## 3.1 Publishable summary

Among the physical limitations which challenge progress in nanoelectronics for aggressively scaled More Moore, Beyond CMOS and advanced More-than-Moore applications, process variability and the interactions between and with electrical, thermal and mechanical effects are getting more and more critical. Effects from various sources of process variations, both systematic and stochastic, influence each other and lead to variations of the electrical, thermal and mechanical behavior of devices, interconnects and circuits. Correlations are of key importance because they drastically affect the percentage of products which meet the specifications. Whereas the comprehensive experimental investigation of these effects is largely impossible, modelling and simulation (TCAD) offers the unique possibility to predefine process variations and trace their effects on subsequent process steps and on devices and circuits fabricated, just by changing the corresponding input data. This important requirement for and capability of simulation is among others highlighted in the International Technology Roadmap for Semiconductors ITRS.

Within SUPERTHEME, the most important weaknesses which limit the use of current TCAD software to study the influence of both systematic and stochastic process variability and its interaction with electro-thermal-mechanical effects have been removed, and the study of correlations has been enabled. The project has efficiently combined the use of commercially available software and leading-edge background results of the consortium with the implementation of the key missing elements and links. It bridges the current critical gap between variability simulation on process and device/interconnect level, and includes the treatment of correlations. The capabilities of the software system have been demonstrated both on advanced analog circuits and on aggressively scaled transistors.

**The SUPERTHEME Consortium**

| | |
|---|---|
| Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. | Germany |
| ams AG | Austria |
| Gold Standard Simulations ltd | United Kingdom |
| UNIVERSITY OF GLASGOW | United Kingdom |
| TECHNISCHE UNIVERSITÄT WIEN | Austria |
| ASML NETHERLANDS B.V. | Netherlands |
| LASSE (formerly Excico France) | France |
| HQ-Dielectrics GmbH | Germany |
| ION BEAM SERVICES | France |

**Work performed and results achieved**

Within SUPERTHEME, all main components of the project progressed as scheduled and achieved important results:

- Detailed benchmark specifications were performed by ams. These benchmarks referred to four different high performance analog sensor applications, plus two circuits which use these modules.
- Additional less formal specifications were drawn from interactions with the International Technology Roadmap for Semiconductors ITRS and extracted from conferences and literature.
- Sources of process variability at equipment level were identified by the industrial partners in the project. Quantitative data for these variations was compiled based on published and partly own data.

- The integration between the core software components to be used in the project was implemented. This referred especially to the link between equipment simulation carried out on reactor scale and feature-scale simulation of deposition and etching, and between feature-scale variation-aware process and variation-aware device simulation. The device simulation tool GARAND which enables the simulation of the impact of variations such as Random Dopant Fluctuations and Line Edge Roughness on device performance was extended to enable the simulation of arbitrary three-dimensional device geometries which results from variation-aware process modeling. Physical device models were improved as required for the predictive simulation of the impact of discrete dopants and traps.
- Compact modeling capabilities were implemented which include the impact of both systematic process variations which are largely caused by the process equipment and stochastic process variations caused by the granularity of matter and discreteness of charges. The benefits of these new capabilities were demonstrated in several publications.
- The integration between variation-aware process, device, and circuit simulation was demonstrated in several More-than-Moore and More Moore applications. Among others, the impact of variations in litho-freeze-litho-etch double patterning lithography on SRAM performance was studied and presented in September 2013 at the SISPAD conference. The simultaneous simulation of the impact of systematic variations caused by equipment and stochastic variations caused by the granularity of matter and discreteness of charges was demonstrated among others at SISPAD 2014. The full integration from equipment through process and device simulation up to variation-aware compact models was demonstrated on a More Moore benchmark for an SRAM circuit based on 14nm node FinFET technology structured with Self-Aligned Double Pattering and Litho-Etch-Litho-Etch Double Patterning.

**Final results and potential impact**

SUPERTHEME has enabled and demonstrated the simulation of the impact of systematic and stochastic process variations on devices and circuits. Software developed within the project has complemented externally available commercial tools to reach this target.

The exemplary quantification of process variability at its source, which is at equipment level, has been one of the key results because such data was largely missing before. Analog benchmarks conducted at ams have demonstrated that variations are not only important for aggressively scaled CMOS but also for several More-than-Moore applications. The functionality and advantages of the software system developed within SUPERTHEME have additionally been demonstrated with benchmark simulations dealing with state-of-the-art More Moore devices and SRAM circuits.

The quantification of process variations at their source and the assessment of their impact on devices and circuits will considerably support the optimization of yield in semiconductor manufacturing.

**Project web site**

http://www.supertheme.eu

**Coordinator contact details**
Dr. Jürgen Lorenz
Fraunhofer Institut für Integrierte Systeme und Bauelementetechnologie IISB
Schottkystrasse 10, Germany
Phone +49 (9131) 761-210, Fax +49 (9131) 761-212
juergen.lorenz@iisb.fraunhofer.de