SEMICONDUCTOR TECHNOLOGIES

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Preface

Semiconductor technologies continue to evolve and amaze us. New materials, new structures, new manufacturing tools, and new advancements in modelling and simulation form a breeding ground for novel high performance electronic and photonic devices. This book covers all aspects of semiconductor technology concerning materials, technological processes, and devices, including their modelling, design, integration, and manufacturing.

High costs, long manufacturing cycles, and enormous increase in computing power are behind a recent rapid progress of the modelling, simulation, optimisation, and design of semiconductor devices. The first two chapters present the state-of-the-art in modelling of semiconductor processes and devices. Several examples are given: simulation of the switching characteristics of SiC GTO, MOSFET DC modelling for distortion analysis, or high-k dielectric-semiconductor modelling.

Continuous advancement of semiconductor technology and growth of semiconductor industry impose new requirements on semiconductor manufacturing. Semiconductor manufacturing belongs to the most challenging and complicated production systems involving huge capital investment and cutting-edge technologies. Chapter 3 discusses automation and integration in semiconductor manufacturing; chapter 4 is devoted to the contamination monitoring and analysis. Chapter 5 covers advanced plasma processing techniques and their emerging applications of etching, deposition, and surface modification of semiconductor materials. Chapters 6 and 7 concern themselves with oxidation techniques of III-V compounds and their application in MOS-based structures and gas sensors.

Tremendous interest in gallium nitride for high-frequency and high-power applications stems mainly from its wide and direct energy bandgap, thermal and chemical stability, and highelectron drift velocity. Chapter 8 is a comprehensive presentation of the GaN-based MOS devices with the emphasis on the description of various deposition methods of the dielectric film.

In chapter 9, the authors address two novel concepts for a mid-to-high voltage power semiconductor switch directly addressing the limitations of current IGBT and SJ MOSFET technologies. Chapter 10 is devoted to the study of the external optical feedback in nanostructure-based semiconductor lasers. In chapter 11, the authors investigate the influence of the electron transport on the optical properties of quantum-cascade structures.

Chapter 12 is dedicated to the preparation of transparent conductive oxide based on aluminumdoped ZnO for solar cells. Chapter 13 summarizes the preparation of high purity III-V layers grown by liquid phase epitaxy from rare-earth treated melts.

Optical technologies are the future of communication systems. Chapter 14 is a review of a device engineering method to provide high functionality of passive nonlinear vertical-cavity devices exploiting saturable absorption in semiconductor MQWs. Chapter 15 is a summary of the stateof-the-art of all-optical flip-flops based on semiconductor technologies. Chapter 16 reviews the current development of optical detection technologies on silicon photonics platform. In chapter 17, the authors describe the design, fabrication technology, and device performance of InP Mach-Zehnder modulator monolithically integrated with semiconductor optical amplifier. In chapter 18, the authors propose a new approach to ultra-fast all-optical signal processing based on quantum dot devices. Chapter 19 discusses present status and future direction of all-optical digital processing through semiconductor optical amplifiers.

Finally, chapter 20 presents a new approach to biomedical monitoring and analysis of selected human cognitive processes.

Jan Grym

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SEMICONDUCTOR PROCESSES AND DEVICES MODELLING

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1. 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.

2. Models in micro and nanoelectronics

2.1 Modelling simulation and analysis

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.

2.2 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.

3. 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 it is better known. In comparison, several physical processes manufacturing of integrated circuits is still not well understood and must rely on the empirical models.

4. Empirical models

4.1 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.

4.2 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 Deal-Grove model. Nicollian and Reisman created a model for this area $t_{ox}=a(t+\tau)^b$ with a, b=constant, t=time of growth and τ=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.

5. 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

6. 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: full-factorial 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 VT is the output data and the input data are the following factors: oxide thickness TOX, Nsub concentration of substrate, the peak concentration of channel implant for threshold voltage adjustment VTPEAK, the peak concentrations of LDD source and drain NLDDpeak, distance between the windows of the source and drain Lgate.

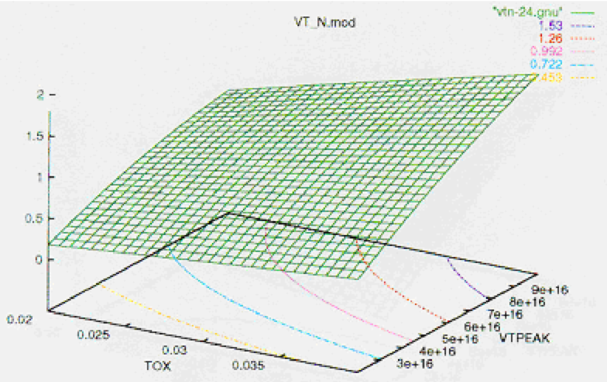

Fig. 1. RSM results for MOSFET threshold voltage VT

Were identified the main parameters that determines the threshold voltage of MOSFET like the MOS oxide thickness and the implantation dose for threshold adjustment, fig. 1.

7. Process optimisation

7.1 Introduction

TCAD software packages first need equipment models using configuration and settings as input parameters in order to obtain the process environment and process model to create the wafer data characteristics. Next using TCAD process simulator obtains the wafer state and using TCAD device simulator obtain device performance and the input data for circuit simulation. A final challenge and grand opportunity for future process modelling is to implement the accurate atomic scale reaction models respectively reaction energies, rates, products and process equipment models respectively gas flows, reactant concentrations and temperatures versus equipment settings.

In the state of the art devices small geometry effects including hot electron transport, punch-trough, avalanche multiplication, drain induced barrier lowering, oxide and junction breakdown, leakage currents, grain size effects and discrete doping elements effects are of great importance (Veendrick, 2008). Devices are also starting to exhibit significant quantum effects including gate oxide and bandgap tunnelling, inversion layer quantization, quantum transport and carrier density smoothing.

7.2 Optimisation strategies

Optimising a process technology or a device parameter involves an optimum set of factor setting such that a number of relevant results meet predefined targets. This problem is solved using the concepts of statistical Design of Experiments-DOE, for planning a number of experiments for different settings of input factors.

The simulation of process, device and circuit are performed in specific points respectively specific values for input factors for which the simulation are running. The results of experiments are analysed for each of the responses as a function of the input factors and we obtain a response surface model-RSM. The DOE/RSM concept guarantees that with a minimum number of experiments we obtain a maximum information respectively detection of the important main effects, factor interaction effects or which factor are the most important. The RSM models are used to find factor settings that produce devices with desired specifications (Govoreanu, 2002).

7.3 Example

Process optimisation example refers to n-type MOSFET realized in 0,5μm technology using Taurus-workbench software package from Synopsys. We start with substrate <100> boron doped at $5x10^{18}$. Then epitaxial growth of 6μm silicon layer, 0,2μm oxide layer and 0,15μm nitride and in the last two layers is successively configured ISLAL and NWELL and phosphorus is implanted with $2x10^{12}$ dose and 300KeV energy. After nitride removing and oxide configuration the threshold voltage adjusting doping is performed in two steps VTN implant with boron and PUNCH implant with boron at $5x10^{11}$ dose and 50KeV energy.

The gate oxide is grown, the polysilicon gate is deposited configured and implanted with phosphorus at $5x10^{15}$ dose and 45KeV energy. After NLDD implant in the gate and source/drain area the deep implant for source/drain configuration with phosphorus at $4x10^{15}$ dose and 80KeV energy is performed.

The next process steps perform the contact and interconnection between devices and the circuit protection layer.

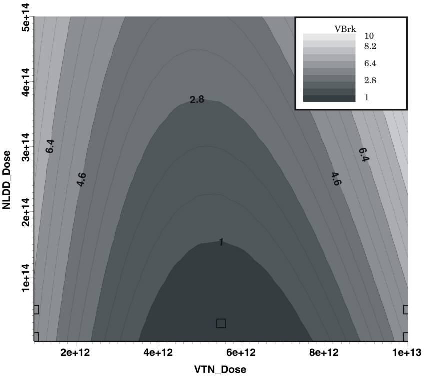

Fig. 2. RSM-V_{BRK} versus NLDD, VTN

Wafer	Units	Samp.1	Samp.2	Samp.3	Samp.4
VTN_Dose	Dose	1E+13	1.0E+13	1.0E+12	1.0E+12
PNCH_Dose	Dose	5E+11	5.0E+11	5.0E+11	5.0E+11
PNCH_Energy	Energy	50	50	50	50
tox	nm	11.9786	11.9786	11.996	11.996
NLDD_Dose	Dose	7E+12	5.0E+13	7.0E+12	5.0E+13
Xj	nm	192.945	231.634	214.388	347.719
Lchan	nm	538.034	393.185	376.42	254.542
Vt	V	0.9348	0.9338	0.3487	0.3222
IDSat	A/um	1.8E-04	3.3E-04	5.1E-04	6.7E-04
VBrk	V	5.57	5.57	5.91	5.73

Table 1. The samples parameters

Using DOE and RSM techniques the most sensitive process steps were identified respectively V_t adjusting implant and NLDD implant. These two parameters were modified successively.

The RSM results indicate a high dependence of breakdown voltage function of NLDD implant dose and a strong decreasing around $5x10^{12}$ VTN implant dose (fig. 2.), a big dependence of threshold voltage versus PUNCH implant dose and a small dependence versus VTN implant dose and a high dependence of saturation current (I_{DSS}) function of NLDD implant dose and a decreasing around $8x10^{12}$ VTN implant dose.

The increase of NLDD implant dose at Sample 2 and 4 reduces the polysilicon depletion effect, by reducing the voltage drop across the polysilicon gate and improving the device transconductance (the higher slope of transfer characteristics for Sample 2 and 4), fig. 7.

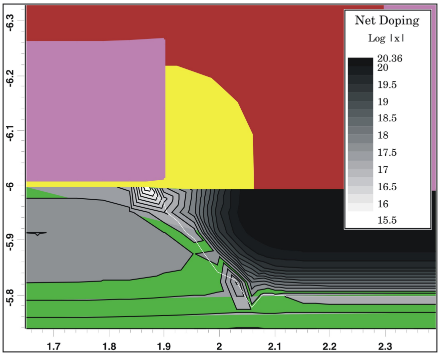

Fig. 3. Net Doping Sample 1

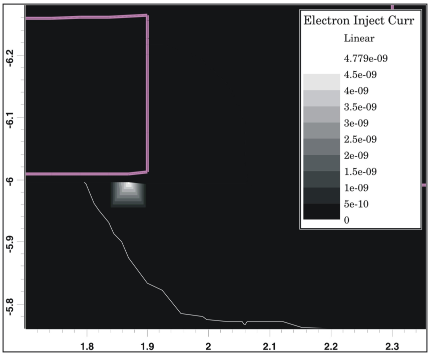

Fig. 4. Electron Injection Current Sample 2

According to Table 1 and fig. 3 to 6 the breakdown voltage is proportionally with the radius of source/drain junction (Kwong, 2002). Output resistance is reduced by decreasing the VTN boron adjusting implant dose (Sample 3 and 4) and can be explained by higher electron concentration in the channel, which allows a shorter pinchoff region. A shorter pinchoff region gives rise to a much larger magnitude of the Early voltage.

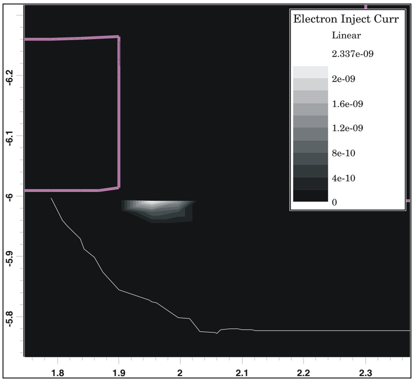

Fig. 5. Electron Injection Current Sample 3

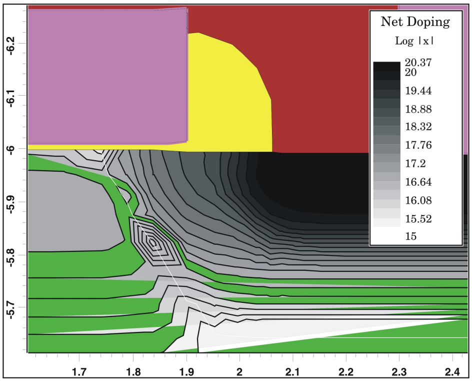

Fig. 6. Net Doping Sample 4

The decrease of NLDD dose in Sample 3, fig. 5, comparing with Sample 2 fig. 4 move the electron injection current from gate oxide to spacer decreasing the gate oxide breakdown possibility and reduces electron injection concentration which improve reliability. For the all four samples the transfer characteristics are presented in fig. 7 and the external characteristics in fig. 8 (Campian, 2003).

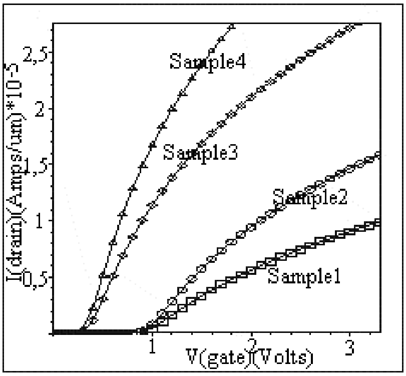

Fig. 7. I_D-V_{GS} Characteristics

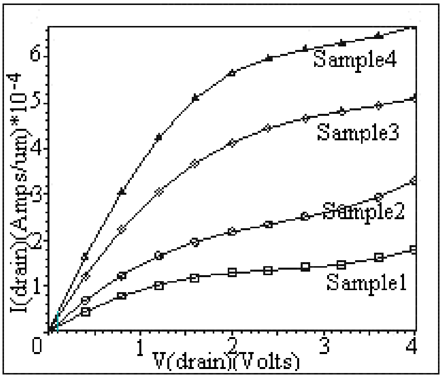

Fig. 8. I_D-V_{DS} Characteristics

The higher electron concentration in the channel gives a large Early voltage very useful in analog circuits. Increasing of lateral source/drain slope lowers also the series resistance, which improves the drive current, but for very abrupt profile junction the improvement is paid by degradation in leakage current due to more severe short channel effects.

8. MOSFET DC modelling for distortions analysis

8.1 Introduction

The scaling-down evolution of semiconductor devices will ultimately attend fundamental limits as transistor reach the nanoscale aria. In this context the MOSFET models must give the process variations and the relevant characteristics like current, conductance, transconductance, capacitances, flicker thermal or high frequency noise and distortion (Ytterdal, 2003). The new challenge of nanotechnology needs very accurate models for active devices (Scholten, 2009). The design of linear analog circuits lacks models for state-of-the-art MOS transistors to accurately describe distortion effects. This is produced by the inaccurate modelling of the second order effects induced by high vertical gate field such as mobility degradation and series resistance and second order effects induced by parallel drain field like velocity saturation in the ohmic region, channel length modulation, static feedback, weak avalanche and selfheating in the saturation region. After a rigorous description of transistor transconductance and channel conductance in ohmic and saturation region we included these effects in the MOSFET model, using a compact drain current expression for time computation reasons.

8.2 Gate induced distortions modelling

Carriers mobility degradation modelling

The channel mobility must be treated quantum-mechanically because the thickness of the inversion layer is in the order of a few Å, smaller than the De Broglie wavelength of the carriers. Quantum-mechanical calculations show that energy subbands of electrons and holes are formed in different energy valleys. The spacing of these subbands increases with the normal electric field Ex. In the weak inversion region where many subbands are occupied, quantum effects can be neglected, but in the strong inversion region where only