PHILIPS

Modelling of Si and SiGe bipolar transistors with the compact model Mextram, level 504

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Introduction

- Mextram is a bipolar compact model
  - just as Spice-Gummel-Poon, but more advanced
- Mextram has been developed by Philips Research
  - Physics based
  - Suitable for digital and analogue applications
  - Ready for SiGe processes
- History

  1985 Introduction

  1987 Mextram 502

  1993 Mextram 503

  2000 Mextram 504

Introduction

Why did we make an update Mextram, level 504?

- Applications go to higher frequencies
- Distortion becomes more important
- New important physical effects (e.g. self-heating)
- New technologies (e.g. SiGe)

- Easier parameter extraction
- Better operating point information

Major differences Mextram 503 and 504

- Addition of Early voltage parameters
- More independence in extraction
- Smoother behaviour in quasi-saturation/f_T
- Addition of optional effects
  - Grading in Ge profile
  - Neutral base recombination
  - Self-heating
- Better operating point output
- Better documentation

Why this tutorial?

- Many people use Mextram: design/characterisation
- To be able to do this they need to understand
  - basics the model
  - some details of specific parts
  - what is part of the model, and what is done outside
  - how to use it
  - what some of the limitations are
- This presentation intends to help in understanding Mextram

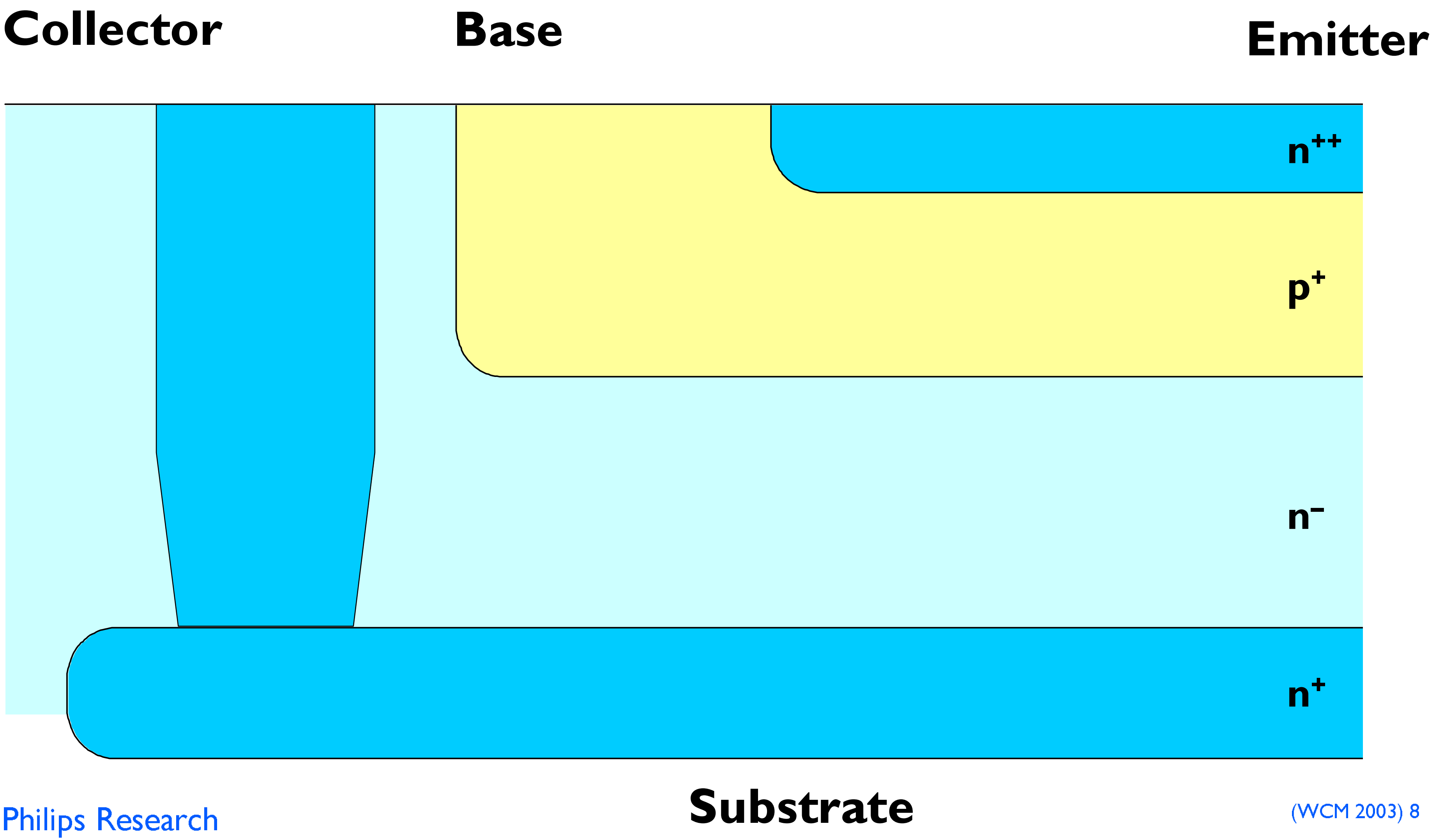
Contents

- Equivalent circuit
- Intrinsic transistor
  - main current
  - depletion and diffusion capacitances
  - optional: graded SiGe profile
- Base resistance
- Avalanche
  - optional: snapback
  - optional: neutral-base-recombination
- Epilayer model

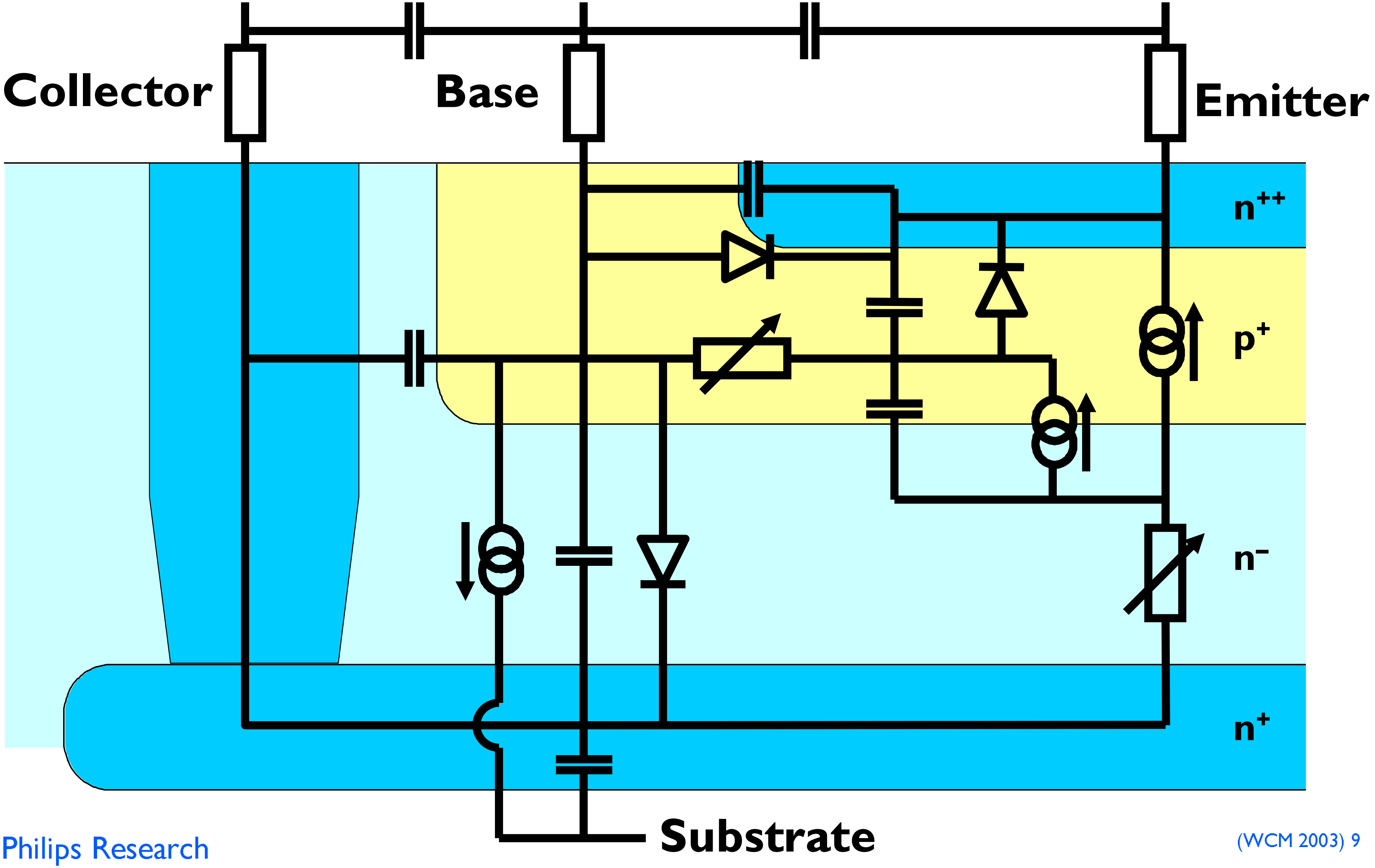
Contents (cont.)

- Extrinsic regions
  - substrate network
- Temperature scaling
- Self-heating
  - mutual heating
- Geometry scaling
- Noise
- Status
  - availability, documentation, code, standardisation

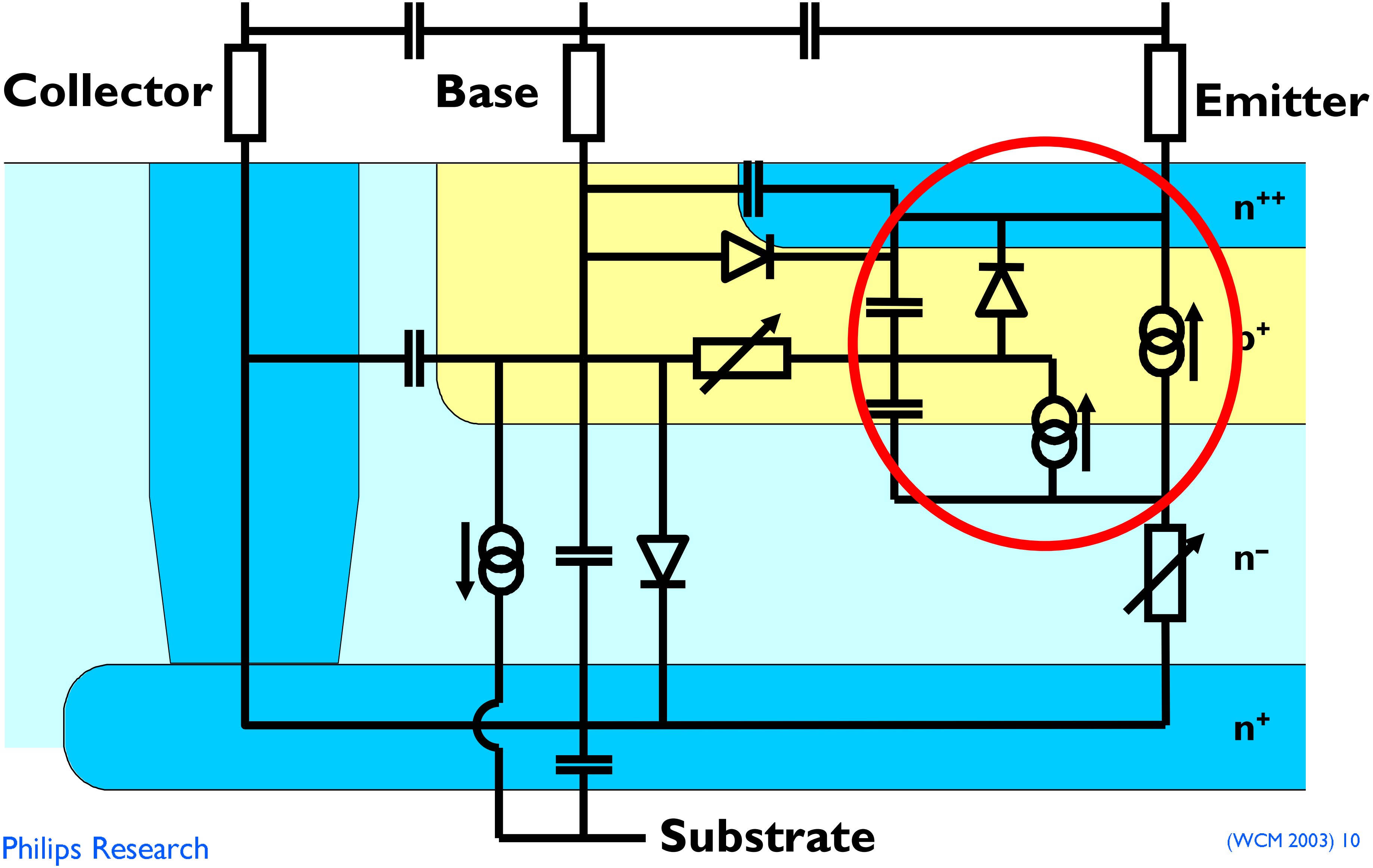
Simplified cross section



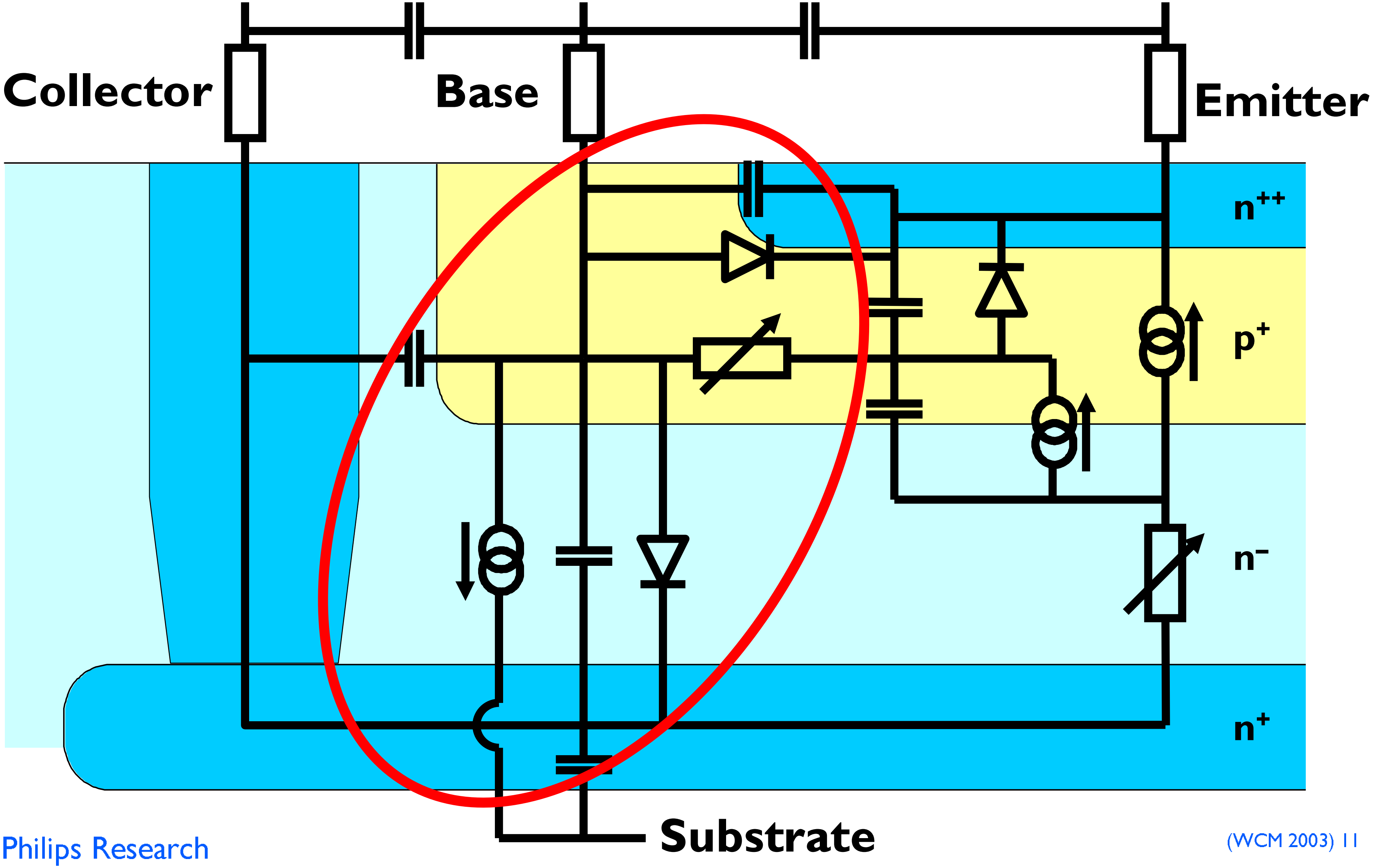
Equivalent circuit (w/o optional elements)



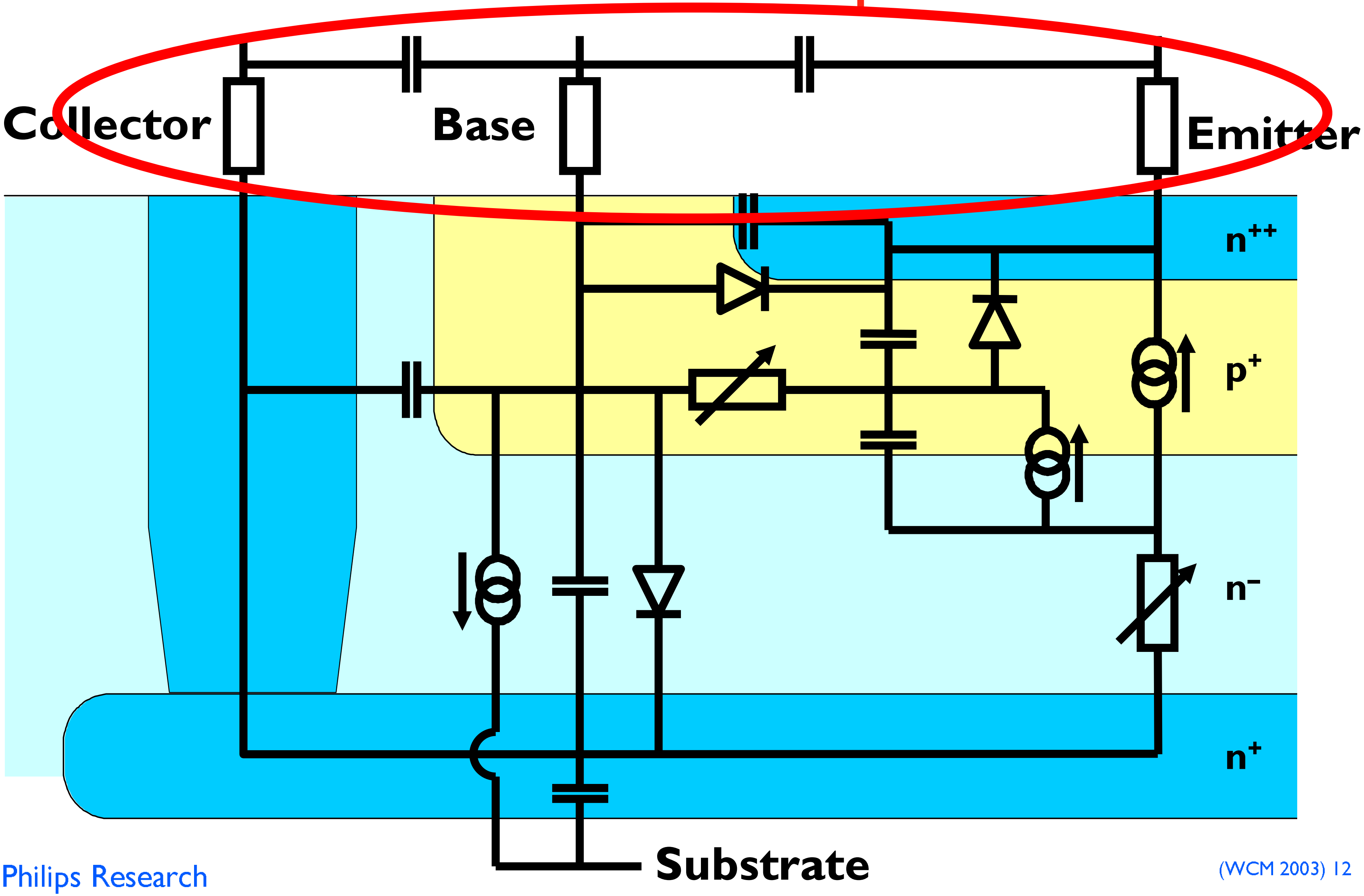
Intrinsic transistor



Extrinsic transistor and parasitic PNP



Constant resistances and capacitances



Constant resistances

Emitter resistance	RE
Collector resistance	RCC
Base resistance	RBC

Constant capacitances

Base-emitter overlap capacitance	CBEO
Base-collector overlap capacitance	CBCO

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⇒Intrinsic transistor
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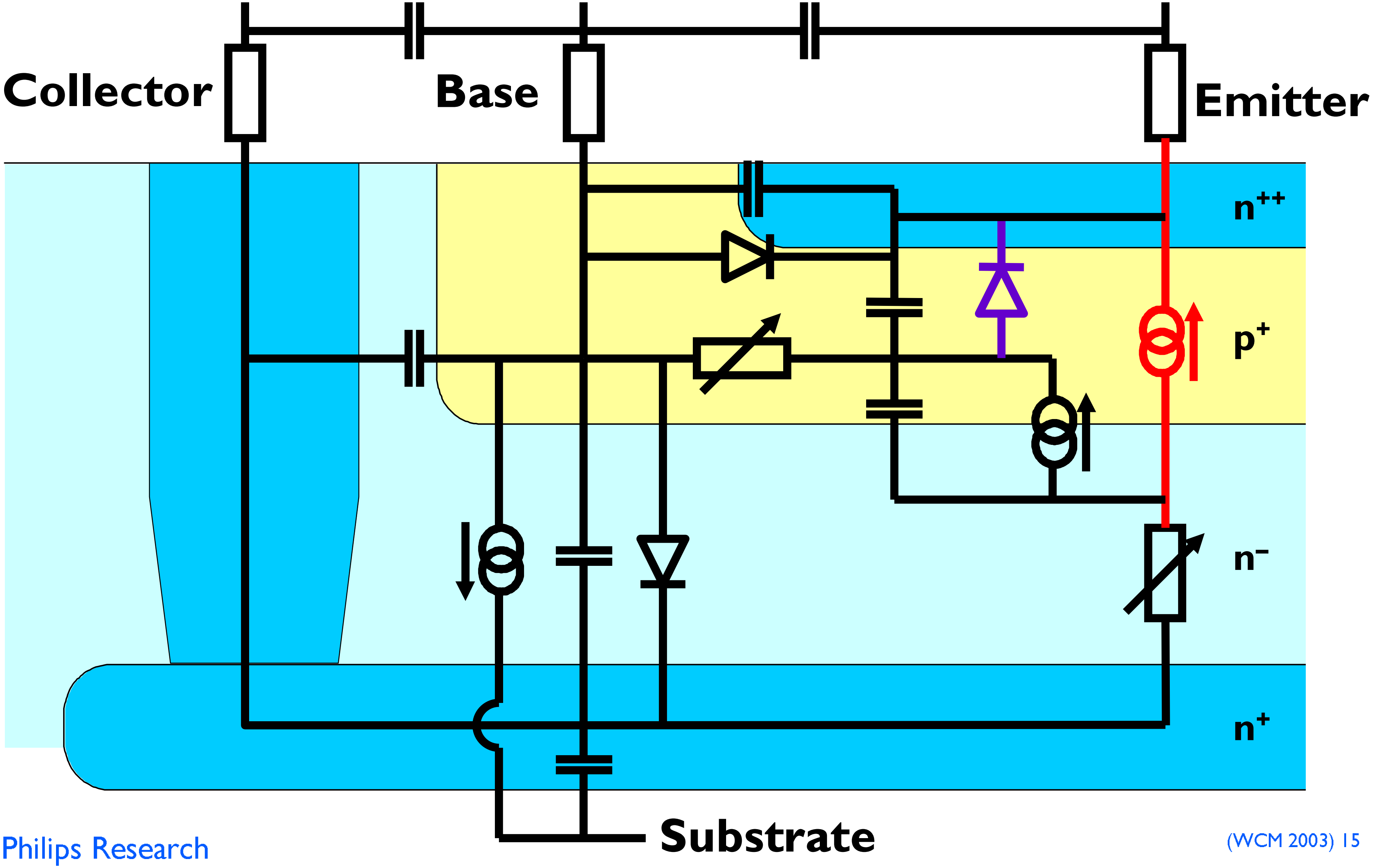
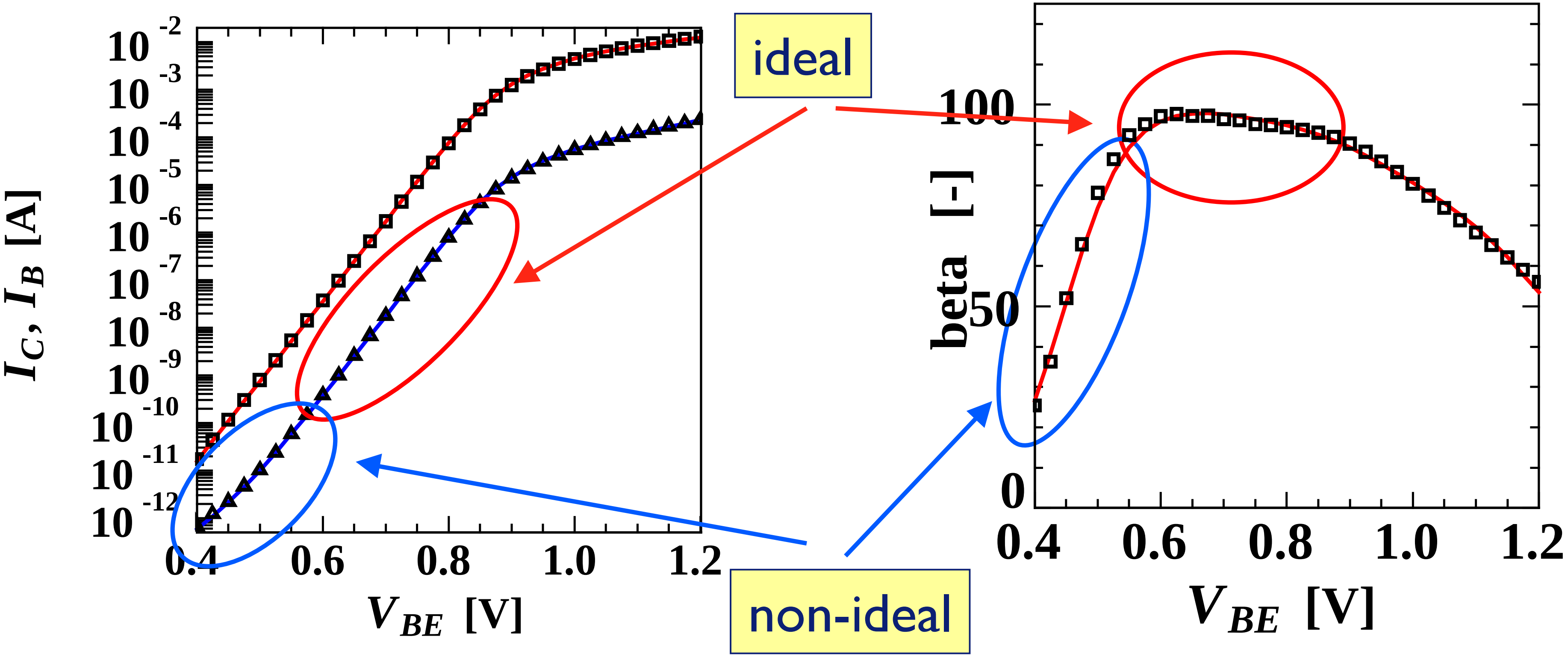
Main current I_N and forward base current



Forward base current



ideal

non-ideal

- Both an ideal and a non-ideal part

$$IB = \frac{IS}{BF}\left[\exp\left(V_{BE}/VT\right) - 1\right] + IBF\left[\exp\left(V_{BE}/MLF \cdot V_T\right) - 1\right]$$

Main current

- All modern compact models are based on

  Gummel's charge control relation

$$I_C = IS\left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right)\right]\frac{Q_{B0}}{Q_{Btot}}$$

- Symmetric w.r.t. emitter and collector
- Q_{Btot} (total hole charge in base) contains:
  - Early effect
  - High injection in the base (knee effect)
  - Quasi-saturation/Kirk effect

Main current: Early effect

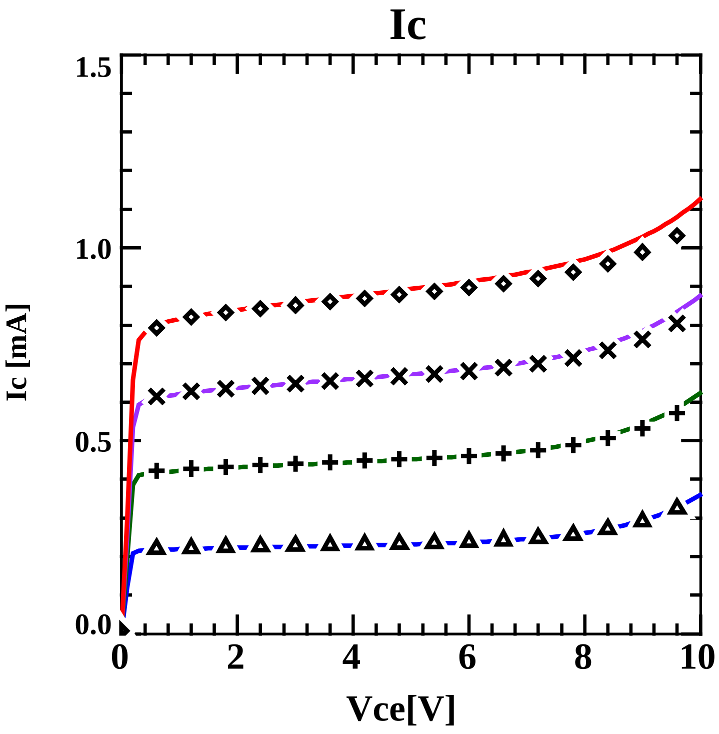
- Early effect:
  - change in depletion layer width
  - change in depletion charges $Q_{BE,depl}$ and $Q_{BC,depl}$
  - $Q_{Btot} = Q_{B0} + Q_{BE,depl} + Q_{BC,depl}$
- Actual implementation uses normalisation

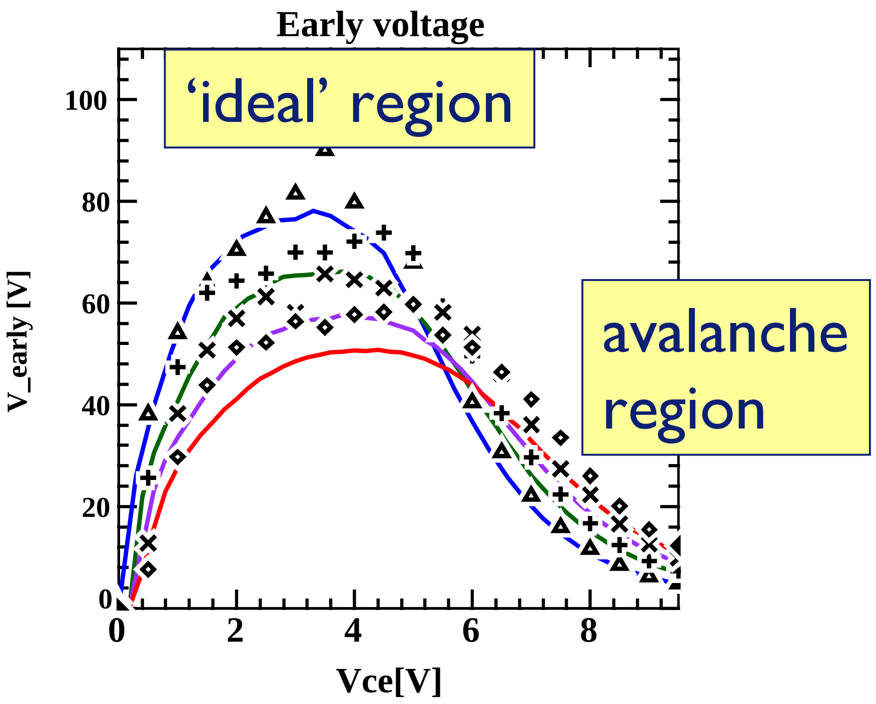
$$\frac{Q_{Btot}}{Q_{B0}} = 1 + \frac{V_{BE,depl}}{VER} + \frac{V_{BC,depl}}{VEF}$$

- Two Early parameters VEF and VER

Main current: Early effect

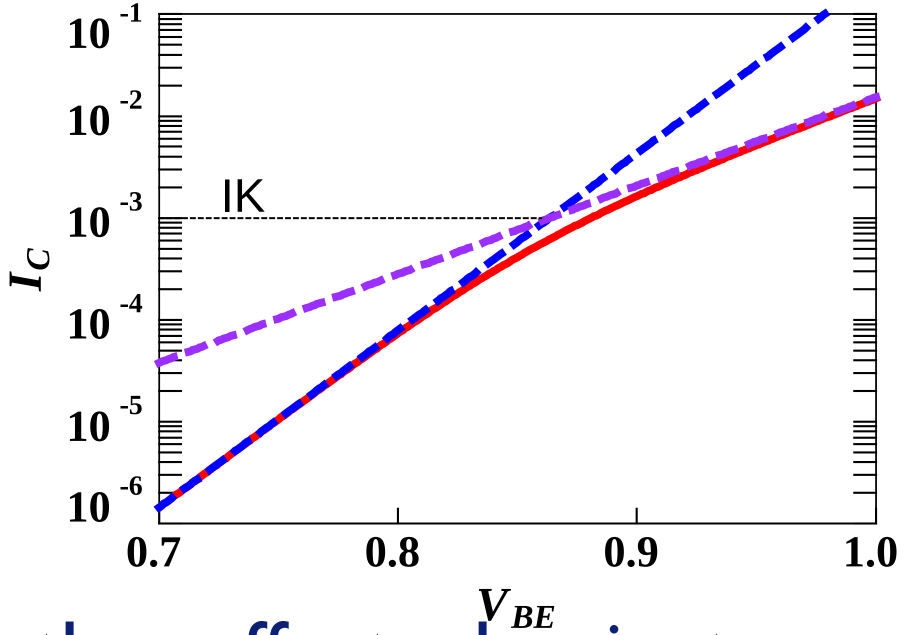
- Collector current shows curvature
  →non-constant Early voltage around





Main current: knee

- Intrinsic current contains knee
- Mextram: only one knee current parameter IK



- Normally other effects dominate
- SiGe: sometimes high-injection in emitter-cap

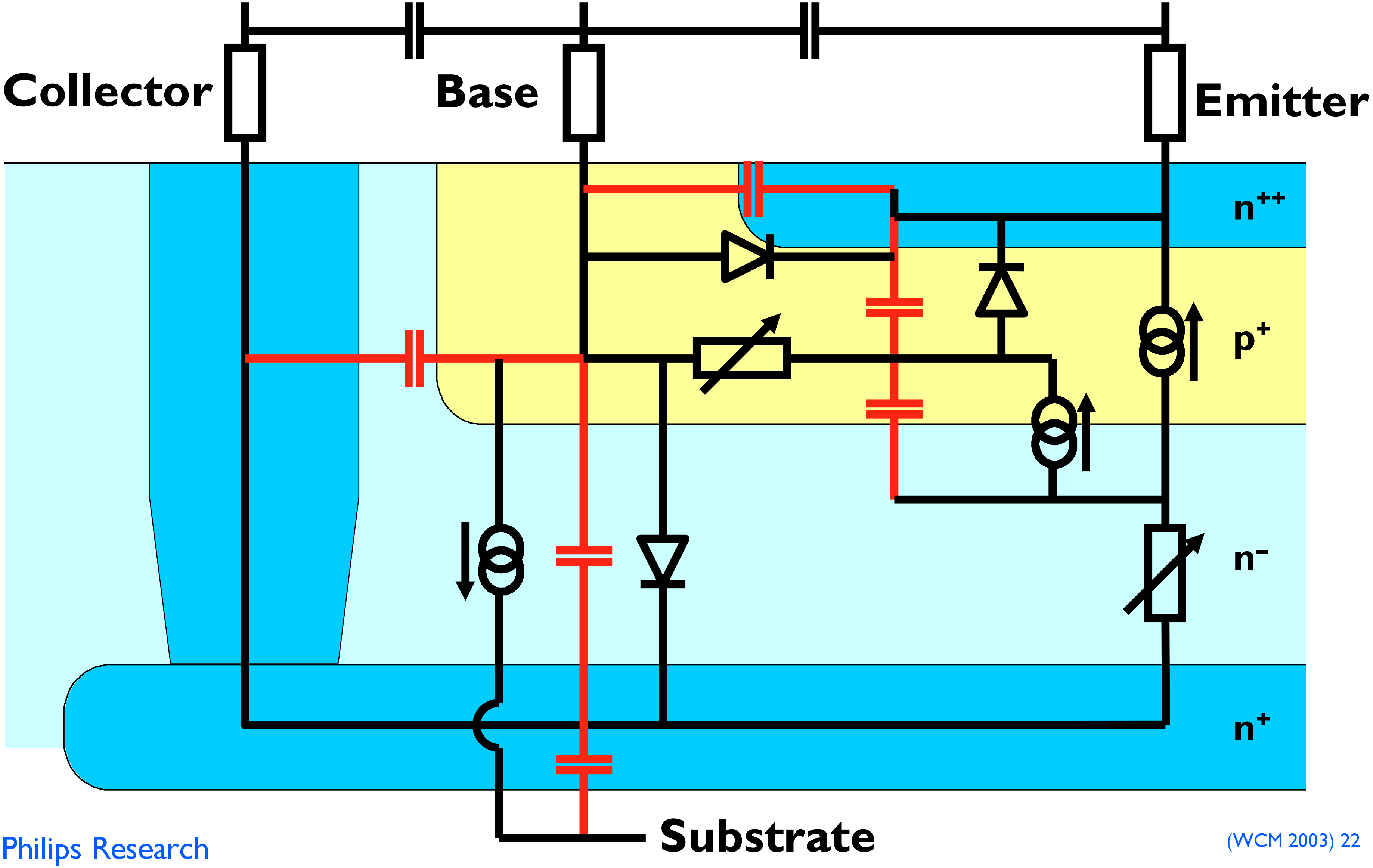
Main current: knee

- High injection in base:
  - charge in base: diffusion charges $Q_{BE,diff}$ and $Q_{BC,diff}$
  - $Q_{Btot} = Q_{B0} + Q_{BE,diff} + Q_{BC,diff}$
  - charges proportional to electron densities n_{BE}, n_{BC}
  - charges depend on voltage not current

- Actual implementation uses normalisation

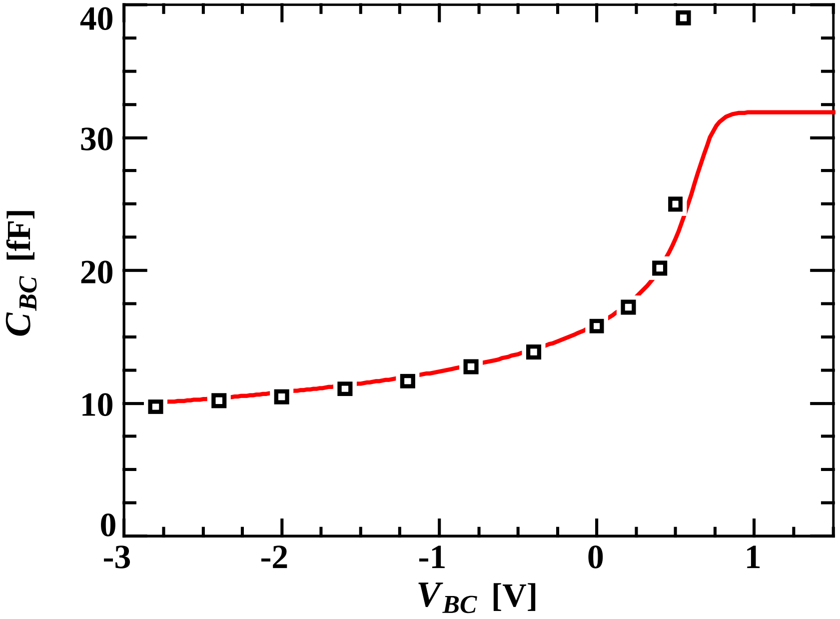
$$\frac{Q_{Btot}}{Q_{B0}} = 1 + \tfrac{1}{2} n_{BE}(V_{BE}) + \tfrac{1}{2} n_{BC}(V_{BC})$$

Depletion capacitances



Depletion capacitances

- Normal behaviour in reverse bias
- Constant capacitance in forward bias
  (where diffusion capacitance dominates)

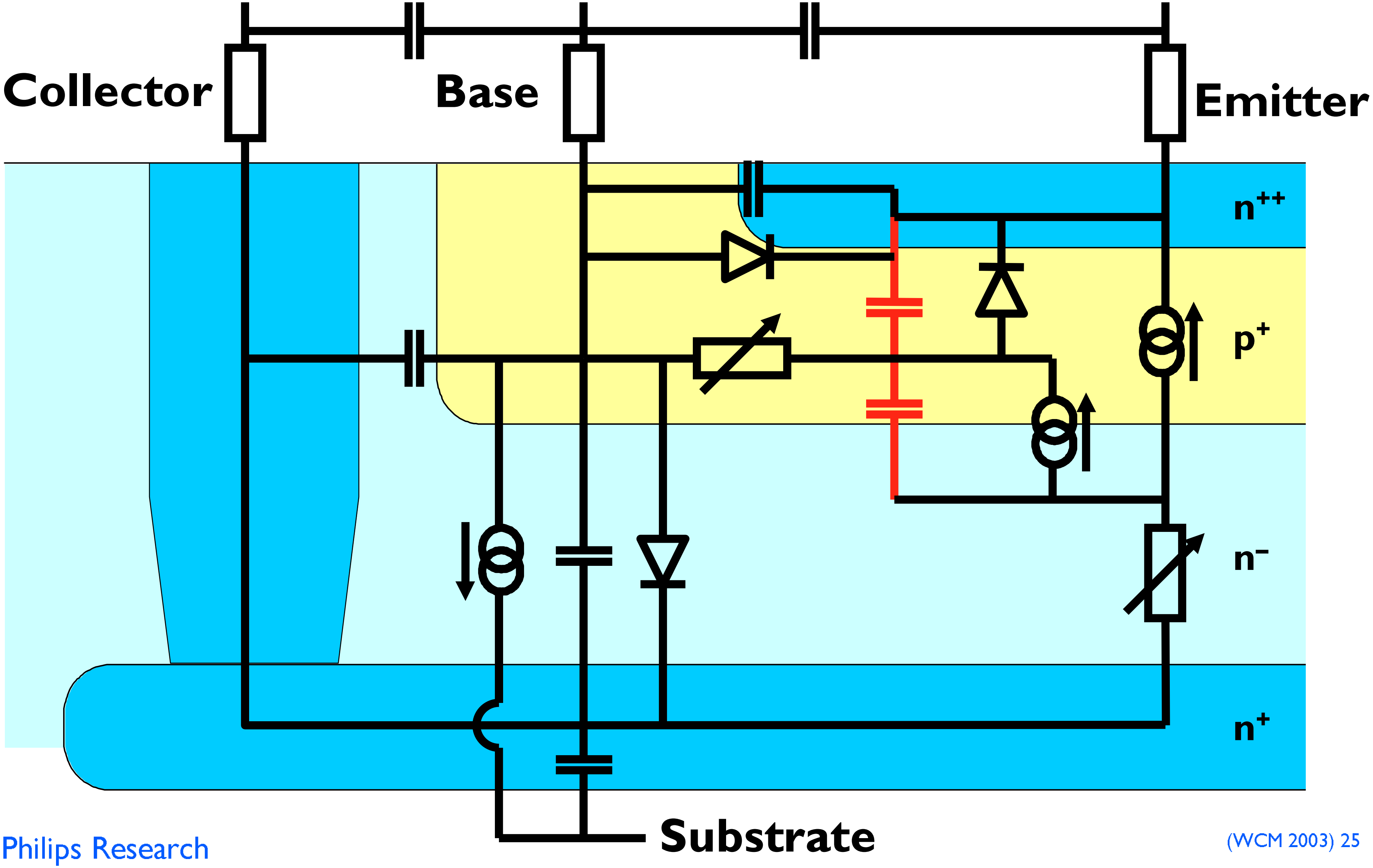


Depletion capacitances

- Zero-bias capacitances: CJE, CJC, CJS
- These parameters do not influence current

- Capacitances are split
  - Base-Emitter: 2 parallel
  - Base-Collector: 3 parallel
- Better RC-delay time modelling
- Forms basis for geometry scaling

Diffusion charges



Diffusion charges

- Again based on electron densities n_{BE}, n_{BC}
- Parameter is base-transit time TAUB

- Extra diffusion charge in emitter
  - Contains also non-ideality
  - extra parameter TAUE

- These parameters do not influence current

Contents

- Intrinsic transistor ⇒SiGe modelling
- Variable base resistance
- Avalanche
- Collector epilayer model
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SiGe modelling

- Good model for ‘Si’ suffices for large part
- In some processes additional effects can be seen

- Two optional dedicated model features
  - Gradient in Germanium content
    - seen in reverse Early effect
  - Neutral base recombination
    - seen in output conductance

SiGe modelling

- We tested Mextram on SiGe processes from:
  - Philips (obviously), production and research
  - ST
  - Infineon
  - Temic/Atmel
  - device simulations

- Also other companies use Mextram
  - TSMC, TI, …

Main current (recap.)

- All modern compact models are based on
  Gummel's charge control relation

$$I_C = IS\left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right)\right]\frac{Q_{B0}}{Q_{Btot}}$$

- Q_{Btot} (total hole charge in base) contains:
  - Early effect
  - High injection in the base (knee effect)
  - Quasi-saturation/Kirk effect

Main current for SiGe transistors

- Generalised charge control relation:

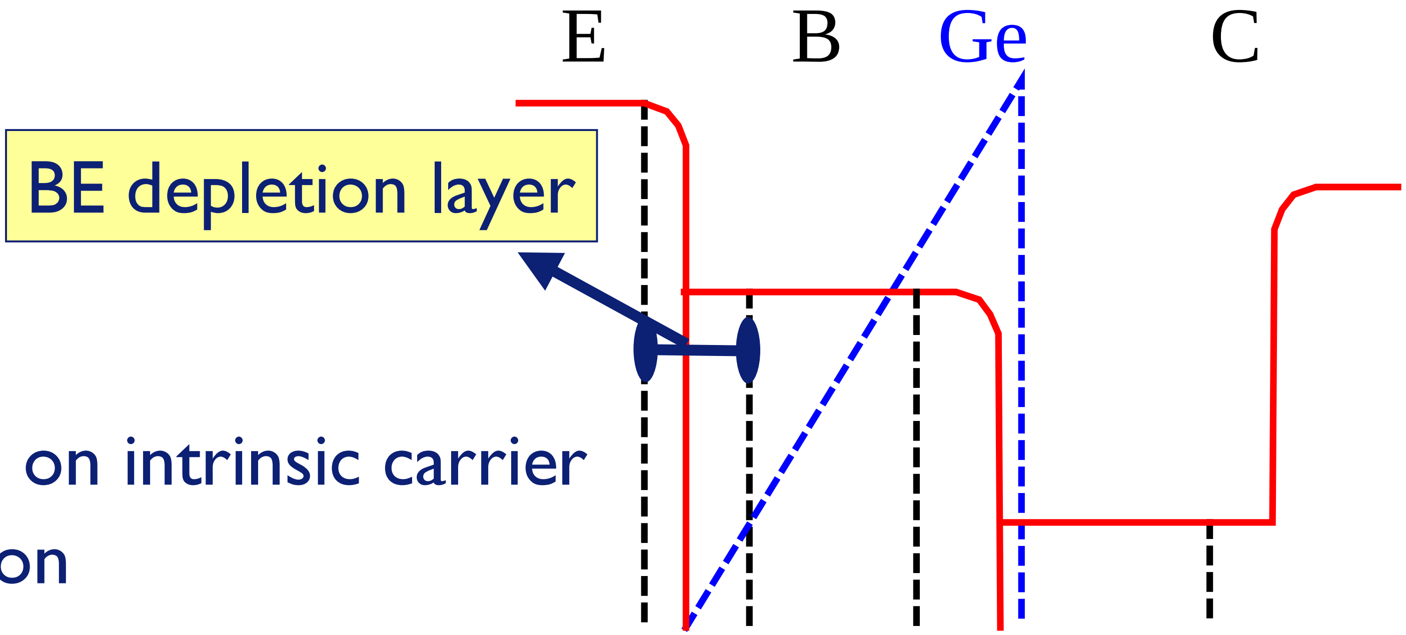
$$I_C = IS\left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right)\right]\frac{G_{B0}}{G_{Btot}}$$

- Expressed in terms of Gummel number

$$G_{Btot} = \frac{n_{i0}^2}{D_n}\int \frac{p(x)}{n_i^2(x)}\,dx$$

- G_{Btot} contains also:
  - dependence on intrinsic carrier concentration

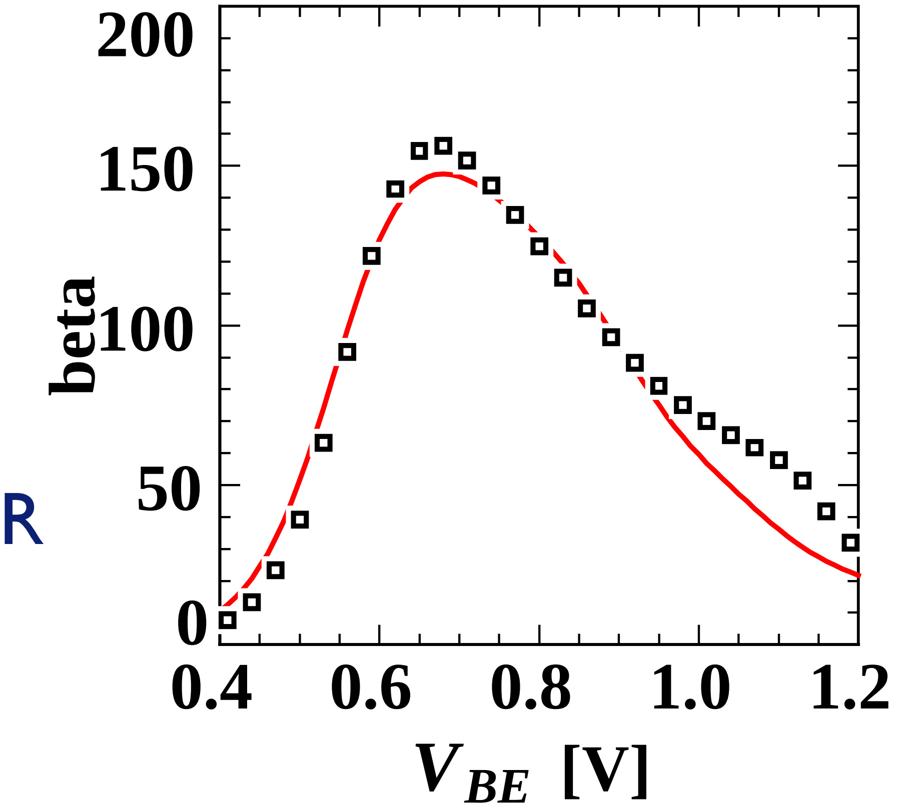
What in case of a SiGe base?



- G_B depends on intrinsic carrier concentration
- G_B depends exponentially on Ge-content

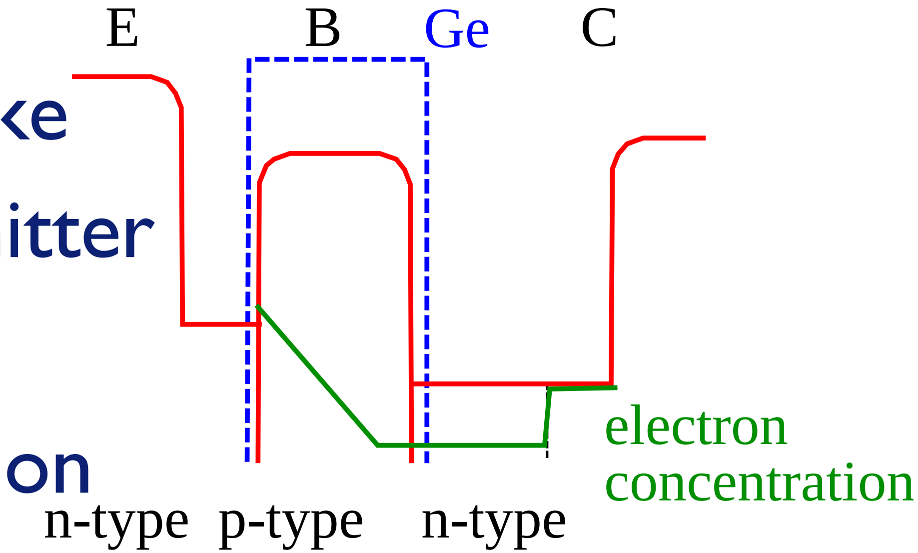
→ Early effect is sensitive to precise Ge-profile

Example



- Reverse Early effect
  - larger than in Si
  - cannot be modelled with VER because of punchthrough
- New model is optional
  - different effect on current and charge
  - parameter: DEG=ΔE_g (grade): difference in bandgap between emitter side and collector side

Alternative doping concentration



- Ge-content now step-like
- Injection of holes to emitter
  - in Si region, not SiGe
  - Large G_{Btot} contribution

- Modelled by either
  - new feature (DEG) with low VER
  - low knee current (IK)

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- Intrinsic transistor

⇒Variable base resistance

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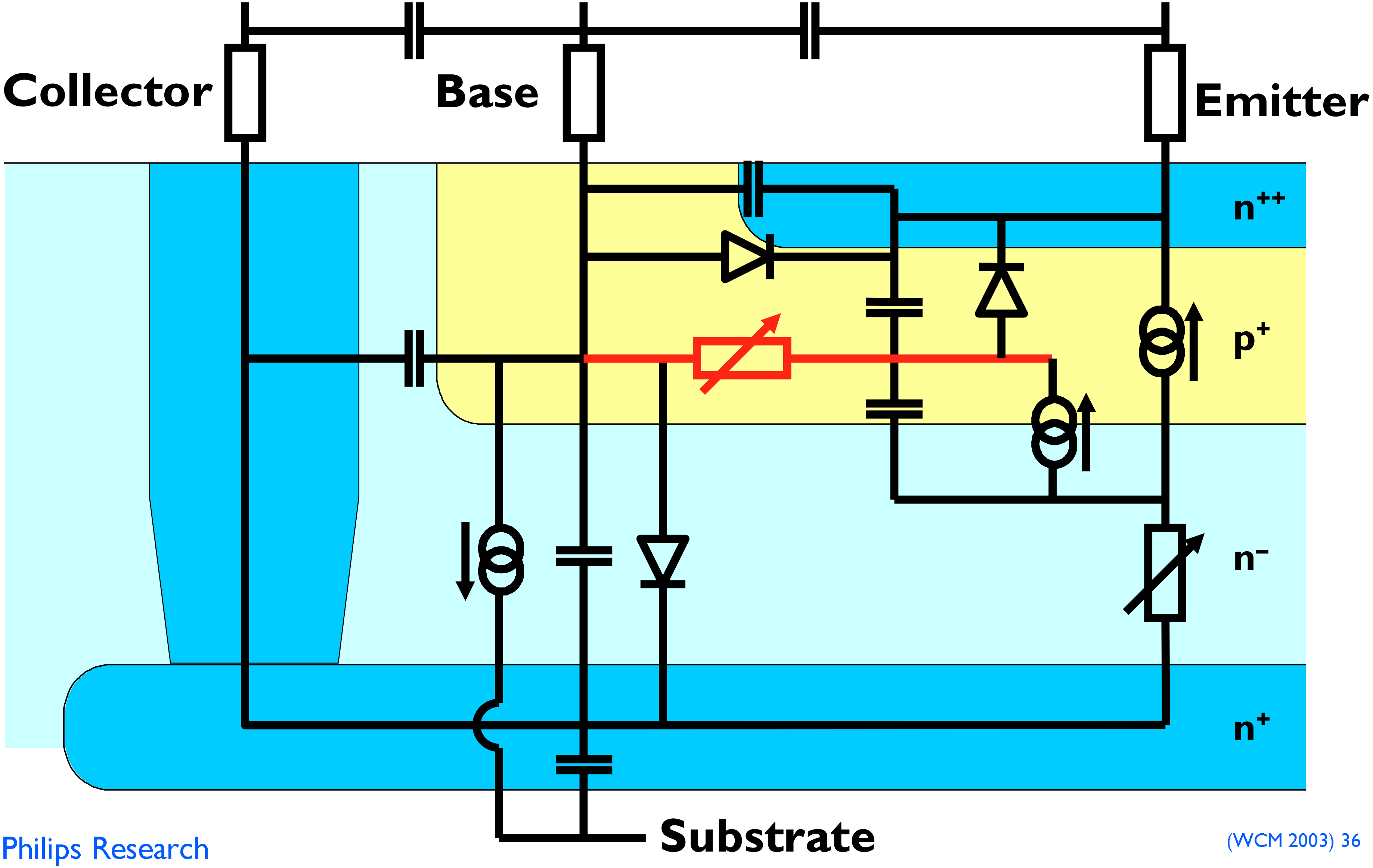
Variable base resistance



Variable base resistance

- Low current value: RBV
- High currents: models current crowding & base charge modulation
- Note:
  - do not model resistance directly
  - instead model I-V characteristic
  - gives correct resistance in DC and AC

$$I_{B_1B_2} = \frac{\left(2\,V_T\left[\exp\left(V_{B_1B_2}/V_T\right)-1\right]+V_{B_1B_2}\right)}{3\,RBV\cdot q_B}$$

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- Intrinsic transistor
- Variable base resistance

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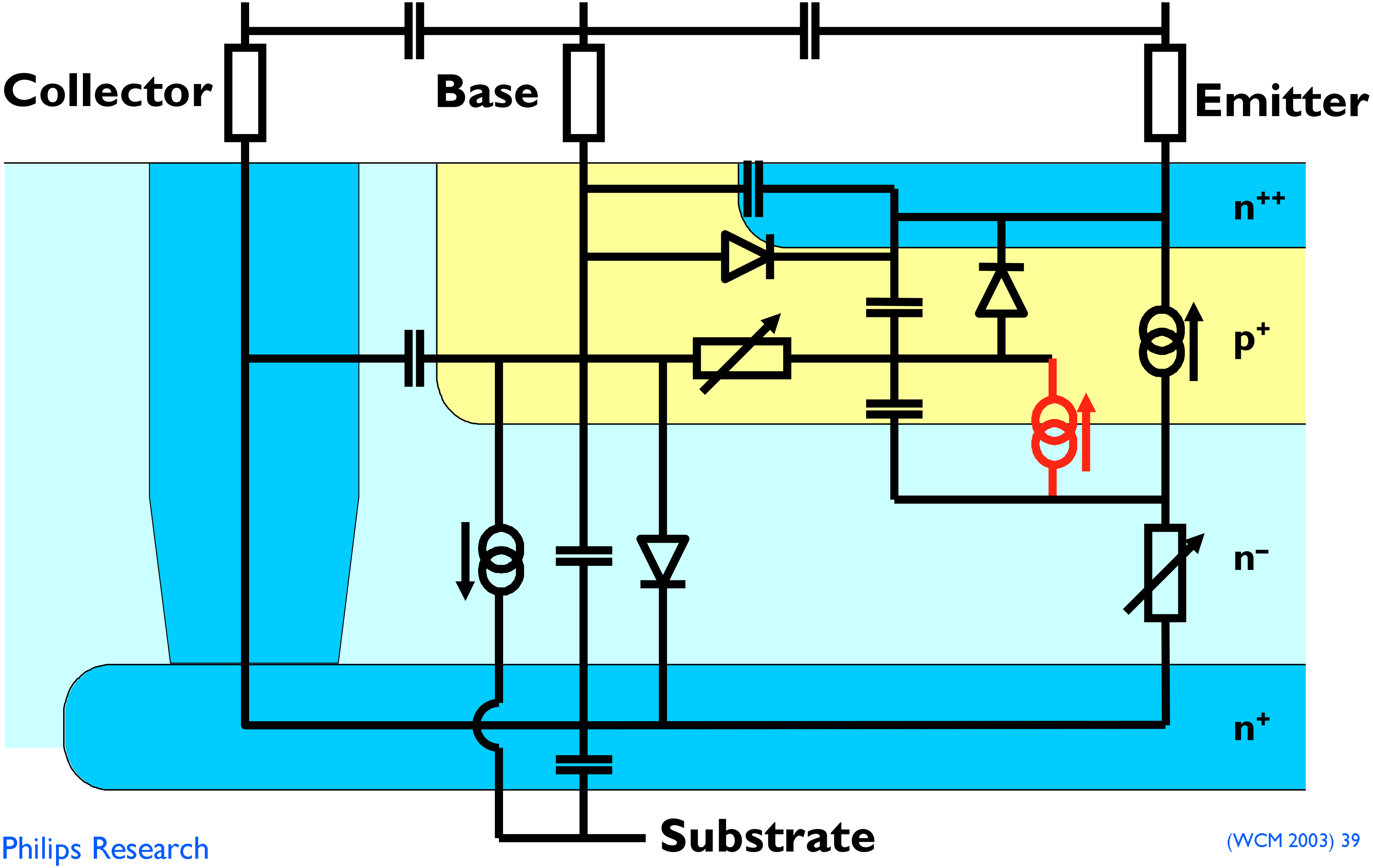
Avalanche current



Avalanche current

- Mextram models Impact Ionization

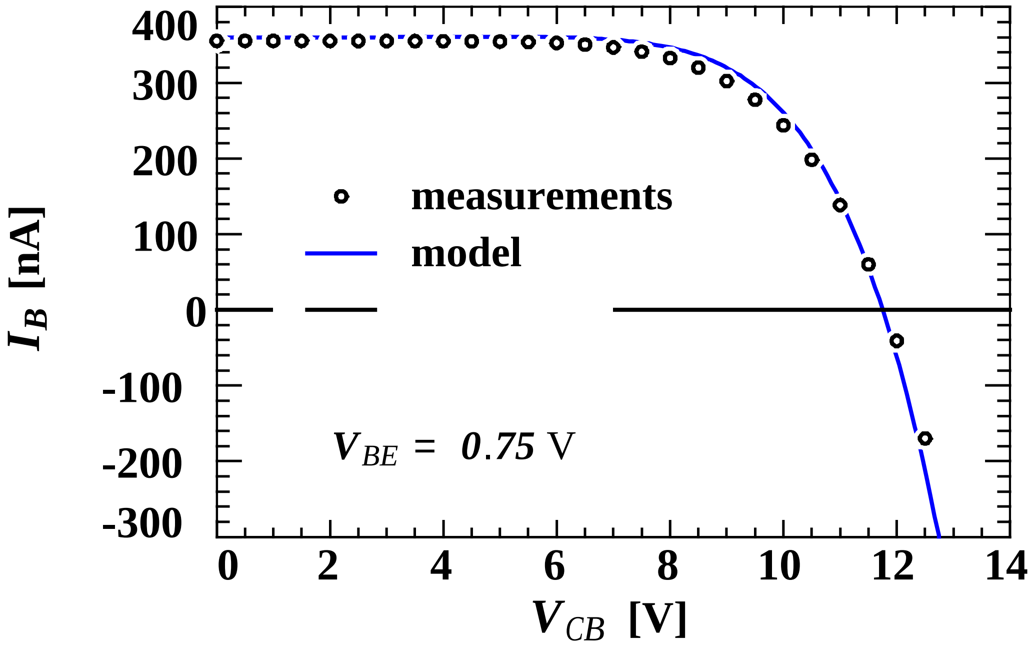
$$I_{avl} = I_C \times G_{I.I.}(V_{CB})$$

- This will not describe diode-breakdown
- Does model collector-emitter breakdown BV_{CEO}

- Uses simple I_C-dependent depletion layer model
  - independent of base-collector depletion capacitance
  - parameters: WAVL (physical effective width), VAVL

Extended avalanche

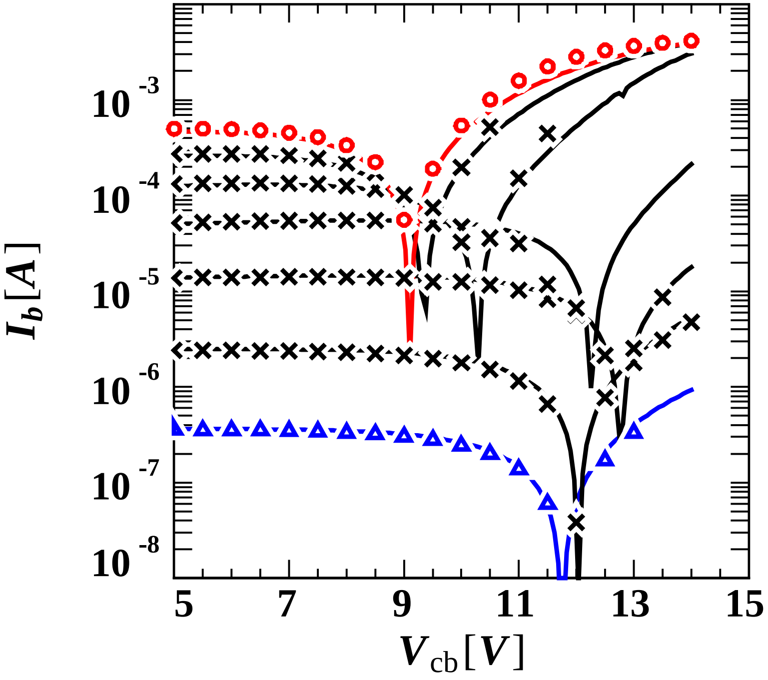
Base current



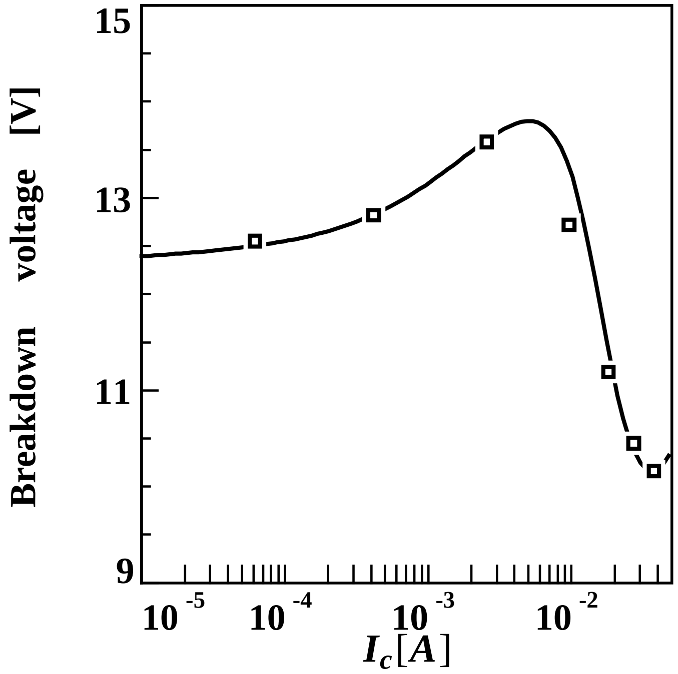
- Breakdown voltage is where $I_B=0$
  - at constant V_{BE}
  - for this process: $BV_{CEO} \approx 12$ V

Extended avalanche

Base current



$BV_{CEO} = V_{CE}$ @ $I_B=0$

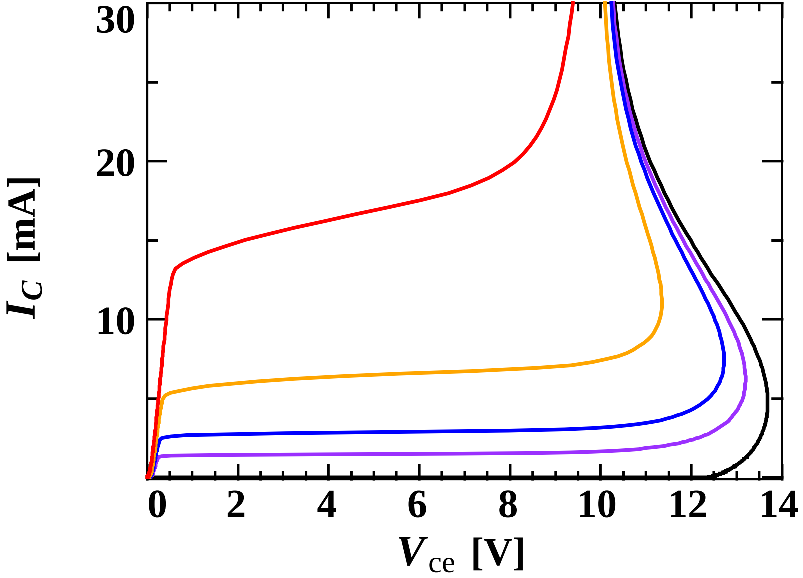


- For increasing currents, BV_{CEO} normally increases
- At high currents BV_{CEO} decreases due to Kirk effect

Extended avalanche: snapback

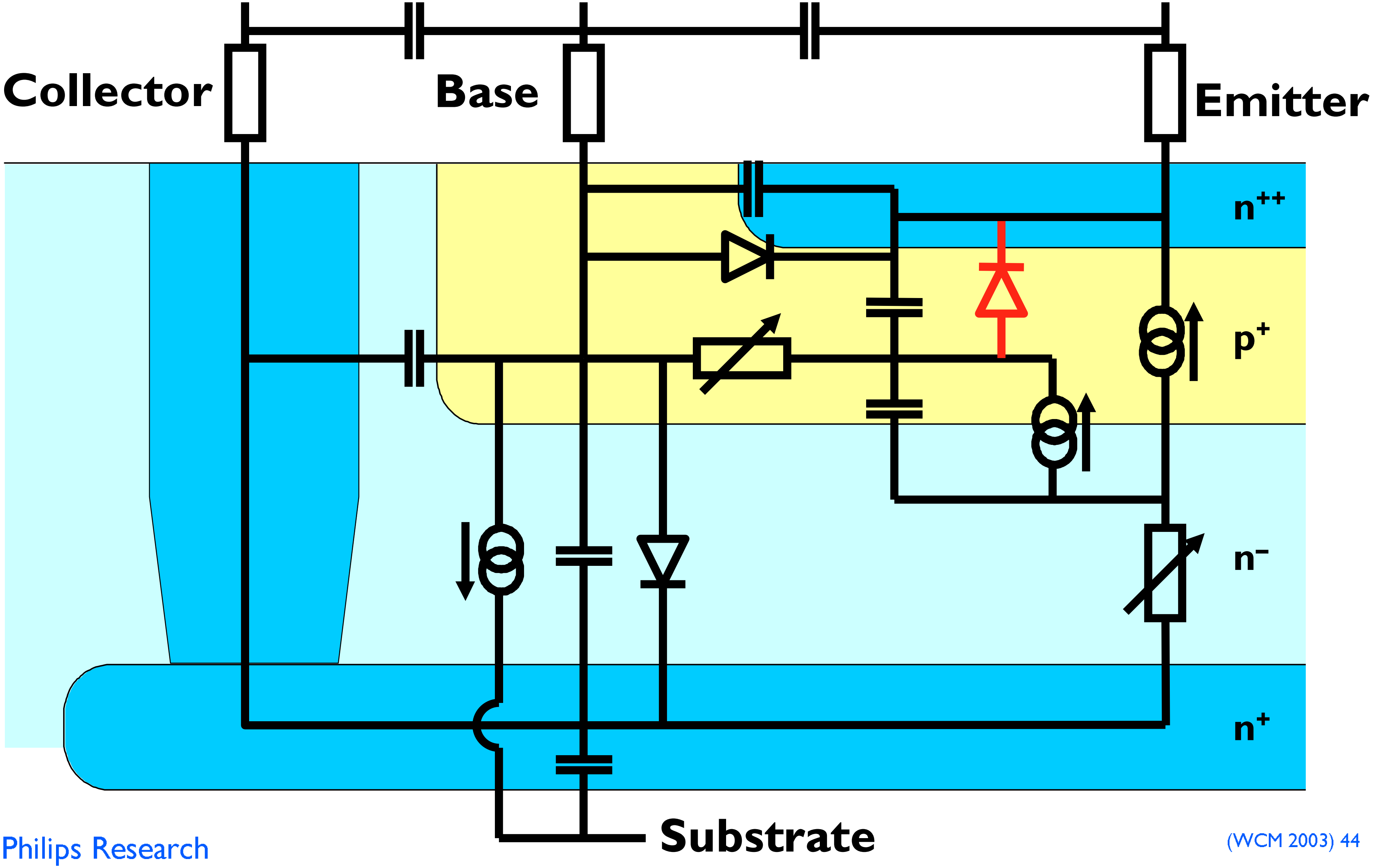
- Mextram: only model that can describe snapback

Output characteristic at constant base current



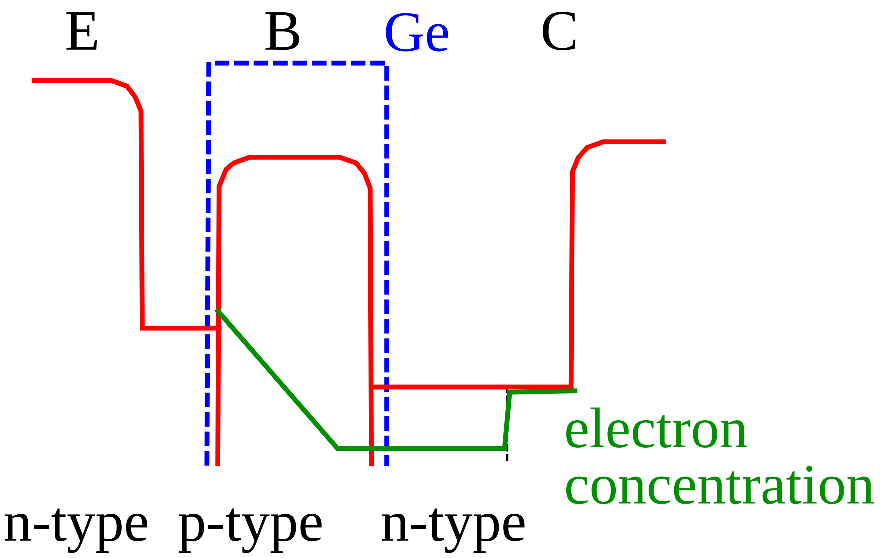
- snapback is bad for convergence: optional

Neutral base recombination (base current)



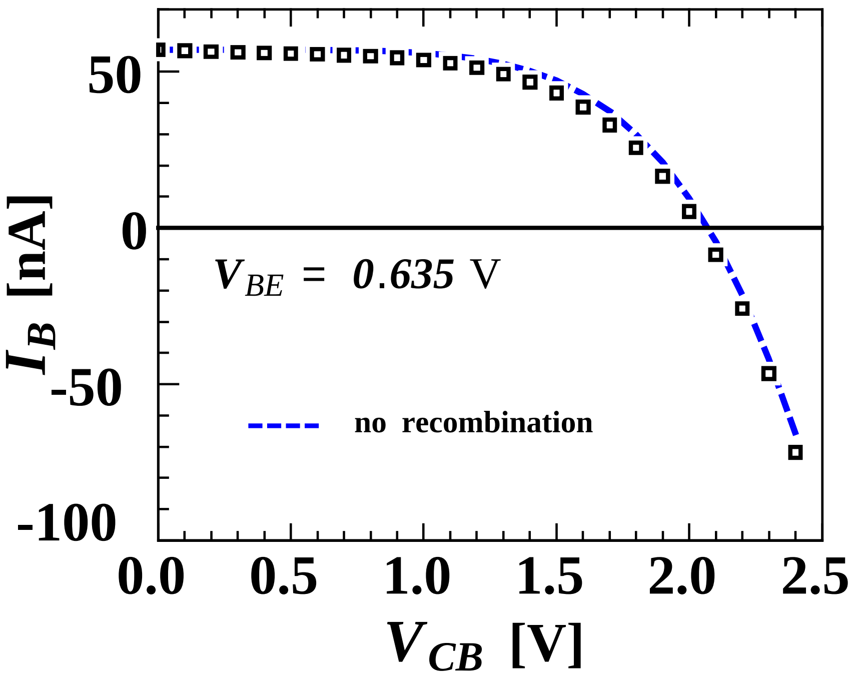
Neutral base recombination

- SiGe process
  - – higher base dope
  - – more traps
  - →more recombination



- Base current:
  - – injection of holes into emitter
  - – recombination in base (not relevant in Si)
    - → collector voltage dependent

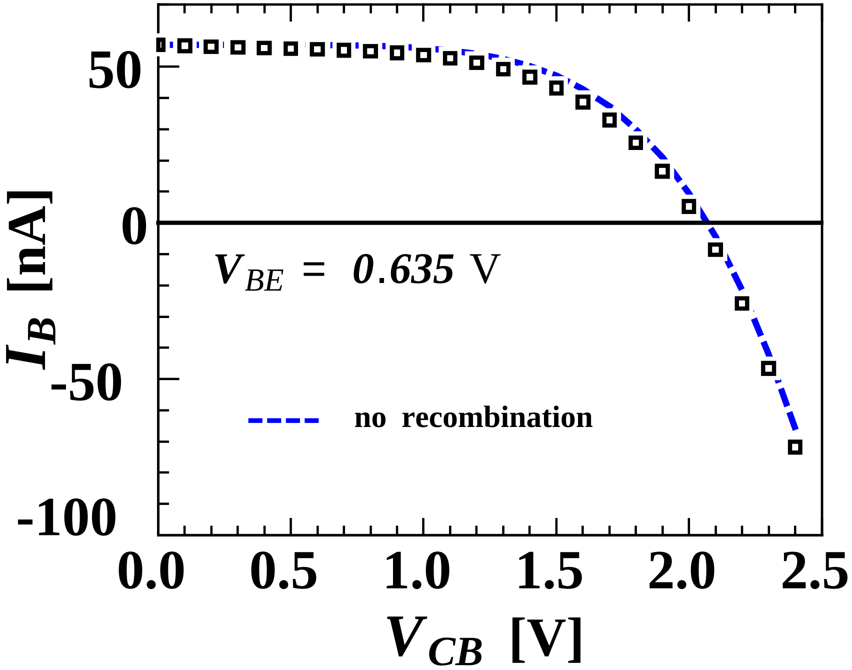
Neutral base current



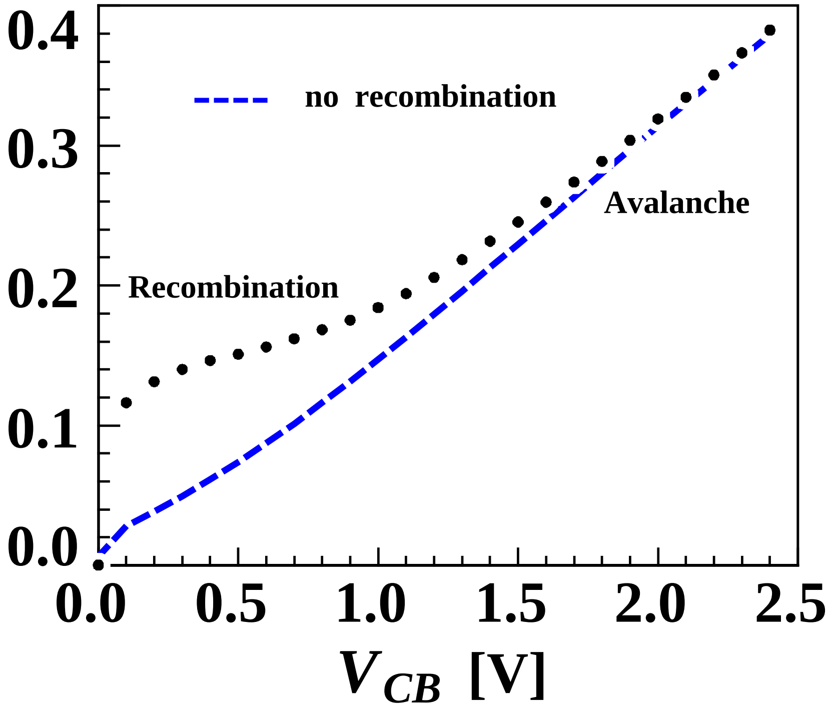
- Base current decreases with collector bias
- Large part is due to avalanche

Neutral base current

Base current

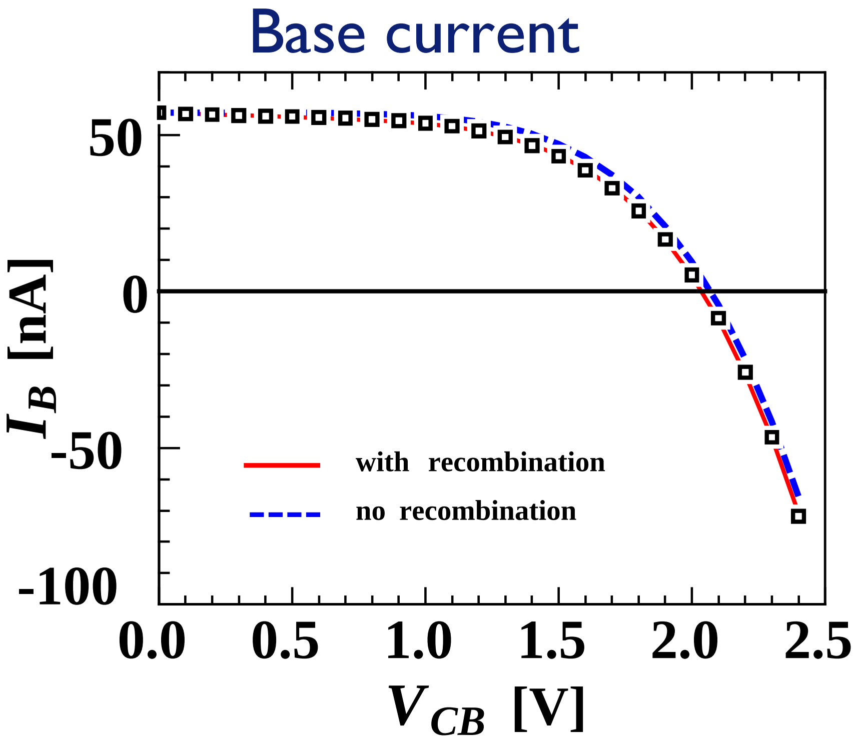


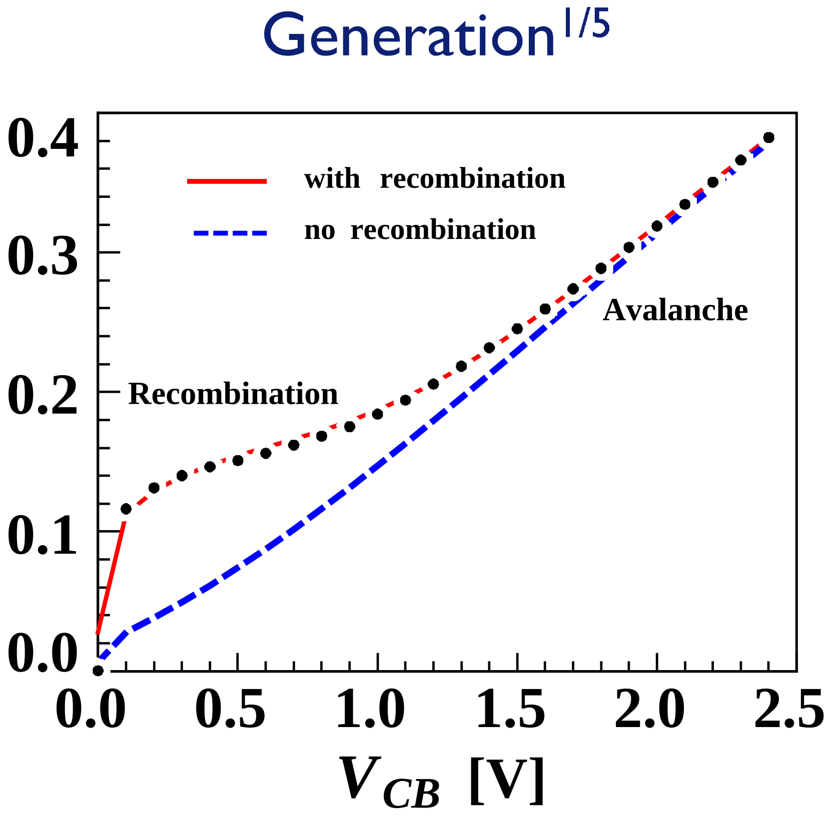
Generation$^{1/5}$



- For pure avalanche: (empirical) $I_B \approx I_{B0} - I_C \left(\frac{Vcb}{BVcbo} \right)^5$

Neutral base current



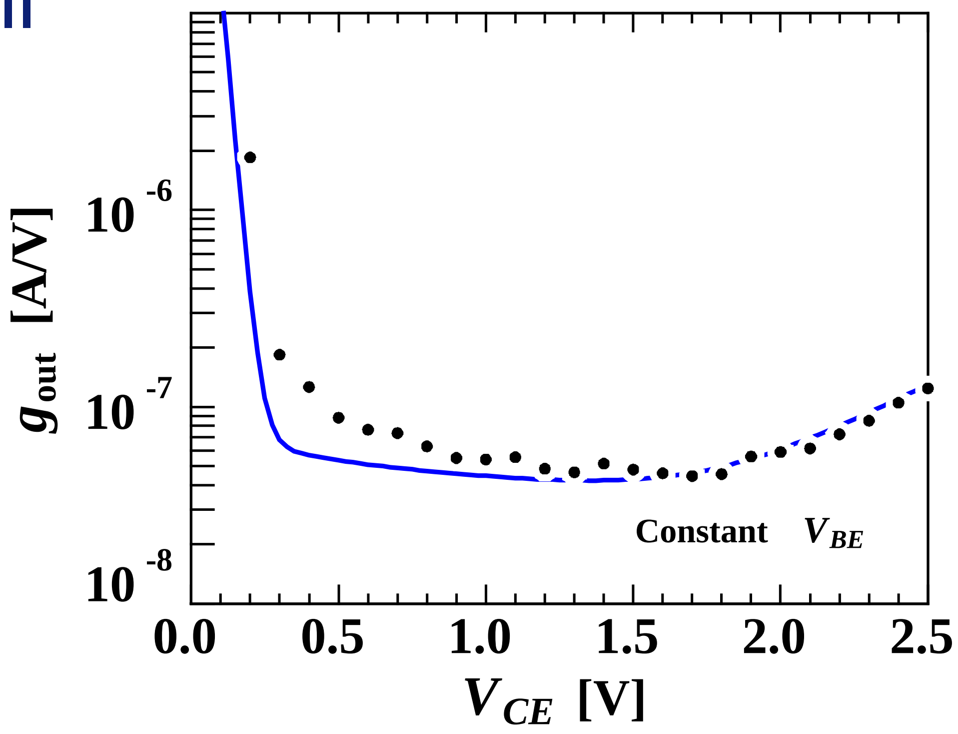


- New formulation captures the effect

Effect on output conductance

- Designers want a small output conductance

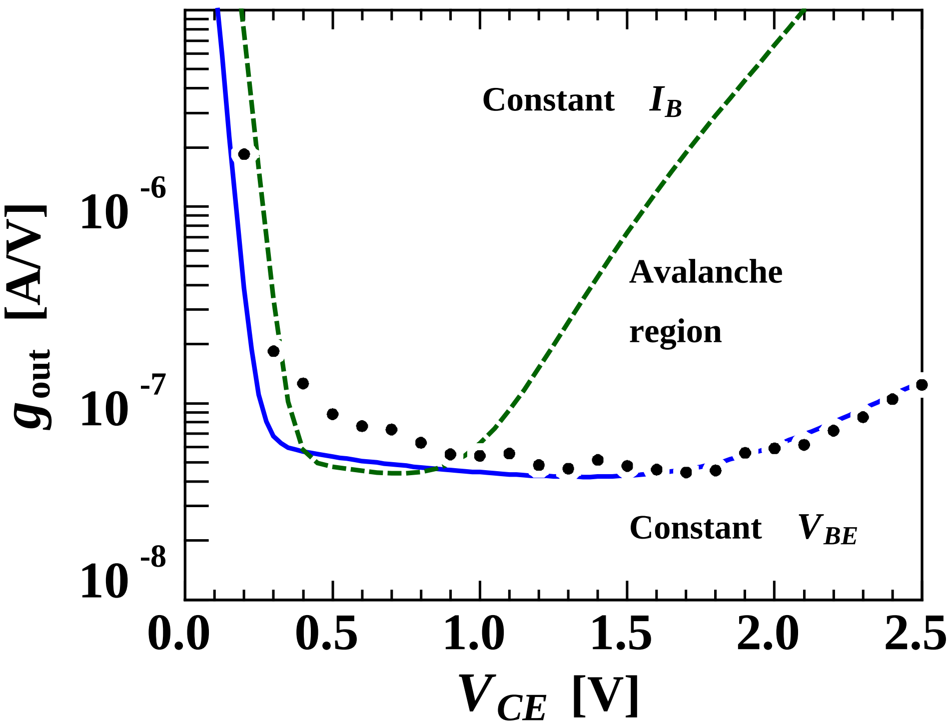
Output conductance dI_C/dV_C



Effect on output conductance

- Two ways of steering:
  - Base-emitter voltage
  - Base current (old)

Output conductance dI_C/dV_C

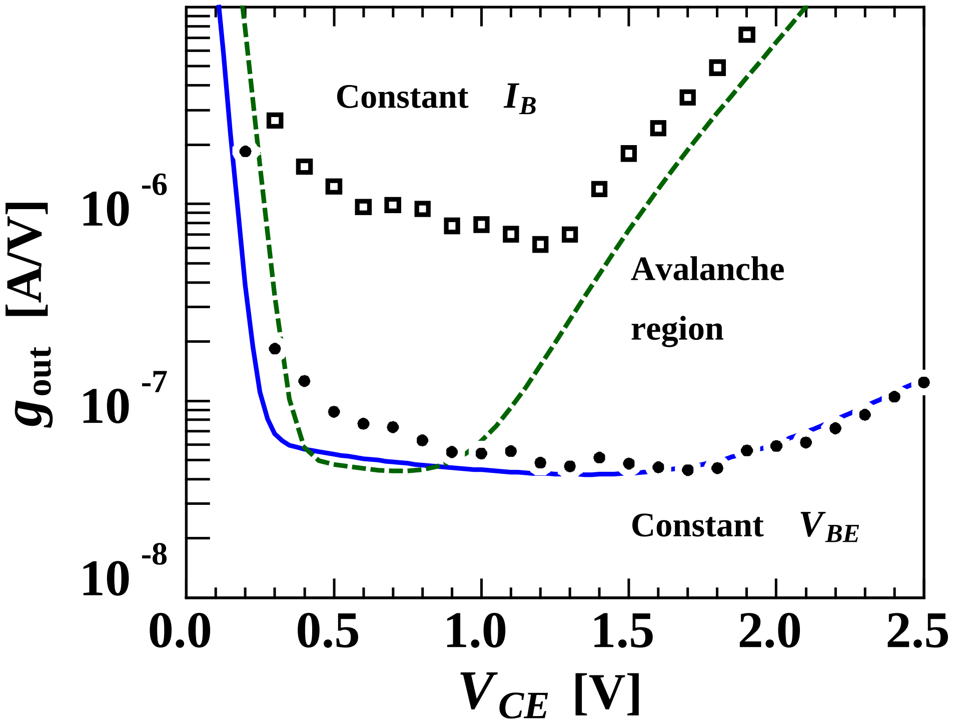


- Difference above 1.0V due to avalanche

Effect on output conductance

- Two ways of steering:
  - Base-emitter voltage
  - Base current (old)

Output conductance dI_C/dV_C

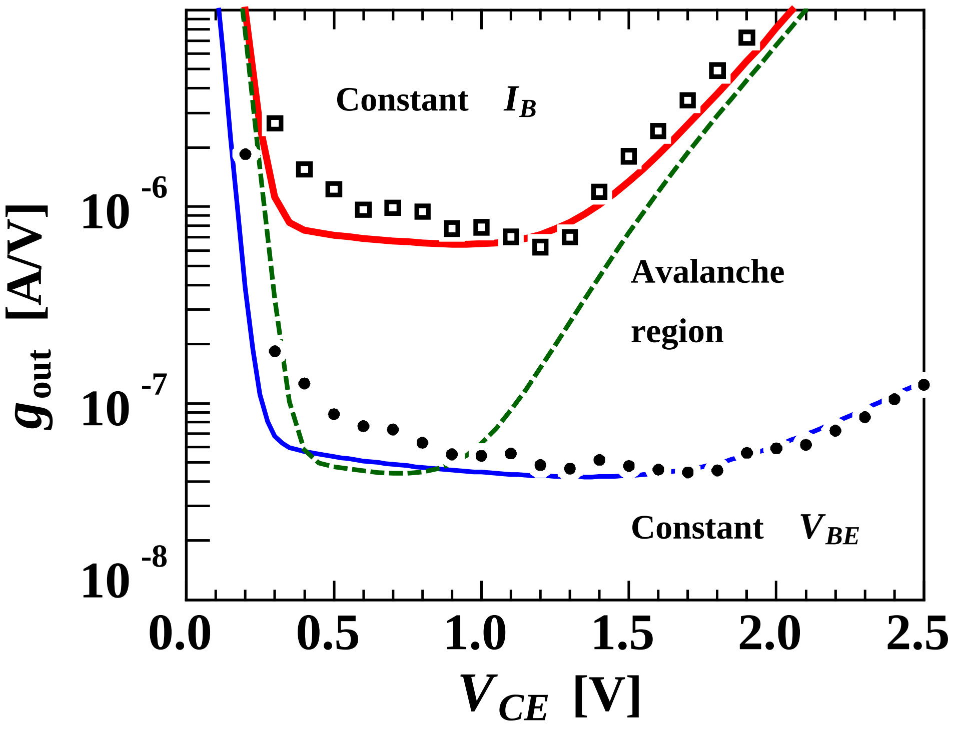


- Different output conductance

Effect on output conductance

- Two ways of steering:
  - – Base-emitter voltage
  - – Base current (old)
  - – Base current (new)

Output conductance dI_C/dV_C



- Different output conductance

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⇒Collector epilayer model

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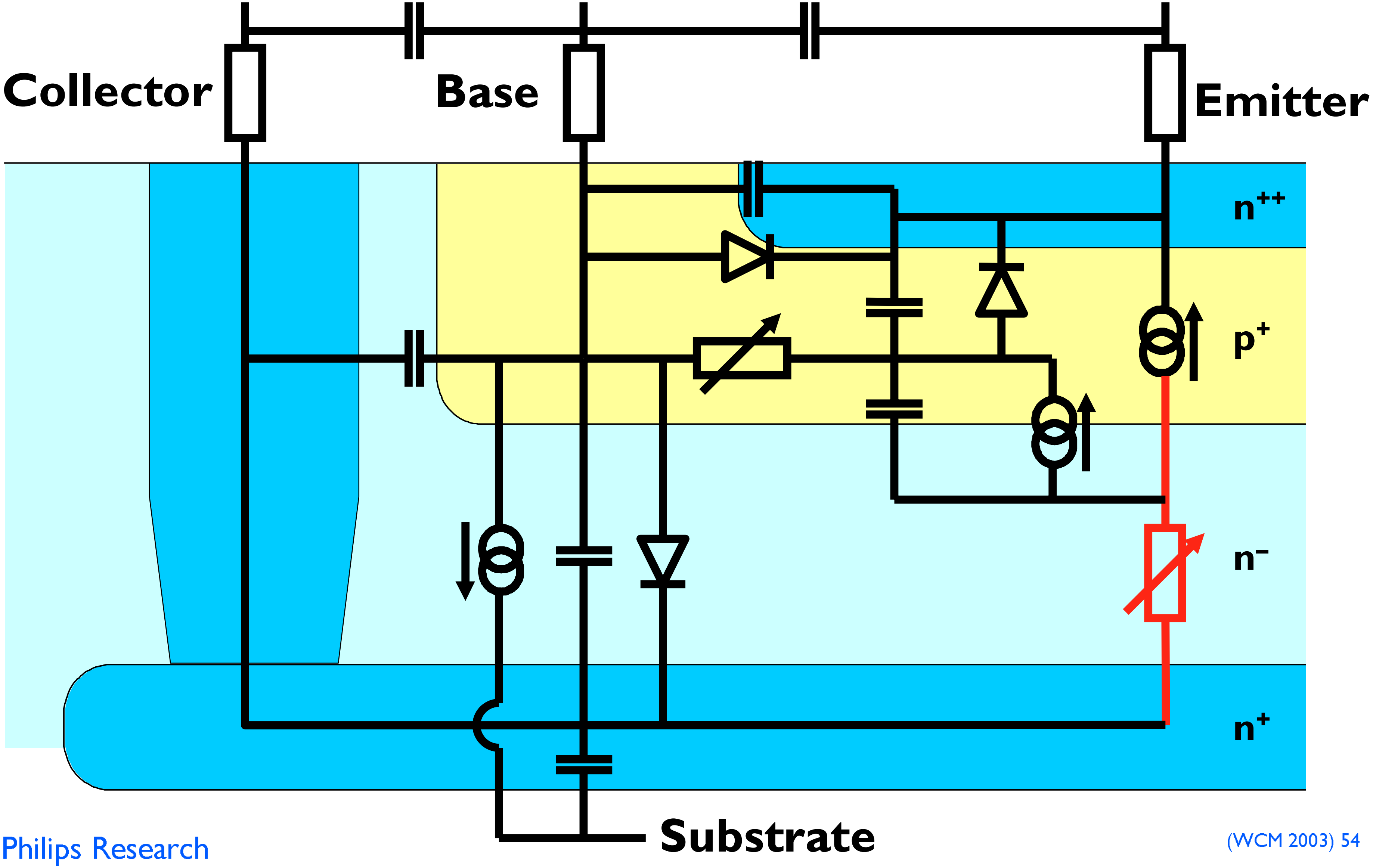
Collector epilayer model



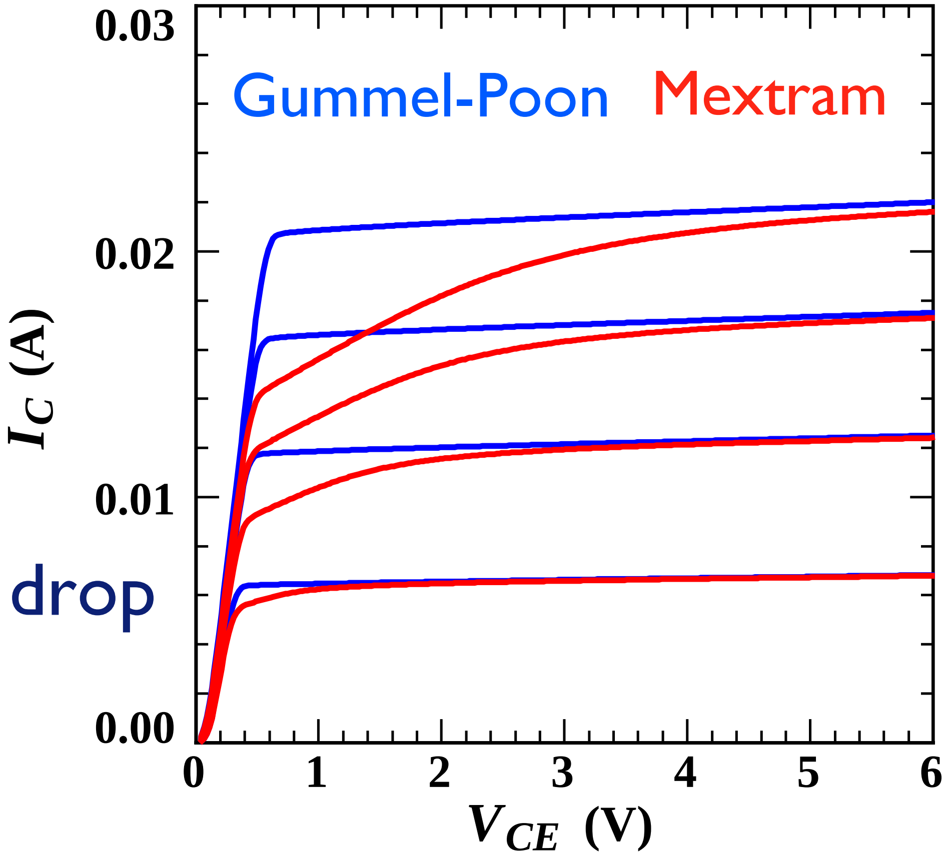
Collector epilayer model

- Most difficult part of the model
- Needs to describe:
  - Ohmic resistance at low currents
  - Space charge resistances at higher currents
  - Injection of holes into collector epilayer
- This includes e.g.
  - Quasi-saturation: internal BC-junction forward biased
  - Kirk effect
  - Depletion and diffusion charge in collector epilayer

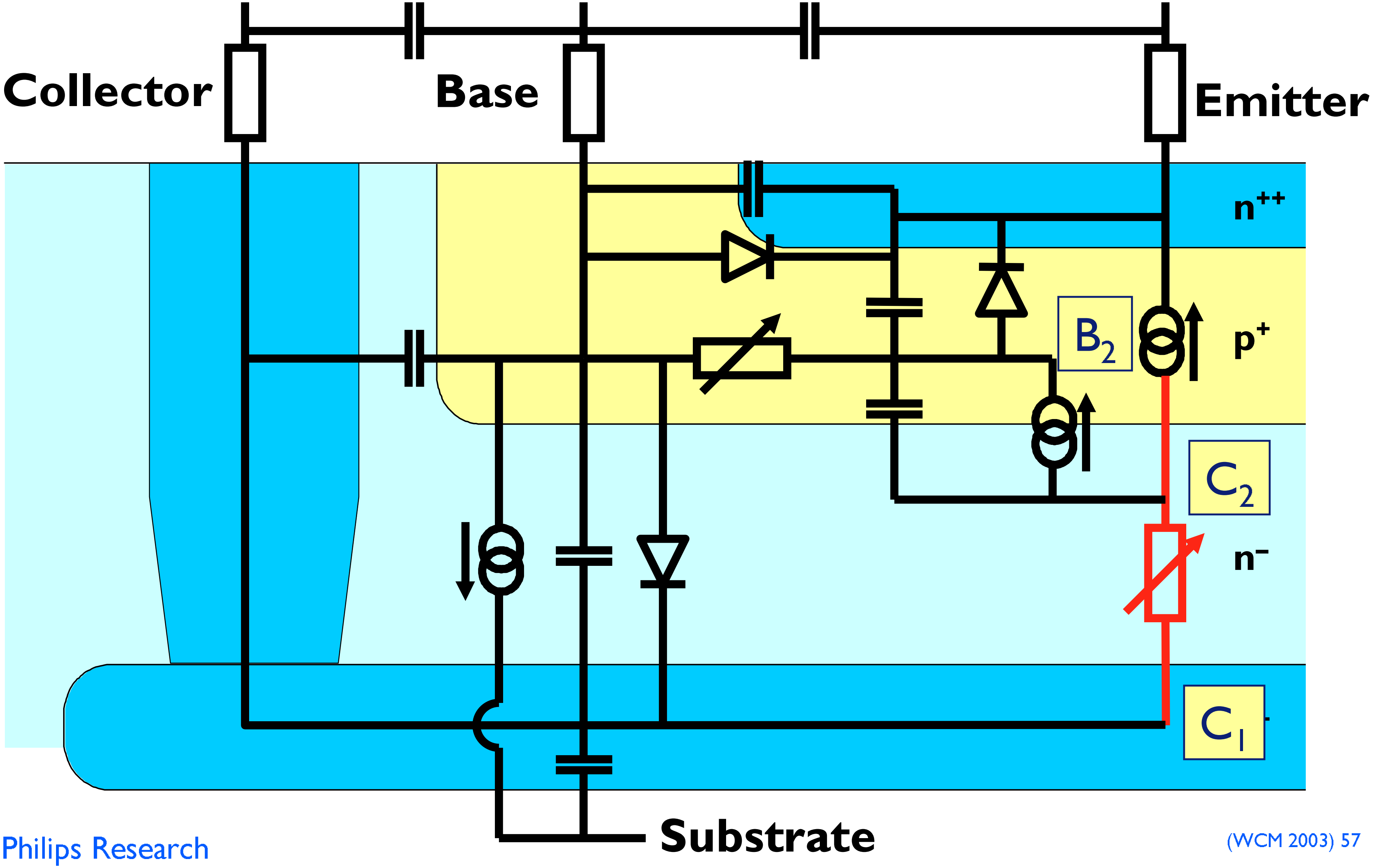
Collector epilayer model

- Quasi-saturation
  - reduces I_C at low V_{CE}
  - increases g_{out}
  - decreases V_{early}
  - decreases f_T

  - due to ohmic voltage drop
  - or Kirk effect



Collector epilayer model: how does it work?

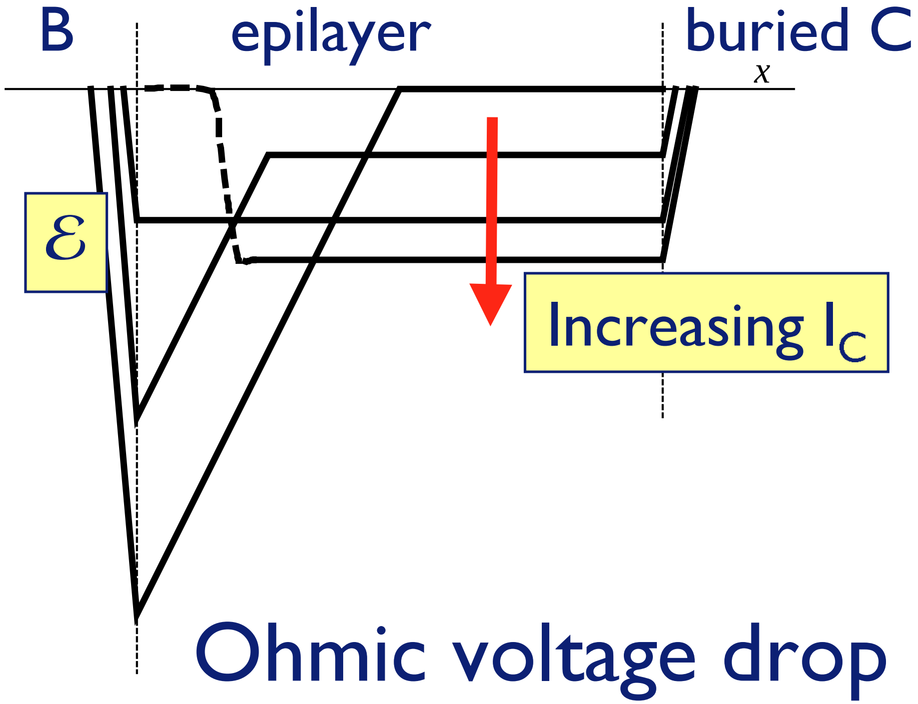


Collector epilayer model: how does it work?

- Goal: voltage at internal collector node C_2
- low current densities
  - I_C < IHC
  - ohmic voltage drop:
  - $V_{C2} = V_{C1} + I_C$ RCV
- high current densities (Kirk effect)
  - I_C > IHC: charge of electrons > background dope
  - space charge limited voltage drop
  - $V_{C2} = V_{C1} + I_C$ SCRCV

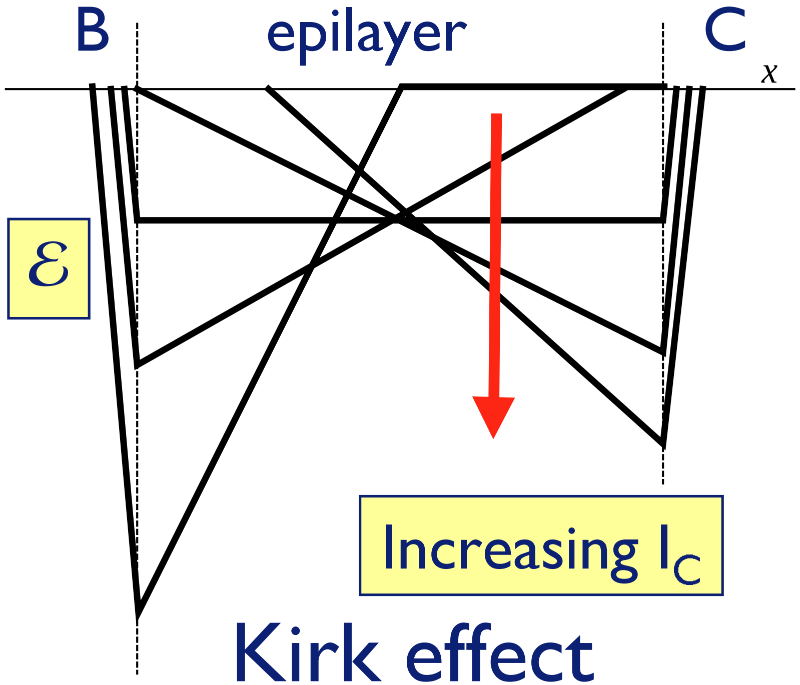
Collector epilayer model: how does it work?

- Electric field in collector epilayer



Ohmic voltage drop

I_C < IHC

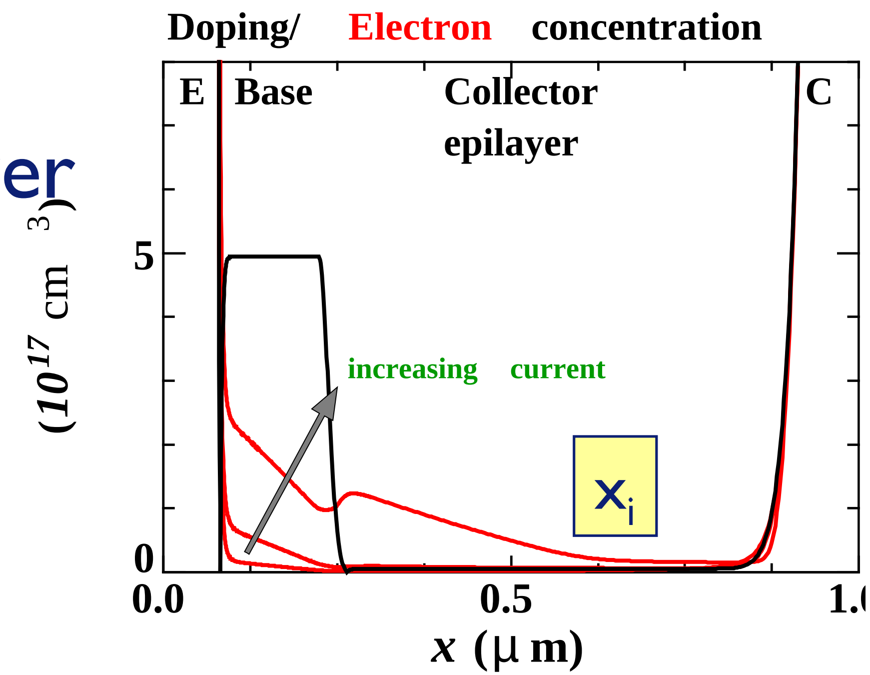


Kirk effect

I_C > IHC

Collector epilayer model: how does it work?

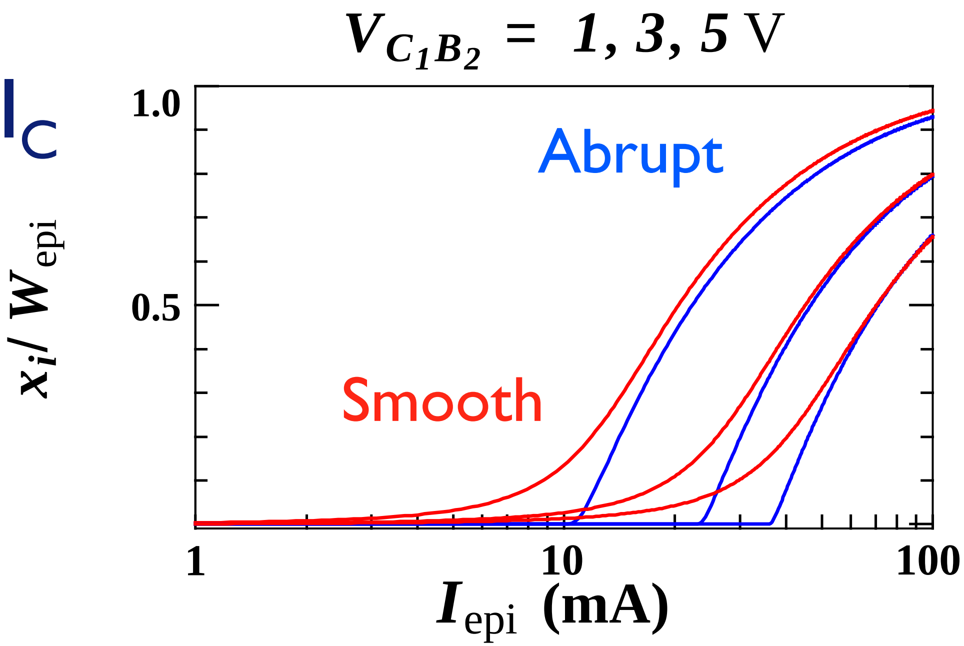
- At some point: internal BC bias forward biased
  - →$V_{B2} - V_{C2} \approx$ VDC
  - →electron density ≈ hole density
  - →high injection in epilayer
- Thickness of injection layer
  - determined from I & V
  - called x_i



- From x_i follows V_{C2} (Kull model in neutral region)

Collector epilayer model: how does it work?

- x_i/W_{epi} as function of I_C
  - depends on V_{CB}
  - can be smooth (Si) or more abrupt (SiGe)



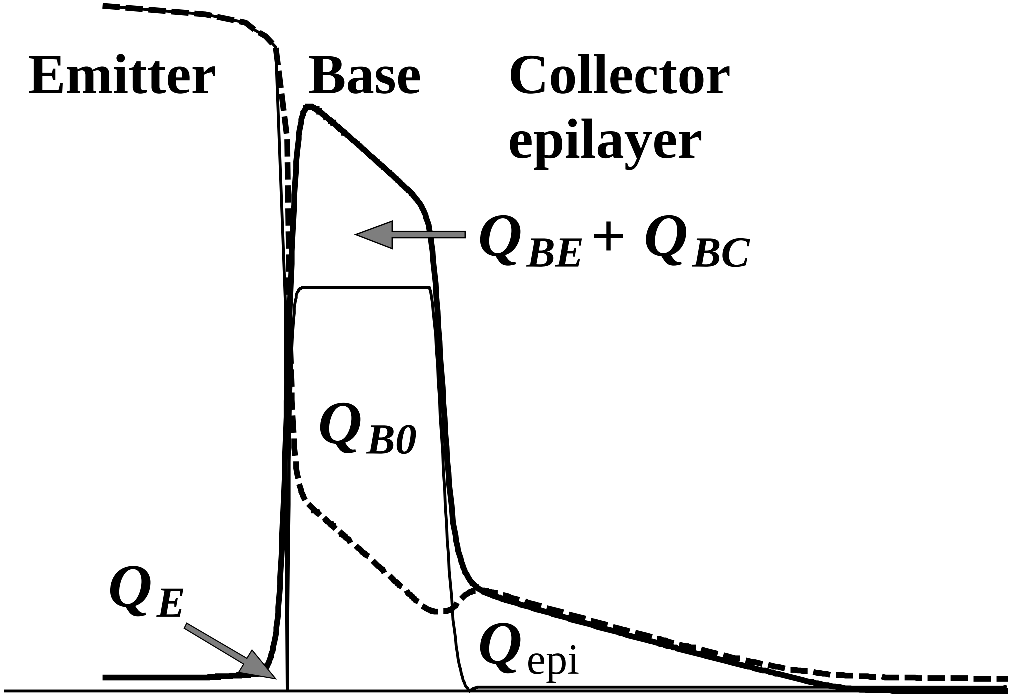
- Epilayer diffusion charge (normal forward)

$$Q_{epi} \approx \text{TEPI}\left(\frac{x_i}{W_{epi}}\right)^2 I_C$$

Cut-off frequency

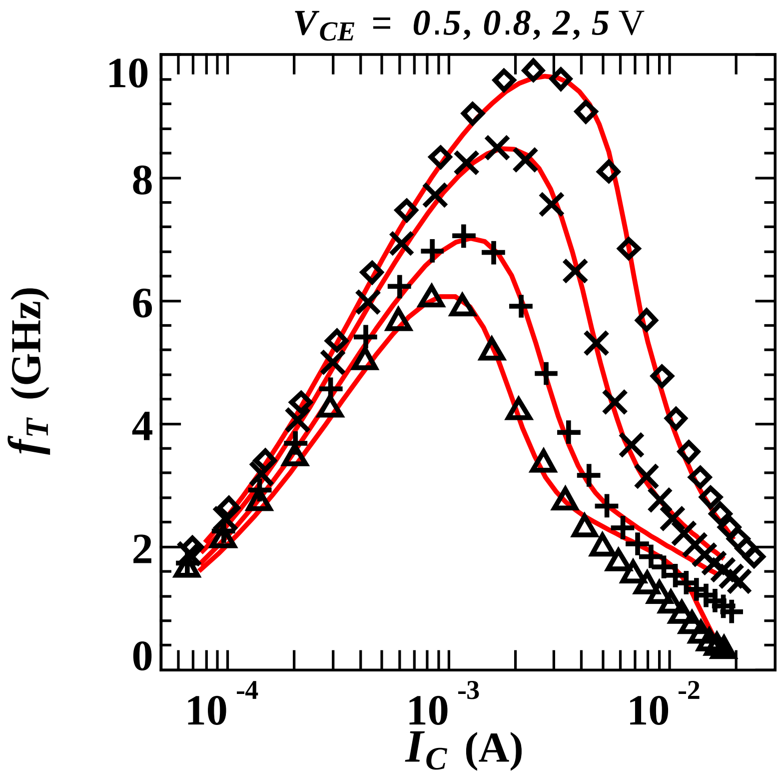
- For f_T most parts of model are needed
  - – current description
  - – collector epilayer model
  - – charge description
    - depletion
    - diffusion
  - – RC-times

Location of diffusion charges

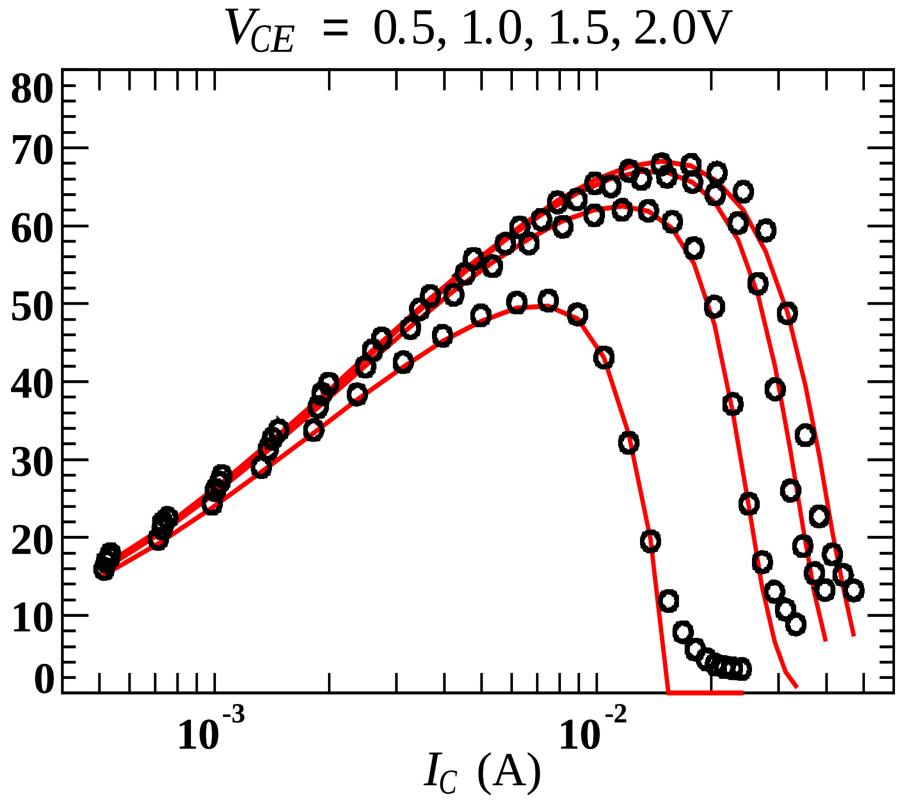


Cut-off frequency, examples

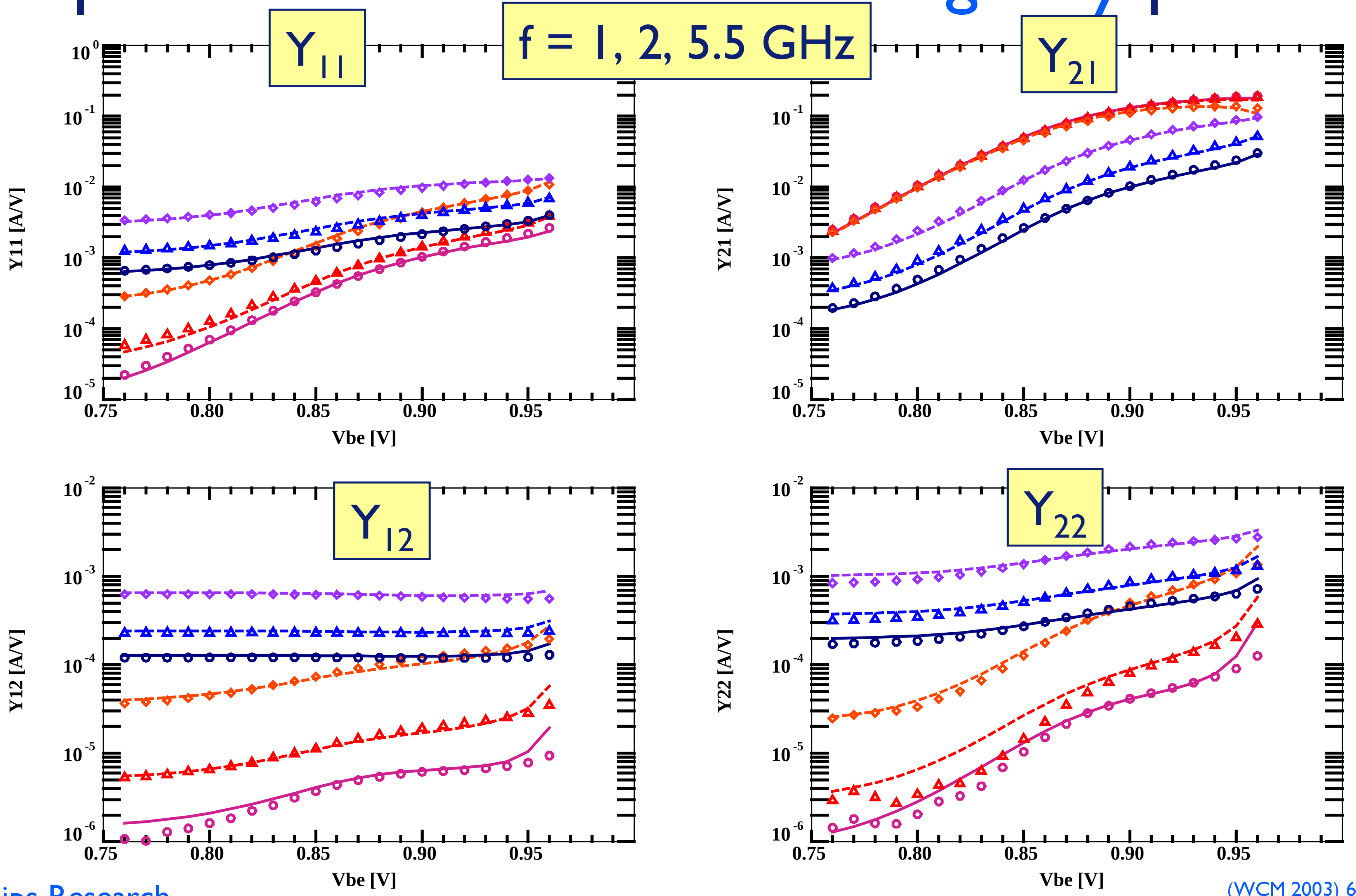
High voltage Si device



SiGe device



Y-par verification: Real and Imaginary parts



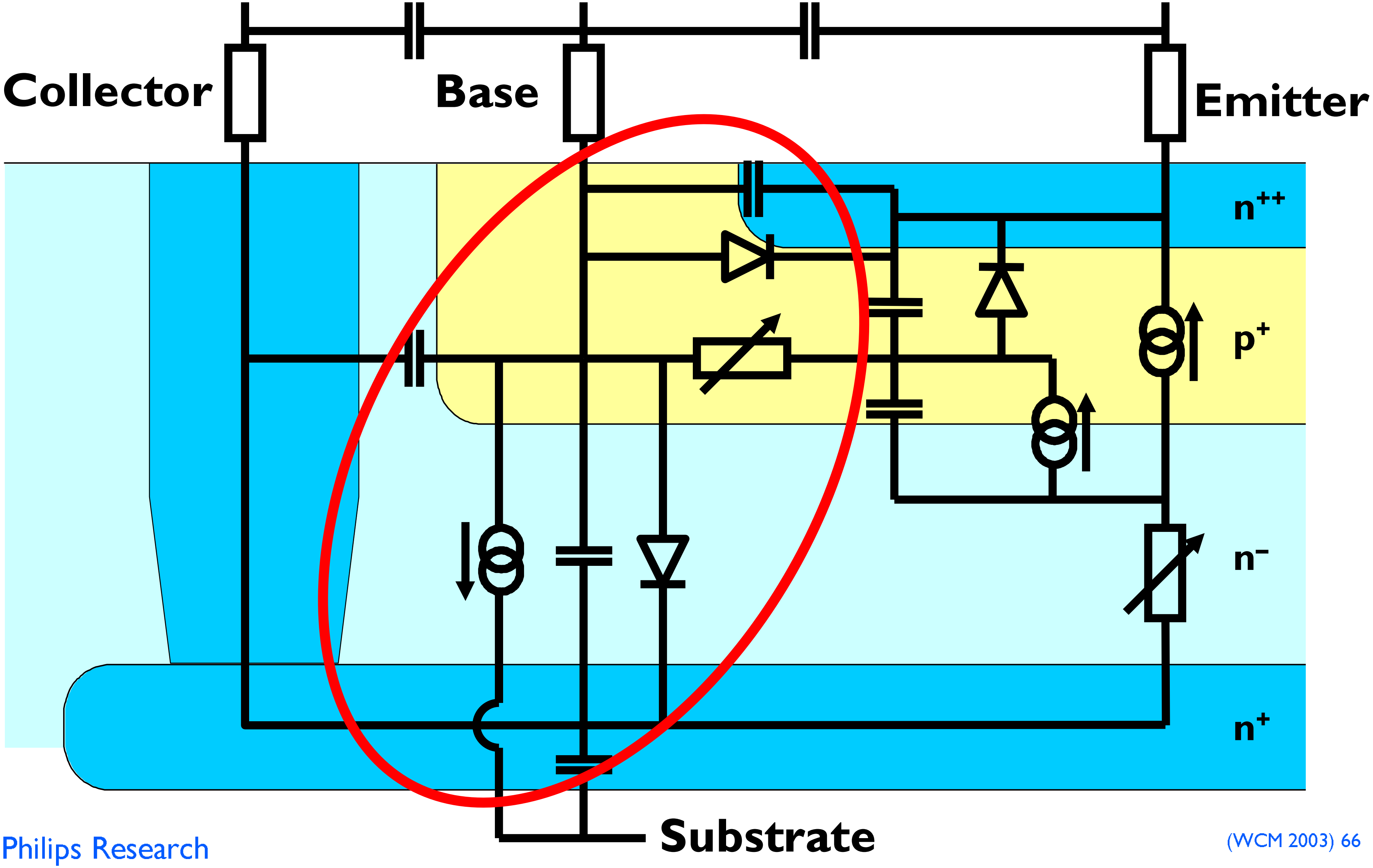
Contents

- Intrinsic transistor
- Variable base resistance
- Avalanche
- Collector epilayer model

⇒Extrinsic regions

- Temperature scaling
- Self-heating
- Geometry scaling
- Noise
- Status

Extrinsic regions



Extrinsic regions

- Sidewall base-emitter base current
- Sidewall base-emitter depletion capacitance

- Ideal reverse base current
- Non-ideal reverse base current
- Substrate current (parasitic PNP)
- collector-substrate depletion capacitance

- Variable base resistance

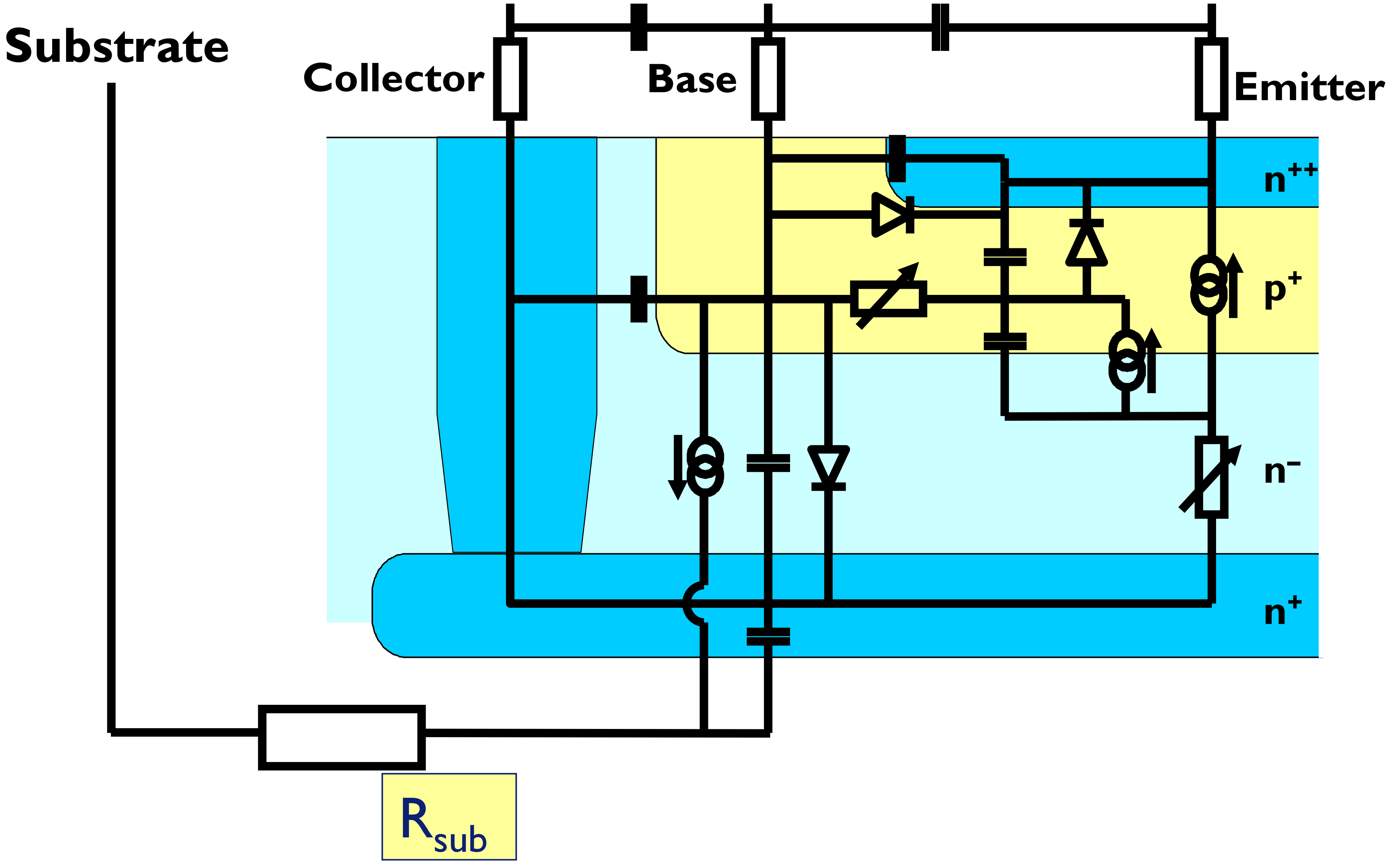
Substrate resistance

- Mextram does not contain substrate resistance

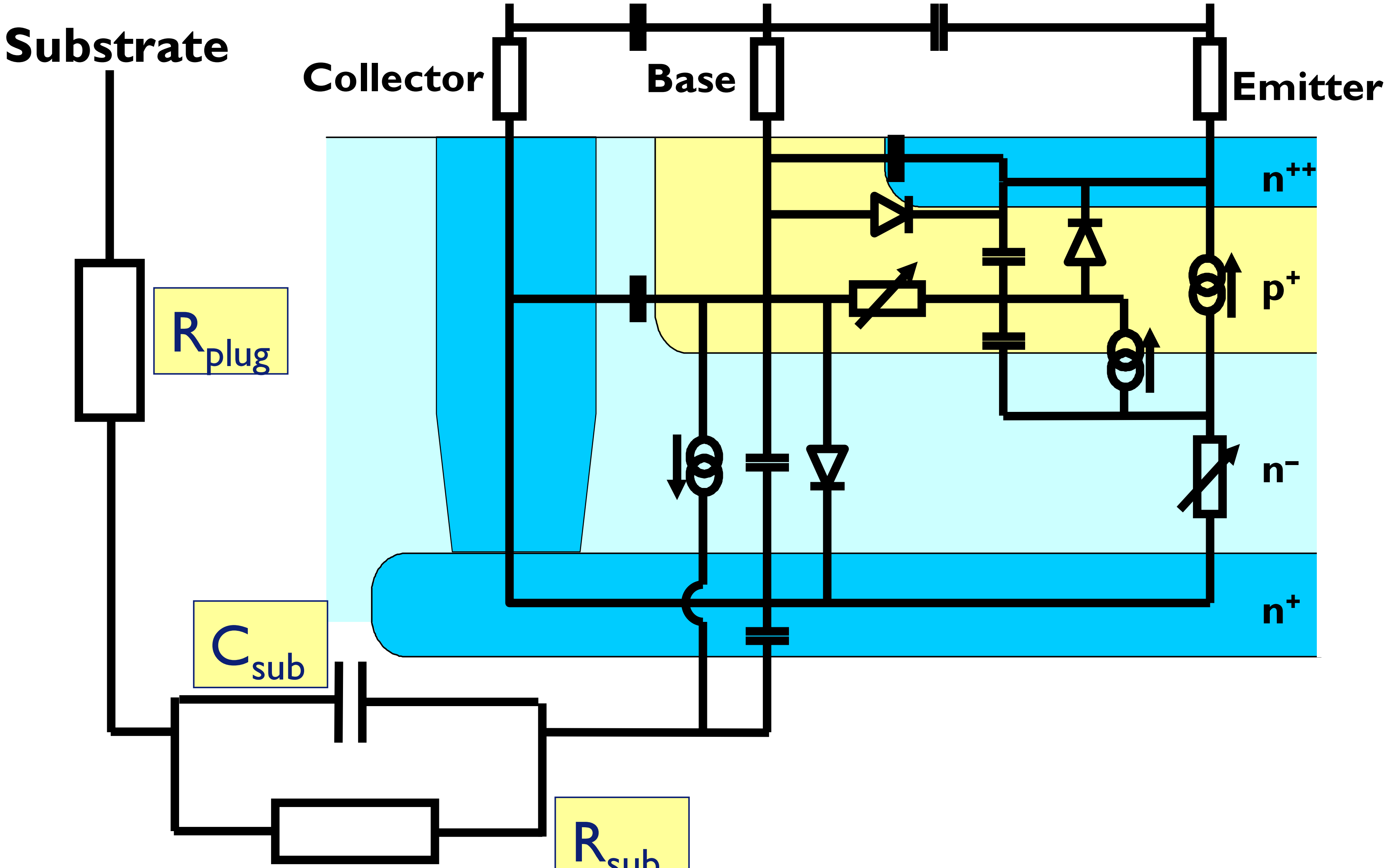
- Substrate resistance network sometimes needed:
  - Y_{22} or S_{22} modelling
  - F_{max} prediction
  - …

- However …

Substrate resistance: simple macro model



Substrate resistance: better macro model



Substrate modelling

- Advanced modelling needed when Rsub/Csub is really important
- Actual model depends on final layout
- If values are present it will be assumed accurate: it probably is not

→Flexibility: keep network outside of Mextram

Contents

- Intrinsic transistor
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⇒Temperature scaling

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Temperature scaling

- What is temperature scaling
  - Reference temperature TREF
    - Where parameters are defined, like IS
  - Actual temperature T
    - The electrical parameter used, like IS_T
  - Scaling rule gives relation between IS and IS_T
    - Using temperature scaling parameters, like VGB

- Mextram has temperature scaling
  - for most electrical parameters
  - based on physics

Temperature scaling

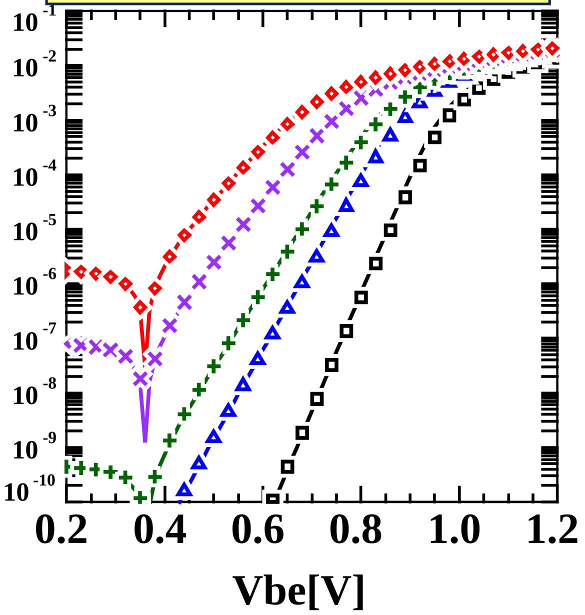
- Two kinds of temperature scaling parameters

- bandgaps (VGB, DVGBF, …)
  - saturation currents
  - current gain (using difference in bandgaps)
  - emitter transit time
- mobility exponents (AE, AB, …)
  - resistances
  - transit times

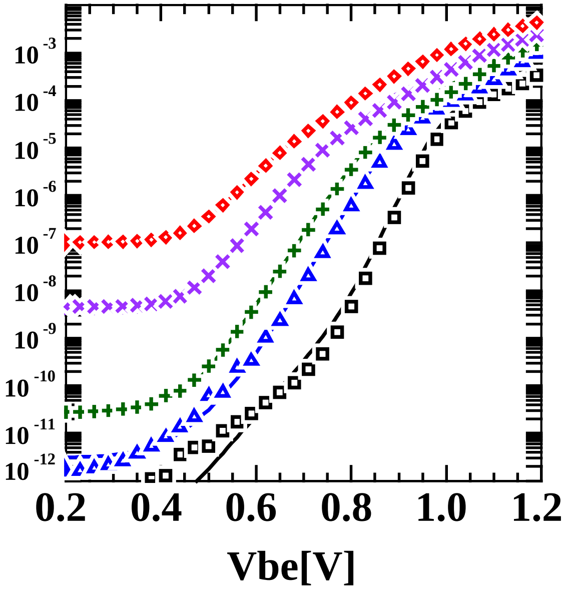
Temperature scaling

- Some results:
  - – T = –50, 25, 62.5, 137.5 and 200C

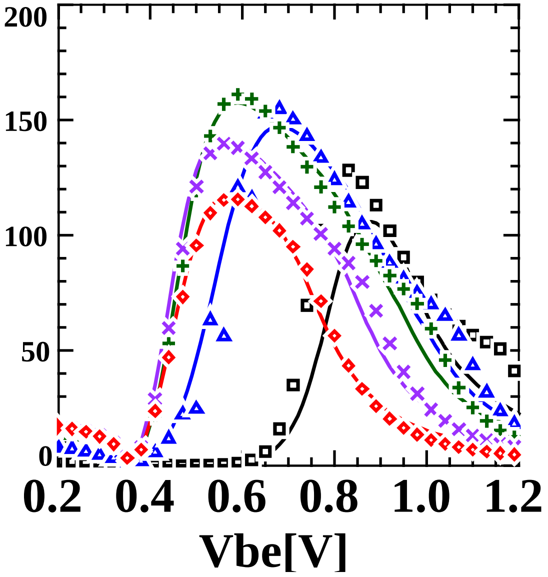
Collector current



Base current



Current gain



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⇒Self-heating

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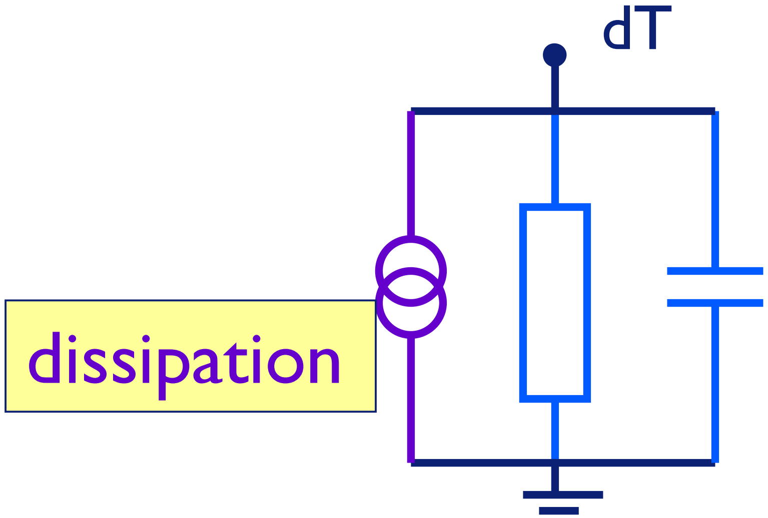
Self-heating

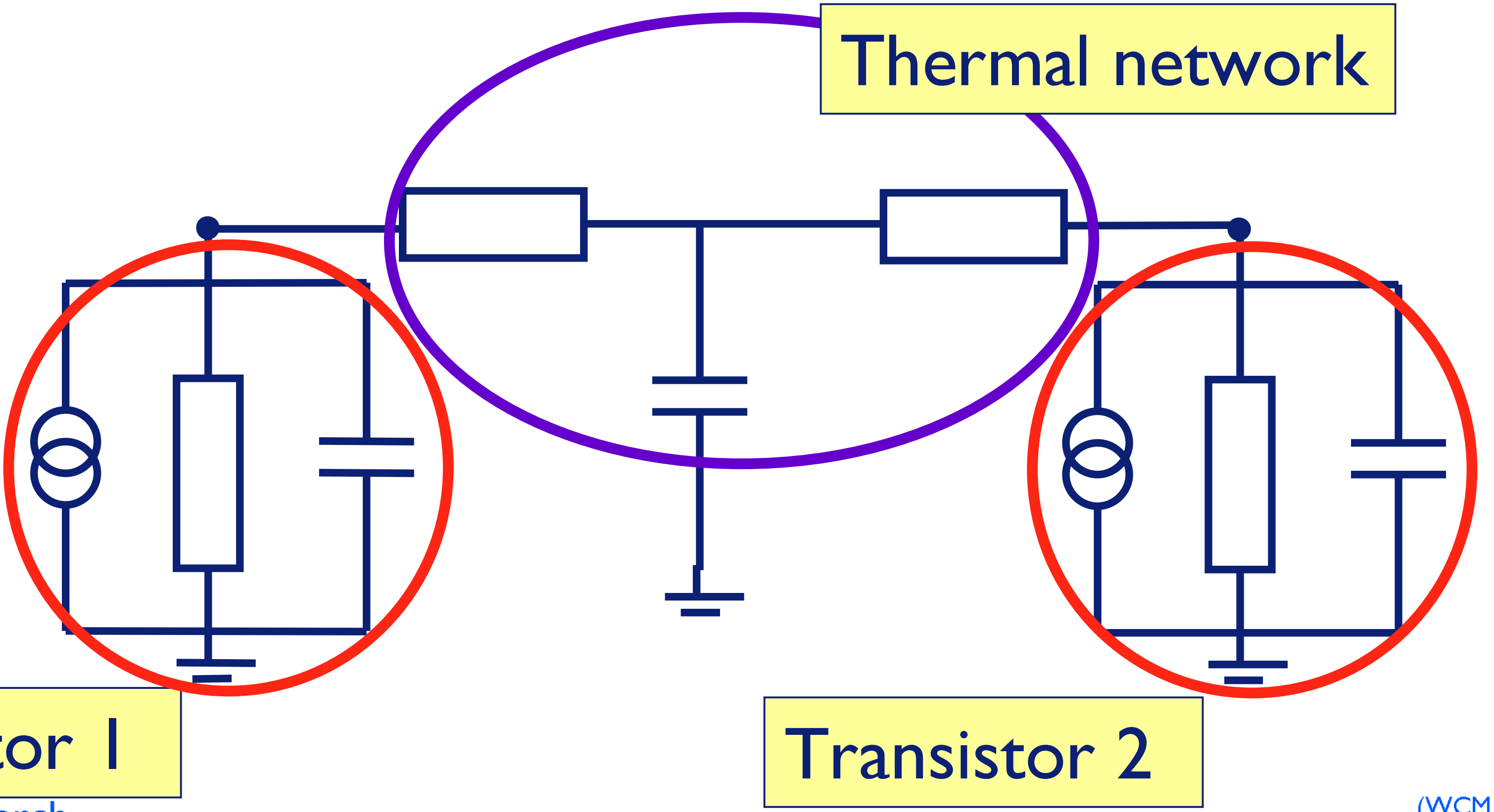
- Mextram contains self-heating network
- Two parameters:
  - RTH: thermal resistance
  - CTH: thermal capacitance



- Node dT is available to user:
  - More advanced thermal network possible
  - Mutual heating possible

Mutual heating

- Connecting the self-heating nodes of 2 or more transistors gives a thermal network


Thermal network

Transistor 1

Transistor 2

Self-heating and DTA

- Mextram: 2 ways to increase temp. of device:
- Static heating using DTA:
  - $T_{\text{local ambient}} = T_{\text{global ambient}} + \text{DTA}$
- Dynamic heating using self-heating network:
  - $T_{\text{device}} = T_{\text{local ambient}} + (\Delta T)_{\text{dynamic heating}}$
- Both are independent: no influence on each other

  →DTA does not generate heat flow in thermal network

Self-heating and DTA

- Static heating (using DTA)
  - Large number of transistors
  - Temperature increases calculated up front
  - Need to determine global temperature profile
  - No extra simulation time

- Dynamic heating (using self-heating network)
  - Small number of transistors
  - Temperature increase calculated dynamically
  - Need to determine heating network
  - Extra simulation time and more difficult convergence

Contents

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⇒Geometry scaling

- Noise
- Status

Geometry scaling

- The model parameters for a single transistor are called electrical parameters
- These are a function of geometry
- Geometry is given by
  - $W_{EM} \times L_{EM}$, $W_{base} \times L_{base}$, …
  - layout variation (no. of base contacts, …)
- Freedom for designers in choice of size, layout
- Possibility of automatic optimisation of design

PHILIPS

Geometry scaling: example

Consider the base-emitter depletion capacitance CJE

$$\mathrm{CJE} = \mathrm{CJEA} \cdot W_{EM} \cdot L_{EM} + 2 \cdot \mathrm{CJEP} \cdot (W_{EM} + L_{EM})$$

Area : $A_{EM} = W_{EM} \cdot L_{EM}$

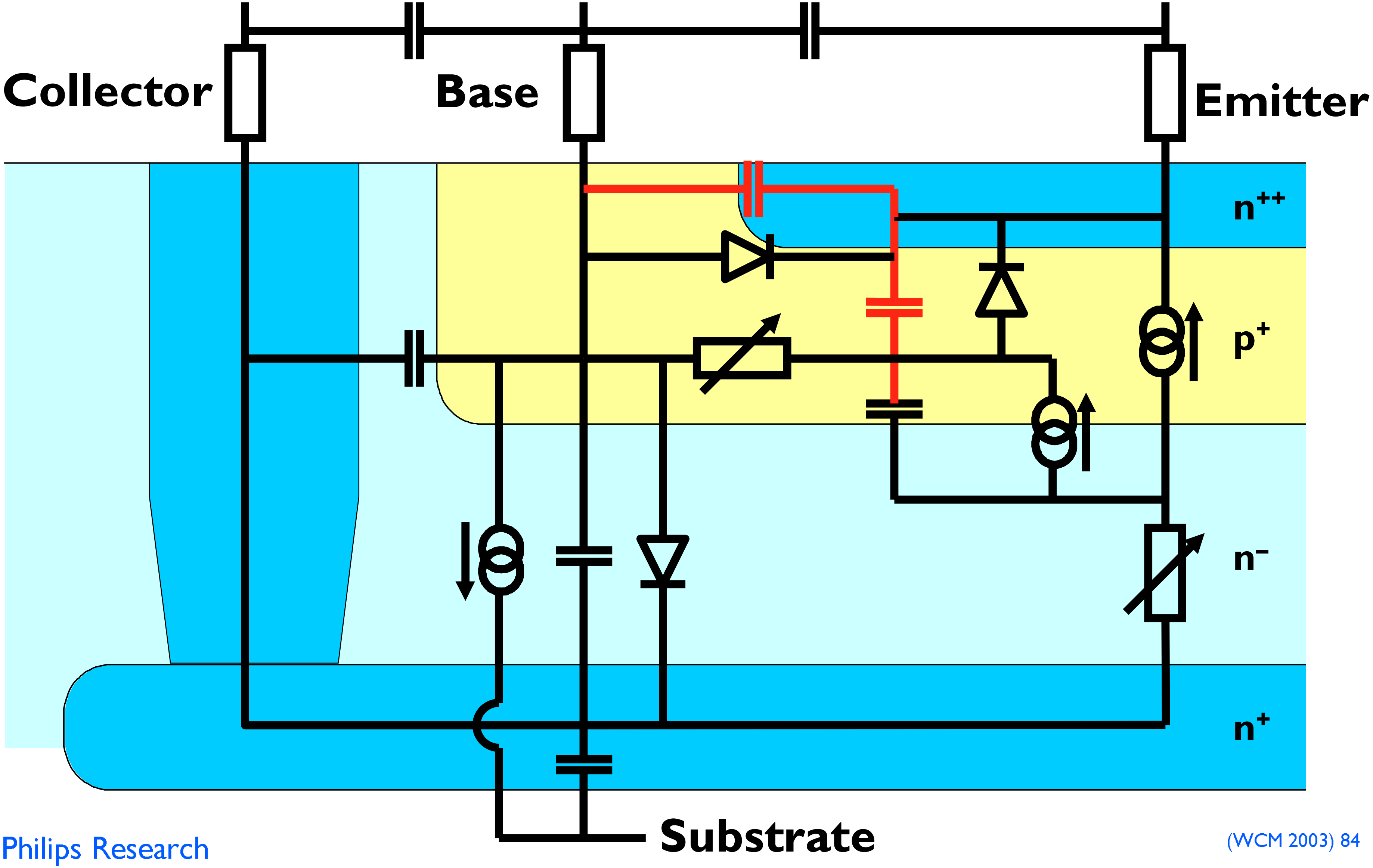
Perimeter: $P_{EM} = 2 \cdot (W_{EM} + L_{EM})$

Two ‘unit’ parameters:

Specific area capacitance: CJEA

Specific perimeter capacitance: CJEP

Geometry scaling (CJE)



Geometry scaling

- Geometry scaling is done during characterisation
- To do this one needs information about the device structure (measured or estimated):
  - layout variations
  - doping profile
  - cross-sections
  - location of oxide, poly and other layers
  - sheet resistances, contact resistances

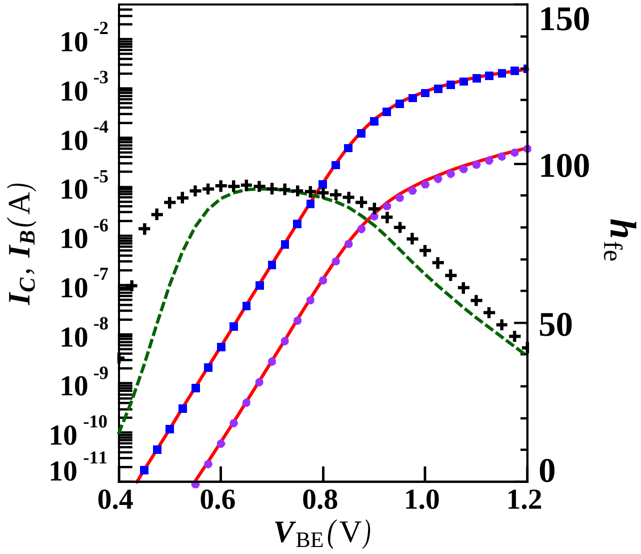
Geometry scaling

- Not built into Mextram
  - depends on process and layout variations
  - different scaling rules for different situations
- Geometry scaling is in principle the same for all models (Mextram, Spice-Gummel-Poon, …)
  - Same kind of scaling equations can be used
  - Same extraction strategy can be used
  - Mextram has more elements: more flexibility
- Basic set of scaling rules documented in a report

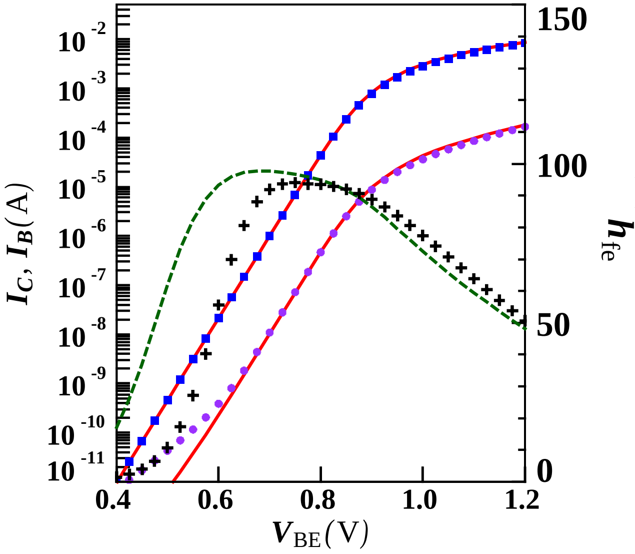
Geometry scaling results: current gain

- 0.35 µm BiCMOS process
- Now including full Mextram simulations
- Note statistical variation in non-ideal base current

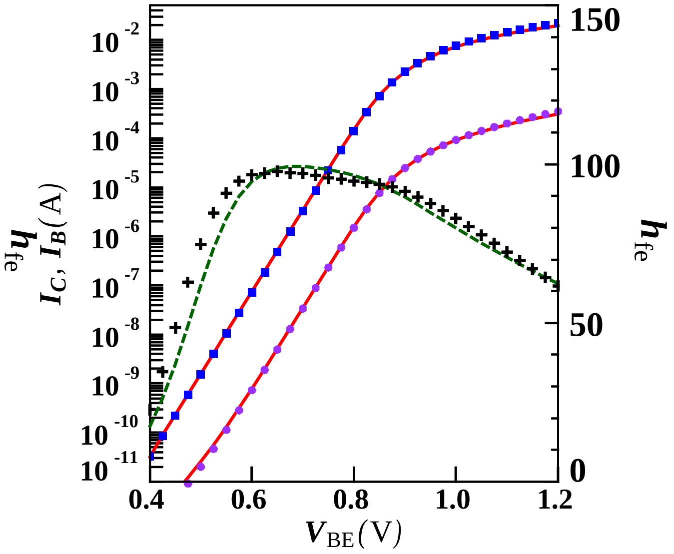
0.7×1.4µm²



0.7×5.6µm²

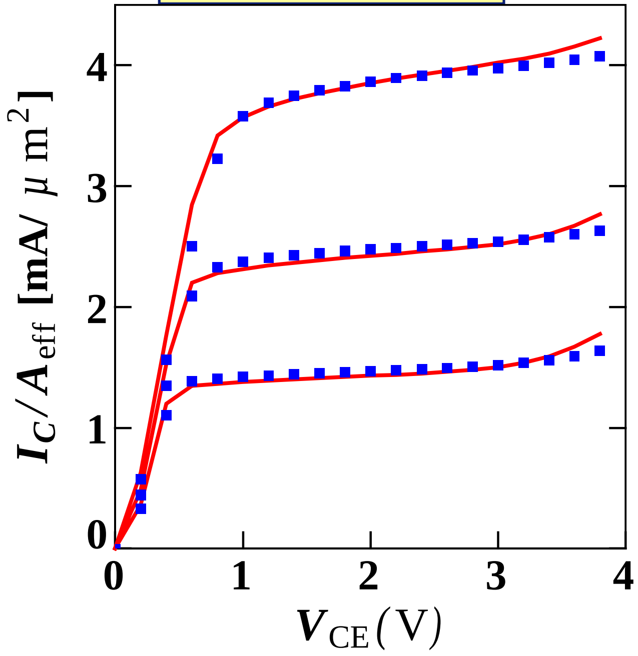


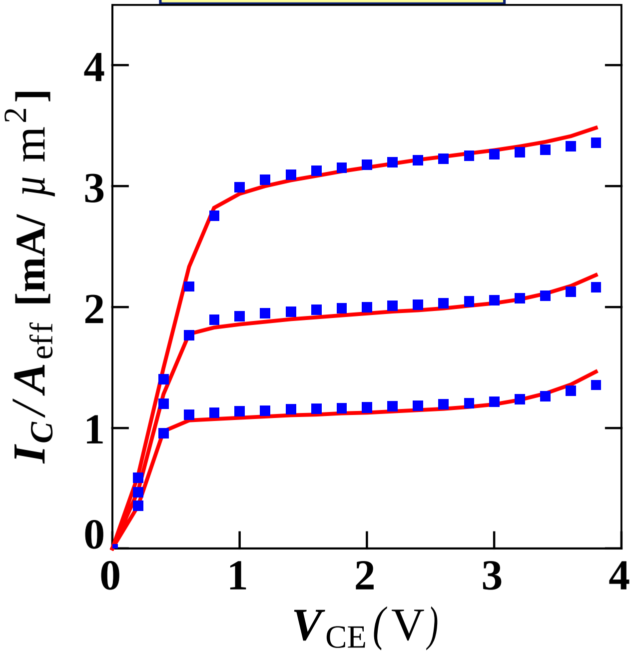
0.7×20µm²

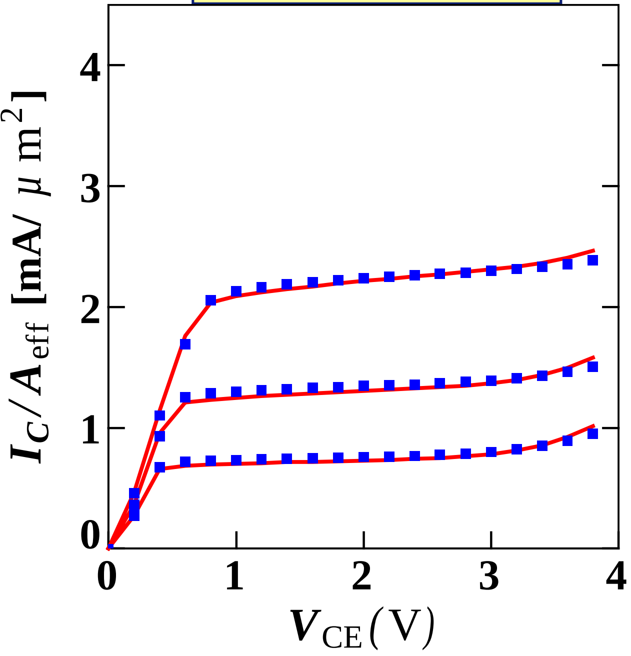


Geometry scaling results: output characteristic

- Including full Mextram simulations
- Different values are due to different base currents


0.7×1.4µm²

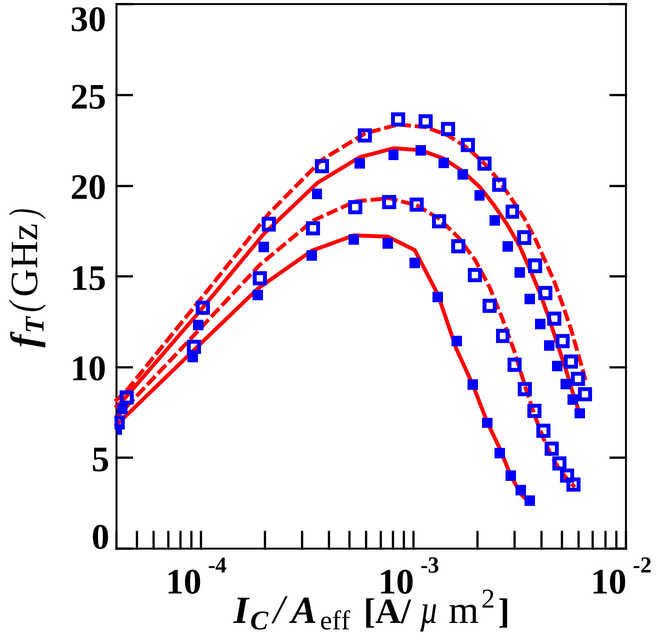

0.7×5.6µm²


0.7×20µm²

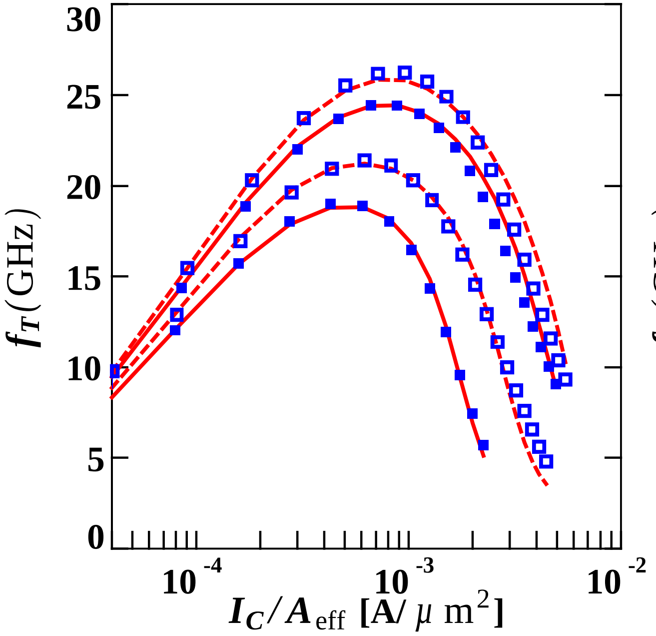
Geometry scaling results: cut-off frequency

- Including full Mextram simulations
- V_{CE} = -0.4, 0, 1.5, 3.0V

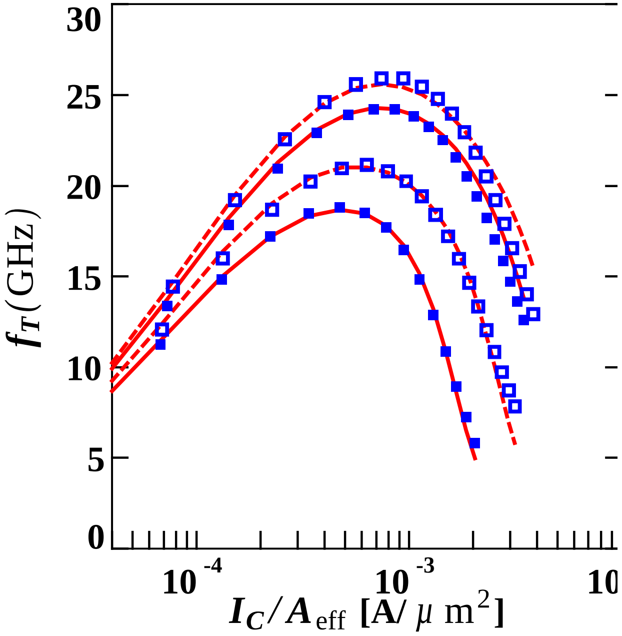
$0.7\times1.4\mu m^2$



$0.7\times5.6\mu m^2$



$0.7\times20\mu m^2$



Geometry scaling and statistical modelling

- Geometry scaling gives physical relation between
  - layout, device structure, and process information
  - model parameters
- This relation gives basis for statistical modelling
  - statistics of PCM data leads to statistics of model parameters
- From statistical models also corner models can be made

Geometry scaling: final implementation

- Final implementation depends on simulator
- We provide full scalable models
  - any length and width is allowed
- Example: (incl. statistical or slow/fast simulations)

Mextram call

```
.MODEL &1 BJT504 TYPE=\NPN   &
  We=&2   Le=&3   &
  CJE=BN_CJE(&2,&3,5e-15,3e-16) &
  BF=100*Nhfe  &
  RE=BN_RE(&2,&3,50)   &

  RCC=BN_RCC(&2,&3,1,100)
```

Initialisation file

```
SET rhosbn=20.0
FUNCTION we(w)=w-0.30+ddem
FUNCTION le(l)=l-0.30+ddem
FUNCTION Ae(w,l)=le(l)*we(w)
FUNCTION Pe(w,l)=2*(le(l)+we(w))
FUNCTION BN_CJE(w,l,CJEA,CJEP)=\
          CJEA*Ae(w,l)+CJEP*Pe(w,l)
FUNCTION BN_RE(w,l,Rea)=Rea/Ae(w,l)
FUNCTION BN_RCC(w,l,st,RCC1)=&
(st=1)*(RCC1/lc(l)+rhosbn*1.40/lc(l))+&
(st=2)*(RCC1/lc(l)+rhosbn*0.95/lc(l))
```

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⇒Noise

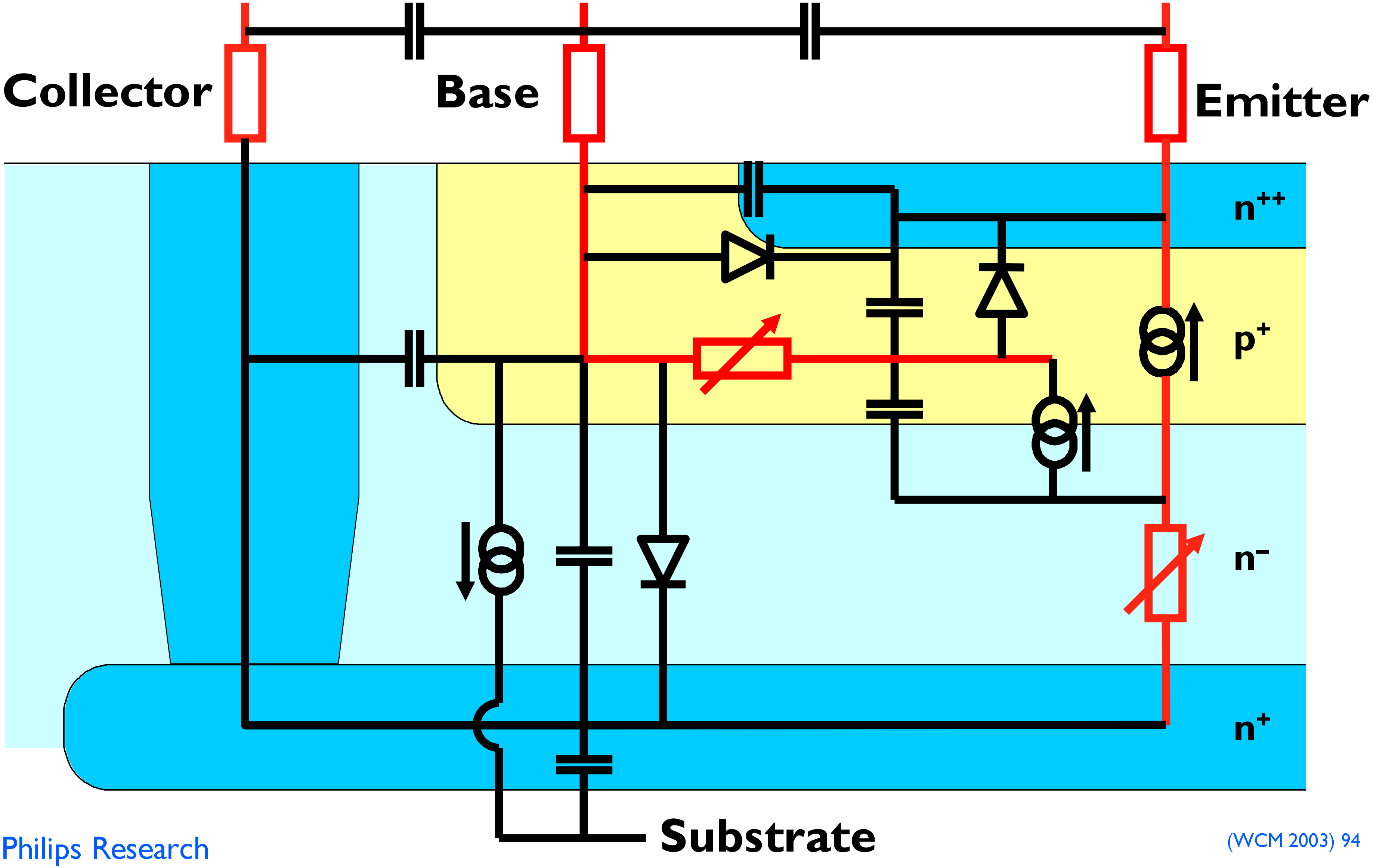
- Status

Noise model

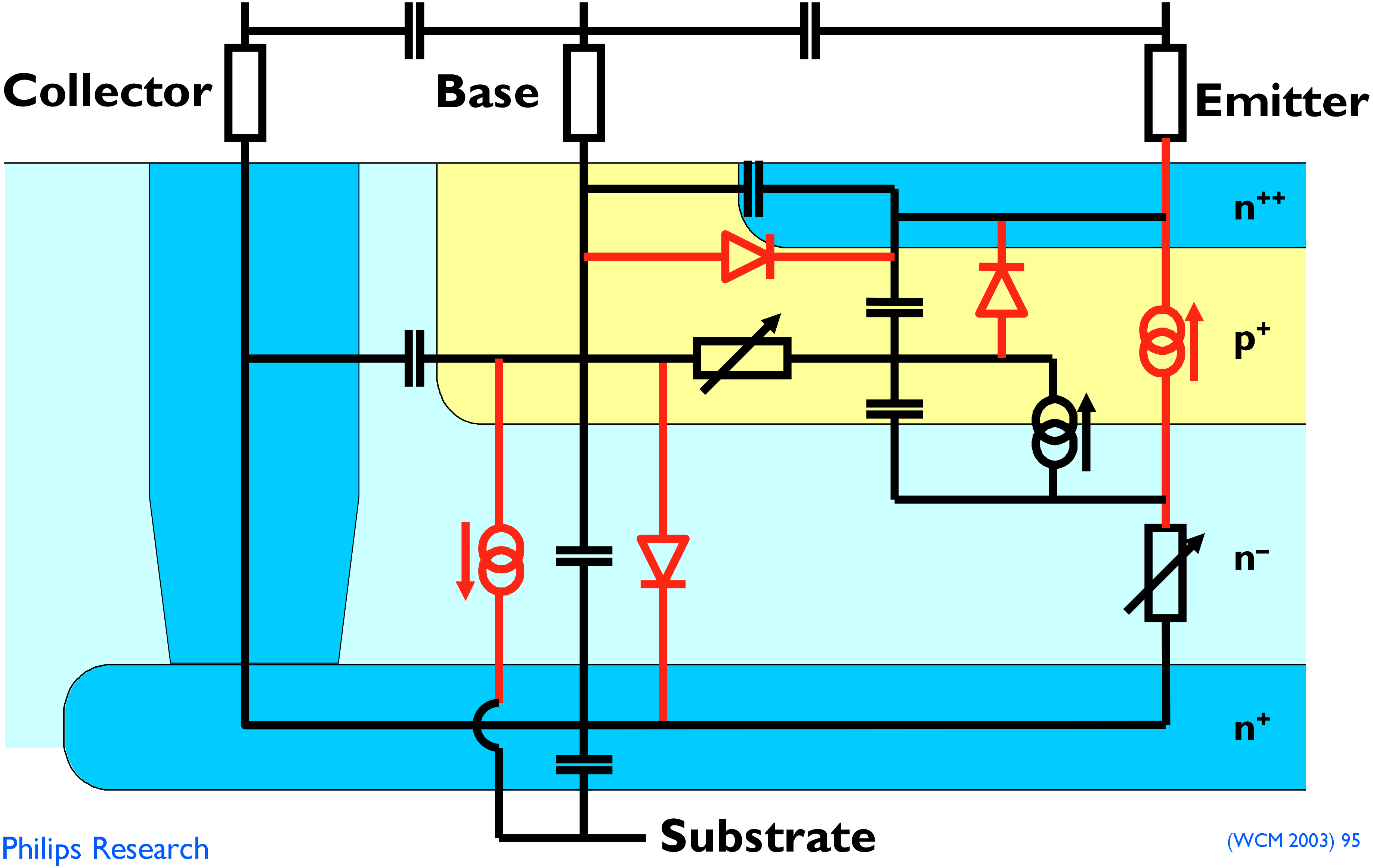
- Mextram has standard noise model

- Thermal noise: $4kT/R$
- Shot noise: $2qI$
- 1/f noise ideal base current: $KF \cdot I_B^{AF}/f$
- 1/f noise non-ideal base current: $KFN \cdot I_B^2/f$
  - only 1/f noise has parameters

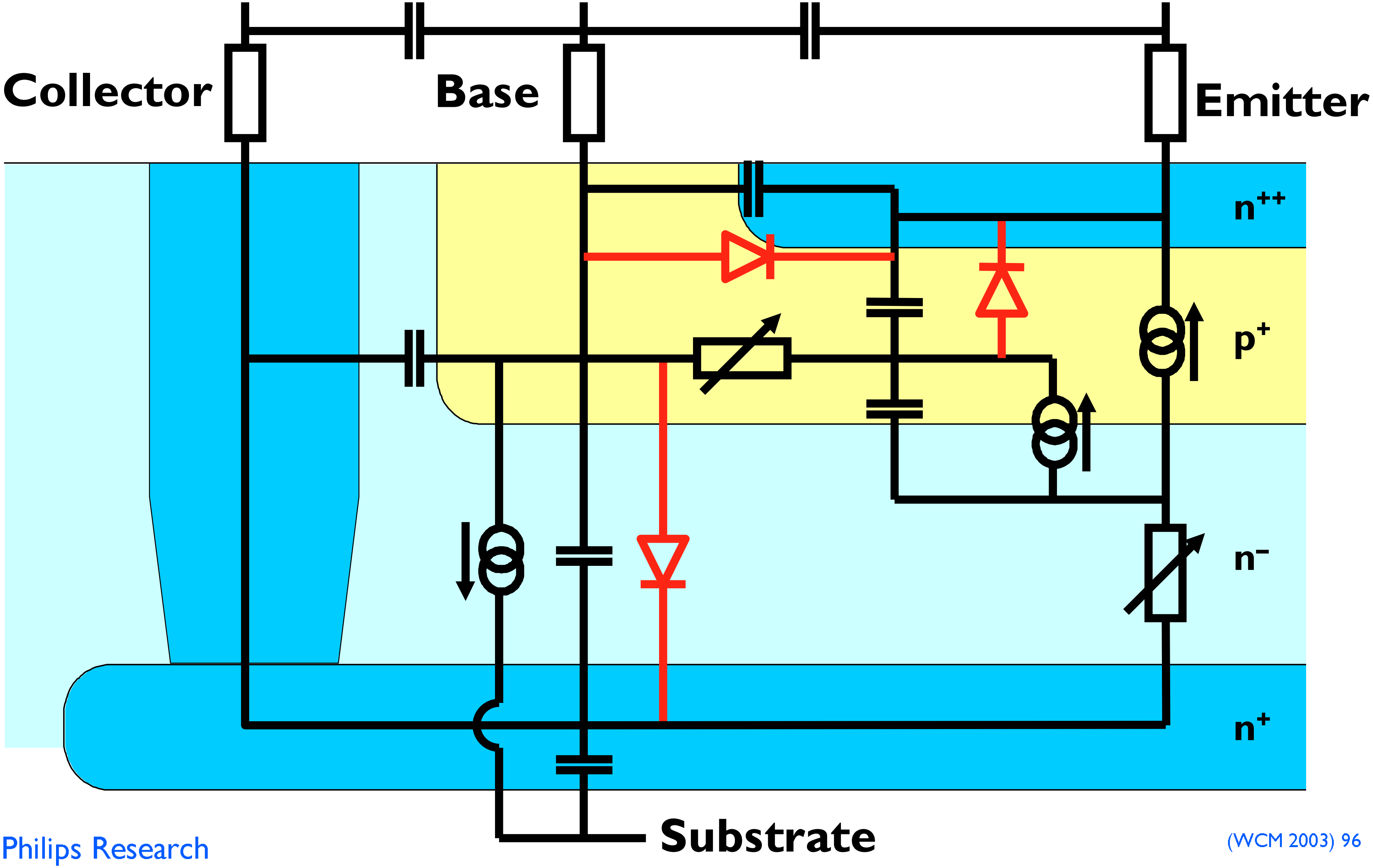
Thermal noise



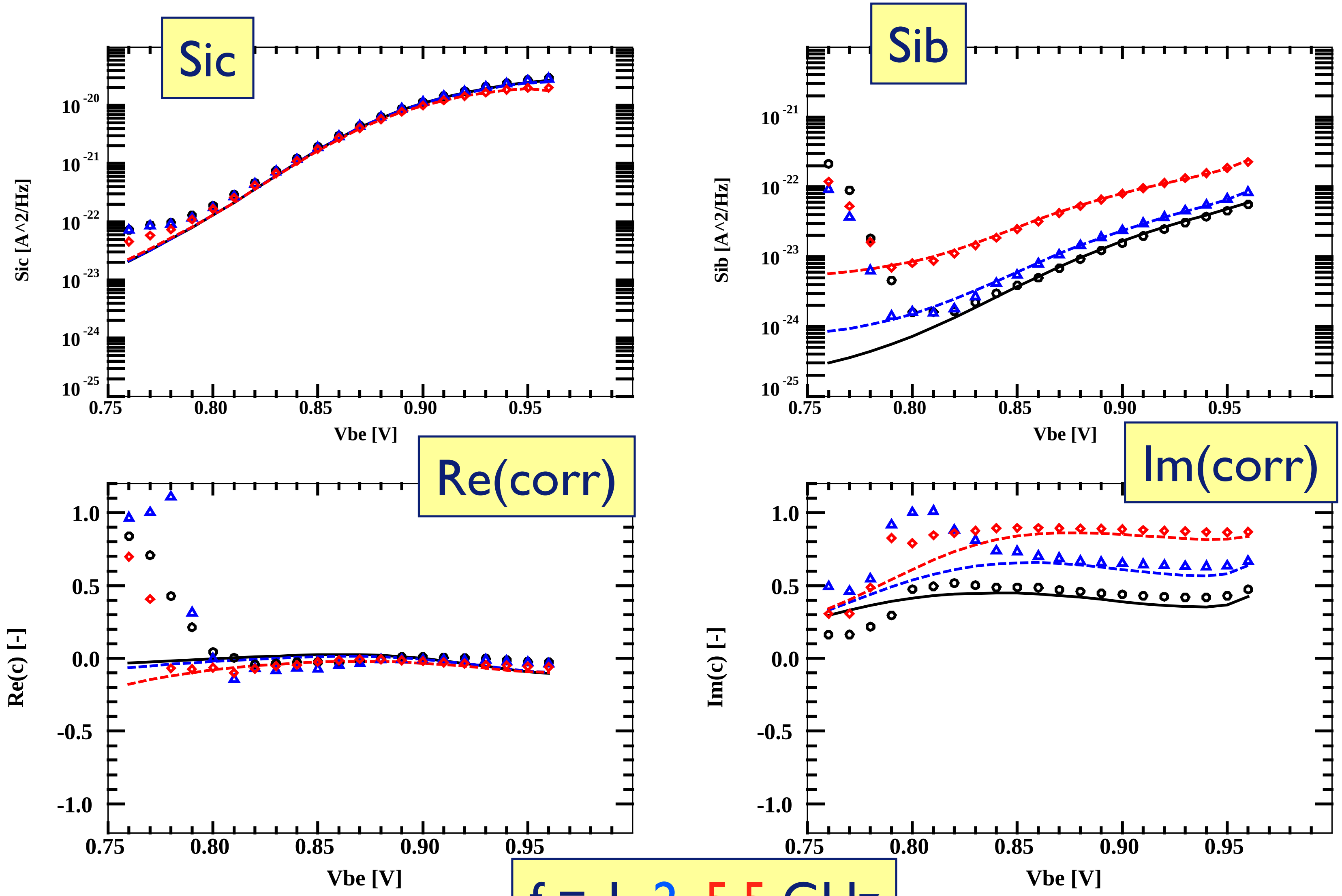
Shot noise



Flicker noise (1/f noise)



Verification: input&output noise + correlation



f = 1, 2, 5.5 GHz

Contents

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⇒Status

More information

- Our web-site
  - www.semiconductors.philips.com/Philips_Models
  - Contains
    - model definition
    - C source-code with examples
    - compiled Spectre CMI library
    - documentation (reports, articles, presentations)
    - other models (e.g. MOS Model 11)
- University of Delft, The Netherlands
  - Mextram related research projects for 3rd parties

Available reports

- Model definition
  - equivalent circuit, parameters, model equations, …
- Physical background of model
  - derivation of all equations
- Parameter extraction
  - including temperature and geometrical scaling
- Introduction and usage
  - including comparison with Spice-Gummel-Poon

Standardisation

- Alternative models for bipolar transistors
  - Spice-Gummel-Poon
    - widely used but old (1972) and insufficient
  - VBIC (Vertical Bipolar Inter-company Model)
    - Introduced in 1995
  - HiCuM (High Current Model), Univ. Dresden
    - Introduced in 1985

- Mextram proposed as standard model by CMC
    - Compact Model Council will vote in March

Availability in simulators & extractors

Vendor	Simulator	Version	Status
Philips	Pstar	4.4	Proprietary
	Pstar modelkit	4.4	Free download
	Spectre modelkit	1.3	Free download
Agilent Technologies	ADS	2002	Available
Mentor Graphics	Eldo	5.7_1.1 (22)	Available
Cadence	Spectre	4.4.6, 5.0	Available
Synopsys	Star-Hspice	2002.2	Available
Silvaco	Smart Spice	1.9.4.R	Available
Analogy	Saber		?
Aplac	Aplac		?

Vendor	Extractor	Version	Status
Agilent Technologies	IC-CAP	2002	Available
Silvaco	UTMOST	17.10.0.R	Available

Summary

- We described different parts of Mextram
  - following the equivalent circuit
  - explaining the physical basis
- With emphasis on SiGe transistors
  - In many cases no special features necessary
  - Sometimes optional model formulations needed
- Discussed temperature and geometrical scaling
- Shown where detailed information is available

World's first 20x20 crosspoint switch at 10Gb/s first-time right design using Mextram based on 1D simulations + geometrical scaling