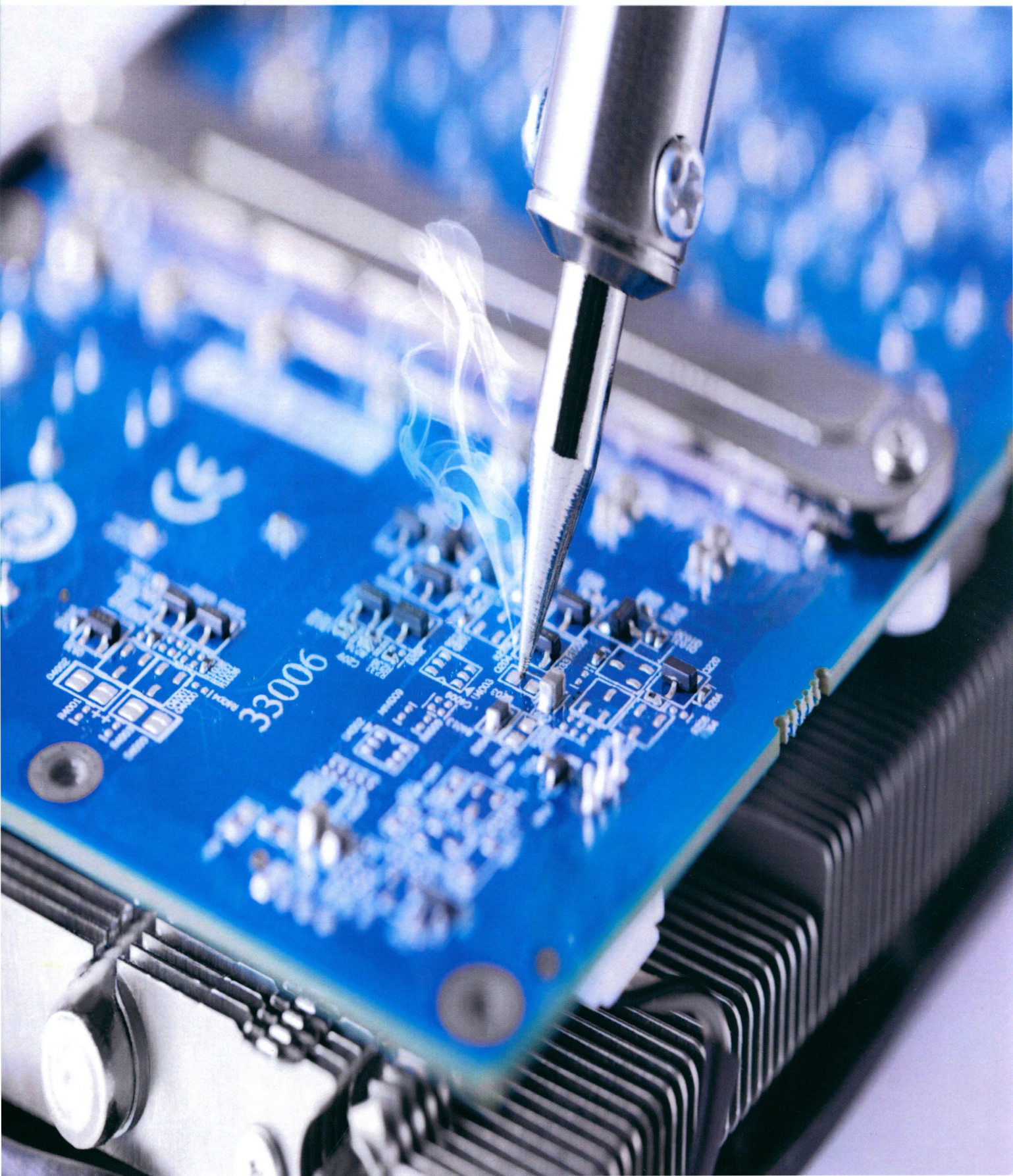


Fundamentals of Semiconductors: Physics and Materials

Contributors: Florin Babarada, et al.



About the Book

Semiconductors have had a monumental impact on our society. You find semiconductors at the heart of microprocessor chips as well as transistors. Anything that's computerized or uses radio waves depends on semiconductors. Today, most semiconductor chips and transistors are created with silicon. You may have heard expressions like "Silicon Valley" and the "silicon economy," and that's why -- silicon is the heart of any electronic device. The study of semiconductor materials began in the early 19th century. The elemental semiconductors are those composed of single species of atoms, such as silicon (Si), germanium (Ge), and tin (Sn) in column IV and selenium (Se) and tellurium (Te) in column VI of the periodic table. Semiconductors are used extensively in electronic circuits. As its name implies, a semiconductor is a material that conducts current, but only partly. The conductivity of a semiconductor is somewhere between that of an insulator, which has almost no conductivity, and a conductor, which has almost full conductivity. Most semiconductors are crystals made of certain materials, most commonly silicon.

Fundamentals of Semiconductors: Physics and Materials is a compilation of research articles by providing detailed explanations of the electronic, vibrational, transport, and optical properties of semiconductors. The approach is physical and intuitive rather than formal and pedantic. Theories are presented to explain experimental results. This book has been compiled with both students and researchers in mind.

Semiconductor devices have become indispensable for generating electromagnetic radiation in every day applications. Visible and infrared diode lasers are at the core of information technology, and at the other end of the spectrum, microwave and radio frequency emitters enable wireless communications. But the ultrafast electromagnetic waves, whose frequency locates in terahertz (THz) region (0.3 – 30 THz; 1 THz = 10^{12} Hz), has remained largely underdeveloped, despite the identification of various possible applications. One of the major applications of THz spectroscopy systems is in material characterization, particularly of lightweight molecules and semiconductors. Furthermore, THz imaging systems may find important niche applications in security screening and manufacturing quality control. THz systems also have broad applicability in a biomedical context, such as the T-ray biosensor.



www.aurisreference.com



Barbara Fundamentals of Semiconductors: Physics and Materials



Fundamentals of Semiconductors: Physics and Materials

Contributors

Florin Babarada, et al.



www.aurisreference.com

Fundamentals of Semiconductors: Physics and Materials

Contributors: Florin Babarada, et al.

Published by Auris Reference Limited

www.aurisreference.com

United Kingdom

Copyright 2017

The information in this book has been obtained from highly regarded resources. The copyrights for individual articles remain with the authors, as indicated. All chapters are distributed under the terms of the Creative Commons Attribution License, which permit unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Notice

Contributors, whose names have been given on the book cover, are not associated with the Publisher. The editors and the Publisher have attempted to trace the copyright holders of all material reproduced in this publication and apologise to copyright holders if permission has not been obtained. If any copyright holder has not been acknowledged, please write to us so we may rectify.

Reasonable efforts have been made to publish reliable data. The views articulated in the chapters are those of the individual contributors, and not necessarily those of the editors or the Publisher. Editors and/or the Publisher are not responsible for the accuracy of the information in the published chapters or consequences from their use. The Publisher accepts no responsibility for any damage or grievance to individual(s) or property arising out of the use of any material(s), instruction(s), methods or thoughts in the book.

Fundamentals of Semiconductors: Physics and Materials

ISBN: 978-1-78802-146-3

British Library Cataloguing in Publication Data

A CIP record for this book is available from the British Library

Printed in the United Kingdom

Fundamentals of Semiconductors: Physics and Materials

List of Contributors

Florin Babarada
Faculty of Electronics Telecommunications and Information Technology University Politehnica of Bucharest, Romania

Gianluca Berrettini

Antonella Bogoni
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Emma Lazzeri
Scuola Superiore Sant'Anna, Pisa Italy

Gianluca Meloni
Scuola Superiore Sant'Anna, Pisa Italy

Claudio Porzi
Scuola Superiore Sant'Anna, Pisa Italy

Luca Poti
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Mirco Scaffardi
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Ching-Ting Lee
Institute of Microelectronics, Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan, Republic of China

Michael Shearn
Thomas J. Watson, Sr., Laboratory of Applied Physics California Institute of Technology Pasadena, California 91125 USA

Xiankai Sun
Thomas J. Watson, Sr., Laboratory of Applied Physics California Institute of Technology Pasadena, California 91125 USA

M. David Henry
Thomas J. Watson, Sr., Laboratory of Applied Physics California Institute of Technology Pasadena, California 91125 USA

Amnon Yariv
Thomas J. Watson, Sr., Laboratory of Applied Physics California Institute of Technology Pasadena, California 91125 USA

Axel Scherer
Thomas J. Watson, Sr., Laboratory of Applied Physics California Institute of Technology Pasadena, California 91125 USA

Antonella Bogoni
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Gianluca Berrettini
Scuola Superiore Sant'Anna, Pisa Italy

Paolo Ghelfi
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Antonio Malacarne
Scuola Superiore Sant'Anna, Pisa Italy

Gianluca Meloni
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Luca Potì
Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), Pisa Italy

Jing Wang
Department of Electronic Engineering, Tsinghua University, Beijing China

Preface

Semiconductors have had a monumental impact on our society. You find semiconductors at the heart of microprocessor chips as well as transistors. Anything that's computerized or uses radio waves depends on semiconductors. Today, most semiconductor chips and transistors are created with silicon. You may have heard expressions like "Silicon Valley" and the "silicon economy," and that's why -- silicon is the heart of any electronic device. The study of semiconductor materials began in the early 19th century. The elemental semiconductors are those composed of single species of atoms, such as silicon (Si), germanium (Ge), and tin (Sn) in column IV and selenium (Se) and tellurium (Te) in column VI of the periodic table. Semiconductors are used extensively in electronic circuits. As its name implies, a semiconductor is a material that conducts current, but only partly. The conductivity of a semiconductor is somewhere between that of an insulator, which has almost no conductivity, and a conductor, which has almost full conductivity. Most semiconductors are crystals made of certain materials, most commonly silicon.

Fundamentals of Semiconductors: Physics and Materials is a compilation of research articles by providing detailed explanations of the electronic, vibrational, transport, and optical properties of semiconductors. The approach is physical and intuitive rather than formal and pedantic. Theories are presented to explain experimental results. This book has been compiled with both students and researchers in mind.

Semiconductor devices have become indispensable for generating electromagnetic radiation in every day applications. Visible and infrared diode lasers are at the core of information technology, and at the other end of the spectrum, microwave and radio frequency emitters enable wireless communications. But the ultrafast electromagnetic waves, whose frequency locates in terahertz (THz) region (0.3 – 30 THz; 1 THz = 10^{12} Hz), has remained largely underdeveloped, despite the identification of various possible applications. One of the major applications of THz spectroscopy systems is in material characterization, particularly of lightweight molecules and semiconductors. Furthermore, THz imaging systems may find important niche applications in security screening and manufacturing quality control. THz systems also have broad applicability in a biomedical context, such as the T-ray biosensor.

Contents

	List of Contributors.....	vii
	Preface.....	ix
Chapter 1	Semiconductor Processes and Devices Modelling.....	1
	Florin Babarada	
Chapter 2	Electrons and Holes in Semiconductors	27
Chapter 3	Semiconductor Devices and Applications	49
Chapter 4	All-optical Digital Processing Through Semiconductor Optical Amplifiers: State of the Art and Perspectives	67
	Gianluca Berrettini, Antonella Bogoni, Emma Lazzeri, Gianluca Meloni, Claudio Porzi, Luca Potì and Mirco Scaffardi	
Chapter 5	Bipolar Junction Transistors (BJTs)	91
Chapter 6	GaN-based Metal-Oxide-Semiconductor Devices.....	117
	Ching-Ting Lee	
Chapter 7	Advanced Plasma Processing: Etching, Deposition, and Wafer Bonding Techniques for Semiconductor Applications.....	165
	Michael Shearn, Xiankai Sun, M. David Henry, Amnon Yariv, and Axel Scherer	
Chapter 8	All-optical Flip-Flops Based on Semiconductor Technologies	185
	Antonella Bogoni, Gianluca Berrettini, Paolo Ghelfi, Antonio Malacarne, Gianluca Meloni, Luca Potì and Jing Wang	
	Citations	209
	Index.....	211

1

SEMICONDUCTOR PROCESSES AND DEVICES MODELLING

Florin Babarada

Faculty of Electronics Telecommunications and Information Technology University
Politehnica of Bucharest, Romania

INTRODUCTION

The advancement of knowledge in the electronic design is strongly influenced by Technology Computer Aided Design–TCAD. Here is an interesting positive feedback, because the computing power helps the designers to perform modelling, simulation, optimisation and design of the new devices with improved performance, which have the capability to increase the computing power. The chapter present the basic aspects and the state-of-the-art of processes and devices modelling completed with the new aspects presented by the author in their last few year's papers like the results of his researches.

Models in Micro and Nanoelectronics

Due to high costs and long manufacturing cycle the modelling, simulation and optimisation or simply TCAD is the foundation of micro/nanoelectronics rapidly progress.

The analysis involves the separation of the entire in component parts, characterization and judgment them and also the examination of the elements of system and the relations between them to understand.

Simulation is the imitative representation of the operation of a system or process through the operation of other's or the examination of a problem without experimentation. If the analysis can be precise about the simulation we accept the idea of approximation.

Modelling is the production of a representation or simulation of a problem, process or device, making a description or analogies to help the visualization of the aspects that can't be directly observed. Modelling is a need for analysis, simulation and design optimisation.

A model for a pure simulation, such as that produced by fitting of the curves, is usually much simpler than a model for analysis, which should reflect the physical aspects in a qualitative manner. An example is the application of Monte Carlo method, which is equivalent to producing an imitative representation of the system functioning. We

must always know the limitations of a model in order to don't interpret to naive the obtained results only through the improper application of the model. Also must have experience from previous experiments and simulations.

Development of electronic devices involves many tests and scraps for manufacturing until the scope respectively the designed operation parameters are performed. Implementation of device models, simulation and analysis, can now and in the future, to decrease substantially the number of iterations during development. A rough estimation of the development effort saved by analysis and simulation is of the order of 40%. This percentage depends heavily on the conditions of each individual project. The complete elimination of the tests and scraps of development is not possible today due to the uncertainty of many parameters of the models available that are already very sophisticated and too large. It is expected that modelling of devices, especially those with high scaling factor, at which the quantum mechanical aspects become predominate, to become more important in the future. This prediction is supported by the decreased cost of computing resources and special increases the cost of experimental investigation. Numerical modelling of the devices becomes more important for miniaturized models for which only large models are the existing and imaginable tools for precise prediction and analysis of device performances.

Technological Models

The technological model is a schematic or analog description of the phenomenon or system that matter for his knowledge or associated properties and could be used to the further study of its properties. When possible the models used in microelectronics are physical models that mean the modelled phenomena are represented by physical effects well understood. When the studied phenomena are unknown is calling to the empirical models. In this case the relationships between phenomenon variables are experimental determined. Quantitative empirical model in this case is a mathematical expression that fits to the experimental data. Models can contribute to technological progress as follows:

- Physical models can produce explanations or views of the phenomenon or device studied even the studied effect is not directly observable
- Physical and empirical models serve as vehicles for processes or devices studied; certain aspects of real devices or processes can be examined by studying the characteristics or the respectively model operation by simulation

Although the simulation does not replace the manufacturing, it reduces the test time and errors to a stable and optimised process. Often, a simulation allows studying windows of process to help optimise the device structure by setting the process conditions. The biggest challenge is to develop models that can quickly, cheaply and accurately to simulate processes and phenomena of advanced semiconductor devices.

PHYSICAL MODELS DEVELOPMENT

The development of physical models is generally in the following stages:

- Making the model qualitatively
- Making the model quantitatively
- Solving equations of quantitative model and centering process

Achieving quality model is the design, mechanisms deduction and relationships that comprise the essence of the phenomenon observed. In this form the model can realize the visualisation of the phenomena or devices studied. This is particularly important in microelectronics, where the phenomena being investigated are not usually directly observable. An example is the description of the Bohr atom model, the nuclei surrounded by electrons occupying orbits well defined. Another example is the description of the drift current in semiconductors as the movement of discrete particles of electric charge, respectively the electrons and holes, moving under the influence of electric field. In this case qualitative model can be translated into a set of equations or computing operations, resulting in a quantitative model. Finally the solution equations representing the quantitative model must be found and compared with experimental data to ensure that the simulation correctly emulates the phenomenon observed. In microelectronics quantitative physical models often take the form of equations with partial derivatives, Partial Differential Equations-PDE.

Simulation of micro/nanoelectronics devices and processes equations requires the evaluation model, computing operations, numerical analysis and advanced computer graphics (Rusu, 1990). Simulation helps manufacture of devices by increasing the success probability of the first experiment, for new products or processes. Existing manufacturing processes can be improved by centering process, ie finding the process combination of conditions for that we have the smallest results at the changing of the process conditions. Thus, circuit simulating behaviour modification based on conditions changing of manufacturing can identify the process tolerances.

In general, semiconductor devices can be simulated more precisely as the manufacturing processes of devices and integrated circuits because the physics of semiconductor devices is better known. In comparison, several physical processes manufacturing of integrated circuits is still not well understood and must rely on the empirical models.

EMPIRICAL MODELS

Introduction

The empirical models are only representations of experimental data and have a little or nothing physical background. Experimental data are used to create an empirical model as follows:

- Experimental results are stored in a database in the computer but are not provided information's about the interpolation results for approximation of unknown values between two points
- It used a mathematical function, which is adjusted by experimental data

To adjust the experimental data can use the next methods:

- Is used a polynomial function to pass through all points, leading to very complex functions and some experimental points may be wrong
- At one set of data graphically represented is choose a close mathematical function, which don't passes through all points and which can be adjusted

The most popular method of adjustment is the method of least squares, respectively the minimal sum of squares differences between points and the curve. If a data set match on a straight line $y=a+bx$, the process of finding the coefficients a and b , known as regression coefficients, is called linear regression. If it adopts a non-linear functional approximation, is used non-linear regression to find the regression coefficients.

Empirical Models in Semiconductor Simulation

The empirical models are used to simulate semiconductor because:

- We don't have other option when the physical background is not yet known
- If incorporated as part of a program for simulation of a process or device, empirical models can serve as a tool for storing experimental data
- The simulation results for these models is fast and direct
- The empirical models can provide accurate simulations for some particular experimental conditions
- If the simulated conditions are between the experimental data, the interpolation results can be found with reasonable accuracy

Sometimes, if the individuals do not produce quantitative expressions, which constitute these models, this major limitation makes it impossible to extrapolate to conditions out of the experimented field.

Semiempirical models are the models in which phenomena are modelled by equations based on physical parameters corresponding to these phenomena. Most models used in simulation of semiconductor devices and processes are semiempirical models. Thus, the silicon oxidation in dry oxygen, at thickness of less than 350Å does not correspond DealGrove model. Nicollian and Reisman created a model for this area $t_{ox}=a(t+t)^b$ with $a, b=\text{constant}$, $t=\text{time of growth}$ and $t=\text{time required to raise an initial layer thickness } x_i$. Other example is the boron implantation effects arising from sewage, ie penetration of boron ions deeper than monocrystalline silicon. For modelling this effect, an exponential portion was added to Pearson IV model. The length of the falling exponential part is determined empirically to the value of 450Å. This empirical model is available in TSUPREM III and IV.

DESIGN OF EXPERIMENT

Simulation of the manufacturing process using process simulators and extracting electrical characteristics using device simulators allow prediction of the behaviour and characteristics of the circuit from the design phase. The problem arises is that every attempt to obtain a performance model that is capable to incorporate the change effects in a broader set of parameters, is hit by hinder or even impossible to generate an analytical model that can be used effectively in design. Such as particularly important are the following aspects:

- Choosing a set of factors as more comprehensive
- Choosing the set of responses that characterize the best performance expected from the product design

The problem is usually solved iterative following the overlapping findings resulting from a series of individual experiments. Optimising a design involves finding a complete set of factors chosen so that the founding responses to have a high degree of confidence. Also, the sensitivity of the responses, given by the statistical nature of the technological implementation steps, is of particular importance in assessing the limits of tolerance of the desired response. Thus, by using based models simulation, can identify the input variables that allow the attainment of targets. More precisely, starting from the process variables such as temperature, time, energy and dose of implantation, may control the threshold voltage of the MOS transistors, parameter which influences the shape of the IV characteristics and so on the device parameters used in the circuit simulation and finally influences the circuit performances. Design of Experiment-DOE goal is to minimize the number of experiments in parallel with extraction of maximum information useful to designers. In this respect distinguish the following stages of analysis:

- Defining a set of factors that are considered to be sufficient for analysing the performance parameters of the requisite responses; the choice is based on previous knowledge
- Choosing a field of operation and a nominal value for each factor, considered acceptable in terms of tolerance of the technological process
- Defining a matrix corresponding with the DOE strategy selected
- Experimentation in selected points and collecting the results for each response
- Building a response surface model and analysis the conclusions from that study
- The revaluation of the set factors and the strategy of experimentation
- Obtaining the final response surface model

RESPONSE SURFACE MODELLING

Design of experiments is the key point of the optimisation process design. Results of experiments are used to generate the Response Surface Model-RSM. Are taken into account three model categories:

- Linear models, where the responses are linear functions of factors
- Models of order two for higher order design, the answers are obtained as functions of parabolic factors; these models constitute the standard in RSM techniques
- Transcendental models for higher order design, which provides improved techniques for analysing data and are used in analysis of amended RSM

Linear models assume that response R_i is a linear combination of factors $f_1, f_2, \dots, f_n$. When using these models only one factor is change in each run. The experiments are chosen in star. These are easily designed and expanded to higher dimensions.

The square models guess that the response R_i is a square combination of input factors with two power grade of the factors and products of factors. In this way is take into account the interactions between factors. Strategies to design experiments in this case are different: fullfactorial type and fractional-factorial type. Full-factorial strategies take into consideration all possible combinations of factors. This approach provides more information but also presents the inconvenience of requiring a long running time. Fractional-factorial strategies select a subset of the experimental points from the set full-factorial. Presents the advantage of data reuse at increasing of the problem size and easy change to full-factorial analyse.

The transcendental models assume the existence of a mechanism for transforming an initial set of factors in a modified set used for RSM.

The data obtained by experiments and those obtained by simulation are used to build a RSM, from which analysis may conclude a set of information about:

- Main effects, linear or nonlinear
- The interaction of factors
- Various factors importance in the evolution of a response
- Sensitivities of response to some factor
- Comparing the effect of a factor with the others, etc.

These results are iterative used for adjustment of coefficients, which are the input data of the RSM.

Like example, for the case of MOSFET technology flow the threshold voltage V_T is the output data and the input data are the following factors: oxide thickness TOX , N_{sub} concentration of substrate, the peak concentration