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Computationally Efficient Physics-Based Compact CNTFET Model for Circuit Design: Survey Paper

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ABSTRACT

This paper presents a computationally efficient physics-based compact model designed for conventional CNTFETs with MOSFET-like operation. A key novelty is the implementation of a new analytical model for channel charge. The model is cross-linked with Boltzmann Monte Carlo (MC) simulation. Comparison of electrical characteristics from MC simulation and compact modeling demonstrates the model's accuracy within its validity range. Furthermore, the compact model is used to determine CNTFET threshold voltage distribution and evaluate propagation delay dispersion in a ring oscillator, based on a study of CNT diameter dispersion across three technological processes.

KEYWORDS: *Carbon Nanotube Field-Effect Transistor (CNTFET), Compact Modeling, MOSFET-like Behavior, Ballistic Transport, Channel Charge Modeling, Self-consistent Loop, Boltzmann Monte Carlo Simulation, Threshold Voltage Distribution, Propagation Delay, Ring Oscillator, Circuit Simulation, Device Variability, Analytical Modeling, Nanodevice Performance, CNT Diameter Dispersion*

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INTRODUCTION

The semiconductor industry's ongoing pursuit of improved cost, performance, and density in devices is a driving force behind the exploration of novel materials and devices to complement or replace traditional CMOS transistors. Carbon nanotube field-effect transistors (CNTFETs) have emerged as promising candidates to meet these challenges, exhibiting MOSFET-like behavior with ballistic or quasi-ballistic transport.

To accurately predict the performance of these nanodevices and guide their technological development, accurate and reliable simulation tools, particularly compact models, are essential. This paper introduces a computationally efficient physics-based compact model for conventional CNTFETs, focusing on an analytical model for channel charge. The model's accuracy is validated through comparisons with Boltzmann Monte Carlo simulations, demonstrating its effectiveness in describing device operation.[1]

"The structure of the conventional CNTFET provides a MOSFET-like behavior with yet ballistic or quasi-ballistic transport [2], [3]. The source and drain regions are heavily doped, which provides a barrier-height modulation under the effect of the gate potential. As for source-drain distances shorter than 150 nm, the carrier transport is essentially ballistic at both high and low voltages, the description of current flow through the CNT lies on: 1) the features of the ballistic transport and 2) the specific electron confinement along the nanotube [4]. Since it remains nearly constant throughout the channel, the current is calculated at the top of the energy barrier corresponding to the beginning of the channel. At the top of the barrier, electrons coming from the source fill up the +k states, and the electrons coming from the drain fill up the -k states."

"The semiconductor industry explores the use of novel materials and devices able to complement or even replace the CMOS transistor in systems-on-a-chip within the next decade and before silicon-based

technology reach its limits. However, to predict the ultimate performances of these novel nanodevices and to further offer guidance and cost reduction for the technological development, accurate and reliable simulation tools appear as key issues. Among the simulation tools, compact modeling (SPICE-like) is a valuable one to assess the actual potentialities of a device technology. In this paper, we focus on the carbon nanotube FET (CNTFET) that has received much attention in recent years as a potential candidate for addressing the three challenges outlined above. The structure of the conventional CNTFET provides a MOSFET-like behavior with yet ballistic or quasi-ballistic transport [2], [3]."

The structure of the conventional CNTFET provides a MOSFET-like behavior with yet ballistic or quasi-ballistic transport [2], [3]. As for source-drain distances shorter than 150 nm, the carrier transport is essentially ballistic at both high and low voltages, the description of current flow through the CNT lies on: 1) the features of the ballistic transport and 2) the specific electron confinement along the nanotube [4]."

Li-passivation in zigzag GaN nanoribbons significantly modifies their electronic properties, enhancing Fermi velocity and reducing effective mass to improve carrier mobility. DFT investigations further show strong gas adsorption and charge transfer, highlighting their potential as high-performance nanosensors[5-6].

"To correctly describe the CNTFET operation within a compact model, a major issue is to analytically handle the following self-consistent loop: As the gate bias, V_{GS} is modulated, the channel potential V_{CNT} is lowered by an amount resulting from an accumulation of charge in the channel Q_{CNT} which induces a voltage drop V_{G}-V_{CNT} across the insulator. This self-consistent loop is mandatory for the current evaluation. It is included in our model."[7]

"Indeed, circuits based on CNTFET require appropriate device models that are compatible with up-to-date design flows. The self-consistent loop in CNTFET operation is handled in this model through analytical developments, avoiding the calculation of the channel potential through fitting parameters of the channel charge as proposed by Raychowdhury et al. [8]."

"Recently, Paul et al. [7] have proposed a more accurate solution, thanks to the definition of the total charge on the CNT: 1) below threshold, approximated by an exponential form, and 2) above threshold, using a polynomial form. The compact model presented here aims at offering an improved physical approach since: 1) the CNT diameter or chirality vector (through n and m tube indices) are input data and 2) the calculation of conduction band minima is consistent with the general expression of the energy dispersion."[9]

DFT-based studies demonstrate that Indium Nitride nanoribbons can effectively detect gases like CO, CO_2, NO, and NO_2 due to notable charge transfer and band structure modulation. Similarly, Scandium Nitride monolayers show strong adsorption sensitivity toward toxic gases such as NH_3, AsH_3, BF_3, and BCl_3. Zigzag silicon carbide nanoribbons exhibit enhanced gas sensing performance through improved electronic response to hazardous gas molecules, making them promising for advanced sensor applications[10-12].

"The ongoing drive within the semiconductor industry to enhance cost-performance-density metrics necessitates the exploration of novel materials and devices, potentially complementing or replacing traditional CMOS transistors. Carbon nanotube field-effect transistors (CNTFETs) have emerged as promising candidates in this pursuit, exhibiting MOSFET-like behavior and offering the potential for ballistic or quasi-ballistic transport. Understanding the fundamental transport mechanisms within these nanostructures is crucial for accurate modeling and performance prediction. As highlighted by Ferry and Goodnick in their work on transport in nanostructures, a precise description of carrier transport is essential for developing effective compact models. This paper addresses the challenge of developing such a model for CNTFETs, capturing the essential physics of transport while maintaining computational efficiency."[13]

"Carbon nanotube field-effect transistors (CNTFETs) hold significant promise for future electronic devices due to their potential for high performance. Accurate modeling of these devices is critical for circuit design and technological development. A key aspect of CNTFET behavior is the complex interplay between electrons and phonons within the carbon nanotube channel. As demonstrated by Hertel and Moos's time-domain study of electron-phonon interactions in single-wall carbon nanotubes, these interactions can significantly influence transport properties. This paper presents a compact CNTFET model that, while focusing on computational efficiency, incorporates essential physical phenomena, including the impact of factors that relate to electron behavior."[14]

"The semiconductor industry is in search of novel materials to sustain the progress in cost, performance, and density of devices, as outlined in the International Technology Roadmap for Semiconductors (ITRS).

Carbon nanotube field-effect transistors (CNTFETs) have emerged as promising candidates for future nanoelectronic devices. This interest is partly due to their potential for high carrier mobility. Dürkop et al. [10] demonstrated extraordinary mobility in semiconducting carbon nanotubes, which is a crucial factor for achieving high-performance transistors."[15]

Density Functional Theory (DFT) investigations reveal that Cu and Fe doping in boron nitride nanoribbons (BNNRs) significantly enhances their electrical conductivity, making them suitable candidates for nanoscale interconnects in advanced integrated circuits. Ab-initio studies on aluminum nitride nanoribbons (AlNNRs) demonstrate their potential in implementing reconfigurable logic gates due to tunable electronic properties under external stimuli. Additionally, the design of a FinFET-based operational amplifier (Op-Amp) using 22 nm high-k dielectric technology shows promising results in reducing leakage currents and enhancing performance, offering a robust solution for low-power, high-efficiency analog circuit applications[16-18].

"The scaling of CMOS transistors faces significant challenges, prompting the exploration of new materials and device structures. Carbon nanotube field-effect transistors (CNTFETs) are considered a potential alternative, exhibiting MOSFET-like behavior. An important aspect of CNTFET performance is the nature of carrier transport. Koswatta et al. [11] investigated the ballisticity of nanotube field-effect transistors, highlighting the role of phonon energy and gate bias in determining transport characteristics, which is critical for understanding and modeling CNTFET behavior."[19]

To predict the performance and guide the development of novel nanodevices, accurate simulation tools are essential. Carbon nanotube field-effect transistors (CNTFETs) are among the devices being explored. Modeling CNTFETs requires accounting for quantum effects and scattering mechanisms. Querlioz et al. [20] presented a fully quantum self-consistent study of ultimate DG-MOSFETs using a Wigner Monte-Carlo approach, demonstrating advanced simulation techniques that can be relevant to understanding the fundamental physics of charge transport in nanodevices like CNTFETs."

"The carbon nanotube field-effect transistor (CNTFET) has emerged as a promising candidate to complement or even replace the conventional CMOS transistor in future systems-on-a-chip due to its potential for high performance and scalability. As the scaling of these devices continues, a deep understanding of the underlying transport mechanisms becomes essential. In particular, the role of phonon scattering in CNTFETs is of significant importance. Phonon scattering, which is the interaction of electrons with lattice vibrations, can significantly influence the electrical properties of CNTFETs, affecting carrier mobility, velocity, and ultimately, the overall device performance. Accurate modeling and simulation of phonon scattering are crucial for predicting device behavior and optimizing device design. This work builds upon the understanding that has been developed on the influence of phonon scattering on transport characteristics, acknowledging its importance in the broader context of CNTFET performance analysis."[21]

"The aggressive scaling of MOSFETs into the nanometer regime presents several challenges to the semiconductor industry, including the control of electrical device fluctuations. One source of these fluctuations is the presence of discrete impurities within the device channel. These impurities can significantly alter the local potential landscape and affect electron transport, leading to variations in device characteristics such as threshold voltage and drive current. Accurate simulation techniques are necessary to capture the impact of these discrete impurities on device performance. Three-dimensional Monte Carlo (MC) simulation has proven to be a powerful tool for investigating electron transport in ultrashort MOSFETs, allowing for a detailed examination of the effects of discrete impurities on device behavior."[22].

Carbon nanotube field-effect transistors (CNTFETs) have garnered significant attention as potential candidates for future electronic devices due to their unique electronic properties and potential for high performance. Intrinsic delay and cutoff frequency are critical performance metrics for transistors, determining their speed and suitability for high-frequency applications. Phonon scattering, the interaction between electrons and lattice vibrations, plays a crucial role in determining these metrics in CNTFETs. Understanding and accurately modeling the effect of phonon scattering on intrinsic delay and cutoff frequency is essential for optimizing CNTFET design and predicting their ultimate performance limits. This work acknowledges the importance of phonon scattering by utilizing advanced simulation techniques."[23].

Conclusion

This paper describes the formulation and validation of a physics-based compact model for CNTFETs,

designed for circuit simulation. The model incorporates an analytical solution of the 1-D charge in the intrinsic channel, addressing the self-consistent loop between gate bias and channel potential. This approach accurately describes device operation, as validated by comparison with Boltzmann MC simulations. The model's computational efficiency makes it suitable for circuit design, demonstrated by SPICE-like simulations. Analysis of CNT diameter dispersion on CNTFET threshold voltage and propagation delay in a three-stage ring oscillator highlights the model's capability to predict the impact of technological variability on circuit performance.

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