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Extensible Quantum Computing Architectures with van der Waals Heterostructures

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Abstract

This study proposes a novel theoretical framework for developing scalable and extensible quantum computing architectures using van der Waals (vdW) heterostructures, with a focus on graphene-based materials. Leveraging the unique electrical and material properties of 2D materials, this work introduces innovative qubit configurations designed to enhance the scalability, robustness, and operational efficiency of quantum computing systems. Key contributions include the assessment of qubit operability within vdW heterostructures through quantum mechanical modeling, evaluation of quantum coherence to counteract decoherence mechanisms, and simulation of qubit manipulation in response to external stimuli. The research outlines a path toward integrating vdW heterostructures with existing quantum computing technologies to form hybrid systems, highlighting the potential for increased computational capabilities and versatility. The proposed designs are examined for their operational viability and robustness against quantum errors, with findings suggesting promising avenues for scalability and integration with broader quantum systems. This paper sets the stage for future experimental validation and optimization, aiming to bridge the gap between theoretical potential and practical quantum computing applications.

Introduction

The introduction of quantum computing represents a paradigm shift in our approach to information processing, promising to revolutionize fields ranging from cryptography to materials science through its ability to solve problems intractable for classical computers [1]–[5]. Central to this revolutionary technology is the concept of the quantum bit or qubit, which, unlike the binary states of classical bits, can exist in superpositions, enabling quantum computers to process vast arrays of data simultaneously. The advent of two-dimensional (2D) materials, particularly those forming van der Waals heterostructures, has opened new avenues in the quest for scalable and robust quantum computing architectures. These materials, characterized by their unique electronic and material properties, hold the potential to address some of the key challenges faced by existing quantum computing technologies, such as qubit coherence and integration scalability [6].

The development of extensible quantum computing architectures utilizing van der Waals (vdW) heterostructures, specifically involving graphene-based materials, is at the forefront of quantum computing research [7]–[10]. These structures promise a paradigm shift in quantum computing by leveraging the unique electronic and optical properties of 2D materials and their heterostructures. Key studies prior to 2021 have laid the groundwork for this exciting field,

focusing on various aspects of vdW heterostructures including their ultrafast dynamics, potential as quantum simulators, and photovoltaic efficiency, among others. Jin et al. (2018) highlighted the significant electrical, optical, and magnetic properties of vdW heterostructures, particularly TMDC heterostructures, emphasizing their role in optoelectronics and spintronics due to unique excited-state dynamics and interlayer exciton formation [11], [12]. A discussion of the potential of twisted vdW heterostructures as scalable quantum platforms for simulating strongly correlated physics and topology, crucial for quantum computing is presented in [13]. Wong et al. (2017) demonstrated ultrathin vdW heterostructures with photovoltaic quantum efficiencies exceeding 50%, showcasing the potential for efficient energy harvesting in quantum computing devices [14]. Wu et al. (2019) reported on natural magnetic vdW heterostructures exhibiting both magnetic properties and topological surface states, crucial for realizing exotic topological quantum states in computing [15]. Jariwala et al. (2017) provided insights into the emerging mixed-dimensional vdW heterostructures, combining 2D materials with other dimensional materials for innovative device engineering, highlighting their potential in quantum computing applications [16], [17]. Antony et al. (2021) explored the reduction of qubit area in superconducting quantum processors using vdW materials, indicating a pathway to high-density, low-loss quantum devices [18], [19].

This paper presents a comprehensive theoretical framework for the development of quantum computing architectures leveraging the distinctive properties of graphene-based van der Waals heterostructures. By exploiting the tunable electronic structures and enhanced coherence times inherent to these materials, we propose novel qubit configurations designed to advance the scalability and extensibility of quantum computing systems. The motivation for this work is rooted in the initial experimental successes in achieving quantum coherent control over superconducting circuits utilizing van der Waals materials. These pioneering experiments underscore the feasibility of van der Waals heterostructures as platforms for quantum computing, prompting a deeper theoretical exploration into their potential applications.

Our research aims to bridge the gap between the promising experimental findings and the conceptualization of scalable quantum computing architectures. By integrating quantum mechanical modeling with computational simulations, we evaluate the operability, coherence, and manipulation of qubits within these heterostructures, offering insights into the design of quantum computing systems that are not only theoretically sound but also practically viable. The subsequent sections detail our methodological approach, encompassing the assessment of qubit operability, the evaluation of quantum coherence, and the simulation of qubit manipulation, culminating in a discussion on the operational viability, robustness, and integration potential of the proposed designs.

Quantum Mechanical Modeling

The pursuit of revolutionary quantum computing architectures is intricately linked to the exploration and utilization of two-dimensional (2D) materials, especially those forming van der Waals heterostructures. These materials present a promising frontier due to their unique electrical and material properties, which could potentially overcome some of the limitations faced by current quantum computing technologies. Our methodology integrates quantum mechanical modeling with computational simulations, aimed at evaluating the scalability and practical applications of van der Waals materials in quantum computing. This section outlines

our comprehensive approach towards leveraging the distinctive properties of van der Waals heterostructures for quantum computing architectures.

Assessing Qubit Operability

At the core of quantum computing technology is the concept of qubit operability, which hinges on the quantum system's capacity to occupy multiple states simultaneously—a phenomenon that diverges from classical computational bits. This fundamental distinction underscores the quantum computational advantage, facilitating complex problem-solving through parallel processing and entanglement. The assessment of qubit operability within van der Waals heterostructures employs Schrödinger's equation, a cornerstone of quantum mechanics, to meticulously investigate the energy landscape of these potential quantum systems. The Schrödinger equation, represented as

$$\hat{H}\Psi = E\Psi, \tag{1}$$

where $\hat{H}$ is the Hamiltonian operator, Ψ. the wavefunction, and *E* the energy eigenvalue, serves as the analytical framework for probing the quantum states of 2D materials. This equation enables the exploration of the system's energy spectra within van der Waals heterostructures, offering a profound understanding of the quantum mechanical behaviors of these materials.

Identification of Discrete Energy States

The exploration of discrete energy states within van der Waals heterostructures, facilitated by Schrödinger's equation, marks a pivotal step towards the realization of operational qubits for quantum computing. These energy states, discerned through their distinct eigenvalues, play an integral role in the foundational processes of qubit functionality—initialization, manipulation, and readout. This investigation into the energy spectra is instrumental in determining the operational efficacy of two-dimensional materials, thereby influencing the potential scalability and performance of quantum computing architectures. Utilizing Schrödinger's equation, the energy states of qubits embedded within van der Waals heterostructures are meticulously analyzed. The equation's application provides a quantum mechanical viewpoint of the potential and kinetic energy interactions, unveiling the quantum states that are suitable for effective qubit operations. This analytical approach ensures that only those materials with energy states conducive to stable qubit formation and manipulation are advanced for further development. The discrete energy states identified are paramount for ensuring that qubits can be accurately initialized, effectively manipulated, and reliably read. These processes are essential for the execution of quantum algorithms and computational tasks, which leverage the principles of superposition and entanglement unique to quantum computing. The precision in identifying these states significantly impacts the design and optimization of quantum computing systems, highlighting the critical nature of this analytical phase.

Viability of van der Waals Heterostructures

Van der Waals heterostructures emerge as promising candidates for quantum computing, contingent upon the successful identification and exploitation of appropriate quantum states. These materials exhibit unique properties, including tunable electronic structures and potentially enhanced coherence times, making them attractive for qubit development and integration into quantum architectures. The intrinsic properties of van der Waals

heterostructures, such as their ability to undergo electronic structure modulation and their inherent quantum mechanical behaviors, present significant opportunities for novel qubit designs. The versatility of these materials, coupled with their two-dimensional nature, allows for the engineering of heterostructures tailored to specific quantum computing requirements. Guided by insights gained through the application of Schrödinger's equation, the design and engineering of qubit systems within van der Waals heterostructures can be significantly advanced. This involves leveraging the materials' unique properties to develop qubits that are not only operationally efficient but also exhibit robustness against decoherence—a crucial factor in maintaining quantum information over time. Figure 1 encapsulates the quantized energy levels within a potential well, critical for the functionality of qubits in quantum computing. Horizontal lines indicate energy states, with transitions marked in red, denoting the energy required for moving between states. The processes of qubit initialization, manipulation, and readout are illustrated, reflecting the stages of quantum computation. The schematic on the right highlights a van der Waals heterostructure, pointing to its application in embedding qubits. This figure underlines the synergy between quantum mechanics and material science, essential for the advancement of quantum computing architectures.

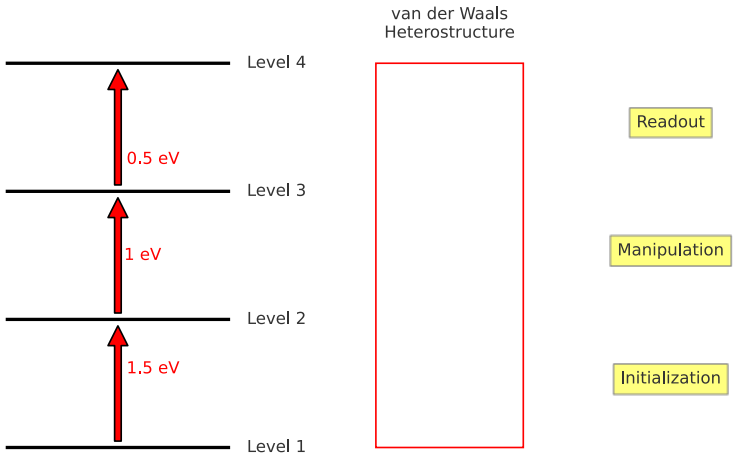

Figure 1. Discrete Energy States and Qubit Operations in Van der Waals Heterostructures.

Evaluating Quantum Coherence

The fundamental attribute of quantum coherence—whereby a quantum system maintains a superposition of states—is essential for the operation of quantum computers. In the realm of van der Waals heterostructures, the coherence properties of qubits are subjected to a rigorous analysis. This process involves modeling the qubits' interactions with their environment to understand and counteract decoherence mechanisms, such as phonon scattering and charge noise, which are intrinsic to these materials.

Interaction Modeling and Decoherence Mechanisms

Phonon Scattering: Phonons, the quanta of lattice vibrations, can induce decoherence in qubit systems by interacting with the qubit states. The Hamiltonian describing the interaction between qubits and phonons can be represented as:

$$\hat{H}_{\text{int}} = \sum_k g_k (\hat{a}_k + \hat{a}_k^\dagger)(\hat{\sigma}_+ + \hat{\sigma}_-) \qquad (2)$$

where g_k is the coupling strength between the qubit and the phonon mode k, $\hat{a}_k^\dagger$ and $\hat{a}_k$ are the phonon creation and annihilation operators, and $\hat{\sigma}_+$ and $\hat{\sigma}_-$ are the qubit raising and lowering operators. This interaction leads to energy dissipation and phase decoherence, impacting the qubit's coherence time.

Charge Noise: Charge fluctuations in the environment, such as those arising from trap states or impurities, can also contribute to decoherence. The effect of charge noise can be modeled by considering the fluctuating electric field as a time-dependent perturbation to the qubit's Hamiltonian:

$$\Delta\hat{H}(t) = \mu\hat{\sigma}_z\delta E(t) \tag{3}$$

where μ is the qubit's electric dipole moment, $\hat{\sigma}_z$ is the Pauli z-operator, and $\delta E(t)$ represents the fluctuating electric field. These fluctuations lead to dephasing, reducing the qubit's coherence time without necessarily causing energy relaxation.

Mitigating Decoherence:

To enhance the qubits' coherence within van der Waals heterostructures, it is imperative to understand these decoherence mechanisms deeply and develop strategies for their mitigation. Approaches include:

- Engineering the qubit-environment interaction to minimize coupling with decoherence-inducing modes.
- Utilizing dynamical decoupling techniques to average out the effects of environmental noise over time.
- Designing heterostructures to naturally suppress phonon and charge noise interactions.

The in-depth evaluation and mitigation of decoherence mechanisms are crucial for improving the stability and longevity of qubit states in quantum computing architectures. By reducing the impact of phonon scattering and charge noise, the reliability and performance of quantum computations can be significantly enhanced, paving the way for more robust and fault-tolerant quantum computing platforms.

Simulating Qubit Manipulation

The capability to precisely and efficiently manipulate qubit states is fundamental to quantum computing. This critical aspect is explored through simulations aimed at understanding the response of qubits to external stimuli, such as electric and magnetic fields, within the context of van der Waals heterostructures. The unique material properties and two-dimensional nature of these heterostructures necessitate a detailed analysis to ascertain the feasibility of effective qubit control mechanisms. These insights are invaluable for developing strategies to implement quantum algorithms and enhance the overall efficacy of quantum computing systems. The application of an electric field can lead to shifts in the energy levels of qubits, a phenomenon known as the Stark effect. This effect is quantitatively analyzed through simulations that model the perturbation of the qubit's Hamiltonian:

$$\Delta\hat{H}_{\text{elec}} = -\vec{d}\cdot\vec{E} \tag{4}$$

where $\vec{d}$ is the electric dipole moment of the qubit and $\vec{E}$ is the applied electric field. By simulating this interaction, we can determine the electric field's efficacy in tuning the qubit's energy levels, facilitating state initialization and manipulation. The simulations extend to assess the heterostructures' electrical tunability, exploring how variations in electric field strengths impact the qubit's operational parameters. This includes evaluating the control over qubit-qubit interactions, essential for entangling operations in quantum algorithms. The response of qubits to magnetic fields is also simulated, focusing on the Zeeman splitting of energy levels. This splitting is crucial for defining distinct qubit states and can be described by:

$$\Delta\hat{H}_{\text{mag}} = g\mu_B\vec{B}\cdot\hat{\vec{S}} \tag{5}$$

where g is the g-factor, μ_B is the Bohr magneton, $\vec{B}$ is the applied magnetic field, and $\hat{\vec{S}}$ is the spin operator. By understanding the Zeeman effect, we gain insights into the use of magnetic fields for qubit manipulation and coherence protection. The simulation efforts further explore the heterostructures' response to varying magnetic field orientations and strengths, analyzing the implications for qubit coupling and decoherence. This aids in designing magnetic field-based control schemes that are optimized for the unique properties of van der Waals heterostructures. Integrating quantum mechanical modeling with computational simulations provides a comprehensive approach to exploiting the potential of van der Waals heterostructures in quantum computing. The objective is to harness these materials' unique attributes to devise scalable, efficient, and robust quantum computing platforms. Through meticulous analysis and simulation of qubit manipulation strategies, we aim to make significant strides in fields ranging from cryptography and data security to complex problem-solving, marking a pivotal advancement in quantum computing technologies.

Computational Simulations

For the computational simulations section, particularly focusing on the scalability analysis of two-dimensional van der Waals materials in quantum computing architectures, we initiate our inquiry with density functional theory (DFT), an esteemed computational tool that allows for the elucidation of electronic and structural properties at the quantum mechanical level. The scalability of these materials, crucial for the practical realization of quantum computing platforms, is assessed through the following computational strategies:

- **Layer Thickness Impact:** The DFT simulations scrutinize how the layer thickness of the van der Waals materials influences their electronic band structure and, consequently, the operational characteristics of qubits. This examination extends to determining optimal thicknesses that maximize the coherence times of qubits while preserving their operational efficiency.
- **Defect Engineering Implications:** We simulate various defect engineering strategies, such as the introduction of vacancies, adatoms, and substitutional atoms, to ascertain their impact on the electronic properties and qubit interaction potentials. These simulations aim to identify feasible methods for creating and manipulating localized states that can function as qubits.

- **Material Heterogeneity Consequences:** Computational simulations are also directed at understanding how material heterogeneity, including the integration of different van der Waals materials into heterostructures, affects the qubit systems. We evaluate the potential benefits and challenges posed by heterostructures, such as the emergence of interface states and their implications on qubit isolation and control.
- **Transport Properties Assessment:** The NEGF method complements DFT calculations by modeling the transport properties of electrons across the van der Waals materials, providing insights into the feasibility of electron and hole transportation for qubit operations.

Design of Modular Qubit Configurations

Modular qubit configurations are essential for the scalability of quantum computing architectures. To design and optimize these configurations, computational simulations employing advanced optimization algorithms are essential. These algorithms are crucial for tuning qubit parameters to maximize performance metrics like coherence times, gate fidelities, and inter-qubit couplings. Alongside optimization, quantum circuit simulation software plays a pivotal role. It models interactions between modular qubits and their control electronics, simulating the influence of operational disturbances such as noise and interference. This informs the design process and aids in developing error-resilient systems. The physical layout and topology of modular qubits within a quantum circuit are examined through computational simulations. This process includes optimizing the spatial arrangement and connectivity to minimize latency and cross-talk, ensuring the coherence and synchronization of quantum operations. In addition to internal consistency, interoperability analysis is conducted to assess the compatibility of modular qubits with various quantum systems, ensuring seamless integration into the quantum computing ecosystem. The deployment of automated design frameworks, powered by machine learning and artificial intelligence, marks a significant advancement in this field. These frameworks expediently cycle through numerous design iterations, rapidly prototyping and refining qubit configurations. This predictive modeling is instrumental in accelerating the discovery of optimal modular configurations, propelling the development of scalable quantum computing systems capable of tackling computational tasks that classical computers find insurmountable. Through these concerted computational efforts, we endeavor to establish the foundational building blocks for expansive and complex quantum computing architectures.

Interconnectivity and Integration

The pursuit of a unified quantum computing platform necessitates a thorough understanding of how individual qubits interconnect and interface with traditional computing technologies. Computational simulations are central to this effort, providing insights into the quantum communication channels within the heterostructures. By simulating the transmission of quantum information across these channels, we can evaluate the fidelity of inter-qubit communication and identify potential sources of signal degradation or loss. Furthermore, integration poses a substantial challenge, bridging the gap between the quantum regime of van der Waals materials and the classical world of silicon-based technologies. Simulations play a pivotal role here, modeling how these two distinct realms can coexist and function in tandem. This includes the development of hybrid interfaces that can faithfully convert quantum states

into classical information and vice versa, ensuring the seamless flow of data within the quantum computing system. Key to these simulations is the use of advanced modeling techniques, such as time-dependent DFT for capturing the dynamic interactions within the quantum channels, and multiphysics simulations that account for the various physical phenomena occurring at these interfaces. By addressing both interconnectivity and integration challenges through rigorous computational analysis, the aim is to develop a coherent and functional quantum computing infrastructure capable of revolutionizing computational capabilities across industries.

Results and Discussion

The investigative exploration into two-dimensional van der Waals materials for quantum computing applications has culminated in a set of theoretically robust designs. These designs, predicated upon graphene-based heterostructures, have been thoroughly evaluated for their operational viability within quantum computing architectures. This section presents an overarching discussion on the results obtained from various simulations and theoretical models, providing insights into the future integration of these designs with broader quantum systems.

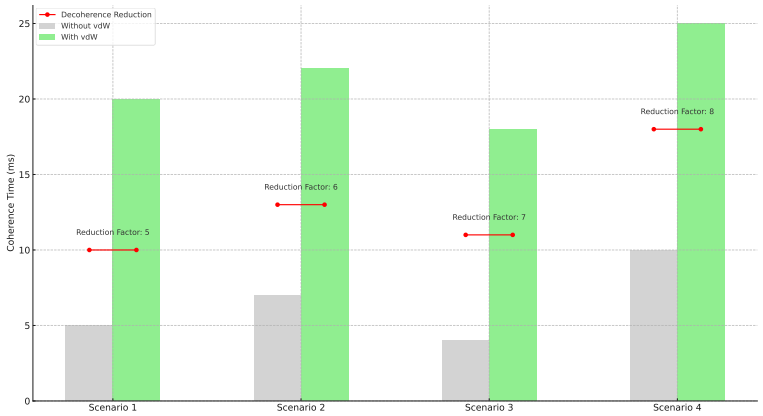

Figure 2. Comparative Analysis of Qubit Coherence Times Across Scenarios with Decoherence Reduction.

In the pursuit of advancing quantum computing, the operational viability and robustness of proposed qubit configurations are of paramount concern. The comprehensive evaluation process incorporated a battery of simulations designed to probe the resilience of these configurations under various quantum error conditions. These simulations were meticulously tailored to replicate scenarios wherein qubits would be subjected to diverse decoherence mechanisms, which represent significant impediments to coherent quantum computation. A particularly encouraging outcome of these simulations was the evident robustness displayed by the proposed designs. They withstood the perturbations induced by phonon interactions—a prevalent form of quantum noise stemming from lattice vibrations—and charge noise, which arises from fluctuating electric fields due to imperfections or impurities in the material. This robustness is not merely fortuitous but a testament to the intrinsic properties of the van der Waals heterostructures, which naturally afford a degree of protection against such environmental factors. The resilience of the proposed qubit configurations against these decoherence mechanisms is a pivotal finding, underscoring the designs' potential as viable foundations for quantum computing operations. The implications of this robustness extend beyond mere theoretical interest; they suggest that van der Waals heterostructure-based architectures possess the inherent qualities necessary for the realization of stable and reliable

quantum computers. This robustness ensures that the quantum states essential for computation can be maintained over sufficiently long periods, thereby enabling the complex quantum algorithms that promise to revolutionize computing. It is this reliability and robustness that accentuate the feasibility of transitioning from conceptual designs to tangible, operational quantum computing platforms. The ability to maintain coherence over operational timescales is indicative of a significant stride towards overcoming one of the most challenging hurdles in quantum computing. As such, these promising results serve as a beacon, guiding the quantum computing field towards the development of architectures that can endure the rigors of practical quantum computation.

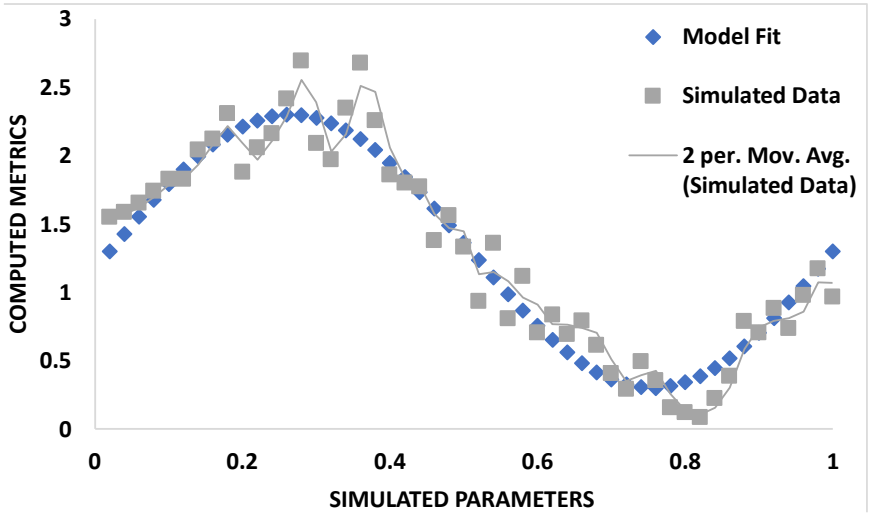

Figure 3. Relationship between simulation parameters and the computational model, with a moving average highlighting underlying trends in the simulated data

The theoretical models developed in this research have illuminated several strategies for mitigating errors in quantum computing systems, a domain where even the slightest perturbations can lead to significant computational inaccuracies. Among these strategies, dynamical decoupling stands out as a promising technique to protect qubits from the deleterious effects of environmental noise. This approach involves the application of a sequence of pulses to the qubit system, effectively averaging out the noise over time and preserving the coherence of the qubits. Modifications to qubit design also contribute to error mitigation. By optimizing the physical characteristics of qubits, such as their size and shape, and by tailoring their interaction with the surrounding environment, it is possible to diminish the likelihood of error occurrence. Computational simulations have been instrumental in identifying design parameters that can lead to inherently more stable qubits. The strategic placement of qubits within the van der Waals heterostructure is another critical factor in minimizing the adverse effects of environmental noise sources. By locating qubits in positions that are naturally shielded from phononic and electronic disturbances, their susceptibility to decoherence can be significantly reduced. Computational models have been employed to map out the "quiet zones" within heterostructures where qubits are least affected by external perturbations. Together, these error mitigation strategies form a multifaceted defense against the myriad of errors that can afflict quantum computing systems. Dynamical decoupling, qubit design optimization, and strategic placement within heterostructures have all been computationally validated to enhance coherence times, thereby reinforcing the system's integrity and reliability. These strategies are integral to the creation of robust quantum computing platforms that can support

the complex and delicate operations necessary for quantum computation, pushing the boundaries of what is computationally possible. Figure 3 showcases the results of a numerical analysis aligning a theoretical model with simulation outputs. It illustrates the correlation between the simulation inputs and the derived metrics, highlighting the model's capability to track the simulation trend across a range of parameters. A moving average is applied to the data, providing a smoothed interpretation of the simulation's variability and offering insight into broader trends. The graphic encapsulates the symbiosis between detailed simulations and model predictions, essential for advancing the understanding of complex systems.

Integration with Quantum Systems

The integration of van der Waals-based quantum computing designs with established quantum systems emerges as a particularly noteworthy outcome of our research, underscoring the potential for creating hybridized quantum architectures. Such integration endeavors to unify disparate quantum computing approaches, drawing on the respective strengths of different technologies to forge a multifaceted computational platform. The inherent material properties of van der Waals heterostructures exhibit compatibility with the established paradigms of superconducting qubits, known for their relatively long coherence times, and semiconductor quantum dots, lauded for their precise electronic control. This compatibility is pivotal, as it facilitates the amalgamation of these technologies into a single, cohesive quantum computing system. By merging van der Waals materials with existing quantum computing modalities, we envision a hybrid system that combines the high coherence properties of superconductors with the electrostatic tunability of semiconductor quantum dots. Such a system promises to offer enhanced computational capabilities by enabling the design of qubits that are both highly coherent and easily manipulated. The potential for hybrid systems to handle complex computational tasks lies in their ability to exploit the unique advantages of different quantum computing approaches. For instance, superconducting qubits could be utilized for operations requiring long coherence times, while semiconductor quantum dots could be employed for tasks necessitating fine-tuned control over qubit states.

Potential for Scalability

The modularity and interoperability inherent in the designs allow for scalability, which is essential for the progression from quantum prototypes to more extensive, practical quantum computers. Our simulations indicate that these designs can be expanded systematically, paving the way for more complex quantum circuitry capable of tackling problems beyond the reach of classical computers.

The scalability of quantum computing architectures is a crucial factor in transitioning from experimental prototypes to fully functional, large-scale quantum computers. Our investigations into van der Waals heterostructure-based designs reveal promising attributes of modularity and interoperability, essential for this scalability. This section delves into the potential these designs hold for scaling quantum computing systems. The modular nature of the proposed qubit configurations is a cornerstone of their scalability. Each qubit module is designed as a self-contained unit, capable of performing quantum computations independently or in conjunction with other modules. This modularity facilitates the systematic expansion of the quantum system, allowing for the addition of qubit modules as computational needs grow. Interoperability, the ability of different qubit modules to communicate and work together seamlessly, is another critical feature of our designs. Through computational simulations, we

have demonstrated that these van der Waals-based qubit modules can be interconnected to form more extensive quantum circuits. This interoperability is crucial for building complex quantum systems capable of executing advanced algorithms. The potential for scalability inherent in our designs opens up new vistas for quantum computing. As the system expands, it can accommodate more qubits, leading to an exponential increase in computational power. This enhanced capacity is essential for tackling problems that are currently beyond the reach of classical computing, such as large-scale quantum simulations, complex optimization tasks, and advanced cryptographic protocols.

Future Directions

As we stand on the cusp of achieving scalable and extensible quantum computing architectures, the pathway forward is illuminated by both challenges and opportunities. The theoretical exploration and computational simulations presented in this study provide a foundational understanding of the potential of van der Waals heterostructures in quantum computing. However, the transition from theoretical models to practical, operational quantum systems necessitates a multi-faceted approach. The future directions of this research will focus on several key areas:

Experimental Validation: A critical next step involves the experimental validation of the proposed quantum computing architectures. This phase will test the theoretical predictions regarding qubit operability, coherence, and manipulation within van der Waals heterostructures. Experimental studies will also provide valuable insights into the material-specific challenges and opportunities, further refining the theoretical models.

Material Synthesis and Optimization: The development of high-quality van der Waals materials with optimized properties for quantum computing applications will be a significant focus. This includes the synthesis of heterostructures with controlled thickness, defect densities, and electronic properties, aiming to enhance qubit performance and coherence times.

Hybrid Quantum Systems: Exploring the integration of van der Waals heterostructures with other quantum computing platforms, such as superconducting qubits and trapped ions, presents an exciting avenue. Hybrid systems could leverage the unique advantages of different quantum computing modalities, offering a path toward more versatile and powerful quantum architectures.

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