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A Review on Triple-Gate Graphene Nanoribbon Tunnel FETs and Performance Analysis of GNRFETs for Low-Power Electronics

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ABSTRACT

Graphene nanoribbons (GNRs), due to their tunable bandgaps, excellent carrier mobility, and compatibility with advanced device architectures, have emerged as strong candidates for next-generation nanoscale electronics. This review provides an in-depth analysis of triple-gate graphene nanoribbon tunnel field-effect transistors (TFETs) and GNR-based field-effect transistors (GNRFETs), focusing on their potential for ultra-low-power and high-frequency applications. The triple-gate GNR TFET demonstrates a subthreshold swing (SS) as low as 47 mV/dec at cryogenic temperatures, independent up to 40 K, with strong electrostatic control enabled by the gate configuration. Additionally, device performance is evaluated under various doping and dielectric conditions using the Non-Equilibrium Green's Function (NEGF) approach. The review also covers fabrication techniques, simulation models, material synthesis methods, and the impact of quantum confinement and edge roughness on device behavior. The advantages and limitations of both MOS- and Schottky-barrier-type GNRFETs are compared. This comprehensive survey highlights the challenges and opportunities in adopting GNRFETs and GNR TFETs in future energy-efficient and high-performance nanoelectronic systems.

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INTRODUCTION

In a triple top gate graphene tunnel field-effect transistor (TFET), we establish a temperature independent sub thresholds lope (SS) of about 47mV/duc at low temperature. The middle gate is utilized to switch the device between the ON and OFF states, while the outer gates define the p and n-doped areas of the about 9.4 nm wide grapheme nano ribbon. The device characteristics are examined in several configurations, notably field-effect transistor (FET) mode and TFET mode, because of the versatility of electrostatic doping. At 5 K, the TFET mode achieves a saturation current density of around 8.51 µA/µm and a minimum SS of approximately 47 mV/dec. Up to 40 K, this low SS is shown to be independent; beyond that, an exponential growth with a slope of 8.4 V/decat300 K is observed[1].

In this work, we examine how the gate insulator dielectric constant and contact doping concentration affect the device performance of graphene nanoribbon field effect transistors (GNRFETs). The simulations are based on a two-dimensional Poisson equation in the ballistic domain in conjunction with the Non-Equilibrium Green's function (NEGF) approach. We assume a mode space representation of a tight-binding Hamiltonian. When appropriate symmetric source and drain doping concentrations are applied, it is found that the GNRFET with low doping concentration has a greater ratio of On-current to Off-current (Ion/Ioff), a smaller Sub threshold Swing, a higher trans conductance, and a lower Off-current (Ioff).Furthermore, compared to low doping GNRFETs, the high doping concentration GNRFET has a lower gate capacitance, a greater intrinsic cut-off frequency, and a smaller quantum capacitance[2-4].

The upward trend of Moore's law has extended to the future, when carbon-based technologies have the potential to displace complementary metal-oxide semiconductor technology based on silicon. Quantum-dot cellular automata, graphene nanoribbon field-effect transistors (GNRFETs), carbon nanotube field-effect transistors, and nanowire transistors are some of these substitutes. The development of graphene, its production method, and graphene-based field-effect transistor device architectures are reviewed in this work. Graphene's structural, electrical, and thermal characteristics provide it a wide range of characteristics. This article provides a brief overview of the methods used to fabricate GNRFETs[5-8].

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[9-10].

Recently, there has been a lot of interest in graphene nanoribbons (GNRs), particularly polymer composites, because of their unique properties and potential applications in a variety of industries. This paper provides a summary of GNR synthesis methods and properties in polymer composites. In order to adjust the size of GNRs and obtain the proper attributes, their synthesis is essential. The two main approaches that have been used to create GNRs are top-down and bottom-up. Each approach has advantages and disadvantages with regard to cost-effectiveness, scalability, and dimension control. To shed light on the current state of the art, the advantages and disadvantages of the different synthesis techniques are examined[11-14]

According to our findings, ideal-edge GNRFETs perform better than Si-CMOS technology in terms of power and delay at scaled supply voltages. The performance of GNRFET circuits is severely hampered by edge roughness, though, to the point where its 320-fold smaller energy-delay product at VDD = 0.4V rises to 10% and 40% of Si-CMOS for roughness amplitudes of 0.04 and 0.1, respectively GNR [15-18].

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[19-21].

The gate, source, drain, and substrate electrodes of each independent ribbon can be shared, together with two parasitic capacitances (CGD and CGS) for fringing fields between the gate and the reservoirs, to create a multi-channel graphene nanoribbon GNRFET [22-23].

Due to the quantum confinement effect and edge effect, the width, boundary configuration, and heteroatom doping of quasi-one-dimensional graphene nano ribbons (GNRs) are all strongly correlated with their electrical structure [24-25].

A new device that has drawn a lot of interest recently is the graphene nano-ribbon field effect transistor (GNRFET). According to recent research on GNRFET circuit simulations, GNRFETs might be useful in low power applications. This study reviews the literature on GNRFET circuit modeling, compares the two types of GNRFETs—Scotty-Barrier (SB-)type and Metal-Oxide Semiconducting (MOS-)type GNRFETs—and thoroughly examines and discusses each type's advantages in terms of noise margin, power, and delay [26-27].

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[28-30].

Particularly with the advent of performance-demanding and energy-intensive Artificial Intelligence (AI) systems, transistors—the essential building blocks of logic and memory technologies—must constantly advance to attain and maintain high performance while functioning within acceptable energy budgets. After more than 50 years of use, silicon transistors are increasingly finding it difficult to fulfill these expanding demands, requiring new materials that can overcome silicon's drawbacks[31].

According to Moore's law, electronic circuits continue to get smaller. On the other hand, lateral dimensions of photonic waveguides and circuit elements remain on the wavelength order. A significant size reduction is essential to achieving a microelectronics-like breakthrough in photonics. We require a low-loss nanoscale waveguide with an extremely high effective refractive index and a significantly smaller mode area in order to do this. Here, we suggest a number of graphene nano-ribbon-based low-loss waveguide topologies for this purpose[32].

It was explained by the existence of V and Hove singularities in the one-dimensional _1D_electrodes' density of states. According to Farajian, NDR can also arise in metallic carbon nanotube junctions when incoming and outgoing modes with distinct rotation symmetries are mismatched [33].

A method for simulating the small-signal and steady-state behavior of graphene nanoribbon metal-semiconductor-oxide field-effect transistors (GNR MOSFETs) is introduced. A commercial device simulator is used to incorporate GNR material properties and a technique to take into consideration the density of states of one-dimensional systems such as GNRs. The current-voltage characteristics, cutoff frequency f T, and maximum oscillation frequency f max of GNR MOSFETs are all determined using this modified tool. As an example, we look at two transistor layouts and 50- nm gate GNR MOSFETs with N = 7 armchair GNR channels. As other organizations typically study, the initial configuration is a simpler MOSFET structure with a single GNR channel[34].

A family of one-dimensional (1D) materials with a graphitic lattice structure is known as graphene nano ribbons (GNRs). GNRs are interesting candidates for quantum electronic applications because of their large band gap, high mobility and current-carrying capacity, and adaptable electrical characteristics. The successful creation of semiconducting GNR arrays on insulating substrates that may be helpful for large-scale digital circuits, as well as the atomically precise bottom-up synthesis of GNRs and hetero junctions that offer the perfect platform for functional molecular devices, have both advanced during the last five years [35]. Bottom-up methods for creating graphene nanoribbons provide atomic-level structure and exact control over their physical characteristics. Sponsor photons are necessary for the manipulation of single charges in quantum technology applications. However, because it is difficult to touch individual nanoribbons, especially on-surface produced ones, it is experimentally impossible to achieve this at the level of single graphene nanoribbons[36].

Conclusion:

Graphene nanoribbon-based transistors present a compelling solution to the limitations of traditional silicon CMOS technology, particularly in the face of growing energy demands and device scaling challenges. The triple-gate GNR TFET stands out for its steep subthreshold swing and strong electrostatic control, making it highly suitable for ultra-low-power switching applications. GNRFETs further offer significant performance enhancements in terms of on/off current ratio, transconductance, and cutoff frequency, particularly when optimized for doping concentration and dielectric properties. However, challenges such as fabrication scalability, edge roughness, and reliable contact formation still hinder widespread adoption. Continued progress in bottom-up synthesis, quantum transport modeling, and device architecture innovation will be critical to unlocking the full potential of GNR-based devices in post-CMOS and AI-era computing technologies.

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