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Current status and future development of quantum computing

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Abstract. To overcome the scaling limitations of conventional semiconductor chips, quantum computing has emerged and experienced significant growth in recent years. Quantum computing utilizes resources such as quantum superposition and quantum entanglement to encode and process information. Compared to classical computing, this technology can provide exponential acceleration in the field of ultra-large-scale parallel computing. Consequently, its practical application is anticipated to have profound impacts on information and related technologies. The paper employs a comparative analysis approach to systematically examine the research progress of quantum computer technology. Specifically, the study emphasizes the analysis and consolidation of various quantum computing technology routes, critically evaluates their advantages and disadvantages, and provides a foresight into their future development trends. Currently, research on quantum computing technology is in its early stages and is evolving rapidly. Multiple technical paths are being pursued, resulting in a diverse and competitive landscape that is expected to persist in the short term, as it will take some time before the practical application of quantum computers becomes feasible.

Keywords: Quantum computing, neural network, quantum computer, comparative analysis.

1. Introduction

In the 21st century, widely recognized as the era of information, the processing capacity of information is undoubtedly the core competitiveness in this age of information explosion. While existing computers have already achieved a significant leap in computational power, they are currently facing challenges such as slowing the development speed of traditional chips, reaching the microscopic limits of processes, and difficulties in addressing thermal issues, making it difficult to sustain the rapid pace of development. Consequently, quantum computing has emerged as a viable alternative to break through the process scale limits of traditional chips and has experienced vigorous growth in recent years. In 2019, Google claimed to have achieved quantum supremacy [1] and demonstrated, for the first time, the superiority of quantum computers over traditional architecture computers. In an experiment where the world's top supercomputer Summit would take 10,000 years to complete, Google's quantum computer accomplished the task in only 3 minutes and 20 seconds. Quantum computing has become a focal point of attention and expectation from various stakeholders. Major countries and regions worldwide have increased their support and investment in public research and development funding in the field. Notably, there have been remarkable scientific and technological advancements, with multiple technology pathways progressing in parallel.

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Previous comprehensive articles on quantum computing have explored research progress, application exploration, and the cultivation of industrial ecosystems. Some focus on explaining why quantum computing is still in the NISQ era, while others analyze specific technological pathways. Existing research mostly analyzes quantum computing as a whole or focuses on individual technology directions. There is a lack of comprehensive comparative analysis studying the technical principles, developmental trajectories, advantages, and disadvantages among the major factions of quantum computing.

However, breakthroughs often emerge from interdisciplinary discussions, where different technology directions can combine their similarities and differences in horizontal comparisons, thereby propelling the next wave of development in quantum computing. Thus, the paper selects four currently influential major factions: superconducting quantum, ion traps, silicon quantum dots, and Rydberg atoms. The research aims to provide a thorough analysis of the research progress in quantum computing technology and compare the technical principles, developmental trajectories, advantages, and disadvantages of various quantum computing technology routes. Moreover, the paper provides a perspective on their future development trends. Through this systematic introduction of multiple factions in quantum computing and the prediction of possible future optimization directions, the study hopes to guide the realization of practical application scenarios that society expects.

2. Introduction to Quantum Computing

Quantum computing refers to a brand new information technique based on the principles of quantum mechanics and through various coherent characteristics of quantum systems, applying quantum superposition, quantum entanglement, and other behaviors for information processing [2]. It has been demonstrated that it offers significant advantages over classical computing in addressing various problems. Once practical, it will have a far-reaching impact on information-related technologies.

Since the development of quantum computing, after decades of development, multi-faceted research and exploration have developed simultaneously, and countless schools of parallel development and open competition have emerged. This article will select four major influential schools to briefly introduce and evaluate their current status and future.

Superconducting loops are characterized by the presence of a current that circulates within the circuit without encountering any resistance, exhibiting oscillatory motion as it alternates back and forth. The microwave signal injected stimulates the current, causing it to transition into a superposition state. This is the technology adopted by most quantum computing corporations, including Google and IBM.

Trapped ions use carefully tuned lasers to cool and trap ions whose quantum energy is determined by the position of their electrons, bringing them into a superposition state. IonQ is a pioneer of ion trap technology.

Silicon Quantum dots refer to the creation of an artificial atom that uses a microwave to control the quantum state of electrons by adding electrons to pure silicon. Intel mainly uses this technology.

The quantum calculation of neutral atoms based on Rydberg atoms has made a huge leap in recent years. A Rydberg atom is an atom in a highly excited state. In this state, some electrons inside the atom are excited to orbits with a higher principal quantum number, giving it many special physical properties.

In addition, there has been some research progress in the Ultracold yard, topological qubits, diamond vacancies, and other directions, but they are still in the basic research stage. There has never been a substantial breakthrough in the physical implementation of topology. The scalability of diamond vacancies is limited by principles, and future development remains to be seen. Therefore, this article only discusses and analyzes the above four quantum computing technology routes.

3. Comparative analysis

There are similarities and differences between various technical paths, and the development speed is also fast or slow. Which path will ultimately lead to success? It is still difficult to conclude. The current development of technical routes is still in a diversified and parallel trend, and the possibility of technological convergence has not yet been seen.

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The study selected three aspects: technical principles, development history, and advantages and disadvantages as the entry point. By comparing different technical paths, the uniqueness of each school was obtained.

3.1. Technical Principles

Currently, the mainstream technological routes, although collectively referred to as quantum computing, exhibit significant differences in their underlying principles. It can even be argued that "quantum" simply denotes the requirement to utilize quantum bits for computation, while the approaches to realizing these quantum bits vary greatly.

The Josephson junction, or JJ for short, serves as a fundamental component in the construction of superconducting qubits. To construct a Josephson junction, two superconducting layers are separated by an insulator, such as nitride-oxide-nitride-oxide (ONO), forming a sandwich-like structure. According to the "BCS theory", at a temperature close to 0K, electrons combine remotely into a "BCS pair" or "Cooper pair" by interacting with the positively charged ion lattice. This condensation of electrons into Cooper pairs is part of the mechanism that causes the phase transition of metals from their normal to superconducting states. It makes a rigorous quantum interpretation possible. Cooper pairs circulate within the superconducting solid without any resistance. Their electrons are entangled in their lowest energy state. Cooper pairs are weakly bonded and easily affected by heat, which increases and accelerates the vibrations of the ion lattice. This is why superconductivity usually occurs at pretty low temperatures. Nowadays, almost all superconducting qubit circuits are composed of Josephson junctions. Josephson junctions can be used to alter the coupling between different components of a circuit, making superconducting circuits essentially lossless at frequencies well below the superconducting gap.

An ion trap is a device that traps ions in a vacuum. The main principle is to bind charged ions (which can be macroscopic particles) to a specific area in space through the alternating electric field in space. The alternating electric field can form a structure similar to a rotating saddle surface. When the saddle shape and rotation speed are high enough, the ions can be stably bound. In an ion trap quantum computer, electrodes are used to generate an electric field, and ultra-cold ions are "trapped" in the electric field. The trapped ions act as entangled qubits to perform advanced calculations. One solution for the ion trap is the chip trap, which is designed for the QCCD architecture of the ion trap. It can control the potential well around the ions to move the ions to any position on the spatial plane so that the two ions to be entangled are closely connected. Arrange them together (less than 5 microns), and then use lasers to align them to perform MS gate or phase gate operations to build entanglement. Another solution is to use a multi-channel laser: Instead of moving the ions around, we can fix the ions and shine a beam of light at each ion. In this way, we only use the control function to control the laser. The switch can perform logic gate operations on the ions, thus reducing the task execution time by one to two orders of magnitude.

Silicon-based quantum technology creates silicon quantum dots by adding electrons to pure silicon, relying on microwaves to control the quantum state of electrons. Research directions have mainly focused on gallium arsenide, silicon-germanium heterojunction, and Metal-Oxide-Semiconductor (MOS) materials, which eliminate other electrons by isolating one electron from the outside in three-dimensional space. According to the influence of quantum dots, qubits can be encoded according to the different degrees of freedom of electrons in quantum dots. Single-electron self-selected encoding, hole encoding, charge qubits, and qubits using multiple electron manipulation encoding have been developed. On this basis, research on long-range coupling and expansion of multi-qubits is also progressing steadily.

Rydberg atoms are not atoms corresponding to a specific element, but a type of atom in a highly excited state. In this state, some electrons inside the atom are excited to orbits with higher principal quantum numbers, giving them many special physical properties. For example, when the principal quantum number n of a Rydberg atom is pretty large, there will be a dipole-dipole interaction with the n^4. This strong dipole-dipole interaction raises the Rydberg energy level of the ground-state atoms around the Rydberg atom. This is called the Rydberg blocking effect, and it is a very important property. The radiative lifetime of Rydberg atoms scales with the cube of the principal quantum number n.

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Therefore, the utilization of atoms with higher atomic numbers becomes necessary to achieve longer radiative lifetimes. Currently, Rb atoms are generally used, and a few also use other atoms such as Sr. Due to the limited spatial overlap between the ground state wave function and the Rydberg state wave function of an atom, the coupling between the two through the electromagnetic field is weak. This means that the Rydberg state is difficult to decay to the ground state, that is, it has a relatively long atomic lifetime. The lifetime of Rydberg atoms is on the order of hundreds of microseconds, while the atomic lifetime of ordinary low-excited states is only tens of nanoseconds.

All in all, different technical routes have their unique characteristics, and realize qubits and their precise control through different ways, creating the possibility of practical quantum computers.

3.2. Development History

The emergence of quantum computing came rather late, with the concept of combining quantum mechanics with computer technology being first proposed by American physicist Feynman in 1982. He introduced the idea of utilizing quantum computers to simulate and study quantum systems [3]. In 1985, David Deutsch and his team at the University of Oxford further elaborated on the concept of quantum computers and proposed the universal quantum Turing machine as a model for general-purpose quantum computing [4]. They emphasized that the composition of logic networks using quantum logic gates is the core aspect of achieving universal quantum computation.

In 2019, international experts reached a consensus on the three stages of development for quantum computing in the "White Paper on Quantum Information and Quantum Technology" (Hefei Declaration) [5]. The first stage involves achieving quantum computational supremacy, where a quantum computer surpasses classical computers in solving specific problems, requiring the coherent manipulation of at least 50 qubits. The second stage aims to develop specialized quantum simulation systems with practical applications, enabling the coherent manipulation of hundreds of qubits to outperform classical computers in solving real-world problems. The third stage focuses on realizing programmable universal quantum computers, requiring the coherent manipulation of at least several million qubits. Currently, only a few countries possess quantum computers that have completed the first stage.

When examining the history of superconducting quantum technologies, the undeniable starting point can be traced back to the discovery of the Josephson effect by Welsh theoretical physicist Brian D. Josephson in the early 1960s [6]. This effect describes the quantum tunneling of Cooper pairs through a very thin insulating barrier inserted into a superconducting material. Based on this discovery, the Josephson junction became the foundation for superconducting qubits. The NEC Research Institute in Japan was the first to demonstrate the use of superconducting circuits as qubits in 1999 [7]. However, it was only after 2006 that superconducting technology began to lead the development of quantum computing hardware. In 2016, IBM announced a 5-qubit superconducting quantum processor and launched a cloud platform [8]. In 2019, Google designed the Sycamore processor, which successfully demonstrated quantum computational supremacy by surpassing classical supercomputers in solving random quantum circuit sampling problems [9]. In 2021, a research team led by Pan Jianwei and Zhu Xiaobo at the University of Science and Technology of China successfully developed a 66-qubit programmable superconducting quantum computing prototype that also achieved quantum computational supremacy [10].

At present, IBM is at the forefront of global technological advancements in the field of superconducting quantum computing. Judging from the current development trend, it will be difficult for other superconducting quantum computing companies, including Google, to surpass them in a short time. IBM also reflects the United States' dominance in the field of superconducting quantum computers. In 2021, IBM launched Eagle, the first quantum processor with more than 100 qubits [11]. In 2023, the company launched Condor, featuring an impressive 1121 qubits [12]. At present, superconducting quantum computers can achieve double-qubit gate fidelity: 99.72% (MIT 2021), system scalability: 65 qubits (IBM 2021) / 18 qubits entanglement (ZJU & USTC 2019), double-qubit gate time-consuming /Coherence time: 10~200ns/1ms (IBM 2021)

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Silicon-based quantum theory was proposed almost at the same time as superconducting quantum. The beginning of silicon-based quantum research is generally considered to be in 1997 when DiVincenzo and Loss proposed using the spin electrons of semiconductor quantum dots as the carrier of qubits to build a quantum computer [13]. In 2007, Eriksson's research at the University of Wisconsin-Madison was the first to achieve single electron occupation in doped silicon-germanium heterojunction quantum dots [14]; a year later, the spin-blocking phenomenon was observed on the same structure [15]. However, the fidelity of dual-qubit gates in silicon-based quantum technology has been difficult to improve for a long time and has always stagnated below 99%. This is also the biggest bottleneck encountered by this technology. This is also the biggest bottleneck encountered by this technology. Until 2022, Nature rarely published three papers in succession, which marked that silicon-based quantum computing broke out of the fog. Researchers from the QuTech Quantum Computing Laboratory in the Netherlands [16], the RIKEN Center for Emergent Matter Science in Japan [17], and the University of New South Wales (UNSW) in Australia [18] verified that the fidelity of the silicon two-qubit gate reached 99 % or more, exceeding the fault tolerance threshold of quantum computing. This means that the quantum error correction of silicon-based quantum has met the fidelity access requirements, making silicon-based quantum computers a feasible proposition. The "last mile" of silicon-based quantum practicality is being cleared.

The ion trap was proposed by Dehmelt, Wolfgang Paul, and others and they jointly received the Nobel Prize in Physics in 1989 for their "development of the ion trap technique" [19]. In 1995, Ignacio Cirac and Peter Zoller proposed a method using ultracold-trapped ions to achieve quantum gates [20]. This proposal led to a new quantum technology approach known as ion trap quantum computing.

Currently, ion trap technology can be categorized into two schemes. The first one is chip traps, which had a late start and achieved ion confinement only in 2010 but still faced difficulties in controlling the ion's position. It was not until 2020, that Honeywell demonstrated the execution of quantum algorithms (6 qubits) using the chip trap architecture [21]. So far, this architecture still only allows ion transport in one dimension and cannot be extended to a two-dimensional plane. Metaphorically speaking, it can only make ions travel straight on a road without the ability to make turns.

The other scheme involves multi-channel laser setups. IONQ, as a pioneer in this field, announced in 2020 the development of the "most powerful" ion trap quantum computer in the world. This quantum computer is equipped with 32 "perfect" quantum bits with low gate error rates, resulting in a quantum volume of 4 million [22]. In 2020, the University of Maryland (UMD) achieved a 13-qubit quantum circuit and completed error correction using the Shor code [23]. Currently, IonQ, AQT, and Quantinuum (a subsidiary of Honeywell) have all achieved at least 20 qubits.

Presently, ion trap systems can achieve a two-qubit gate fidelity of 99.94% (GTRI 2021), system scalability of 32 qubits (IONQ 2022)/24 qubit entanglement (Innsbruck 2021), and a duration/coherence time for a two-qubit gate of 1 μs to 200 μs/60 minutes (Tsinghua 2020).

In comparison, the connection between Rydberg atoms and quantum computing emerged much later. It was first proposed in 2000 by Jaksch, Lukin, and others to confine atoms in an array of optical traps and excite them to Rydberg states [24]. The dipole-dipole interaction between the Rydberg atoms can be utilized to implement universal quantum logic gates. Subsequently, Lukin's team further proposed trapping a cloud of Rydberg atoms in an optical lattice, where the collective excitation levels of the Rydberg atom ensemble are not equidistant due to the dipole blockade effect between the atoms. By achieving single-excitation states, quantum bits (qubits) and universal quantum logic gates can be defined.

However, before 2016, neutral atom systems, compared to other systems, were not competitive in implementing quantum computing. Although the single-atom resolution in optical lattices had been achieved, along with remarkable accomplishments such as observing the superfluid-mott insulator transition, the loading of atoms was random, and most of the coherent operations on atoms were global. In other words, large-scale qubit preparation without defects and addressing capabilities were challenging in optical lattice systems. As a result, these systems mainly focused on quantum simulation.

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A turning point occurred in 2016 when three research groups made significant progress. Jaewook Ahn of KAIST in South Korea [25], A. Browaeys of CNRS in France [26], and M.D. Lukin of Harvard in the United States [27] utilized spatial light modulators (SLMs) and acoustic-optical deflectors (AODs) to achieve defect-free preparation of atom arrays. This breakthrough demonstrated the potential for large-scale defect-free atom arrays and the ability to address individual atoms for qubit rotation. Consequently, numerous research groups started building experimental platforms for atom arrays in the subsequent years, leading to a simultaneous advancement of theoretical proposals and experimental techniques.

In summary, the development trajectories of various technological paths, although varying in length, share a common characteristic of facing challenges and experiencing seemingly insurmountable moments as well as breakthroughs. Currently, superconducting and ion trap systems remain at the forefront, consistently leading the field. The prospects for other approaches are also promising, arousing anticipation for their future development.

3.3. Advantages & Disadvantages

There are three main indicators for comparing the advanced nature of quantum computer technology: Two-qubit gate fidelity, System scalability, and Two-qubit gate time consumption/coherence time. These indicators can not only reflect the current results of each technical route but also predict its future development prospects to a certain extent, providing a reference for the reasonable allocation of talent and capital.

Superconductivity, being the longest-developed, most heavily invested, and extensively researched technological pathway, undoubtedly possesses unique advantages. The designability and adjustability of superconducting qubits are advanced because their manufacturing is similar to traditional silicon-based chips and can be compatible with existing chip processes. Companies in the traditional silicon-based chip field all hope to achieve breakthroughs in the direction of superconducting quantum so that they can easily improve production lines and manufacture microelectronic components without having to overthrow everything. By manipulating the processing technology, the inductance, capacitance, and Josephson energy of a superconducting qubit can be adjusted. This enables the modification of the qubit’s energy level and its coupling strength, ultimately altering the qubit’s Hamiltonian. Superconducting quantum computing can greatly reduce the probability of error. In ordinary conductors, free electrons collide with and bounce off the positively charged ions of the crystal lattice, transferring kinetic energy into vibrations. The vibrations generate heat, thus consuming information about the scattered electrons before they can be calculated, thus creating noise. But in a superconductor, Cooper pairs have no resistance when passing through the lattice, that is, they do not collide, and therefore do not cause information loss caused by resistance.

Under the exploration of scientific researchers, the limitations of superconducting quantum are still constraints to its expanded development and application fields. At present, it seems that the short coherence time is the most troublesome major shortcoming of superconducting qubits. The difficulty of achieving quantum coherence is proportional to the number of qubits. As the number of qubits grows, evaluating the fidelity of quantum computing across the entire chip becomes progressively more challenging. The coherence time of superconducting qubits is less than 300 μs, making it difficult to maintain stability. Beyond that, its coupling is limited to neighboring qubits, meaning superconducting qubits tend to interact only with neighboring individuals, making complex calculations a challenge. Likewise, door fidelity still needs improvement. To reduce the high cost of encoding logical qubits under prototype algorithms. Energy dissipation due to the quantum system environment is another major problem in superconducting quantum, which can lead to quantum errors. It is quite difficult to maintain the temperature near absolute zero, and any deviation in temperature will cause elements such as the Josephson junction to dissipate energy, affecting the stability of the quantum computer. There are many ways to minimize quantum dissipation, such as using Purcell filters in superconducting resonators to minimize qubit-environment coupling and enabling “quantum non-collapse” in three-qubit circuits, using two The qubit detects potential errors in the remaining qubit and resolves the deviation. Last but not least, superconducting quantum computing devices are large and difficult to miniaturize. Transistors have shrunk to the nanometer scale, but superconducting quanta are still measured in millimeters. Superconducting quantum computers operate at ultra-cold temperatures and have very high-frequency electric fields, where quantum coherent information may be lost or absorbed in some random fashion as it passes through the dielectric layer. The current common practice is to use an open capacitor, dilute the electric field, and use a vacuum as an insulating layer, at the expense of a much larger capacitor than other implementations.

The ion trap, advancing alongside superconductivity, is a remarkable method for controlling quantum bits. Its most captivating feature is the remarkably long coherence time. Currently, the record for quantum bit coherence time is achieved using ion trap technology by the research group led by Dr. Qihan Jin at Tsinghua University, surpassing an hour for a single quantum bit [28]. Furthermore, the preparation and readout of ion trap quantum bits are more direct. The fidelity of initialization and readout data is unparalleled by any other quantum technology. Currently, the ion trap system developed by Quantinuum, utilizing barium ion qubits, has achieved a state preparation and measurement fidelity of 99.9904%—the highest among all existing quantum technologies [29]. Moreover, ion trap quantum bits possess the advantage of high reproducibility. All ions of a specific type and isotope are fundamentally identical, resulting in the same microwave or laser frequencies required for each ion within the processing system, as well as equal coherence times for each ion. This enhances the reproducibility of quantum bits compared to other technologies, while also limiting the number of calibration steps required at the start of computations.

For ion trap technology, its problems need to be considered from two perspectives: short-term (<100qubits) and long-term (100-100kqubits). In the short term, the biggest problems faced by ion traps are the design and manufacturing process of chip traps and the control of multi-channel lasers, and these are only a matter of time. The QCCD architecture can theoretically achieve an almost unlimited number of qubits with a limited number of lasers. However, if the moving distance of the ions is too large, it will cause serious time-consuming problems (on the order of microseconds), so the chip trap needs to be made very small (1mm~1cm) to maximize time-saving. However, this will lead to serious heating problems for the ions in the chip trap (the heating rate of the ions is inversely proportional to the fourth power of the distance from the surface of the chip trap. Making the system smaller means a serious heating rate). If the heating rate is too high If it is greater than 100 phonons/s, the fidelity of the logic gate will be too low (less than 99.9%). In addition to the time-consuming execution of logic gates, the movement of the ions themselves and the laser cooling process after the ions have moved are also time-consuming, and this time-consuming part accounts for 98%-99% of the time to run a task. Taking all of these factors into account, the time it takes for the ion system to execute a 2-qubit logic gate is usually around 1 ms. The excessively long logic gate operation time is the result of the ion trap system. A disappointing fact is, compared to the 50 ns operating time of the superconducting system, as the number of multi-channel laser ions increases, the degree of freedom of the system increases proportionally, and the vibration modes become more and more complex. The selection of a certain vibration mode of ions will often stimulate other vibration modes, thereby reducing the system logic gate. Fidelity. The laws of physics determine that as the number of ions increases, it will increasingly exhibit macroscopic properties rather than quantum properties.

In the long term, the biggest problem of the ion trap system is the low fidelity of the logic gates. This problem is not the most urgent at this stage, but it will become more and more serious in the future. If you want to expand the number of qubits to tens of thousands, then whether it is the QCCD solution whose time is too long or the multi-channel laser solution whose coupling is too weak) only involve close-neighbor coupling, or local full connectivity, the same as superconducting systems, and it is not realistic to expand to tens of thousands of qubits, so the only way out is a quantum network. This solution draws on the concept of quantum teleportation and is similar to quantum computing in photon systems. It can perform logic gate operations on two qubits without direct interaction, so multiple different ions can be All ions in the trap are contained within the system. This requires the establishment of a quantum network, which is not very optimistic at the moment.

Compared with other quantum computing, silicon quantum dots technology has three main outstanding advantages: First, most of its micro-nano processing technologies are compatible with traditional metal-oxide-semiconductor (MOS) processes and are large-scale scalable. The potential of chip processing will be easy to connect with the semiconductor industry in the commercialization stage, and it will be a "quantized version" of the traditional semiconductor industry; secondly, the most superior property of spin qubit is that it will not be interfered too much by charge noise. As long as isotope-purified Si is used as quantum dots, theoretically, the coherence time will be longer. For example, the nuclear spin coherence time of silicon-based phosphorus atoms can reach 30 s, and the electron spin coherence time exceeds 500 ms. Single-bit gate operation features high precision; third, in the spin of electrons, holes, or nuclei Bit encoding is performed on the computer, which is a semiconductor quantum computing platform based on electrical control and has the advantage of full electrical control.

Although silicon quantum dots have made great progress in the past 10 years, it is still in the laboratory exploration stage. It still faces the problem of a small number of qubits, insufficient fidelity, unstable bit gate operation, and state reading fidelity, and measurement and control circuits. Problems such as imperfection and inability to automatically measure integrated quantum chips. For quantum dot systems that break through the double-qubit fault-tolerance threshold, when the number of bits increases, factors such as inter-gate crosstalk will significantly increase the complexity of controlling quantum dot parameters and reduce the fidelity of gate operations. Based on Si/SiGe heterojunction Work on one-dimensional six-bit arrays of quantum dots enables high-fidelity single-bit gates, but two-bit logic gates have only about 90% fidelity. Based on the current technical status, the next core research task of silicon-based quantum computing is to use modern silicon semiconductor industry technology to achieve universal logic gate control and multi-qubit coupling, thereby building a large-scale and stably scalable silicon quantum chip. Toward a fault-tolerant quantum computing prototype.

Utilizing Rydberg atoms as qubits offers distinct advantages that cannot be replaced by other technologies. The inherent indistinguishability of identical particles significantly improves the similarity of quantum bits. Its scalability should not be underestimated either, as there are already quantum simulators with 256 atoms. Without considering defects, current optical trapping techniques can generate atom arrays with over 800 atoms. The unique long-lived characteristics of Rydberg atoms suggest that they possess long coherence times, which are crucial for the stability of quantum computations.

Rydberg atoms exhibit rich, direct, and long-range interactions. Leveraging the Rydberg states of atoms, interactions can take the form of diagonal van der Waals interactions or nondiagonal resonant dipole-dipole interactions. This enables coupling between qubits that goes beyond nearest-neighbor interactions, allowing for interactions between distant qubits. However, there are still several major bottlenecks to address. For instance, the fidelity of gates is still not sufficiently high, making qubits impractical when there are many. The efficiency of preparing initial states, such as antiferromagnetic states, is low when performing quantum simulations. Rydberg laser technology can also be improved, mainly by reducing linewidth and various types of noise. Additionally, achieving single-qubit addressing in large-scale atom arrays remains unrealized.

4. Conclusion

Through the method of comparative analysis, this article intuitively introduces and compares four mainstream quantum computing technology routes, including superconducting quantum, ion trap, silicon quantum dots, and Rydberg atomic qubits, and evaluates their current status and future possibilities. At present, there are various systems of quantum computing. Some quantum computing methods have achieved achievements that are beyond the reach of other routes. Some quantum computing methods are still in their infancy, but which route can achieve truly practical quantum computers in the future is not yet known.

The current quantum computer is still in the NISQ - Noisy Intermediate-Scale Quantum era. It reveals that the current qubits have strong instability. Beyond the extremely short stable duration, the quantum superposition state stored by the qubits has a large collapse probability. Existing quantum computers

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can only achieve several qubits within a few hundred. Existing limitations in physical implementation hinder the possibility of building large-scale quantum computers that can maintain stable states. The extremely high error rate and short stabilization time make quantum computing error correction capabilities urgent. However, all current research can only achieve corresponding quantum error correction when the number of qubits exceeds 1,000, which is contrary to the current status of quantum computers. Generally speaking, quantum computing technology research is still in the early and rapid development stage, and various technical routes are showing a diversified and open competitive situation. This competitive situation will continue to exist in the short term, and it will take some time before the practical application of quantum computers is implemented.

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