MEXTRAM (level 504)
the Philips model for bipolar transistors

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  - some basic bipolar characteristics
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  - The effect of a graded Ge content in the base
  - Neutral base recombination
  - Self-heating
  - Advanced avalanche modelling: snapback
- Geometric scaling
- Status of Mextram 504
History

- Mextram has been developed by Philips Research

- Physics based, suitable for digital and analog applications

- Introduced in 1985

- Updates
  - level 502: 1987
  - level 503: 1993
  - level 504: 2000

- In public domain since 1995

http://www.semiconductors.philips.com/Philips_Models
History

Modelled effects
some basic bipolar characteristics

Improved description of output conductance and $f_T$
How an improved description gives smoother behaviour

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Neutral base recombination
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Status of Mextram 504
Modelled effects: Gummel plot

Collector current, base current and current gain

Non-ideal base current ($V_{BE} < 0.55\text{V}$)

Bias dependent reverse Early effect (o.a. in $h_{fe}$: $V_{BE} = 0.5–0.9\text{V}$)

High current effects (resistances, knee, Kirk effect) ($V_{BE} > 0.9\text{V}$)
Modelled effects: Output characteristic

Bias dependent Early effect (\(g_{\text{out}}\) not constant)
Quasi-saturation/Kirk effect: current reduction at lower voltages/high current densities

Hard saturation (\(V_{CE} < 0.6\text{V}\))
Avalanche (\(V_{CE} > 4\text{V}\))
Depletion capacitances

Depletion capacitances in Mextram:

When diffusion charge becomes important ($V_{BC} > 0.5$V): depletion capacitance levels off (not important anymore)
Diffusion charges

Spice-Gummel-Poon: as function of current

\[ Q_{\text{diff}} = \tau_f I_f \]

Mextram: as function of carrier densities

\[ Q_{\text{diff,E}} = \tau_E l_s e^{V_{BE}/m \tau V_T} \]

\[ Q_{\text{diff,B}} = \frac{1}{2} Q_{B0} \quad (n_0 + n_B) \propto \tau_B \]

\[ Q_{\text{diff,epi}} = \frac{1}{2} Q_{\text{epi0}} \frac{x_i}{W_{\text{epi}}} \quad p_0 \propto \tau_{\text{epi}} \]

\( n_0, n_B \): electron concentration in base

\( p_0 \): hole concentration in epilayer
Modelled effects: Cut-off frequency (Research SiGe)

Capacitances (low currents)
Transit times (around top of $f_T$)
Quasi-saturation/Kirk effect (beyond top $f_T$)
Reverse transit time (hard saturation, negative $V_{CB}$)

Graph showing $f_T$ vs. $I_C/A_{em}$ with different $V_{CB}$ values.
Independence of parameters

- Capacitance values and transit times do not influence DC behaviour

- **Base parameters** $I_s, I_k, \tau_B$ are separate from **epilayer parameters** $R_{CV}, SCR_{CV}, I_{hc}, \tau_{epi}$

  \[ \Rightarrow \text{Ge in base does not influence epilayer parameters} \]

- Independency simplifies parameter extraction
Small-signal parameters $V_{CB} = -0.4, 0, 0.75, 1.5V$ (Research SiGe)
Temp. scaling $V_{CB} = -0.36\text{V}$, $T = -50, 25, 62.5, 137.5, 200^\circ\text{C}$
RF noise model \((0.5 \times 20.3 \, \mu \text{m}^2, f = 1, 2, 5.5 \, \text{GHz}, V_{CE} = 2 \, \text{V})\)
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Equivalent circuit describing the elements of a bipolar transistor
Substrate resistance

Mextram does not contain substrate network:

- On-wafer characterization layout differs from final design
- Never complex enough when really needed
List of modelled effects

Modelled better in Mextram than in Spice-Gummel-Poon

- Current gain (incl. reverse Early effect)
- Early effect (bias dependent) $\rightarrow$ output conductance
- Reverse behaviour
- Cut-off frequency $f_T \rightarrow$ all high-frequency behaviour
- Both low and high-frequency distortion
- Large signal modelling $\rightarrow$ e.g. power amplifiers
List of modelled effects (cont.)

Modelled in **Mextram**, but not in **Spice-Gummel-Poon**

- AC and DC Current crowding in base-resistance

- Substrate effects (parasitic transistor)

- descriptions for emitter-base sidewall region

- descriptions for collector-base extrinsic region

- Splitting of capacitances $\rightarrow$ extra delay times

- Overlap capacitances
List of modelled effects (cont.)

Modelled in **Mextram**, but not in **Spice-Gummel-Poon**

- Specific SiGe effects
- Self-heating
- Weak avalanche, also at high currents
- Quasi-saturation and Kirk effect → better HF behaviour

These last effects are important when **supply** voltage is low
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For large enough currents **base widening** occurs:

a lot of charge gets injected into the collector epilayer.

**Consequence:** reduction of current and of cut-off frequency.

Not modelled in Spice-Gummel-Poon model
Modelling quasi-saturation/Kirk effect

The intrinsic part of Mextram looks like

Model for epilayer resistance:

\[ I_{\text{epi}}(V_{BCi}, V_{BCx}) \]

The model contains:

- Ohmic resistance
- Resistance modulation due to excess electrons
- Quasi-saturation (incl. Kirk effect)
504 improvement: model comparison

old model: shows kinks in output conductance

Mextram (new model): smoother behaviour
Mextram (new model). As one can see: measurements do not show kink at the point where quasi-saturation starts.

Blue line: current where quasi-saturation starts
Green line: result from old model
504 improvement: experimental results: (12V BiCMOS process)

old model

Mextram (new model)

Also for cut-off frequency description improved
2\textsuperscript{nd} and 3\textsuperscript{th} derivative of collector current $I_C$ in Gummel plot

Temperature = 25, 75, 125 °C
Contents

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- Equivalent circuit
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Optional features of Mextram

- SiGe transistor in case of a graded Ge-profile

- Collector-bias dependent base current for SiGe

- Self-heating

- Advanced avalanche modelling at high currents
SiGe transistors

Mextram 504 tested on on various SiGe processes

• Device simulations

• Philips (QUBiC4G, various versions from research)

• Infineon, ST (data from international model comparison)

• Temic/Atmel

For most processes no special SiGe options needed, however . . .
First IBM process and Infineon process have graded Ge-content
Philips has box-like Ge profile
For both cases an option is available in Mextram
Reverse Early effect can be seen in two different measurements:

**Reverse Early measurement**

\[ I_E \] vs. \[ V_{EC} \]

\[ V_{BC} = 0.65 \text{ V} \]

**Forward current gain**

\[ h_{fe} \] vs. \[ V_{BE} \]

Blue lines are for one parameter set:

not possible to fit both forward and reverse measurement.
Graded Ge profile: Reverse Early effect

Reverse Early measurement

Forward current gain

Green lines are for another parameter set:
Better result for $V_{EC} < 0.5$ V, but not for larger voltages.
Graded Ge profile: model improvement

\[ n_i^2 \propto \exp \left( \frac{x}{W_B} \frac{\Delta E_g}{kT} \right) \]
Graded Ge profile: model improvement

\[ n_i^2 \propto \exp \left( \frac{x}{W_B} \frac{\Delta E_g}{kT} \right) \]

Base charge:

\[ \frac{Q_B}{Q_{B0}} \approx 1 + \frac{V_{BE}}{V_{er}} + \frac{V_{BC}}{V_{ef}} \]

Gummel number:

\[ \frac{G_B}{G_{B0}} \approx \frac{\exp \left( \left[ 1 + \frac{V_{BE}}{V_{er}} \right] \frac{\Delta E_g}{kT} \right) - \exp \left( -\frac{V_{BC}}{V_{ef}} \frac{\Delta E_g}{kT} \right)}{\exp \left( \frac{\Delta E_g}{kT} \right) - 1} \]
Graded Ge profile: Reverse Early effect

With **new Mextram** option, now including the Ge grading:

Reverse Early measurement

![Graph showing Reverse Early measurement with labels $I_E$ [\(\mu A\)] vs. $V_{EC}$ [V].]

Forward current gain

![Graph showing Forward current gain with labels $h_{fe}$ [-] vs. $V_{BE}$ [V].]

Effective reverse Early voltage:

- large
- small
Optional features of Mextram

- SiGe transistor in case of a graded Ge-profile
- Collector-bias dependent base current for SiGe
- Self-heating
- Advanced avalanche modelling at high currents
Modern Ge profile

Doping profile: high base doping, smaller emitter-cap doping

Ge content: square profile

![Doping Profile Diagram]

Due to high base doping Neutral Base Recombination (NBR) becomes important.
Modern Ge profile: Neutral base recombination (Atmel SiGe)

dotted: without Neutral Base Recombination (NBR)

Base current

\[ I_B \text{ [nA]} \]
\[ V_{BE} = 0.635 \text{ V} \]

\[ G_{I.I.}^{1/5} = (I_B@0V - I_B)/I_C \]

For pure avalanche effect (no NBR): \( G_{I.I.}^{1/5} \) is straight line.
Modern Ge profile: Neutral base recombination

dotted: without Neutral Base Recombination (NBR)
solid: with NBR: new Mextram 504 option, one extra parameter

Base current

New base current: $I_B \sim \frac{l_s}{\beta_f} \exp \left( \frac{V_{BE}}{V_T} \right) \cdot \left( 1 - X_{rec} \frac{V_{CB}}{V_{ef}} \right)$
Modern Ge profile: NBR effect on output conductance

**Constant** $V_{BE}$ with or without Neutral Base Recombination (NBR)

**Constant** $I_B$ without NBR (dashed)

**Constant** $I_B$ with NBR (new model option)
Optional features of Mextram

- SiGe transistor in case of a graded Ge-profile

- Collector-bias dependent base current for SiGe

- Self-heating

- Advanced avalanche modelling at high currents
Self-heating:

an increase in temperature due to power dissipation

• Standard extra sub-circuit

\[ dT \]

\[ R_{th} \]

\[ C_{th} \]

\[ P_{diss} \]

• Dissipation \( P_{diss} \): sum over the dissipation in every branch
Selfheating: output characteristic at constant $I_B$

Mextram 504 is first Philips model with full self-heating
(our simulator allowed a trick to handle self-heating)

In case of selfheating: $V_{BE}$ decreases always

For pure Si transistors: $I_C$ increases with $V_{CE}$
For SiGe transistors: $I_C$ decreases with $V_{CE}$
Selfheating and mutual heating

It is possible to model **mutual heating** using an external network.
Optional features of Mextram

- SiGe transistor in case of a graded Ge-profile
- Collector-bias dependent base current for SiGe
- Self-heating
- Advanced avalanche modelling at high currents
Breakdown voltage $BV_{ceo}$ is where $I_B = 0$ (at constant $V_{BE}$).
For this process $BV_{ceo} \approx 12 \text{ V}$.
Extended avalanche: breakdown voltage depends on current level

For increasing currents $BV_{ceo}$ normally increases

For high currents $BV_{ceo}$ can decrease again due to Kirk effect
Extended avalanche: snapback

Mextram is the only model capable of describing snapback

Output characteristic at constant base current

Snapback is bad for convergence → optional feature
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Geometric scaling

Status of Mextram 504
Geometric scaling

The model parameters for a single transistor are called electrical parameters

These electrical parameters are a function of geometry

Geometry is given by $W_{\text{em}} \times L_{\text{em}}$, $W_{\text{base}} \times L_{\text{base}}$ etc.

Example:

$$I_S = I_{S}^{\text{bottom}} W_{\text{em}} L_{\text{em}} + 2 I_{S}^{\text{sidewall}} (W_{\text{em}} + L_{\text{em}})$$

⇒ $I_{S}^{\text{bottom}}$ and $I_{S}^{\text{sidewall}}$ are unity parameters
Geometric scaling

MOS transistors

Miniset
→ Electrical parameters and temperature scaling

Maxiset
→ Geometry scaling parameters

Bipolar technologies have more geometric variations

Bipolar transistors

Within Mextram
→ Electrical parameters and temperature scaling

Outside of Mextram
→ Geometry scaling
Equivalent circuit describing the elements of a bipolar transistor.
Example: cut-off frequency $f_T$ (0.35µm BiCMOS)

$V_{CB} = -0.4, 0, 1.5, 3.0$ V

0.7 $\times$ 1.4 µm$^2$  

0.7 $\times$ 5.6 µm$^2$  

0.7 $\times$ 20.0 µm$^2$

→ a designer is free to choose any length within layout rules.
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Status of Mextram 504
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Companies **using** Mextram:
- Philips (of course), TSMC, TI

Companies **evaluating** Mextram:
- Analog Devices, Samsung, IBM

Mextram is **implemented** in (as far as we know):

- **Spectre** (Cadence) (DLL: on our web—4.4.6: Dec. 2001)
- **HSpice** (Synopsys/Avant!) (2002)
- **ADS** (Agilent) (March 2002)
- **Eldo** (Mentor Graphics) (March 2001)
- **Pstar** (In-house) (4.1, June 2001)
**Summary**

*Mextram* is an advanced compact bipolar model:

- is based on *physics*

- can be used for *analogue* and *digital* applications

- special attention is paid to (higher-order) *derivatives*

- describes the various *regions* of the transistor

- contains *temperature* scaling and can be scaled *geometrically*
Summary (cont.)

- Mextram gives **excellent description of**
  - **Early** effect and output conductance
  - **High-current** effects
  - **High-frequency** behaviour
  - **Noise** behaviour

- Mextram contains **features for**
  - Non-constant **Ge profiles**
  - **Early** effect on the **base** current
  - Extended **avalanche** for high currents
  - **Self-** and **mutual heating**

- Mextram is **implemented** in various commercial simulators
More information

Our Web-site [1] contains:

Documentation

→ Model definition [2]
→ Derivation of all equations [3]
→ Parameter extraction [4]
→ Comparison between Mextram 503 and Vbic 95 [5]
→ A number of publications like [6, 7, 8, 9, 10]
→ A number of presentations like [11,12,13,14]

Source code

→ Full Mextram 504 code including simple solver
→ Spectre Model Kit (dynamically linkable library)
Real example

World’s first $20 \times 20$ 10Gb/s crosspoint switch (optical networking)

Designed using Mextram (first time right)
Based on 1D simulations combined with measured scaling rules
References

1. For the most recent model descriptions, source code, and documentation, see the website http://www.semiconductors.philips.com/Philips_Models.


