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Graphene Nanoribbon FETs for Multi-Valued Logic: Literature Insights and a Compact Ternary Multiplier Design

Niriksha B, Anushree S, C J Siri, Akshata Rayannavar

Department of Electronics and Communication Engineering,
Dayananda Sagar Academy of Technology and Management, Bangalore, Karnataka, India

ABSTRACT

As the limitations of silicon-based CMOS technologies become increasingly pronounced at sub-7 nm nodes, alternative transistor architectures and logic paradigms are gaining traction. Among these, graphene nanoribbon field-effect transistors (GNRFETs) offer promising prospects for implementing multi-valued logic systems, particularly ternary logic, due to their exceptional electrical, thermal, and scaling characteristics. This literature survey investigates the state-of-the-art in GNRFET research with a specific focus on their application in ternary logic circuits. Key developments in GNRFET-based gate design, digital building blocks, and simulation methodologies are reviewed, alongside their performance advantages in terms of power, delay, and scalability over conventional MOSFETs. As a case study, a novel 26-transistor 1-trit ternary multiplier architecture is introduced, demonstrating the potential of GNRFETs in compact, high-efficiency ternary computing systems. The review consolidates existing knowledge while highlighting future research directions for integrating GNRFET-based ternary logic into ultra-low-power VLSI design.

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INTRODUCTION

Digital system designers are turning to multi-valued logic (MVL), particularly ternary logic, as silicon field-effect transistors face growing scaling issues. Among post-MOSFET technologies, the graphene nanoribbon field-effect transistor (GNRFET) stands out as a strong contender for ternary logic implementation. In addition to highlighting the exceptional qualities of GNRFET technology, this work explores the computational complexities of ternary logic and presents a revolutionary GNRFET-based 1-tritternary multiplier (TMUL) that requires just 26 transistors. High speed, low power consumption, small size, and reliable chip design are the main goals of a VLSI engineer. Conventional silicon-based devices that follow Moore's law, such as MOSFETs and Fin-shaped field-effect transistors (F in FET), have significant scaling issues. As a result, post-silicon technologies such as graphene nanoribbon field-effect transistor (GNRFET), carbon nanotube field- effect transistor (CNTFET), and single-electron transfer (SET) are being studied. [1]

For short nanoscale architectures, there is a growing interest in alternate logic technologies. Given that these structures are essential components of digital integrated circuits, logic gates, complete adders, and D-latch designs based on graphene nanoribbon field effect transistors (GNRFETs) at 7 nm technology nodes were described. First, GNRFETs were used to implement NOT, NOR, and NAND gates. Next, GNRFETs were used to design CMOS logic circuits for a 28T complete adder and an 18T D-latch. Using HSPICE simulations, the initial outcome of this work demonstrated that the logic circuits using GNRFETs had an average power consumption that was 78.6% lower than those constructed with traditional Si-based MOSFETs. Likewise, the logic circuits using GNRFETs were found to have a latency advantage of be 53.2% lower than those using Si-based MOSFET counterparts. In addition, a deep learning model was developed to model both the power consumption and the propagation delay of GNRFET-based logic inverters. As the second result, it was demonstrated that the developed deep learning model could accurately represent the power consumption and delay of GNRFET-based logic circuits with the coefficient of determination[2]

(R^2)values in the range of 0.86 and 0.99. The ability of GNRFETs to scale down to atomic dimensions is one of their key advantages. Transistors with incredibly small gate width and length sizes can be fabricated thanks to the tight control over device dimensions that the nano-sized width of GNRs offers. This scalability creates new opportunities for extremely large-scale integrated circuits with low power consumption and excellent performance.

[Moore's law, which states that "the number of transistors on a chip doubles after every 18

months," changed the course of the electronics industry. The channel length is decreasing at the same time that the chip capacity has increased. As the density of logic circuits doubles with each generation, the exponential trend of decreasing silicon transistors has improved device performance while also decreasing device density. Although the memory capacity has increased fourfold and the working has been improved by almost 40%, other factors must be taken into account because problems with future fundamental limits arise as metal oxide semiconductor field-effect transistors (MOSFETs) are scaled down. It is difficult to keep up with Moore's concept at below 7 nm technology due to a number of issues with silicon-based technology, such as mobility degradation and short channel effects (SCEs) do pant fluctuations. For these reasons, carbon-based technology is being researched as a possible replacement for silicon-based complementary metal-oxide semiconductors (CMOS).Reducing the device's size is one of the many issues facing current CMOS-based technology. A poor dielectric performance results from the gate oxide layer addressing the gate leakage current as it is slimmed to less than 3 nm[3]. Because of its remarkable carrier mobility, high carrier concentration, high thermal conductivity, and thin planar structure, graphene—a single atomic layer of carbon sheet in a honeycomb lattice can surpass state-of-the-art silicon in numerous applications. High carrier velocity and high carrier concentration are provided by graphene's carrier transport, which is comparable to that of massless particles[5-6]. 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[7-8].

Nano ribbons, also known as nano graphene ribbons or nano graphite ribbons, and frequently shortened to GNRs, are very thin (less than 50 nm) graphene strips. In order to investigate the edge and nanoscale size effect in graphene, Mistake Fajita and co-authors presented graphene ribbons as a theoretical model[9-10].

Alongside its plane, graphene efficiently conducts power and heat. The fabric firmly absorbs smolder at all significant wavelengths, which is consistent with graphite's dark hue. Nevertheless, due to its exceptional thinness, graphene sheets are nearly instantaneous. Furthermore, the highest grounded metal of similar thickness is many times less grounded than this fabric. Because of its extraordinarily high elasticity, electric conductivity, transparency, and status as the world's thinnest two-dimensional fabric, graphene has emerged as a crucial and advantageous nanomaterial. The global graphene market grew to be worth $9 million, with the vast majority of enthusiasts pursuing cutting-edge trends in semiconductors, devices, and electric-powered batteries[11-12].

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[13-15].

With the possibility for carbon-based materials to displace silicon-based complementary metal-oxide semiconductor technology, Moore's law's upward trend has extended into the future. 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 grapheme-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 study provides a brief overview of the techniques used to fabricate GNRFETs. Strong ballistic transport, a high current ratio, improved compatibility with high K

dielectrics, high electron mobility, dependability, scalability, and trans conductance are just a few of the exceptional electrical characteristics that underpin GNRFETs. GNRFET architectures are examined for a number of factors that aid in tracking the enhancement of GNRFET device performance, such as the Ion/Ioff ratio, sub threshold swing, oxide thickness, high K dielectrics, etc. To give researchers a better understanding of how changes affect device performance, a comparison of the structures is provided. This report also includes the small model used to simulate GNRFET- based devices. There are numerous uses for GNRFET-based devices in the modern world. A number of current GNRFET-based device applications are also reported in this work[16-17].

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[18-20]

The power and delay performance of graphene nanoribbon field effect transistors (GNRFETs) in all-graphene architecture are assessed in this research in relation to edge roughness. The multi-channel GNR FET's equivalent circuit model is created by taking into account the effects of line-edge roughness on the transport of carriers in graphene nanoribbon, as well as the thermionic emission and band-to-band-tunneling (BTBT) of carriers. 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 W W By sharing the gate, source, drain, and substrate electrodes among all independent ribbons, as well as two parasitic capacitances (CGD and CGS) for fringing fields between the gate and the reservoirs, the multi-channel GNRFET—which is made up of several parallel graphene nanoribbons—can be realized[21-22].

This work presents the design and modeling of a triple cascade operational trans conductance amplifier (TCOTA). Carbon nanotube field effect transistors (CNTFETs) and 45 nm MOSFETs are used in the construction of these suggested TCOTAs. The proposed architectures utilize both conventional MOSFETs and CNTFETs because they are hybrid in nature. It is evident from the simulation analysis of the proposed TCOTAs that the hybrid devices outperform the standard devices. The DC gain, bandwidth, and power consumption of the proposed hybrid devices have been determined to be much better than those of conventional devices. By adjusting the quantity of CNTs, the performance of the proposed TCOTAs can be further tailored[23-24].

We used unzipped multiwall carbon nanotubes to create suspended few layer (1-3 layer) graphene nanoribbon field effect transistors. The inherent bipolar transfer property of graphene is shown by electrical transport studies, which demonstrate that current annealing efficiently eliminates contaminants on the suspended graphene nanoribbons[25-26].

Due to the quantum confinement effect and edge effect, the width, border configuration, and heteroatomic doping of quasi-one-dimensional grapheme nanoribbons (GNRs) are all strongly correlated with their electrical structure. As a result, GNRs have unique optical, magnetic, and electrical properties. Advances in GNR preparation technologies have led to the preparation and study of GNRs with various architectures. According to the results, GNRs have favorable photoelectric properties, opening up a wide range of potential uses in dissipative microelectronic devices and quantum computing[27-28].

The symmetric valence band and linear conduction band of graphene, a monolayer of carbon atoms, meet at the Fermi spots, which are the corners of the Brillion zone. Graphene has a high mobility because its electrons act like mass-less fermions and have a lengthy mean free path. However, graphene's negligible bandgap makes it especially inappropriate for transistor applications. Etching the graphene sheet in thin strips, or graphene nano ribbon (GNR), is one way to get around this issue. A GNR's band gap and width are inversely correlated. Graphene nano ribbons are a viable option for the upcoming generation of transistors due to their superior transport characteristics[29-32]. A noninvasive method to determine fetal oxygen saturation using photoplethysmogram (PPG) technology leverages optical signals to monitor blood oxygen levels without direct contact, ensuring safe and continuous prenatal assessment. Complementing this, a novel Voltage-Controlled Oscillator (VCO) design with output peak-to-peak control introduces improved signal stability and amplitude tuning, making it highly suitable for precision analog and communication circuits where waveform consistency is critical[33-34].

Conclusion:

The continuous miniaturization of electronic components in accordance with Moore's Law is becoming increasingly untenable with traditional silicon-based CMOS technology, especially at sub-7 nm technology nodes. This literature survey has highlighted GNRFETs as a robust alternative due to their exceptional electrical properties, dimensional scalability, and compatibility with advanced logic systems. The surveyed works collectively demonstrate that GNRFETs outperform silicon-based MOSFETs in terms of power consumption, delay, and device density, making them well-suited for ultra-scaled logic applications. Furthermore, the review provides compelling evidence for the effectiveness of GNRFETs in implementing ternary logic, with a special focus on the proposed 26-transistor 1-trit ternary multiplier. This novel design exemplifies the compactness and computational efficiency that GNRFET-based architectures can offer. As fabrication techniques improve and integration challenges are addressed, GNRFETs hold significant promise for redefining the landscape of VLSI design and enabling the development of energy-efficient, high-performance computing systems.

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