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The Modeling and Simulation of Ballistic Nano-scaled MOSFET Planar Double-Gate Transistor

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Gain compression is a reduction in incremental gain caused by nonlinearity of the transfer function of the amplifying device. Gain compression of gain is caused by non-linear characteristics of the device when run at large amplitudes. As the input level is increased beyond the linear range of the amplifier, gain compression may occur depending on the characteristics of the device. This nonlinearity may be caused by heat due to power dissipation or by overdriving the active device beyond its linear region. It is a large-signal phenomenon of circuits. This may also

cause harmonic distortion from the device. To model this non-linear behavior, a VBE multiplier (Q1,etc.) and Zener (D2), (see Figure 3) are used to mimic the non-linear behavior of the device near where ID shows a maximum. To model the quasi-sat behavior from the lightly doped drain variable resistance, a polynomial voltage controlled modeling circuit (E1) is used to mimic this non-linear aspect of the device. The gain compression and quai-sat behavior of lightly doped drain MOSFETs can be modeled by using the full gain compression circuit shown in Figure 3. This can be very valuable to accurately simulate the current-voltage behavior of lightly doped drains in high voltage/power MOSFETs. Both the gain compression (gm fall-off) and quasi-sat (variable effective drain resistance) behavior can be accurately modeled and simulated by the subcircuit model shown in Figure 3. By proper setting of the various circuit elements and their model parameters very accurate current-voltage behavior of lightly doped drain MOSFETs can be simulated to obtain accurate gate-source and gate-drain capacitances. Bridges the gap between device modelling and analog circuit design. Includes dedicated software enabling actual circuit design. Covers the three significant models: BSIM3, Model 9 &, and EKV. Presents practical guidance on device development and circuit implementation. The authors offer a combination of extensive academic and industrial experience. This is the first book dedicated to the next generation of MOSFET models. Addressed to circuit designers with an in-depth treatment that appeals to device specialists, the book presents a fresh view of compact modeling, having completely abandoned the regional modeling approach.Both an overview of the basic physics theory required to build compact MOSFET models and a unified treatment of inversion-charge and surface-potential models are provided. The needs of digital, analog and RF designers as regards the availability of simple equations for circuit designs are taken into account. Compact expressions for hand analysis or for automatic synthesis, valid in all operating regions, are presented throughout the book. All the main expressions for computer simulation used in the new generation compact models are derived.Since designers in advanced technologies are increasingly concerned with fluctuations, the modeling of

fluctuations is strongly emphasized. A unified approach for both space (matching) and time (noise) fluctuations is introduced. ' A reprint of the classic text, this book popularized compact modeling of electronic and semiconductor devices and components for college and graduate-school classrooms, and manufacturing engineering, over a decade ago. The first comprehensive book on MOS transistor compact modeling, it was the most cited among similar books in the area and remains the most frequently cited today. The coverage is device-physics based and continues to be relevant to the latest advances in MOS transistor modeling. This is also the only book that discusses in detail how to measure device model parameters required for circuit simulations. The book deals with the MOS Field Effect Transistor (MOSFET) models that are derived from basic semiconductor theory. Various models are developed, ranging from simple to more sophisticated models that take into account new physical effects observed in submicron transistors used in today''s (1993) MOS VLSI technology. The assumptions used to arrive at the models are emphasized so that the accuracy of the models in describing the device characteristics are clearly understood. Due to the importance of designing reliable circuits, device reliability models are also covered. Understanding these models is essential when designing circuits for state-of-the-art MOS ICs. Contents: OverviewReview of Basic Semiconductor and pn Junction TheoryMOS Transistor Structure and OperationMOS CapacitorThreshold VoltageMOSFET DC ModelDynamic ModelModeling Hot-Carrier EffectsData Acquisition and Model Parameter MeasurementsModel Parameter Extraction Using Optimization MethodSPICE Diode and MOSFET Models and Their ParametersStatistical Modeling and Worst-Case Design Parameters Readership: Integrated circuit chip designers, device model developers and circuit simulators. ' Until the 1990s, the reduction of the minimum feature sizes used to fabricate in- grated circuits, called "scaling", has highlighted serious advantages as integration density, speed, power consumption, functionality and cost. Direct consequence was the decrease of cost-per-function, so the electronic productivity has largely progressed in this period. Another usually cited trend is the evolution of the in-

gration density as expressed by the well-know Moore's Law in 1975: the number of devices per chip doubles every 2 years. This evolution has allowed improving signi?cantly the circuit complexity, offering a great computing power in the case of microprocessor, for example. However, since few years, signi?cant issues appeared such as the increase of the circuit heating, device complexity, variability and dif?culties to improve the integration density. These new trends generate an important growth in development and production costs. Though is it, since 40 years, the evolution of the microelectronics always f- lowed the Moore's law and each dif?culty has found a solution. Circuit simulation is essential in integrated circuit design, and the accuracy of circuit simulation depends on the accuracy of the transistor model. BSIM3v3 (BSIM for Berkeley Short-channel IGFET Model) has been selected as the first MOSFET model for standardization by the Compact Model Council, a consortium of leading companies in semiconductor and design tools. In the next few years, many fabless and integrated semiconductor companies are expected to switch from dozens of other MOSFET models to BSIM3. This will require many device engineers and most circuit designers to learn the basics of BSIM3. MOSFET Modeling & BSIM3 User's Guide explains the detailed physical effects that are important in modeling MOSFETs, and presents the derivations of compact model expressions so that users can understand the physical meaning of the model equations and parameters. It is the first book devoted to BSIM3. It treats the BSIM3 model in detail as used in digital, analog and RF circuit design. It covers the complete set of models, i.e., I-V model, capacitance model, noise model, parasitics model, substrate current model, temperature effect model and non quasi-static model. MOSFET Modeling & BSIM3 User's Guide not only addresses the device modeling issues but also provides a user's guide to the device or circuit design engineers who use the BSIM3 model in digital/analog circuit design, RF modeling, statistical modeling, and technology prediction. This book is written for circuit designers and device engineers, as well as device scientists worldwide. It is also suitable as a reference for graduate courses and courses in circuit design or device modelling. Furthermore, it can be used as a textbook for industry courses

devoted to BSIM3. MOSFET Modeling & BSIM3 User's Guide is comprehensive and practical. It is balanced between the background information and advanced discussion of BSIM3. It is helpful to experts and students alike. Most of the recent texts on compact modeling are limited to a particular class of semiconductor devices and do not provide comprehensive coverage of the field. Having a single comprehensive reference for the compact models of most commonly used semiconductor devices (both active and passive) represents a significant advantage for the reader. Indeed, several kinds of semiconductor devices are routinely encountered in a single IC design or in a single modeling support group. Compact Modeling includes mostly the material that after several years of IC design applications has been found both theoretically sound and practically significant. Assigning the individual chapters to the groups responsible for the definitive work on the subject assures the highest possible degree of expertise on each of the covered models. This book presents the art of advanced MOSFET modeling for integrated circuit simulation and design. It provides the essential mathematical and physical analyses of all the electrical, mechanical and thermal effects in MOS transistors relevant to the operation of integrated circuits. Particular emphasis is placed on how the BSIM model evolved into the first ever industry standard SPICE MOSFET model for circuit simulation and CMOS technology development. The discussion covers the theory and methodology of how a MOSFET model, or semiconductor device models in general, can be implemented to be robust and efficient, turning device physics theory into a production-worthy SPICE simulation model. Special attention is paid to MOSFET characterization and model parameter extraction methodologies, making the book particularly useful for those interested or already engaged in work in the areas of semiconductor devices, compact modeling for SPICE simulation, and integrated circuit design. Double-Gate (DG) MOSFET is a newly emerging device that can potentially further scale down CMOS technology owing to its excellent control of short channel effects. Currently, much research effort is devoted to the development of DG MOSFETs. This dissertation focuses on the compact modeling of DG

MOSFETs, aiming to extract the physics of DG MOSFETs and provide a tool for simulating DG MOSFET circuits. We start from the basic Poisson's equation and current continuity equation to rigorously derive the long-channel drain current model without the charge sheet approximation. The model is based on an analytical solution to the potential distribution at any point in the DG MOSFET. It employs one single equation to cover all the operation regions: linear, saturation, and subthreshold, continuously with no fitting parameter. Volume inversion, a non-charge-sheet phenomenon in symmetric DG MOSFETs, is accurately captured by the model. For AC and transient simulations, analytical charge and capacitance models are developed. Both symmetric and asymmetric DG MOSFET models are verified by extensive two dimensional numerical simulations. For small-geometry devices, compact models of the physical phenomena such as short channel effects are developed. In the development of the compact models, special attention is paid to ensure the model is symmetric and continuous in all the operation regions. Quantum effect is also incorporated in the long channel core model. As body doping may be needed to adjust the threshold voltage, we also studied the body doping effect on DG MOSFET and concluded that lightly doped DG MOSFETs can be modeled by adding a threshold voltage shift to the undoped DG MOSFET model. The model has been implemented into SPICE3 and Verilog-A platforms so that it can be used by circuit designers. In the implementation, Newton method is used for solving an implicit equation in the calculation of drain current. We also calibrated the model with respect to the published hardware data to affirm its consistency with the experimental I-V curves. Finally, the model has been released in public domain http://taur.ucsd.edu/~hlu for circuit simulation. To be perfect does not mean that there is nothing to add, but rather there is nothing to take away Antoine de Saint-Exupery The drift-diffusion approximation has served for more than two decades as the cornerstone for the numerical simulation of semiconductor devices. However, the tremendous speed in the development of the semiconductor industry demands numerical simulation tools that are efficient and provide reliable results. This makes the development of a simulation tool

an interdisciplinary task in which physics, numerical algorithms, and device technology merge. For the sake of an efficient code there are trade-offs between the different influencing factors. The numerical performance of a program that is highly flexible in device types and the geometries it covers certainly cannot compare with a program that is optimized for one type of device only. Very often the device is sufficiently described by a two dimensional geometry. This is the case in a MOSFET, for example, if the gate length is small compared with the gate width. In these cases the geometry reduces to the specification of a two-dimensional device. Here again the simplest geometries, which are planar or at least rectangular surfaces, will give the most efficient numerical codes. The device engineer has to decide whether this reduced description of the real device is still suitable for his purposes. Metal Oxide Semiconductor (MOS) transistors are the basic building block ofMOS integrated circuits (I C). Very Large Scale Integrated (VLSI) circuits using MOS technology have emerged as the dominant technology in the semiconductor industry. Over the past decade, the complexity of MOS IC's has increased at an astonishing rate. This is realized mainly through the reduction of MOS transistor dimensions in addition to the improvements in processing. Today VLSI circuits with over 3 million transistors on a chip, with effective or electrical channel lengths of 0. 5 microns, are in volume production. Designing such complex chips is virtually impossible without simulation tools which help to predict circuit behavior before actual circuits are fabricated. However, the utility of simulators as a tool for the design and analysis of circuits depends on the adequacy of the device models used in the simulator. This problem is further aggravated by the technology trend towards smaller and smaller device dimensions which increases the complexity of the models. There is extensive literature available on modeling these short channel devices. However, there is a lot of confusion too. Often it is not clear what model to use and which model parameter values are important and how to determine them. After working over 15 years in the field of semiconductor device modeling, I have felt the need for a book which can fill the gap between the theory and the practice of MOS transistor modeling. This book is an attempt in

that direction. A reprint of the classic text, this book popularized compact modeling of electronic and semiconductor devices and components for college and graduate-school classrooms, and manufacturing engineering, over a decade ago. The first comprehensive book on MOS transistor compact modeling, it was the most cited among similar books in the area and remains the most frequently cited today. The coverage is device-physics based and continues to be relevant to the latest advances in MOS transistor modeling. This is also the only book that discusses in detail how to measure device model parameters required for circuit simulations. The book deals with the MOS Field Effect Transistor (MOSFET) models that are derived from basic semiconductor theory. Various models are developed, ranging from simple to more sophisticated models that take into account new physical effects observed in submicron transistors used in today's (1993) MOS VLSI technology. The assumptions used to arrive at the models are emphasized so that the accuracy of the models in describing the device characteristics are clearly understood. Due to the importance of designing reliable circuits, device reliability models are also covered. Understanding these models is essential when designing circuits for state-of-the-art MOS ICs. This book is the first to explain FinFET modeling for IC simulation and the industry standard – BSIM-CMG - describing the rush in demand for advancing the technology from planar to 3D architecture, as now enabled by the approved industry standard. The book gives a strong foundation on the physics and operation of FinFET, details aspects of the BSIM-CMG model such as surface potential, charge and current calculations, and includes a dedicated chapter on parameter extraction procedures, providing a step-by-step approach for the efficient extraction of model parameters. With this book you will learn: Why you should use FinFET The physics and operation of FinFET Details of the FinFET standard model (BSIM-CMG) Parameter extraction in BSIM-CMG FinFET circuit design and simulation Authored by the lead inventor and developer of FinFET, and developers of the BSIM-CM standard model, providing an experts' insight into the specifications of the standard The first book on the industry-standard FinFET model - BSIM-CMG This is the first book dedicated to the next

generation of MOSFET models. Addressed to circuit designers with an in-depth treatment that appeals to device specialists, the book presents a fresh view of compact modeling, having completely abandoned the regional modeling approach.Both an overview of the basic physics theory required to build compact MOSFET models and a unified treatment of inversion-charge and surface-potential models are provided. The needs of digital, analog and RF designers as regards the availability of simple equations for circuit designs are taken into account. Compact expressions for hand analysis or for automatic synthesis, valid in all operating regions, are presented throughout the book. All the main expressions for computer simulation used in the new generation compact models are derived.Since designers in advanced technologies are increasingly concerned with fluctuations, the modeling of fluctuations is strongly emphasized. A unified approach for both space (matching) and time (noise) fluctuations is introduced. The essentials of analog circuit design with a unique all-region MOSFET modeling approach. Practicing designers, students, and educators in the semiconductor field face an ever expanding portfolio of MOSFET models. In Compact MOSFET Models for VLSI Design , A.B. Bhattacharyya presents a unified perspective on the topic, allowing the practitioner to view and interpret device phenomena concurrently using different modeling strategies. Readers will learn to link device physics with model parameters, helping to close the gap between device understanding and its use for optimal circuit performance. Bhattacharyya also lays bare the core physical concepts that will drive the future of VLSI development, allowing readers to stay ahead of the curve, despite the relentless evolution of new models. Adopts a unified approach to guide students through the confusing array of MOSFET models Links MOS physics to device models to prepare practitioners for real-world design activities Helps fabless designers bridge the gap with off-site foundries Features rich coverage of: quantum mechanical related phenomena Si-Ge strained-Silicon substrate non-classical structures such as Double Gate MOSFETs Presents topics that will prepare readers for long-term developments in the field Includes solutions in every chapter Can be tailored for use among students and

professionals of many levels Comes with MATLAB code downloads for independent practice and advanced study This book is essential for students specializing in VLSI Design and indispensible for design professionals in the microelectronics and VLSI industries. Written to serve a number of experience levels, it can be used either as a course textbook or practitioner's reference. Access the MATLAB code, solution manual, and lecture materials at the companion website: www.wiley.com/go/bhattacharyya This volume provides a timely description of the latest compact MOS transistor models for circuit simulation. The first generation BSIM3 and BSIM4 models that have dominated circuit simulation in the last decade are no longer capable of characterizing all the important features of modern sub-100nm MOS transistors. This book discusses the second generation MOS transistor models that are now in urgent demand and being brought into the initial phase of manufacturing applications. It considers how the models are to include the complete drift-diffusion theory using the surface potential variable in the MOS transistor channel in order to give one characterization equation. An expert guide to understanding and making optimum use of BSIM Used by more chip designers worldwide than any other comparable model, the Berkeley Short-Channel IGFET Model (BSIM) has, over the past few years, established itself as the de facto standard MOSFET SPICE model for circuit simulation and CMOS technology development. Yet, until now, there have been no independent expert guides or tutorials to supplement the various BSIM manuals currently available. Written by a noted expert in the field, this book fills that gap in the literature by providing a comprehensive guide to understanding and making optimal use of BSIM3 and BSIM4. Drawing upon his extensive experience designing with BSIM, William Liu provides a brief history of the model, discusses the various advantages of BSIM over other models, and explores the reasons why BSIM3 has been adopted by the majority of circuit manufacturers. He then provides engineers with the detailed practical information and guidance they need to master all of BSIM's features. He: Summarizes key BSIM3 components Represents the BSIM3 model with equivalent circuits for

various operating conditions Provides a comprehensive glossary of modeling terminology Lists alphabetically BSIM3 parameters along with their meanings and relevant equations Explores BSIM3's flaws and provides improvement suggestions Describes all of BSIM4's improvements and new features Provides useful SPICE files, which are available online at the Wiley ftp site Analysis and Design of MOSFETs: Modeling, Simulation, and Parameter Extraction is the first book devoted entirely to a broad spectrum of analysis and design issues related to the semiconductor device called metal-oxide semiconductor field-effect transistor (MOSFET). These issues include MOSFET device physics, modeling, numerical simulation, and parameter extraction. The discussion of the application of device simulation to the extraction of MOSFET parameters, such as the threshold voltage, effective channel lengths, and series resistances, is of particular interest to all readers and provides a valuable learning and reference tool for students, researchers and engineers. Analysis and Design of MOSFETs: Modeling, Simulation, and Parameter Extraction, extensively referenced, and containing more than 180 illustrations, is an innovative and integral new book on MOSFETs design technology. Modern, large-scale analog integrated circuits (ICs) are essentially composed of metal-oxide semiconductor (MOS) transistors and their interconnections. As technology scales down to deep sub-micron dimensions and supply voltage decreases to reduce power consumption, these complex analog circuits are even more dependent on the exact behavior of each transistor. High-performance analog circuit design requires a very detailed model of the transistor, describing accurately its static and dynamic behaviors, its noise and matching limitations and its temperature variations. The charge-based EKV (Enz-Krummenacher-Vittoz) MOS transistor model for IC design has been developed to provide a clear understanding of the device properties, without the use of complicated equations. All the static, dynamic, noise, non-quasi-static models are completely described in terms of the inversion charge at the source and at the drain taking advantage of the symmetry of the device. Thanks to its hierarchical structure, the model offers several coherent description levels, from basic hand

calculation equations to complete computer simulation model. It is also compact, with a minimum number of process-dependant device parameters. Written by its developers, this book provides a comprehensive treatment of the EKV charge-based model of the MOS transistor for the design and simulation of low-power analog and RF ICs. Clearly split into three parts, the authors systematically examine: the basic long-channel intrinsic charge-based model, including all the fundamental aspects of the EKV MOST model such as the basic large-signal static model, the noise model, and a discussion of temperature effects and matching properties; the extended charge-based model, presenting important information for understanding the operation of deep-submicron devices; the high-frequency model, setting out a complete MOS transistor model required for designing RF CMOS integrated circuits. Practising engineers and circuit designers in the semiconductor device and electronics systems industry will find this book a valuable guide to the modelling of MOS transistors for integrated circuits. It is also a useful reference for advanced students in electrical and computer engineering. This book presents the art of advanced MOSFET modeling for integrated circuit simulation and design. It provides the essential mathematical and physical analyses of all the electrical, mechanical and thermal effects in MOS transistors relevant to the operation of integrated circuits. Particular emphasis is placed on how the BSIM model evolved into the first ever industry standard SPICE MOSFET model for circuit simulation and CMOS technology development. The discussion covers the theory and methodology of how a MOSFET model, or semiconductor device models in general, can be implemented to be robust and efficient, turning device physics theory into a production-worthy SPICE simulation model. Special attention is paid to MOSFET characterization and model parameter extraction methodologies, making the book particularly useful for those interested or already engaged in work in the areas of semiconductor devices, compact modeling for SPICE simulation, and integrated circuit design. Circuit simulation is widely used for the design of circuits, both discrete and integrated. Device modeling is an impor tant aspect of circuit simulation since it is the link between the physical device

and the sim ulate d device. Curren tly available circuit simulation programs provide a variety of built-in models. Many circuit designers use these built-in models whereas some incorporate new models in the circuit sim ulation programs. Understanding device modeling with particular emphasis on circuit simulation will be helpful in utilizing the built-in models more efficiently as well as in implementing new models. SPICE is used as a vehicle since it is the most widely used circuit sim ulation program. How ever, some issues are addressed which are not directly appli cable to SPICE but are applicable to circuit simulation in general. These discussions are useful for modifying SPICE and for understanding other simulation programs. The gen eric version 2G. 6 is used as a reference for SPICE, although numerous different versions exist with different modifications. This book describes field effect transistor models commonly used in a variety of circuit sim ulation pro grams. Understanding of the basic device physics and some familiarity with device modeling is assumed. Derivation of the model equations is not included. (SPICE is a circuit sim ulation program available from EECS Industrial Support Office, 461 Cory Hall, University of Cali fornia, Berkeley, CA 94720.) Acknowledgements I wish to express my gratitude to Valid Logic Systems, Inc. Compact Hierarchical Bipolar Transistor Modeling with HICUM will be of great practical benefit to professionals from the process development, modeling and circuit design community who are interested in the application of bipolar transistors, which include the SiGe:C HBTs fabricated with existing cutting-edge process technology. The book begins with an overview on the different device designs of modern bipolar transistors, along with their relevant operating conditions; while the subsequent chapter on transistor theory is subdivided into a review of mostly classical theories, brought into context with modern technology, and a chapter on advanced theory that is required for understanding modern device designs. This book aims to provide a solid basis for the understanding of modern compact models. The editors and authors present a wealth of knowledge regarding the most relevant aspects in the field of MOS transistor modeling. The variety of subjects and the high quality of content of this volume make it

a reference document for researchers and users of MOSFET devices and models. The book can be recommended to everyone who is involved in compact model developments, numerical TCAD modeling, parameter extraction, space-level simulation or model standardization. The book will appeal equally to PhD students who want to understand the ins and outs of MOSFETs as well as to modeling designers working in the analog and high-frequency areas. This book will help CMOS circuit designers make the best possible use of SPICE models, and will prepare them for new models that may soon be introduced. Introduces SPICE modeling and its use in CMOS circuit design. Presents the formalism of model building and the semiconductor physics of MOS structures. Covers each important SPICE model, showing how to choose the appropriate model. Discusses the popular HSPICE Level 28, as well as Levels 1-3, BSIM 1-3, and MOS Model 9. Presents techniques for accounting for systematic process variations. Describes new model candidates, including the Power-Lane Model, the PCIM Model, and the EKV Model. Includes extensive examples throughout. Practicing engineers and scientists in the semiconductor industry; engineering faculty and students. The primary aim of this book is to discuss various aspects of nanoscale device design and their applications including transport mechanism, modeling, and circuit applications. . Provides a platform for modeling and analysis of state-of-the-art devices in nanoscale regime, reviews issues related to optimizing the sub-nanometer device performance and addresses simulation aspect and/or fabrication process of devices Also, includes design problems at the end of each chapter Covering the essentials of analog circuit design, this book takes a unique design approach based on a MOSFET model valid for all operating regions, rather than the standard square-law model. Opening chapters focus on device modeling, integrated circuit technology, and layout, whilst later chapters go on to cover noise and mismatch, and analysis and design of the basic building blocks of analog circuits, such as current mirrors, voltage references, voltage amplifiers, and operational amplifiers. An introduction to continuous-time filters is also provided, as are the basic principles of sampled-data circuits, especially switched-capacitor circuits. The final

chapter then reviews MOSFET models and describes techniques to extract design parameters. With numerous design examples and exercises also included, this is ideal for students taking analog CMOS design courses and also for circuit designers who need to shorten the design cycle.

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