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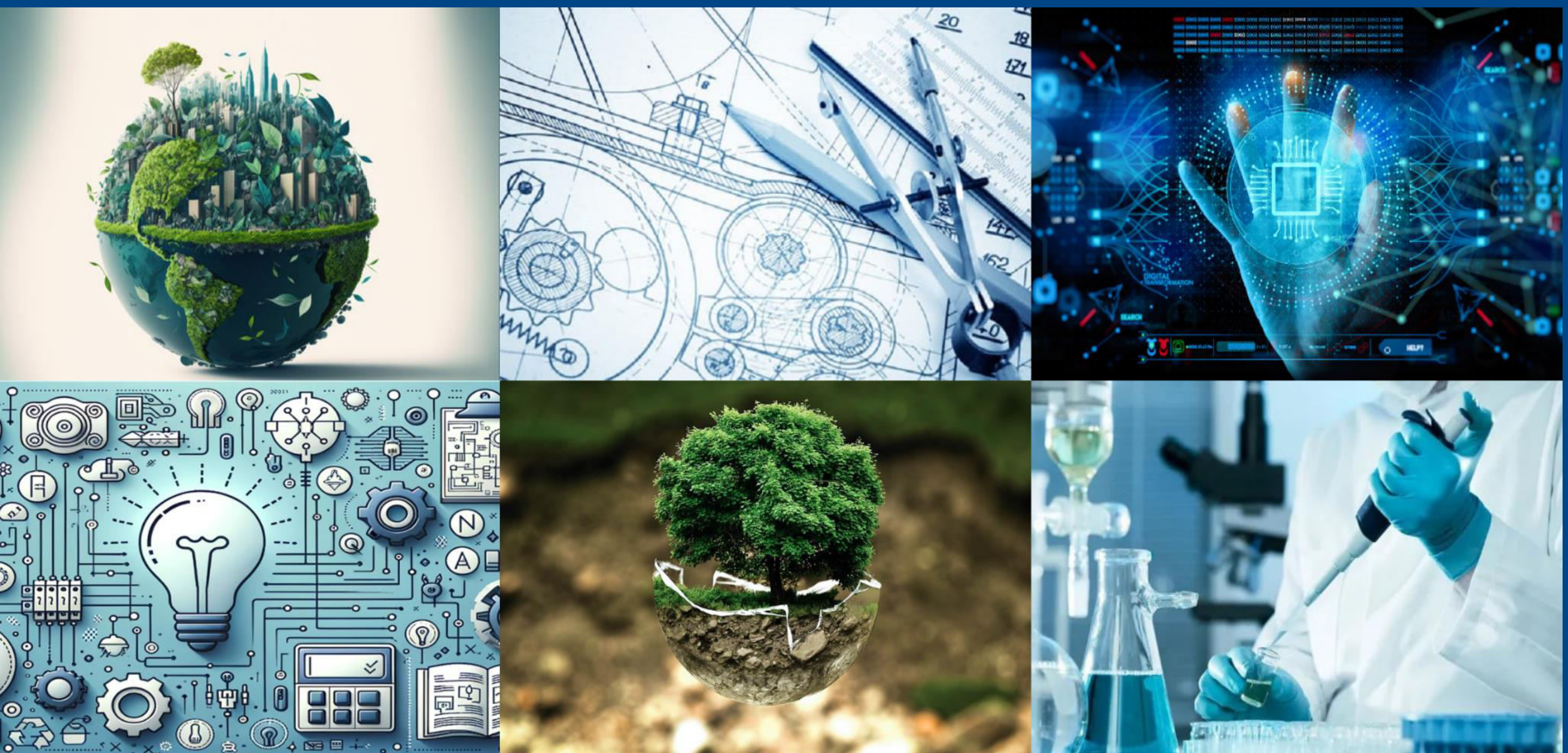

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Semiconductor Device Modeling: A Review

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ABSTRACT: Semiconductor device modeling is fundamental for predicting the behavior of diodes, BJTs, MOSFETs, and advanced semiconductor devices. Accurate models reduce design cost, minimize fabrication iterations, and improve circuit performance by enabling designers to evaluate device characteristics before manufacturing. This review summarizes classical and modern modeling approaches, including compact models, Technology Computer-Aided Design (TCAD), AI-assisted modeling, and their applications, advantages, and challenges. With the continuous scaling of semiconductor technology and the emergence of nanoscale devices, modeling techniques have become increasingly sophisticated to capture quantum effects, short-channel phenomena, and process variations. Advanced simulation tools enable researchers and engineers to optimize device performance, power consumption, and reliability while reducing development time and manufacturing costs. Furthermore, recent advancements in machine learning and physics-informed neural networks have introduced new opportunities for improving modeling accuracy and computational efficiency. This review highlights the evolution of semiconductor device modeling, discusses current research trends, and identifies future directions for the development of next-generation electronic and nanoelectronic devices.

KEYWORDS: Semiconductor devices, TCAD, MOSFET, compact model, SPICE, device simulation

I. INTRODUCTION

Semiconductor device modeling represents the mathematical description of electrical behavior of semiconductor devices. It enables designers to simulate device operation before fabrication. Modeling combines semiconductor physics, numerical methods and experimental parameter extraction. With shrinking technology nodes, accurate models are increasingly important for analog, digital, RF and power electronics. The rapid advancement of semiconductor technology has led to the development of highly integrated and miniaturized electronic devices, making accurate device modeling more critical than ever. As transistor dimensions continue to scale into the nanometer regime, conventional analytical models are often insufficient to describe complex physical phenomena such as short-channel effects, carrier mobility degradation, quantum confinement, and self-heating. Consequently, advanced modeling techniques, including physics-based models, compact models, numerical simulations using Technology Computer-Aided Design (TCAD), and data-driven approaches based on artificial intelligence, have emerged to improve prediction accuracy. These modeling techniques play a vital role in device optimization, circuit design, process development, and reliability analysis, thereby reducing development time, manufacturing costs, and the number of expensive fabrication cycles.

II. OBJECTIVES OF THE STUDY

The primary objective of this review is to provide a comprehensive overview of semiconductor device modeling by analyzing the research contributions made in this field over the years. The specific objectives are:

1. To review the evolution of semiconductor device modeling from classical analytical models to modern simulation techniques.
2. To study the various modeling approaches proposed by researchers, including physics-based models, compact models, numerical models, and TCAD-based simulations.
3. To examine recent advancements in semiconductor device modeling, including AI and machine learning-based techniques.
4. To compare the advantages, limitations, and applications of different semiconductor device modeling methods reported in the literature.

5. To identify current research trends, challenges, and future directions in semiconductor device modeling for advanced electronic and nanoelectronic devices.

III. REVIEW OF RELATED LITURATURE

Early work focused on Shockley diode equations and Ebers-Moll BJT models. Later BSIM models became the industry standard for MOSFET simulation. TCAD tools solved Poisson and carrier continuity equations numerically. Recent studies explore machine learning to accelerate parameter extraction and surrogate modeling while maintaining physical consistency.

3.1 Evolution of Semiconductor Device Modeling

Semiconductor device modeling has evolved significantly over the past several decades. The earliest mathematical model was proposed by **Shockley**, who developed the ideal diode equation describing the current-voltage relationship of a p-n junction diode. This model became the foundation for semiconductor device analysis and circuit simulation **[1]**. As transistor technology progressed, the **Ebers-Moll model** was introduced for bipolar junction transistors (BJTs), enabling accurate prediction of transistor behavior under different operating conditions **[2]**.With the introduction of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), researchers developed analytical models capable of describing threshold voltage, channel current, and carrier mobility. The work of **Tsividis** significantly contributed to MOS transistor modeling by incorporating physical parameters into mathematical equations suitable for integrated circuit design **[3]**.As semiconductor fabrication entered the deep-submicron and nanometer technology era, traditional analytical models became insufficient because of short-channel effects, mobility degradation, and quantum mechanical phenomena. Consequently, compact models such as the **Berkeley Short-channel IGFET Model (BSIM)** were developed and became industry standards for SPICE-based circuit simulation **[4]**.

3.2 Physics-Based and Numerical Modeling Approaches

Physics-based semiconductor models solve the fundamental semiconductor equations, including Poisson's equation, carrier continuity equations, and transport equations. These models provide highly accurate predictions of carrier concentration, electric field distribution, and current flow within semiconductor devices **[5]**.Numerical simulation tools based on Technology Computer-Aided Design (TCAD) have become indispensable in semiconductor research and industry. Commercial software such as **Synopsys Sentaurus** and **Silvaco ATLAS** numerically solve semiconductor equations using finite-element and finite-volume methods, allowing engineers to optimize device geometry before fabrication **[6], [7]**.TCAD simulations significantly reduce fabrication cost and development time by predicting electrical characteristics, process variations, and thermal behavior. However, these methods require considerable computational resources and detailed material parameters **[6]**.

3.3 Compact Modeling Techniques

Compact models simplify complex semiconductor physics into mathematical equations that can be efficiently used in circuit simulators such as SPICE. Among these, the **BSIM family of models** developed by the University of California, Berkeley, has become the most widely accepted compact model for CMOS technology **[4]**.According to **McAndrew and Coram**, compact modeling provides an excellent compromise between computational efficiency and modeling accuracy, making it suitable for analog, digital, RF, and mixed-signal integrated circuit design **[8]**.Modern compact models incorporate effects such as channel length modulation, velocity saturation, drain-induced barrier lowering (DIBL), gate leakage, and self-heating, enabling accurate simulation of advanced CMOS technologies below 10 nm **[4], [8]**.

3.4 Artificial Intelligence-Based Semiconductor Modeling

Recent research has focused on integrating Artificial Intelligence (AI) and Machine Learning (ML) techniques into semiconductor device modeling. Unlike traditional physics-based methods, ML algorithms learn device characteristics directly from simulation or experimental datasets **[9]**.Researchers have demonstrated that neural networks, Gaussian Process Regression (GPR), Support Vector Machines (SVM), and Physics-Informed Neural Networks (PINNs) can accurately predict semiconductor device characteristics while significantly reducing computational time compared with conventional TCAD simulations **[9], [10]**.AI-assisted modeling has shown promising applications in parameter extraction, process optimization, compact model generation, and reliability prediction. Nevertheless, these approaches depend heavily on high-quality training datasets and often lack complete physical interpretability **[10]**.

3.5 Comparative Analysis of Existing Modeling Techniques

Several researchers have compared analytical, compact, numerical, and AI-based semiconductor modeling techniques. Analytical models are computationally simple and useful for understanding device operation but exhibit limited accuracy for nanoscale devices **[3]**.Physics-based numerical models offer excellent accuracy by solving semiconductor transport equations but require high computational power and long simulation times **[6]**. Compact models provide fast simulation suitable for circuit design but require periodic parameter updates for emerging semiconductor technologies **[8]**.AI-based methods offer substantial improvements in computational speed and parameter optimization but require extensive datasets and careful model validation to ensure reliability **[9], [10]**.

3.6 Current Research Trends and Future Directions

Current semiconductor device modeling research focuses on emerging devices such as FinFETs, Gate-All-Around (GAA) transistors, Tunnel FETs (TFETs), Carbon Nanotube FETs (CNTFETs), and two-dimensional semiconductor materials such as graphene and MoS_2 **[11]**.

Researchers are increasingly combining physics-based equations with machine learning algorithms to create hybrid models that maintain physical accuracy while reducing computational complexity **[10]**. Future research is expected to emphasize quantum transport modeling, multi-physics simulations, reliability prediction, and AI-assisted compact model generation for next-generation nanoelectronic devices **[11], [12]**.

IV. RESULTS AND DISCUSSIONS

Physics-based models provide high accuracy but require intensive computation. Compact models are efficient for SPICE simulation and IC design. TCAD accurately predicts process variations and device characteristics but requires expertise. AI-based methods reduce modeling time but depend on high-quality datasets. Future work integrates physics-informed neural networks with TCAD for improved efficiency.

V. CONCLUSION

Semiconductor device modeling has undergone remarkable evolution from the early analytical models of diodes and bipolar junction transistors to today's sophisticated physics-based, compact, numerical, and artificial intelligence (AI)-assisted modeling techniques. This review highlights that each modeling approach plays a distinct and complementary role in semiconductor device design and development. Classical analytical models provide fundamental insights into device operation and are computationally efficient, whereas compact models have become indispensable for circuit-level simulation due to their balance between accuracy and computational speed. Physics-based numerical models and Technology Computer-Aided Design (TCAD) tools offer detailed analysis of semiconductor behavior, enabling accurate prediction of electrical, thermal, and reliability characteristics while significantly reducing fabrication cost and development time.

The review further demonstrates that continuous scaling of semiconductor devices into the deep-submicron and nanometer regimes has introduced complex physical phenomena, including short-channel effects, quantum confinement, mobility degradation, and process variability, which cannot be accurately represented using conventional analytical techniques alone. Consequently, advanced compact models and TCAD-based simulations have become essential for the design and optimization of modern semiconductor devices such as FinFETs, Gate-All-Around (GAA) FETs, Tunnel FETs (TFETs), and other emerging nanoelectronic technologies.

Recent advances in artificial intelligence and machine learning have opened new directions for semiconductor device modeling by enabling faster parameter extraction, surrogate modeling, process optimization, and reliability prediction. Hybrid approaches that combine physics-based principles with data-driven learning methods are emerging as promising solutions, offering improved computational efficiency while preserving physical accuracy. However, challenges remain in terms of model interpretability, availability of high-quality training datasets, scalability, and validation across different technology nodes and device architectures.

Overall, semiconductor device modeling continues to be a cornerstone of modern electronic system design, supporting device innovation, integrated circuit development, and manufacturing optimization. Future research is expected to

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focus on quantum-aware modeling, multi-physics simulations, AI-assisted compact model generation, and modeling of novel semiconductor materials and nanoscale devices. These advancements will play a critical role in accelerating the development of next-generation low-power, high-performance, and reliable electronic and nanoelectronic systems. Consequently, continuous improvements in modeling methodologies will remain essential for meeting the growing demands of advanced semiconductor technologies and future integrated circuit design.

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