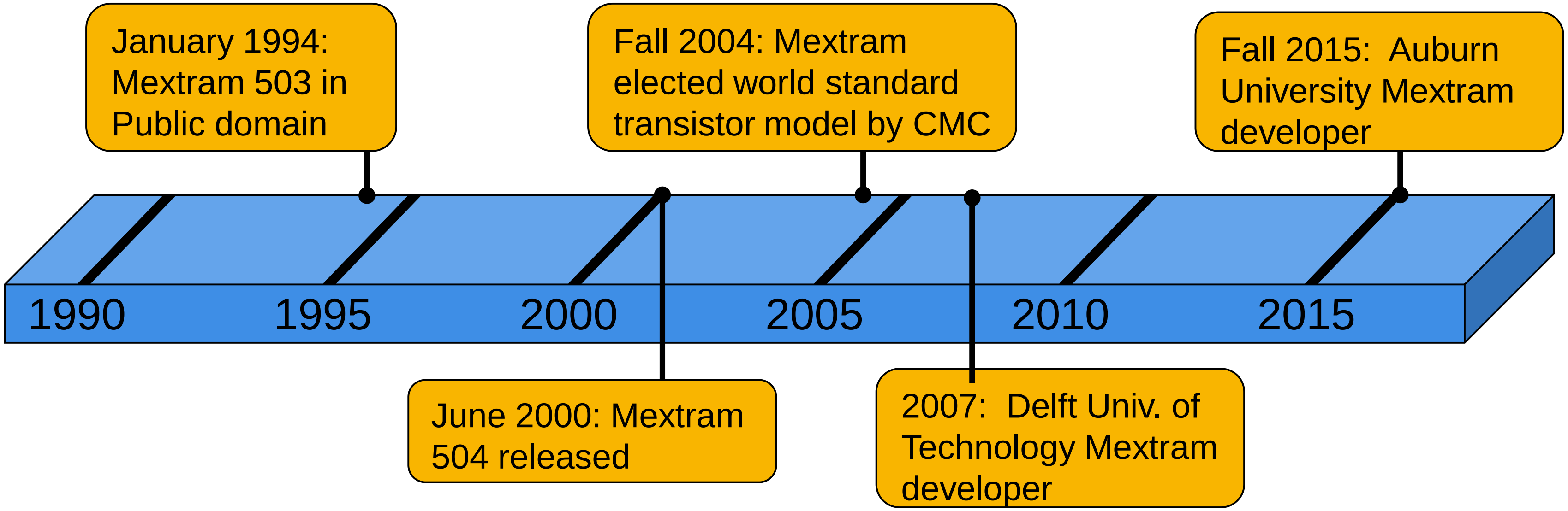
Fall 2004: Mextram elected world standard transistor model by CMC

June 2000: Mextram 504 released

2007: Delft Univ. of Technology Mextram developer

- March 2005 - Release of Mextram 504.6
  - Added parameter DAIS for fine tuning temp. dep. of IST
  - G_{EM}=0 added to weak avalanche
  - Upper clipping value 1.0 of KAVL introduced
- March 2008 - Release of Mextram 504.7
  - Added resistances of buried layer RCBLX and RCBLI, and their temperature scaling ACBL
  - Lower clipping value of resistances RE,RBC,RBV,RCC,RCV,SCRCV increased to 1mΩ
  - Bux fix high temperature limit BnT
- June 2009 - Release Mextram 504.8
  - Zener tunneling current in emitter-base junction

History Mextram (V)



January 1994: Mextram 503 in Public domain

Fall 2004: Mextram elected world standard transistor model by CMC

Fall 2015: Auburn University Mextram developer

June 2000: Mextram 504 released

2007: Delft Univ. of Technology Mextram developer

- Q2 2010 - Release of Mextram 504.9
  - Added lower clip value to parameter TVGEB
  - Added operating point information V_{BE},V_{BC},V_{CE},V_{SE},V_{BS},V_{SC},I_E,I_S
  - Added parameters collector-substrate model ICSS, ASUB
  - Physics-based temperature scaling ideal collector-substrate current
- Q1 2011 - Release of Mextram 504.10
  - Parameter EXSUB in parasitic BCS transistor model
  - Revised documentation of GMIN
- Q1 2012 - Release of Mextram 504.10.1
  - Bug fix in OP-info f_T
  - Bug fix equilibrium state parasitic BCS transistor
- Q4 2012 - Release of Mextram 504.11.0
  - Added operating point information of Iqs
  - Extended range of EXMOD

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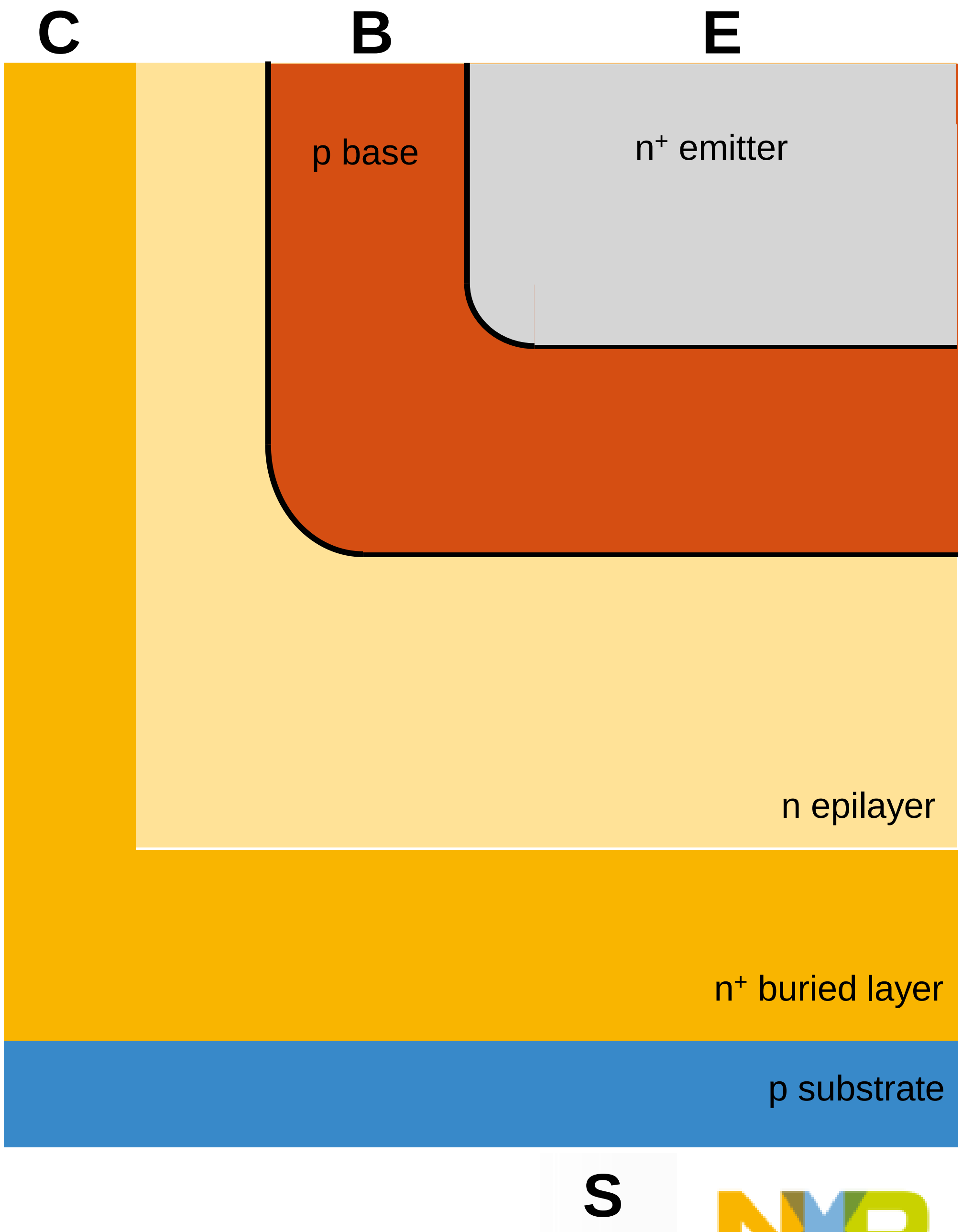
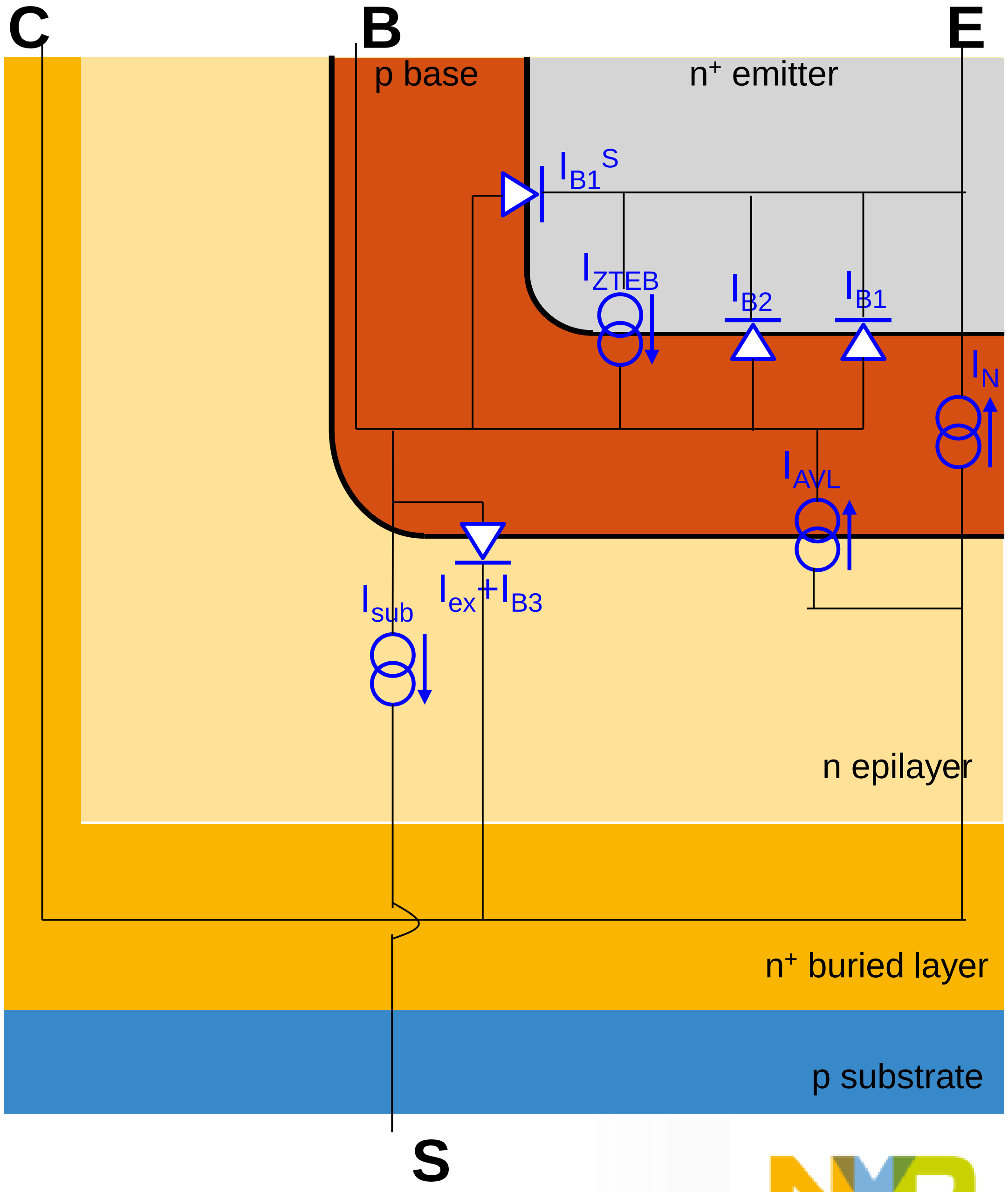
Device cross section

- Device cross section used in Mextram
    - not on scale



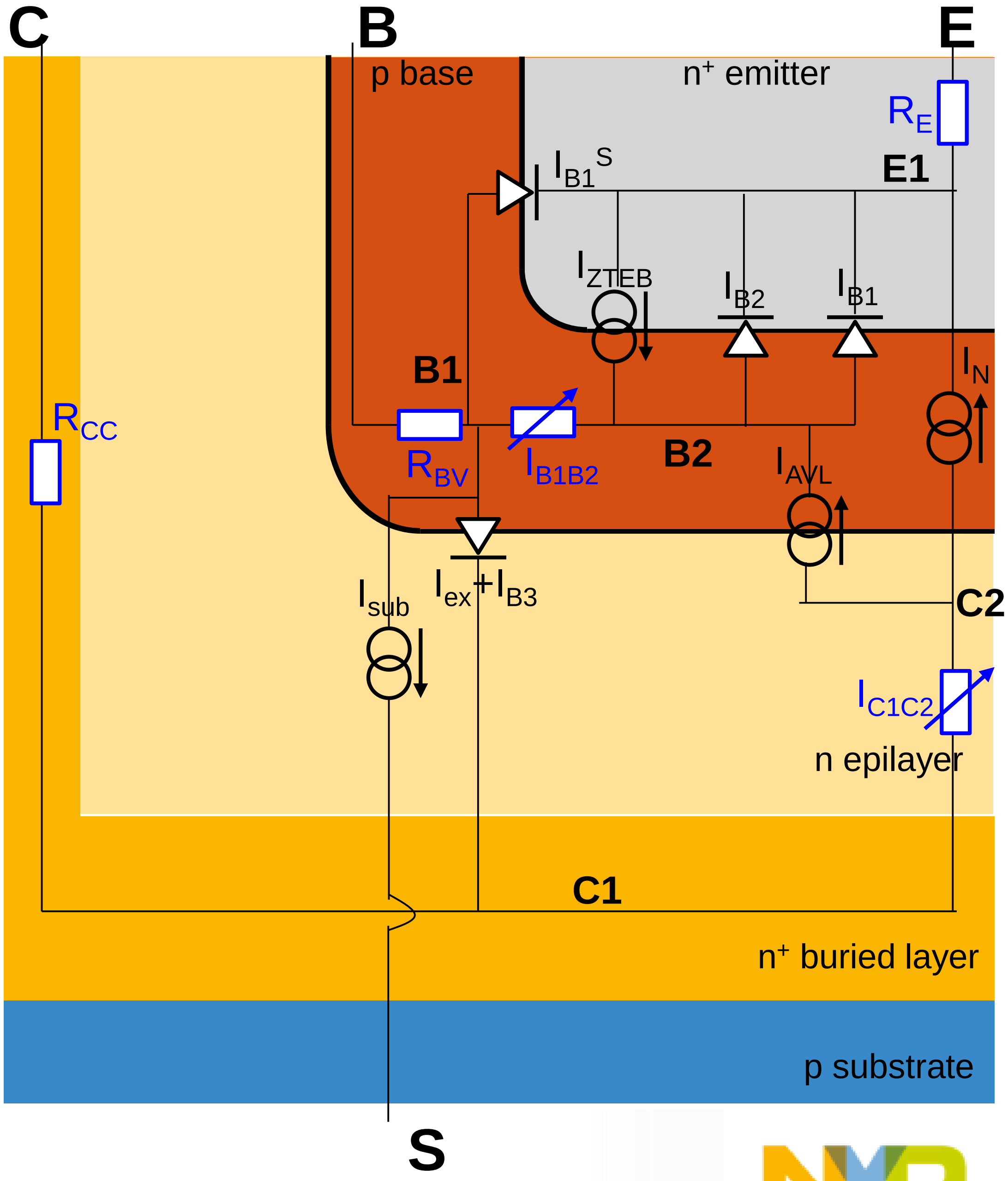
Equivalent circuit (I)

- Current sources
  - Main current source I_N based on Gummel's charge control relation
  - Base current
    - Forward mode
      - Ideal base current I_{B1}
      - Ideal base current side-wall I_{B1}^S
      - Non-ideal base current I_{B2}
    - Reverse mode (extrinsic transistor)
      - Ideal base current I_{ex}
      - Non-ideal base current I_{B3}
  - Weak avalanche current I_{AVL}
  - Zener tunneling base-emitter junction I_{ZTEB}
  - Parasitic base-collector-substrate transistor I_{sub}



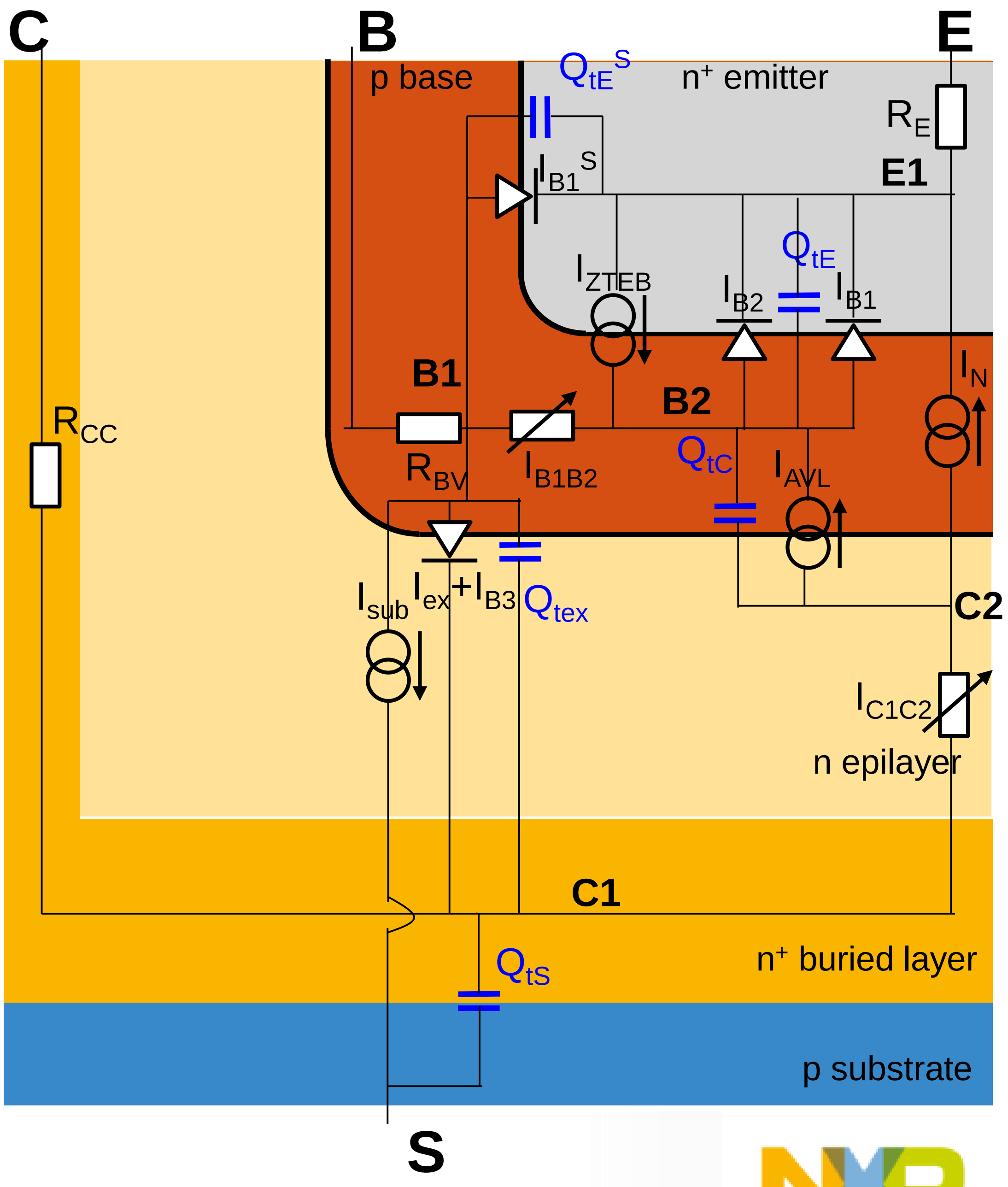
Equivalent circuit (II)

- Resistances
  - Emitter resistance
    - Constant emitter resistance R_E
  - Base resistance
    - Constant base resistance R_{BV}
    - Variable base resistor I_{B1B2} → current crowding underneath the emitter
  - Collector
    - Constant collector resistance R_{CC}
    - Epi-layer model I_{C1C2}



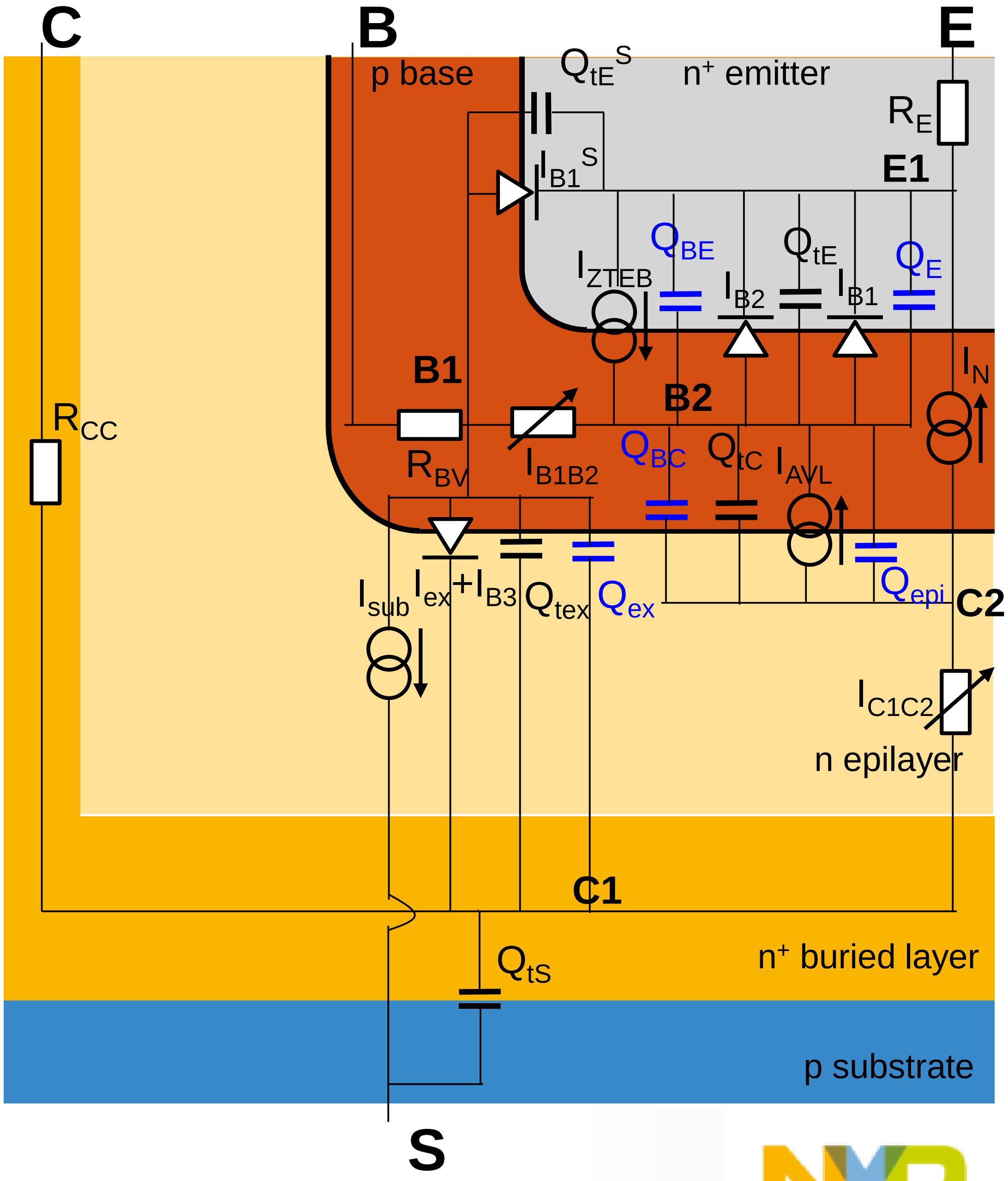
Equivalent circuit (III)

- Depletion charges and capacitances
  - Depletion charge base-emitter pn-junction intrinsic transistor Q_{tE}
  - Depletion charge base-emitter pn-junction sidewall Q_{tE}^{S}
  - Depletion charge base-collector pn-junction intrinsic transistor Q_{tC}
  - Depletion charge base-collector pn-junction extrinsic transistor Q_{tex}
  - Depletion charge collector-substrate pn-junction Q_{tS}



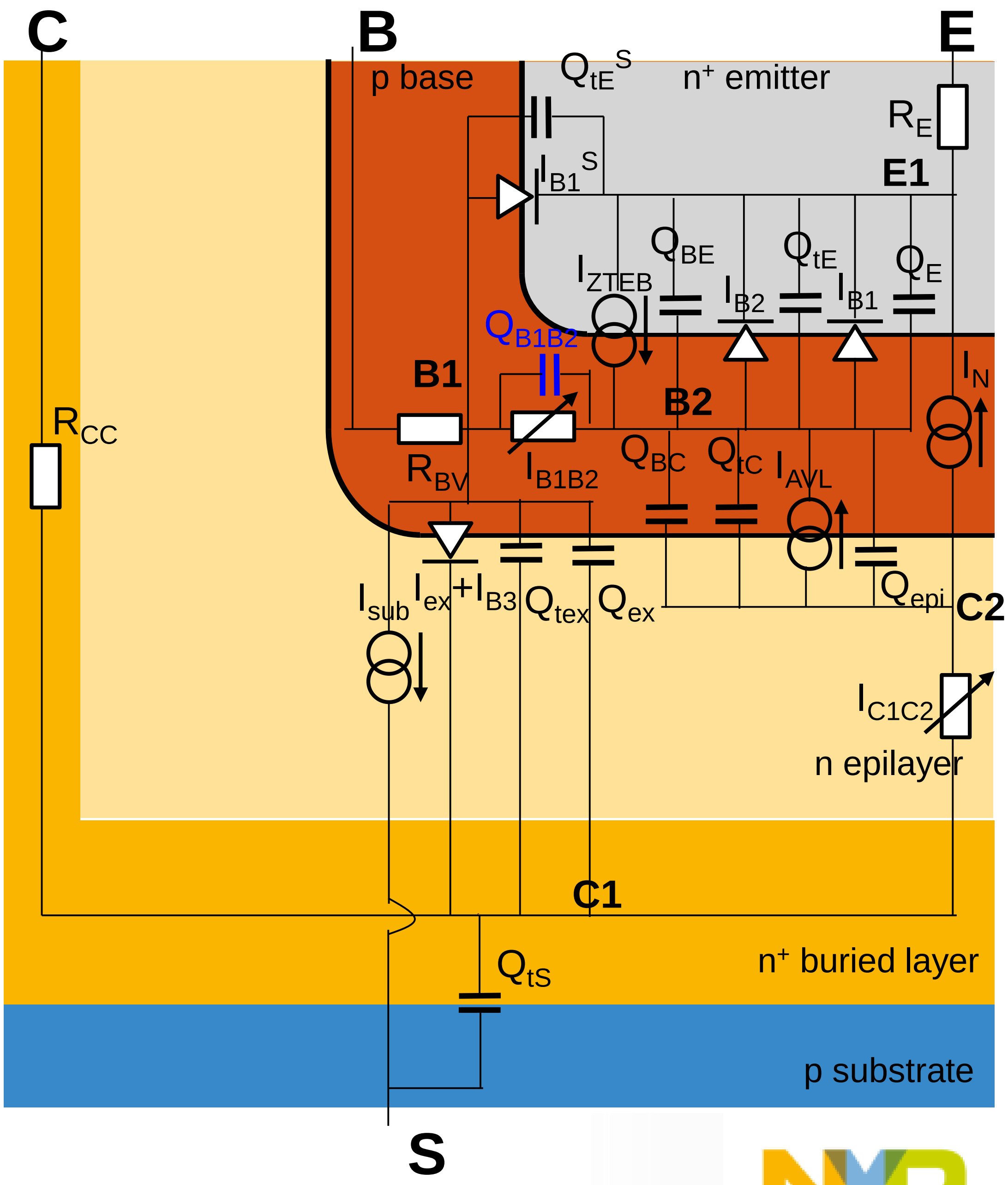
Equivalent circuit (IV)

- Diffusion charges and capacitances
  - Diffusion charges related to built-up of charge in the base due to the main current
    - Forward operation Q_{BE}
    - Reverse operation Q_{BC}
  - Charge built-up of holes in the emitter Q_E
  - Charge built-up in the epilayer Q_{epi}
  - Charge built-up in the epilayer extrinsic transistor Q_{ex}



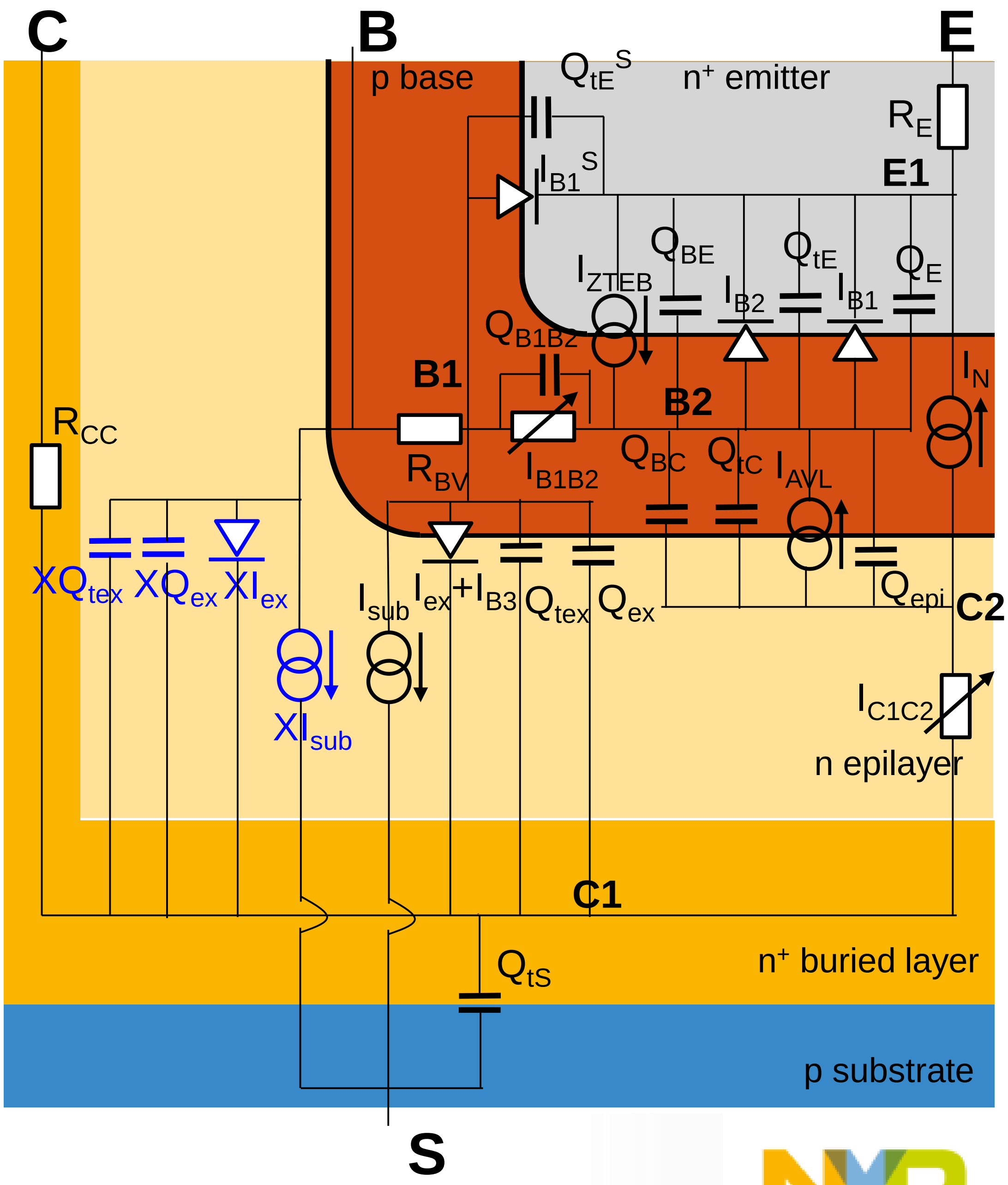
Equivalent circuit (V)

- Modelling of high frequency effects in the base:
  base charge partitioning Q_{B1B2}
  - Effect in the vertical direction
  - Part of the base-emitter charge Q_{BE} is assigned to the base collector junction (Q_{BC})
  - Result of this effect is an extra phase shift in the transconductance
  - Parameter Excess phase change **EXPHI**
    - **EXPHI**=1 ON
    - **EXPHI**=0 OFF



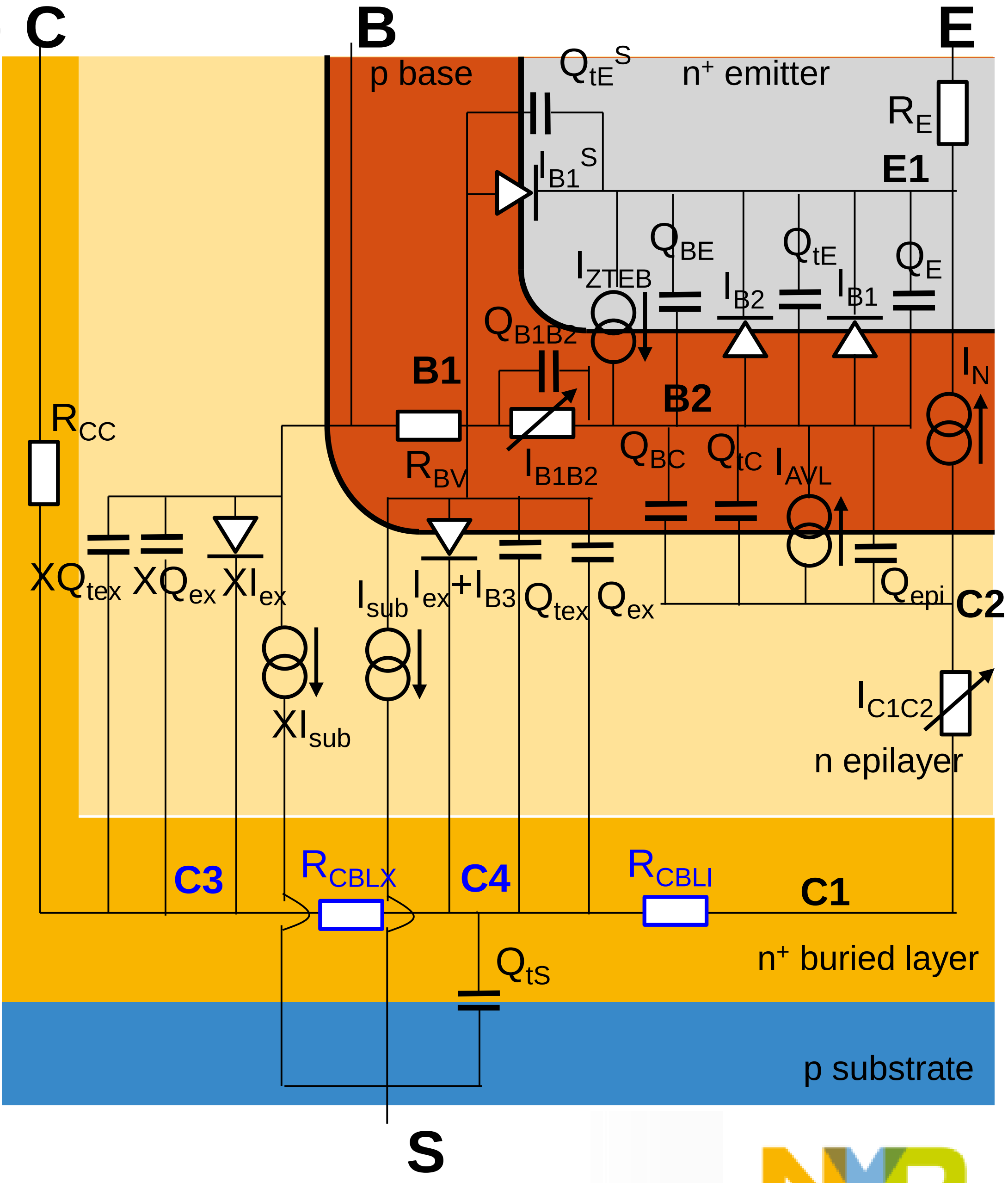
Equivalent circuit (VI)

- Modelling of external region
  - Ideal reverse base current XI_{ex}
  - Parasitic base-collector-substrate transistor XI_{sub}
  - Depletion charge base-collector pn-junction Q_{tex}
  - Diffusion charge base-collector pn-junction Q_{ex}
- Switch for external region
  - ON **EXMOD**=1
  - OFF **EXMOD**=0
- Partitioning <u>extrinsic transistor</u> and <u>external region</u> with parameter **XEXT**
  - Extrinsic transistor ~(1-**XEXT**)
  - External region ~**XEXT**



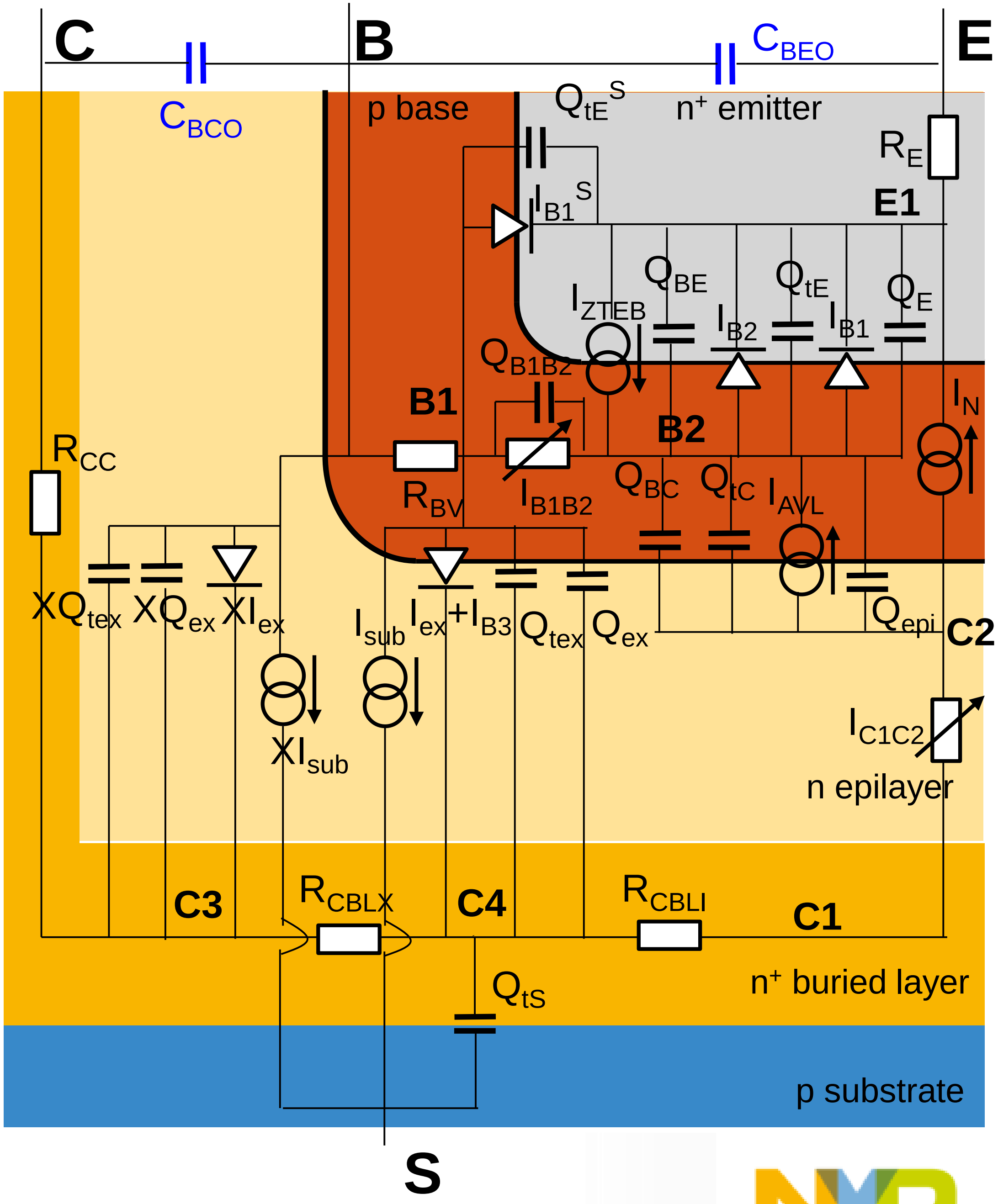
Equivalent circuit (VII)

- Buried layer resistances
  - Extrinsic part RCBLX
  - Intrinsic part RCBLI
- Implementation based on flexible topology
  - Resistances are included in equivalent circuit for parameter values of parameters RCBLX and RCBLI larger than 0
  - 4 different equivalent circuits possible



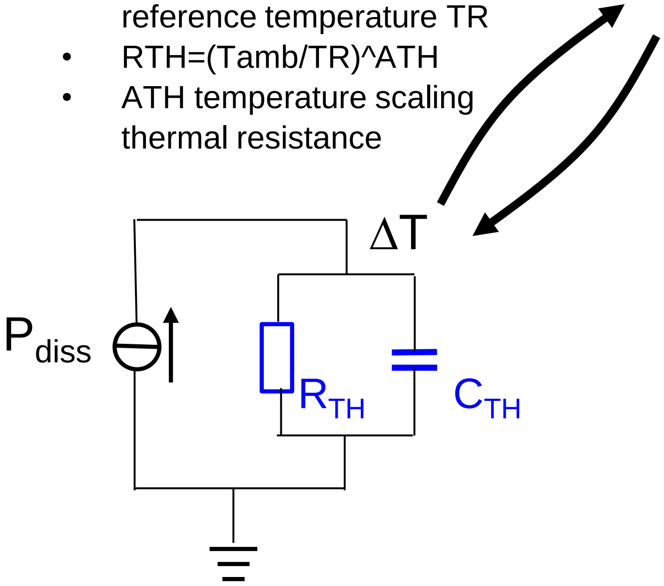
Equivalent circuit (VIII)

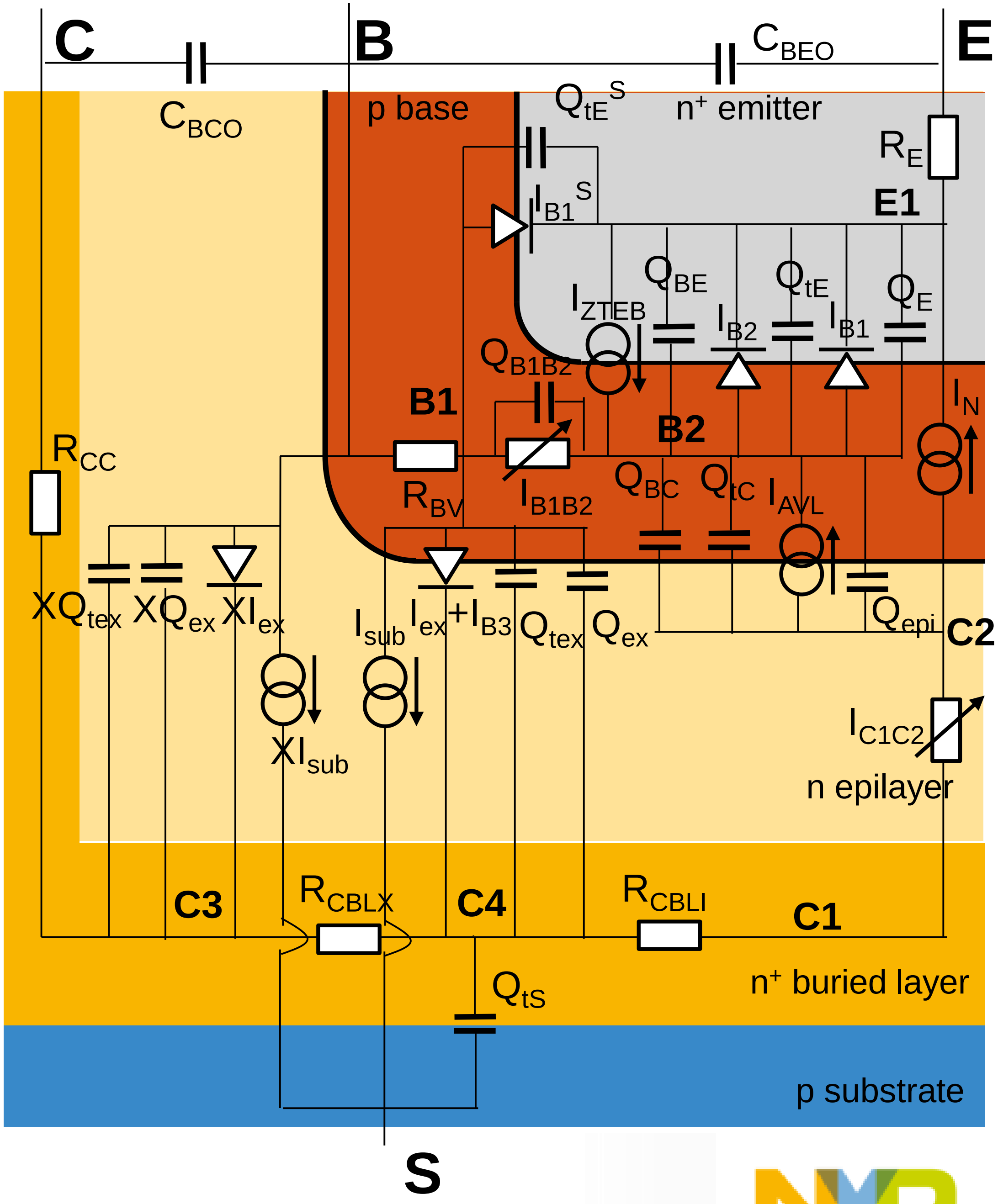
- Overlap capacitances (constant)
    - Base-emitter overlap capacitance CBEO
    - Base-collector overlap capacitance CBCO



Equivalent circuit (IX)

- Self-heating
  - First order thermal-network
    - Thermal resistance RTH
    - Thermal capacitance CTH
  - Geometry scaling MULT
    - RTH ~ 1/MULT
    - CTH ~ MULT
  - Temperature scaling
    - RTH scales with ambient temperature Tamb w.r.t. reference temperature TR
    - RTH=(Tamb/TR)^ATH
    - ATH temperature scaling thermal resistance





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Parameter extraction process (I)

- Overview of parameter extraction process in Mextram
  - Mextram has around 90 model parameters (flags and switches included)

- Demonstration of how the most important parameters are extracted
  - Parameters are often extracted in groups on specific measurement data
  - Typical results are shown

Parameter extraction process (II)

- Parameter extraction in Mextram
  - Extensive documentation how to extract parameters
  - Many possibilities to adapt parameter extraction procedure to own needs and requirements

- Order followed in this presentation
  - Base-emitter depletion capacitance
  - Base-collector depletion capacitance
  - Gummel characteristics
  - Output characteristics
  - Base current
  - Avalanche current
  - Zener Tunneling
  - Series resistances
  - Figures of merit f_T etc.

Parameter extraction :

Base emitter depletion capacitance

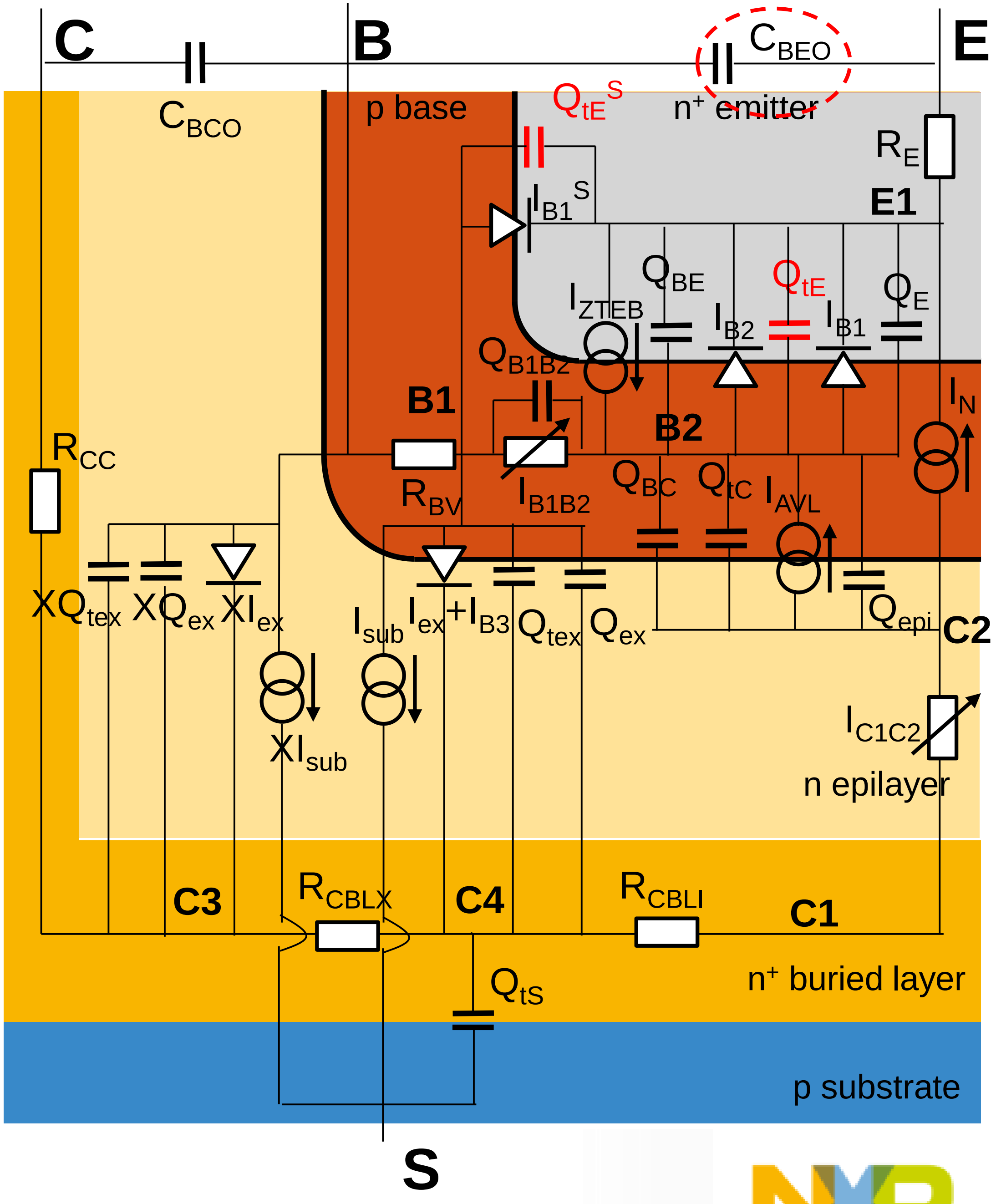
- In case the base-emitter voltage is not too far in forward the total base-emitter capacitance can be approximated by the depletion and overlap capacitance

$$C_{BE} = \frac{\boldsymbol{CJE}}{(1 - V_{BE}/\boldsymbol{VDE})^{\boldsymbol{PE}}} + \boldsymbol{CBEO}$$

Parameters:

- $\boldsymbol{CJE}$ **:** depletion capacitance
- $\boldsymbol{VDE}$ **:** built-in voltage
- $\boldsymbol{PE}$ **:** grading coefficient
- $\boldsymbol{CBEO}$ **:** overlap capacitance

- Two contributions in Mextram
  - Intrinsic component Q_{tE}
    - Proportional to parameter **XCJE**
  - Side wall component Q_{tE}^{S}
    - Proportional to parameter 1-**XCJE**
- Clipping depletion capacitance when $V_{BE} \approx \boldsymbol{VDE}$ included in Mextram (see next slide)



Base emitter depletion capacitance – implementation

- Text book formula for depletion capacitance/charge

$$C_{BE}^{dep} = \frac{\boldsymbol{CJE}}{(1-V_{BE}/\boldsymbol{VDE})^{\boldsymbol{PE}}}, \qquad Q_{BE}^{dep} = \frac{\mathbf{CJE}\cdot\mathbf{VDE}}{1-\mathbf{PE}}\cdot\left[1-\left(1-\frac{V_{je}}{\mathbf{VDE}}\right)^{1-\mathbf{PE}}\right]$$

  - Smoothing needed for $V_{BE} \approx \boldsymbol{VDE}$
  - Note that clipping is used, since for $V_{BE} > \boldsymbol{VDE}$ the diffusion charge dominates

- Implemented base-emitter depletion charge

Clipping voltage

$$\boxed{V_{fe} = \mathbf{VDE}\left(1 - aje^{-1/\mathbf{PE}}\right)}$$

Clipping equation

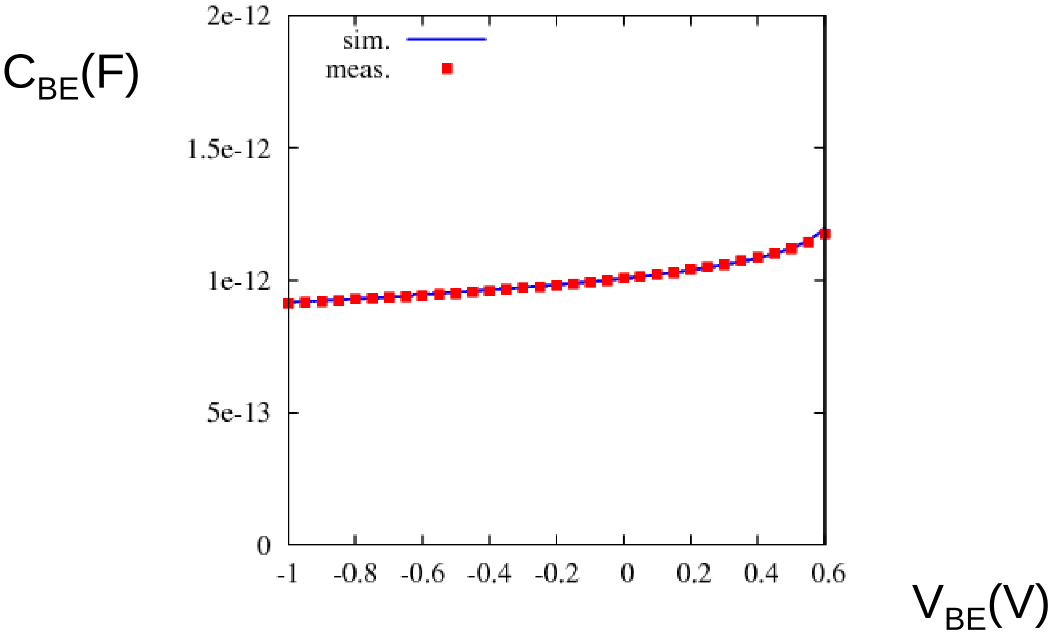
$$\boxed{V_{je} = \begin{cases} V_{BE} - 0.1\cdot\mathbf{VDE}\cdot ln\left(1 + exp\left(\dfrac{V_{BE}-V_{fe}}{0.1\cdot\mathbf{VDE}}\right)\right) & : V_{BE} < V_{fe} \\ V_{fe} - 0.1\cdot\mathbf{VDE}\cdot ln\left(1 + exp\left(\dfrac{V_{fe}-V_{BE}}{0.1\cdot\mathbf{VDE}}\right)\right) & : V_{BE} > V_{fe} \end{cases}}$$

Depletion charge

$$\boxed{\begin{gathered} Q_{BE} = \frac{\mathbf{CJE}\cdot\mathbf{VDE}}{1-\mathbf{PE}}\cdot\left[1-\left(1-\frac{V_{je}}{\mathbf{VDE}}\right)^{1-\mathbf{PE}}\right] + \mathbf{CJE}\cdot aje\cdot\left(V_{BE}-V_{je}\right) \\ Q_{BE} = \mathbf{CJE}\cdot\boldsymbol{V_{te}} \end{gathered}}$$

$\boldsymbol{V_{tE}}$ reused in calculation of reverse Early effect

Base emitter depletion capacitance – Extraction result



V_{BC}=0V
f=2GHz

- Base-emitter capacitance obtained from y-parameter measurements
- Extracted parameters
  - $\boldsymbol{CJE}$ depletion capacitance
  - $\boldsymbol{VDE}$ built-in voltage
  - $\boldsymbol{PE}$ grading coefficient
  - $\boldsymbol{CBEO}$ overlap capacitance
  - $\boldsymbol{1-XCJE}$ part of depletion capacitance attributed to side wall (multiple geometries needed with variation in emitter area)
- Parameter optimization for V_{BE}=-1..0.5V

Parameter extraction :

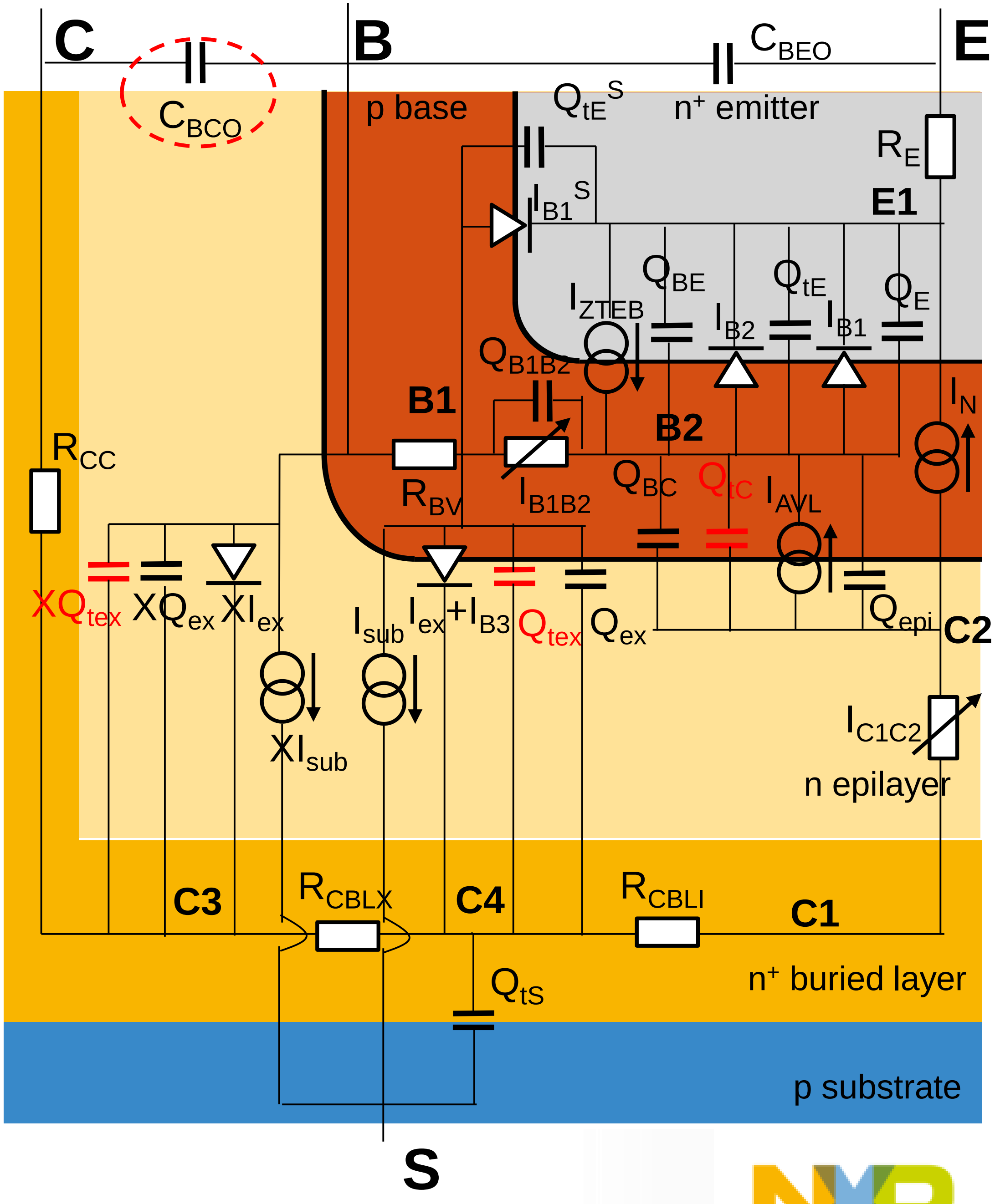
Base collector depletion capacitance

- In case the base-collector voltage is not too far in forward the total base-collector capacitance can be approximated by the depletion and overlap capacitance

$$C_{BC} = \frac{(1-\boldsymbol{XP})\cdot\boldsymbol{CJC}}{(1-V_{BC}/\boldsymbol{VDC})^{\boldsymbol{PE}}} + \boldsymbol{XP}\cdot\boldsymbol{CJC} + \boldsymbol{CBCO}$$

  Parameters:
  - $\boldsymbol{CJC}$ **:** depletion capacitance
  - $\boldsymbol{VDC}$ **:** built-in voltage
  - $\boldsymbol{PC}$ **:** grading coefficient
  - $\boldsymbol{CBCO}$ **:** overlap capacitance
  - **XP** : fraction of depletion capacitance which is constant, *i.e*, runs into buried layer

- Three contributions in Mextram
  - Intrinsic component Q_{tC}
    - Proportional to parameter **XCJC**
  - Extrinsic components Q_{tex}+XQ_{tex}
    - Proportional to parameter 1-**XCJC**
      - Q_{tex} proportional to 1-**XEXT**
      - XQ_{tex} proportional to **XEXT**



Base collector depletion capacitance – implementation

- Similar clipping methodology followed as for base-emitter depletion capacitance
- Text book formula for depletion capacitance/charge

$$C_{BC}^{dep} = \frac{\boldsymbol{CJC}}{(1-V_{BC}/\boldsymbol{VDC})^{\boldsymbol{PC}}} \qquad Q_{BC}^{dep} = \frac{\mathbf{CJC}\cdot\mathbf{VDC}}{1-\mathbf{PC}}\cdot\left[1-\left(1-\frac{V_{jc}}{\mathbf{VDC}}\right)^{1-\mathbf{PC}}\right]$$

  - Smoothing needed for $V_{BC} \approx \boldsymbol{VDC}$
  - Note that clipping is used, since for $V_{BC} > \boldsymbol{VDC}$ the diffusion charge dominates

- Implemented base-emitter depletion charge

Clipping voltage

$$\boxed{V_{fc} = \mathbf{VDC}\left(1-ajc^{-1/\mathbf{PC}}\right)}$$

Clipping equation

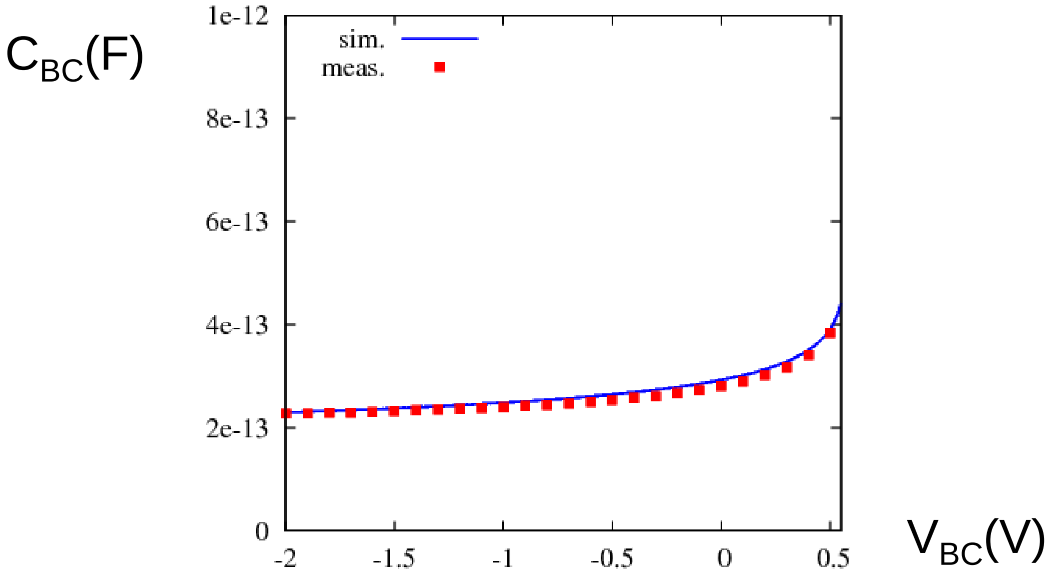
$$\boxed{V_{jc} = \begin{cases} V_{BC} - 0.1\cdot\mathbf{VDC}\cdot ln\left(1+exp\left(\dfrac{V_{BC}-V_{fc}}{0.1\cdot\mathbf{VDC}}\right)\right) & : V_{BC} < V_{fc} \\ V_{fc} - 0.1\cdot\mathbf{VDC}\cdot ln\left(1+exp\left(\dfrac{V_{fc}-V_{BC}}{0.1\cdot\mathbf{VDC}}\right)\right) & : V_{BC} > V_{fc} \end{cases}}$$

Depletion charge

$$\boxed{\begin{gathered} Q_{BC} = \frac{(\mathbf{1-XP})\cdot\mathbf{CJC}\cdot\mathbf{VDC}}{\mathbf{1-PC}}\cdot\left[1-\left(1-\frac{V_{jc}}{\mathbf{VDC}}\right)^{\mathbf{1-PC}}\right]+ \\ (\mathbf{1-XP})\cdot\mathbf{CJC}\cdot aje\cdot\left(V_{BC}-V_{jc}\right)+\mathbf{XP}\cdot\mathbf{CJC} \\ Q_{BC} = \mathbf{CJC}\cdot\boldsymbol{V_{tc}} \end{gathered}}$$

V_{tC} reused in calculation of forward Early effect

Base emitter depletion capacitance – Extraction result



V_{BE}=0V
f=2GHz

- Base-collector capacitance obtained from y-parameter measurements
- Extracted parameters
  - **CJC** depletion capacitance
  - **VDC** built-in voltage
  - **PC** grading coefficient
  - **CBCO** overlap capacitance
  - **XP** part of depletion capacitance which is constant, *i.e*, runs into buried layer
  - $\mathbf{1-XCJC}$ part of depletion capacitance attributed to extrinsic transistor
  - **XEXT** part of depletion capacitance of extrinsic transistor not underneath the base
- Parameter optimization for V_{BC}=-2..0.5V

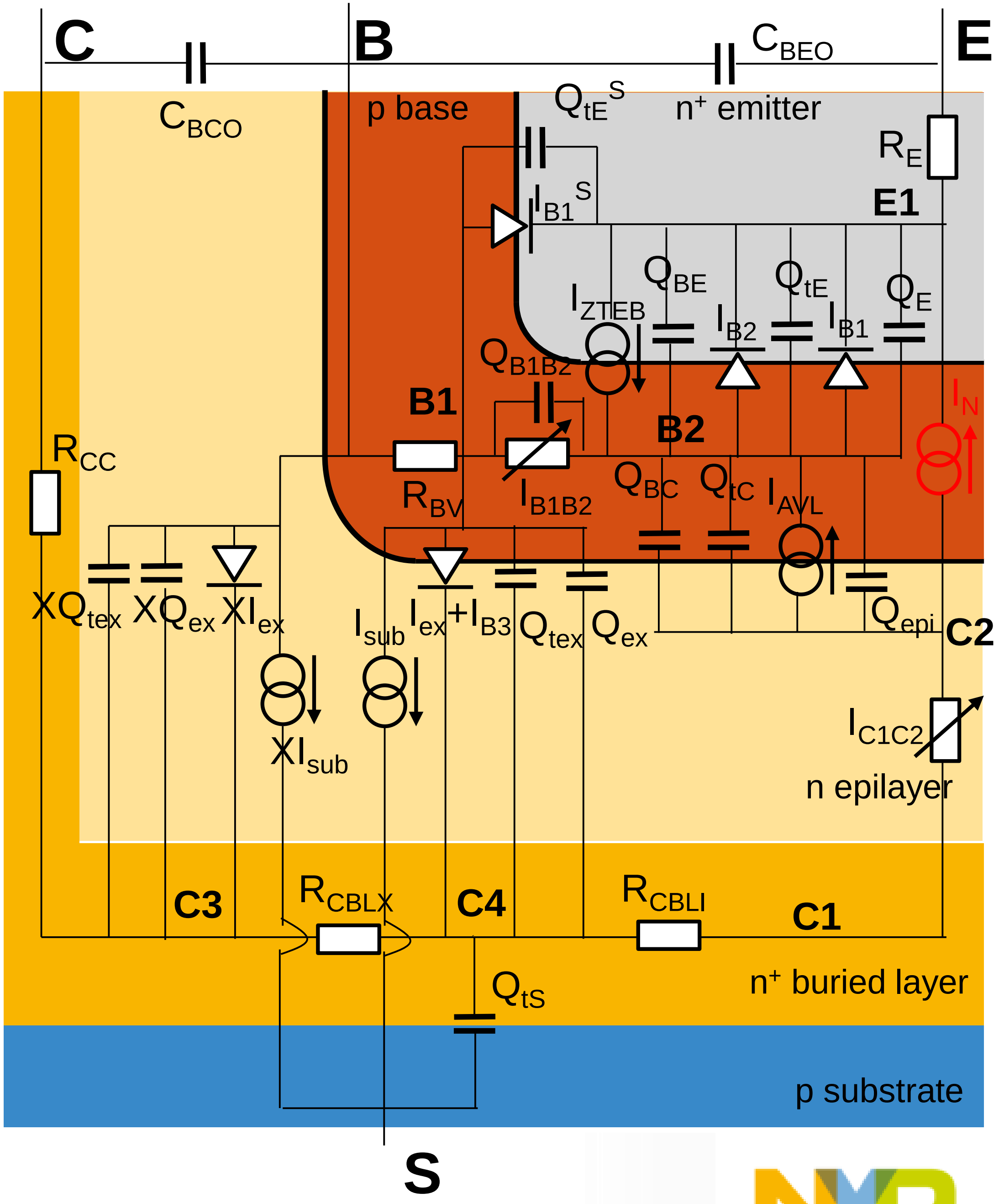
Parameter extraction :

- Main current / Transfer current
- Extracted parameters
  - **IS** : saturation current intrinsic transistor
  - **MULT** : # devices in parallel
- Approximation collector current for small base-emitter voltages, *i,e.*, 0.4 V<V_{BE}<0.65 V,

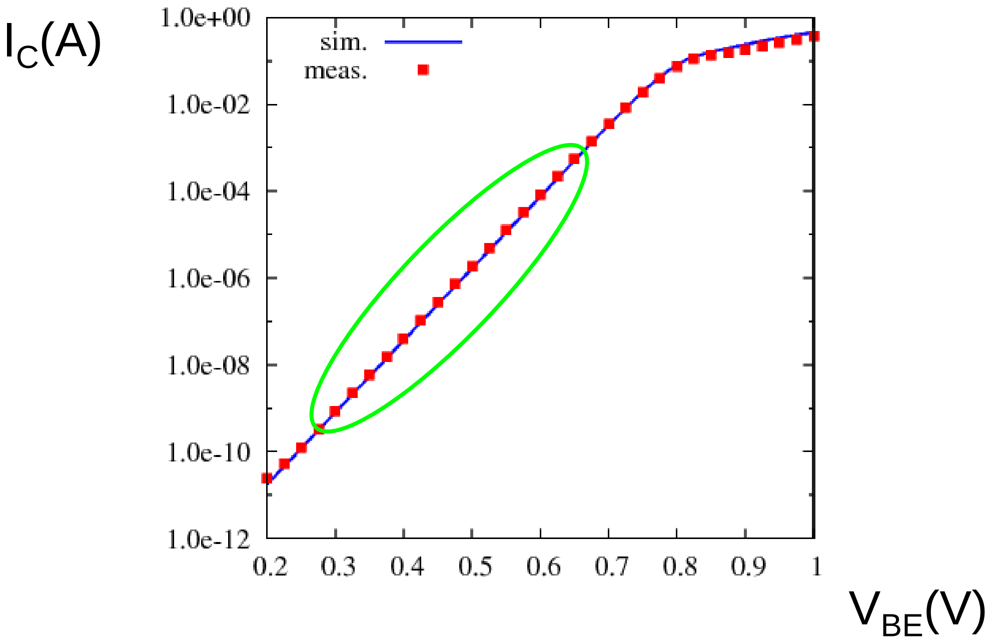
$$I_C \approx \mathbf{MULT}\cdot\mathbf{IS}\cdot\left(\frac{e^{V_{BE}/V_T}}{1+\frac{V_{tE}}{\mathbf{VER}}+\frac{V_{tC}}{\mathbf{VEF}}}\right)$$

neglecting high-injection, quasi-saturation and series resistances.

  - **VER**: reverse Early voltage
  - **VEF**: forward Early voltage
  - V_{tE}, V_{tC} reused from depletion charge calculation



Transfer current – Extraction result



V_{BC}=0V

- Collector current obtained from Gummel measurement
- Extracted parameters
  - **IS** : saturation current intrinsic transistor
  - **MULT** : # devices in parallel
- Parameter optimization for 0.3 V<V_{BE}<0.65 V

Some remarks on Transfer current – Heterojunction features

- Extended model for SiGe in base included in Mextram
  - Extra model parameter **DEG** for bandgap difference over the base ΔE_g due to Ge-profile
  - Gummel number G_B recalculated

$$\frac{G_B}{G_{B0}} = \frac{exp\left(\left[\frac{V_{tE}}{\mathbf{VER}} + 1\right] \cdot \frac{\Delta E_g}{kT}\right) - exp\left(-\frac{V_{tC}}{\mathbf{VEF}} \cdot \frac{\Delta E_g}{kT}\right)}{exp\left(\frac{\Delta E_g}{kT}\right) - 1}$$

- G_{B0} : Gummel number at zero bias
- **VER, VEF** : reverse and forward Early voltages
- V_{tE}, V_{tC} see depletion charge calculation
- Expression reduces to result without Ge, *i.e.* for ΔE_g=0,

$$\frac{G_B}{G_{B0}} = 1 + \frac{V_{tE}}{\mathbf{VER}} + \frac{V_{tC}}{\mathbf{VEF}}$$

- Previous approximation for collector current becomes

$$I_C \approx \mathbf{MULT} \cdot \mathbf{IS} \cdot \left(\frac{e^{V_{BE}/V_T}}{G_B/G_{B0}}\right)$$

- Full background of calculation and derivation can be found in documentation

Parameter extraction : Forward base current

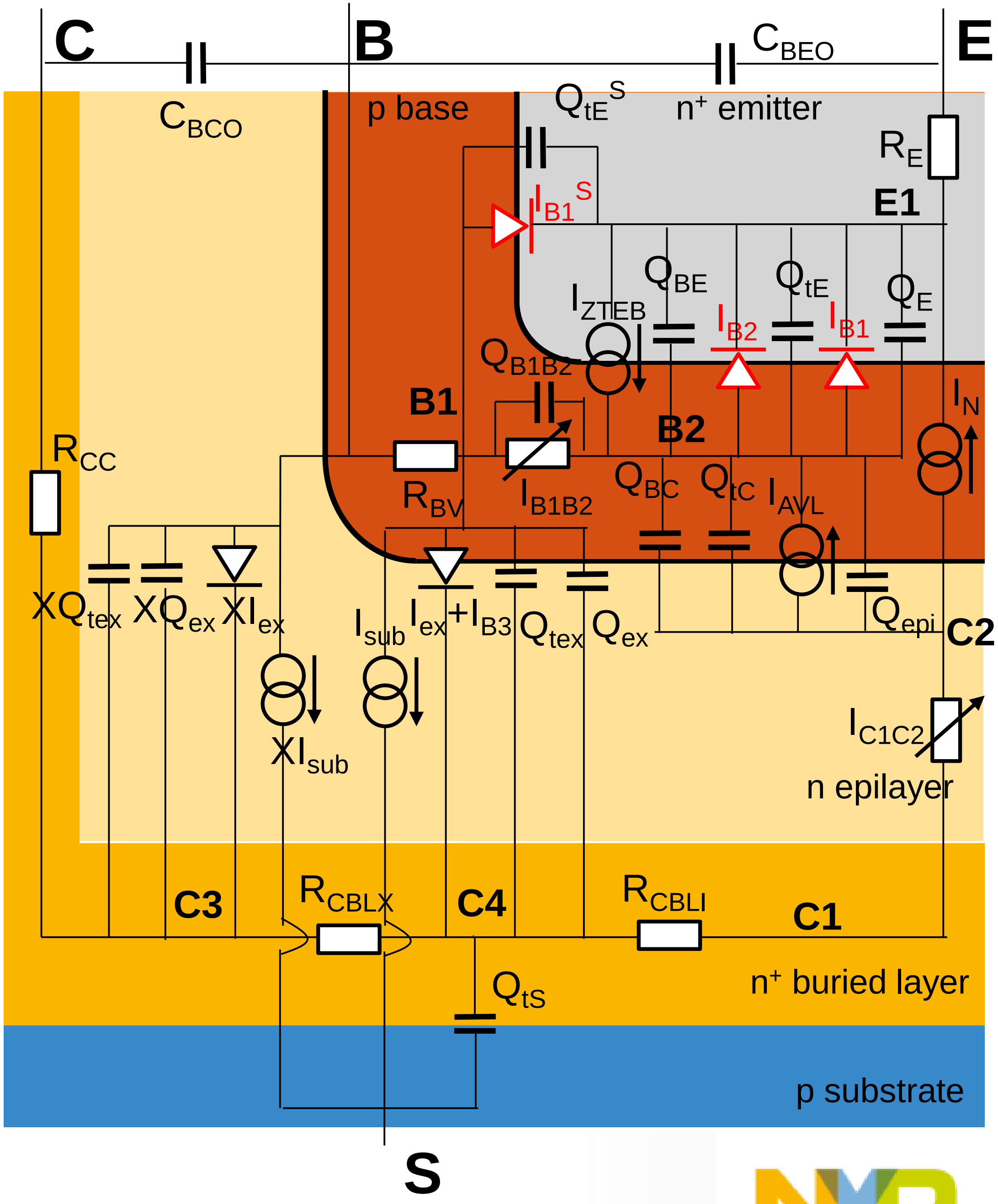
- Contributions
  - Ideal base current intrinsic transistor I_{B1}
  - Ideal base current side-wall I_{B1}^S
  - Non-ideal base current intrinsic transistor I_{B2}
- Implementation

$$I_{B1} = (1 - \mathbf{XIBI}) \cdot \frac{\mathbf{IS}}{\mathbf{BF}} \cdot \left(e^{V_{B2E1}/k\cdot T} - 1\right)$$

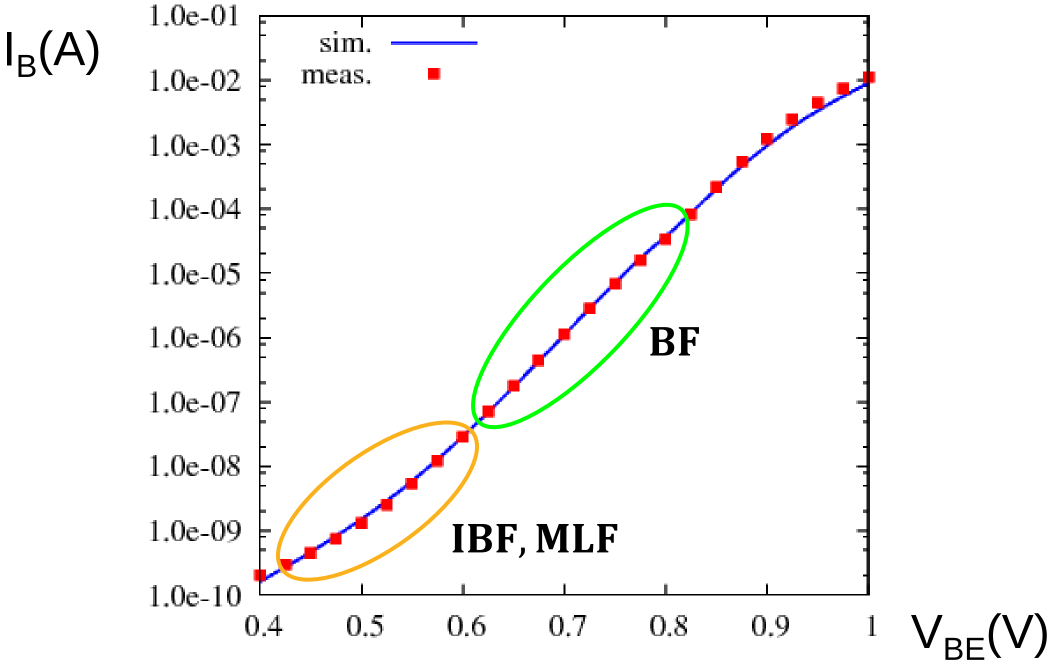
$$I_{B1}^S = \mathbf{XIBI} \cdot \frac{\mathbf{IS}}{\mathbf{BF}} \cdot \left(e^{V_{B1E1}/k\cdot T} - 1\right)$$

$$I_{B2} = \mathbf{IBF} \cdot \left(e^{V_{B2E1}/(\mathbf{MLF}\cdot k\cdot T)} - 1\right)$$

- Extracted parameters
  - **BF :** forward gain
  - **IBF :** Saturation current of non-ideal base current
  - **MLF :** Non-ideality factor of the non-ideal forward base current
  - **XIBI :** part of base current that belongs to the sidewall



Forward base current – Extraction result

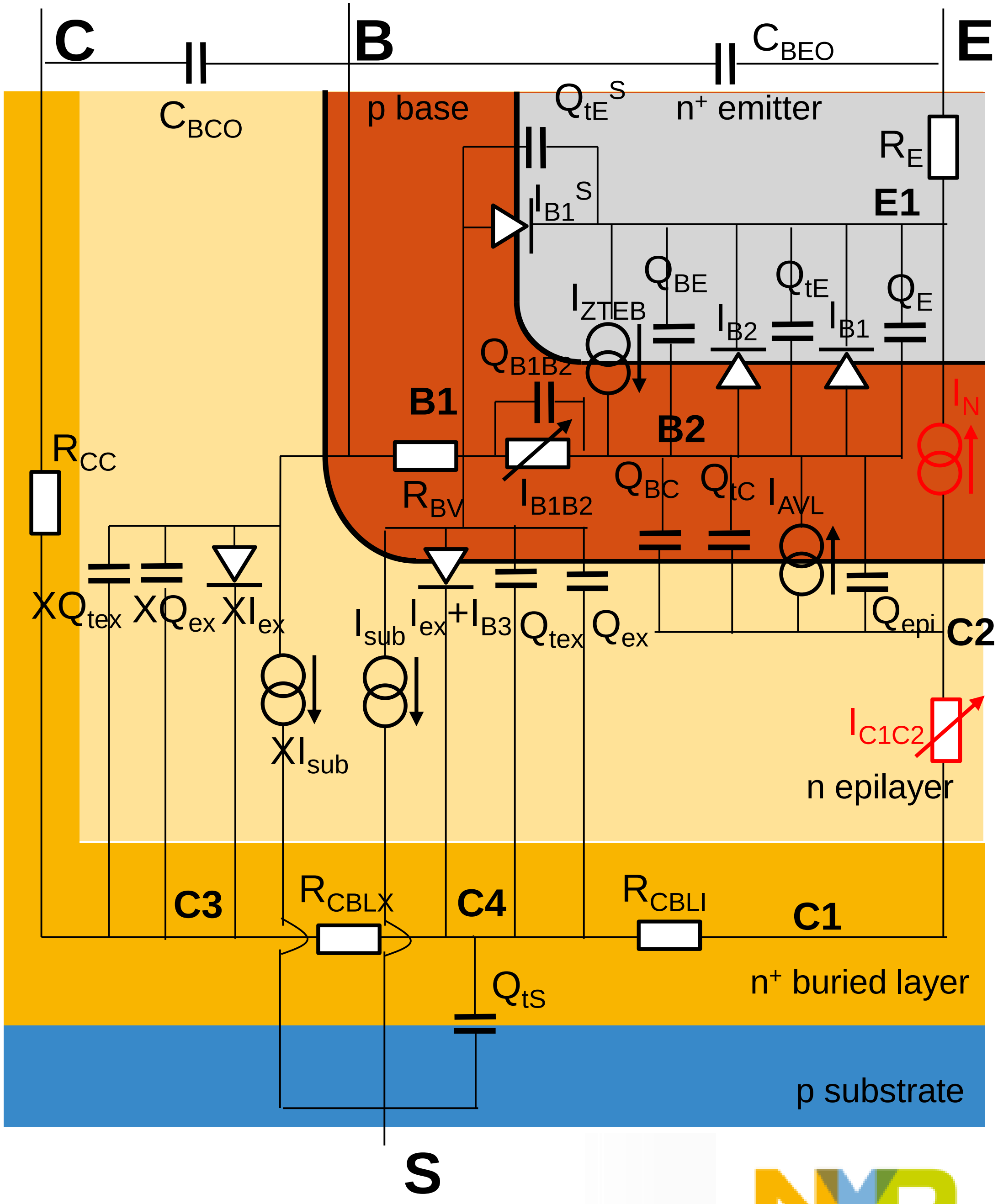


V_{BC}=0V

- Base current obtained from Gummel measurement
- Extracted parameters
  - **BF :** forward gain
  - **IBF :** Saturation current of non-ideal base current
  - **MLF :** Non-ideality factor of the non-ideal forward base current
  - **XIBI :** part of base current that belongs to the sidewall (multiple layout needed)

Parameter extraction : Epilayer model (I)

- Important part of epilayer model is the Kull model
  - Kull model without velocity saturation is implemented in current source I_{C1C2}
  - Kull model can be applied to regions of the epilayer with a neutral charge, *i.e.*,
    - Ohmic region
    - Injection region
  - Parameters of Kull model (I_{C1C2})
    - **RCV** : resistance of un-modulated epilayer
    - **VDC** : collector-base diffusion voltage (already extracted on base-collector depletion capacitance)



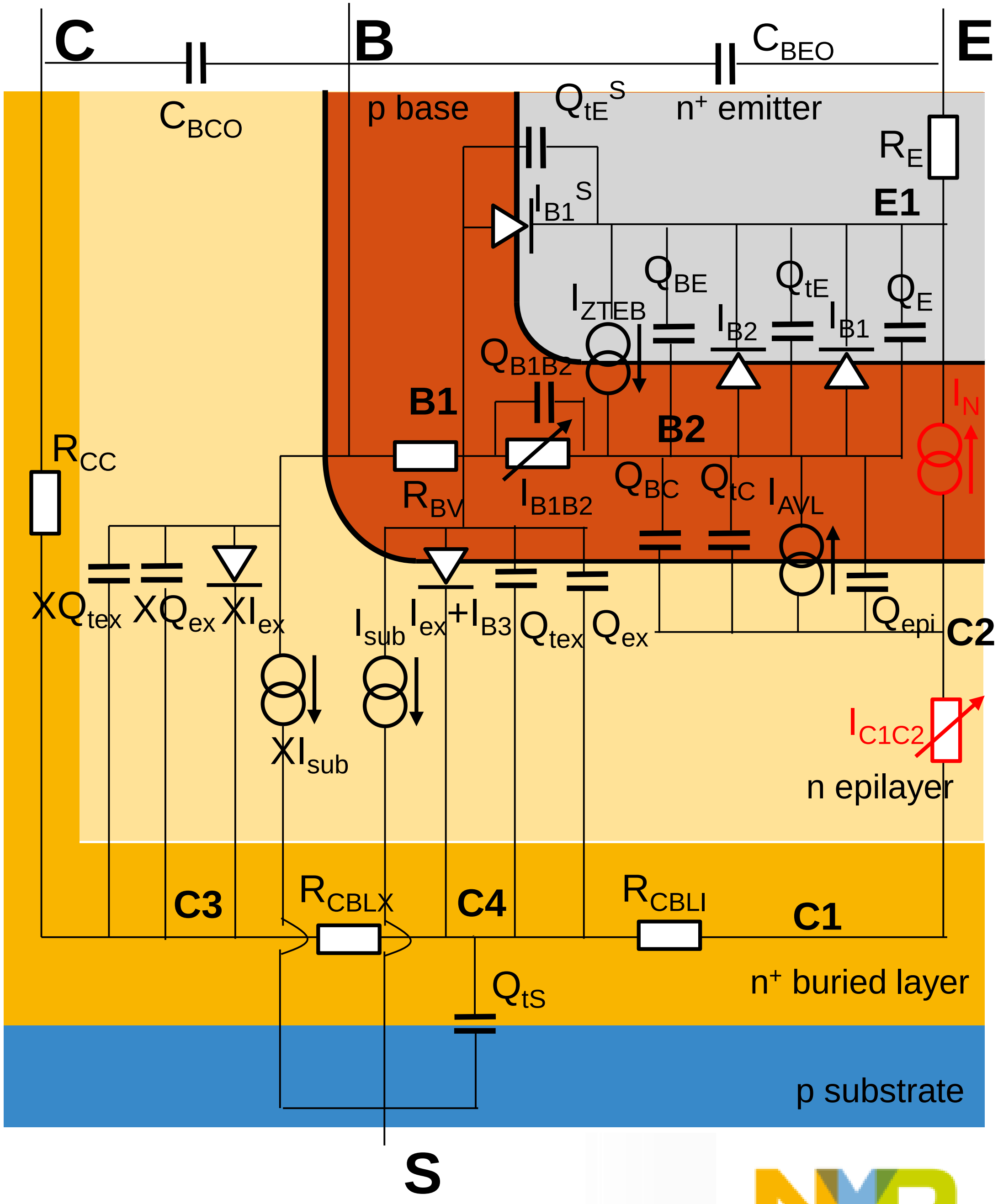
Parameter extraction : Epilayer model (II)

- Important effect in epilayer is velocity saturation
  - Velocity saturation calculation uses the current of the Kull model I_{C1C2}
  - Expression for the internal base-collector bias at the intrinsic junction V_{B2C2}* obtained from velocity saturation calculation
  - V_{B2C2}* used in the transfer current, *i.e.*,

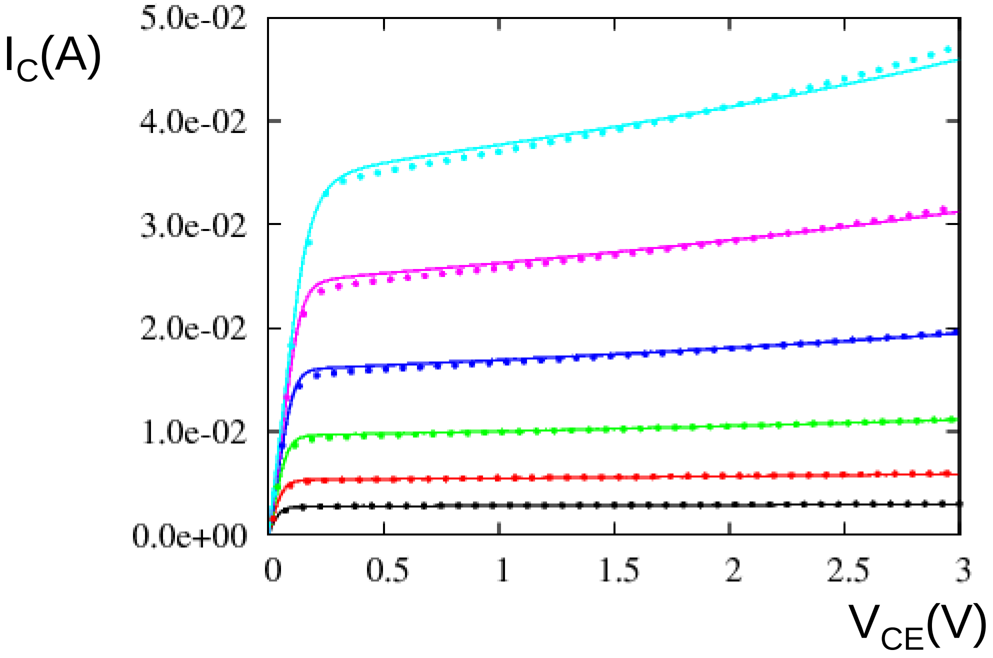
$$I_N = \mathbf{IS} \cdot \left(\frac{exp\left(\frac{V_{B2E1}}{V_T}\right) - exp\left(\frac{V^*_{B2C2}}{V_T}\right)}{q^I_B} \right)$$

q^I_B normalized base charge

  - Parameters to describe velocity saturation in the epilayer
    - **IHC** : critical current for velocity saturation in epilayer
    - **SCRCV** : space charge resistance of the epilayer
    - **AXI** : smoothness parameter for the onset of quasi saturation



Output characteristics – Extraction result



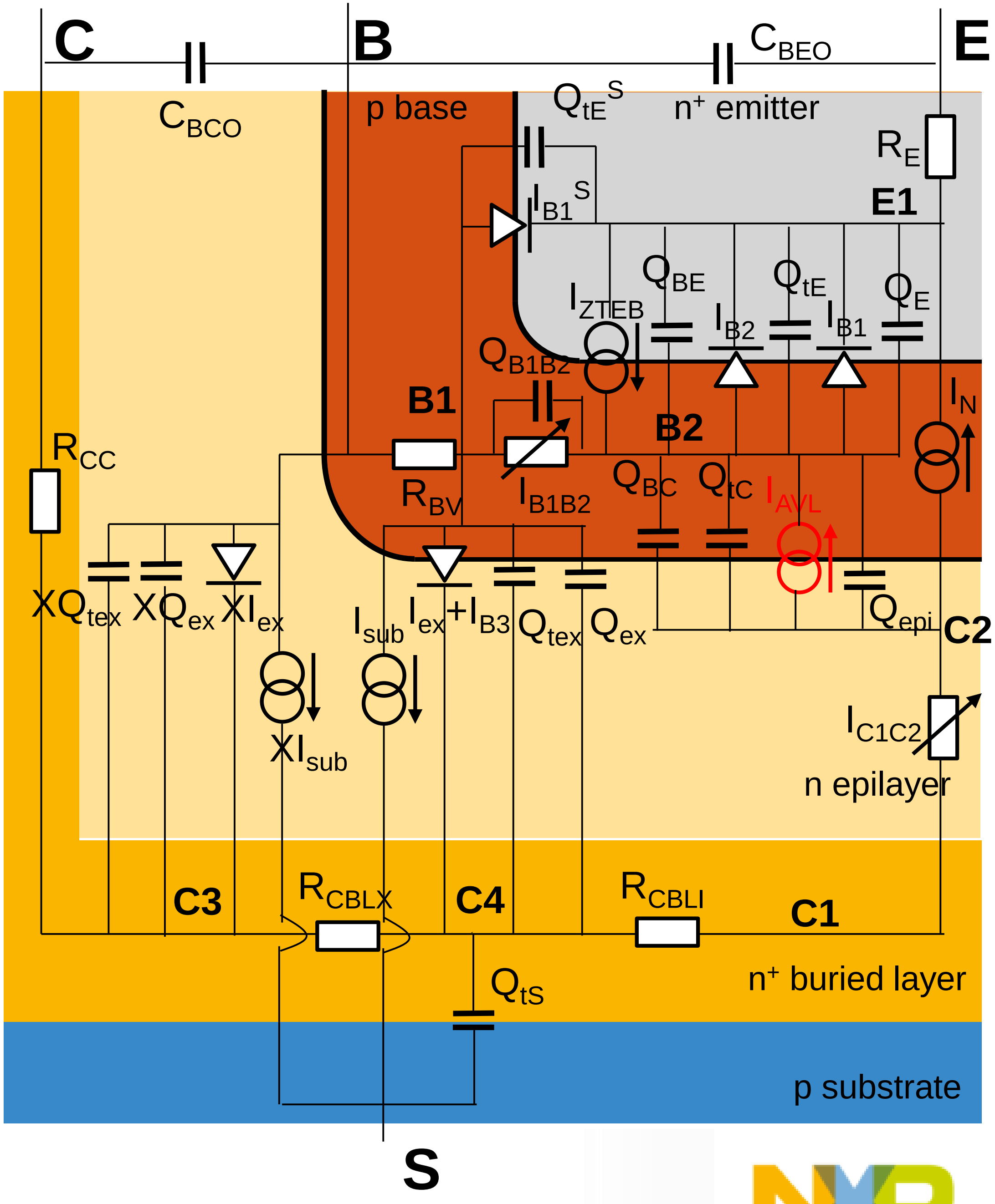
symbols – measurements
lines – Mextram

V_{BE}=0.7-0.8V

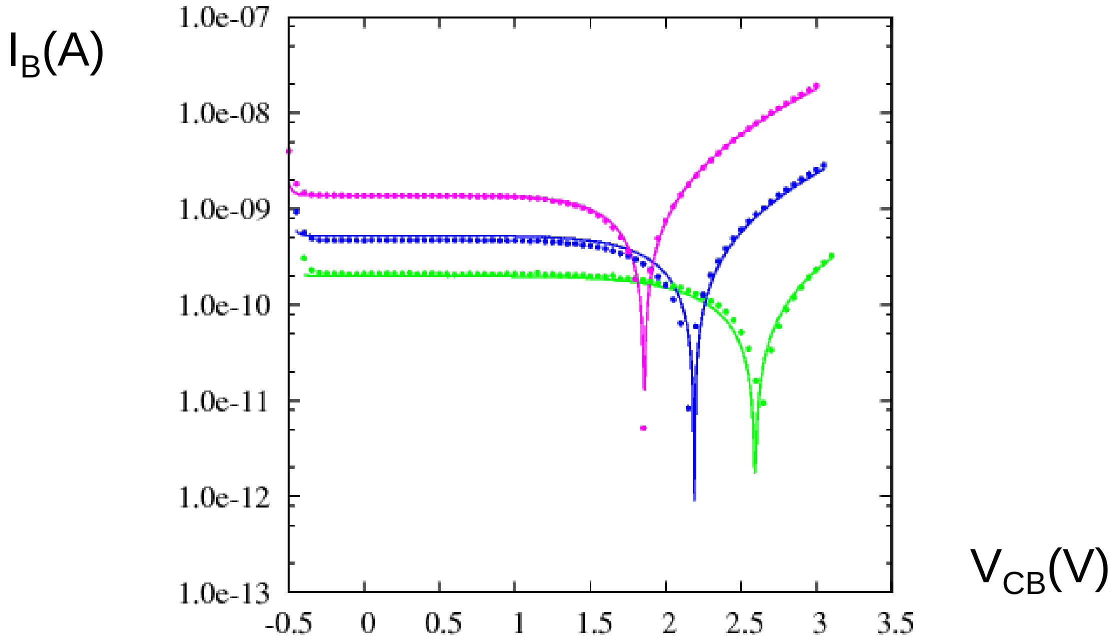
- Epilayer model extracted on output characteristics at high current conditions
- Extracted parameters
  - **RCV** : resistance of un-modulated epilayer
  - **IHC** : critical current for velocity saturation in epilayer
  - **SCRCV** : space charge resistance of the epilayer
  - **AXI** : smoothness parameter for the onset of quasi saturation
  - (**RTH** : thermal resistance)

Parameter extraction : Avalanche current

- Weak-avalanche of base-collector junction included in Mextram
- Avalanche model parameters
  - **WAVL** : epilayer thickness used in avalanche model
  - **VAVL** : voltage determining curvature of avalanche current
- Avalanche model parameters are extracted from forward Early measurements (V_{CE} sweep at constant V_{BE}).
  - In case of avalanching the base current drops and becomes negative



Avalanche current – Extraction result



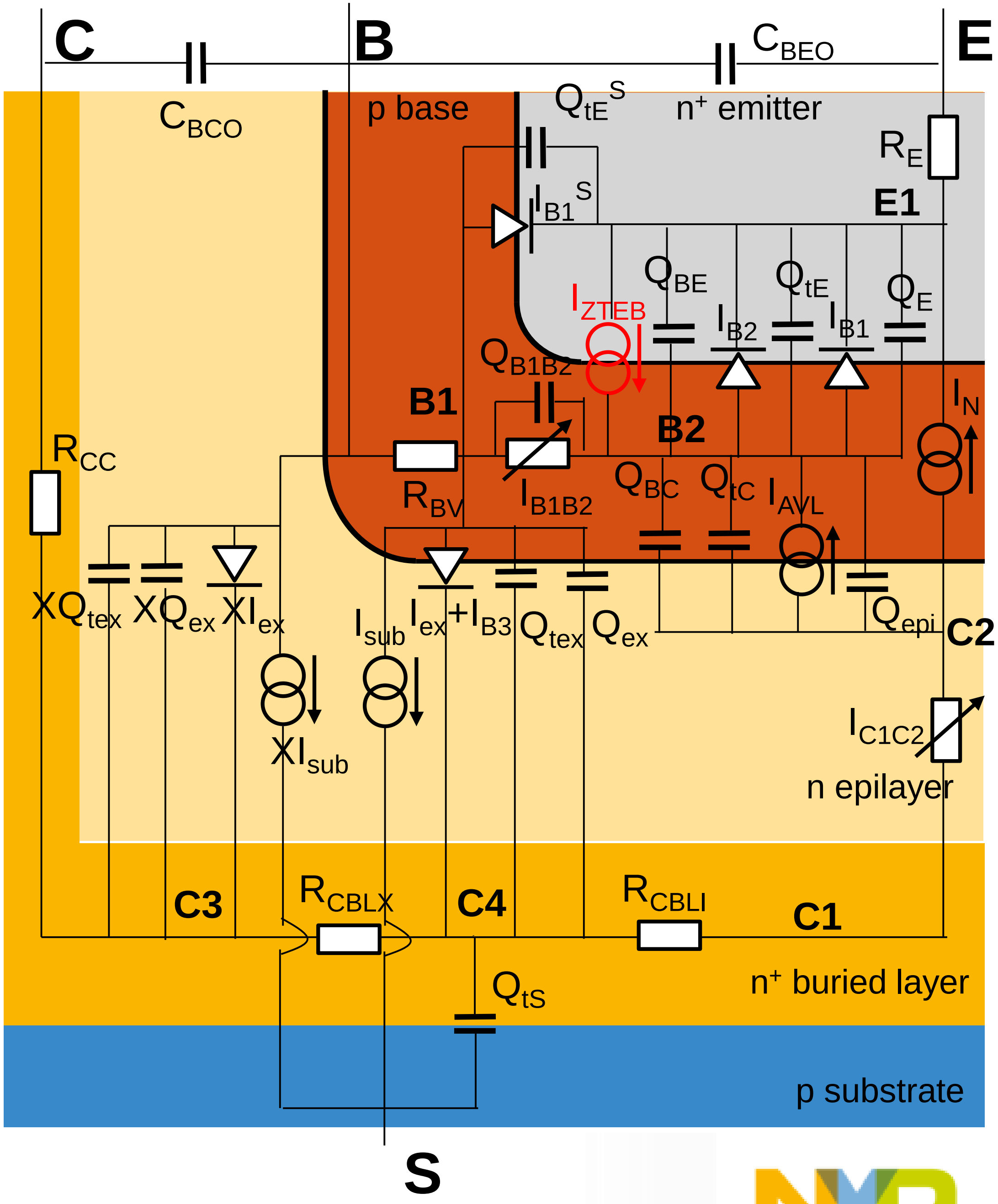
V_{BE}=0.4,0.45,0.5V

Symbols – measurements
Lines - Mextram

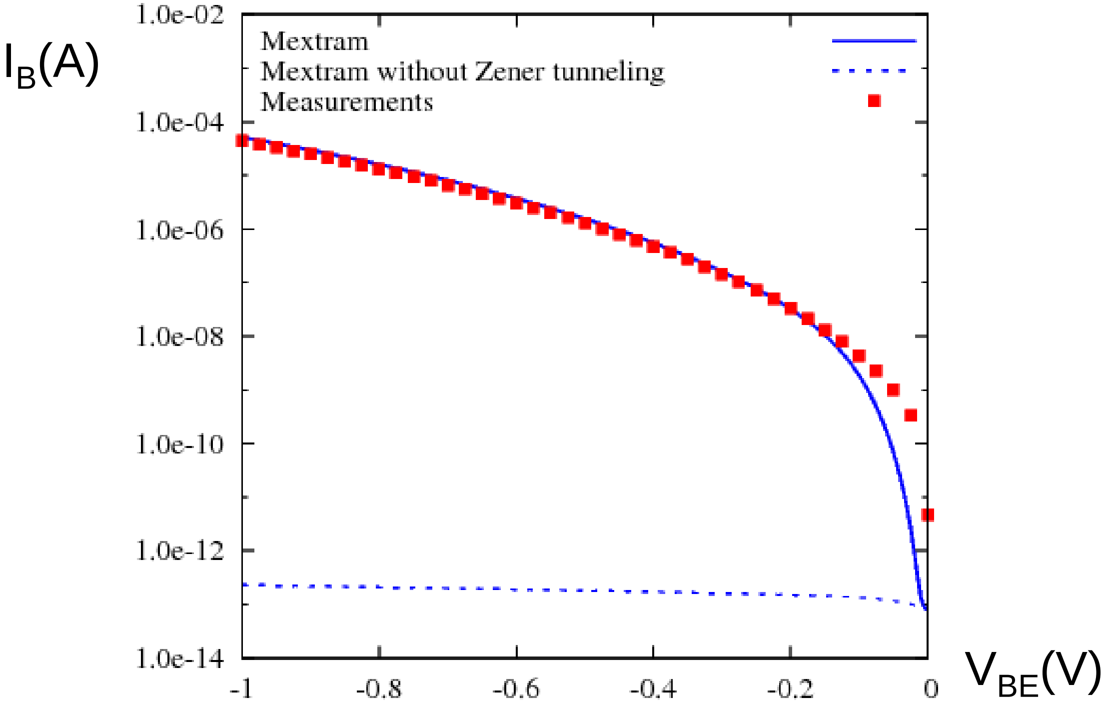
- Base current from forward Early measurement
- Extracted parameters
  - **WAVL** : epilayer thickness used in avalanche model
  - **VAVL** : voltage determining curvature of avalanche current
- Parameter optimization for V_{CB}=0.5..3V

Parameter extraction : Zener tunneling

- Zener tunneling of base-emitter junction included in Mextram
- Avalanche model parameters
  - **IZEB:** Pre-factor Zener tunneling
  - **NZEB:** Coefficient Zener tunneling
  - **AVGEB** : Temperature scaling coefficient of Zener tunneling
  - **TVGEB** : Temperature scaling coefficient Zener tunneling
  - (**VGZEB** : Bandgap at ref. temperature relevant for Zener tunneling)
- Zener tunneling parameters are extracted from V_{BE} sweep with V_{BE}<0V



Zener tunneling – Extraction result

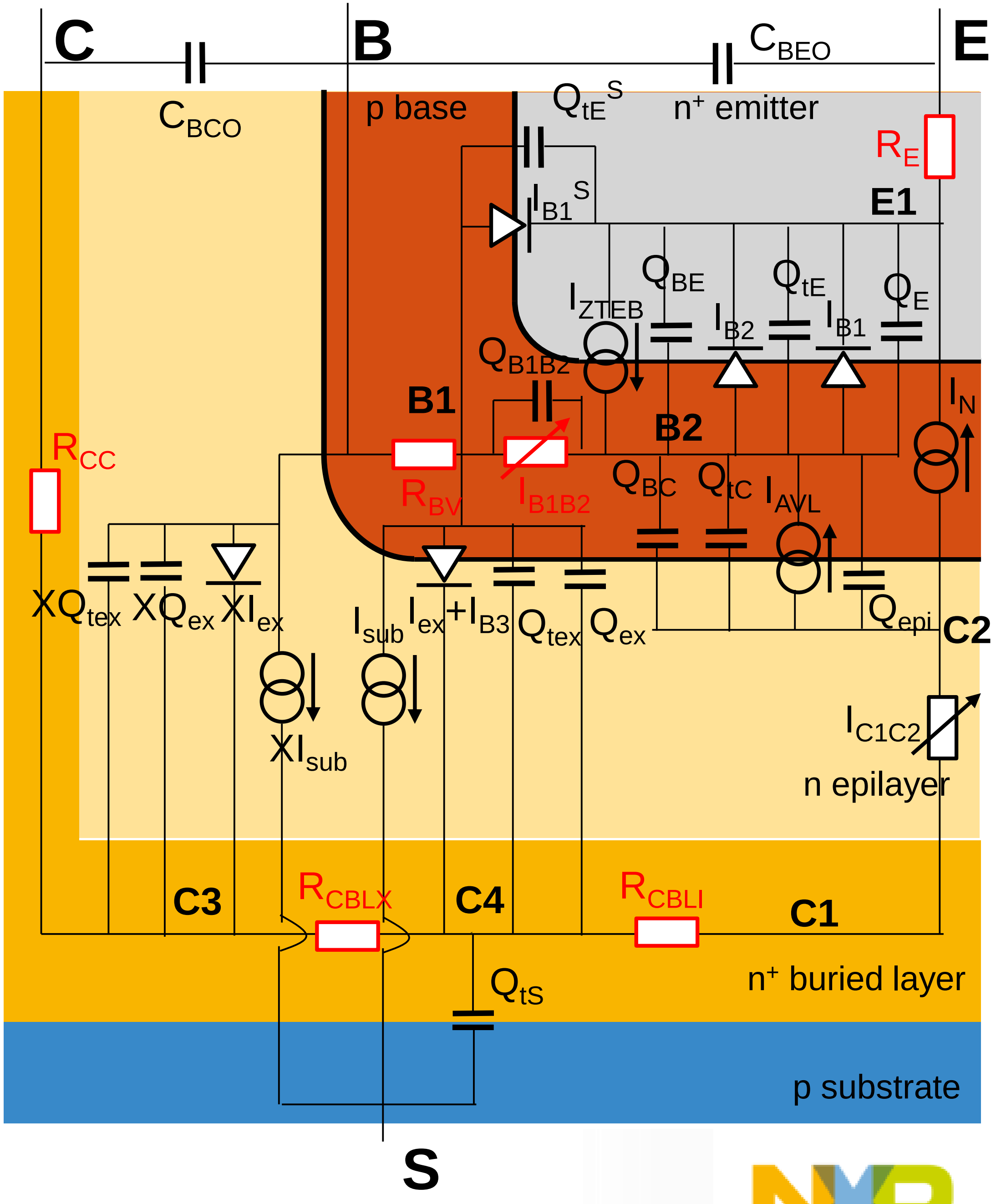


V_{BC} =-0.8V

- Base current
- Extracted parameters
    - **IZEB:** Pre-factor Zener tunneling
    - **NZEB:** Coefficient Zener tunneling
    - **AVGEB** : Temperature scaling coefficient of Zener tunneling
    - **TVGEB** : Temperature scaling coefficient Zener tunneling
- Parameter optimization for V_{BE}=-1..-0.2V

Parameter extraction : series resistances

- Series resistance can be extracted directly on measured currents
- However, more insight is obtained if dedicated extraction method of the series resistance is used
  - Allows to make comparisons between measurements and simulations **and** a sanity check with extracted model parameter(s)



Parameter extraction : emitter resistances

- Emitter resistance
  - Many extraction methodologies available from literature
    - Gm-method (DC) [1]
    - Gobert method (AC) [2]
    - Ning-Tang [3]
    - Raya method (AC) [4]
    - McAndrew method (AC) [5]

1. A. Huerta, T. Vanhoucke, and W.D. van Noort, PR-TN-2004/00489, 2004
2. Y. Gobert, P.J. Tasker, and K.H. Bachem, IEEE Trans. Microw. Theory Techn., vol. 45, pp. 149-153, Jan. 1997.
3. T.H. Ning and D.D. Tang, IEEE Trans. Electron Devices, vol. 31, pp. 409-412, Apr. 1984
4. C. Raya, B. Ardouin, and Z. Huszka, IEEE BCTM, Oct. 2011, pp. 191-194
5. C.C. McAndrew, IEEE BCTM, Oct. 2006, pp. 1-4

Extraction emitter resistance: Gm method

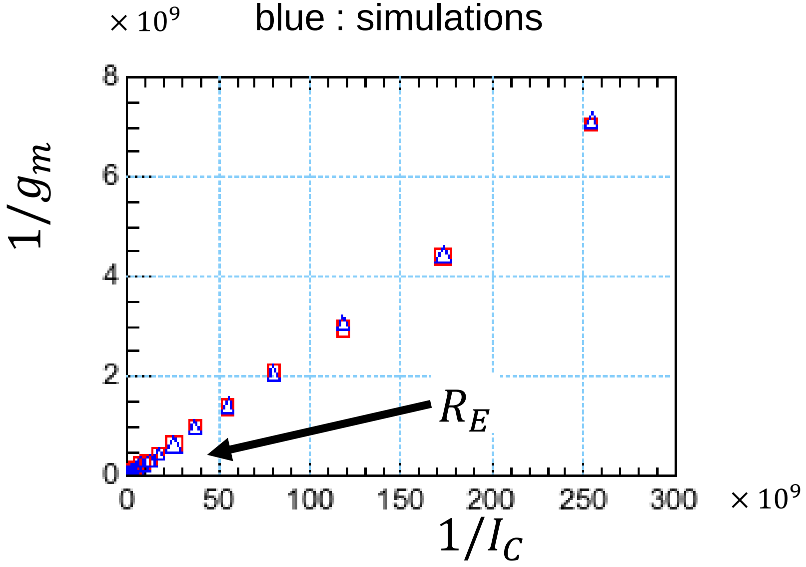
- **Measurements:** DC (forward Gummel)
  - *inputs:* sweep Vb, Vc = Vb, Ve = 0 *outputs:* Ic, Ib

- **Description:**
  - Calculate g_m from measured collector current

$$I_C \approx I_S \exp\left(\frac{V_{BE} - I_C R_E}{m_C V_T}\right) \Rightarrow \frac{1}{g_m} \approx \frac{m_C V_T}{I_C} + R_E$$

  - Plot $1/g_m$ vs. $1/I_C$ and extract emitter resistance from the y-axis intercept.

- **Example:** red : measurements
  blue : simulations



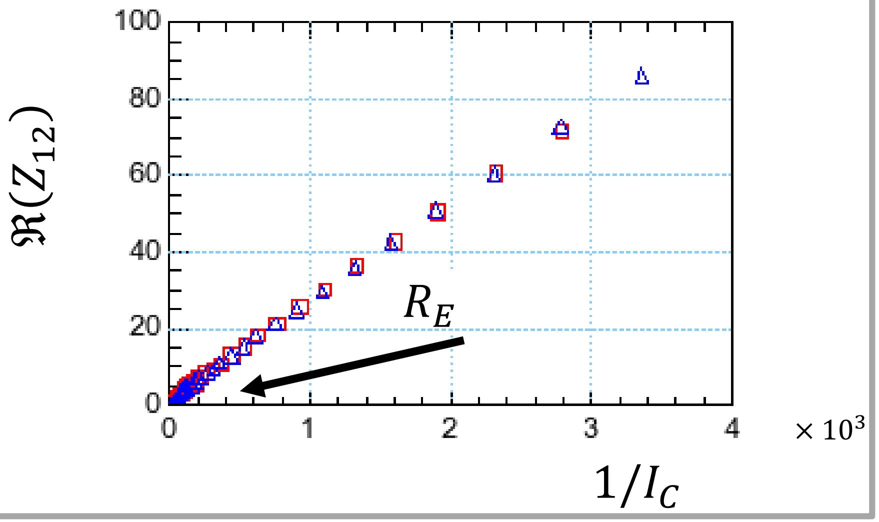
Extraction emitter resistance: Gobert method

- **Measurements:** AC
  - *inputs:* sweep Vb, Vc = 1.5 V, freq = 2 GHz *outputs:* S parameters
- **Description:**
  - Convert S parameters to Z parameters and take the real part of Z_{12}

$$\boxed{\Re(Z_{12}) \approx \frac{m_C V_T}{I_C} + R_E}$$

  - Plot $\Re(Z_{12})$ vs. $1/I_C$ and extract emitter resistance from the y-axis intercept.
  - In practice very similar to the Gm method.

- **Example:** Solid lines : simulations (Mextram)
Symbols : measurements



Extraction emitter resistance: Ning-Tang method

- ○ **Measurements:** DC (forward Gummel)
  - *inputs:* sweep Vb, Vc = Vb, Ve = 0, *outputs:* Ic, Ib

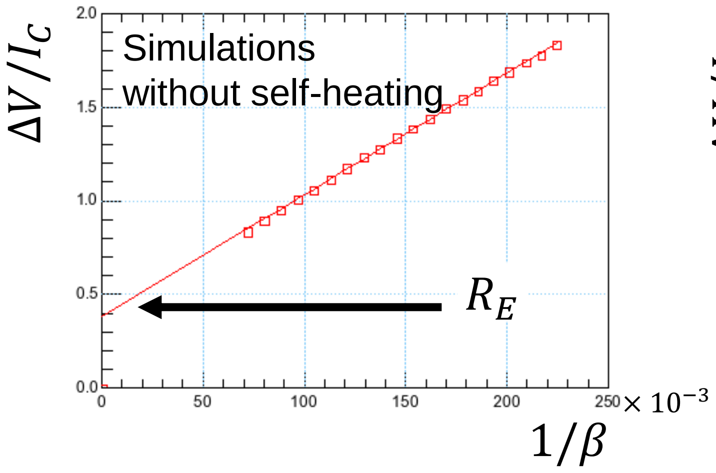
- ○ **Description:**
  - Compare ideal base current I_{BO} against measured one I_B

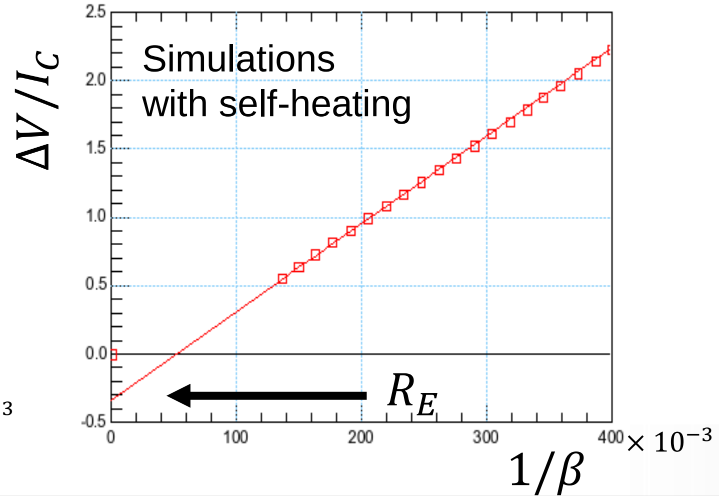
$$I_{BO} = I_{SB} \exp \frac{V_{BE}}{V_T}$$

  - Plot $\Delta V / I_C$ vs. $1/\beta$ and extract emitter resistance from the y-axis intercept.

$$I_B = I_{SB} \exp\left(\frac{V_{BE} - \Delta V}{V_T}\right) \Rightarrow \frac{\Delta V}{I_C} = R_E + \frac{1}{\beta}(R_E + R_{BC})$$

- ○ **Examples:**





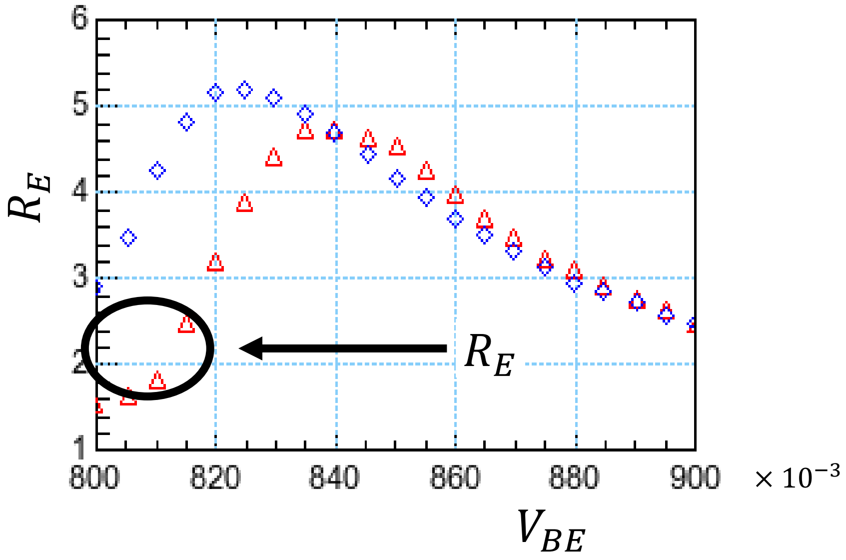
Extraction emitter resistance: Raya method

- **Measurements:** AC
  - *inputs:* sweep Vb, Vc = 1.5 V, freq = 2 GHz *outputs:* S parameters

- **Description:**
  - Convert S parameters to Z parameters and calculate $R_E(V_{BE})$ from two-port considerations.
  - Extract the emitter resistance as $R_E = \min R_E(V_{BE})$.

- **Example:**

Red : measurements
Blue : Simulations



Extraction emitter resistance: McAndrew method

- **Measurements:** AC
  - *inputs:* sweep Vb, Vc = 1.5 V, freq = 2 GHz *outputs:* S parameters

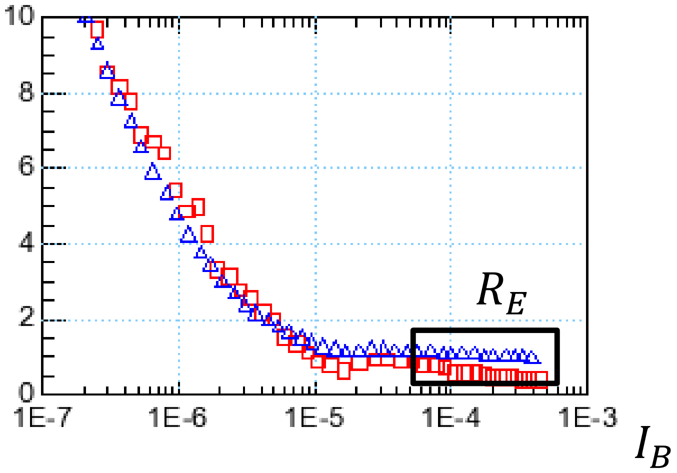
- **Description:**
  - Convert S parameters to Y parameters and calculate $R_E(I_{BE})$ from two-port considerations:

$$\boxed{R_E = \frac{\partial V_{BE}}{\partial I_B}\left[\beta_0\left(1+\frac{\partial \log \beta_0}{\partial \log I_B}\right)-\frac{\partial I_C/\partial V_{CE}}{\partial I_B/\partial V_{CE}}\right]^{-1}}$$

  - Extract the emitter resistance from the flat region of $R_E(I_B)$.

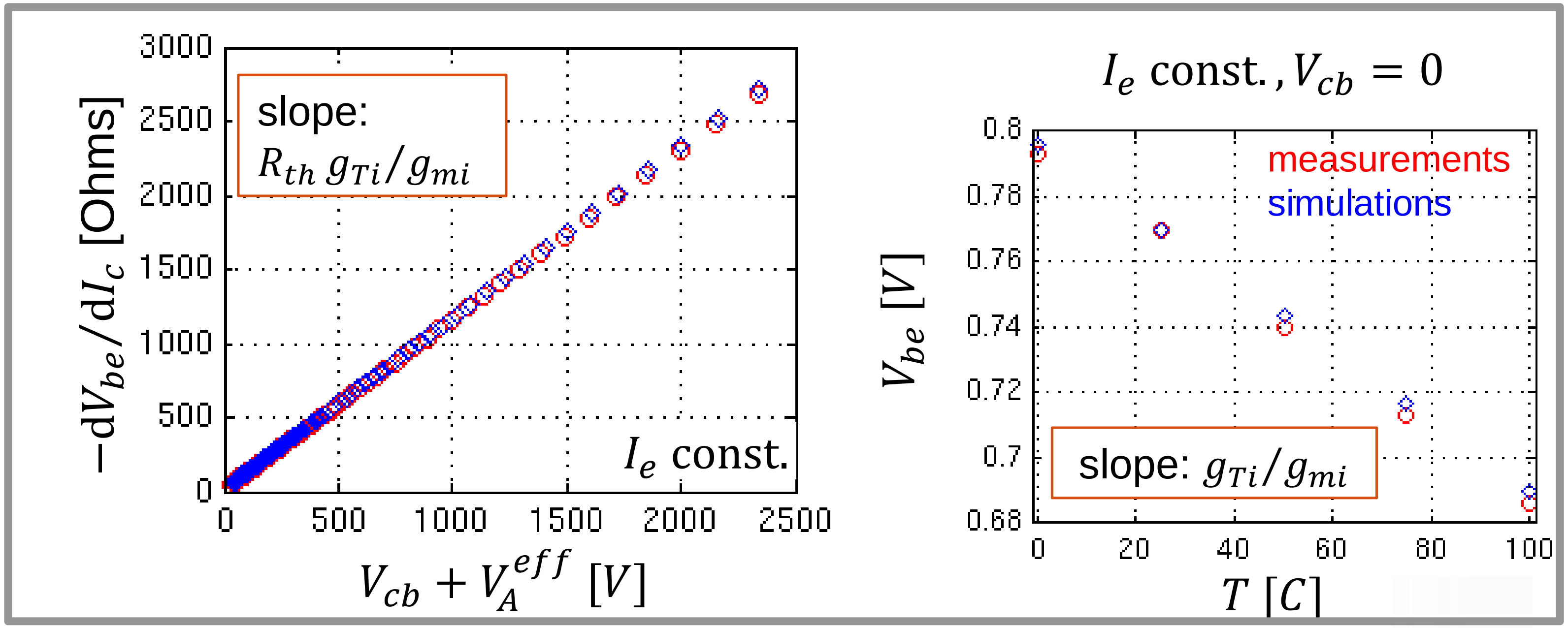
- **Example:**

Red : measurements
Blue : simulations



R_{TH} – R_B – extraction

- Using method Vanhoucke and Hurkx’s
- **Measurements:** DC / Temperature on common base structure
  - *inputs:* sweep V_{CB} , I_E = const., V_B = 0 *outputs:* V_{EB}, I_C, I_B
- **Description:**
  - Calculate $\mathrm{d}V_{be}/\mathrm{d}I_c$ and $V_A^{eff} = I_c\,(\mathrm{d}V_{cb}/\mathrm{d}I_c)$
  - $-\frac{\mathrm{d}V_{be}}{\mathrm{d}I_c} \approx R_b - R_{TH}\frac{g_{Ti}}{g_{mi}}\left(V_{cb} + V_A^{eff}\right)$, with $g_{Ti} = \frac{\mathrm{d}I_c}{dT}$, $g_{mi} = \frac{\mathrm{d}I_c}{dV_{be_i}}$
  - Plot $-\mathrm{d}V_{be}/\mathrm{d}I_C$ vs. $(V_{cb}+V_A^{eff})$ and extract R_{TH} from the slope.

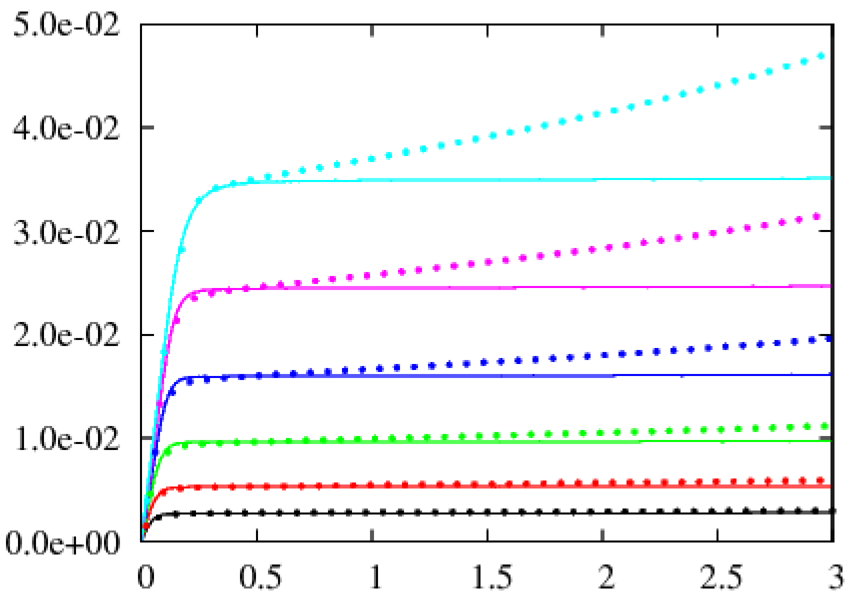


Thermal resistance – Extraction result

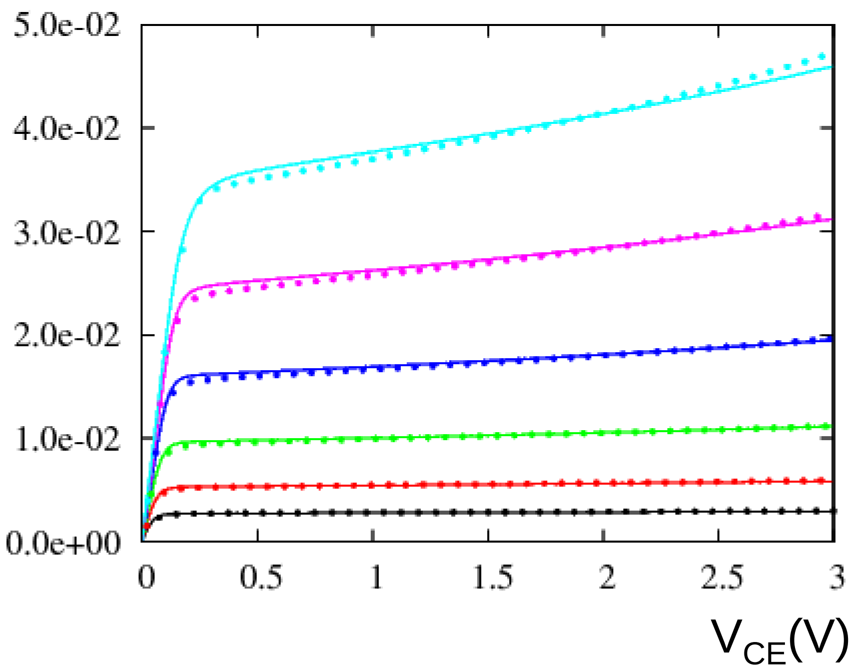
V_{BE}=0.7-0.8V

I_C(A)

symbols – measurements
lines – Mextram <u>without</u> self-heating



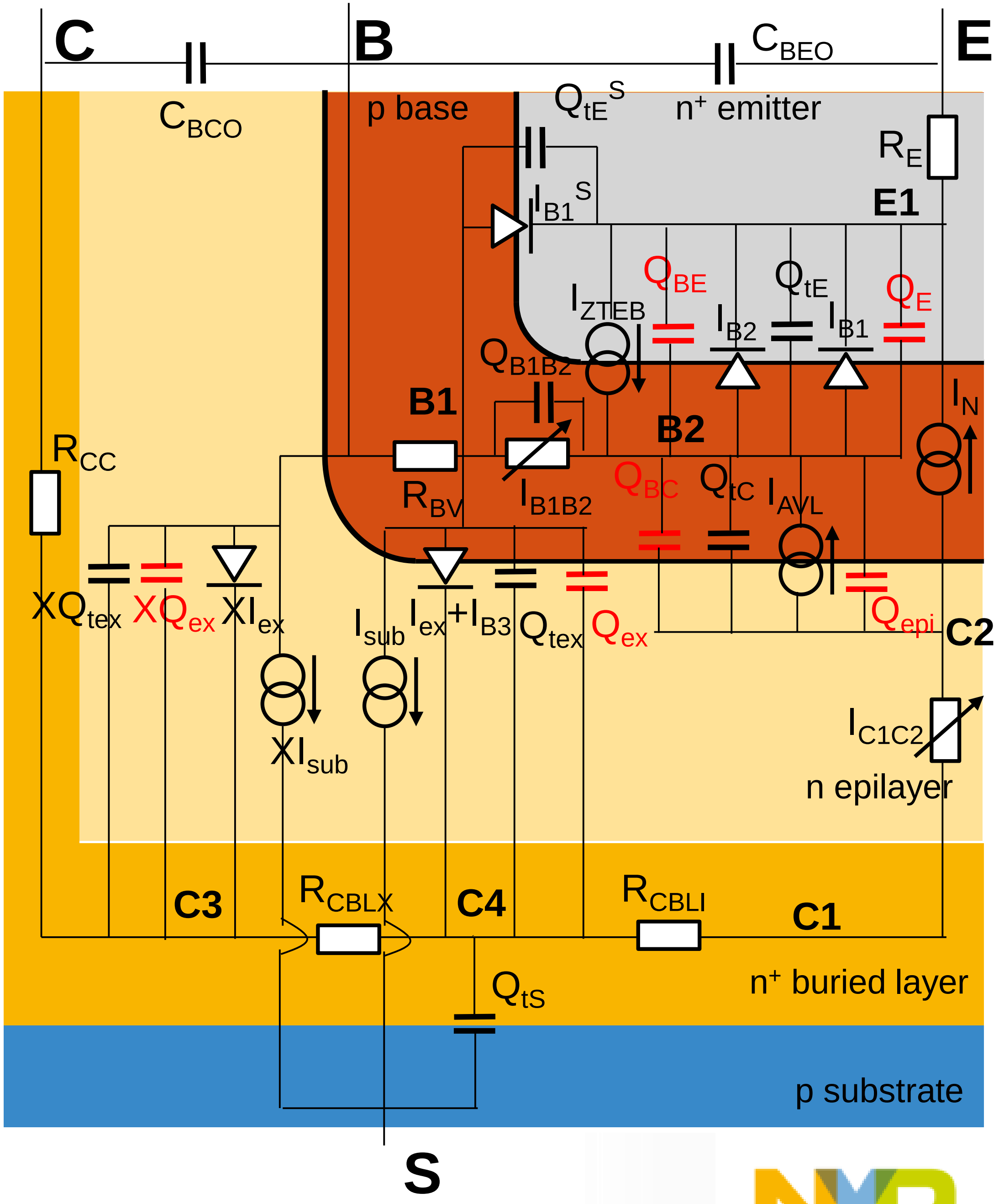
symbols – measurements
lines – Mextram <u>with</u> self-heating



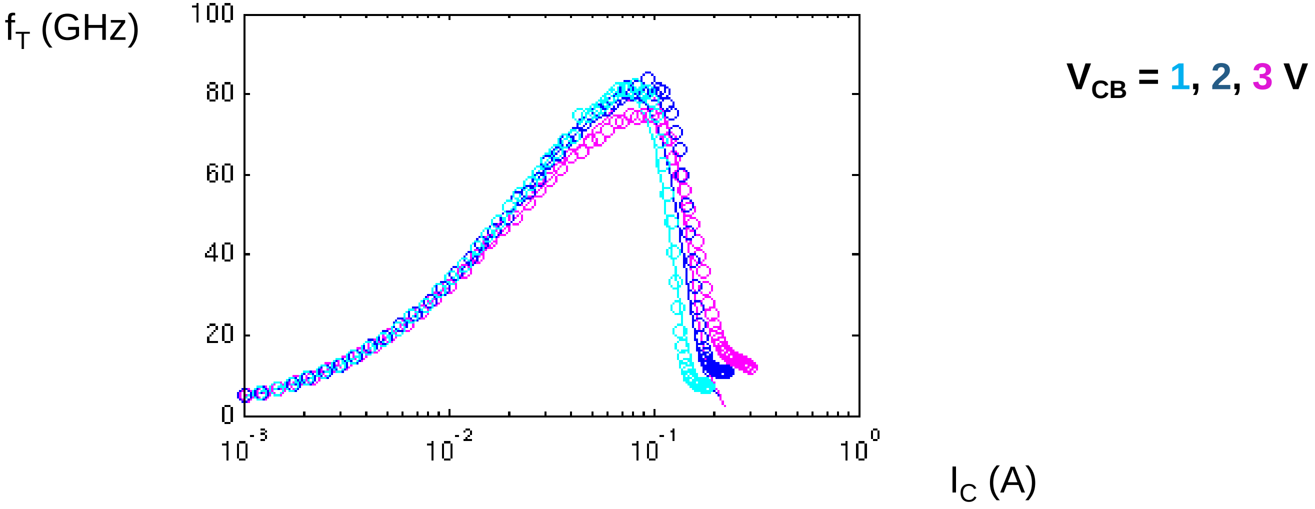
- Impact of self-heating on output characteristics

Parameter extraction : Diffusion charges

- Parameters of diffusion charges are extracted/fine tuned on RF figures of merit calculated from y-parameter measurements
- Parameters
  - **MTAU:** Non-ideality factor of the emitter stored charge (Q_E)
  - **TAUE:** Minimum transit time of stored emitter charge (Q_E)
  - **TAUB** : Transit time of stored base charge (Q_{BE}+Q_{BC})
  - **TEPI** : Transit time of stored epilayer charge (Q_{epi})
  - **TAUR** : Transit time of reverse extrinsic stored base charge (Q_{ex}+ XQ_{ex})



Cut-off frequency



- Extraction of diffusion charge parameters on RF-quantities
  - Parameters
    - **MTAU:** Non-ideality factor of the emitter stored charge
    - **TAUE:** Minimum transit time of stored emitter charge
    - **TAUB** : Transit time of stored base charge
    - **TEPI** : Transit time of stored epilayer charge
    - **TAUR** : Transit time of reverse extrinsic stored base charge
  - f_T shown as an example

Contents

- History Mextram
- Equivalent circuit Mextram
- Parameter extraction: procedure & results
- Overview Mextram documentation and Mextram related publications
- Summary

Documentation (I)

- ”The Mextram bipolar transistor model, level 504.7” J.C.J. Paasschens, R. van der Toorn and W.J. Kloosterman. Last update March 2008.
- ”Introduction to and usage of the bipolar transistor model Mextram” J.C.J. Paasschens and R. van der Toorn, Unclassified Report NL-UR 2002/823, Philips Nat.Lab., 2002.
- “Model derivation of Mextram 504. The physics behind the model”, J.C.J. Paasschens, W.J. Kloosterman, and R. van der Toorn, Unclassified Report NL-UR 2002/806, Philips Nat.Lab., 2002. Last update March 2005.
- ”Parameter Extraction for the Bipolar Transistor Model Mextram, Level 504” J.C.J. Paasschens, W.J. Kloosterman, and R.J. Havens, Philips Research, Nat.Lab. Unclassified Report 2001/801, 2001 (588kB).
- ”Comparison of Mextram and the Vbic95 bipolar transistor model” W.J. Kloosterman, Philips Research, Nat.Lab. Unclassified Report 034/96, 1996.
- ”Parameter extraction methodology for the Mextram bipolar transistor model” W.J. Kloosterman and J.A.M. Geelen, Philips Research, Nat.Lab. Unclassified Report 003/96, 1996.
- ”Modelling of Si and SiGe bipolar transistors with the compact model Mextram, level 504”, J.C.J. Paasschens and R. van der Toorn, presented at the Workshop Compact Modeling, February 27, 2003.
- ”Mextram (level 504). The Philips model for bipolar transistors”, J.C.J. Paasschens, W.J. Kloosterman, and R. van der Toorn, presented at the FSA modeling workshop, September 10, 2002.

Documentation (II)

- ”Mextram 504 Experimental Results”, J.C.J. Paasschens and W.J. Kloosterman, presented at the Compact Model Council Meeting of March 27, 2000.

- ”Mextram 504”, J.C.J. Paasschens and W.J. Kloosterman, presented at the Compact Model Council Meeting of December 9, 1999.

- ”Bipolar Model Standardization Mextram 503.2”, W.J. Kloosterman, J.C.J. Paasschens, and D.B.M. Klaassen, presented at the Compact Model Council Meeting of September 29, 1999.

- ”The Bipolar Transistor Model Mextram” W.J. Kloosterman, J.C.J. Paasschens, and H.C. de Graaff, presented at the Compact Model Council Meeting of December 10, 1998.

Mextram related publications (I)

- “Compact modelling of the noise of a bipolar transistor under DC and AC current crowding conditions”, J.C.J. Paasschens, IEEE Trans. Elec. Dev., vol.51, pp.1483-1495, 2004.
- “Modelling the correlation in the high-frequency noise of (heterojunction) bipolar transistor using charge-partitioning”,J.C.J. Paasschens, R.J. Havens, and L.F. Tiemeijer, in Proc. of the Bipolar Circuits and Technology Meeting, pp.221-224, 2003.
- ”Modelling the excess noise due to avalanche multiplication in (heterojunction) bipolar transistors”, J.C.J. Paasschens and R.de Kort, in Proc. of the Bipolar Circuits and Technology Meeting, pp.108-111, 2004.
- ”Dependence of thermal resistance on ambient temperature and actual temperature” J.C.J. Paasschens, S. Harmsma, and R.van der Toorn, in Proc. of the Bipolar Circuits and Technology Meeting, pp.96-99, 2004.
- ”Modelling two SiGe HBT specific features for circuit simulation”, J.C.J. Paasschens, W.J. Kloosterman, and R.J. Havens, in Proceedings of the Bipolar Circuits and Technology Meeting, pp. 38-41, 2001. Paper 2.2.
- ”Explorations for high performance SiGe-heterojunction bipolar transistor integration” P. Deixler, H.G.A. Huizing, J.J.T.M. Donkers, J.H. Klootwijk, D.Hartskeerl, W.B. de Boer, R.J. Havens, R.van der Toorn, J.C.J. Paasschens, W.J. Kloosterman, J.G.M. van Berkum, D. Terpstra, and J.W. Slotboom, in Proceedings of the Bipolar Circuits and Technology Meeting, pp. 30-33, 2001.
- ”Improved compact modeling of the output conductance and cutoff frequency of bipolar transistors”, J.C.J. Paasschens, W.J. Kloosterman, R.J. Havens, and H.C. de Graaff, IEEE J. of Solid-State Circuits, vol. 36, pp. 1390-1398, 2001.
- ”Improved modeling of output conductance and cut-off frequency of bipolar transistors”, J.C.J. Paasschens, W.J. Kloosterman, R.J. Havens, and H.C. de Graaff, in Proceedings of the Bipolar Circuits and Technology Meeting, pp. 62-65, 2000. Paper 3.3.

Mextram related publications (II)

- ”A comprehensive bipolar avalanche multiplication compact model for circuit simulations”, W.J. Kloosterman, J.C.J. Paasschens, and R.J. Havens, in Proceedings of the Bipolar Circuits and Technology Meeting, pp. 172-175, 2000. Paper 10.1.
- ”An S-parameter technique for substrate resistance characterization of RF bipolar transistors”, S.D. Harker, R.J. Havens, J.C.J. Paasschens, D. Szmyd, L.F. Tiemeijer, and E.F. Weagel, in Proceedings of the Bipolar Circuits and Technology Meeting, pp. 176-179, 2000. Paper 10.2.
- ”Improved Extraction of Base and Emitter Resistance from Small Signal High Frequency Admittance Measurements”, W.J. Kloosterman, J.C.J. Paasschens and D.B.M. Klaassen, Proceedings of the 1999 Bipolar Circuits and Technology Meeting (BCTM'99), pp. 93-96.
- ”Extension of the Collector Charge Description for Compact Bipolar Epilayer Models”, Leo C.N. de Vreede, Henk C. de Graaff, Joseph L. Tauritz, and Roel G.F. Baets, IEEE Trans. on Electron Devices, vol. ED-45, no. 1, pp. 277-285, 1998.
- ”Advanced modeling of distortion effects in bipolar transistors using the Mextram model”, L.C.N. de Vreede, H.C. de Graaff, K. Mouthaan, M. de Kok, J.L. Tauritz, and R.G.F. Baets, IEEE J. of Solid-State Circuits, vol 31, pp. 114-121, Jan. 1996.
- ”Efficient Parameter Extraction for the Mextram model”, W.J. Kloosterman, J.A.M. Geelen and D.B.M. Klaassen, Proceedings of the 1995 Bipolar Circuits and Technology Meeting (BCTM'95), pp. 70-73.
- ”Modeling of the Collector Epilayer of a Bipolar Transistor in the Mextram Model”, H.C. de Graaff and W.J. Kloosterman, IEEE Trans. on Electron Devices, vol. ED-42, no. 2, pp. 274-282, 1995.
- ”Advanced modelling of distortion effects in bipolar transistors using the Mextram model”, L.C.N. de Vreede, H.C. de Graaff, K Mouthaan, M. de Kok, J.L. Tauritz and R.G.F. Baets, Proceedings of the 1994 Bipolar Circuits and Technology Meeting (BCTM'94), pp. 48-51.

Mextram related publications (III)

- ”Distributed high frequency effects in Bipolar Transistors” M.P.J.G. Versleijen, Proceedings of the 1991 Bipolar Circuits and Technology Meeting (BCTM'91), pp. 85-88.
- ”The influence of Non-Ideal Base Current on 1/F noise Behaviour of Bipolar Transistors”, M.C.A.M. Koolen and J.C.J. Aarts, Proceedings of the 1990 Bipolar Circuits and Technology Meeting (BCTM'90), pp. 232-235.
- "Compact Transistor Modelling for Circuit Design", H.C. de Graaff and F.M. Klaassen, Springer-Verlag, Wien, New York, 1990.
- ”Avalanche multiplication in a compact bipolar transistor model for circuit simulation”, W.J. Kloosterman and H.C. de Graaff, IEEE Trans. Elec. Dev., vol. ED-36, pp. 1376-1380, 1989.
- “Experience with the New Compact Mextram Model for Bipolar Transistors”, H.C. de Graaff, W.J. Kloosterman, J.A.M. Geelen and M.C.A.M. Koolen, Proceedings of the 1989 Bipolar Circuits and Technology Meeting (BCTM'89), pp. 245-249.
- "Compact Bipolar Transistor Model for CACD, with Accurate Description of Collector Behaviour", H.C. de Graaff, W.J. Kloosterman, and T.N. Jansen, in Proc. Conf. on Solid-State Dev. and Mat. (Tokyo), pp. 287-290, 1986.
- "New Formulation of the Current and Charge Relations in Bipolar Transistor Modeling for CACD Purposes", H.C. de Graaff and W.J. Kloosterman, IEEE Trans. on Electron devices, vol. ED-32, no. 11, pp. 2415-2419, 1985.

Conclusions – Summary

- History Mextram development given
  - Since fall 2015 Mextram is maintained and developed by Auburn University (Guofu Niu)
- Equivalent circuit of Mextram discussed
- Parameter extraction methodology and results addressed
- Overview of documentation and Mextram related publications provided

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