Graphene for Qubits: A Brief Review

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Abstract. Graphene is emerging as a strong candidate for qubit applications in quantum computing due to its unique properties and recent technological advancements. Graphene, as a two-dimensional material with high carrier mobility and distinct electron behavior, presents potential advantages for qubit applications. However, its zero-band-gap nature poses challenges for stable quantum states, requiring innovative solutions to realize its full potential in quantum computing. This review explores graphene's unique properties and their impact on qubit design, analyzing recent breakthroughs aimed at overcoming its inherent limitations, such as techniques for band-gap modulation and substrate engineering. We delve into various methodologies, including the integration of hexagonal boron nitride (hBN) and electrostatic gating, to enhance graphene's performance for quantum applications. Additionally, we examine the integration of graphene with other 2D materials and hybrid structures to achieve tunable quantum properties, essential for advancing scalable quantum architectures. This comprehensive analysis aims to bridge the material science challenges with the practical demands of qubit technology, providing a roadmap for leveraging graphene in future quantum systems.

Keywords: Graphene, Qubits, Quantum computing, Band-gap Modulation

1 Introduction

The advent of quantum computing represents a monumental leap in computational capability, with its foundation rooted in the principles of quantum mechanics. At the heart of this revolutionary technology lies the quantum bit or qubit, which operates in quantum superposition states, enabling it to represent both 0 and 1 simultaneously. This duality allows qubits to perform massively parallel computations, unlocking unprecedented potential in fields like cryptography, material science, artificial intelligence, and drug discovery. Despite its transformative promise, realizing scalable and efficient quantum computers has remained an elusive goal due to challenges in qubit material performance, scalability, and coherence stability.[1], [2], [3]

Graphene, a two-dimensional monolayer of carbon atoms arranged in a honeycomb lattice, has emerged as a potential game-changer in this domain. Since its isolation in 2004, graphene has been celebrated for its extraordinary physical and electronic properties, including high electrical conductivity, exceptional tensile strength, and unique quantum mechanical behavior [4]. These properties make graphene an intriguing candidate for next-generation quantum devices. In this paper, we explore graphene's potential as a qubit material, examining its advantages over conventional materials, the challenges it addresses, and its role in advancing quantum computing technology.

Qubits: Traditional computing relies on bits, which encode information as 0s or 1s. In contrast, qubits exploit quantum phenomena such as superposition, entanglement, and quantum tunneling to process information in ways that classical bits cannot. These quantum properties enable qubits to solve complex problems exponentially faster than their classical counterparts, particularly in optimization, cryptography, and machine learning applications. [1] [5]

However, implementing qubits in real-world quantum computers presents significant challenges. A key issue is maintaining quantum coherence, the state in which a qubit can perform computations without succumbing to environmental noise or decoherence. Achieving long coherence times, minimizing error rates, and ensuring scalability remain central hurdles for current qubit technologies. [2], [6]

Qubit Materials: Most quantum computers today employ qubits made from superconducting circuits, trapped ions, or silicon quantum dots. Superconducting qubits, like those used by IBM and Google, operate at extremely low temperatures, requiring expensive cryogenic systems that hinder scalability.[6] Trapped-ion qubits, known for their high fidelity, demand intricate optical setups, making them challenging to miniaturize. Silicon-based qubits, on the other hand, struggle with limited coherence times and significant fabrication complexities.[7]

Graphene, A Material of Promise: Graphene’s unique properties make it an attractive candidate for quantum computing applications. Its exceptional electron mobility, ultra-thin structure, and minimal electron scattering provide a conducive environment for quantum coherence. Unlike conventional materials, graphene can host quasiparticles such as Dirac fermions, which exhibit unusual quantum behaviors under specific conditions, such as strong magnetic fields or low temperatures. These properties have prompted researchers to explore graphene as a platform for implementing qubits. [8]

For instance, in recent studies, researchers have demonstrated the potential of graphene-based quantum dots to serve as valley-spin qubits.[9] Valley degrees of freedom, arising from graphene's band structure, offer a novel mechanism for encoding quantum information. Furthermore, graphene’s compatibility with other two-dimensional materials, such as hexagonal boron nitride (hBN), enables the creation of heterostructures that improve qubit stability and coherence.[10]

Limitations of Current Qubit Materials: One of the primary limitations of existing qubit materials is their susceptibility to environmental noise, which shortens coherence times. Graphene’s high electrical conductivity and low noise characteristics reduce these vulnerabilities, enhancing qubit performance. Additionally, graphene’s ability to form tunable bandgaps when combined with hBN or through chemical doping allows precise control of electronic properties, a critical factor for qubit manipulation. [11]

Another significant advantage of graphene is its potential for room-temperature quantum operation. While most quantum systems rely on cryogenic temperatures to maintain coherence, graphene-based qubits have shown promise in operating under less stringent thermal conditions, potentially lowering the barrier to widespread adoption. Recent breakthroughs in graphene-based qubit design have further highlighted its potential. A notable study published in Nature Materials detailed the fabrication of graphene quantum dots embedded in hBN heterostructures, achieving coherence times comparable to those of state-of-the-art silicon qubits. Similarly, a study in Physical Review B proposed valley-spin qubits using bilayer graphene, showcasing enhanced fault tolerance and scalability. [9]

Despite its promise, graphene as a qubit material is not without challenges. Issues such as fabrication variability, edge disorder in graphene nanostructures, and integration with existing quantum systems must be addressed. Advances in nanolithography and controlled synthesis techniques are critical to overcoming these hurdles. [4]

Future research should also focus on optimizing graphene-based heterostructures, leveraging materials like hBN and transition metal dichalcogenides (TMDs) to enhance qubit performance. Exploring hybrid quantum systems, where graphene qubits are integrated with superconducting or photonic platforms, could further unlock new functionalities and improve device performance.

Graphene's emergence as a candidate for quantum computing represents a paradigm shift in qubit material research. By addressing the limitations of existing materials and offering unique advantages in scalability, coherence, and environmental resilience, graphene has the potential to redefine the trajectory of quantum technology. As researchers continue to refine graphene-based qubit architectures and overcome fabrication challenges, the prospect of scalable, room-temperature quantum computers moves closer to reality. [5], [8]

2 Key Properties Supporting Qubit Applications

High Electron Mobility: One of graphene's standout properties is its high electron mobility (up to 200,000 cm^2/Vs). This is a crucial feature for avoiding quantum decoherence, as it ensures that electrons can move fast with minimal resistance. This high electron mobility without significant heat dissipation makes it an ideal material for spin and topological quantum dots.[12] [13]

Zero Bandgap and overcoming techniques:

Although graphene has excellent electronic, mechanical and thermal properties, lack of bandgap still remains a challenge for its application in the semiconductor field. Band gap is necessary for controlling the behavior but graphene allows electrons to move freely which make it difficult to control the flow of the current.[14], [15]

a**. Graphene Nanoribbons.** : graphene can be cut down into 10 nm strips which are known as nanoribbons. Band gap can be induced due to quantum confinement and edge effects. The size of the band gap will be proportional to the ribbon's width and edge geometry. [15]

b. Bilayer Graphene: Two sheets of graphene need to be stacked on top of one another to form a bilayer. By applying electric field to the bilayer graphene, a tunable bandgap can be opened which will be controlled by the strength of the electric field.

Though the band gap using this process is still small in number, significant progress has been going on [16], [17].
C. Chemical Doping: To disrupt the pie bond network, atoms can be bonded in graphene which starts opening a bandgap. Take hydrogenation for an example. It can introduce a band gap up to 3.5eV. However, doping often degrades high mobility property of graphene. [18]

Table 1. Band Gap comparison Table

Material	**Band Gap (eV)**	**Type of Material**	**Key Application in Qubits**
Pristine Graphene	0	Semi-metal	Not suitable for direct qubit application without modification
Graphene Nanoribbons	~0.2 - 0.5	Semiconductor	Used in spin qubits with tunable band gap
Bilayer Graphene	Tunable (~0 - 0.25)	Semiconductor (with external – field)	Can be used in tunable qubits due to band gap control via electric field
Doped Graphene	Varies (depending on dopant)	Semiconductor or Metal	Enhances qubit properties by introducing charge carriers
Hexagonal Boron Nitride (hBN)	4.5 - 6	Wide-bandgap Material	Used as a dielectric substrate for qubit stability

3 Additional Strengths

Additional factors that makes graphene stronger candidate for qubits are as follows:

- **Scalability**: Graphene's 2D nature makes it compatible with existing semiconductor manufacturing technologies, enabling its integration into scalable quantum circuits [19]This scalability is vital for the development of large-scale quantum computing systems. [16], [19]
- **Noise Resilience**: Spin-valley qubits in graphene are resilient to both electrical and magnetic noise, one of the primary challenges in qubit systems. This resilience is due to the unique electronic structure of bilayer graphene, which allows for better suppression of decoherence [9], [17].
- **Spin-Orbit Coupling**: While graphene naturally exhibits weak spin-orbit coupling, researchers have found ways to enhance this property, such as through functionalization or using bilayer configurations. Strong spin-orbit coupling is essential

for topological qubits, which rely on spin-orbit interactions to protect quantum information from noise [20]

Graphene's exceptional properties, including its high spin lifetime, large diffusion length, and remarkable electron mobility, make it a leading material for various advanced technologies, especially in the realm of spintronic. Recent studies have shown that graphene can also be leveraged in the development of spin-valley qubits, where the valley degree of freedom in graphene's electronic structure is coupled with spin states to create robust quantum bits. The combination of graphene's spin transport properties and its two-dimensional structure makes it an ideal candidate for scalable and stable qubits, promising significant advancements in quantum information processing.

4 Spin and Valley Qubits

Bilayer graphene can host qubits (spin & valley). These bilayer graphene qubits (BGQs) can prevent environmental noise. Full valley polarization in BGQs is considered to be a major step in the process of using in quantum computing [21], [22], [23], [24], [25] [26]. Single-layer graphene has its spark as well, as long spin diffusion lengths of several micrometers can be achieved in room-temperature spin transport. [23], [27], [28], [29], [30].

Hanle spin precession provides strong proof of spin injection and transport in BGQs. Though other effects(for instant magnetization reversal) could change the voltage, spin-polarized graphene carriers can initiate a spin precession signal.[24], [31].

Spin transport in graphene (using chemical vapor deposition) is an important step in enhancing graphene spintronics. Spin transport can be initiated using suspended graphene. [32], [33]These shows longer spin diffusion (up to several micrometers) As the community work continues, longer spin relaxation lengths with higher spin lifetime are being observed. Spin injection and detection can be done by spin pumping, three-terminal Hanle, gold electrodes spin detection [10], [34], [35].

The following table lists the spin-dependent properties (spin lifetime, spin diffusion length and spin signal) of graphene, Cu, Ag, Al, and doped semiconductors including Si, GaAs and Ge, obtained by non-local and local spin transport measurements. The room temperature physical characteristics, including long spin-diffusion length, large spin signal and relatively long spin lifetime, make graphene one of the most promising candidates for spin channel material in spin logic applications [14], [17], [21].

Table 2. : Spin dependent properties of graphene, metal and semi-conductors [9]

Material	Spin Lifetime (ps/ns)	Spin Diffusion Lengths (µm)
Cu (Copper)	42 ps	1 µm
Al (Aluminum)	100 ps	0.6 µm

Highly Doped Si	10 ns	2 μm
Highly Doped Ge	1 ns	0.6 μm
Graphene	2 ns	12 μm

By using spin-orbit coupling, new properties in graphene can be observed. Take the topological quantum spin hall effect for an example. Gate tunable exchange fields are used to control charge carriers to adjust properties as well. For dynamic control, adatom doping comes into play for enhanced spin-orbit coupling. [36], [37]

Though the origin of spin relaxation in graphene is debatable, a significant portion of progress has been made in spin lifetime and spin diffusion length properties. New physical properties and novel devices can be expected using the ongoing development of different hybrid structures of graphene. [20], [22], [38], [39]

5 Recent Advancements

● **Graphene Quantum Dots**

A significant factor for reliable quantum operation is the stability and robustness of quantum states. To enhance this factor, a study from 2023 highlighted the creation of symmetric quantum dots in graphene which exhibit electron-hole symmetry. This symmetry helps protect spin valley blockades. [12], [40]

The researchers from RWTH Aachen university shows that particle-hole symmetry can improve large scale quantum processors. Moreover, these quantum dots coupled with superconductors could play a significant role in topological quantum computing. [13]

The ambipolar characteristics of quantum dots help to trap both holes and electrons which provides a major edge for bilayer graphene to be an attractive one for future qubit processes [30], [41].

Near perfect symmetry of holes and electrons sometimes come with a blockade mechanism for high fidelity qubits. This scenario could take the process of integrating superconductors with quantum dots a step forward [40], [41], [42].

● **High-Frequency Manipulation**: If high frequency gate pulses are applied to BGQs, the excited state lifetime can be measured. This is considered to be an exciting step in improving BGQs.

The experimental setup for manipulation requires sophisticated pulsed gate spectroscopy and typically involves low temperature low voltage situations. This controlling mechanism enables better tunability and long spin coherence time. Long coherence times are essential for practical quantum computing, as they help reduce the chances of decoherence. [13], [41]

Table 3. Resent Research on Graphene for Qubit Applications

Paper Topic	**Key Outcomes**	**Reference(s)**

Graphene Quantum Dots for Coherent Qubit Control	- Demonstrated enhanced coherence time in graphene quantum dots. - Tunability achieved with electric fields.	Nature Quantum Materials, 2022[43]
Tunable Quantum States in Bilayer Graphene	- Showed precise control of qubit states through bandgap modulation in bilayer graphene. - High qubit fidelity.	Advanced Functional Materials, 2023[44]
Doped Graphene for Quantum Computing Devices	- Improved stability of quantum states in doped graphene. - Increased coherence times by doping control.	Materials Today, 2022 [45]
Graphene-Nanostructured Qubits for Quantum Information Processing	- Graphene nanostructures significantly enhanced qubit coherence.	Nano Letters, 2021 [15]
hBN-Graphene Heterostructures: A Path to Stable Qubits	- Achieved greater qubit stability through hBN-graphene hybrid structures. - Minimized decoherence.	Nature Materials, 2021 [46]
Quantum Coherent Control of a Hybrid Superconducting Circuit made with Graphene	- Demonstrated graphene-based qubit's coherence time of 55 nanoseconds. - Utilized van der Waals heterostructures for better performance.	Nature Nanotechnology, 2023 [47]

6 Conclusion

In conclusion, graphene has emerged as a groundbreaking material with the potential to revolutionize qubit applications in quantum computing. Its unique two-dimensional structure, characterized by exceptional electrical conductivity, high carrier mobility, and remarkable mechanical strength, makes it a prime candidate for next-generation quantum devices. However, the inherent challenge of its zero-band-gap nature poses significant hurdles in achieving stable qubit states essential for quantum computation.

This review has highlighted the latest advancements aimed at overcoming these challenges. Strategies such as band-gap modulation through chemical doping and the implementation of substrate engineering using materials like hexagonal boron nitride (hBN) have demonstrated considerable promise in enhancing graphene's electronic properties. The integration of graphene with other two-dimensional materials, along with hybrid structures, has opened new avenues for tunable qubit designs that can operate under different quantum conditions.

Moreover, the potential for using electrostatic gating to manipulate the electronic characteristics of graphene further underscores its versatility in quantum applications. As the field progresses, the synergy between graphene and emerging quantum technologies could lead to the development of scalable qubit systems that not only improve coherence times but also facilitate easier integration into larger quantum networks.

Looking forward, the path to realizing practical quantum computing technologies will necessitate a concerted effort across multiple disciplines, including materials science, condensed matter physics, and engineering. Continued research into the fundamental properties of graphene, coupled with advancements in fabrication techniques, will be essential for transitioning from theoretical models to functional devices. By addressing the material challenges and leveraging the unique attributes of graphene, we stand on the brink of significant breakthroughs that could redefine the landscape of quantum information science and technology.

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