Mixed-Mode Device/Circuit Simulation

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Outline

Circuit simulation and compact models

Numerical models instead of compact models

Challenges in numerical modeling

Mixed-mode device/circuit simulation

Examples

Conclusion

Circuit simulation fundamental

- Development of modern IC
- To understand and optimize the way a circuit works

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- Lumped elements: R, C, L, etc.
- Current and voltage sources, controlled sources
- Semiconductor devices
- Thermal equivalent circuit (coupling and self-heating)

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For the simulation of large circuits we need compact models

- Obtained from simplified solutions of these PDEs or empirically
- Must be very efficient (compact!)

Compact Modeling

Derivation of compact models based on fundamental equations

- Often the drift-diffusion framework is used
- Simplifying assumptions on geometry, doping profiles, material parameters
  - $\Rightarrow$ *Compact model*
- It is becoming increasingly difficult to extract main features

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Compact modeling challenges (ITRS)

- Quantum confinement
- Ballistic effects
- Inclusion of variability and statistics

Simulation with Compact Models

Advantages of using compact models

- Very fast execution (compared to PDEs)

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Disadvantages

- Many parameters
  - Physically motivated parameters
  - Fit parameters
- Parameter extraction can be quite cumbersome
- Device optimization via geometry and doping profile hardly possible
- Considerable model development effort
  - *Limited model availability (DG, TriGate, FinFETs, GAAFETs, etc.)*
- Scalability questionable
  - *Quantum effects*
  - *Non-local effects*

Mixed-Mode Simulation

Instead of

- Analytical expressions describing the device behavior (compact models)

Rigorous device simulation based on

- Coupled partial differential equations!

Compact Modeling – Numerical Modeling

Advantages of numerical device simulation

- Fairly arbitrary devices (doping, geometry)
- Realistic doping profiles from process simulation
- Natural inclusion of
  - *2D/3D effects*
  - *Non-local effects (via appropriate transport model)*
  - *Quantum mechanical effects (via simplified model or Schrödinger's equation)*
  - *Temperature dependencies*
- Sensitivity of device/circuit figures of merit to process parameters
- Better predictivity for scaled/modified devices

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Disadvantages of numerical modeling

- Performance (don't compare!)
- Convergence sometimes costly/difficult to obtain
- Realistic doping profiles from process simulation

Challenges in Device Simulation

Feature size approaches mean free path

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  - *No ballistic transistor in sight, but still important effect*

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  - *Critical gate length aroung* $10\,nm$
  - *Modified transport parameters for thin channels*

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- Strain effects used to boost mobility
- Substrate orientation and channel orientation

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Exploitation of new materials

- Strained silicon, SiGe, Ge, etc.
- High-k dielectrics

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Classical transport described by Boltzmann's equation

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Simplest moment-based model: the classic drift-diffusion model

$$\epsilon \nabla^2 \psi = \mathrm{q}(n - p - C)$$

$$\nabla \cdot (D_n \nabla n - n \, \mu_n \nabla \psi) - \frac{\partial n}{\partial t} = R$$

$$\nabla \cdot (D_p \nabla p + p \, \mu_p \nabla \psi) - \frac{\partial p}{\partial t} = R$$

Requires models for physical parameters D, μ, and R

These models capture fundamental physical effects

- *Velocity saturation, SRH recombination, impact-ionization*
- *Models can be quite complex*

Used to be basis for the derivation of compact models

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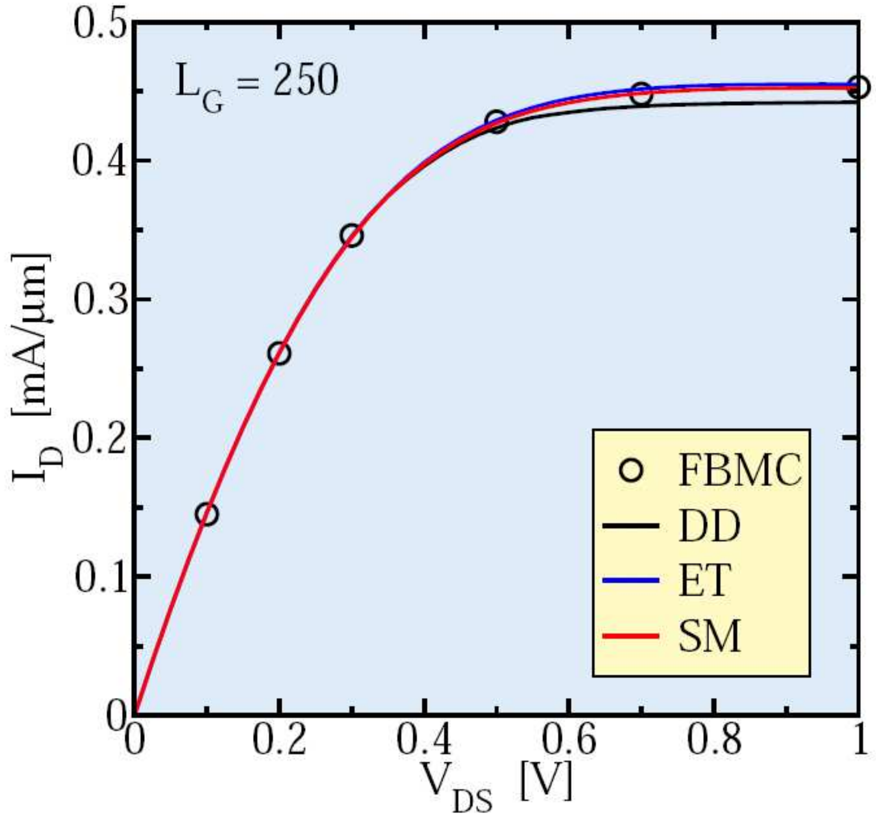
- DD accurate down to $250\,\mathrm{nm}$
  - *No velocity overshoot*



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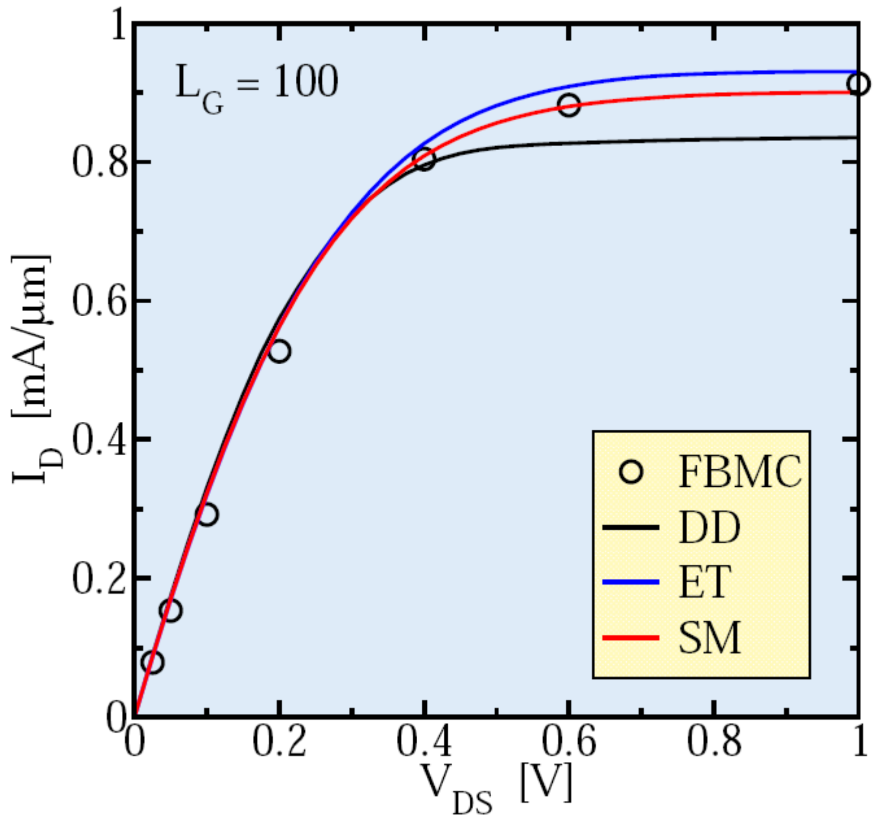
  - *Maxwellian distribution function*



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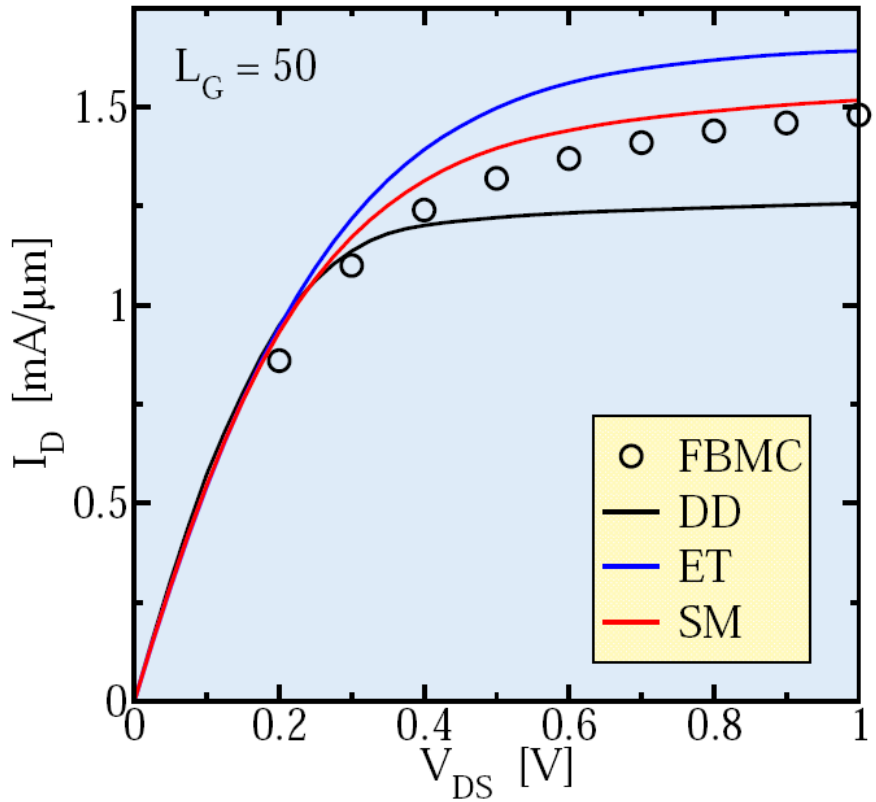
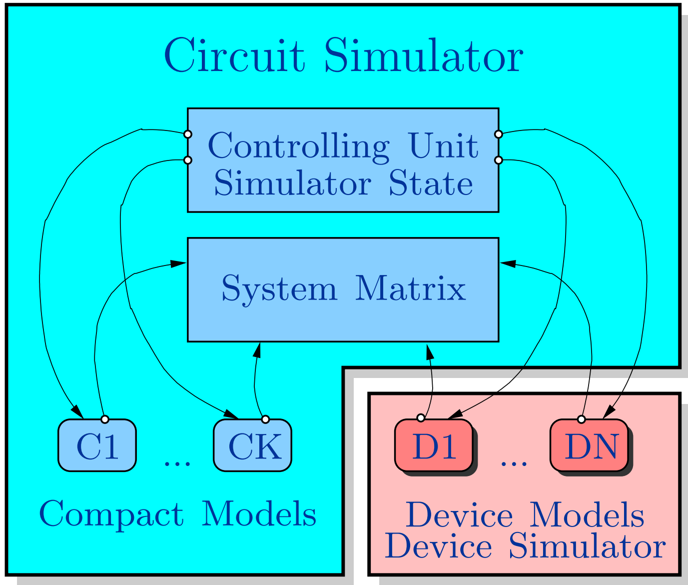
- ET accurate at $100\,\mathrm{nm}$
  - *Maxwellian distribution function*
- SM accurate at $50\,\mathrm{nm}$
  - *Non-Maxwellian effects*
  - *Low computational effort*
  - *'TCAD' compatible*



Mixed-Mode Simulation

Simulator coupling

- Simple, straight forward solution
- Two-Level Newton algorithm
- SPICE-like damping algorithms usable
- Many iterations for device equations needed
- Parallelization straight-forward



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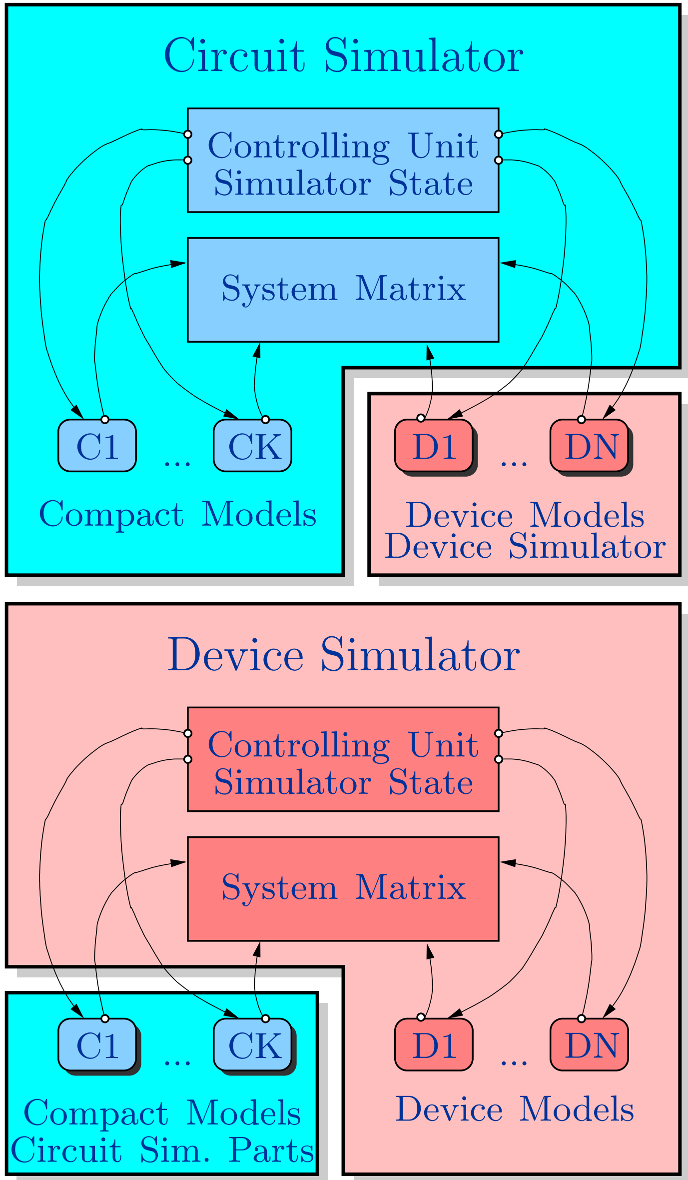
All-In-One solution (Full-Newton)

- Circuit and device equations in one single matrix
- Full-Newton algorithm
- Complex convergence behavior
- Parallelization more complicated



Simulator Coupling

Two-Level Newton

- Device simulator is called for each circuit iteration
  - *Fixed set of contact voltages*
  - *Contact current response* I_{C}^{k}
  - *Problematic:* $g_{\mathrm{eq}}^{k} = \frac{\partial I_{\mathrm{C}}}{\partial V_{\mathrm{C}}}|_{k}$
- Device simulator iterates until convergence
- Last iteration as initial-guess
  - *Linear prediction algorithm*

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- Only one iteration of device simulator
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Disadvantages

- Considerable overhead

Full-Newton Approach

Device and circuit equations in one matrix

Simultaneous damping of device and circuit equations

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No simulator communication overhead

No input-deck generation, no temporary input and output files, etc.

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- Quadratic convergence properties for a good initial-guess (fast!)
- Initial-guess hard to construct
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Reliable DC operating point calculation of utmost importance

- Drift-diffusion solution as initial-guess for
  - *Higher-order transport models*
  - *Electro-thermal solution*
- Transient simulations better conditioned

Convergence

Why is convergence hard to obtain?

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Conventional boundary condition for numerical devices

$V_{\mathrm{C},i}$ (device contact potential) $= \varphi_{\mathrm{C},i}$ (node voltage)

Carrier concentrations depend exponentially on the potential

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No pure voltage boundary conditions

- Current flowing out of the contact affects node voltages
  - *System is extremely unstable at the beginning of the iteration*
- Similar situation as with current boundary condition
- Shifts in the DC offset require many iterations
  - *Distributed quantities provide 'internal state'*

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Alternative boundary condition for numerical devices

$$V_{\mathrm{C},i} = \varphi_{\mathrm{C},i} - V_{\mathrm{ref}} \qquad \text{with} \qquad V_{\mathrm{ref}} = \frac{1}{N_{\mathrm{c}}} \sum_j \varphi_{\mathrm{C},j} \quad \text{(average potential)}$$

Average potential changes during the iteration and operation

Convergence – Damping Schemes

Simple Methods

- Limitation of node voltage update to $2V_{\mathrm{T}}$
  - *Many iterations needed*
- Initial guess close to the solution (experimental value: $\pm 0.2\ \mathrm{V}$)

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Traditional device simulation methods

- Damping after Bank and Rose (SIAM 1980)
- MINIMOS damping scheme

Standard damping schemes not suitable for mixed-mode problems

Convergence – Embedding Scheme

Shunt an iteration dependent conductance G_S^k at every contact

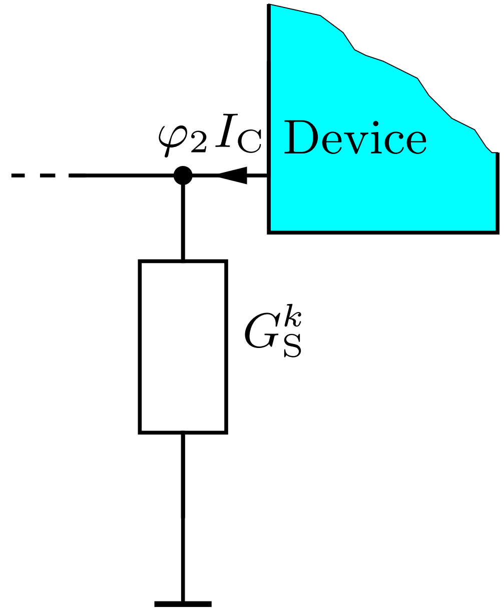
Purely empirical expression

$$G_\mathrm{S}^k = \max\left(G_\mathrm{min},\; G_0 \times 10^{-k/\kappa}\right)$$

$$G_0 = 10^{-2}\,\mathrm{S}$$

$$G_\mathrm{min} = 10^{-12}\,\mathrm{S}$$

$$\kappa = 1.0\;\ldots\;4.0$$



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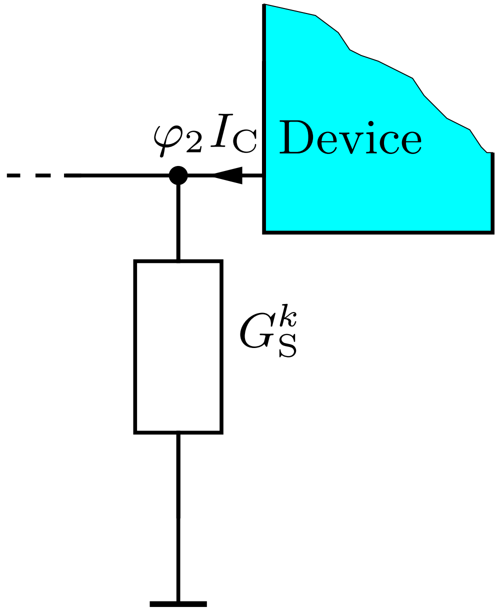


Method works for small circuits

Zero initial-guess for node voltages

Charge neutrality assumptions for semiconductor devices

Convergence within 20–50 iterations

Comparable to SPICE with compact models

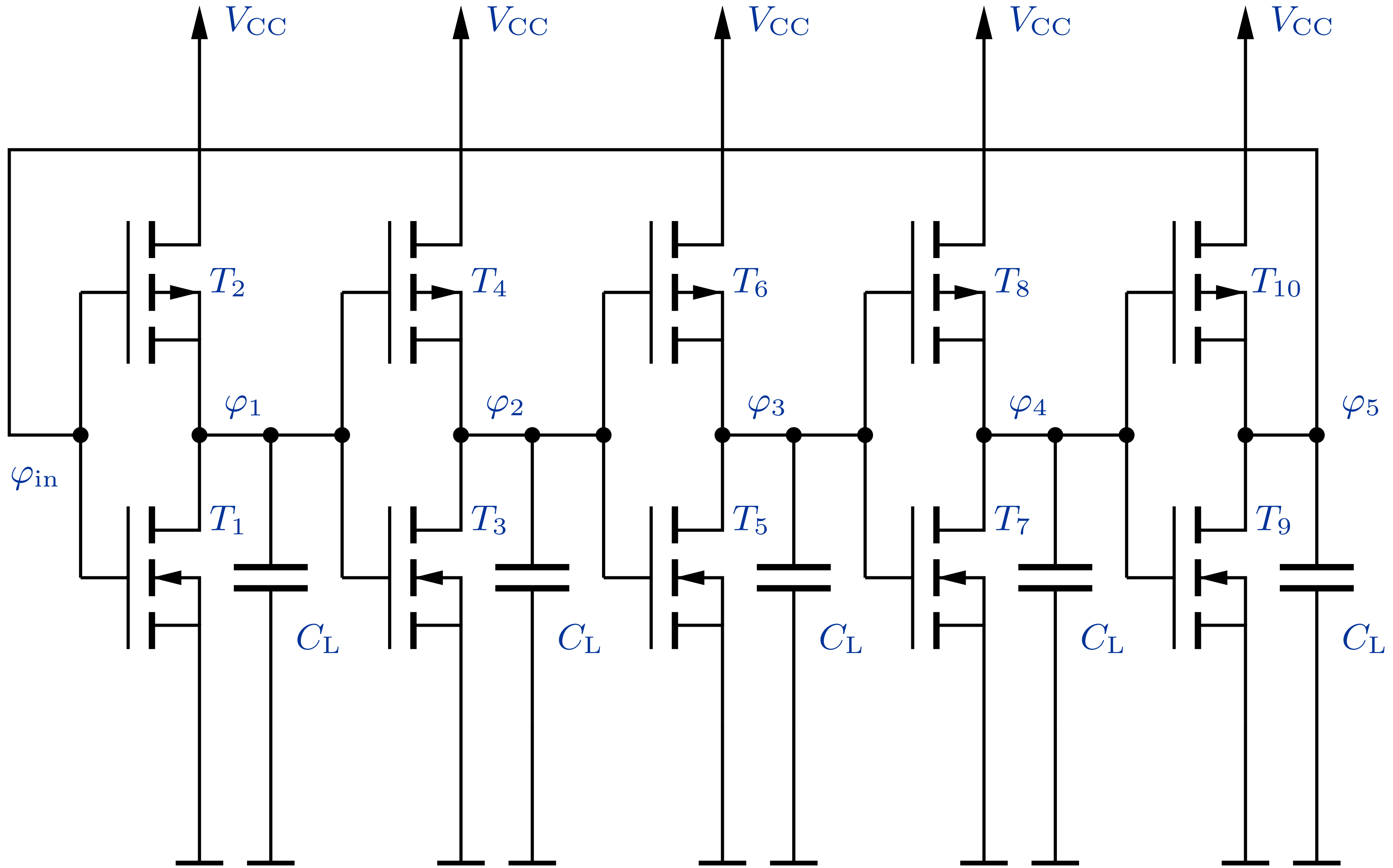
Examples

Five-stage CMOS ring oscillator

- Long-channel/short-channel behavior

Electro-thermal analysis of an operational amplifier (μA709)

Five-Stage CMOS Ring Oscillator



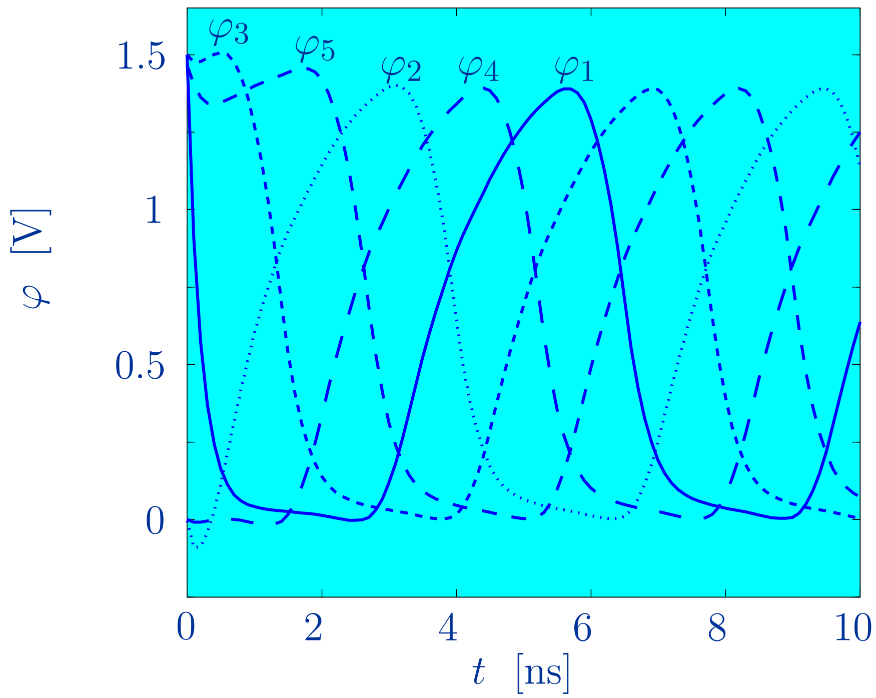
CMOS Ring Oscillators

Long-channel devices ($L_{\mathrm{g}} = 2\,\mu\mathrm{m}$)

First timestep: $\varphi_{\mathrm{in}} = 0$ V

Excellent agreement DD and ET

Non-local effects negligible



CMOS Ring Oscillators

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Excellent agreement DD and ET

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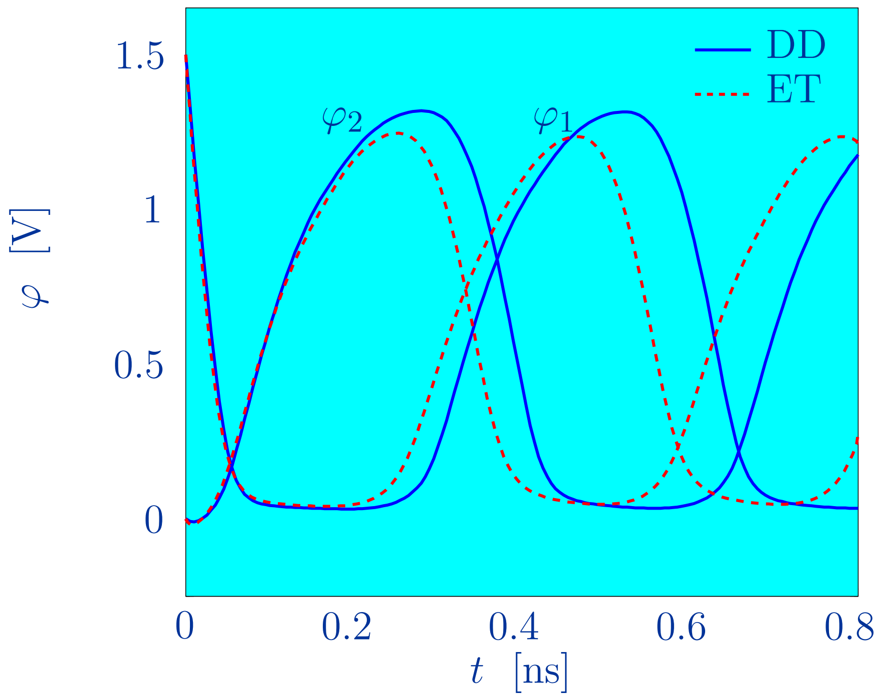
Short-channel devices ($L_g = 0.13\,\mu m$)

Significant difference DD and ET

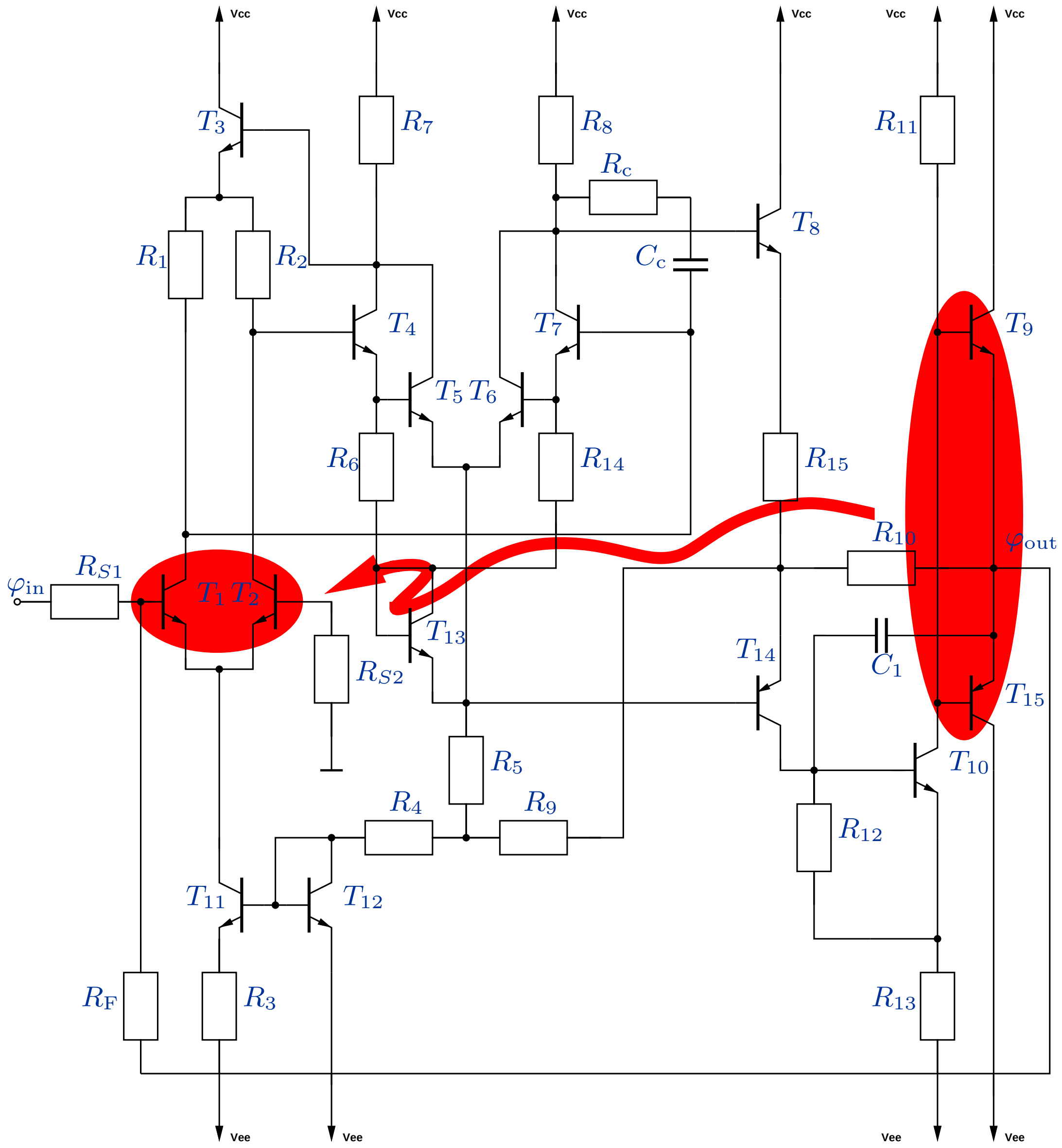
- Non-local effects important
- Larger currents for ET
- 15% difference in delay time

Complexity of models can be increased

- Higher-order transport models
- More accurate quantum corrections
- Different mobility models



Electro-Thermal Analysis of a μA709



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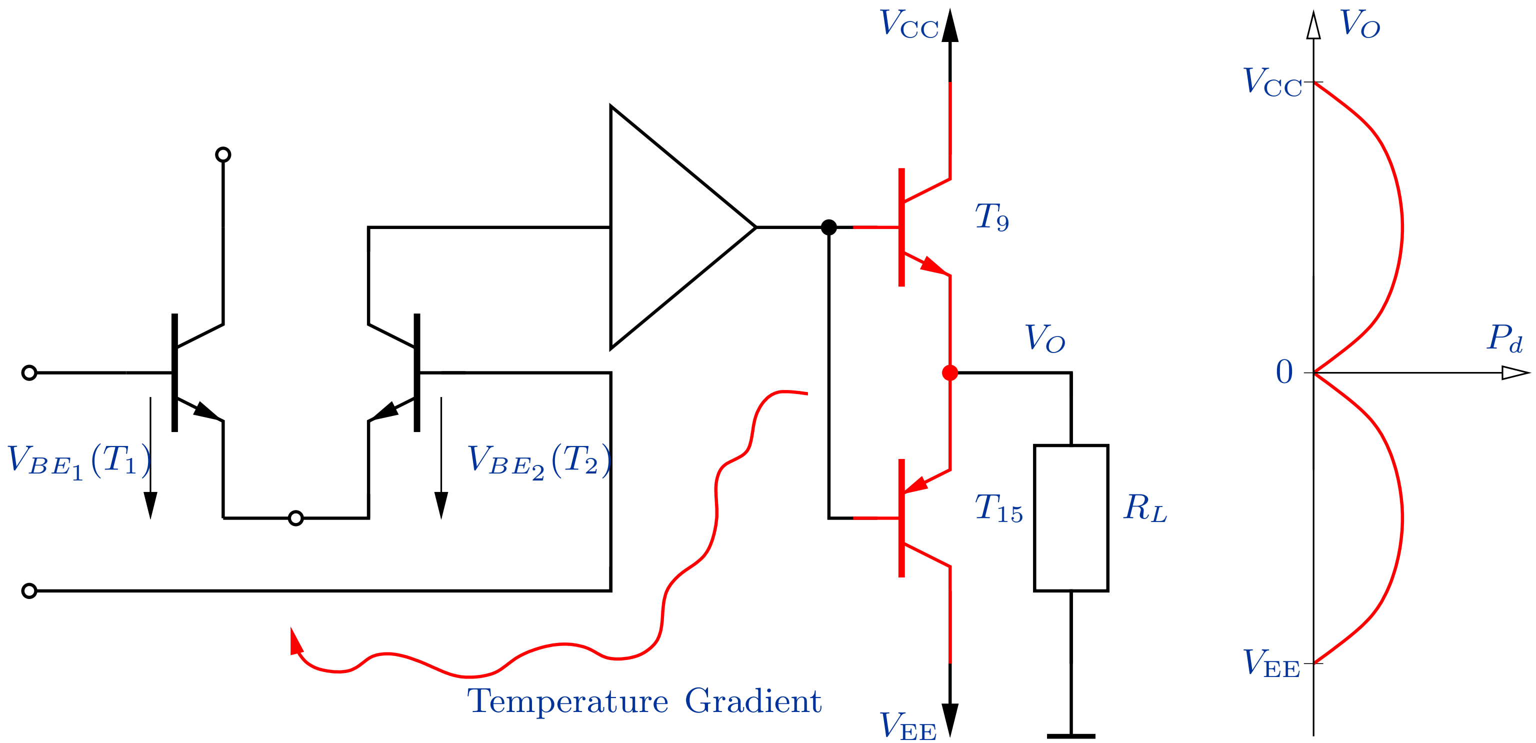
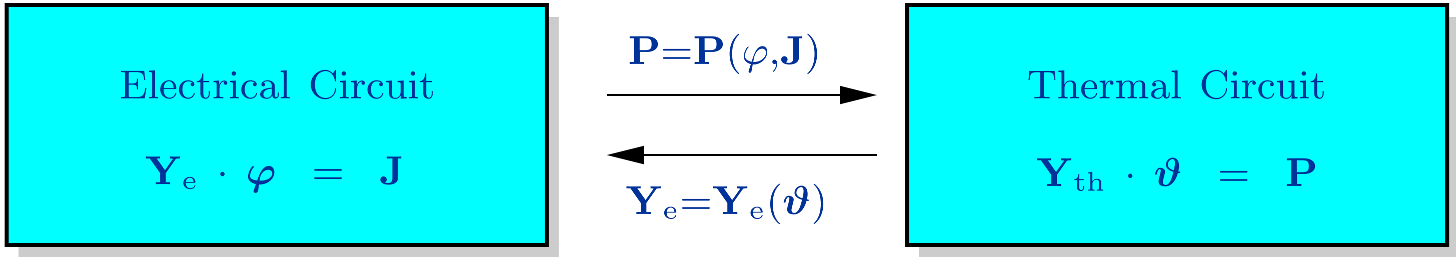


Thermal Circuit

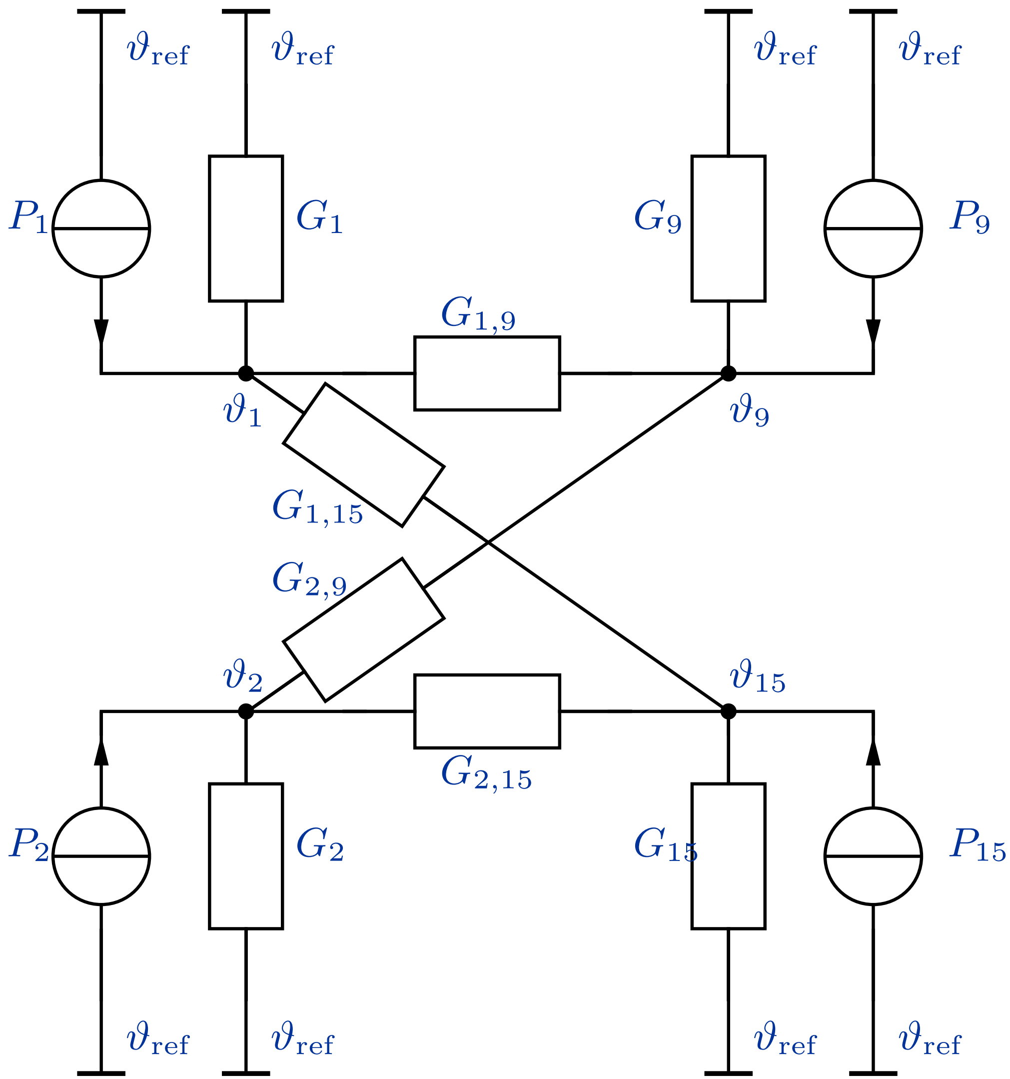
Thermal coupling modeled via a thermal circuit

- Thermal coupling between individual devices
- Thermal equations similar to Kirchhoff's equations
  - *Formally derived from the discretized lattice heat-flow equation*



Electro-Thermal Analysis of a μA709

Simple thermal equivalent circuit



Electro-Thermal Analysis of a μA709

Electrical simulation

All 15 transistors numerically simulated

System-size: 37177, simulation time: $1{:}08$ hours (101 points, DC transfer)

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Electro-thermal simulation

Input and output stage with self-heating (4 Transistors)

Thermal coupling effects

Thermal feedback from the output to the input stage

Thermal interaction between all 4 transistors

Highly non-linear problem, complex convergence behavior

System-size: 40449, simulation time: $3{:}08$ hours

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- System-size: 37177, simulation time: $1{:}08$ hours (101 points, DC transfer)

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Electro-thermal simulation with simplified self-heating model

- Same coupling effects as before
- Practically same results
- System-size: 38477, simulation time: $1{:}22$ hours

Electro-Thermal Analysis of a μA709

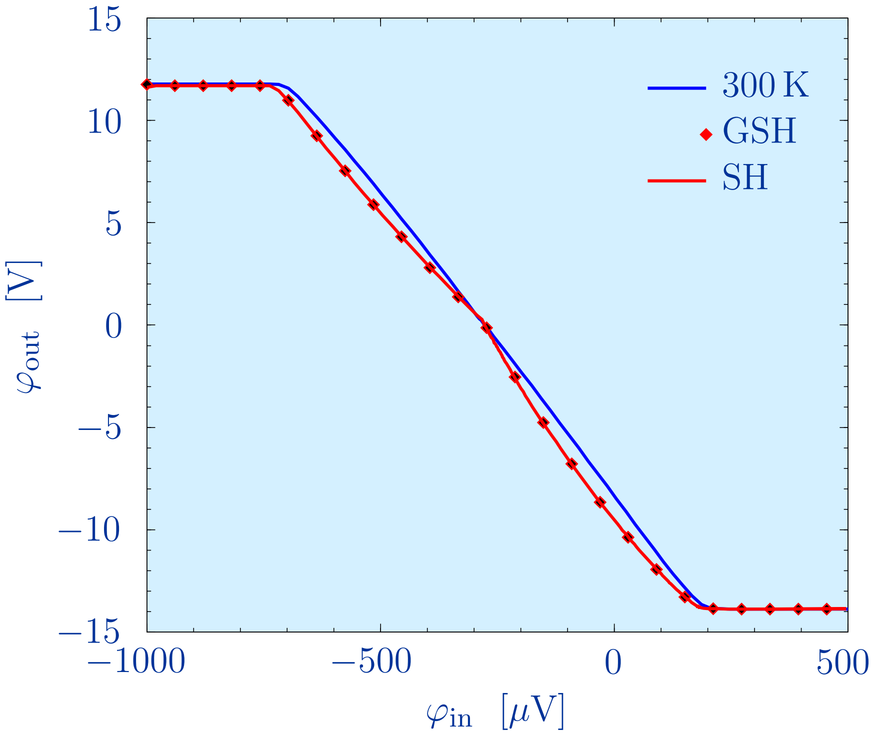
DC Stepping

- Gain ≈ 35000
- $\Delta\varphi_{\text{out}} = 0.7$ V (101 points)
- Critical point 0 V

Thermal feedback caused bumps

Input stage: ΔT

- $\Delta T \propto P$
- $\max(\Delta T) = -22$ mK
- Input voltage difference



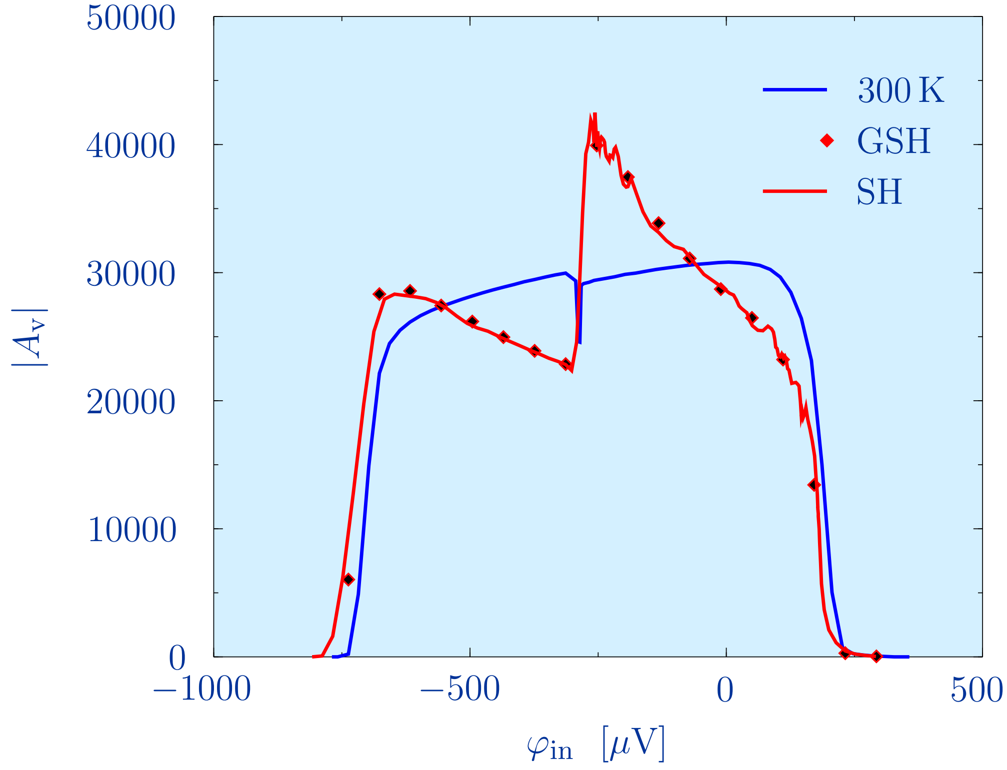
Electro-Thermal Analysis of a μA709

Open-loop voltage gain $|A_{\mathrm{v}}|$

Optimistic thermal conductances

Stronger impact published

- $|A_{\mathrm{v}}|$ can even change sign
- OpAmp can become unstable



Conclusions

For circuit design compact models are indispensable

Intermediate phase when devices structures is not established

- Mixed-mode circuit/device simulation can be used

Motivation for mixed-mode device-circuit simulation

- When compact models are inconvenient/not available
- Verification of compact models in a more realistic environment
- Optimization of devices
- Exploitation of new device designs

Examples have been simulated with MINIMOS-NT

- Go to `http://www.iue.tuwien.ac.at` and try it