



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

Zeheng Wang<sup>✉</sup>, Member, IEEE, Liang Li, Ross C. C. Leon, Jinlin Yang, Junjie Shi, Timothy van der Laan, and Muhammad Usman

**Abstract**—The semiconductor 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

**E**LECTRONIC design automation (EDA) has been crucial in advancing the semiconductor industry by simplifying

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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 formation 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.

# Semiconductor Device Modeling For Computer Aided Design

**Jianjun Gao**



## **Semiconductor Device Modeling For Computer Aided Design:**

*Semiconductor Device Modeling for Computer-aided Design* Gerald J. Herskowitz, 1972 *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

**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

**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 Modeling for Computer-aided Design](#) Gerald J. Herskowitz, Ronald B. Schilling, 1972

*Semiconductor Device Modeling with SPICE* Paolo Antognetti, 1988 *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 **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 *Acquisition of Computer Aided Design/Analysis Models for Semiconductors* GR. Case, 1973 Because of the role of the digital computer in the design and analysis of electronic systems it is becoming increasingly desirable to have suitable computer aided analysis models of semiconductor devices at the time these devices are available for experimental development This paper describes the development of such computer aided design analysis CAD A models The procedures described can be used to develop models based on statistically significant populations of devices The statistical procedures for selecting devices to be tested the testing procedures and the computer codes used for reducing data are described Examples of computer output and a complete CAD A model derived using the procedure are included for a sample device **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 development 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 contemporary 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 consistently 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.

**MOSFET Models for VLSI Circuit Simulation** Narain D. Arora, 2012-12-06 Metal Oxide Semiconductor MOS transistors are the basic building block of MOS integrated circuits. IC 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 ICs 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.

**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](http://www.wiley.com/go/gao)

Semiconductor Modeling: Roy Leventhal, Lynne Green, 2007-01-10 Semiconductor Modeling For Simulating Signal Power and Electromagnetic Integrity assists engineers both recent graduates and working product designers in designing high speed circuits The authors apply circuit theory circuit simulation tools and practical experience to help the engineer understand semiconductor modeling as applied to high speed digital designs The emphasis is on semiconductor modeling with PCB transmission line effects equipment enclosure effects and other modeling issues discussed as needed The text addresses many practical considerations including process variation model accuracy validation and verification signal integrity and design flow Readers will benefit from its survey of modeling for semiconductors packages and interconnects along with usable advice on how to get complex high speed prototypes to work on the first try Highlights include Presents a very complete and well balanced treatment of modeling of semiconductors packages and interconnects Facilitates reader comprehension of the whole field of high speed modeling including digital and RF circuits Combines practical modeling techniques with the latest EDA tools for simulation and successful high speed digital design Facilitates resolution of practical every day problems Presents modeling from its historical roots to current state of the art Facilitates keeping abreast of the latest modeling developments as they continue to unfold *Semiconductor Device Modeling with SPICE* Paolo Antognetti, Giuseppe Massobrio, 1988 *Introduction to Device Modeling and Circuit Simulation* Tor A. Fjeldly, Trond Ytterdal, Michael S. Shur, 1998 This book is a useful reference for practicing electrical engineers as well as a textbook for a junior senior or graduate level course in electrical engineering The authors combine two subjects device modeling and circuit simulation by providing a large number of well prepared examples of circuit simulations immediately following the description of many device models **Silicon And Beyond: Advanced Device Models And Circuit Simulators** Tor A Fjeldly, Michael S Shur, 2000-04-20 The steady downscaling of device feature size combined with a rapid increase in circuit complexity as well as the introduction of new device concepts based on non silicon material systems poses great challenges for device and circuit designers One of the major tasks is the development of new and improved device models needed for accurate device and circuit design Another task is the development of new circuit simulation tools to handle very large and complex circuits This book addresses both these issues with up to date reviews written by leading experts in the field The

first three chapters of the book discuss advanced device models both for existing technologies and for new emerging technologies. Among the topics covered are models for MOSFETs, thin film transistors, TFTs, and compound semiconductor devices including GaAs HEMTs and HFETs, heterodimensional devices, quantum tunneling devices, as well as wide bandgap devices. Chapters 4 and 5 discuss advanced circuit simulators that hold promise for handling circuits of much higher complexity than what is possible for typical state of the art circuit simulators today.

Analytical and Computer-aided Models for III-V Compound Semiconductor Devices An-Jui Shey, 1990 *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.

**Technology Computer Aided Design** Chandan Kumar Sarkar, 2017-11-22. 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

**Semiconductor Device Modelling** Roel Baets,John Barker,Joseph A Barnard,1989-05-01

The Enigmatic Realm of **Semiconductor Device Modeling For Computer Aided Design**: Unleashing the Language is Inner Magic

In a fast-paced digital era where connections and knowledge intertwine, the enigmatic realm of language reveals its inherent magic. Its capacity to stir emotions, ignite contemplation, and catalyze profound transformations is nothing short of extraordinary. Within the captivating pages of **Semiconductor Device Modeling For Computer Aided Design** a literary masterpiece penned by way of a renowned author, readers embark on a transformative journey, unlocking the secrets and untapped potential embedded within each word. In this evaluation, we shall explore the book's core themes, assess its distinct writing style, and delve into its lasting effect on the hearts and minds of those that partake in its reading experience.

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