Table Based Models

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Outline

- Table look-up models
  - Interpolation methods
  - Generation of data tables
- SPICE implementation and performance
- Further developments and critique of the approach
- Summary/conclusion

Table look-up models

Model setup

Tables of electrical characteristics

Search function

Interpolation routines

Interface to simulator

j	i / V_{GS} \ V_{DS}	0	1	2	3	4	5	6
		0	**0.1**	**0.5**	**1.0**	**1.5**	**2.5**	**3.5**
0	**0.3**	0.0	5×10^{-7}	6×10^{-7}	7×10^{-7}	8×10^{-7}	1×10^{-6}	2×10^{-6}
1	**0.5**	0.0	6×10^{-5}	7×10^{-5}	8×10^{-5}	9×10^{-5}	1×10^{-4}	2×10^{-4}
2	**0.7**	0.0	0.0014	0.0020	0.0023	0.0025	0.0028	0.0032
3	**0.9**	0.0	0.004	0.0082	0.0089	0.0094	0.010	0.011
4	**1.2**	0.0	0.007	0.020	0.022	0.023	0.025	0.027
5	**1.8**	0.0	0.011	0.042	0.055	0.058	0.062	0.065
6	**2.5**	0.0	0.014	0.059	0.09	0.10	0.11	0.11
7	**3.5**	0.0	0.017	0.073	0.12	0.15	0.17	0.18

Table of I_{DS}, ids[i][j]

Given bias values search for nearest table entries

V_{DS}=1.7 V, V_{GS}=1.5 V
i=4, j=4

Interpolate $I_{DS}(V_{DS},V_{GS})$

Interpolation method requirements

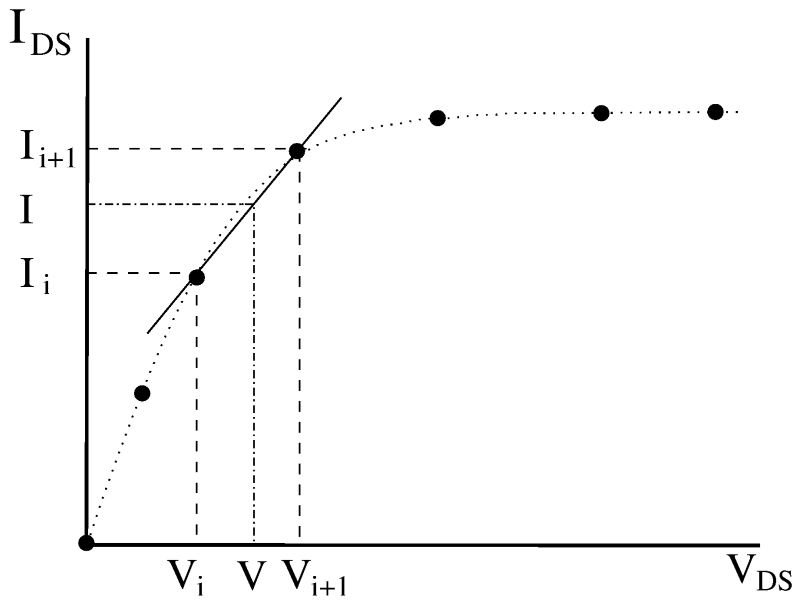
- Compatible with the Newton-Raphson algorithm
  - Continuous
  - Preserve monotonicity of data (non-oscillatory)
  - Preferably C^1 smooth (continuous derivatives) or better
- Accurate
- Fast
- Optimal memory usage
- Easy to understand

Interpolation and approximation methods

- Polynomial interpolation
  - Linear
  - Quadratic
  - Exponential
- Variation diminishing B-spline approximation
- Combined interpolations
- Other interpolations
  - Spline interpolations
  - Variation diminishing interpolations (ENO)

Linear interpolation

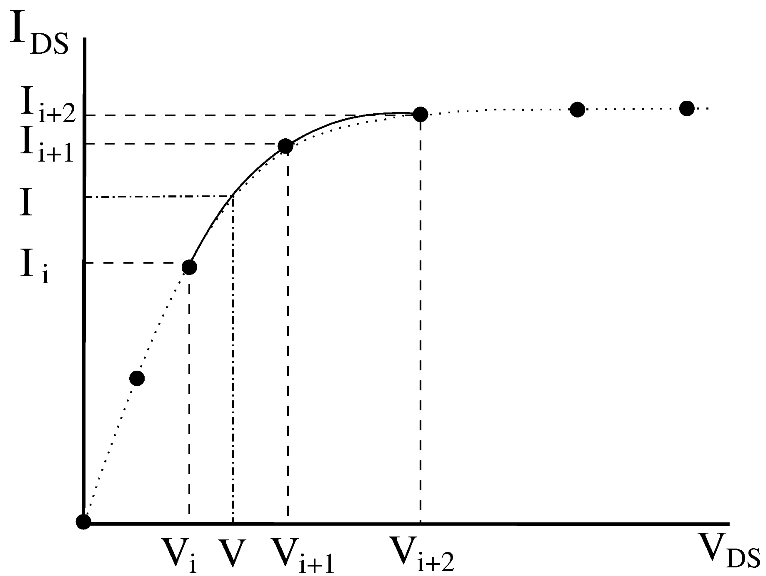
- Advantages
  - Computationally simple
  - Preserves monotonicity of data
  - Accuracy is easily controlled by table density
- Disadvantages
  - Discontinuous first derivatives
  - Relatively large tables are needed for good accuracy



$$I_{DS}(V) = I_i + (I_i - I_{i+1})\frac{V - V_i}{V_{i+1} - V_i}$$

Quadratic interpolation

- Advantages
  - More accurate than linear interpolation
  - Accuracy is easily controlled by table density
  - Control of derivative continuity
- Disadvantages
  - Not guaranteed to be monotonic
  - Slower than linear interpolation



$$L_{0,i}(V) = \frac{(V - V_{i+1})(V - V_{i+2})}{(V_{i+2} - V_i)(V_{i+1} - V_i)}$$

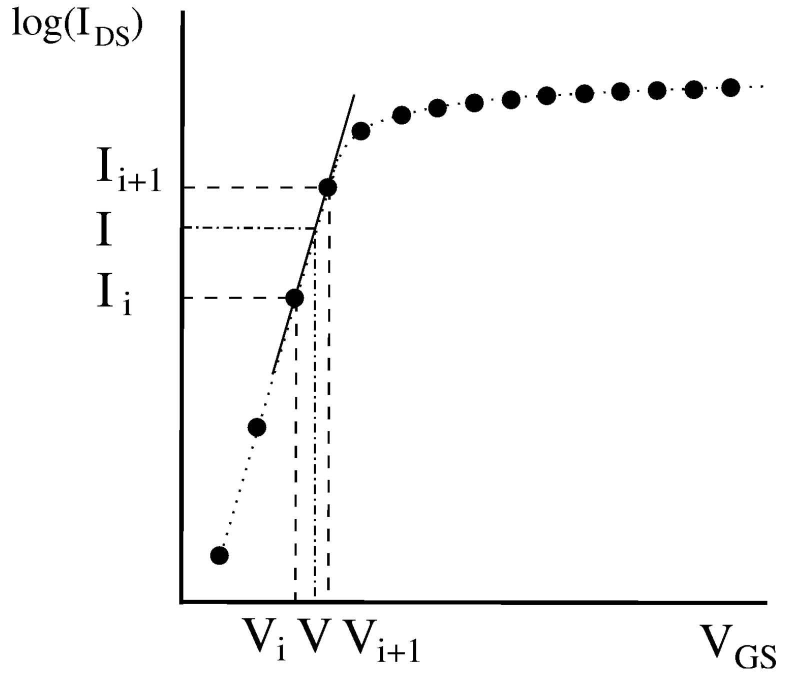
$$L_{1,i}(V) = \frac{(V - V_i)(V - V_{i+2})}{(V_{i+1} - V_{i+2})(V_{i+1} - V_i)}$$

$$L_{2,i}(V) = \frac{(V - V_{i+1})(V - V_i)}{(V_{i+2} - V_i)(V_{i+2} - V_{i+1})}$$

$$I_{DS}(V) = I_i L_{0,i}(V) + I_{i+1} L_{1,i}(V) + I_{i+2} L_{2,i}(V)$$

Exponential interpolation

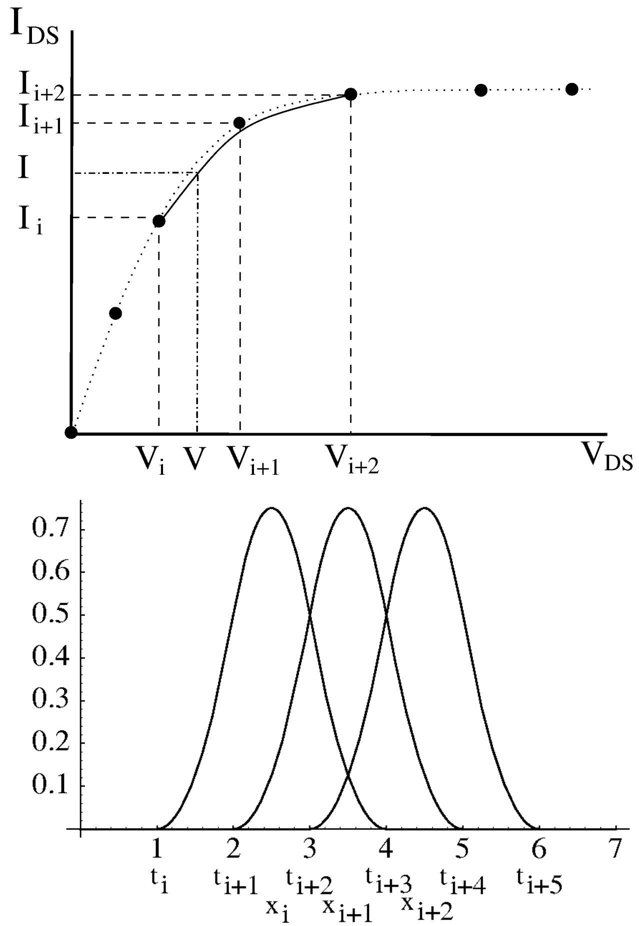
- Advantages
  - Preserves monotonicity of data
  - Very good fit to experimental data
- Disadvantages
  - Computationally expensive
  - Discontinuous first derivatives



$$I_{DS}(V) = I_i e^{\frac{V-V_i}{V_{i+1}-V_i}\ln(\frac{I_{i+1}}{I_i})}$$

B-spline approximation

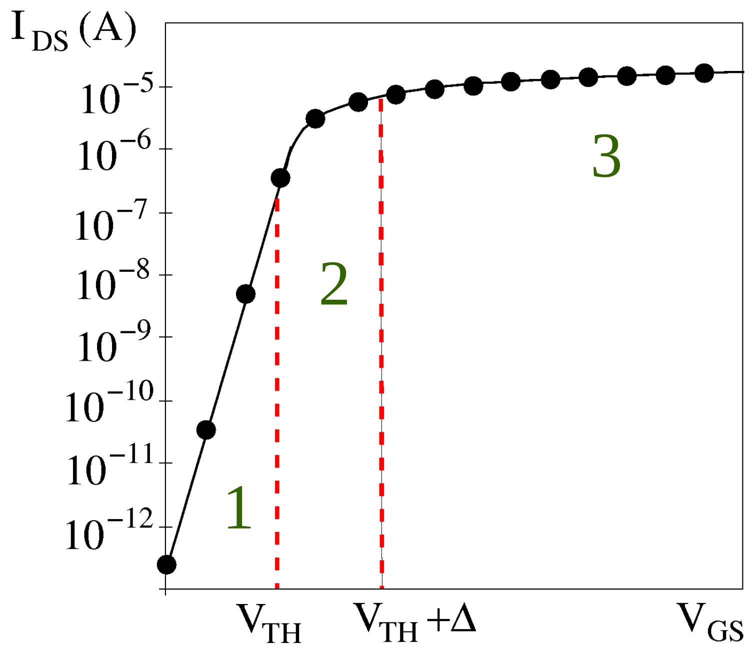
- Advantages
  - Continuous first derivative
  - Preserves monotonicity of data
  - Accuracy is easily controlled by table density
- Disadvantages
  - Slower than linear or quadratic interpolations
  - Approximation is not as accurate as interpolation



$$I_{DS}(V) = I_i B_{i,t}(V) + I_{i+1} B_{i+1,t}(V) + I_{i+2} B_{i+2,t}(V)$$

Combined interpolation

- 1. Subthreshold region: exponential interpolation $f_{EXP}(V_{GS})$
- 3. Strong inversion: linear (quadratic) interpolation $f_{LIN}(V_{GS})$
- 2. Transition region: blending function [#]



$$\mu(V_{GS}) = \frac{V_{GS} - V_{TH}(V_{BS}, V_{DS})}{\Delta}$$

$$I_{DS}(V_{GS}) = (1 - \mu(V_{GS}))\, f_{EXP}(V_{GS}) + \mu(V_{GS})\, f_{LIN}(V_{GS})$$

[#] V.Bourenkov, K. G. McCarthy, A. Mathewson. ICMTS 2003

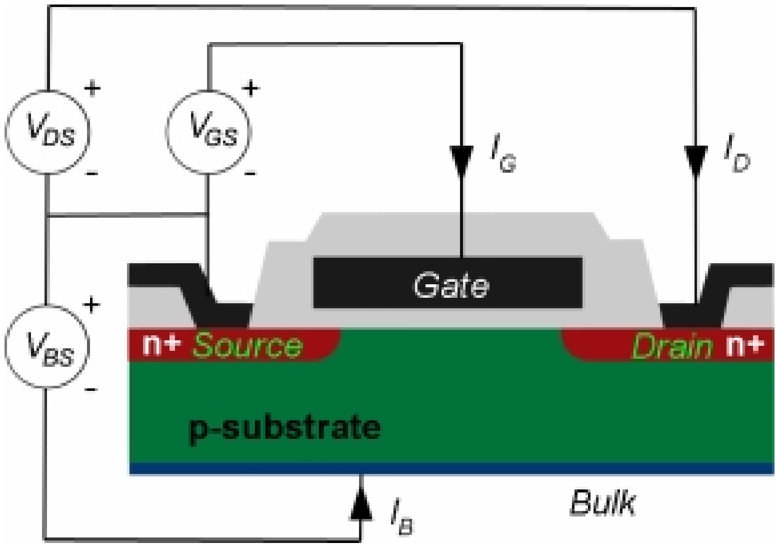
Other interpolations

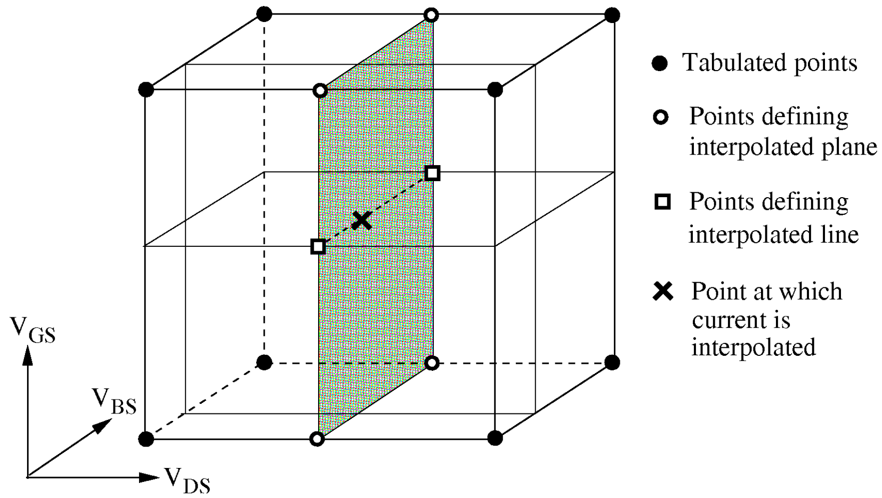
- Cubic spline interpolation
  - Smooth first derivatives
  - May oscillate, computationally expensive
- Bicubic interpolation (in 2D)
  - Monotonic, continuous first derivatives
  - Complex implementation for 3D
- Essentially Non-Oscillatory approximation[#]
  - Monotonic, continuous first derivatives
  - Complex implementation

[#] B. Yang, B. McGaughy. DAC 2004

3D Interpolation

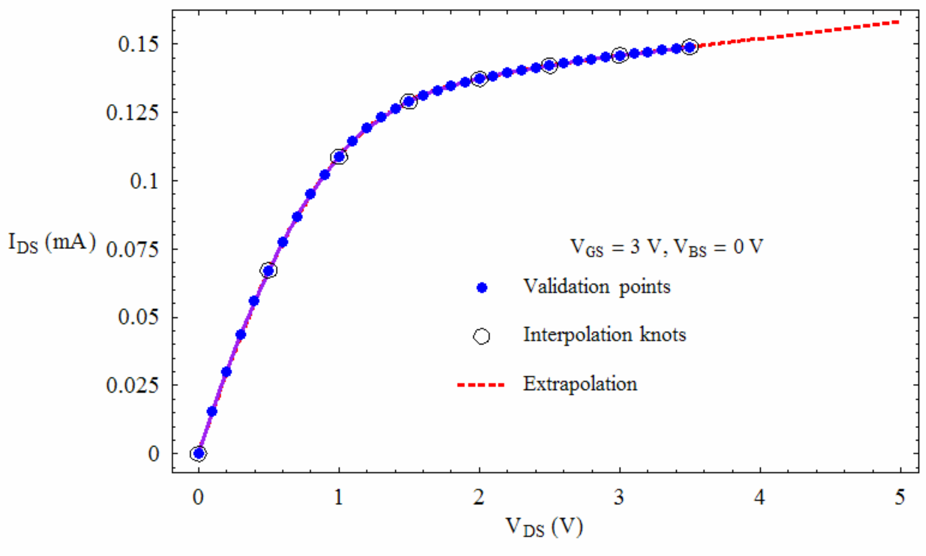
- MOSFET is a four-terminal device
- Device characteristics are functions of three relative voltages
- Three-dimensional tables to store measured data
- Three-dimensional interpolation

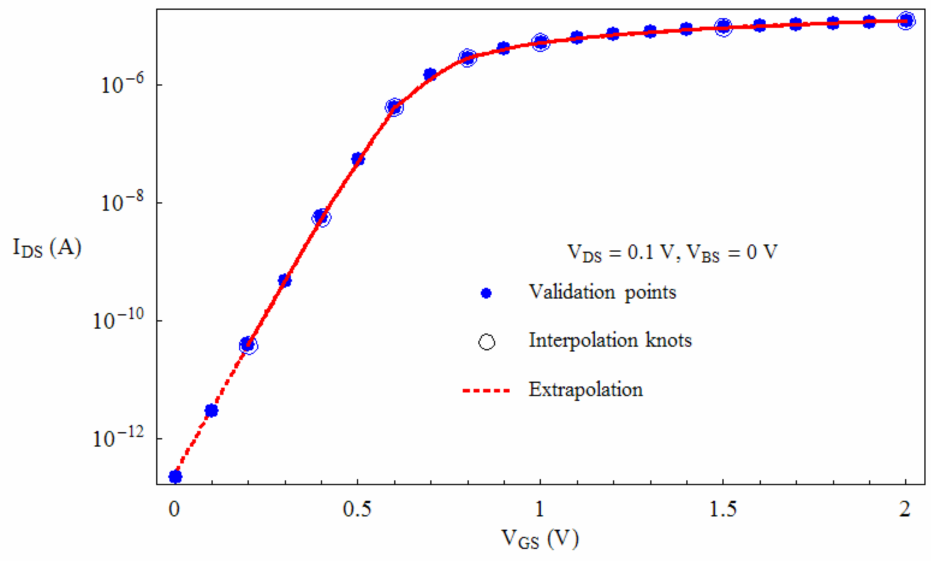




Extrapolation

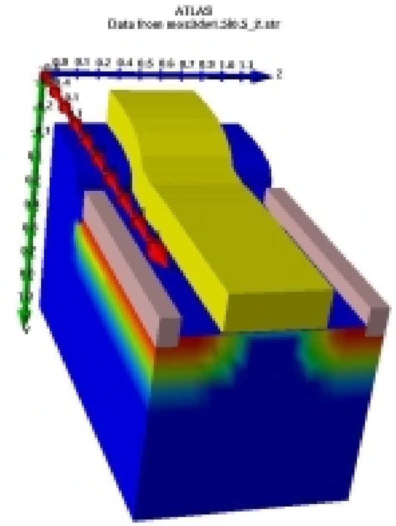
- “Phantom vertices” method
  - Linear extrapolation in strong inversion
  - Exponential extrapolation in weak inversion



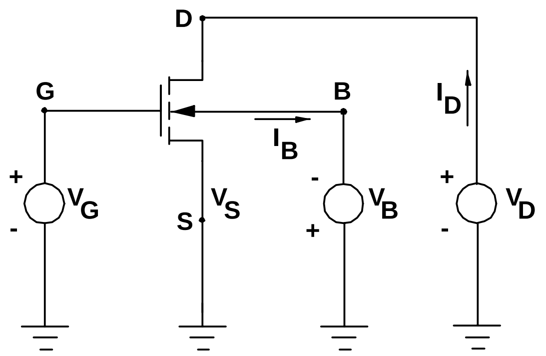


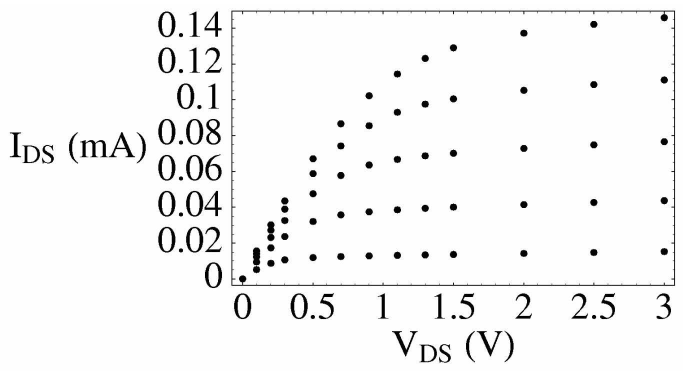
Generation of data tables (I)

- Measurements
- Device simulations
- Analytical compact models



Measure DC currents for
different bias conditions





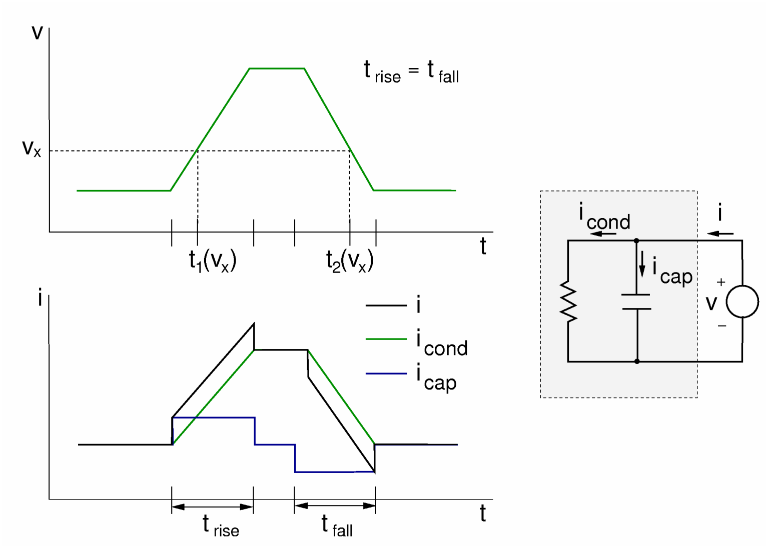
Generation of data tables (II)

Extraction of terminal charges

From analytical model

From transient analysis (QS)[#]

From DC and s-parameter measurements (NQS)[@]



$$i_{cond}(v) = \frac{1}{2}[i(t_1(v)) + i(t_2(v))]$$

$$i_{cap}(v) = \frac{dQ}{dt} = \frac{dQ}{dv}\frac{dv}{dt}$$

$$i_{cap}(v) = \frac{1}{2}[i(t_1(v)) - i(t_2(v))]$$

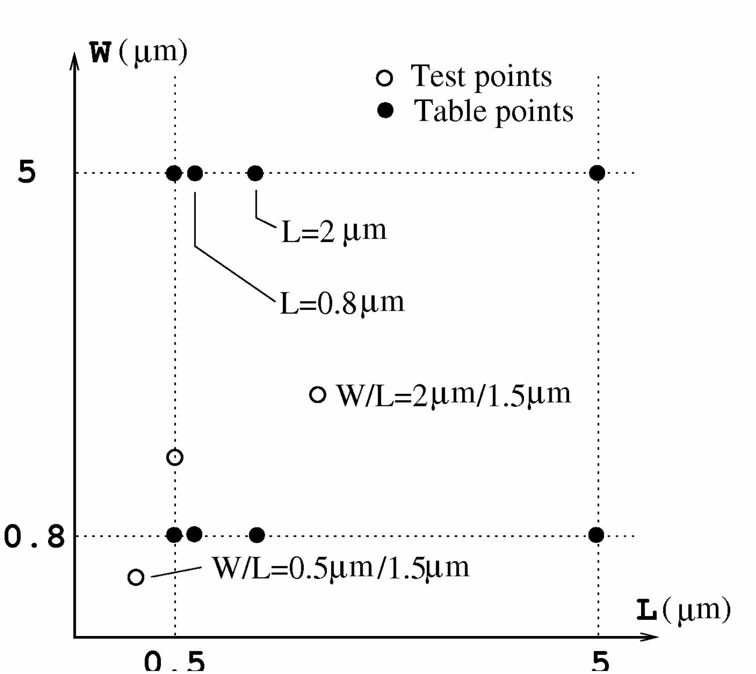
$$Q(v) = Q_0 + \int_{v}^{v_0} i_{cap}(u)du$$

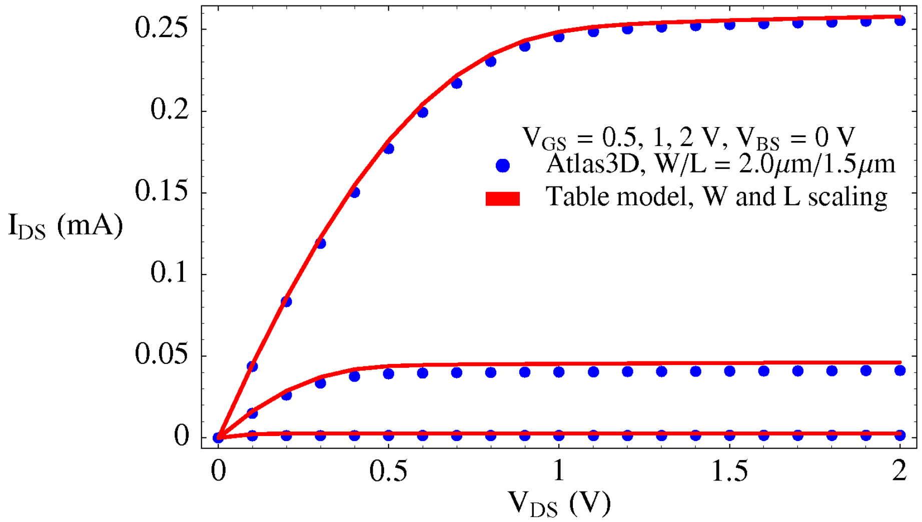
[#] G. Schrom, A. Stach, S. Selberherr. Microelectronics Jornal, 1998.

[@] M. F. Barciela *et al*. IEEE Tran. On Microwave Theory and Technics, 2000.

Channel geometry scaling

- Inter-table interpolation
- Linear interpolation in W dimension
- Quadratic interpolation in L dimension





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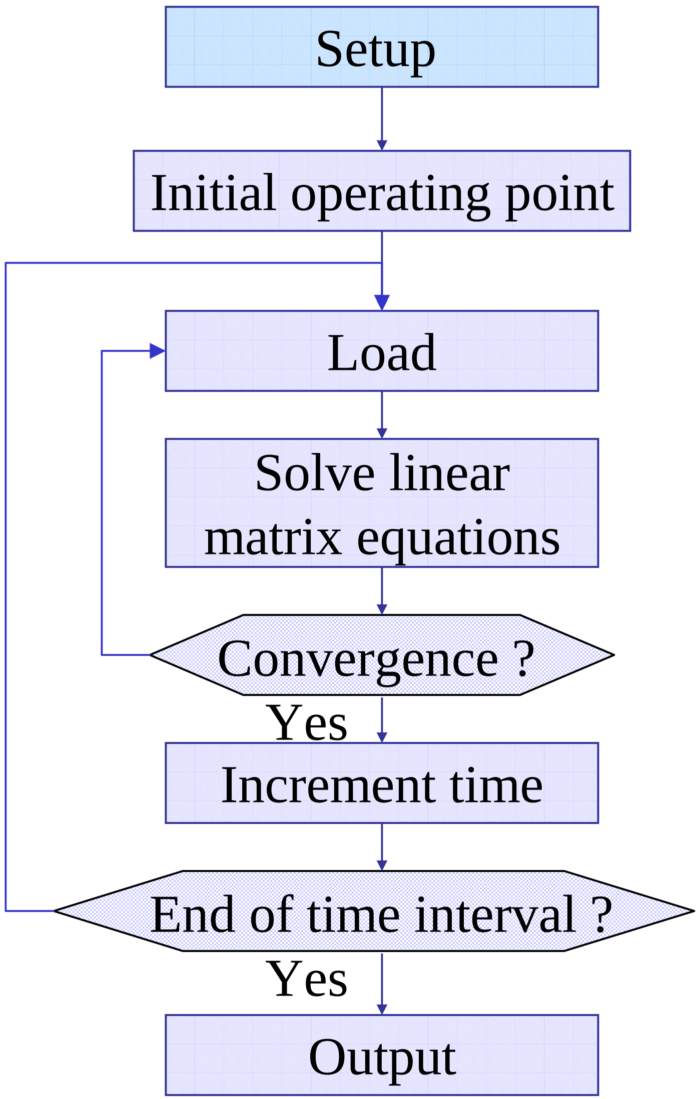
SPICE implementation



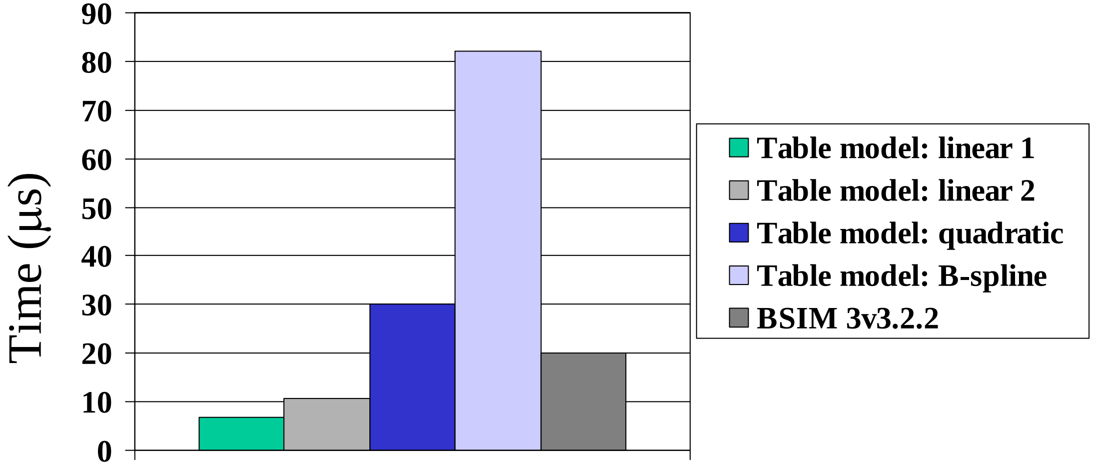
Main device model routines

```
DEV.c
DEVpar.c
DEVmpar.c
DEVsetup.c
DEVload.c
DEVacload.c
DEVcvtest.c
DEVask.c
DEVmask.c
```

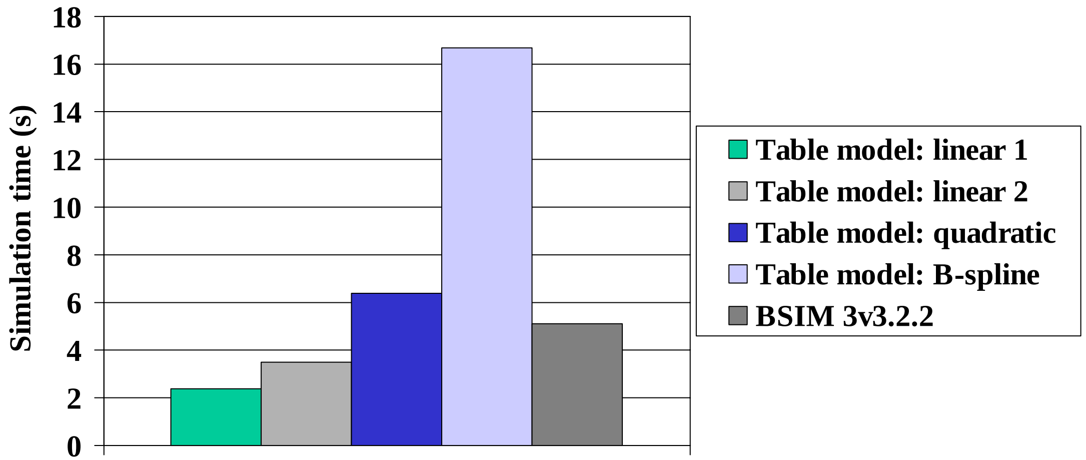
[#] V.Bourenkov, K. G. McCarthy, A. Mathewson. Electrosoft V (2001)

Performance

Model run time per transistor

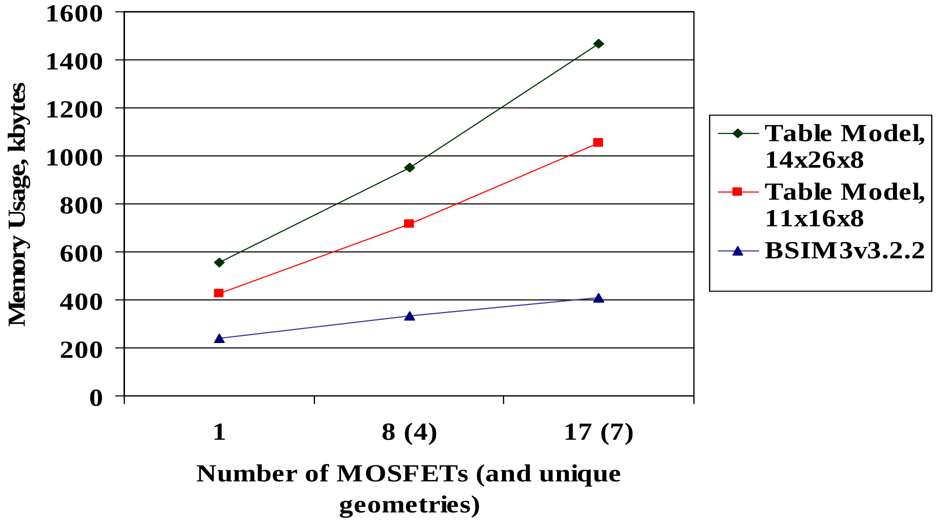


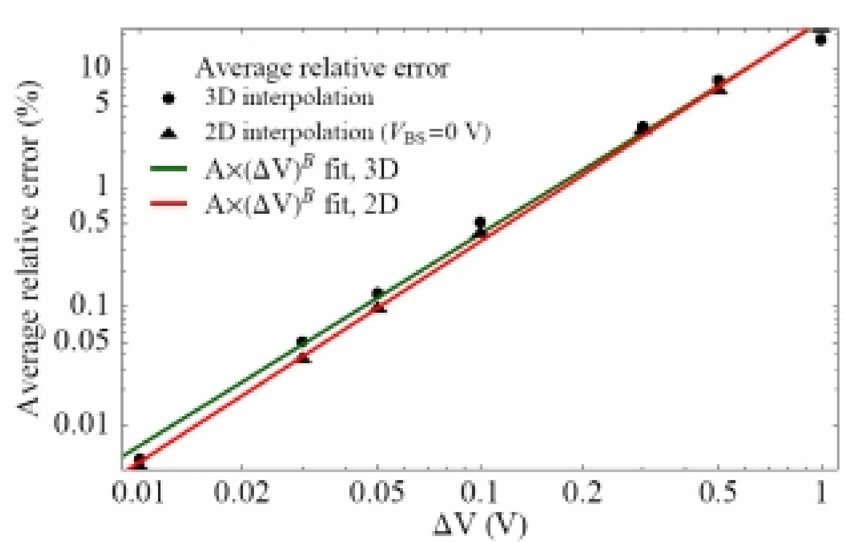
Total simulation time



Performance

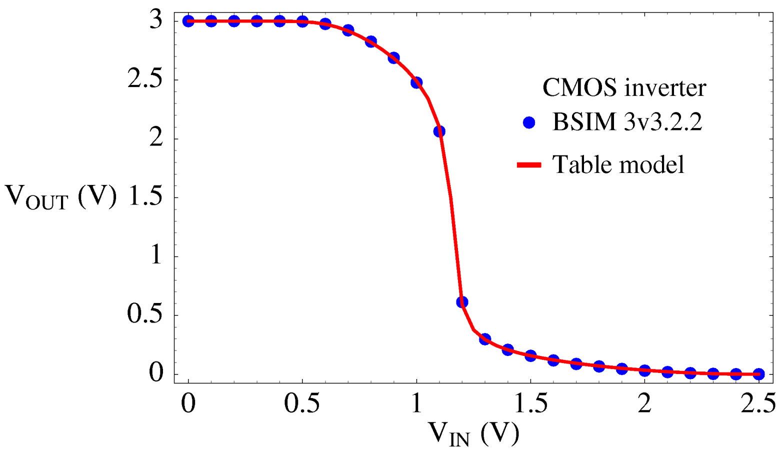
- Accuracy and table size
- Memory requirements

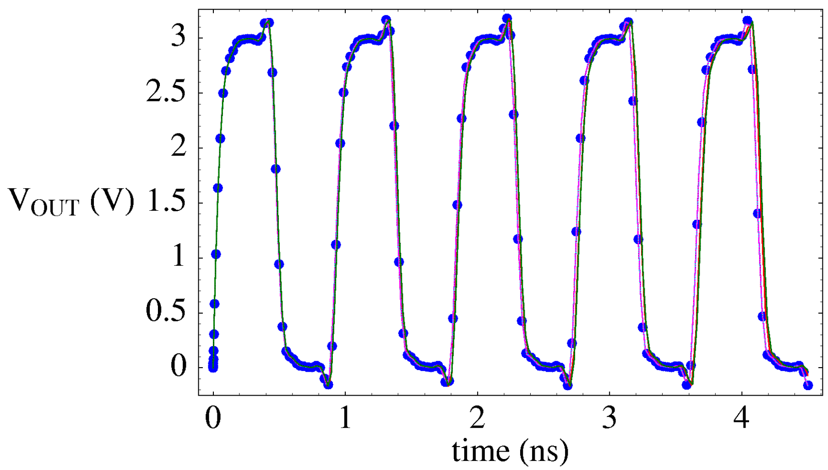




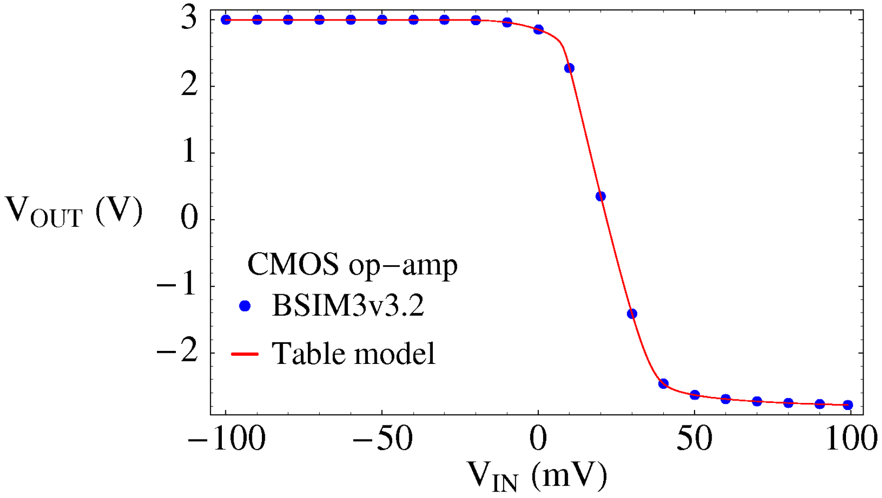
Circuit simulation results (I)

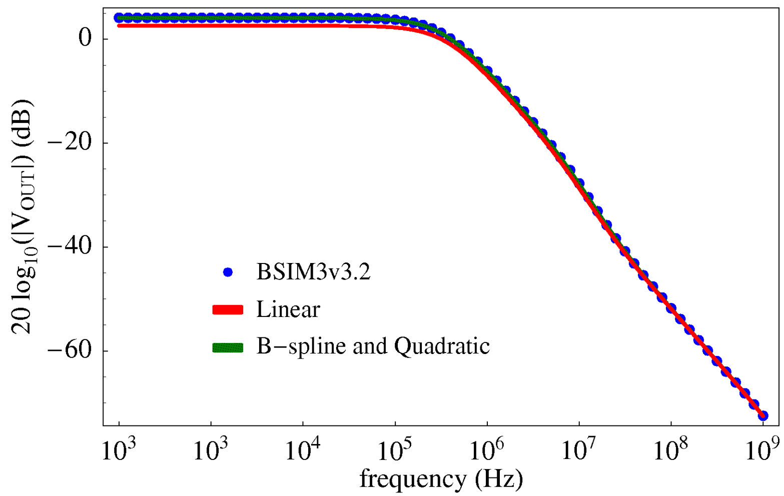
- Data tables generated from BSIM3v3.2.2
- Analyses:
  - CMOS inverter, DC analysis
  - Ring oscillator, transient analysis
  - Op-amp, DC and frequency response

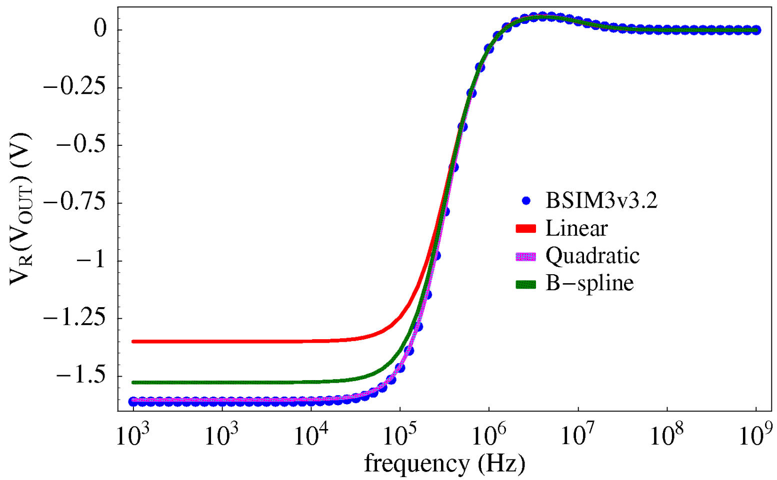


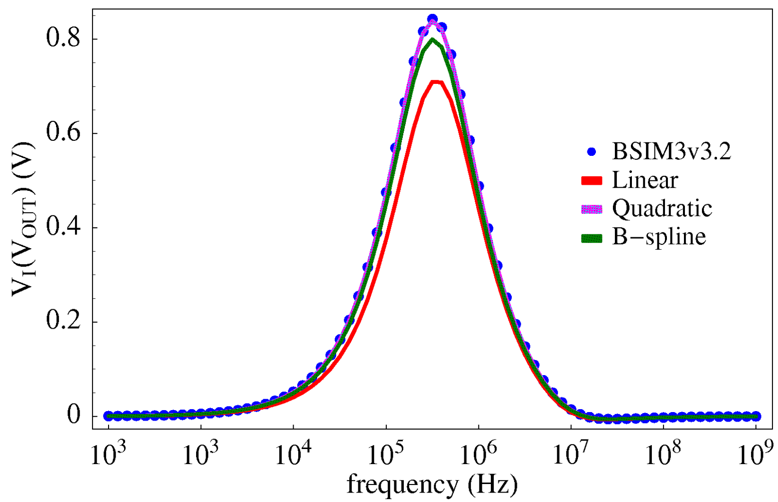


Circuit simulation results (II)

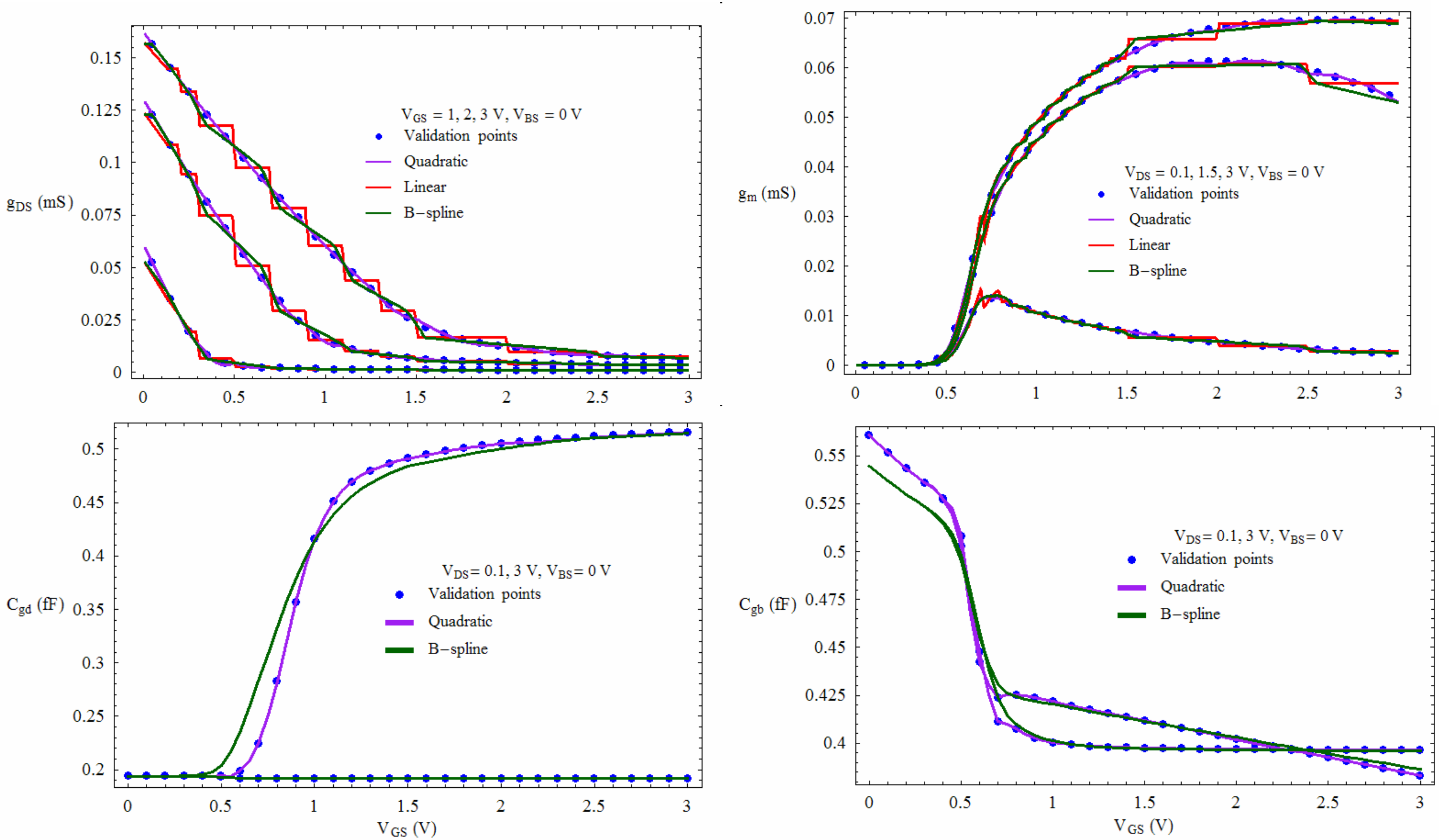








Interpolation of derivatives



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Further developments

- “Context aware” interpolation
- Subcircuit level table models
- Hybrid table/analytical approach
- Temperature scaling
- Noise modelling

Subcircuit modelling

•Sub-circuits can be represented by table models

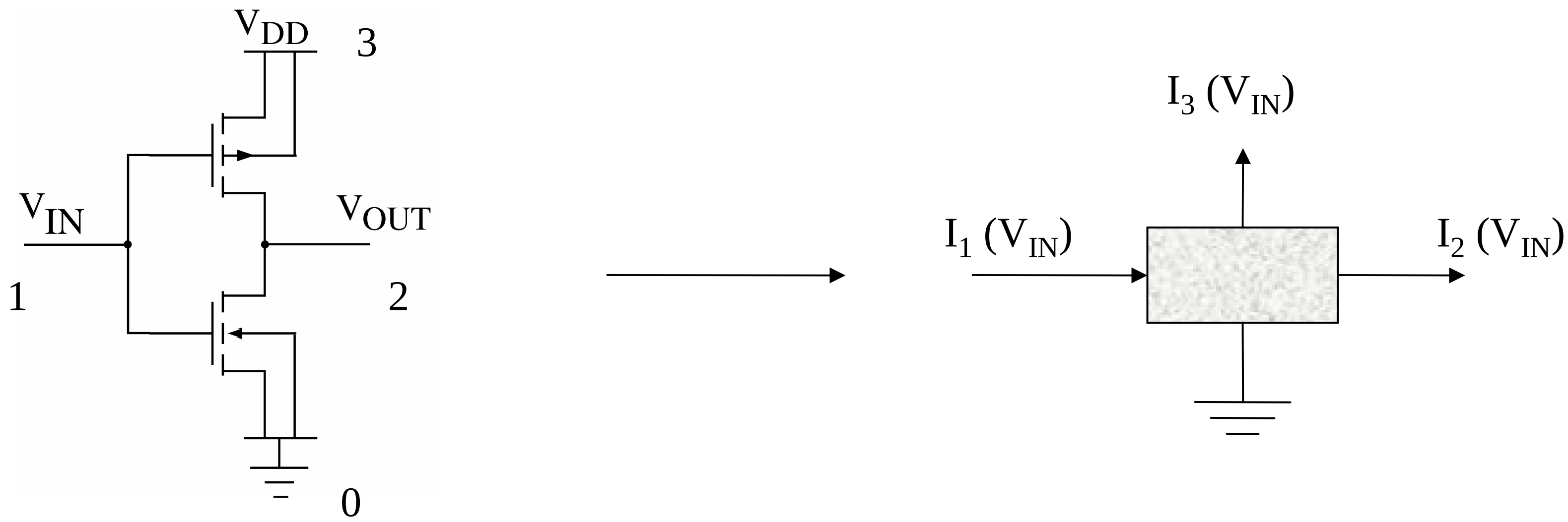

Table Model: The good points

- Models for new devices can be implemented quickly
- Less time-consuming parameter extraction
- Fewer errors in implementation
- Controllable accuracy
  - Density of table data and interpolation method
- Measurement-based model
  - no need to change model equations

Table Models: The not so good points

- Limited predictive capabilities
- Large “model files” – storage and distribution issues
- Larger memory requirements
- “Black-box” not suitable for every purposes

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Summary

- Speed up circuit simulations
  - Fast interpolation with minimum loss of accuracy
- Modelling new devices
  - TCAD simulations, pre analytical model
- Combine table and analytical models
  - Table based DC model, analytical charge formulation, hybrid approaches
- Implementation issues

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