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Graphene for Computing: Devices to Architectures

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ABSTRACT Graphene has long been considered a revolutionary material for the field of electronics due to its remarkable set of electronic properties, standing as a very promising candidate for the post-silicon era. However, it is not just a silicon replacement, but rather an enabling material for different computing paradigms. In this work, we investigate the use of graphene in devices and circuits that are employed for the realisation of computing architectures and systems. More specifically, we focus on impactful key applications such as conventional computing and Boolean logic, high-radix computing and multi-valued logic, memristive devices and in-memory-computing, neuromorphic applications, quantum computing and photonics. Additionally, taking into consideration the state-of-the-art as well as the existing graphene-related challenges that are still present, this work attempts to assess the possible future development of graphene-based devices, circuits and systems in each of the aforementioned fields and to propose a coarse yet directive roadmap for the material's future in computing architectures.

INDEX TERMS Graphene, graphene nanoribbons, field-effect transistors, memristors, photonics, neuromorphic computing, quantum computing.

I. INTRODUCTION

Research on alternative materials for electronic device manufacturing has been ongoing since the early years of transistors. Various categories of semiconductor materials have undergone thorough examination, resulting in the successful incorporation of several of them into transistors and switching devices in general, significantly enhancing the performance of both conventional and emerging computing paradigms. The intensity of this study has increased significantly in recent times, as the challenges associated with silicon have become more severe [1]. As a result, the transition to a post-silicon era is increasingly viewed as inevitable step in the evolution of electronics [2].

Advances in material science and fabrication machinery have generated considerable interest in novel materials. Among others, carbon, in its numerous allotropic forms, is widely regarded as an auspicious material to lead the future of computing electronics, as it entails a unique set of compelling electrical, thermal and mechanical properties, promising to fulfill roles beyond what silicon can achieve [3], [4].

One of the aforementioned allotropes of carbon is graphene, which began to captivate both academia and industry in the early 2000s, when it was isolated for the first time. It was the first ever stable two-dimensional (2D) material to be fabricated. It practically created the field of 2D materials, which attracted significant interest, mainly due to graphene's extraordinary properties. Specifically, its outstanding electronic, thermal, and optical properties made it an ideal candidate for early exploration in electronic applications. Although other 2D materials with interesting properties have since emerged, graphene remains central to 2D materials research, among others for its broad applicability, relative ease of fabrication and compatibility and promising integration with other materials [5], [6].

Graphene is a term used to describe a layer of carbon atoms that covers a wide area and is only one atom thick. Alongside graphene, other derivatives, such as graphene oxide (GO), reduced graphene oxide (rGO), and graphene quantum dots (GQDs), each offer unique properties that expand graphene's range of applications. However, as the dimensions of the material scale down to a few nanometers, its properties change notably [7]. Originally, large area graphene proved to be a zero-bandgap material, meaning that it exhibited a metallic behavior and could not in any way stop the flow of electrons through it. This feature posed a significant obstacle to the incorporation of the material in switching devices. Graphene Nanoribbons (GNRs) on the other hand, whose operation is governed by quantum phenomena, allow for bandgap modulation. A variety of approaches to tune this bandgap have been proposed, including external electric or magnetic fields, stacking and twisting graphene layers, and modulating its shape [8], [9], [10], [11], [12]. While each approach has its advantages and disadvantages, ongoing research is focused on identifying optimal methods to achieve controllable conductivity in graphene-based devices.

A wide variety of graphene derivatives, especially those with reduced dimensions, have been explored for potential use in switches and electronic devices. Single-layer graphene sheets of relatively small dimensions for the development of Graphene Field Effect Transistors (GFETs) and comparable devices have already been presented both in theoretical and experimental forms [13], [14]. These early devices showcased impressive capabilities, including operation within the GHz range, indicating their suitability for high-speed electronic systems and computing circuits. While graphene's electronic and thermal properties hold potential for integration into conventional Complementary Metal-Oxide-Semiconductor (CMOS) systems, its other attributes, especially in small-scale derivatives, can drive the advancement of future electronics by expanding the scope of applications into novel scientific domains. The optical and mechanical properties of graphene, for example, are particularly valuable for creating enhanced electronic devices designed for specialized applications. The transparency of graphene, absorbing only 2.3% of light in the visible spectrum, makes it ideal for light-sensing and transparent electronic devices [15], [16]. Additionally, graphene's high Young's modulus offers strong potential for flexible electronics and applications on adaptable substrates, fabrics, and other specialty materials [17] and its biocompatibility enables promising applications in biosensing and tissue engineering [18], [19], [20].

Given graphene's extensive range of advantageous properties, the material is under active investigation for its potential role in computing circuits, not only within traditional architectures but also in emerging, unconventional paradigms. This exploration seeks to identify the domains where graphene can offer the greatest performance benefits and uncover unique applications that leverage its distinctive characteristics. Accordingly, this review will examine the applications of graphene within various computing architectures to assess its promises and advancements across diverse types of computing applications. Specifically, we will investigate graphene's integration in Boolean logic and conventional computing in Section II, high-radix computing in Section III, memristive devices and their applications in Section IV, neuromorphic systems featuring neurons and synapses in Section V, quantum computing in Section VI, and finally optical computing, including photonic applications in Section VII. Through this examination, we aim to provide a comprehensive overview of the latest trends of computing with graphene and explore graphene's suitability and potential in driving forward the future of computing.

II. BOOLEAN LOGIC - CONVENTIONAL COMPUTING

Building upon the promising results of Carbon Nanotube Field-Effect Transistors (CNTFETs) and their successful integration into computing circuits that contain thousands of transistors, and also targeting to further harness the intriguing and very promising electronic properties of graphene, researchers investigate the possibility of its incorporation into transistors, the basic building block of today's computing circuits and architectures.

Graphene Field Effect Transistors (GFETs) are switching devices that use graphene instead of silicon as a conductive material due to its very appealing properties. Already several GFET structures have been proposed, operating mainly based on 4 different mechanisms. First are the polarity-programmable ambipolar GFETs that realize complementary-like gates by biasing or light doping a single graphene layer, enabling the design of inverters and Boolean logic gates with high intrinsic speed. The bandgap-engineered devices in the form of either Graphene Nanoribbon Field-Effect Transistors (GNRFETs) or dual-gated bilayer GFETs that further improve ON/OFF ratio and noise margins, allowing for more robust logic levels. The barrier-height based devices such as the Schottky-Barrier GNRFETs (SB-GNRFETs) that use gate-controlled Schottky barriers to obtain large ON/OFF, and finally the tunneling and vertical heterostructure FETs that leverage interlayer tunneling in graphene/2D stacks to reduce switching energy and offer CMOS compatibility in terms of integration. Each one of those GFET types offers different performance in terms of speed, ON/OFF ratio and variability, all crucial for robust logic circuit design [14], [25], [26], [27], [28].

Early studies realized complementary graphene inverters directly on monolayer graphene and later on wafer-scale

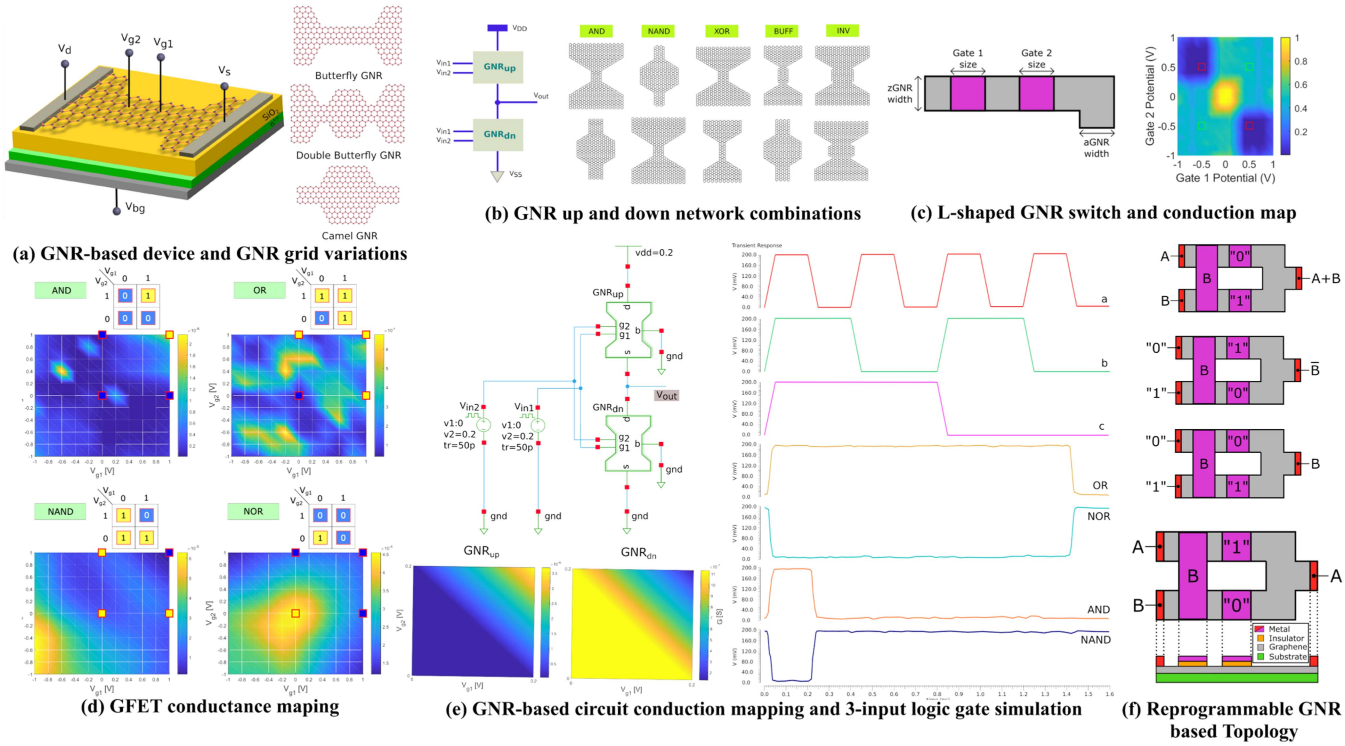


FIGURE 1. Uses of graphene-based devices for Boolean logic. Subfigures illustrate (a) The GNR-based basic building block of conduction mapping Boolean gates, and the different types of GNR grids that are used [21], [22], (b) The different GNR grid combination in terms of up and down network of complementary gates, (c) L-shaped gnr switch and the changes of its conductance based on the applied top gates [23], (d) Conduction maps for basic two input logic operations, (e) Complementary gates simulation setup, up and down network complementary conduction maps and simulation results, and (f) Reprogrammable GNR-based topology based on L-shaped switches and its different operation modes through input and top gate changes [24].

Chemical Vapour Deposition (CVD) graphene, achieving cascadable operation under ambient conditions [29]. Multi-stage ring oscillators fabricated from such inverters validated dynamic digital functionality up to the GHz range [30]. Ambipolar GFETs were also configured via electrostatic polarity control to implement complementary-like NAND/NOR, while chemical p/n doping enabled flexible, transparent complementary logic (NOT/NAND/NOR) with ion-gel gating [31], [32]. To improve ON/OFF ratios for digital switching, dual-gated bilayer graphene devices opened an electric-field-induced bandgap and supported semiconducting Bilayer Graphene (BLG) inverters [33]. Finally, graphene "barristors", that is, gate-tunable Schottky triodes in which the gate controls the graphene/semiconductor Schottky barrier height, have demonstrated ON/OFF ratios on the order of 10^5. Using these devices, basic digital building blocks such as inverters and half-adders have been realized [34].

Recently, another approach on the realization of Boolean logic circuits with graphene, and more specifically Graphene Nanoribbons has been proposed [26]. Graphene Nanoribbons reportedly encompass the capability to change their electronic properties with the changes of the shape and structure of their grid [35]. This capability allows the tailoring of the conductance of a GNR, which can be further modulated with the help of external bias application. Thus, a GFET device incorporating such GNR grids, as seen in Fig. 1(a), is able to map a logic operation [11], [36]. An example of conduction mapping of GFETs that use grids of different dimensions and under the influence of external bias is presented in Fig. 1(d). A set of those devices interconnected together, in combinations of up and down networks as in Fig. 1(b) are able to successfully implement logic gates (Fig. 1(e)) in a complementary form, the basic cell of logic circuits [37]. Those types of complementary GFET circuits, provide a very promising alternative to conventional CMOS, as they effectively exploit the special properties of the material, providing power efficiency, increased operation speed, increased integration density and overall comparable or even better performance compared to the state-of-the-art [8].

Another significant feature of this technology is its CMOS compatibility. This coexistence of conventional CMOS circuits, and novel unconventional circuit technologies increases the possibilities for their survival and further use. In this case, the aforementioned complementary GFET architecture operates at a similar principle with conventional CMOS and also in similar voltage levels, making the two technologies easy to interconnect, without the requirement of any additional interfacing circuitry. There are, however, certain hurdles related to the fabrication compatibility of the two technologies, including the growth and transfer of high-quality, large-area graphene without introducing defects or contamination, the integration of suitable dielectric stacks and low-resistance contacts, the tight thermal budget required for CMOS back-end processes, and the precise patterning of GNRs at the nanometer scale [38], [39]. All of these aspects are currently under active investigation by the research community.

Beyond complementary GFETs, the conductance mapping of graphene grids has been further explored and exploited. L-shaped graphene nanoribbons have also been proven to operate as switches [40]. This switching capability is again based on the ability to modulate conductance via changes in the GNR grid geometry. The ratio of the width of the two parts of the L-shaped GNR, the horizontal and the vertical, as well as the application of external electric bias are of vital significance for further tuning of the conductance, the bandgap and the ON-OFF ratio, as shown in Fig. 1(e). In practice, L-shaped GNRs have been used in switching devices with multiple top gates, through which they are set either in the OFF or the ON state. Importantly, these devices do not require a back gate to operate, which provides an additional level of freedom, allowing them to be operable on top of different kinds of substrates and thereby increasing the set of possible applications [41].

When combined together, switches based on L-shaped GNRs create topologies that map the operation of logic gates [42]. In these topologies, input signals are applied not only to the top-gate terminals (as in conventional complementary circuits) but also to the source terminals, resembling the basic operation and behavior of pass-transistor logic (PTL) circuits [24]. Furthermore, topologies constituted by L-shaped GNR-based switches are reprogrammable: the same topology, with a different arrangement of input signals, can change its logic behavior (Fig. 1(f). This implies a natural extension to reconfigurable computing [23].

In the context of Boolean logic, graphene competes and coexists with other emerging channel materials such as carbon nanotubes (CNTs) and transition-metal dichalcogenides (TMDs) like MoS_2. CNTFET-based logic circuit including ring oscillators, adders, and even arithmetic logic units (ALUs), have already demonstrated energy efficiency and delay–power products comparable to CMOS counterparts, but at the expense of challenging control over chirality, placement, and density of CNTs [43], [44]. In parallel, MoS_2 FET technology has enabled the realization of integrated digital logic circuits with improved threshold control and device-to-device uniformity [45]. Compared to these platforms, graphene GFETs and GNRFETs offer very high carrier mobility and naturally ambipolar transport, which enable high intrinsic speed and compact complementary-like gate design but require sophisticated bandgap engineering and interface control to achieve CMOS-class ON/OFF ratios and noise margins [14], [25], [26].

III. HIGH-RADIX COMPUTING

As an extension to its employment in conventional Boolean logic, graphene shows significant potential for application in high-radix computing systems. Initially, another derivative of graphene found application in the field of Multi-Valued-Logic (MVL). CNTs have been previously successfully utilized to create circuits operating based on the radix-3 (ternary) and radix-4 (quaternary) numerical systems [43], [44]. This was accomplished by incorporating the material into switching devices, where different threshold voltages were achieved with the use of CNTs with varying diameters. The resulting variable threshold CNTFETs allowed the efficient design of several high-radix computing circuits in a complementary-like architecture [47], [48].

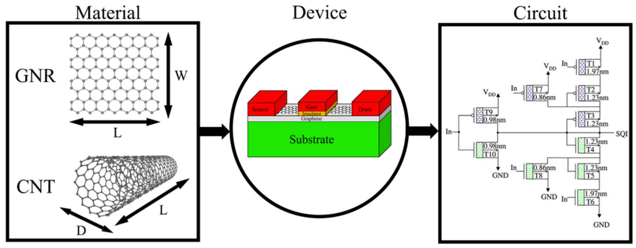


FIGURE 2. Multi-Valued Logic, implemented with circuits that consist of variable threshold devices that use carbon based materials as conductive channels. Changes in the dimension of the conductive channel changes the voltage threshold of the device. Images adopted from [46].

The same principle was recently exploited for the realization of ternary and quaternary computing circuits using graphene-based devices. Specifically, variable threshold switching devices in the form of Graphene Field Effect Transistors (GFETs), were used again to create MVL computing circuits [46], [49]. Instead of relying on CNTs with varying diameters to achieve different threshold voltages, this approach utilized Graphene Nanoribbons (GNRs) of different dimensions (dimer lines), as seen in Fig. 2 [46]. This type of circuits managed to provide improved performance even compared to their CNTFET counterparts, based on the superior electronic properties of GNRs over CNTs. With this approach, all the basic set of ternary and quaternary logic gates were implemented, as well as all various types of inverters.

Another approach on MVL with graphene goes beyond the use of graphene-based devices in complementary-like circuits, as described above, and proposes the use of GNR topologies in current mode. In this occasion, the proposed circuits do not employ the use of switches with variable thresholds, but instead, they utilize the GNR topologies as resistive switches. Each topology can be tuned to a distinct conductance level through the application of external electric biases, where each different conductance level corresponds to a different digit of the selected numerical system. Based on this operation mode, basic MVL computing circuits have been proposed, such as a quaternary full adder cell [50] and a quaternary MIN logic gate (QAND) [51], exploiting mainly the ballistic properties of the material that offer enhanced performance and contribute to increased computing density. This circuit design approach is also versatile as it can be used not only for ternary logic, but it can also be extended even for higher radix numerical systems, evaluating a larger number of conductance levels.

High-radix logic has also been actively explored in other material platforms, most notably CNTFET-based ternary and quaternary logic as previously mentioned, where different nanotube diameters naturally provide multiple threshold voltages [43], [47], [48]. Such CNTFET-based MVL schemes have demonstrated reduced interconnect complexity and lower energy per operation compared with equivalent binary CMOS implementations [44], [49]. The GNR-based MVL schemes discussed here exploit geometry-programmed conductance in GNR grids instead of diameter engineering, which can potentially offer denser integration and more uniform threshold control [50], [51]. Compared to TMD-based MVL approaches, which benefit from well-defined semiconductor bandgaps but typically exhibit lower mobility and larger device footprints, GNR MVL aims to combine ballistic transport, multi-level operation and compact layouts, provided that nanometer-scale patterning and edge disorder can be reliably controlled [52].

IV. GRAPHENE-BASED MEMRISTORS AND IN-MEMORY-COMPUTING

Apart from its application in transistor-like devices targeted mainly to Boolean logic and von-Neumann architectures, graphene finds application through its various derivatives, in memristive devices, highlighting significant improvements in performance, power efficiency, flexibility, and endurance of memristor-based hardware accelerators [53]. Numerous studies have demonstrated the superior properties of graphene-based memristor devices over conventional approaches in a wide range of different applications [54], [55].

A. GRAPHENE IN MEMRISTORS

Graphene's exceptional electrical, thermal, and mechanical properties make it an ideal candidate for enhancing all kinds of electronic devices. Various derivatives of graphene have been employed in the fabrication of graphene-based memristive devices, acting either as the primary switching medium or serving as a critical structural component. [58], [59], [60], [61].

Graphene Oxide (GO) and reduced Graphene Oxide (rGO) are common graphene derivatives that are employed as the active switching layer in a memristor stack. In this type of use, the resistive switching (RS) operation occurs within the GO (or rGO) layer itself, where conductive filaments are formed or ruptured due to the migration of oxygen or metal ions under the effect of externally applied voltage [62]. Those specific derivatives of graphene, due to their scalable fabrication techniques, are ideal for low-cost and large-scale production, even on unconventional substrates with special characteristics like flexible polymers [63]. In other approaches, pristine graphene is being used, mainly as an atomically thin electrode or as an interfacial barrier layer [55]. Its high conductivity and impermeability can be used to confine the electric field and control filament growth in an adjacent, traditional switching material, enhancing device stability and performance.

Perhaps the most sophisticated application involves engineering graphene at the nanoscale. Graphene quantum dots (GQDs), which are nanometer-sized fragments of graphene, can be embedded within the memristor's active layer [64]. Due to their abundant oxygen-containing functional groups, GQDs act as oxygen-reservoirs that regulate the local ion concentration. This provides fine-grained control over filament formation, dramatically improving the stability and repeatability of analog resistance states, a critical requirement for high-precision neuromorphic computing [65]. Finally, graphene is often integrated into hybrid heterostructures with other 2D materials, such as hexagonal boron nitride (h-BN), to create devices with superior insulation and reduced current leakage [66].

B. ADVANTAGES COMPARED TO THE STATE-OF-THE-ART

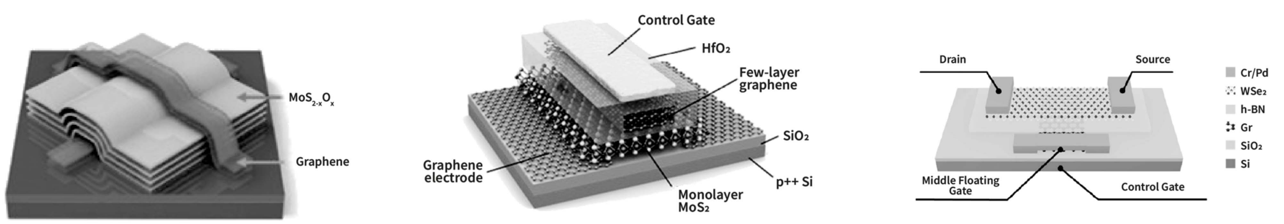
The use of graphene in memristive devices can provide significant performance improvements, such as faster switching, lower energy operation, and enhanced endurance, as well as enhanced mechanical properties, such as flexibility, making these devices highly attractive for next-generation computing architectures. Such devices allow for increased switching speed of less than 10˜ns, with switching energy maintained as low as 10˜pJ per event, making them ideal for energy-efficient hardware acceleration applications. Its robust atomic structure and chemical stability lead to state-of-the-art reliability, with measured endurance exceeding 10^8 cycles and projected data retention over 10 years [67]. Also, its 2D nature can minimize randomness in filament formation, leading to lower Cycle-To-Cycle variability and thus improving the stability and repeatability of resistive states [68]. This has been reported primarily in devices that employ graphene quantum dots, significantly reducing variability. Finally, its intrinsic flexibility and transparency allow for the fabrication of high-performance memory on unconventional substrates, enabling new form factors for computing hardware [69].

C. APPLICATIONS IN ADVANCED COMPUTING AND ELECTRONICS

Researchers are constantly investigating the capabilities of graphene-based memristors, using them as building blocks for the development of novel, functional computing architectures. This enables a plethora of diverse applications, with enhanced properties.

As many different types of memristors, graphene-based memristors can also be used as basic building blocks for In-Memory-Computing architectures. In-memory computing (IMC) aims to integrate memory and logic functions within a single device, thereby reducing data transfer times and energy consumption.

At the array level, graphene memristors map naturally to crossbars for in-memory computing (IMC) and analog matrix–vector multiplication (MAC), enabling dataflow that manages to overcome the notorious von-Neumann bottlenecks. Beyond oxide-based Resistive Random-Access Memories (RRAMs), graphene floating-gate devices (FGTs), as in Fig. 3(b), provide non-volatile charge storage with excellent retention and endurance, and can be composed into IMC bit-cells [56]. Hybrid van-der-Waals devices such as



(a) RRAM (b) FET (c) MFGFET

FIGURE 3. Structure of graphene-based (a-b) memory devices and (c) in-memory computing architectures. Adapted from [56], [57].

the WSe_2/h-BN/graphene middle-floating-gate (MFG) FETs (Fig 3(c)) exploit ambipolar transport and graphene tunability to implement reconfigurable Boolean functions (e.g., AND/XNOR) within a single device, illustrating LiM at the device scale [57]. In neuromorphic settings, GQD-stabilized analog states act as synaptic weights with improved linearity and repeatability, supporting on-chip learning and low-voltage operation [58]. Together, these directions point to embedded memory-computation components and flexible/wearable IMC form factors [70].

Graphene-based RRAM (Fig. 3(a)) has been integrated into 2D/3D crossbar arrays for in-memory matrix vector multiplication (MVM), online classification, and even logic primitives within the array. Examples include prGO planar crossbars used for pattern classification and 3D vertical RRAM architectures that replace metal interconnects with graphene for improved electrical/thermal performance. Graphene vertical RRAM (VRRAM) has demonstrated MNIST inference and logic (e.g., XOR/XNOR) within the array [67].

Another field where graphene-based memristors are expected to provide significant boost is data storage. They are expected to offer substantial improvements in data storage technologies. Their low power consumption, high retention times, and stable switching characteristics make them suitable for non-volatile memory applications. The high-density storage capabilities and multi-level storage potential of these devices can significantly enhance the performance and capacity of next-generation memory systems [71]. All this, in combination with the computing capabilities of memristors, can also lead toward improved graphene-based in-memory computing architectures.

One of the most promising applications of graphene-based memristors is in neuromorphic computing systems. These systems mimic the neural networks of the human brain to perform complex computational tasks with high efficiency. The high repeatability of analog resistance states in graphene quantum dot-enhanced memristors makes them ideal for emulating synaptic weights in artificial neural networks, potentially leading to more accurate and efficient learning capabilities [58]. This will be more analytically explored in Section V.

Graphene-based memristors are part of a wide family of 2D-material RRAM technologies that also includes MoS_2, WS_2, WSe_2, h-BN and their heterostructures [56]. MoS_2 -based and other TMD-based memristors have shown high ON/OFF ratios and low switching energies, and several optimized stacks report reasonably long retention for two-level operation, with some having even been integrated in wafer-scale crossbar arrays for in-memory computing and pattern classification tasks [72]. At the same time, many conventional 2D TMD memristors still face challenges in endurance and long-term stability, especially under repeated analog programming, motivating toward the realization of hybrid stacks and interface engineering [56], [73]. h-BN-based devices provide excellent insulating properties and stable switching behavior, while vertical WS_2/MoS_2 stacks can reach extremely high integration densities but still face endurance and retention challenges [53], [73]. In this context, graphene and its derivatives can act both as active switching media (GO/rGO, GQDs) and as high-quality electrodes or interfacial layers, improving filament confinement, variability and electrode transparency, and enabling flexible or printed memristive devices [53]. As a result, graphene is often most competitive in hybrid stacks, where it complements TMD-based memristive layers instead of directly replacing them.

V. NEUROMORPHIC COMPUTING

The rapid advancement of machine learning and artificial intelligence (AI) necessitates increasingly efficient computational systems, pushing researchers toward innovative materials and architectures. Graphene nanoribbons (GNRs) have emerged as a transformative material for neuromorphic computing, offering energy-efficient, scalable solutions capable of mimicking the complex dynamics of biological neurons and synapses [22], [78], [79]. Their unique properties enable the development of neural components such as artificial synapses and neurons, as well as larger systems for advanced computing tasks.

GNR-based synaptic devices have been extensively studied for their ability to replicate biological synaptic behaviors, including Spike Timing Dependent Plasticity (STDP), Long-Term Depression (LTD), and Long-Term Potentiation (LTP) [21], [78], [80]. By tuning their dimensions, shapes, and applied voltage biases, these devices can exhibit both excitatory and inhibitory synaptic responses, as illustrated in Fig. 4(a). Such capabilities have been demonstrated in compact graphene nanoribbon-based synapses, which feature versatile plasticity and low operational voltages (around 200 mV), akin to biological neural systems [21], [22].

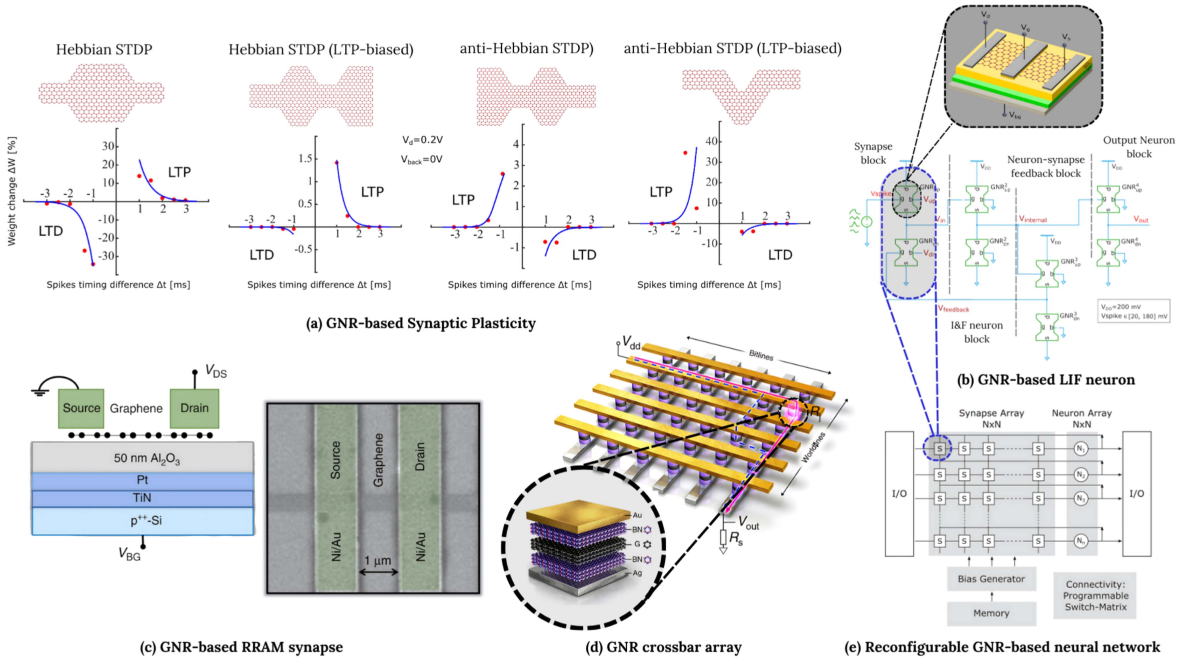


FIGURE 4. Key components and architectures of GNR-based neuromorphic computing. Subfigures illustrate (a) synaptic plasticity (LTP, LTD) under various GNR topologies [21], [22], (b) LIF neuron circuit [74], (c) RRAM synapse for adaptive learning [67], [75], (d) crossbar array for high-speed spike processing [72], [76], and (e) reconfigurable neural network for pattern recognition and image processing [77].

Recent advancements have also incorporated resistive random-access memory (RRAM) technologies into GNR-based synapses, which enhance their durability and low-energy operation. These synapses enable adaptive learning by leveraging memory-lock features that respond dynamically to external stimuli, as highlighted in Fig. 4(c) [67], [75]. This adaptability makes them highly suitable for neuromorphic architectures, particularly in applications requiring frequent synaptic updates [81], [82].

In addition to synapses, GNRs have proven effective in replicating the functionality of biological neurons. Using GNR devices, researchers have implemented Leaky Integrate-and-Fire (LIF) neuron models, a cornerstone in neuromorphic systems. These neurons emulate critical biological functions such as spike accumulation, threshold-based firing, and refractory behavior [74], [83]. GNR-based circuits achieve this by exploiting charge trapping and detrapping phenomena to recreate membrane dynamics and generate biologically plausible spiking behavior [22], [74]. A schematic of such a GNR-based neuron is depicted in Fig. 4(b) [22], [74]. Ultra-compact circuits employing entirely graphene-based LIF neurons were demonstrated to operate efficiently at biologically relevant voltages, showcasing their scalability and power-saving advantages [74], [84]. Furthermore, these neurons have been optimized for energy-efficient designs through nanoporous graphene memristors, further enhancing their utility in advanced neuromorphic tasks [83], [85].

By integrating GNR-based synapses and neurons, researchers have created fully GNR-based spiking neural networks (SNNs) that excel in tasks such as pattern recognition and image processing. These networks leverage the material's reconfigurability, which allows for operational adjustments to switch seamlessly between tasks like supervised and unsupervised learning [22], [81]. This dynamic adaptability aligns with the increasing computational demands of artificial intelligence and machine learning. An example of such a reconfigurable GNR-based neural network is shown in Fig. 4(e).

Key innovations include compact GNR crossbar arrays that support spike-based processing functions. These arrays, as illustrated in Fig. 4(d), operate at sub-femtojoule energy levels, ensuring high-speed signal transduction and low power consumption, essential for real-time data processing [86], [87]. Furthermore, robust performance in challenging environments has extended the potential of GNR-based neuromorphic systems to real-world applications [88], [89].

GNR-based neuromorphic architectures exhibit significant advantages in metaplasticity, a property where synaptic behavior adjusts dynamically to evolving input patterns. This versatility is achieved through multi-gate GNR resistors, which enable variable resistive states and allow for fine-tuned synaptic modulation within the network [75], [80]. Such tunability is critical for implementing advanced learning algorithms, particularly in adaptive neural networks that must respond dynamically to complex input data [22], [82]. For example, recent implementations using graphene memristive synapses have demonstrated high precision in neuromorphic computing tasks, offering reliable performance and scalability for large-scale systems [75], [90]. The ability to adjust operational parameters dynamically further enhances these systems' flexibility, making them an excellent choice for diverse AI applications [77], [91].

The integration of GNR-based neurons and synapses paves the way for large-scale neuromorphic systems capable of brain-like processing. Leveraging the biocompatibility, scalability, and energy efficiency of graphene, these architectures promise transformative advancements in the AI field. Fully GNR-based SNNs have demonstrated success in tasks such as supervised learning, pattern recognition, and image processing [90], [91]. Further, these systems capitalize on graphene's inherent reconfigurability to perform complex neural computations efficiently. This property enables their application in dynamic neuromorphic architectures capable of evolving based on task requirements, bridging the gap between conventional electronics and brain-inspired systems [75], [77], [91].

Neuromorphic hardware based on 2D materials encompasses not only graphene but also MoS_2, WSe_2, h-BN, and black phosphorus, which have all been explored for implementing artificial synapses and neurons [78]. TMD-based synaptic devices often provide strong gate tunability and rich plasticity (STDP, LTP/LTD), but their endurance, and in particular the stability of intermediate analog conductance states under repeated pulsed programming, remains a key challenge [92]. In contrast, graphene and graphene-derivative synapses typically operate at lower voltages and can exploit high carrier mobility and charge-trapping effects to realize analog weight updates with good linearity and cycle-to-cycle stability, especially when GQDs or van der Waals heterostructures are used. Moreover, graphene's mechanical flexibility and optical transparency are advantageous for neuromorphic hardware on flexible or transparent substrates [69]. Overall, graphene should be viewed as complementary to TMD-based platforms, particularly attractive for energy-efficient, reconfigurable and form-factor-constrained neuromorphic systems.

VI. QUANTUM COMPUTING

Quantum computing (QC) is a relatively novel field, that keeps gathering significant attention from the research community. QC is tightly bound to the investigation of novel materials, whose special properties are then being exploited in order to allow for more efficient, accurate, and scalable quantum computing systems, through their use in the realization of scalable qubits and high-fidelity quantum gates. Graphene (and its derivatives) is one of those materials that encompass a set of very attractive properties for quantum computing systems, such as tunable electronic properties, long coherence times, low spin-orbit interaction and nuclear spin density, as well as plasmonic behavior.

A. GRAPHENE-BASED QUBITS

In theory, graphene is an ideal host material for spin qubits. Its lattice possesses a very weak intrinsic spin-orbit interaction, leading to the minimization of two main causes of decoherence, the hyperfine interaction with nuclear spins and spin-orbit interaction, leading to very long theoretically predicted spin coherence times [94]. However, in reality, there are still significant challenges in terms of confining and controlling a single electron spin within graphene's naturally gapless band structure.

The main approach for overcoming this restriction is the use of electrostatically defined Graphene Quantum Dots (GQDs), that allow the creation of the necessary energy gap and spatial confinement. The performance of GQD-based qubits is really promising. Even though early graphene-based devices showcased charge relaxation times in the range of 60 100 ns [95], later experiments where bilayer graphene quantum dots are employed, managed to achieve significantly higher spin relaxation times, up to 50 ms [96]. This indicates that regardless of the existing significant fabrication and control challenges, the material entails a set of advantages that could be exploited for the effective realization of spin-orbit qubits with high coherence times.

Adding to that, recent advances in the topic have indicated that the valley degree of freedom in bilayer graphene can be exploited towards the realization of qubits. More specifically, the two low-energy valleys in bilayer graphene's band structure can be used as "pseudo-spins" that provide an alternative quantum state for manipulation. These valley states can provide very long relaxation times, achieving values as high as 0.5 s and spin T_1 up to 50 ms [96]. Newer investigations that use bilayer graphene have even demonstrated second-scale relaxation times [97].

Graphene also plays a crucial role in enhancing conventional superconducting qubits, primarily through its use in gate-tunable Josephson junctions. In this qubit category, a graphene sheet, instead of a thin insulating barrier, acts as a weak link between two superconductors, creating a superconductor-graphene-superconductor (SGS) junction [93]. The resulting qubit is known as "gatemon" as seen in Fig. 5, replacing the transmon that uses the aforementioned superconductor-insulator-superconductor junctions. The critical current of the SGS junction, which defines the resonant frequency of the qubit, can be tuned rapidly and locally with a low-power electric gate. This offers a significant advantage over the slower, less precise, and more power-hungry magnetic flux tuning required for conventional transmon qubits [98]. Early experimentation towards the realization of graphene-based superconducting qubits reported a temporal coherence time of just $55ns$ [93], a value still significantly lower compared to the tens-hundreds of microseconds that state-of-the-art superconducting qubits can achieve as seen in [99], with the use of Ta-Si framework. This indicates the still-existing material and fabrication challenges that need to be overcome in order for graphene-based technology to become competitive.

Topological quantum computing is another field that has gained significant attention from the research community. The topological qubits are considered a prominent technology for the future of quantum computing and significant effort is concentrated around solving the problems of their design and control. Those problems arise from the fact that the materials that entail the required properties, namely magnetism

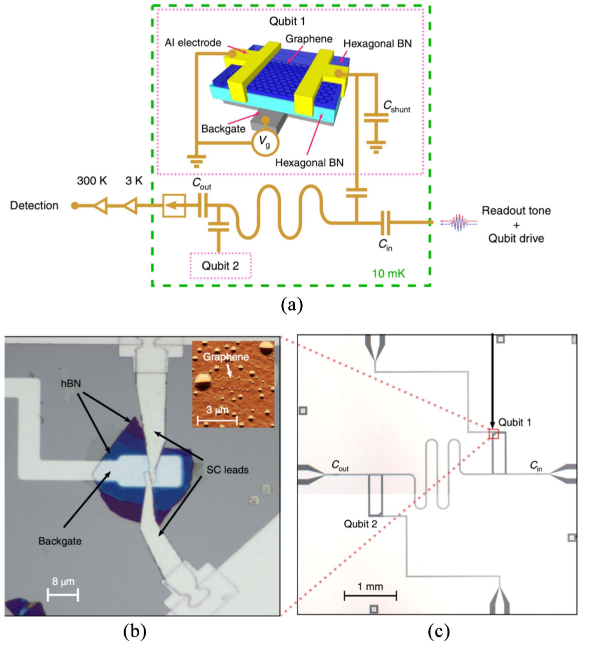


FIGURE 5. (a) Diagram of the superconductor-graphene-superconductor (S-G-S) junctions incorporated in a circuit quantum electrodynamics (cQED) system with hexagonal boron nitride (h-BN) encapsulation, (b) Optical micrograph of the graphene transmon qubit (atomic force microscopy), (c) Qubit chip made of high-quality aluminium. All images adopted from [93].

and superconductivity, are expensive, rare and hard to find in nature.

One of those materials that combine this set of properties is graphene. Recent experiments proved the existence of Yu-Shiba-Rusinov states in graphene, which can be harnessed for the realization of topological qubits through the creation of Majorana states [100]. Similarly, tetra-layer graphene has been experimentally proven to be able to show gate-tunable chiral superconductivity, which again allows the creation of Majorana fermions, crucial for fault-tolerant quantum computing [101]. Generally, due to the Quantum Anomalous Hall Effect (QAHE) that it exhibits and its exceptional and tunable electronic and magnetic properties, graphene is considered an ideal platform for the realization of Majorana modes. This tuning can be achieved through proximity and combination with other 2D materials. [102].

B. GRAPHENE-ENABLED QUANTUM GATES

Graphene provides several distinct physical mechanisms that can be exploited, at the proposal and early-experimental level, for implementing quantum gates.

At the theoretical level, graphene's strong electromagnetic confinement and long-lived, gate-tunable plasmons have been demonstrated to enable single-quantum interactions suitable for room-temperature gate operations. Exploiting graphene's large third-order non-linearity, two coupled graphene nanoribbons have been theoretically shown to implement a universal $\sqrt{\mathrm{SWAP}}$ gate in which strong two-plasmon absorption, together with the quantum Zeno effect, suppresses error channels and yields fault-tolerant-level fidelities at the simulation level [107]. Similarly, related theoretical proposals use collisions of counter-propagating plasmons in nanoribbons to realize a high-fidelity controlled-Z (CZ) gate, providing the entangling primitive required by many quantum algorithms [108].

In SGS gatemons, the qubit frequency and even anharmonicity are electrically tunable, enabling fast Z-control. Experimentally, coherent operation in graphene-based circuits has been demonstrated, and recent spectroscopy of graphene Josephson junctions (graphene-JJs) charge qubits showcases gate-controlled spectra with reduced charge dispersion [93]. Then, like other gatemon platforms, entangling gates follow normal circuit-QED procedures (dispersive CPHASE/ZZ) [109].

The Heisenberg exchange can be used to drive two-qubit entanglement for spin/valley qubits in bilayer graphene double dots by pulsing the interdot barrier. At the proposal level, this exchange interaction can implement $\sqrt{\mathrm{SWAP}}$ and CPHASE two-qubit gates. Experimentally, bilayer-graphene devices have so far demonstrated long relaxation times and reliable charge/spin initialization and readout at the single- and double-dot level. Measured relaxation times reaching $T_1 \sim 50ms$ (spin) and $> 0.5s$ (valley) as mentioned above, are extremely promising for high-fidelity and noise-tolerant gates, but fully realized two-qubit gate operations in graphene remain to be shown [96], [110].

Even though still at a very early experimental stage, topological gates are under active investigation. YSR states in superconducting graphene and gate-tunable chiral superconductivity in rhombohedral multilayers provide experimental indications that support theoretical proposals for Majorana modes and braiding [102], [111]. At present, however, system-level braiding operations and fully functional topological gates in graphene-based platforms are still under investigation.

Based on the above, graphene and graphene-based heterostructures can be exploited in different ways for the realization of qubits, and pose a prominent material to pave the way for future quantum computers with improved characteristics in terms of power, accuracy and cost. In particular, theoretical proposals based on graphene plasmons suggest that certain quantum-logic operations could, in principle, be implemented without cryogenic or vacuum infrastructure [107], hinting at the possibility of tighter integration with conventional computing systems [112]. Further experiments are required to enhance and extend the capabilities of this material in terms of quantum computing, in order to ultimately lead to fully functional quantum computers.

In quantum computing, graphene is being explored alongside conventional semiconductor platforms (Si/SiGe, GaAs) and other 2D materials such as MoS_2, WSe_2 and related TMDs. Silicon spin qubits currently achieve some of the highest experimentally demonstrated coherence times and control fidelities among solid-state spin-qubit platforms, while TMDs

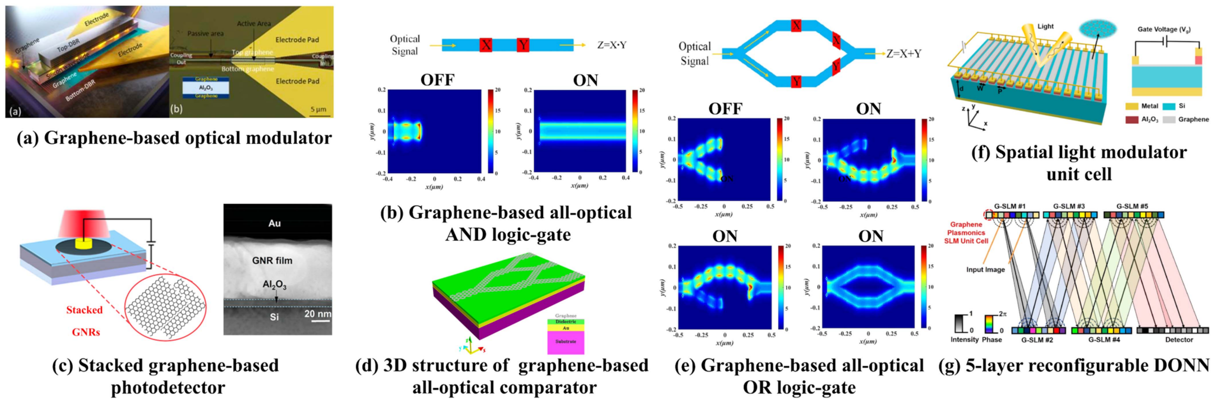


FIGURE 6. Main topics of graphene-based photonics, moving from basic building blocks to complete systems. Subfigures illustrate (a) the basic structure and the crossectional image of a fabricated graphene-based optical modulator [103], (b) A graphene-based all optical AND logic gate and the electric field distribution diagrams for their input combinations [104], (c) The schematic view and the crossectional image of a fabricated graphene-based photodetector [105], (d) 3D structure representation of a graphene-based all-optical comparator [104], (e) A graphene-based all optical OR logic gate and the electric field distribution diagrams for their input combinations [104] and (f) Graphene plasmonics based reflective spatial light modulator (SLM) unit cell and (g) the reconfigurable DONNs, implemented by cascading 5 layers of graphene-based SLMs [106].

provide, mainly at a theoretical level, strong intrinsic spin–orbit coupling and direct bandgaps that are attractive for spin and valley qubit implementations [113], [114]. Pristine graphene, by contrast, has very weak spin–orbit coupling and a gapless band structure, which complicates spin confinement but, in principle, allows for long intrinsic coherence times [94]. These limitations are being mitigated by using bilayer graphene quantum dots and van der Waals heterostructures, where proximity to TMDs such as WSe_2 enables additional control of spin–valley degrees of freedom [96], [102]. In this broader landscape, graphene-based qubits offer a versatile platform for exploring hybrid 2D quantum devices with tailored spin–orbit and valley physics, especially when combined with TMD layers.

VII. GRAPHENE IN OPTOELECTRONICS AND PHOTONICS: BUILDING BLOCKS FOR OPTICAL COMPUTING

Graphene and its derivatives, based on the combined electronic and optical properties of the material, provide a versatile platform for integrated photonics: an atomically thin and gate-tunable medium with strong light–matter interaction and fast carrier dynamics. In combination with the semiconducting and highly non-linear behavior available in graphene oxide, these traits enable low-footprint, energy-efficient components spanning modulation, detection, non-linear processing, and THz manipulation. In what follows, we outline representative devices and architectures that leverage this toolkit toward scalable, CMOS-compatible optical computing.

A. MODERN OPTOELECTRONIC SYSTEMS

Photonic devices are crucial in meeting the increasing demands of modern communication technology and data science. One bottleneck in these technologies is the insufficient bandwidth compression in electrical interconnects due to capacitive charging and thermal budget constraints.

Electro-optic modulators (EOMs), which convert electrical signals to optical signals by adjusting the refractive index of the active material or by rotating the polarization vector of incident light, offer a solution. Heidari et al. [103] demonstrated novel electro-optic modulators using graphene as the modulator material, devices like the one in Fig. 6(a). Such modulators, integrated into photonic waveguides, can operate at frequencies up to ∼67 GHz, demonstrating data rates of 80 Gbit/s in both O and C communication bands and achieving a dynamic power consumption as low as ∼ 58 fJ/bit, which is significantly lower compared to conventional silicon-based modulator technologies. The CMOS-compatible fabrication of these devices is a significant advantage for scalable integration with existing silicon photonic systems.

Of course, directly connected with modulators are the photodetectors, presented in Fig. 6(c), complementary components that are responsible for the conversion of optical signals back into electrical. In this domain, the gapless band structure of graphene allows the absorption of photons over a very broad electromagnetic spectrum, making graphene-based photodetectors suitable for a set of applications ranging from visible light imaging to THz sensing [115]. The material's high carrier mobility allows for ultrafast device operation, managing to achieve measured response time of just 2.1 ps, and operating speed of up to 220 GHz. The use of graphene with other materials (i.e. semiconductors) toward the formation of heterojunctions, allows the realization of photodetectors that are able to achieve high responsivity up to 1052 A/W and detectivity of 3.13×10^{13} Jones [105].

B. GRAPHENE OXIDE AS SEMICONDUCTIVE MATERIAL

Despite its potential, graphene's lack of a bandgap in its electronic structure limits its use as an optoelectronic material, classifying it as a "semi-metal." In contrast, graphene oxide (GO) exhibits semiconductive behavior with a typical band-gap ranging from 2.1 to 3.6 eV, ensuring low linear light absorption in the telecom band. GO also displays non-linear optical properties when exposed to high-intensity electric fields from incident light or high-voltage bias [116]. This significant optical non-linearity and low loss make graphene a promising material for superior non-linear performance.

Applications of graphene in non-linear optical processing operations, heavily utilised in fibre-optic communications, include Four-Wave Mixing (FWM). Yang et al. [117] demonstrated enhanced FWM in doped SiO_2 wave-guides using the high Kerr non-linearity and low loss of GO as an active non-linear layer. This approach managed to enhance FWM efficiency by over 10dB, demonstrating the tunable wavelength conversion of data formats, such as a 10 Gbaud quadrature phase-shift keying modulation (QPSK) signal [118]. Another widely used non-linear technique is Self-Phase Modulation (SPM), applied in wide-band optical sources, pulse compression, frequency metrology, and optical coherence tomography [119]. Layers of 2D GO integrated on Silicon-on-Insulator wave-guides have shown significant Kerr non-linearity enhancement, achieving remarkable spectral broadening and a non-linear figure of merit surpassing conventional systems by up to 20 times [120].

C. THZ OPTICAL APPLICATIONS

The THz optical band, ranging from millimeter wavelengths to near-infrared light, remains underutilized due to the lack of mature processing components for signals modulated in this region [121]. Graphene offers a new perspective for development in this area. Its gapless and linear energy absorption in its band structure, along with its frequency-independent absorption spectrum, make it suitable for potential THz band applications [122]. Graphene can enable population inversion and optical pumping in these frequencies through external carrier injection. Ju et al. [123] demonstrated graphene plasmon resonance transfer over a broad THz range by altering the nanoribbon topology and employing in-situ electrostatic doping.

Graphene also contributes to THz technologies as an enhancing element for widely used all-fiberized femtosecond ($\sim fs$) lasers. Kovalchuk et al. [124] developed graphene/polymer/graphene-based capacitive structures acting as saturable absorbers, enabling passive mode-locking (M-L) in fiber-based lasers with simultaneous on/off switching ability of the M-L operation, reporting an extinction ratio of 71 dB. Similar techniques have enabled ultra-short pulse generation in THz lasers [125] and soliton mode-locked lasers [126]. Adding to that, by patterning graphene into metasurfaces, it is possible to create active THz devices such as tunable absorbers, filters, and modulators that can operate efficiently at room temperature [127].

D. ALL-OPTICAL LOGIC GATES

As in every type of computing, the main target of optical computing is to perform logic operations in the photonic domain, bypassing existing limitations, such as latency and power consumption during the opto-electronic conversion and providing substantial performance [128]. Graphene provides a promising platform for the creation of such all-optical logic gates, mainly through the manipulation of surface plasmon polaritons (SPPs) [104].

Such gates are typically realized in structures such as Y-shaped graphene nanoribbons or Mach-Zehnder interferometers. The logic operation is based on the principle of linear interference. When SPP waves from two input waveguides meet, their constructive or destructive interference at the output determines the resulting logic state (‘1’ or ‘0’) [129], [130]. Such types of logic gates, as well as the validation of their successful operation, can be seen in Fig. 6(b) and Fig. 6(e). In Fig. 6(d), those gates are cascaded in order to realize an even more complex circuit of a comparator. By controlling the chemical potential of graphene via an external gate voltage, it is possible to modulate the propagation of the SPPs and reconfigure the device to perform different logic functions, such as AND, OR, and XOR, within the same structure. This approach enables the design of ultra-compact logic gates with a small footprint, low information loss, and high stability [104]. Such an example can be seen in [131], where dual-band, polarization-independent XOR and OR logic gates using an amorphous silicon-graphene metasurface were proposed.

E. GRAPHENE-BASED PHOTONIC ACCELERATORS FOR AI

All of the aforementioned components that have been described, like the modulators and photodetectors, are actually the basic building blocks that can be used for the realization of graphene-based optoelectronic neural networks and AI accelerators. Toward that direction, a novel high-performance optoelectronic architecture leveraging the exceptional carrier mobility and gate-tunable optical properties of graphene, has been already introduced in [132]. The suggested architecture encodes the input vectors to optical intensity values using Spatial Light Modulators (SLMs), which are then projected onto a matrix that consists of graphene-based photodetectors. The photodetectors take advantage of graphene’s adjustable photoresistivity, which functions as a weight, to determine a weighted combination of the inputs. In this manner, the primary function of neural networks (NNs), matrix vector multiplications (MVMs), are carried out in parallel, at high speed, while consuming a very small amount of energy. This proposed architecture was tested on different tasks, including image reconstruction of data compressed with singular value decomposition, learning with a support vector machine (SVM) algorithm, and on a multilayer perceptron (MLP) neural network for MNIST image classification datasets, providing decent performance but excelling in speed and energy efficiency. Similar to this, GNRs have been successfully employed in the field of photonics in conjunction with other materials, such as the Fabry-Perot cavity, to provide phase and modulation capabilities that enable the development of dynamically reconfigurable optical networks. Diffractive optical neural networks (DONNs) with terahertz operation capabilities have been proposed using this design [106]. The basic architecture of this DONN as well as the basic SLM unit

TABLE 1. Comparison of Graphene-based Computing Paradigms

Computing Paradigm	Core Graphene Property Leveraged	Key Device Structure	Primary Advantage	Most Significant Challenge
Boolean Logic	Ambipolar transport; tunable bandgap in BLG/GNRs; gate-controlled barriers	Complementary / complementary-like GFETs; BLG GFETs; graphene *barristors*	High intrinsic speed; potential CMOS-level cascades	ON/OFF ratio & noise margins; process variability; wafer-scale uniformity
High-Radix Logic (MVL)	Ambipolar transfer near Dirac point; geometry-programmed conductance (GNR grids)	Ambipolar GFET ternary/quaternary devices (T-GFETs); GNR "conductance-map" switches	Higher information density per device/gate	Robust level separation; PVT tolerance; calibration/variability
Memristive (In-Memory) Computing	Ion/vacancy migration in GO/rGO; tunable resistivity; charge trapping (incl. GQDs)	Metal/GO/Metal RRAM; GQD-enhanced RS; graphene electrodes; graphene floating-gate variants	High density, low power; multi-level analog states; logic-in-memory	Endurance, device-to-device variability, retention; CMOS/BEOL integration
Neuromorphic Computing	Analog RS and charge trapping in graphene derivatives; low-voltage operation	Memristor crossbars (GO/rGO/GQDs); GNR synapses; GFET-based LIF neurons	Brain-like energy efficiency; massive parallelism; reconfigurability	Analog precision; variability; on-chip learning tolerant to device non-idealities
Quantum Computing	Low spin-orbit coupling; valley degree of freedom; gate-tunable SGS junctions	BLG quantum dots (spin/valley); SGS "gatemons"	Long valley T_1 (ms–s, measured); electrical tunability	Coherence; qubit control/readout; reproducible fabrication
Optical / Photonic Computing	Broadband absorption and fast carrier dynamics (graphene); high $\chi^{(3)}$ in GO	Graphene EOMs; graphene photodetectors; GO non-linear overlays on Si/SiN	High bandwidth; low drive energy; CMOS-compatible photonics	Coupling/insertion loss; efficiency; foundry/packaging integration

that is used, can be seen in Fig. 6(f). When evaluated on classification tasks, the provided NNs were able to get a 94% accuracy rate on the MNIST. Beyond full accelerator architectures, graphene is also being used to create the core building blocks of photonic neural networks. Researchers have proposed graphene-based photonic synapses, a fundamental component that mimics the connections between neurons. One such design consists of a graphene-based electro-absorption modulator embedded within a microring resonator [133]. The synaptic weight is represented by the amount of light transmitted through the device, which can be finely tuned by applying the appropriate voltage to graphene. Such devices are critical for enabling large-scale, on-chip photonic neural networks. The successful integration of these graphene-based components into silicon photonics is a crucial step toward the wafer-scale production of powerful and energy-efficient AI hardware [134].

In integrated photonics, graphene competes with and complements silicon, germanium and TMD-based platforms. Silicon photonics combined with Ge electro-absorption modulators and photodetectors already supports many high-speed optical transceivers and offers a mature, CMOS-compatible technology for large-scale integration [135]. Graphene-on-silicon modulators and photodetectors, however, can achieve very high bandwidths and compact footprints and provide broadband, gate-tunable absorption when used on silicon waveguides [103], [115]. Compared to TMD-based photonic devices, which typically rely on strong excitonic resonances but operate over narrower spectral ranges [115], graphene offers nearly flat absorption from the visible to the mid-infrared and electrically tunable optical conductivity, which is particularly advantageous for reconfigurable modulators and broadband detectors. As a result, graphene is often seen as an active overlay on established Si/Ge photonic platforms, enhancing modulation depth, speed and functionality.

VIII. CONCLUSION

Graphene proves to be not just another promising replacement for silicon, but actually a versatile platform that can be introduced to different computing paradigms. Throughout the presented investigation, we examined the most promising graphene computing applications such as conventional Boolean logic with GFETs and GNR devices, high-radix logic, memristive and in-memory computing, neuromorphic architectures, quantum computing, and finally photonics and optical computing. Combined together, these efforts show that graphene's interesting set of properties, and mainly its electrically and optically tunable properties can be exploited and engineered to satisfy very diverse computational needs, spanning from high-bandwidth communication to analog synapses and reconfigurable digital logic, while also addressing the existing materials, device, and integration challenges.

When talking about computing, the most obvious initial experimentation is related to conventional Boolean logic circuits. In this path, we mentioned CMOS-like logic with the use of GFETs, as well as geometry-programmed GNR-based logic, focusing on conduction-map devices and L-shaped GNR switches used in PTL-style circuit design, entailing also the property of reconfigurability through input signal permutations. All those approaches have effectively managed to enable the creation of simple logic primitives, such as inverters, ring oscillators, NAND, NOR, Majority and reprogrammable gates. However, their use in large-scale circuits is yet restricted, mainly to problems on satisfying simultaneously several crucial factors, such as high ON/OFF ratio, improved noise margins and reduced device-to-device variability. Going downscale to GNR-based devices, the dependence of device performance on the condition of the graphene-grid and thus the extreme fabrication precision that is required, pose also a significant obstacle. High-radix logic using variable-threshold GFET/GNR devices strengthens graphene's potential to raise information density and maintain energy-efficiency. Nevertheless, precision control of thresholds, robust logic-level separation under power-voltage-temperature (PVT) variations, and circuit scaling are yet open research topics.

Graphene derivatives (GO/rGO/GQDs) enable resistive-switching devices with low-voltage operation and stable multi-level states, making them natural building blocks for logic-in-memory and analog MAC operations in crossbar arrays. These devices promise high density and favorable energy per operation, and they offer synaptic-like weight storage and adaptability, which aligns with the neuromorphic goals. In the near term, the priority is to scale from small arrays to larger, reliably calibrated fabrics by improving endurance, state retention, and device-to-device variability, while integrating selectors, write-verify schemes, and back end of line (BEOL)-compatible process flows. With accurate compact models and algorithm-circuit co-design that tolerates device noise and drift, graphene IMC can move from device demos to embedded memory-compute tiles co-packaged with CMOS.

The realization of memristive devices (devices with hysteresis) gives graphene the opportunity to access the field of neuromorphic computing and neuromorphic systems, through GNR-based synapses and neurons, as well as low-power and low-voltage crossbar-based Spiking Neural Networks. This technology targets to brain-like energy efficiency and compactness, while also harnessing materials tunability that can provide additional features such as inherent metaplasticity and adaptive learning. Being a form of analog computing, this graphene-enabled technology requires reliable precision, variability tolerant learning approaches and generally tailored solutions that involve material, circuit and algorithm co-design, in order to adapt to and harness the graphene's special device physics.

Graphene's quantum applications span BLG quantum dots, gate-tunable SGS "gatemons" in circuit-QED, and plasmonic proposals for room-temperature two-qubit gates, complemented by topological approaches. The common advantage is electrical tunability, but the field remains yet at an early-stage. Key hurdles include coherence times, uniform confinement and reproducible BLG gaps, low-loss and high-yield graphene JJs, and quantum-grade integration difficulties (i.e. readout, packaging, cryo for superconducting platforms, sources and loss for plasmonics). In this field, graphene's role is that of a materials-driven testbed and a path to specialized qubit implementations, however progress on coherence and fabrication precision could convert these advantages to scalable quantum computing architectures.

Photonics and optoelectronics is the field where graphene actually excels, can also be considered more mature and closest to offer significant impact. It provides very fast, low-footprint electro-optic modulators and broadband photodetectors, the basic blocks for the realization of any larger-scale optical computing system. It constitutes a platform that can and has been used for the design and implementation of operable and well performing all-optical logic elements, as well as their direct extension, optoelectronic hardware MVM accelerators. Of course, system-level efficiency taking into consideration the coupling and insertion loss, as well as BEOL-compatibility and scalable, wafer-level integration of graphene photonics components with standard silicon foundry flows, are key challenges that have to be taken under consideration.

Beyond the device concepts surveyed in this review, the most significant enabling factors for graphene computing in general, are fabrication and materials maturity and integration. Across all paradigms, wafer-scale uniformity and defect density in CVD-grown graphene, GNRs and bilayer graphene (BLG) remain key bottlenecks: grain boundaries, wrinkles, multilayer patches and transfer-induced cracks in large-area films directly lead to unwanted, uncontrollable phenomena, like threshold dispersion, ON/OFF ratio variability and mobility degradation, and, when related to quantum platforms, decoherence and qubit frequency spread [136], [137].

For GNR-based logic and MVL circuits in particular, patterning widths of a few nanometers using e-beam lithography and anisotropic etching with low line-edge roughness and controlled edge chemistry and geometry is essential to obtain reproducible and utilizable bandgaps and conductance levels, making area uniformity and variability a first-order design constraint [138], [139]. Problematic and inaccurate patterning processes can significantly affect device characteristics crucial for effective power-efficient switching operation, like ON/OFF ratio and leakage current [35].

In BLG devices and spin/valley qubits, the ability to engineer a clean, uniform and stable bandgap via dual gates, displacement fields and high-quality h-BN, or other insulating material encapsulation is equally critical for robust gap opening, confinement and scalable qubit performance [140]. Across all of these technologies, contact engineering, including the choice of contact metals, work-function alignment, local doping control and contact geometry, is central to reducing contact resistance, noise and uncontrollable device variability [141], [142].

Finally, advanced dielectric stacks based on high-*k* oxides such as HfO_2, Al_2O_3 or ZrO_2 and van der Waals insulators such as hexagonal boron nitride (h-BN), with low trap densities and clean interfaces, are required to suppress leakage, unwanted hysteresis and charge noise in GFETs and qubit gate stacks and to stabilize resistive switching and reduce variability in memristive cells [143], [144].

Addressing these cross-cutting challenges in wafer-scale uniformity, defect control, contact resistance and dielectric integration is therefore a core part of the envisioned roadmap and will be as important as new circuit and architecture concepts in moving graphene-based computing from isolated demonstrations to reliable, large-area systems [142].

On the design side, accurate compact models and multi-scale simulation flows that explicitly capture these fabrication non-idealities, from defects and edge disorder to contact resistance and dielectric noise, will be essential to make graphene devices suitable for scalable designs and to accelerate the transition from laboratory prototypes to actual fabricated subsystems [145].

Guided by Table 1, we can draw some clear conclusions and define a coarse roadmap for the future of computing applications with graphene. We expect the fastest progress where graphene augments and is combined with existing platforms, mainly co-packaged photonic I/O and CMOS back-end memories, followed by neuromorphic subsystems. In parallel, better GNR patterning, stable polarity control, and reproducible BLG gaps will give a significant boost to digital logic design, and the progress in graphene quantum dots, SGS junctions, and plasmonic gates, will boost unconventional quantum applications. These developments could lead to the advancement of graphene's role from isolated demonstrations at the laboratory scale to co-packaged subsystems and eventually full system level accelerators.

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