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The Current Landscape of Quantum Hardware Development - An Overview

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Abstract

Quantum computing has developed since the 1980s, with significant progress in its theoretical and practical applications. A critical aspect of this field is quantum hardware development, which supports research and real-world applications. One notable example of quantum computing's potential is cryptography, where the RSA protocol has been employed to secure browsers and other internet applications. The private key of the RSA protocol is based on two prime numbers that are so large that even supercomputers cannot factor them to their prime factors in a reasonable amount of time. In 1994, Caltech alumnus Peter Shor proposed Shor's Algorithm, which exploits the unique properties of quantum computers to factorize large numbers quickly and efficiently [1, pp. 5–8]. Implementing this algorithm on quantum hardware would compromise the security of the RSA protocol. Quantum computing has been touted as revolutionary, but understanding the progress of different quantum hardware types is vital. This paper aims to analyze the types of quantum hardware and applications they are best suited for, presenting a comprehensive look into most quantum hardware in development. By understanding the current state of quantum hardware, we can gain valuable insights into the potential applications of quantum computing.

Introduction

Classical computers have been used since their inception in the mid-20th century for many applications and in many fields. A more recent conception, quantum computers, has been developing since the 1980s and has started proving its superiority in specific applications compared to classical computers. There are even a set of applications that classical computers cannot solve, but quantum computers have been proven to be able to solve [2]. Quantum computers can even be potentially faster than classical computers in some cases. To understand quantum computers and how they can benefit many fields and applications, an analysis of the current progress of quantum hardware needs to be done.

The paper will begin by reviewing the different types of quantum hardware, or more specifically, quantum processors being developed and used. The types of quantum processors we will look into will be divided into processors with commercial applications and processors that are primarily being used for research purposes or not at the level of being commercially viable. We will begin with the most commonly used and one of the most developed types, the superconducting processor, breaking down how it works and its current state in quantum computing. Then, we will look into trapped ion, photonic, and neutral atom quantum processors, which all have smaller commercial applications than superconducting quantum processors. After covering these commercially used quantum processors which have been in development for much longer periods, we will look into quantum processors that are in their research phase and do not have as many significant commercial uses. These non-commercial processors are semiconductor spin, topological, nuclear magnetic, and diamond quantum processors. Similar to the last section, a breakdown of how each processor works and their current applications will be analyzed.

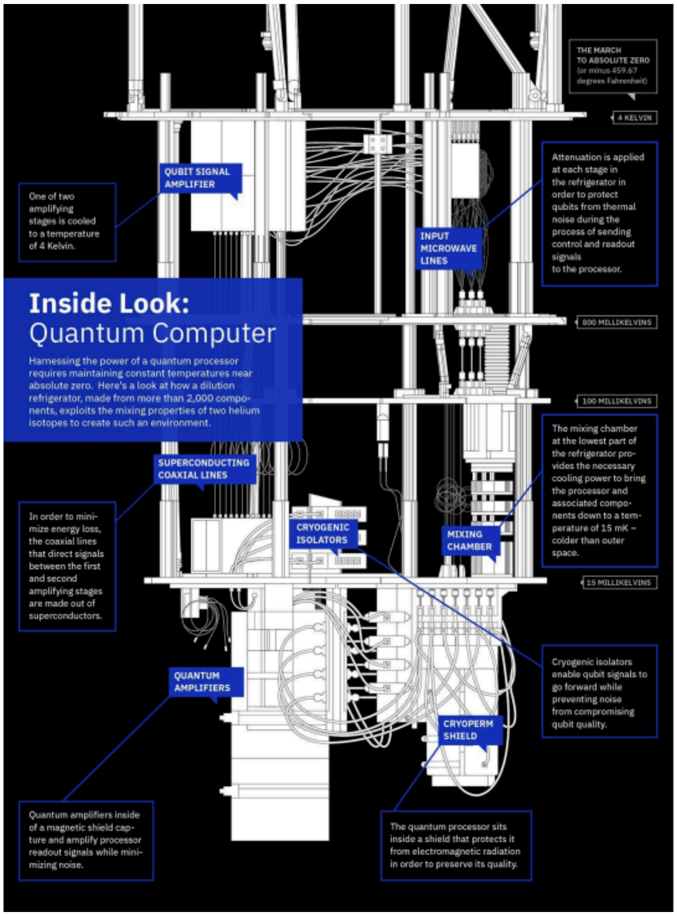
After covering the different types of quantum processors and their respective applications, each section will cover the current performance of these processors, taking into account their current stage of development and the limitations these processors faced based on their fundamental materials and design. Finally, we will recap all of the quantum processors covered and consider the subsequent steps the quantum hardware industry and quantum computing field as a whole can take with the progress all of these processors are having.

Superconducting Quantum Processors and Applications

Superconducting quantum processors utilize superconducting circuits that represent artificial atoms to model qubits. For a superconducting qubit, the zero and one states are represented by the ground state and excited state, or the state which has more energy than the base energy of the ground state. A superconductor, unlike general conductors, has a specific temperature at which resistivity drops to near zero and conductivity is maximized, meaning that if they can be cooled to their optimal temperature, superconductors yield significant benefits over other conductors. With this benefit in mind, a superconducting system is quantized, or transformed from a system that obeys classical mechanics to one that follows quantum mechanics using amplitude complexity, which just changes the phase of the waves flowing through the superconductors [3, pp. 3–4].

With this process implemented, the superconducting quantum processor is nearly done being initialized as a quantum system. The processor is fine-tuned by having its electrical elements classically adjusted, with tuning done to the processor's capacitance/ability to store electrical charge or inductance/capacity to oppose an electric charge. From there, the total energy of the now quantum mechanical system needs to be modified to work by following a series of laws needed to create a quantum processor, including Kirchoff's circuit laws and the properties of a quantum Hamiltonian. Once all these processes can be developed at the scale needed to make at least one quantum processor, there is a careful process needed to physically make the superconducting processors.

When building superconducting processors, lithography is used to etch the metals used in the processors, in addition to scatter patterning of the materials to develop the precise junctions and components for each of the qubits on a superconducting processor [4]. These processors are unique in using Josephson Junctions, which are electrical components not found in traditional conductors. Two thin superconductive wires are placed between an insulator that is only a few atoms thick, resulting in a Josephson Junction that creates a superconducting current or a supercurrent, that finally puts the superconducting quantum processor in a quantum state, with all the qubits activated with the supercurrents in its Josephson Junctions [5, pp. 1–3]. In operation, pulses of microwaves at specific frequencies are sent to each qubit for specified times, allowing for unitary or basic operators to be applied for individual superconducting qubits.



Inside Look:
Quantum Computer

Harnessing the power of a quantum processor requires maintaining constant temperatures near absolute zero. Here's a look at how a dilution refrigerator, made from more than 2,000 components, exploits the mixing properties of two helium isotopes to create such an environment.

One of two amplifying stages is cooled to a temperature of 4 Kelvin.

Attenuation is applied at each stage in the refrigerator in order to protect qubits from thermal noise during the process of sending control and readout signals to the processor.

The mixing chamber at the lowest part of the refrigerator provides the necessary cooling power to bring the processor and associated components down to a temperature of 15 mK – colder than outer space.

In order to minimize energy loss, the coaxial lines that direct signals between the first and second amplifying stages are made out of superconductors.

Cryogenic isolators enable qubit signals to go forward while preventing noise from compromising qubit quality.

Quantum amplifiers inside of a magnetic shield capture and amplify processor readout signals while minimizing noise.

The quantum processor sits inside a shield that protects it from electromagnetic radiation in order to preserve its quality.

FIGURE 1. Inside Look of Superconducting Quantum Processor. Note: Schematic of an IBM Superconducting Quantum Processor. Note that the processor is only the bottom most component of this figure, with the rest being cooling and interactive equipment [6].

Superconducting quantum processors face unique challenges. Superconducting quantum processors also face many challenges that limit their scalability and performance. Some of these challenges are decoherence: the loss of quantum coherence due to interactions with the environment or errors in the control signals. Decoherence causes the qubits to lose their quantum properties and behave like classical bits, reducing the accuracy and reliability of the quantum computation, and a standard solution is to cool the processor to at least 10 millikelvins, near absolute zero [7]. Another issue is from crosstalk, or the unwanted coupling between qubits or between qubits and control lines. Crosstalk can introduce noise and errors in quantum computation, as well as affect the calibration and tuning of the qubits. Moreover, fabrication, or the difficulty of fabricating high-quality superconducting circuits with low loss and high coherence, is another issue faced by superconducting quantum processors. Fabrication also involves designing and integrating complex components such as qubits, resonators, couplers, filters, amplifiers, and readout devices [8, pp. 2–3]. Control is the challenge of generating and delivering precise and fast control signals to manipulate the qubits. Control also involves implementing error correction and mitigation techniques to protect the quantum information from decoherence and errors. Finally, an issue arises in interfacing. The problem of interfacing superconducting quantum processors with other devices or systems, such as classical computers, memory devices, sensors, or other quantum processors. Interfacing requires efficient and low-noise conversion of signals between different domains, such as microwave, optical, or electrical [9].

Superconducting quantum processors offer a promising avenue for achieving quantum computing capabilities. By utilizing superconducting circuits that represent artificial atoms, these processors can model qubits and tap into the unique properties of superconductors. Overcoming challenges such as decoherence, crosstalk, fabrication difficulties, control complexity, and interfacing issues is crucial for their scalability and performance. Researchers and companies are actively working on developing diverse architectures and designs for superconducting quantum processors, with notable examples including Google's Sycamore (used to demonstrate quantum advantage), IBM's Q System One, Rigetti's Aspen, and Intel's Horse Ridge. These processors hold significant potential across various fields, including cryptography, optimization, machine learning, and physics, driving the exploration of quantum computing's transformative capabilities.

Note that in this section, superconducting qubits have been described as a whole, but there are different types of superconducting qubits. Some examples are fixed-frequency qubits and tunable qubits [10, pp. 1–4], with the latter allowing for frequencies of individual qubits to be adjusted.

Trapped Ion Quantum Processors and Applications

Trapped ion quantum processors are among the leading contenders in the race to develop practical quantum computers. We delve into the technical processes behind trapped ion quantum processors, exploring the underlying principles, manipulation of ions (commonly using atoms from ytterbium), and the intricate steps involved in achieving quantum advantage.

Trapping and Cooling Ions

The first step in building a trapped ion quantum processor involves the trapping and cooling of ions [11]. This is achieved by using electromagnetic fields to create a confining potential well, which traps the ions in a localized region, usually a line. By employing techniques such as laser cooling, the kinetic energy of the ions is reduced, allowing them to reach their lowest energy state, called the ground state. The colder the ions, the less they are affected by external noise, ensuring better qubit stability [12].

State Initialization and Manipulation

Once the ions are trapped and cooled, the next challenge is initializing and manipulating their quantum states. State initialization involves preparing the qubits in a well-defined state, often the ground state. For trapped ion quantum processors, this is accomplished through the use of laser pulses or microwave radiation, which excite or de-excite the ions to specific energy levels. To perform quantum operations, such as quantum gates, on the qubits, carefully engineered laser beams are employed to couple different internal energy levels of the ions. By manipulating the laser parameters, such as intensity, frequency, and duration, the quantum state of the qubits can be precisely controlled [12].

Entangling Qubits

Entanglement lies at the core of quantum computing's power. Trapped ion quantum processors generate entanglement by leveraging the strong interactions between ions. By applying carefully designed laser pulses, the quantum state of one ion can be entangled with another, creating a correlated system where the overall state cannot be described independently of each ion's state. Entangling multiple qubits enables complex quantum computations, vastly expanding the computational power of the system.

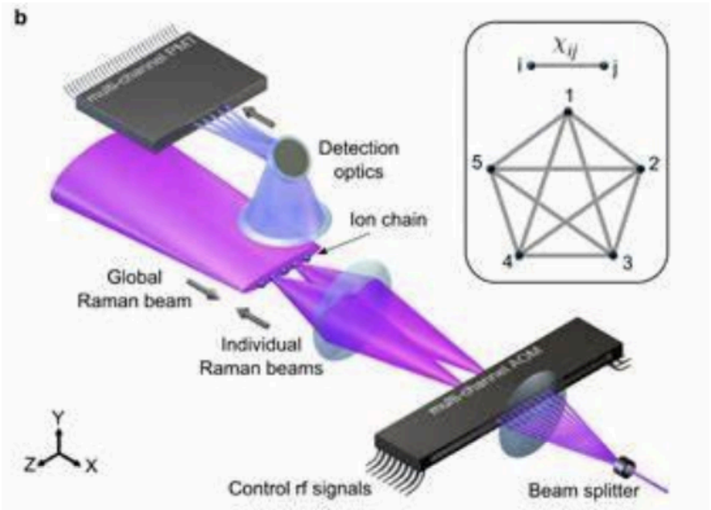


FIGURE 2. Trapped Ion Quantum Processor Layout. Note: Diagram of how a generic trapped ion quantum processor works, not considering how one interacts and implements programs on the processor [13].

Measurement and Quantum Error Correction

To extract information from the qubits, measurements are performed on the ions. The quantum state of the qubit is mapped to a classical state that can be read and interpreted. Measurements are typically achieved by directing separate laser beams from the one that aligns the qubits into the ions, which ionize them and produce detectable electrical currents. Quantum error correction is vital in combating decoherence and preserving the fragile quantum information. Various techniques are employed to correct errors, such as encoding multiple qubits into a single logical qubit and implementing error-detecting codes. These techniques enable fault-tolerant quantum computing and enhance the overall reliability of trapped ion quantum processors.

Recent Progress

There has been continued progress in the field of trapped ion quantum computing. In 2021, IonQ announced that they had built a commercial trapped ion quantum computer that is available for use by researchers. This is a significant step towards making trapped ion quantum computers a reality for businesses and other organizations. Newer systems have been developed, with some using a technique called "surface code" to protect the quantum information from errors. This makes it possible to build larger and more powerful trapped ion quantum computers. More recently, in March 2023, researchers at Tsinghua University in China developed a new programmable quantum phononic processor based on trapped ions, implementing a processor based on both the trapped ion quantum processor and the later-detailed photonic quantum processor [14]. This processor could be easier to scale up in size than other previously proposed trapped ion quantum processors, which could ultimately enable better performances on complex problems. It suggests that this technology is on track to become a viable platform for practical quantum computing.

Conclusion

Trapped ion quantum processors are at the forefront of quantum computing research. By leveraging the unique properties of trapped ions, such as their well-defined energy levels and strong interactions, these processors showcase remarkable capabilities in achieving quantum advantage. The technical processes involved, including trapping and cooling ions, state initialization, entanglement, and quantum error correction, all play crucial roles in the functioning of trapped ion quantum processors. In the coming years, we can expect to see even more progress in this field as researchers continue to develop new and more powerful trapped ion quantum processors.

Photonic Quantum Processors and Applications

Photonic quantum processors are a type of quantum computer that uses photons as its qubits and are designed on a per-gate basis [15]. Photonic quantum processors are based on the principle of quantum entanglement. Quantum entanglement is a phenomenon that occurs when two or more particles are linked together in such a way that they share the same fate, regardless of how far apart they are. This allows photons to be used to transmit information between different parts of a quantum computer without being affected by noise or interference.

How Photonic Quantum Processors Work

A photonic quantum processor works by using photons to store and manipulate qubits. The photons are initialized in a superposition of 0 and 1, and then they are manipulated using optical elements. The optical elements can be used to flip the state of the photons, or they can be used to entangle the photons with each other. The photons are then used to perform calculations. The calculations are performed using a quantum algorithm, which is a set of instructions that tells the quantum computer how to operate on the photons. The results of the calculations are then read out. The readout process is performed using optical elements, and it allows scientists to measure the state of the photons [15]. Note that the photons representing qubits cannot interact with each other in a vacuum, so other media are used to allow for photons in a photonic quantum processor to interact with each other.

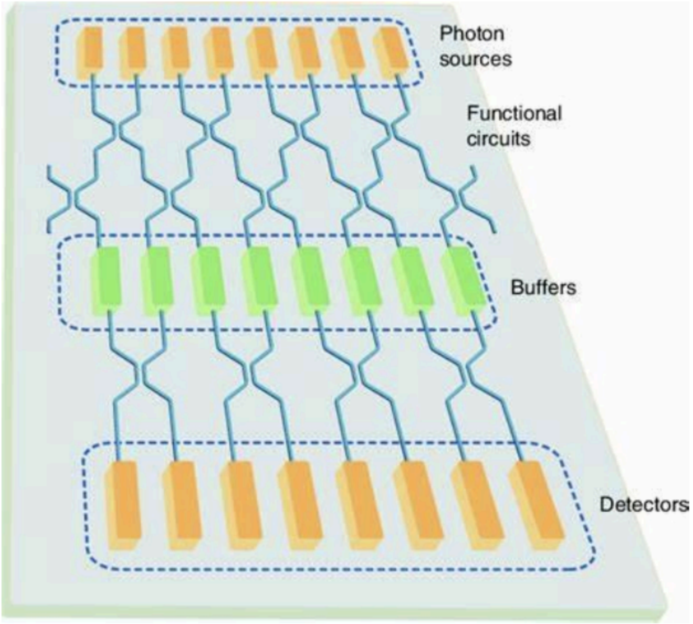


FIGURE 3. Overview of a Photonic Quantum Processor. Note: Simplified diagram of how a photonic quantum processor works. Note the photon emitters, circuits, and the detectors [15].

Advantages of Photonic Quantum Processors

Photonic quantum processors have some advantages over other types of quantum computers. Foremost, they are very fast. Photons can travel at the speed of light, which means that they can perform calculations much faster than classical computers. They are also very scalable [16]. Photonic quantum processors can be easily scaled up to the point where they can be used for practical applications, with less effort in setting up a processor with many qubits compared to other types of quantum processors.

Limitations of Photonic Quantum Processors

Photonic quantum processors also have several limitations. First, they are very sensitive to noise. Noise can cause photons to lose their quantum properties, which can lead to errors in calculations. Second, they are very difficult to manufacture. The process of creating photonic quantum processors is very complex, and it is not yet possible to mass-produce them. Third, they are very expensive. The cost of manufacturing a photonic quantum processor is still very high [16]. While these challenges are seen in different types of quantum processors, photonic processors have gone beyond purely research applications and now have commercial-stage applications.

Current Progress with Photonic Quantum Processors

Despite their limitations, photonic quantum processors are a promising technology. There has been a lot of progress in the development of photonic quantum processors in recent years, and scientists are optimistic that they will eventually be able to overcome their limitations and become a viable alternative to classical computers. One of the most significant advances in photonic quantum computing has been the development of new optical elements that can be used to manipulate photons. These new optical elements have made it possible to perform more complex calculations with photons, and they have also made it possible to scale up photonic quantum processors. Another important advance has been the development of new methods for manufacturing photonic quantum processors. These new manufacturing methods have made it possible to create photonic quantum processors that are more reliable and less expensive. With developments, there have come claims to quantum advantage, with a demonstration done with Xanadu’s Borealis quantum processor, using the special benefits of interacting with individual gates and a large-scale experiment showing a time difference in millions of times compared to a classical device [16, pp. 3–4]. As the technology continues to develop, photonic quantum processors will become more powerful and more affordable. This will make them more accessible to researchers and businesses, and it will accelerate the development of new quantum applications.

Neutral Atom Quantum Processors and Applications

A neutral atom quantum processor consists of a collection of neutral atoms trapped in a vacuum chamber. The atoms are then cooled to extremely low temperatures, reducing their motion and allowing them to be manipulated by lasers. The atoms are then used to encode qubits, the basic unit of information in a quantum computer, with the atoms typically being cesium or rubidium atoms. Qubits can be encoded in various ways for neutral atom processors, but one common approach is to use the atom's spin [17]. The spin of an atom can be in one of two states, up or down, or somewhere in between at one moment, to represent the technically infinite range of states between 0 and 1 inclusive that a single qubit can represent.

Once the qubits are encoded, they can be manipulated using lasers. Lasers can be used to rotate the atoms representing qubits and allow the atoms to entangle with themselves, allowing them to achieve quantum entanglement, and can also be used to generally manipulate the atoms such that they replicate the quantum mechanical phenomena needed in a quantum computer.

Laser Cooling

The first step in creating a neutral atom quantum processor is to cool the atoms down to microkelvins, or a few millionths of a degree above absolute zero. This is done using a process called laser cooling. Laser cooling works by using a laser to repeatedly absorb and re-emit photons from the atoms. This process transfers energy from the atoms to the photons, which causes the atoms to slow down, allowing them to cool. At temperatures of microkelvins, the atoms are moving so slowly that they can be manipulated with lasers for a neutral atom quantum processor [17].

Trapping

Once the atoms have been cooled, they need to be trapped in place so that they can be manipulated. This is done using a variety of trapping techniques, such as magnetic traps and optical traps. Magnetic traps use magnetic fields arranged in different manners to trap the atoms. The magnetic fields are arranged such that they create a well for the atoms. The atoms are then confined or "pushed" into the well, preventing them from escaping. Optical traps use laser beams to trap the atoms. The laser beams are set up such that they create a standing wave. The atoms are then trapped at the standing wave's nodes, where the potential energy is lowest, thereby minimizing the movement of the atoms and holding them in one spot [17].

Qubit Encoding

Once the atoms have been cooled and trapped, they can be used to encode qubits. Qubits can be encoded in a variety of ways, but one common approach is to use the spin of the atom. The spin of an atom can be in one of two states, up or down. These two states can be used to represent the two classical values of a qubit, 0 or 1. The spin of the atom can be manipulated using lasers. Lasers can be used to rotate the spin of the atom, which changes the state of the qubit. Note that multiple atoms can be arranged into arrays to represent multiple qubits and more easily represent a single qubit if need be, but each atom can be manipulated to represent all possible states of qubits.

Quantum Operations

Once the qubits have been encoded, they can be manipulated using quantum operations, which are operations that can be performed on qubits. Some common quantum operations done on neutral atom quantum processors are:

- Rotations: Rotations are operations that rotate the state of the qubit around a particular axis, allowing one to access all possible qubit states.
- Entanglement: Entanglement is a special type of correlation between two qubits. When two qubits are entangled, their states are linked together in such a way that they cannot be described independently and can theoretically have more information when accessed together than when looked at individually.
- Measurement: An operation that collapses the state of the qubit to a single value.

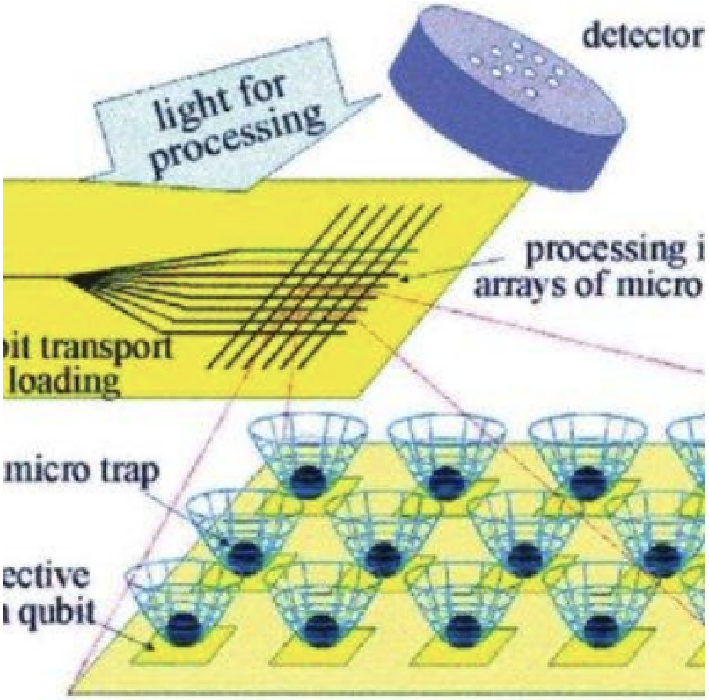


FIGURE 4. Neutral Atom Processor Diagram. Note: Schematic of how a generic neutral atom quantum processor works [18].

Challenges Faced In Developing Neutral Atom Quantum Processors

Decoherence is a major challenge for all quantum computing platforms, however, it is particularly challenging for neutral atom quantum processors because they are very sensitive to their environment being based on atoms [19]. This means that it is difficult to keep the qubits in a coherent state for long periods of time compared to other quantum processors. The lack of control on the atoms also makes it difficult to perform precise operations on the qubits [20]. Neutral atomic quantum processors can be difficult to scale up to a large number of qubits as the coupling between qubits decreases as the distance between them increases, making it difficult to perform operations on multiple qubits at once. Finally, Neutral atomic quantum processors are also expensive to build and operate, due to the need for specialized equipment and facilities.

Future of Neutral Atom Quantum Processors

Neutral atom quantum processors are a promising new approach to quantum computing. They offer a number of advantages over other quantum computing platforms, such as long coherence times (how long qubits can maintain information, high scalability (more qubits per processor), and the ability for integration with classical processors (hybrid computing). While there are still some challenges that need to be overcome, neutral atom quantum processors have the potential to revolutionize a wide range of industries. With continued research and development, one can expect neutral atom quantum computers in the near future.

Semiconductor/Silicon Spin Quantum Processors and Applications

Semiconductor spin quantum processors are a type of quantum computer that uses the spin of electrons in semiconductors as qubits. Qubits are the basic unit of information in a quantum computer and can be used to perform calculations that are impossible for classical computers. Semiconductor spin quantum processors offer several advantages over other quantum computing platforms, including:

- **Scalability:** Semiconductors can be manufactured on a large scale as they are what is currently used in our classical devices, which makes it possible to create quantum processors with a large number of qubits and makes them uniquely suited for

mass-production due to their compatibility with current device production methods [21].
- **Coherence time:** The spin of electrons in semiconductors can have long coherence times, which means that they can be manipulated for long periods without losing their quantum state, which is an advantage that is critical in the current stage of unstable qubits.
- **Compatibility with classical electronics:** Semiconductor spin quantum processors can be integrated with classical electronics, which makes it possible to use them to solve real-world problems, especially with their similar designs, making them easy to integrate from both the hardware and software sides compared to other types of quantum processors.

How Semiconductor Spin Quantum Processors Work

Semiconductor spin quantum processors work by using the spin of electrons in semiconductors as qubits. The spin of an electron can be in one of two states, up or down. These two states can be used to represent the two possible values of a qubit, 0 or 1. The spin of electrons in semiconductors can be manipulated using a variety of techniques, including:

- **Magnetic fields:** Magnetic fields can be used to rotate the spin of electrons by applying torque to the electrons. The torque is proportional to the strength of the magnetic field and the magnitude of the electron's spin [21].
- **Electric fields:** Electric fields can be used to flip the spin of electrons by applying a voltage to the electrons. The voltage causes the electrons to accelerate, which creates a magnetic field that flips the spin of the electrons.
- **Light:** Light can be used to manipulate the spin of electrons through the interaction of the light's electric and magnetic fields. The electric field of the light interacts with the electron's electric charge, while the magnetic field of the light interacts with the electron's spin.

Details of Semiconductor Spin Quantum Processors

The specific and technical details of how semiconductor spin quantum processors work are complex and involve a variety of quantum mechanical principles. However, a general overview of the process is provided below [21]:

1. A semiconductor material is chosen that has a long spin coherence time. This means that the spin of electrons in the material can be maintained for a long period without being lost due to interaction with the environment.
2. A small number of electrons are trapped in the semiconductor material. This is done by using a variety of techniques, some noted previously.
3. \The spin of the trapped electrons is manipulated using a variety of techniques, such as magnetic fields or electric fields.
4. The manipulated spin states of the electrons are then read out using various techniques, such as optical detection or electrical detection.

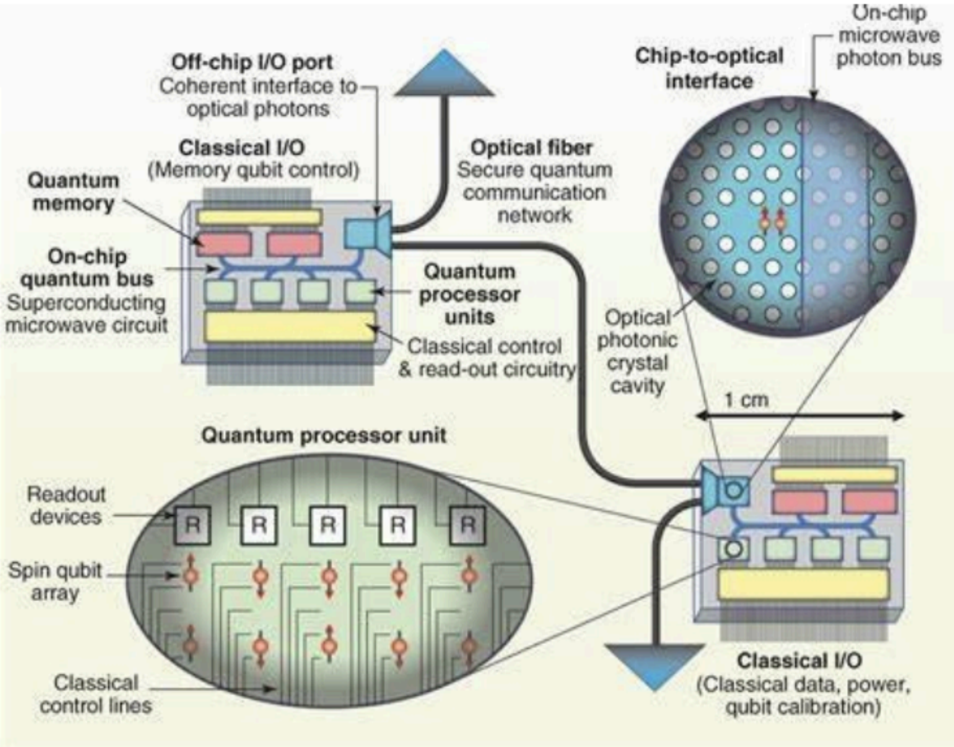


FIGURE 5. User Interface with Silicon Spin Quantum Processor. Note: How one can work and use a silicon spin quantum processor [22].

By repeating these steps, it is possible to perform quantum operations on the spin states of the electrons. Another consideration for these processors is that they have to be cooled, but only to about one kelvin, magnitudes higher than temperatures other quantum processors need to operate. These operations can be used to perform calculations that are impossible for classical computers, a general premise all quantum computers aim to have. To apply operators, a microwave pulse is used.

Semiconductor spin quantum processors are a promising new technology with the potential to revolutionize a wide range of industries. As research in this area continues, we can expect to see even more powerful and efficient semiconductor spin quantum processors in the future [23].

Topological Qubits and Their Applications

Topological qubits are based on the properties of topological materials, which insulate on their inside, but conduct on their surface. Topological materials are characterized by their robust, long-range order, which is not affected by local perturbations, making topological qubits much more resistant to noise and decoherence than traditional qubits, such as those based on superconducting circuits or trapped ions [24]. These characteristics allow for topological qubits to not require any magnetic fields and low temperatures to operate, allowing them to operate at standard room temperatures. The main type of topological qubit are Majorana qubits Majorana qubits use Majorana fermions, which are exotic particles that can exist at the boundaries of topological materials [25].

Topological Processors

Topological processors are quantum computers built using topological qubits. These processors are still in the early stages of development, but they have the potential to be much more powerful and reliable than traditional quantum computers. One of the main challenges in building topological processors is finding suitable topological materials. So far, only a few materials have been identified that have the necessary properties for topological qubits. Another challenge is developing the necessary techniques for fabricating and controlling topological qubits. Despite these challenges, there has been significant progress in the development of topological processors in recent years. In 2018, researchers at Google announced the creation of a topological qubit based on a semiconductor material called InAs [26]. This was the first time that a topological qubit had been created in a solid-state material. In 2021, researchers at the University of California, Santa Barbara (UCSB) announced the creation of a topological processor based on the surface code [27]. This processor was the first to demonstrate the ability to perform quantum error correction, which is essential for building a scalable quantum computer. The development of topological processors is a rapidly evolving field. It is expected that significant progress will be made in the coming years, and that topological processors could become a reality within the next decade.

Technical Details

Here are some of the technical details of topological qubits and processors:

- Majorana qubits are based on the Majorana fermions, which are exotic particles that can exist at the boundaries of topological materials. Majorana fermions are non-Abelian particles, meaning that they can be used to encode qubits.
- Surface code qubits are based on the surface code, which is a quantum error-correcting code that can be implemented in any topological material. The surface code can be used to protect qubits from noise and decoherence.
- Topological processors are quantum computers that are built using topological qubits. These processors are still in the early stages of development, but they have the potential to be much more powerful and reliable than traditional quantum computers.

Advantages of Topological Qubits

There are several advantages of topological qubits:

- They are much more resistant to noise and decoherence than other types of qubits.
- They can be implemented in a variety of materials, which makes them more scalable.
- They can be used to create quantum error-correcting codes, which makes them more reliable.

Disadvantages of Topological Qubits

There are also some disadvantages of topological qubits:

- They are still in the early stages of development, and there are many challenges that need to be overcome before they can be used in practical quantum computers.
- They are more difficult to fabricate and control than traditional qubits.
- They are not as well understood as traditional qubits, which makes it more difficult to develop quantum algorithms that can be implemented using them.

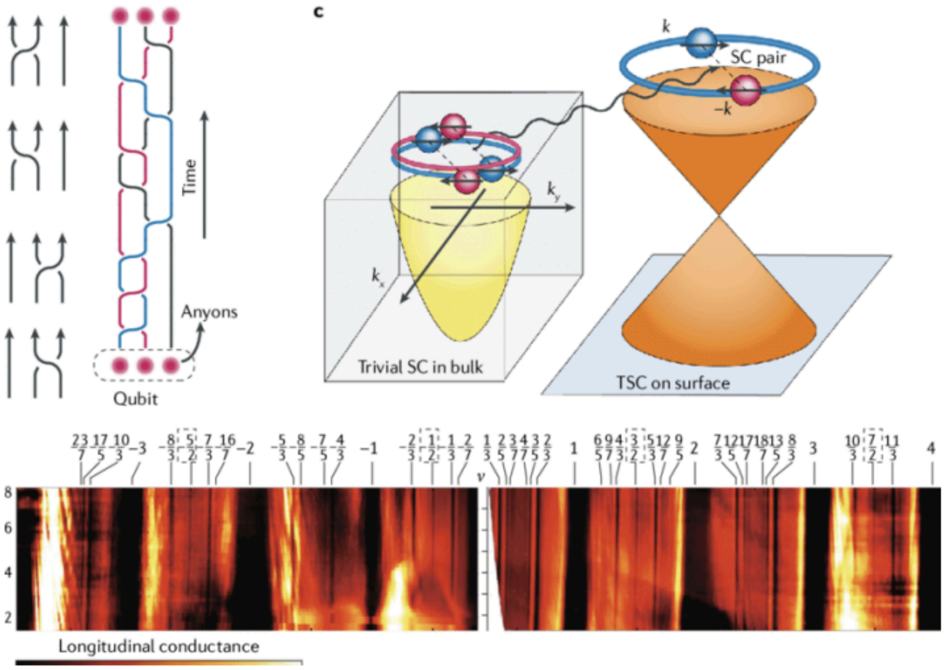


FIGURE 6. Topological Qubit Representation. Note: Representation of topological qubits from the inside and on the surface [28].

Summary of Topological Qubits

Topological qubits are a promising new technology for quantum computing. They have several advantages over traditional qubits, such as their resistance to noise and decoherence. However, they are still in the early stages of development, and there are many challenges that need to be overcome before they can be used in practical quantum computers.

Nuclear Magnetic Resonance Quantum Processors and Applications

Nuclear magnetic resonance (NMR) quantum computing is a type of quantum computing that uses the spin states (polarization) of nuclei within molecules as qubits. The quantum states are implemented through the nuclear magnetic resonances, allowing the system to be set up as a variation of nuclear magnetic resonance spectroscopy. NMR differs from other implementations of quantum computers in that it uses an ensemble of systems, in this case, molecules, rather than a single pure state. The basic idea behind NMR quantum computing is to use the magnetic properties of nuclei to store and manipulate quantum information [29]. Nuclei with a non-zero spin, such as protons and neutrons, can be aligned in a magnetic field. When a radiofrequency pulse is applied to the same elements, the nuclei can be flipped from one spin state to another. This process is used to encode quantum information into the spin states of the nuclei.

Once the quantum information has been encoded, it can be manipulated using different methods. For example, two nuclei with a coupling can be used to perform a controlled-not gate, which is a fundamental building block of quantum computation and uses two qubits. NMR quantum computing has several advantages over other types of quantum computing. First, NMR systems are relatively easy to build and operate. Second, NMR systems have long coherence times, which means that the quantum information can be stored for a long period of time without being lost. Third, NMR systems have been well-studied for over 50 years, which means that there is a large body of knowledge about how to control and manipulate them. However, NMR quantum computing also has some limitations. NMR systems are susceptible to noise, which can lead to errors in the computation, but this is not an issue unique to NMR systems. NMR systems are not scalable, meaning that they cannot be easily increased in size to perform more complex computations [30]. A hypothetical multi-million qubit quantum computer (translated to a few thousand perfect, fault-tolerant qubits), one that can implement most large-scale cases that could completely outperform classical systems in many tasks, could not be achieved with an NMR quantum processor.

Despite these limitations, NMR quantum computing has made significant progress in recent years. In 2001, a team of researchers based in California used NMR to implement a quantum algorithm for factoring 15, a proof-of-concept case of a quantum algorithm (specifically, Shor’s Algorithm, a period-finding function that works to factor numbers) that in the future could be scaled up to demonstrate significant quantum advantage [31]. In recent years, there has been a growing interest in using NMR quantum computing for a variety of applications. These applications include drug discovery, materials science, and financial modeling. NMR quantum computing is also being investigated as a potential way to improve the security of communication networks.

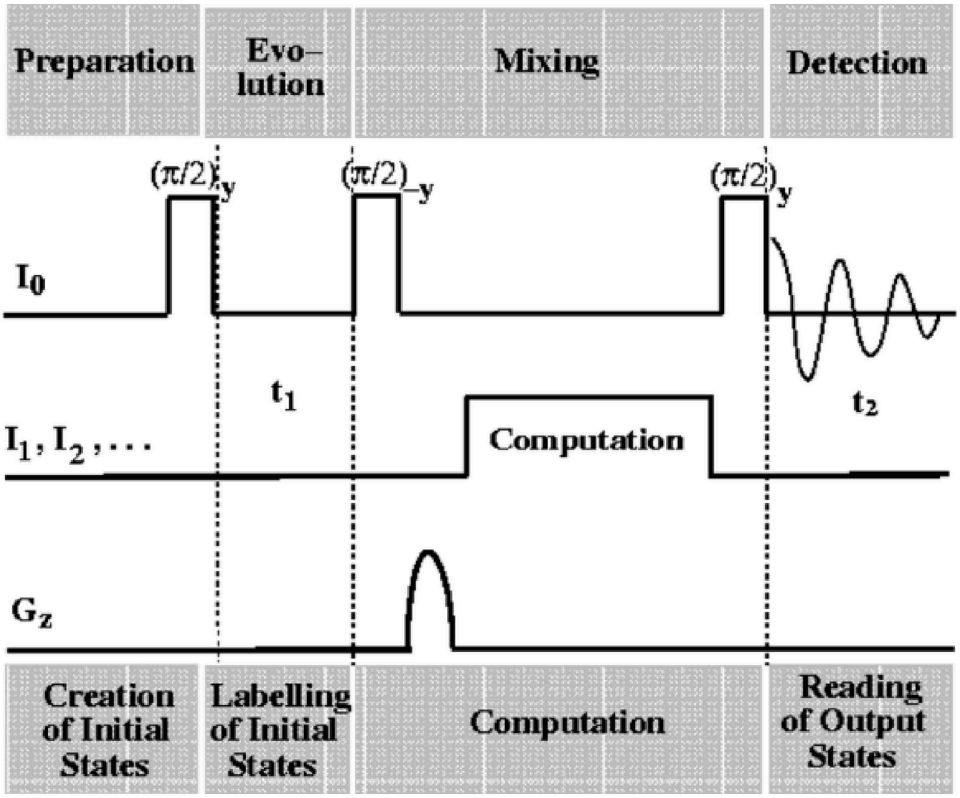


FIGURE 7. NMR Computation Processes Diagram. Note: Visual of how states are created and affected in a NMR system [32].

Current Progress

NMR quantum computing is a rapidly developing field, and there has been significant progress in recent years. In 2017, a team of researchers at the University of California, Berkeley, used NMR to implement a quantum algorithm for simulating the dynamics of a protein. This was the first time that a quantum computer had been used to simulate a biological system. In 2018, a team of researchers at the University of Innsbruck, Austria, used NMR to implement a quantum algorithm for solving a linear system of equations [33]. This was the first time that a quantum computer had been used to solve a problem that is relevant to the field of artificial intelligence. These recent advances demonstrate the potential of NMR quantum computing to solve real-world problems. As the field continues to develop, it is likely that NMR quantum computers will be used for a wider range of applications.

Diamond Quantum Processors and Applications

Diamond quantum processors are a new type of quantum computer that uses diamond as the substrate for its qubits. Diamond quantum processors are based on a defect in the diamond lattice called a nitrogen-vacancy (NV) center [34]. NV centers are created when a nitrogen atom replaces a carbon atom in the diamond lattice, and they have several properties that make them ideal for quantum computing. First, NV centers are very stable, being able to survive for billions of years without degrading, which is important for a quantum computer that needs to store information for long periods. In addition, NV centers can be easily manipulated using light, allowing scientists to control the state of the qubits, which is essential for performing calculations. Finally, NV centers can be coupled to other NV centers, which allows them to be used to create quantum networks, crucial for scaling up these types of processors to usable quantum networks.

How Diamond Quantum Processors Work

A diamond quantum processor works by using NV centers to store and manipulate qubits. The qubits are initialized in a superposition of 0 and 1, and then they are manipulated using light. The light can be used to flip the state of the qubits, or it can be used to entangle the qubits with each other. The qubits are then used to perform calculations. The calculations are performed using a quantum algorithm, which is a set of instructions that tells the quantum computer how to operate on the qubits. The results of the calculations are then read out. The readout process is performed using light, and it allows the scientists to measure the state of the qubits.

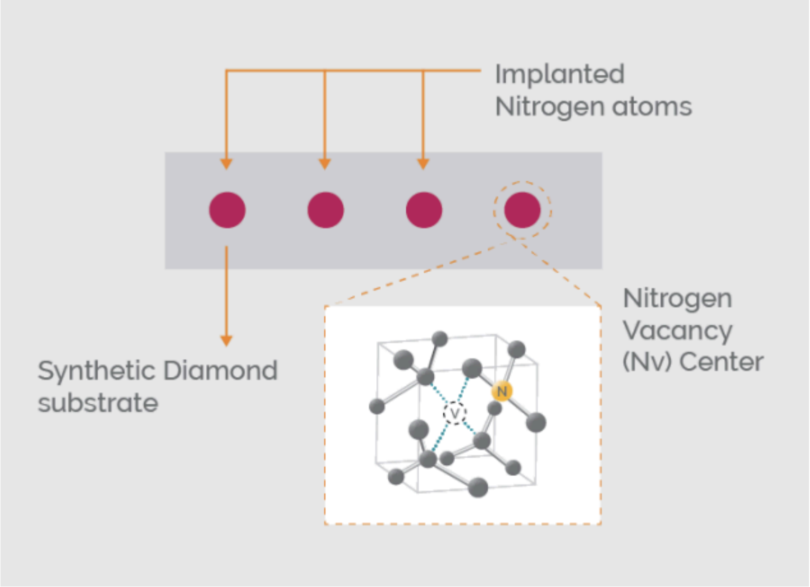


FIGURE 8. Diamond Quantum Processor Schematic - Simplified. Note: A diagram of where the NV centers and synthetic diamonds are in a Diamond quantum processor [35].

Disadvantages of Diamond Quantum Processors

Diamond quantum processors have some limitations. One key limitation is their cost; the cost of manufacturing a diamond quantum processor is still very high. These processors are very difficult to manufacture. The process of creating NV centers in diamonds is very complex, and it is not yet possible to mass-produce diamond quantum processors. Moreover, they are very fragile, as NV centers are easily damaged by heat and radiation, which makes them difficult to use in real-world applications.

Future of Diamond Quantum Processors

Despite their limitations, diamond quantum processors have the potential to revolutionize the way we compute. They are much faster and more efficient than classical computers, and they can be used to solve problems that are impossible for classical computers to solve [36]. As the technology continues to develop, diamond quantum processors will become more affordable and easier to manufacture. This will make them more accessible to researchers and businesses, and it will accelerate the development of new quantum applications. The possibilities are endless, and the future of diamond quantum processors is very bright.

Conclusion

With the rapid development of quantum processors, it becomes crucial to comprehend the various types of quantum hardware, their workings, and their current progress. This comprehensive guide aims to provide a framework for understanding these processors and making informed decisions when working with them. By examining both the leading commercial quantum processors and the more research-based ones, we can gain insights into their unique advantages, limitations, initialization methods, and potential future applications.

The initial focus of this paper is on the quantum processors that are considered leaders in commercial usage. These include Superconducting, Trapped Ion, Neutral Atom, and Photonic quantum processors. By delving into the intricacies of each of these processors, we can explore their fundamental principles, specific benefits, and inherent limitations. Additionally, we will examine their methods of initialization or fabrication and speculate on their potential future applications. Following the analysis of the advanced commercial processors, we shift our attention to the less-developed processors with more research-based applications. These include the Semiconductor/Silicon Spin, Topological, Nuclear Magnetic

Resonance, and Diamond quantum processors or qubits. While some of these processors are currently classified as qubits due to their smaller scale, they still hold significant potential for future larger-scale quantum processors. We will investigate the unique benefits offered by each of these processors, assess their current progress in the research phase, identify their current applications, and explore ways in which they can be further improved or developed for broader applications in the future.

As the number of quantum processors and the companies developing them continues to grow, understanding the workings and progress of different types of quantum hardware is of utmost importance. This guide seeks to facilitate that understanding by providing a detailed overview of various quantum processors, their functionalities, and their current state of development. By gaining a comprehensive understanding of these processors, readers will be empowered to make well-informed decisions when it comes to working with any of these quantum hardware types. By expanding upon the existing content and ensuring a smooth flow of information, this revised guide will serve as an extensive resource for those seeking knowledge about quantum processors. It will provide valuable insights into their workings, benefits, limitations, current progress, and future potential, equipping readers with the necessary information to navigate the ever-changing landscape of quantum computing.

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