Predictive TCAD for automobile electronics

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S. Koffel, A. Burenkov, P. Pichler
Fraunhofer Institute for Integrated Systems and Device Technology (IISB)
Schottkystrasse 10, 91058 Erlangen, Germany

D. Giubertoni, M. Bersani
Fondazione Bruno Kessler, via Sommarive, 18, 38123 Trento, Italy

M. Knaipp, R. Minixhofer, H. Enichlmair, E. Stückler,
E. Wachmann, M. Schrems
austriamicrosystems AG, 8141 Schloss Premstaetten, Austria

Motivation
TCAD simulation of CMOS processes

- Prediction of threshold voltage of MOS transistors wanted
- Simulation of the full CMOS process needed
- Problem: TCAD software fails to predict electrical characteristics

- Study of the segregation and diffusion of boron and phosphorus in the SiO_2/Si system
  - Simulation results at the beginning
  - Evaluation and calibration of models
  - Simulation of full process (up to electrical simulation)
  - Aim: ability to predict threshold voltages

Outline of the presentation

- State at the beginning of the project
- Evaluation and calibration of the segregation models; comparison with SIMS from FBK-irst
- Simulation of the full CMOS process
  - Two-phase segregation
  - Three-phase segregation
- Comparison of simulated and measured threshold voltages

State-of-the art at the begining of the project

- Simulation of 0.35 µm MOS processes of austriamicrosystems
- Main problem: Simulation of threshold voltages fails for pMOS transistors
- →Calibration of models needed

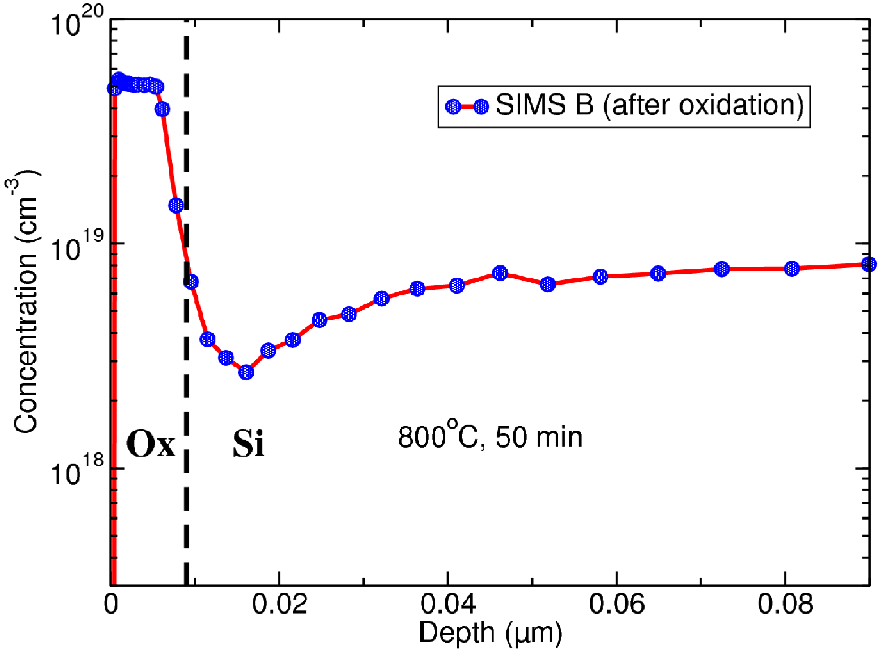
Calibration	**nMOS 3V**	**nMOS 5V**	**pMOS 3V**	**pMOS 5V**
Default Sentaurus	**+0.62 V**	**+0.61 V**	**+2.4 V**	**+1.6 V**
Target V_T	**+0.5 V**	**+0.6 V**	**-0.6 V**	**-0.6 V**

Experiment: SIMS study of oxidation

- Example of a wet oxidation at 800 ℃ for 50 minutes

- Before annealing: samples with uniform boron concentration
  - $3 \times 10^{17} - 7 \times 10^{18}$ cm^{-3}

- After annealing
  - Formation of SiO_2
  - Segregation of boron



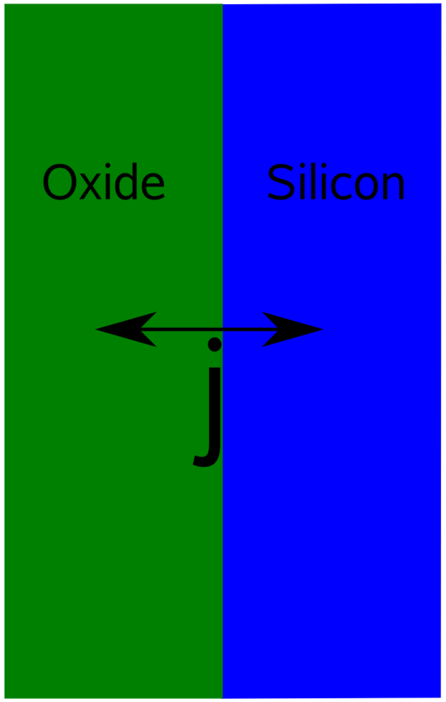
How do we simulate these phenomena?

Two-phase segregation model

- Paper from Grove et al. [1]

  → 1st order kinetic model [2]
- Interface between two materials
  - C_{Si}: concentration on Si side
  - C_{Ox}: concentration on oxide side
- Flux:

$$j \cdot n = h\left(C_{Ox} - \frac{C_{Si}}{m} \right)$$



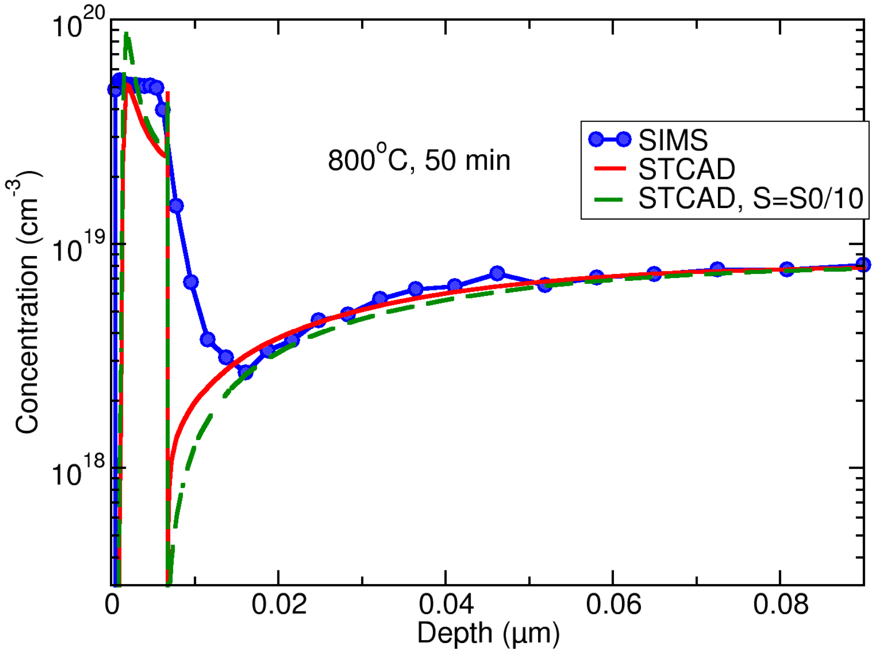
- m: segregation coefficient
- h: transport coefficient

[1] Grove et al., JAP 35 p. 2695 (1964)

[2] Antoniadis et al., Suprem II, Stanford University (1978)

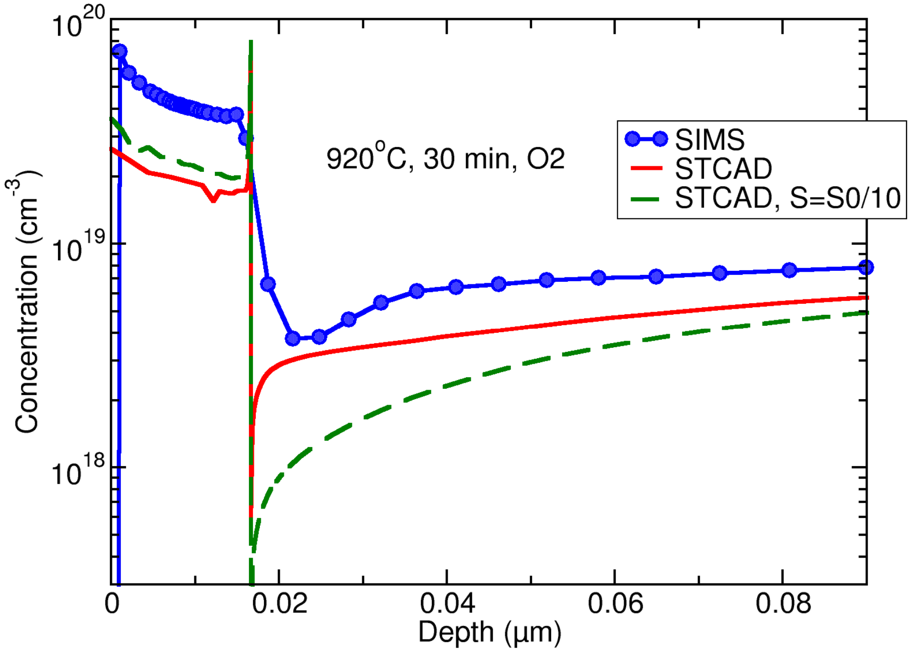
Two-phase model: wet oxidation

- Wet oxidation at 800 ℃ for 50 minutes
- Default parameters (red curve)
  - Agreement between measurement and simulation
- Segregation coefficient divided by 10 (green curve)
  - Agreement between measurement and simulation
- SIMS: unable to resolve the profile near surface



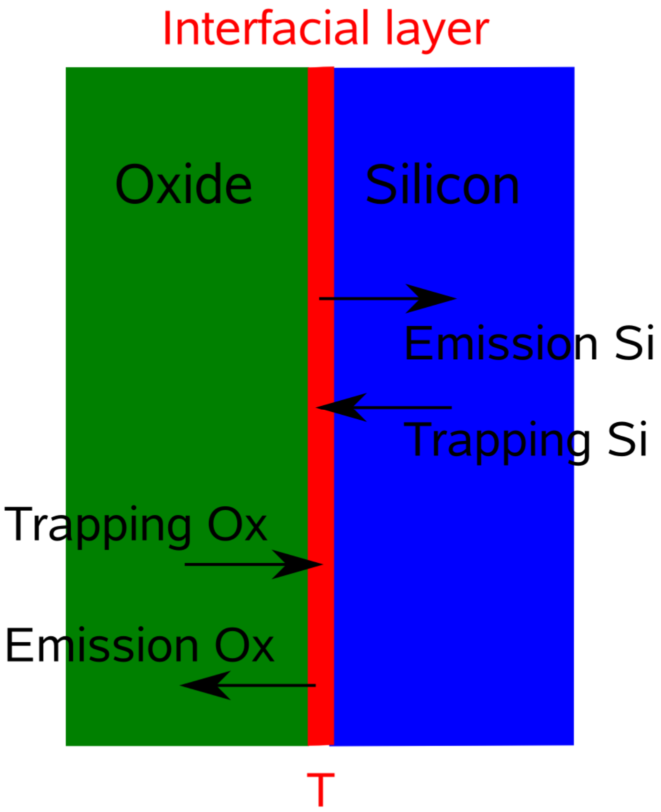
Two-phase model: dry oxidation

- Dry oxidation at 920 ℃ for 30 minutes
- Measured concentration exceeds simulated concentration
- Ratio of B in SiO_2/Si similar in measurement and simulation
- →Segregation model must provide better results



Three-phase segregation model

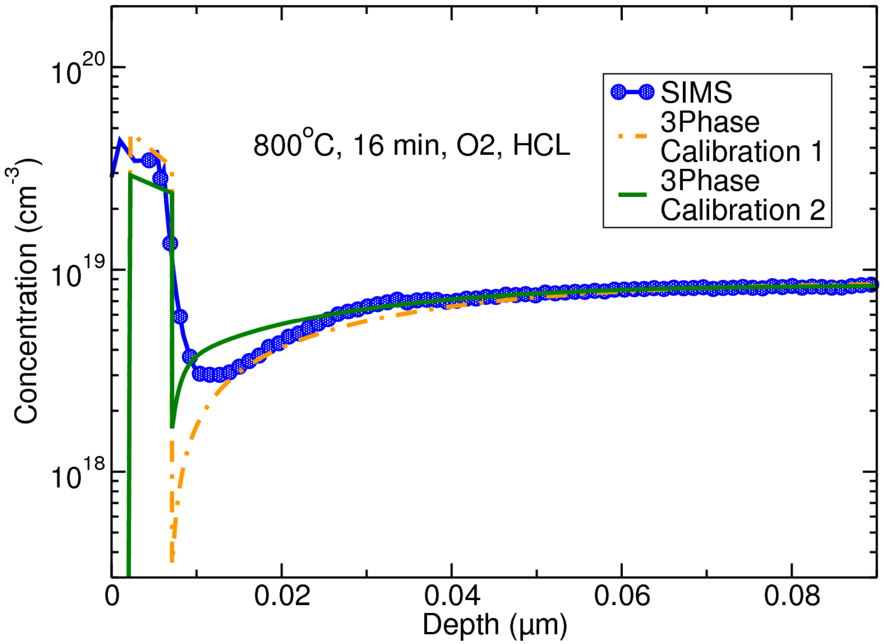
- Proposed by Lau et al. [1]
- Presence of an interface δ-layer between the two materials
- 5 parameters
  - 2 fluxes on Si side
  - 2 fluxes on Ox side
  - 1 interfacial trap density T
- If $\frac{\partial T}{\partial t} = 0$: corresponds to first order kinetic model (two-phase)



[1] Lau et al., Applied Physics A, 49 p. 671 (1989)

Comparison between two-phase, three-phase and SIMS

- Wet oxidation at 800 ℃ for 16 minutes
- Comparison with SIMS results
- Three-phase: results similar to two-phase
- Calibration 1 and calibration 2: compatible with SIMS results
- SIMS results: not accurate enough to get a unique calibration



Full process must be simulated

Accuracy of SIMS profiles

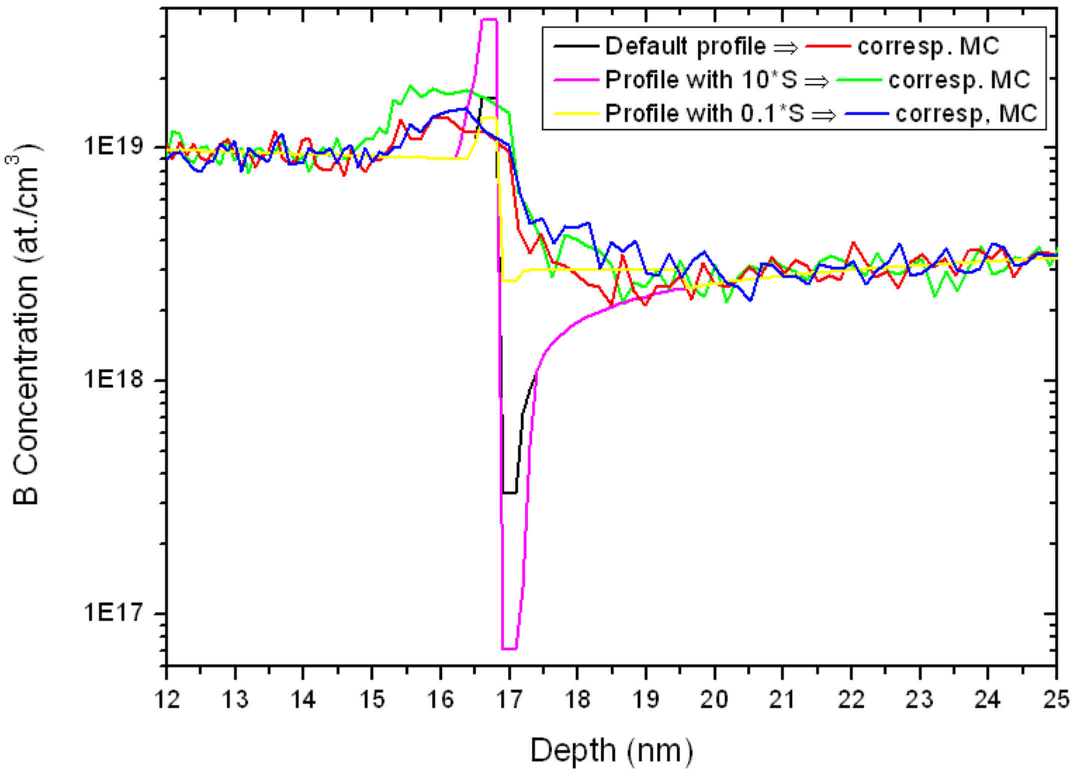
- Monte-Carlo simulation of SIMS profiles

- Simulation of various doping profiles

- Concentration jump always visible

➔ inherent limit to the SIMS technique

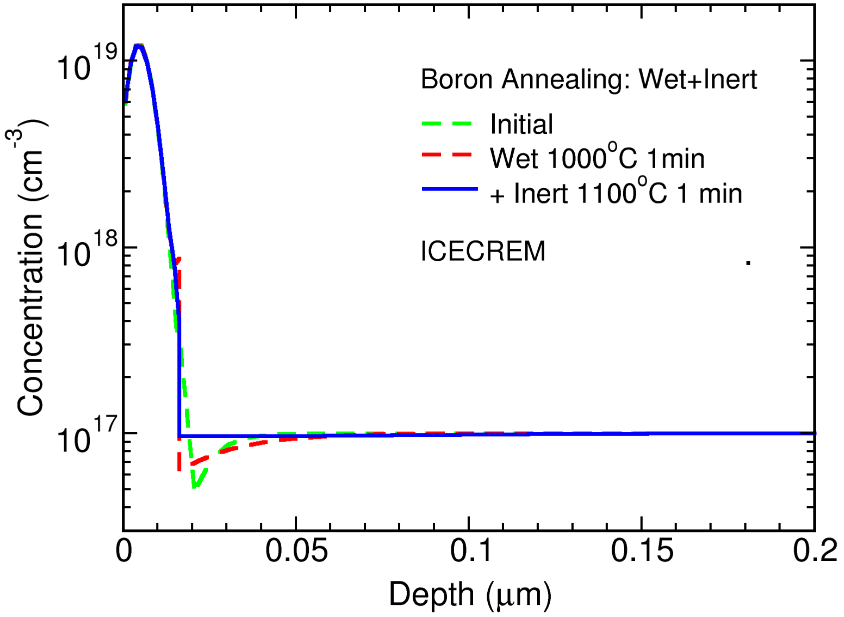
Monte-Carlo simulation of boron SIMS profiles



Full process simulation, using two-phase segregation

Preliminary example, test of model properties

- Two-phase model of Senaturus Process: difficulties when simulating inert annealing step at higher temperature
- Example: wet annealing at 1000 °C followed by inert annealing at 1100 °C
- In Sentaurus Process, boron diffuses back from oxide to silicon during inert annealing at elevated temperatures
- Solution: use of the ICECREM simulator, developped at IISB [1]

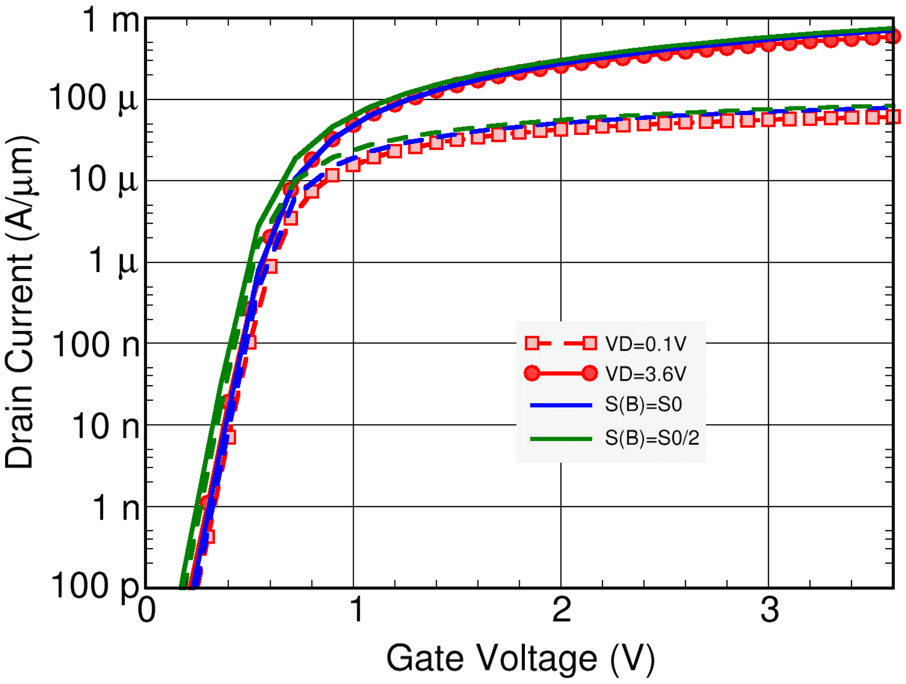


[1] ICECREM, Simulation Program for Processing Steps in Semiconductor Production, Version 4.3, Fraunhofer IISB, 1996

nMOS 3V power supply, full process simulation with two-phase segration model

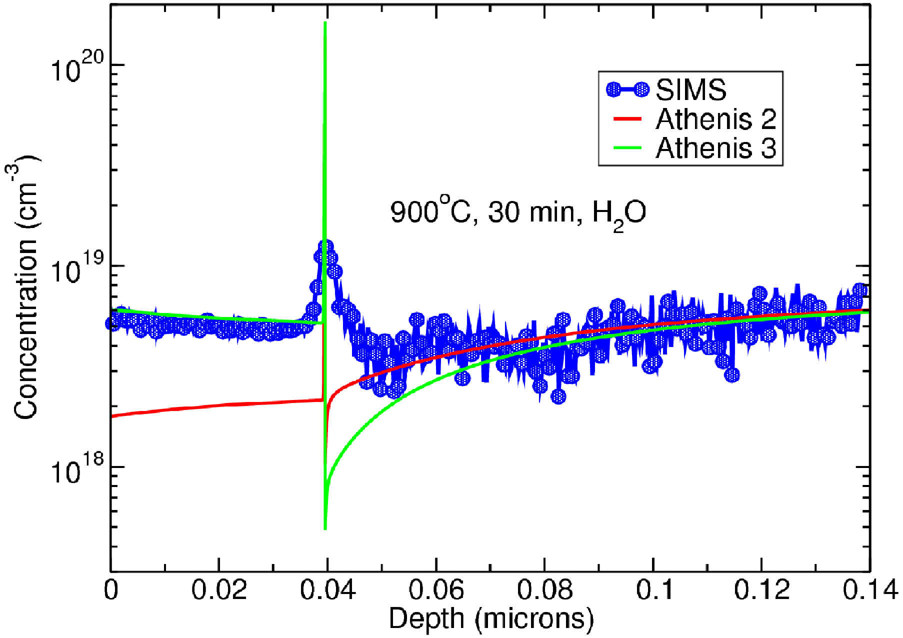
- Simulation of the nMOS transistor with 3V power supply
- Comparison between simulation and experiments (red line)
- Blue curve: results obtained with the default parameters from ICECREM (athenis 1)

- → Electrical characteristics can be simulated
- → Inhomogeneous software environment



Full process simulation with three-phase segregation model

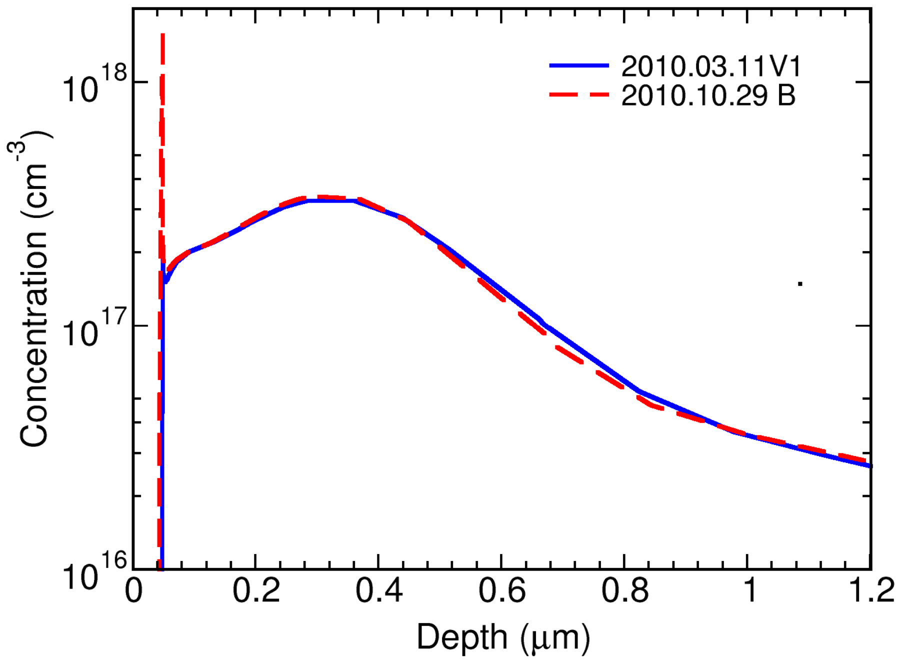
- Three-phase model
  - Recommanded by Synopsis
  - Tool chain homogeneity
- First calibration with one goal (athenis 2)
  - Electrical characteristics
- Second calibration with two goals (athenis 3)
  - Electrical characteristics
  - Relative jump of concentration from silicon to oxide



Full process simulation with three-phase segregation model

- Example of the simulated boron profile of the nMOS transistor
- Comparison between
    - calibration with 1 goal (named athenis 2)
    - calibration with 2 goals (named athenis 3)

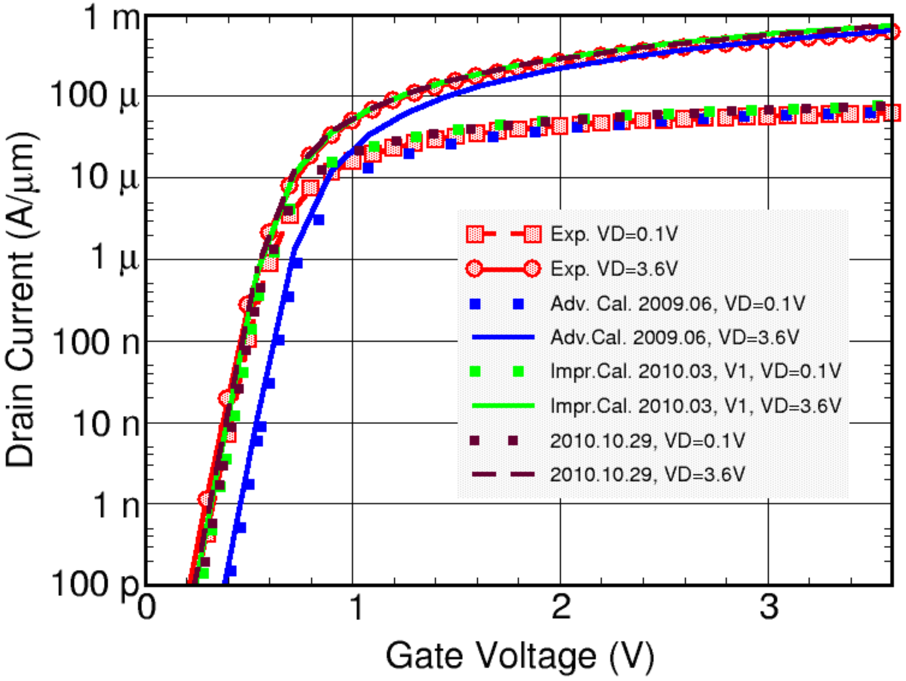
- →Same results obtained in silicon



Full process simulation, nMOS 3V power supply, three-phase segregation model

- Simulation of the electrical characteristics of the nMOS transistor with 3V supply voltage
- Comparison between simulation and experiments (red line)
- Both athenis 2 (green curve) and athenis 3 (brown curve)

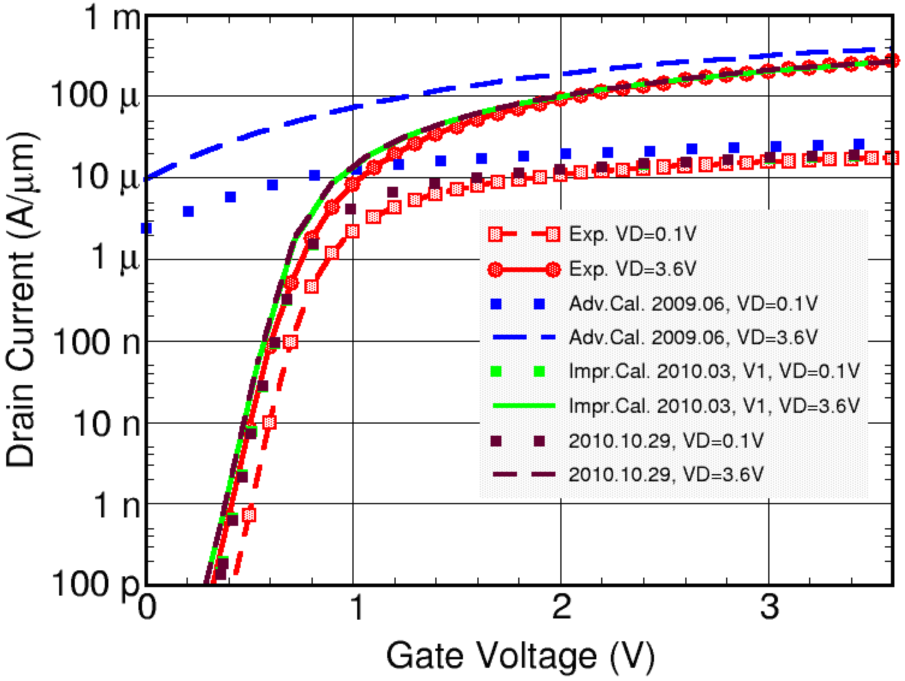
  ➔Simulations agree well with measurements



Full process simulation, pMOS 3V power supply, three-phase segregation model

- Simulation of the electrical characteristics of the pMOS transistor with 3V supply voltage
- Comparison between simulation and experiments (red line)
- Both athenis 2 (green curve) and athenis 3 (brown curve)

➔Simulations agree well with measurements



Comparison of the different calibrations

- V_t values with the different calibrations

Calibration	nMOS 3V	nMOS 5V	pMOS 3V	pMOS 5V
Default Sentaurus	0.62 V	0.61 V	+2.4 V	+1.6 V
AC-2009.06	0.62 V	0.71 V	+1.0 V	-0.31 V
ATHENIS 1	0.40 V	0.41 V	-0.70 V	-0.71 V
ATHENIS 2	0.47 V	0.59 V	-0.57 V	-0.65 V
ATHENIS 3	0.47 V	0.59 V	-0.57 V	-0.81 V
ATHENIS Target	0.5 V	0.6 V	-0.6 V	-0.6 V

Conclusion
TCAD simulation of CMOS processes

- Calibrated model available to predict the threshold voltages of CMOS transistors for the 0.35 µm process of austriamicrosystems specified in the project

- Two segregation models evaluated
  - Two-phase segregation
  - Three-phase segregation

- Commercial TCAD tool chain successfully tested with three-phase segregation model