Quantum Computer Hardware

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1. Quantum Technology

The emergence of second-generation quantum technologies and the understanding of how to use quantum phenomena in computing, measurement, communication, and metrology to reach achievements beyond the ability of classical systems have been discussed in various research and industrial fields in recent years. The use of quantum properties to solve complex problems faster than classical computers led to the creation of a field called quantum computing. Quantum computers are not only faster than conventional classical computers, but they also have a different framework for solving problems due to the laws of quantum mechanics such as superposition and entanglement. The main building blocks of quantum computers, or quantum bits (qubits), which are counterparts of classical bits, are the central components of quantum computing. The quantum features of qubits lead to the ability to perform parallel processing at once. Quantum computing can be a valuable tool for solving complex problems in various fields, including chemistry, cryptography, material science, cosmology, and machine learning.

One of the basic units of quantum technology is the quantum computer. The development of quantum computers has greatly influenced the advancement of other technologies, such as quantum sensing, cryptography, and teleportation. Therefore, in the following, the different parts of quantum computers and their main building blocks, i.e., qubits [1] will be introduced.

2. Quantum Computer Hardware

Two main quantum architectures are gate model quantum systems and Ising machine systems. The gate model uses quantum gates to manipulate qubits and solve problems; however, the stability of qubits and their integration into microchips pose significant challenges. The second technology is the Ising-machine system, named after Ernst Ising, which is a physical device designed to solve complex combinatorial optimization problems by finding the best combination. The basic idea behind these systems is to map optimization problems onto a mathematical model of interacting magnet spins known as an Ising problem. Both quantum annealers and gate-model quantum computers rely on qubits. However, quantum annealers are more robust to noise but are limited to combinatorial optimization problems and lack the universality of gate-based architectures [2]. Henceforth, the gate model will be the topic of discussion in the remaining part of this entry.

There are four abstract layers to model hardware components for an analog or gate-based quantum computer. The “quantum data plane” is where the qubits reside, including physical qubits, structures to hold them, any support circuitry, and the ability to measure the qubits’ state and perform gate operations. The “control and measurement plane” that converts the control processor’s digital signals to the analog control signals needed to perform the operations on the qubits in the quantum data plane also converts the analog output of measurements of qubits in the data plane to classical binary data that the control processor can handle. The “control processor plane” identifies and triggers the proper Hamiltonian or sequence of quantum gate operations and measurements, and the “host processor” handles access to networks, large storage arrays, and user interfaces. Among the mentioned items, the quantum data plane is the “heart” of a quantum computer, and its main part is the qubit [3]. Qubits can be made from structures such as photons, ions, and semiconductor circuits. The important thing is to choose a structure that can produce separate binary states, such as electron spin. Qubits are inherently error-prone and difficult to control; therefore, overcoming these errors is necessary to build stable quantum computers. Therefore, many physical qubits must be used for error correction to produce an entity that logically behaves like a qubit in a quantum circuit or algorithm, a process known as quantum error correction (QEC)

[4]. To have useful quantum computers with stability, error correction, and fault-tolerant capabilities, logical qubits, which usually consist of many physical qubits, are used.

Quantum error correction is a process that reduces errors in qubits using a set of different techniques and algorithms to detect and fix errors. To perform this process, the information stored in a physical qubit must be distributed to some other qubits; the set of these physical qubits is called a logical qubit [5]. Depending on the platform type or algorithm chosen, hundreds or thousands of physical qubits may be needed to support one logical qubit, and a quantum computer needs at least a few hundred logical qubits to perform practical calculations.

After a brief introduction to the different components of a quantum computer, the first question that arises is how close we are to building an ideal quantum computer that would be capable of performing fully controllable operations (fault-tolerant era) [6]. The truth is that quantum computers are currently working in the Noisy Intermediate-Scale Quantum (NISQ) era; this means that existing quantum computers have a significant error rate, and their size (in terms of the number of qubits) is still limited; for this reason, they are still unable to be superior to classical computers [7]. One of the most accessible ways to move from the NISQ era to the fault-tolerant era is to increase the number of physical qubits in quantum hardware. One of the classification models of quantum computers is based on the qubit model, which will be discussed below.

2.1. Superconducting Qubits

Superconducting qubits are artificial atoms made from Josephson junction-based nonlinear superconducting circuits. The mentioned circuit, which acts like a quantum oscillator, causes the formation of different levels. Due to the existence of the Josephson junction, the first two levels have a distinct energy difference from the rest, which ultimately forms the optimal two-state system for qubits. Superconducting qubits require elaborate wiring and very low temperatures of about 10 mK. The energy range required to detect and control superconducting qubits is around 0.1 to 12 GHz [8]. Because of the rapid growth of coherence time in superconducting qubits, beginning with the first demonstration of coherent oscillations in a Cooper pair box circuit in 1999, they have primarily become a central quantum computing platform [9][10]. Notable leaps occurred with the invention of quantronium [11] and the 3D-transmon qubit [12], the latter leading to the widespread use of transmons and related circuits, such as X-mons and C-shunt flux qubits [13][14]. However, despite promising recent developments, the coherence time of superconducting qubits measured with the Ramsey metric has been stuck at about 100 μs for almost a decade [15][16]. The saturation of superconducting qubits' coherence time slows the implementation of practical intermediate-scale quantum algorithms and intensifies the hardware requirement to achieve quantum error correction [17][18][19]. Improving coherence times is crucial for enhancing the scope of superconducting quantum processors and building a fault-tolerant quantum computer. Recent advances in two-qubit gate control have placed their fidelities at the cusp of their coherence limit, implying that improvements in coherence could directly drive gate fidelities past the fault-tolerant threshold. Coherence stability and its impact on multi-qubit device performance are also important since superconducting qubits display large and correlated temporal fluctuations (i.e., $1/f^{\alpha}$) in their energy relaxation times T_1 [20][21][22].

Currently, most superconducting multi-qubit processors use reproducible transmon qubits with coherence times up to several hundred microseconds. This leads to record average gate fidelities of 99.98–99.99% for single-qubit gates and 99.8–99.9% for two-qubit gates [15][23][24][25][26]. The transmon qubit is created by adding a shunt capacitor in parallel with a Josephson junction to a charge qubit. This exponentially suppresses the susceptibility of its transition frequency to charge noise. However, the large shunt capacitance results in a relatively low 200–300 MHz anharmonicity, limiting the speed of quantum gates that can be implemented with transmons [27][28]. This is because leakage errors to states beyond the computational subspace need to be suppressed. Similarly, the low anharmonicity also limits the readout speed of transmon qubits. A high-power readout tone can even excite the transmon to unconfined states beyond the cosine potential. A higher anharmonicity is preferred to speed up the qubit operations and to allow for higher fidelities limited by the finite coherence time. Hence, it is desirable to find new types of superconducting qubits that can increase the anharmonicity-coherence-time product. Recently, there has been significant progress in the development of fluxonium qubits as an alternative to transmons due to their high anharmonicity and long coherence times, which have allowed for an average gate fidelity of over 99.99% for single-qubit gates and 99.7% for two-qubit gates [9][17]. However, these qubits do not provide protection against both relaxation and dephasing due to flux noise at a single operation point. The reproducible fabrication of fluxonium qubits may also be challenged by parasitic capacitances in the superinductor, which can result in parasitic modes. Reducing the total inductance of the junction array in fluxonium enables a zero-flux plasmonium qubit or a half-flux-quantum point-operated quarton qubit, both with high anharmonicity and charge noise protection [17]. Increasing superinductance forms a quasi-charge qubit, retaining protection against charge noise. Although there has been progress in fluxonium, it still needs to demonstrate superiority to transmons in a broader sense. As a solution, Hyyppa et al. presented a new superconducting qubit, the unimon. It consists of a single Josephson junction, a linear inductor, and a capacitor. The qubit operates in a new parameter regime, has high anharmonicity, is resilient against low-frequency charge noise, and is partially protected from flux noise [29]. The competition to modify the materials used in superconducting qubits or find a new and improved mainstream superconducting qubit is still ongoing.

2.2. Trapped Ion Qubits

Cooling the atomic ions by laser in a high-vacuum environment leads to the creation of high-quality qubits that are resistant to noise. These individual charged atoms can be trapped by carefully controlled electric fields [30]. Trapped ions have several advantages over other qubit modalities, such as their exceptionally long coherence times, up to 50 s without dynamical decoupling techniques [30]. Two-qubit gate times typically range from 1 to 100 μs, resulting in coherence time to gate time ratios of approximately 10^6, which is higher than other qubits, such as superconducting qubits (~1000) or Rydberg atom qubits (~200) [31][32]. Another advantage is that trapped ions allow for high-fidelity implementation of single- and two-qubit gates. Single-qubit rotations have achieved fidelities up to 99.9999%, surpassing other modalities. Two-qubit gates have been demonstrated with fidelities up to 99.9% for hyperfine qubits and 99.6% for optical qubits, with only superconducting qubits achieving comparable performance [33][34][35][36]. Trapped ions benefit from being fundamentally identical, ensuring that addressing each ion requires the same frequency, resulting in improved reproducibility of the qubits and fewer calibration steps. This contrasts with superconducting qubits, which have varying frequencies and coherence times due to the fabrication process's variability and thermal cycling [21]. Trapped ions have the highest coherence time to gate operation ratio; however, their absolute gate speeds are slower than some other qubits. Two-qubit gates for trapped ions have been demonstrated as fast as 1.6 μs, while superconducting qubits can perform them in tens of nanoseconds [30]. Trapped-ion-based quantum computation may take considerable time, depending on the number of operations required. Even with optimistic but achievable gate and readout parameters, factoring a 1024-bit and 2048-bit number using a trapped-ion-based quantum computer could take up to ~10 and ~100 days, respectively [37][38]. Trapped-ion quantum processors face challenges due to long gate times, hindering quantum simulations or calculations. Achieving "quantum supremacy" may be difficult if a classical computer's gate speed greatly exceeds that of a trapped-ion quantum processor. One promising research area is performing entangling gates using sequences of ultrafast pulses or shaped pulses of continuous-wave light. However, sub-microsecond gate fidelities have not exceeded 76% [37][39].

One of the last works carried out in quantum computers based on trapped ion qubits is related to increasing scalability by demonstrating a quantum matter link in which ion qubits are transferred between adjacent quantum computer modules. This method is useful for quantum computers based on trapped ions that use architectures such as quantum charge-coupled devices (QCCD) to scale the number of qubits. The number of ions that can be placed on a module is limited according to the chip size. Therefore, the modular model can be used, which makes the need for quantum connections between individual modules essential. In the mentioned research, an exciting solution for this case has been presented [40]. In another work, researchers from the University of Amsterdam have proposed a new architecture for quantum computers based on tripods. Using optical tweezers and oscillating electric fields, they were able to use a creative method to control the trapped ions. This idea, which is based on the collective movement of ions, leads to the formation of a controlled interaction between two ions [41].

Finally, trapped ion systems have difficulties with optical and electronic control, limiting progress towards larger numbers of ions with meaningful control and readout. For instance, 300-ion crystals in Penning traps and linear chains of around 100 ions in RF traps have yet to demonstrate entanglement between arbitrary ions in the system, which is demonstrated with other technologies where control elements are integrated into the qubit chip itself [42].

2.3. Neutral Atom Qubits

The use of optical tweezers (highly focused laser beams) to trap neutral atoms without the need for charging has greatly aided the development of neutral atom qubits.

Neutral-atom qubits have identical characteristics, long coherence times, and can be trapped in multidimensional arrays, making them scalable [43][44]. In addition to their exceptional coherence times in ground states, fast and high-fidelity quantum operations can be achieved by individually addressing atoms with laser pulses and coupling them to highly excited Rydberg states [44][45]. The fidelity of gates based on the interaction between Rydberg states is fundamentally limited by the finite lifetime of the Rydberg states relative to the achievable operation speed. The lifetime of laser-accessible states with orbital angular momentum $l \leq 2$ is 100–200 μs at room temperature, limited by black-body radiation, and can be improved to 1 ms in a cryogenic environment [46]. Circular Rydberg states with the maximal angular momentum $|m| = l = n - 1$ have longer lifetimes, reaching approximately 10 ms at cryogenic temperatures because they have only a single (microwave-frequency) radiative decay pathway to the next highest circular state [47]. Moreover, the lifetime of these particles can be extended by suppressing the local density of states at a specific frequency using a microwave structure [48][49]. Although radiative lifetimes exceeding 100 s can be achieved unfortunately, this increased lifetime does not directly translate into improved gate fidelity within conventional approaches based on the Rydberg blockade because of the difficulty of exciting circular Rydberg states with high fidelity. One significant remaining roadblock for the large-scale application of these systems is the ability to perform error-corrected quantum operations [50].

In one of their last works, Graham et al. demonstrated, for the first time, quantum algorithms encoded in gate-model digital circuits on a programmable neutral-atom processor. They used an architecture based on rapid scanning of tightly focused optical control beams to provide multi-qubit circuit capability. The quantum algorithms were demonstrated on a programmable gate-model neutral-atom quantum computer, which used an architecture based on individual addressing of single atoms with tightly focused optical beams scanned across a two-dimensional array of qubits [51].

Another work conducted by Cong et al. provided a detailed explanation of the errors arising from the finite lifetime of the Rydberg state or imperfections in Rydberg laser pulses, and a novel and distinctly efficient method was developed to address the most important errors associated with the decay of atomic qubits to states outside of the computational subspace [52]. These advances significantly reduced the resource cost for fault-tolerant quantum computation compared to existing general-purpose schemes.

2.4. Other Types of Qubits

There are other types of qubits such as:

- Semiconductor qubits: the field of semiconductor qubits is quite diverse, encompassing various systems, materials, and techniques. The semiconductor qubits demonstrated so far differ from each other in many ways. They range from systems that operate at mill kelvin temperatures, which can only be achieved inside dilution refrigerators, to systems that are suitable for room-temperature operation. They can be artificially engineered potential wells that confine quantized electronic states or single-atom impurities in a lattice. They exploit nuclear or electronic degrees of freedom. Despite these differences, however, they share specific properties, such as the potential for high-density integration on a large scale. This feature arises from the well-established nanofabrication technology of the semiconductor industry [53].

- Nuclear magnetic resonance (NMR) qubits: While nuclear magnetic resonance (NMR) has demonstrated impressive control, it is not a practical candidate for quantum computers due to scalability issues. As the number of qubits grows beyond a dozen, the ratio of gate time to decoherence becomes too small. Therefore, there is a need for other technologies that can handle larger systems.

- Topological qubits: Topological qubits utilize anyons, which are exotic quasiparticles. Anyons have unique properties in fundamental physics as they generalize the statistics of bosons and fermions. Due to their exotic statistical behavior, they exhibit non-trivial quantum evolutions described by their topology. This means that they are abstracted from local geometrical details. When anyons are used to encode and process quantum information, this topological behavior provides much-desired resilience against control errors and perturbations [54].

- Molecular spins: Artificial magnetic molecules can contribute to the achievement of large-scale quantum computation by (a) integrating multiple quantum resources and (b) reducing the computational cost of some applications. Chemical design, guided by theoretical proposals, facilitates the embedding of nontrivial quantum functionalities in each molecular unit, which then act as a microscopic quantum processor able to encode error-protected logical qubits or to implement quantum simulations. Scaling up even further requires “wiring-up” multiple molecules. Recently, this goal was achieved by coupling to on-chip superconducting resonators. The potential advantages of this hybrid approach and the challenges that still lay ahead have been critically reviewed.

Although these qubits possess impressive potential, they are not yet as competitive with the previously mentioned qubits. In addition, there are considerable fundamental challenges regarding the scalability of their platforms, which could hinder their ability to perform complex tasks. Despite these challenges, scientists are working hard to create better qubits that can help advance the field of quantum computing. For instance, Microsoft has collaborated with the Pentagon’s Defense Advanced Research Projects Agency (DARPA) to develop topological qubits, which have shown promising results. According to Microsoft, this qubits model will show very favorable development capabilities in the near future [55]. **Table 1** shows some of the recent projects of leading institutes in quantum computing.

Table 1. Some of the recent projects of leading institutes in quantum computing.

Institutions	Projects
Massachusetts Institute of Technology	• Room-temperature photonic logical qubits via second-order nonlinearities [56] • Capturing Non-Markovian Dynamics on Near-Term Quantum Computers [57] • Creating Majorana modes from a segmented Fermi surface [58]
Harvard University	• Quantum Information and Algorithms for Correlated Quantum Matter [59] • Quantum Computing and Quantum Information Storage [60]
Max Planck Society	• A Quantum-logic Gate Between Distant Quantum-Network Modules [61] • Topological Two-Dimensional Floquet Lattice on a Single Superconducting Qubit [62]
Princeton University	• New material platform for superconducting transmon qubits with coherence times exceeding 0.3 ms [15] • Spin Digitizer for High-Fidelity Readout of a Cavity-Coupled Silicon Triple Quantum Dot [63] • CutQC: using small Quantum computers for large Quantum circuit evaluations [64]
University of Tokyo	• Blueprint for a scalable photonic fault-tolerant quantum computer [65] • Post-Hartree–Fock method in quantum chemistry for quantum computers [66] • Event Classification with Quantum Machine Learning in High-Energy Physics [67]

Currently, researchers in quantum technologies are primarily focused on increasing the number of qubits. However, as qubit numbers increase, new challenges arise in initialization, control, and reading. Addressing these challenges requires new ideas for existing platforms or even finding new quantum platforms to produce qubits. This has led to intense competition between the world's major research and industrial centers.

3. Looking Ahead

Undoubtedly, with significant advances in the NISQ era and moving towards the fault-tolerant era, the utilization of quantum computer technology will also increase. More people, organizations, and companies will participate in this evolution as contributors or consumers. Automotive and transport; real estate, hospitality, and construction; consumer products and retail; financial services; advanced manufacturing and diversified industrial products; telecoms, media, and entertainment; health and life science; and power and utilities are fields that indicate the use cases that large companies are pursuing as quantum computing consumers.

As a result, the presence of large companies such as Google and IBM in superconducting quantum computers has led to more significant progress compared to other fields; the chips provided by these companies are considered a very positive step in industrialization.

Moreover, serious efforts are being made for other types of quantum computers to reach the fault-tolerant era by solving the fundamental challenges of these fields with the help of quantum laws and solutions. It is clear that even large companies that have made significant investments in quantum computers still have a long way to go to achieve a fault-tolerant era. However, it is important to note that according to Neven's law, a quantum computer's power will quadruple within the time it takes a classical computer to double in power. For example, in 2019, Google's 53-qubit Sycamore processor performed complex calculations in about 200 s, while the most influential classical computer took about 10,000 years. However, in 2021, the startup QuEra introduced a 256-qubit processor, which is about five times larger than the Sycamore.

It should also be noted that with the addition of startups and emerging companies and the support of large governments such as America, China, Germany, and Canada, the speed of progress in various dimensions of this field has increased significantly in recent years. Just as a numerical example, according to the report provided by Precedence Research [68], the size of the quantum computing market (By Application: Machine Learning, Optimization, Biomedical Simulations, Financial Services, Electronic Material Discovery, Other; By End Use: Healthcare and Pharmaceuticals, Chemicals, Defence, BFSI, Energy and Power, Others; By Offering Type: Consulting Solutions, Systems) will reach from about 10 billion dollars in 2022 to about 125 billion dollars in 2030, which is a significant growth in just 8 years.

In the past decade, remarkable advancements have been made in qubit technologies, leading to the development of gate-based quantum computers. These advancements have been made possible by improvements in the ability to fabricate and control qubits. Qubits are the basic units of quantum information, and quantum computing relies on their superposition and entanglement to perform calculations. Despite the progress made so far, there are still major challenges that need to be overcome to fully develop quantum computers. One such challenge is the need to increase the number of qubits, as more qubits enable quantum computers to perform more complex calculations. However, increasing the number of qubits is not enough; there is also a need to improve qubit fidelity, which refers to the accuracy of qubits. Higher qubit fidelity will lead to the better performance of quantum computers. To achieve these goals, there is a need for continued research and development in the field of quantum computing. This will require collaboration between researchers and engineers to develop new materials and fabrication techniques, as well as new control methods for qubits. With continued progress, the potential of quantum computing could be fully realized, leading to revolutionary breakthroughs in many areas, including cryptography, drug discovery, and materials science.

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