# nanoCOPS: Nanoelectronic COupled Problem Solutions

**Abstract**

The FP7 project nanoCOPS derives new methods for simulation during development of designs of integrated products. It covers advanced simulation techniques for electromagnetics with feedback couplings to/from electronic circuits, heat and stress. First progress is reported here.

## Introduction

The FP7 project nanoCOPS[49] (Nanoelectronic COupled Problem Solutions) did start on November 1, 2013. Leading experts from industry and science in Europe develop and share new simulation methods to create and improve designs of integrated products. It brings specialists together from various fields: in circuit design, in the semiconductor development, in simulation techniques for electromagnetics and in applied mathematics in research and in software development. In total there are twelve research institutions and companies in the project. The European Consortium supports the work under the 7th Research Framework Programme with a total of 3.5 million euros for three years.

The research project aims to solve complex problems in nanoelectronics. For example, in a so-called "Power-MOS" transistor (see Fig. 22), an electronic component that in many products shows up and which is responsible for the energy efficiency, electrical, thermal and stress interactions are key items for simulations during the design phase. With nanoCOPS such new and accurate transistors can be developed in an efficient way. In addition a long lifetime performance in quality is point of attention.

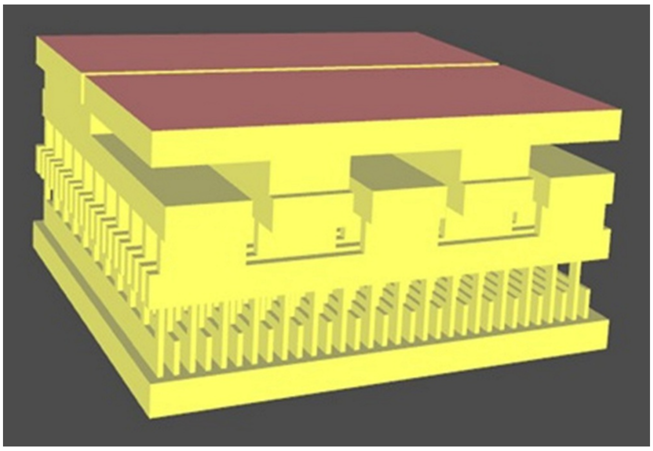
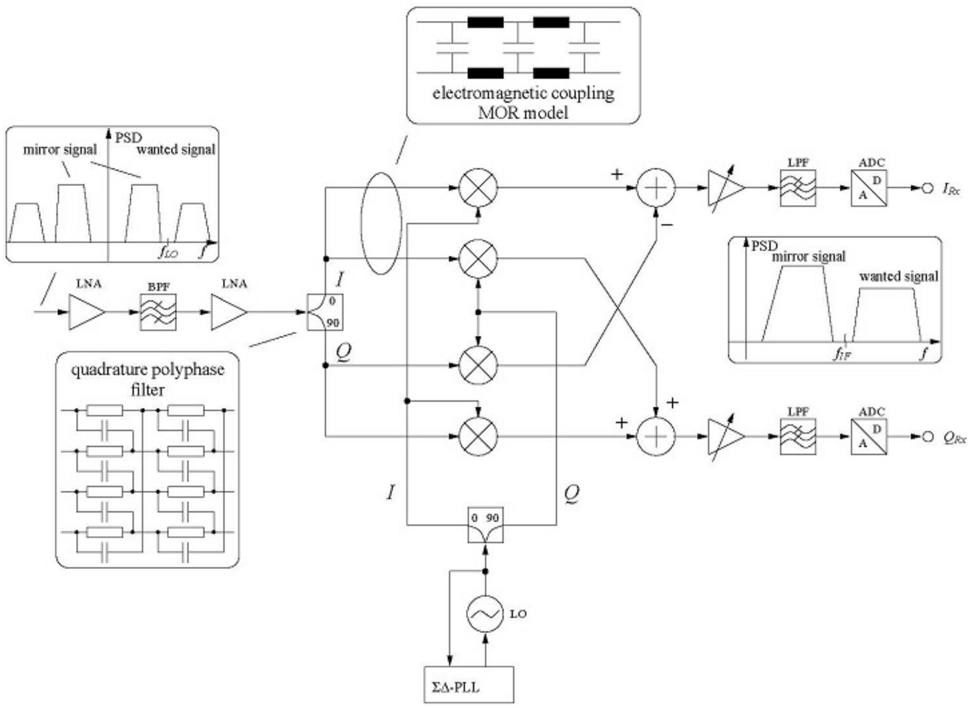


**Figure 22:** *Typical layout of the power transistor (stretched in vertical direction) showing its complex geometry.*

In a second example, RF-circuitry in wireless communication, for reducing signal interference in mobile products (telephone, wireless, mobile television, navigation, etc.), but also in pacemakers, one has to efficiently simulate signals with very different frequencies, asking for multirate time integration techniques that even can deal with analogue-digital signals. Also here interaction occurs between electronic circuits, electromagnetic fields and heat production.




*Block diagram of a low-IF or zero-IF receiver architecture with an image reject filter and a quadrature mixer stage. The schematic also displays the power spectral density (PSD) at different stages. Moreover it shows the realization of the image reject filter by a polyphase RC circuit and the symbolic representation of the crosstalk by a lumped LC network (reduced-order model).*

49 http://www.fp7-nanocops.eu.

In both examples the coupled interactions and the effect of ageing of components are recent topics in research. NanoCOPS develops methods to predict probabilities in the performance of the integrated functionality.

NanoCOPS combines advanced mathematical methods like multirate time integration, co-simulation, uncertainity quantification and model reduction with methods to solve problems in which electromagnetic effects, electronic circuits, heat development and material stress effects are coupled.

In nanoCOPS participate: Bergische Universität Wuppertal (Coordinator), Technische Universität Darmstadt, Humboldt Universität zu Berlin, Ernst-Moritz-Arndt-Universität Greifswald, Max Planck Institut für Dynamik komplexer technischer Systeme in Magdeburg (all Germany), Fachhochschule Oberösterreich in Hagenberg im Mühlkreis (Austria), Brno University of Technology (Czech Republic), Katholieke Universiteit Leuven, MAGWEL NV (Leuven), ON Semiconductor (Oudenaarde) (last three in Belgium), NXP Semiconductors (Eindhoven, the Netherlands), and ACCO Semiconductor (Louveciennes, France). Hence, seven universities, one research institute, two major semiconductor companies and two small or medium enterprises (SMEs).

## The importance of the industrial use cases

The carefully defined Industrial Use Cases in the nanoCOPS project are of critical importance to MAGWEL in order to get the solutions accepted in industry via a track record of silicon-demonstrated predictive quality. Comparison with experimental results pinpoints to the range of application but also brings into the front stage weaknesses in model assumptions that can be corrected for in a next iteration. Moreover, the Industrial Use Cases introduce requirements for usability in a production environment that differs strongly from a research environment. Ease of use and robustness of the proposed solution now will be an important criterion to accept the tools for commodity use.

NXP Semiconductors observes an increasing complexity of wireless systems in terms of frequency bands, modulation schemes, signal paths and signal co-existence results in a serious design flow and thus becoming a design automation (EDA) challenge. At the moment, no existing commercial EDA tools can perform simulations of single chip high-GHz modules. The current EDA tools and design flows are far behind the requirements of circuit designers, leading to a productivity gap. Within nanoCOPS the key ingredients (for Multirate/Multi-tone Simulation, for Model Order Reduction, for Reliability and for Uncertainty Quantification) will be developed as prototype software and tested on Industrial Use Cases to provide solutions to the gaps in the software suites of commercial vendors. NXP will use this to improve its design methodology.

The industrial use cases solved by the new techniques from nanoCOPS include practical and important contributions applicable to approximately 30% of the products developed by ON Semiconductor's automotive business unit. Based on the findings in nanoCOPS, we look for extensions of the tool capabilities to detect and assess important reliability problems including thermo-mechanical induced passivation cracks, bond-wire fusing and electro-migration. Early detection of such reliability risks are of utmost importance in the ever increasing power densities that devices have to endure and the high quality and reliability requirements the automotive industry requires. Adequate detection and prediction will strongly affect overall cost and time to market, key differentiators in the automotive market.

## Objectives

Designs in nanoelectronics often lead to large-size simulation problems and include strong feedback couplings. Industry demands the provisions of variability to guarantee quality and yield. It also requires the incorporation of higher abstraction levels to allow for system simulation in order to shorten the design cycles, while at the same time preserving accuracy.

To meet market demands, the **scientific challenges** are to:

- create efficient and robust simulation techniques for strongly coupled systems, that exploit the different dynamics of sub-systems and that allow designers to predict reliability and ageing;
- include a variability capability such that robust design and optimization, worst case analysis, and yield estimation with tiny failures are possible (including large deviations like 6-sigma);
- reduce the complexity of the sub-systems while ensuring that the operational and coupling parameters can still be varied and that the reduced models offer higher abstraction models that are efficient to simulate.

Achieving solutions to these challenges will have considerable **industrial impact**. The overall **objective** of nanoCOPS is to advance a methodology for circuit and systems-level modelling simulation based on best practice rules to deal with **coupled electromagnetic field-circuit-heat problems** as well as **coupled electro-thermal-stress problems** that arise in nanoelectronic designs. The new methods developed will be robust and allow for **strong feedback coupling** when integrating systems.

With the new techniques it will be possible to efficiently analyze the effects due to **variability**. Our methods are designed to solve **reliability** questions arising from **manufacturability**. They will facilitate robust design as well as enable worst case analysis. They can also be used to study effects due to ageing. **Ageing** causes variations in parameters over a long-term period, which cannot be predicted exactly and thus are typically uncertain. In this project variability due to ageing will be addressed. The challenges in doing this for an Integrated Circuit (IC) are that each device has its own electrical and thermal conditions, which are changing over time (ageing). Here, each device has its own required life-time. Hence, one of the aims of this project is to construct probability distributions or probability density functions, respectively, from which the true statistics can be approximated at a sufficient degree of accuracy.

The new **Model Order Reduction** techniques will be applicable to both coupled systems and parameterized subsystems. New design procedures for systems of components with various levels of abstraction will be developed.

In summary, our **solutions** are

- to develop advanced co-simulation/multirate/monolithic

techniques, combined with envelope/wavelet approaches;
- to produce new generalized techniques from Uncertainty Quantification (UQ) for coupled problems, tuned to the statistical demands from manufacturability;
- to develop enhanced, parameterized Model Order Reduction techniques for coupled problems and for UQ.

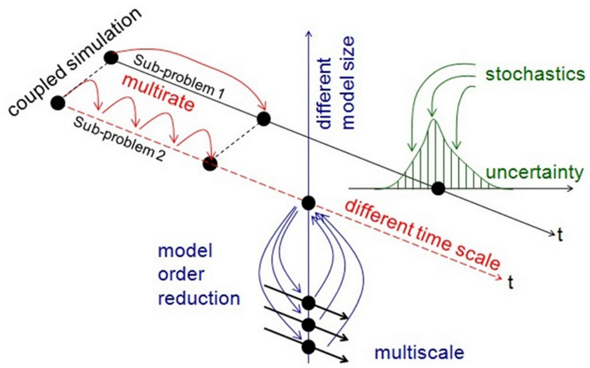



**Figure 23:** *Schematic of a coupled problem (consisting of two sub-problems), including uncertainties. In nanoCOPS, those problems will be efficiently solved in time domain and probability space with exploitation of their multirate (different time steps) and multiscale behaviour (different discretizations). The discretized models will lead to different reduced models by techniques from MOR. Parameterized MOR will guarantee the ability to properly deal with the uncertainties in parameters, geometries, and coupling quantities.*

The whole interplay of the various mathematical approaches is graphically indicated in Fig. 23.

All the new algorithms produced will be **implemented and transferred** to the SME partner MAGWEL. **Validation** will be conducted on industrial designs provided by our industrial partners. These industrial end-users provide feedback during the project life-time and contribute to measurements and provide material data and process data. A thorough comparison to **measurements** on real devices is being made to demonstrate the industrial applicability.

## Project Progress

Recently the Project Prgress after 9 months was presented in Brussels. Here we give an impression.

**FH Oberösterreich** focused on the development of a tool which enables the co-simulation and monolithic/holistic simulation of a circuit/device system or electrical-thermal system based on the multirate envelope approach for different time scales. Different time scales arise from the co-simulation of baseband signals and modulated or bandpass signals, as well as from electro-thermal couplings due to self-heating. The approach is based on the multirate envelope technique which reformulates the system of ordinary Differential-Algebraic Equations (DAEs) by a system of Multirate Partial DAEs (MPDAEs). By separating the time scales an enormous speed-up can be obtained. One generates a time solution that depends on two time parameters, representing the two different time scales. The actual solution can be reconstructed by a special curve over the colored surface in Fig. 24.

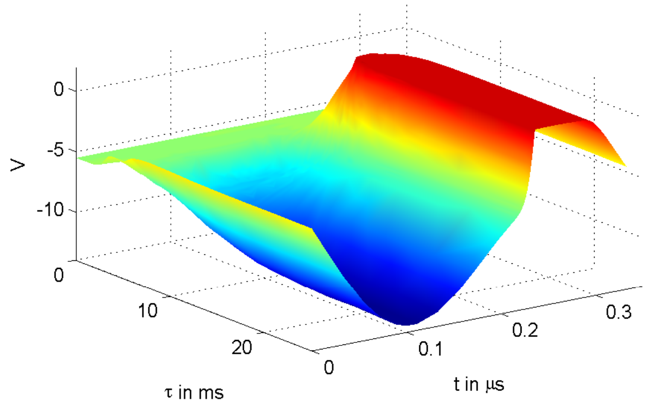



**Figure 24:** *Multirate solution of a 3 MHz Colpitts oscillator. Shown is a surface solution as a function of two different time parameters, one in milli seconds, the other in micro seconds.*

The **Universität Greifswald** and the **Bergische Universität Wuppertal** cooperated on methods for Uncertainty Quantification and applied the approaches to address variations of material properties as well as in the geometry.

For an electromagnetic-thermal coupled problem, including a randomly varying electric conductivity, the mean and standard variations could be efficiently determined for a time dependent ("transient") simulation, both for the currents in the transistor as well as for the temperature, see Fig. 25.

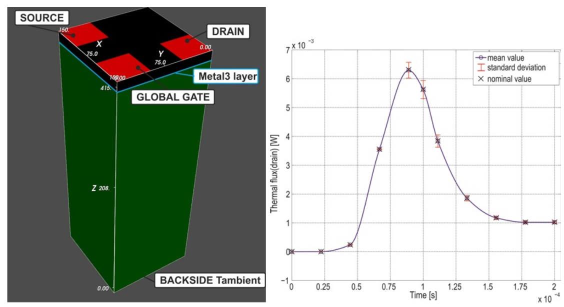



**Figure 25:** *Simplified Power Transistor for which the variability of currents and temperature, due to varying values of the electric conductivity, was determined. This was done much faster than with normal Monte Carlo methods.*

As an additional example, because of prior knowledge, robust topology optimization for a Permanent Magnet (PM) motor was done (which is not of nano scale), where uncertainties of both iron and magnet material parameters in rotor poles were considered. The model of a PM machine, with either input variation or a material random field, is shown in Fig. 26. In this example, the quantities that are assumed as uncertain are the reluctivity of the iron and the PM poles as well as the magnetic permeability of the air-gap all with variations around 10%. This example told us that geometrical variations are yet more difficult to treat by the methods because of re-meshing of the problem.

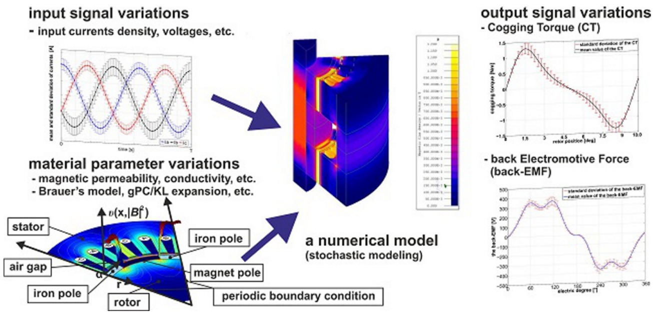



**Figure 26:** *The concept of stochastic forward model for the robust topology optimization.*

**TU Darmstadt**, **KU Leuven** and **ON Semiconductor** worked on bond-wire modelling. Reporting is done in a separate contribution in this Newsletter.

The **Humboldt Universität zu Berlin** and **MAGWEL** developed and tested a Python-C++ interface for a coupled EM-circuit simulation, see Fig. 27. It allows a monolithic transient simulation of lumped circuit equations (arising from the Modified Nodal Analysis), coupled with the electromagnetic field equations (in vector potential formulation). The simulation has as bottleneck a huge dimensional, non-symmetric Jacobian where standard direct and iterative linear solvers fail. However, one can exploit a certain Jacobian block structure that allows a hybrid linear solving combining direct and iterative methods. Details were shown at ECMI-2014 in Taormina.

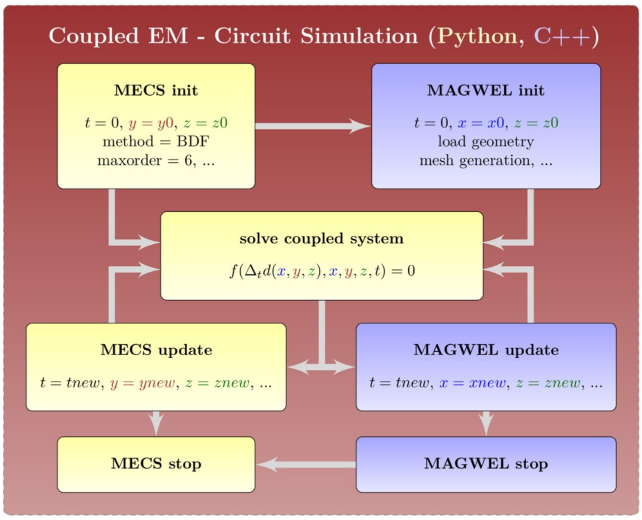



**Figure 27:** *Overview flow for monolithic coupled simulation.*

**MAGWEL** and **ON Semiconductor** co-operated on electro-thermal simulation in order to guarantee industrial acceptance. An important highlight of this work is that the electrothermal simulation tool is very flexible concerning the various device technologies since the nano-scale transistor architecture is incorporated via compact models. Therefore, it is possible to couple the large scale (millimeter) structures and the small scale (sub-micron) of the finger architecture in a single simulation. The computation deals with the coupling of the electrical response and, moreover, the thermal response in a first-principle field solving. Fig. 28 illustrates today's capabilities of the tool.

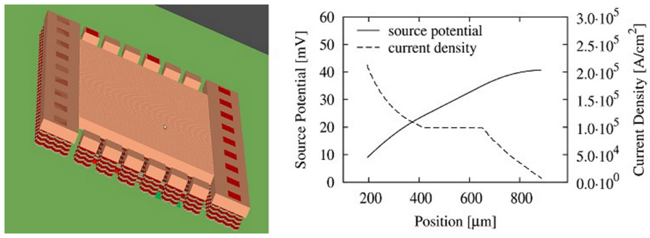



**Figure 28:** *Analysis of a power MOS (left figure) resulting into an asymmetric current density due to thermally induced conductance variations in the metallic interconnect (right figure).*

In the nanoCOPS project, the main responsibilities of the **Max Planck Institute** in Magdeburg are to develop efficient parameterized/parametric MOR (pMOR) methods and techniques for fast simulation of electro-thermal coupled models and to develop pMOR methods for fast Uncertainty Quantification (UQ) of nanoelectronic, electro-thermal models with random variables or stochastic processes; and the compact netlist generation based on the reduced order models. By such a "netlist", these models can be used by a circuit simulator. In a separate contribution in this Newsletter pMOR methods for electro-thermal coupled models are described.

The MP Institute has accumulated experience in MOR for fast UQ of electromagnetic problems, see Fig. 29, which will contribute to developing efficient parameterized MOR methods for fast UQ of nanoelectronic, electro-thermal models in the nanoCOPS project. Compact netlist generation will start once code in MATLAB for MOR is ready for transformation into C++.

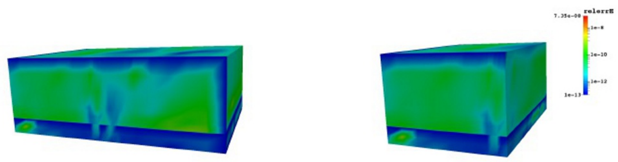


**Figure 29:** *Relative error of the expectation of the electrical field in a coplanar waveguide.*

The industrial partners **NXP Semiconductors**, **ON Semiconductor**, and **ACCO Semiconductors** did provide three data sets with measurements. One data set (NXP) involved the currents of a PMOS/NMOS transistor. The other two data sets (ON and ACCO) did include many material properties for all dies on a wafer and for multiple wafers, where sparse measurements appeared. F.i., NXP provided measurements on the currents of an NMOS and of a PMOS device for a certain technology. For the moment, the main task was to analyze the correlations between the two measured properties. Fig. 30 (a) shows these measurements. Fig. 30 (b) depicts random samples drawn from an approximating normal distribution. Also a 3-sigma ellipse is shown illustrating the mean and the covariance matrix. Multivariate normal distributions are a special class of "elliptically contoured distributions". The data was analyzed statistically by Universität Greifswald and Bergische Universiät Wuppertal. We observed that the measurements have fatter tails.

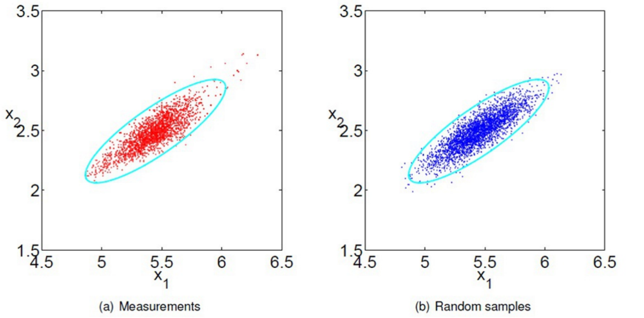



**Figure 30:** *Measurements in the NXP example (a) and random samples taken from an approximating normal distribution (b). The variables $x_1$ and $x_2$ are the currents of an NMOS and of a PMOS device, respectively. In both cases also a $3\sigma$ ellipse is shown.*

Additionally NXP Semiconductors did compile a large set of test examples. For an example, see Fig 31.

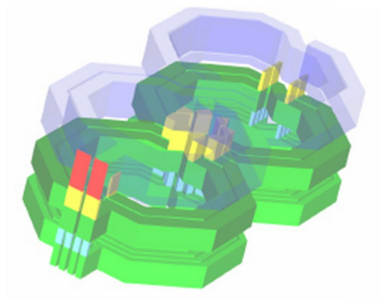


**Figure 31:** *An 8-shaped inductor, an excellent test case to demonstrate the quality of the software for EM solving.*

The **Brno University of Technology**, together with **ON Semiconductor** and **ACCO Semiconductor**, did set up a plan for measurements. With ON Semiconductor this currently concentrates on the bond wire testing. The encapsulated bond wires have already been delivered and the individual bond wires are just to be tested at room temperature. Before that, some informative x-rays have been acquired, as visible in Fig. 32 (left). The location of fusing gaps will be monitored after the test of the package is completed. Each measurement sequence will be controlled by a program, which begins with keeping constant the current and frequency, defining a number of the pulses (in descending order) and after each pulse train is finished, the procedure loop ends with adjusting the duty cycle.

With ACCO Semiconductor the set-up of measuring parts of a Power Amplifier has been started.

## Dissemination

An extensive list of presentations at Conferences and Workshops and a first list of scientific papers can be found online on the project website, http://www.fp7-nanocops.eu. Here, we first summarize the Outreach at ECMI-2014, ACOMEN-2014, and SCEE-2014 conferences.

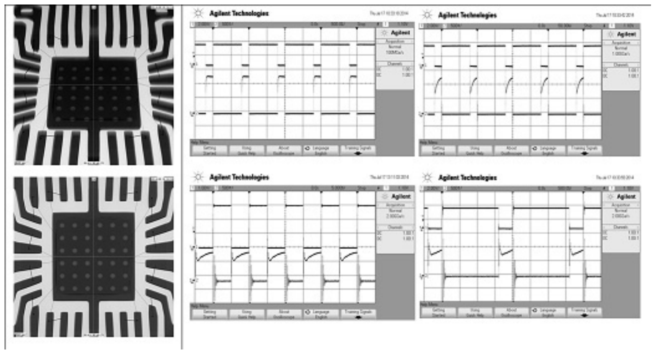


**Figure 32:** *Left: X-rays of available SOIC24 samples (ON Semiconductor) with bond wires. Right: Single-cell experimental measurement (Brno UT), input pulses (upper trace) and voltage drops across sensing resistor (lower trace) and four wire currents.*

- At ECMI-2014, 18th European Conference on Mathematics for Industry, June 9-13, 2014, Taormina, Sicily, eleven presentations have been given by nanoCOPS partners. As part of the 1st nanoCOPS Workshop, a special Minisymposium "Simulation Issues for Nanoelectronic Coupled Problems" was organized with five public talks.
- At ACOMEN-2014, 6th International Conference on Advanced Computational Methods in Engineering, June 23-28, 2014, Ghent, Belgium, nanoCOPS partners were involved in five presentations.
- At SCEE-2014, Scientific Computing in Electrical Engineering, July 22-25, 2014, Wuppertal, Germany, twelve nanoCOPS presentations were given, of which one from partner TU Darmstadt was an Invited Talk.

We also recall a presentation at SIAM UQ-2014, Conf. on Uncertainty Quantification, March 31 - April 3, 2014, Savannah, Georgia, USA (which is major conference in this field). Already two papers have been published in IEEE Journals. One paper did recently appear in COMPEL and another one will appear soon in the International Journal for Uncertainty Quantification. An online publication was in Radioengineering. For the (peer reviewed) ECMI-2014 proceedings several contributions have been submitted. Submissions to proceedings ACOMEN-2014 and SCEE-2014 are currenty being made.

## Acknowledgement

nanoCOPS

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## Conclusion and next Phase

NanoCOPS is ready for entering a new phase in the project: now emphasis will be put on implementation in C++ that will have to be glued into library modules. The software will allow for interaction with the existing software of MAGWEL. During this phase the algorithms will be further developed based on test and validation outcomes. Comparison will be made against measurements.


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