Improving Semiconductor Device Modeling for Electronic Design Automation by Machine Learning Techniques

Zeheng Wang, *Member, IEEE*, Liang Li, Ross C. C. Leon, Jinlin Yang, Junjie Shi, Timothy van der Laan, and Muhammad Usman

Abstract— **The semiconductors industry benefits greatly from the integration of machine learning (ML)-based techniques in technology computer-aided design (TCAD) methods. The performance of ML models, however, relies heavily on the quality and quantity of training datasets. They can be particularly difficult to obtain in the semiconductor industry due to the complexity and expense of the device fabrication. In this article, we propose a self-augmentation strategy for improving ML-based device modeling using variational autoencoder (VAE)-based techniques. These techniques require a small number of experimental data points and do not rely on TCAD tools. To demonstrate the effectiveness of our approach, we apply it to a deep neural network (DNN)-based prediction task for the ohmic resistance value in gallium nitride (GaN) devices. A 70% reduction in mean absolute error (MAE) when predicting experimental results is achieved. The inherent flexibility of our approach allows easy adaptation to various tasks, thus making it highly relevant to many applications of the semiconductor industry.**

Index Terms— **Data augmentation, electronic design automation (EDA), gallium nitride (GaN), machine learning (ML), semiconductor devices.**

I. Introduction

ELECTRONIC design automation (EDA) has been crucial in advancing the semiconductors industry by simplifying design tasks and reducing their time consumption [1]. One particular EDA technique, technology computer-aided design (TCAD), has been especially useful in the area of semiconductor devices. TCAD solves basic physics equations using the finite element method, such as the Poisson and Schrödinger equations, which provides easy access to simulated results that would be difficult to solve manually [2], [3], [4]. In addition, TCAD has significantly reduced the cost of experiments during device design by avoiding them altogether [5].

Nevertheless, simulating complex 3-D device structures requires significant computational resources. While many models and methods have been developed to reduce resource consumption, exploring novel methodologies of TCAD remains a pressing issue to balance the accuracy and time consumption of sophisticated physics simulations. So far, machine learning (ML)-based solutions have been successfully employed in many device modeling cases and offer the advantage of low-resource consumption after model training [6], [7], [8], [9], [10]. However, with expanding size of the ML models, there is an increasing need for input data to fully complete model training [11].

TCAD-based data augmentation, a technique that has garnered significant attention in the semiconductor industry since 2019 [9], [12], [13], [14], has been employed to generate artificial data that can be fed into deep neural network (DNN)-based models. This approach could provide an expanded dataset and then significant boost to DNN-based modeling within the TCAD industry's development. However, many problems in the semiconductor industry cannot be directly solved by TCAD tools, such as the simulation of the formations of ohmic contacts in gallium nitride (GaN) devices, which imposes a formidable challenge on the TCAD-based augmentation technique.

Recently, a study by Sheelvardhan et al. [15] highlighted the potential of knowledge-based ML algorithms in overcoming the limitations of traditional ML-based approaches for semiconductor device modeling. By leveraging prior knowledge, these algorithms offer a promising solution to address the complexities associated with establishing and training ML models. This research represents a significant advancement toward the development of next-generation ML-based TCAD toolkits.

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Semiconductor Device Modeling For Computer Aided Design

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Semiconductor Device Modeling For Computer Aided Design:

Semiconductor Device Modeling for Computer-aided Design Gerald J. Herskowitz,1972 **Semiconductor Device Modeling for Computer-aided Design** Gerald J. Herskowitz,Ronald B. Schilling,1972 *Computer Aided Design Of Micro- And Nanoelectronic Devices* Chinmay Kumar Maiti,2016-10-27 Micro and nanoelectronic devices are the prime movers for electronics which is essential for the current information age This unique monograph identifies the key stages of advanced device design and integration in semiconductor manufacturing It brings into one resource a comprehensive device design using simulation The book presents state of the art semiconductor device design using the latest TCAD tools Professionals researchers academics and graduate students in electrical electronic engineering and microelectronics will benefit from this reference text *Semiconductor Device Modelling* Christopher M. Snowden,2012-12-06 Semiconductor device modelling has developed in recent years from being solely the domain of device physicists to span broader technological disciplines involved in device and electronic circuit design and develop ment The rapid emergence of very high speed high density integrated circuit technology and the drive towards high speed communications has meant that extremely small scale device structures are used in contempor ary designs The characterisation and analysis of these devices can no longer be satisfied by electrical measurements alone Traditional equivalent circuit models and closed form analytical models cannot always provide consis tently accurate results for all modes of operation of these very small devices Furthermore the highly competitive nature of the semiconductor industry has led to the need to minimise development costs and lead time associated with introducing new designs This has meant that there has been a greater demand for models capable of increasing our understanding of how these devices operate and capable of predicting accurate quantitative results The desire to move towards computer aided design and expert systems has reinforced the need for models capable of representing device operation under DC small signal large signal and high frequency operation It is also desirable to relate the physical structure of the device to the electrical performance This demand for better models has led to the introduction of improved equivalent circuit models and a upsurge in interest in using physical models *Statistical Modeling for Computer-Aided Design of MOS VLSI Circuits* Christopher Michael,Mohammed Ismail,2012-12-06 As MOS devices are scaled to meet increasingly demanding circuit specifications process variations have a greater effect on the reliability of circuit performance For this reason statistical techniques are required to design integrated circuits with maximum yield Statistical Modeling for Computer Aided Design of MOS VLSI Circuits describes a statistical circuit simulation and optimization environment for VLSI circuit designers The first step toward accomplishing statistical circuit design and optimization is the development of an accurate CAD tool capable of performing statistical simulation This tool must be based on a statistical model which comprehends the effect of device and circuit characteristics such as device size bias and circuit layout which are under the control of the circuit designer on the variability of circuit performance The distinctive feature of the CAD tool described in

this book is its ability to accurately model and simulate the effect in both intra and inter die process variability on analog digital circuits accounting for the effects of the aforementioned device and circuit characteristics Statistical Modeling for Computer Aided Design of MOS VLSI Circuits serves as an excellent reference for those working in the field and may be used as the text for an advanced course on the subject **Analysis and Simulation of Semiconductor Devices** S. Selberherr,2012-12-06 The invention of semiconductor devices is a fairly recent one considering classical time scales in human life The bipolar transistor was announced in 1947 and the MOS transistor in a practically usable manner was demonstrated in 1960 From these beginnings the semiconductor device field has grown rapidly The first integrated circuits which contained just a few devices became commercially available in the early 1960s Immediately thereafter an evolution has taken place so that today less than 25 years later the manufacture of integrated circuits with over 400 000 devices per single chip is possible Coincident with the growth in semiconductor device development the literature concerning semiconductor device and technology issues has literally exploded In the last decade about 50 000 papers have been published on these subjects The advent of so called Very Large Scale Integration VLSI has certainly revealed the need for a better understanding of basic device behavior The miniaturization of the single transistor which is the major prerequisite for VLSI nearly led to a breakdown of the classical models of semiconductor devices *Introducing Technology Computer-Aided Design (TCAD)* Chinmay K. Maiti,2017-03-16 This might be the first book that deals mostly with the 3D technology computer aided design TCAD simulations of major state of the art stress and strain engineered advanced semiconductor devices MOSFETs BJTs HBTs nonclassical MOS devices finFETs silicon germanium hetero FETs solar cells power devices and memory devices The book focuses on how to set up 3D TCAD simulation tools from mask layout to process and device simulation including design for manufacturing DFM and from device modeling to SPICE parameter extraction The book also offers an innovative and new approach to teaching the fundamentals of semiconductor process and device design using advanced TCAD simulations of various semiconductor structures The simulation examples chosen are from the most popular devices in use today and provide useful technology and device physics insights To extend the role of TCAD in today s advanced technology era process compact modeling and DFM issues have been included for design technology interface generation Unique in approach this book provides an integrated view of silicon technology and beyond with emphasis on TCAD simulations It is the first book to provide a web based online laboratory for semiconductor device characterization and SPICE parameter extraction It describes not only the manufacturing practice associated with the technologies used but also the underlying scientific basis for those technologies Written from an engineering standpoint this book provides the process design and simulation background needed to understand new and future technology development process modeling and design of nanoscale transistors The book also advances the understanding and knowledge of modern IC design via TCAD improves the quality in micro and nanoelectronics R D and supports the training of semiconductor specialists It is intended

as a textbook or reference for graduate students in the field of semiconductor fabrication and as a reference for engineers involved in VLSI technology development who have to solve device and process problems CAD specialists will also find this book useful since it discusses the organization of the simulation system in addition to presenting many case studies where the user applies TCAD tools in different situations **Computer Aided Design and Design Automation** Wai-Kai Chen,2018-03-12 This volume of The Circuits and Filters Handbook Third Edition focuses on computer aided design and design automation In the first part of the book international contributors address topics such as the modeling of circuit performances symbolic analysis methods numerical analysis methods design by optimization statistical design optimization and physical design automation In the second half of the text they turn their attention to RF CAD high performance simulation formal verification RTK behavioral synthesis system level design an Internet based micro electronic design automation framework performance modeling and embedded computing systems design **Optoelectronic Integrated Circuit Design and Device Modeling** Jianjun Gao,2011-09-19 In Optoelectronic Integrated Circuit Design and Device Modeling Professor Jianjun Gao introduces the fundamentals and modeling techniques of optoelectronic devices used in high speed optical transmission systems Gao covers electronic circuit elements such as FET HBT MOSFET as well as design techniques for advanced optical transmitter and receiver front end circuits The book includes an overview of optical communication systems and computer aided optoelectronic IC design before going over the basic concept of laser diodes This is followed by modeling and parameter extraction techniques of lasers and photodiodes Gao covers high speed electronic semiconductor devices optical transmitter design and optical receiver design in the final three chapters Addresses a gap within the rapidly growing area of transmitter and receiver modeling in OEICs Explains diode physics before device modeling helping readers understand their equivalent circuit models Provides comprehensive explanations for E O and O E conversions done with laser and photodiodes Covers an extensive range of devices for high speed applications Accessible for students new to microwaves Presentation slides available for instructor use This book is primarily aimed at practicing engineers researchers and post graduates in the areas of RF microwaves IC design photonics and lasers and solid state devices The book is also a strong supplement for senior undergraduates taking courses in RF and microwaves Lecture materials for instructors available at www wiley com go gao Compound Semiconductor Device Modelling Christopher M. Snowden,Robert E. Miles,2012-12-06 Compound semiconductor devices form the foundation of solid state microwave and optoelectronic technologies used in many modern communication systems In common with their low frequency counterparts these devices are often represented using equivalent circuit models but it is often necessary to resort to physical models in order to gain insight into the detailed operation of compound semiconductor devices Many of the earliest physical models were indeed developed to understand the unusual phenomena which occur at high frequencies Such was the case with the Gunn and IMPATI diodes which led to an increased interest in using numerical simulation methods Contemporary devices

often have feature sizes so small that they no longer operate within the familiar traditional framework and hot electron or even quantum mechanical models are required The need for accurate and efficient models suitable for computer aided design has increased with the demand for a wider range of integrated devices for operation at microwave millimetre and optical frequencies The apparent complexity of equivalent circuit and physics based models distinguishes high frequency devices from their low frequency counterparts Over the past twenty years a wide range of modelling techniques have emerged suitable for describing the operation of compound semiconductor devices This book brings together for the first time the most popular techniques in everyday use by engineers and scientists The book specifically addresses the requirements and techniques suitable for modelling GaAs InP ternary and quaternary semiconductor devices found in modern technology

Introduction to Semiconductor Device Modelling Christopher M. Snowden,1998 This book deals mainly with physical device models which are developed from the carrier transport physics and device geometry considerations The text concentrates on silicon and gallium arsenide devices and includes models of silicon bipolar junction transistors junction field effect transistors JFETs MESFETs silicon and GaAs MESFETs transferred electron devices pn junction diodes and Schottky varactor diodes The modelling techniques of more recent devices such as the heterojunction bipolar transistors HBT and the high electron mobility transistors are discussed This book contains details of models for both equilibrium and non equilibrium transport conditions The modelling Technique of Small scale devices is discussed and techniques applicable to submicron dimensioned devices are included A section on modern quantum transport analysis techniques is included Details of essential numerical schemes are given and a variety of device models are used to illustrate the application of these techniques in various fields **Technology Computer Aided Design** Chandan Kumar Sarkar,2018-09-03 Responding to recent developments and a growing VLSI circuit manufacturing market Technology Computer Aided Design Simulation for VLSI MOSFET examines advanced MOSFET processes and devices through TCAD numerical simulations The book provides a balanced summary of TCAD and MOSFET basic concepts equations physics and new technologies related to TCAD and MOSFET A firm grasp of these concepts allows for the design of better models thus streamlining the design process saving time and money This book places emphasis on the importance of modeling and simulations of VLSI MOS transistors and TCAD software Providing background concepts involved in the TCAD simulation of MOSFET devices it presents concepts in a simplified manner frequently using comparisons to everyday life experiences The book then explains concepts in depth with required mathematics and program code This book also details the classical semiconductor physics for understanding the principle of operations for VLSI MOS transistors illustrates recent developments in the area of MOSFET and other electronic devices and analyzes the evolution of the role of modeling and simulation of MOSFET It also provides exposure to the two most commercially popular TCAD simulation tools Silvaco and Sentaurus Emphasizes the need for TCAD simulation to be included within VLSI design flow for nano scale integrated circuits Introduces the advantages of TCAD simulations for device

and process technology characterization Presents the fundamental physics and mathematics incorporated in the TCAD tools Includes popular commercial TCAD simulation tools Silvaco and Sentaurus Provides characterization of performances of VLSI MOSFETs through TCAD tools Offers familiarization to compact modeling for VLSI circuit simulation R D cost and time for electronic product development is drastically reduced by taking advantage of TCAD tools making it indispensable for modern VLSI device technologies They provide a means to characterize the MOS transistors and improve the VLSI circuit simulation procedure The comprehensive information and systematic approach to design characterization fabrication and computation of VLSI MOS transistor through TCAD tools presented in this book provides a thorough foundation for the development of models that simplify the design verification process and make it cost effective *MOSFET Models for VLSI Circuit Simulation* Narain D. Arora,2012-12-06 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 **3D TCAD Simulation for Semiconductor Processes, Devices and Optoelectronics** Simon Li,Suihua Li,2011-10-01 Technology computer aided design or TCAD is critical to today s semiconductor technology and anybody working in this industry needs to know something about TCAD This book is about how to use computer software to manufacture and test virtually semiconductor devices in 3D It brings to life the topic of semiconductor device physics with a hands on tutorial approach that de emphasizes abstract physics and equations and emphasizes real practice and extensive illustrations Coverage includes a comprehensive library of devices representing the state of the art technology such as SuperJunction LDMOS GaN LED devices etc

Modeling And Parameter Extraction Techniques Of Silicon-based Radio Frequency Devices Ao Zhang,Jianjun Gao,2023-03-21 This comprehensive compendium describes the basic modeling techniques for silicon based semiconductor devices introduces the basic concepts of silicon based passive and active devices and provides its state of the art modeling

and equivalent circuit parameter extraction methods The unique reference text benefits practicing engineers technicians senior undergraduate and first year graduate students working in the areas of RF microwave and solid state device and integrated circuit design **Analogue Electronic Circuits and Systems** Amitava Basak,1991-11-29 This book is an undergraduate textbook for students of electrical and electronic engineering It is written with second year students particularly in mind and discusses analogue circuits used in various fields Technology CAD Systems Franz Fasching,Stefan Halama,Siegfried Selberherr,2012-12-06 As the cost of developing new semiconductor technology at ever higher bit gate densities continues to grow the value of using accurate TCAD simu lation tools for design and development becomes more and more of a necessity to compete in today s business The ability to tradeoff wafer starts in an advanced piloting facility for simulation analysis and optimization utilizing a virtual fab S W tool set is a clear economical asset for any semiconductor development company Consequently development of more sophisticated accurate physics based and easy to use device and process modeling tools will receive continuing attention over the coming years The cost of maintaining and paying for one s own internal modeling tool development effort however has caused many semiconductor development companies to consider replacing some or all of their internal tool development effort with the purchase of vendor modeling tools While some noteably larger companies have insisted on maintaining their own internal modeling tool development organization others have elected to depend totally on the tools offered by the TCAD vendors and have consequently reduced their mod eling staffs to a bare minimal support function Others are seeking to combine the best of their internally developed tool suite with robust proven tools provided by the vendors hoping to achieve a certain synergy as well as savings through this approach In the following sections we describe IBM s internally developed suite of TCAD modeling tools and show several applications of the use of these tools **VLSI and Hardware Implementations using Modern Machine Learning Methods** Sandeep Saini,Kusum Lata,G.R. Sinha,2021-12-30 Machine learning is a potential solution to resolve bottleneck issues in VLSI via optimizing tasks in the design process This book aims to provide the latest machine learning based methods algorithms architectures and frameworks designed for VLSI design The focus is on digital analog and mixed signal design techniques device modeling physical design hardware implementation testability reconfigurable design synthesis and verification and related areas Chapters include case studies as well as novel research ideas in the given field Overall the book provides practical implementations of VLSI design IC design and hardware realization using machine learning techniques Features Provides the details of state of the art machine learning methods used in VLSI design Discusses hardware implementation and device modeling pertaining to machine learning algorithms Explores machine learning for various VLSI architectures and reconfigurable computing Illustrates the latest techniques for device size and feature optimization Highlights the latest case studies and reviews of the methods used for hardware implementation This book is aimed at researchers professionals and graduate students in VLSI machine learning electrical and electronic engineering

computer engineering and hardware systems **Mixed Analog-digital VLSI Devices and Technology** Yannis Tsividis,2002 Improve your circuit design potential with this expert guide to the devices and technology used in mixed analog digital VLSI chips for such high volume applications as hard disk drives wireless telephones and consumer electronics The book provides you with a critical understanding of device models fabrication technology and layout as they apply to mixed analog digital circuits You will learn about the many device modeling requirements for analog work as well as the pitfalls in models used today for computer simulators such as Spice Also included is information on fabrication technologies developed specifically for mixed signal VLSI chips plus guidance on the layout of mixed analog digital chips for a high degree of analog device matching and minimum digital to analog interference This reference book features an intuitive introduction to MOSFET operation that will enable you to view with insight any MOSFET model besides thorough discussions on valuable large signal and small signal models Filled with practical information this first of its kind book will help you grasp the nuances of mixed signal VLSI device models and layout that are crucial to the design of high performance chips **Springer Handbook of Semiconductor Devices** Massimo Rudan,Rossella Brunetti,Susanna Reggiani,2022-11-10 This Springer Handbook comprehensively covers the topic of semiconductor devices embracing all aspects from theoretical background to fabrication modeling and applications Nearly 100 leading scientists from industry and academia were selected to write the handbook s chapters which were conceived for professionals and practitioners material scientists physicists and electrical engineers working at universities industrial R D and manufacturers Starting from the description of the relevant technological aspects and fabrication steps the handbook proceeds with a section fully devoted to the main conventional semiconductor devices like e g bipolar transistors and MOS capacitors and transistors used in the production of the standard integrated circuits and the corresponding physical models In the subsequent chapters the scaling issues of the semiconductor device technology are addressed followed by the description of novel concept based semiconductor devices The last section illustrates the numerical simulation methods ranging from the fabrication processes to the device performances Each chapter is self contained and refers to related topics treated in other chapters when necessary so that the reader interested in a specific subject can easily identify a personal reading path through the vast contents of the handbook

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Table of Contents Semiconductor Device Modeling For Computer Aided Design

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