Analysis on the Mechanism of Superconducting Quantum Computer

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Abstract. Nowadays the quantum computer has been drawing public attention, and how to realize a quantum computer is one of the difficult problems. However, superconducting circuit is a good system for solving the physics of quantum computers, as it has a solid development history and a perfect fit with quantum computers. In this paper, the development history of the superconducting quantum computer will be reviewed. In addition, the Josephson junction is the basis of superconducting quantum computation, based on which as well as in combination with DiVincenzo’s five requirements, superconducting quantum computers have a great potential. For the main part, the advantages and disadvantages of superconducting a quantum computer are analyzed. Some suggestions are also given and the future of superconducting computer is predicted. In conclusion, the superconducting system is found to be a suitable system for quantum computers.

1. Introduction
With the development of traditional computers, their hardwares are getting smaller and smaller, and the quantum effect such as quantum tunneling is becoming too big to ignore and classical physics begins to become inadequate. In a traditional computer, thermal energy loss is an obvious problem, since there are many irreversible and unnecessary processes in a classic computer. The information is represented by a qubit in quantum computer. Qubits are usually made up of microscopic quantities, for example, the horizontal and vertical polarization of the photon can represent 0 and 1 respectively. The difference between a qubit and a classic bit is that a qubit can be also in a superposition state of 0 and 1. Therefore quantum computer can solve the two problems mentioned above, and some algorithms prove the superiority of quantum computers. Shor proposed a large number factorization algorithm in 1994[1], which proved that quantum computers can effectively solve the problem of factorization of the large numbers. In 1997, Grover discovered the quantum search algorithm[2]. Traditional computers need to search one by one, so its complexity is N (N is the total number of all phone numbers), but the complexity of the quantum algorithm is the complexity of the square root of N. Because of the universality of the search algorithm, Grover’s algorithm proves the superiority of quantum computers. Although quantum computers look great, how to realize them is a difficult problem. There are many potential ways to implement qubits, such as ion trap system, NMR system, Rydberg atomic system, and superconducting systems. Among them, superconducting system is the most likely to be realized because of its good compatibility with traditional microelectronic technology and convenient extension.

2. Mechanism of superconducting quantum computation
In the superconducting environment, two electrons having different spins are attracted by the Coulomb force of positive ions which make up the crystal lattice. They combine with each other to form a Cooper
pair which has the characteristics of bosons and tends to crowd into a quantum state. And the research team provided the experimental evidence about observation of energy level quantization by the Josephson junction[3]. Because of that, the Josephson junction becomes the basis of the superconducting quantum computer.

2.1. Josephson junction
In a superconducting quantum computer, energy levels are quantized. However, the gaps of the energy levels need to be different. Therefore, quantum computer needs a component which is non-linear and non-dissipative. It is known to all that Josephson junction is one of those things. The structure of a Josephson can be seen in figure 1. There is an insulation layer which is typically thin between two superconducting layers. The Cooper pairs have a quantum tunneling effect. They cross the barrier and the insulation, to form a superconducting electric current[4].

2.2. Five requirements for the implementation of quantum computation
Scientists could use a Josephson junction to construct the qubits, but whether these systems could form a quantum computer is unknown. The DiVincenzo’s five requirements[6] can judge whether there is a good system to help apply the quantum computer. These criteria are discussed respectively below.

2.2.1. A scalable physical system with well characterized qubits.
To begin with, a superconducting system with three feasible qubits is an applicable system to quantum operation. These qubits include charge qubits, flux qubits and phase qubits. The simplest system is charge qubits, which is based on the Cooper pair box shown in figure 2(a). And the Hamiltonian of this system can be written in the follow equation:

\[ H = 4E_c(N - N_g)^2 - E_j \cos \varphi. \]  

Here \( E_c = (2e)^2/2C \) is the charging energy of the island of the Cooper pair box. And N is the number of Cooper pairs of the island; Ng is equivalent charge of the control electrode; \( \varphi \) is the phase of the charge island. In this system, the voltage of the control electrode can be adjusted to make two of the lowest energy levels close and far below other energy levels. Therefore, this system can be viewed approximately as a two-energy-level system. A flux qubits system is made up of several Josephson junction loops with a plus bias magnetic field(see figure 2(b)). This device is usually called an RF-SQUID. The current in the loop can be controlled by adjusting the positive magnetic field. The potential energy landscape has two valleys, and these two minimums can act as a two quantum state. And these two states can correspond to the two directions of the current. The last kind of a qubit (phase
qubit) system is made of a circuit biased junction with a fixed DC-current source like that in figure 2(c). The potential energy landscape of the Josephson junction has several potential wells. The number of energy levels can be controlled by adjusting the bias current. Generally, there are three energy levels in a potential well, and the lowest two energy levels are used as the phase qubit.

![Figure 2. The three basic superconducting qubits. (a) Cooper pair box (prototypal charge qubit); (b) RF-SQUID (prototypal flux qubit); and (c) current-biased junction (prototypal phase qubit). The charge qubit and the flux qubit require small junctions fabricated with e-beam lithography, while the phase qubit can be fabricated with conventional optical lithography[5].](image)

2.2.2. The ability to initialize the state of the qubits to a simple fiducial state, such as \( |000...0 > \).

Before the start of the computation, registers should know all of the qubits' values like in the classic computer. However, the natural qubits are disjointed and they need initialization. There is another important reason for initialization as it is good for quantum error correction which makes the result of computation more reliable. There is a very common approach that is ‘naturally’ cooling the system to the ground state, which is a fiducial state. All three qubits mentioned above can reach their initial state after a long period of relaxation. In addition, digital feedback control makes the initialization of the superconducting environment qubits faster, simpler and more configurable[7].

2.2.3. Long relevant decoherence times, much longer than the gate operation time.

Decoherence time characterizes the time a normal qubit in a coherent state transforming to the mixture qubit which has no coherence. A good quantum computation system should ensure the decoherence time to be long enough to guarantee the smooth operation of quantum computation. And now how to keep the quantum decoherence time in an appropriate time becomes the main problem of the quantum computation. However, there is still no appropriate approach to solve this problem from the principle of decoherence. Therefore, reducing the impact of the environment is another way to extend decoherence time.

2.2.4. A “universal” set of quantum gates.

Like the classic computer, all of problems of computation could be simplified into two-body problem and one-body problem. For the two-body problem, a quantum XOR gate which is digital gate giving the true output when the two inputs are different is usually used. And quantum C-NOT gate is usually used to solve the one-body problem. C-NOT gate is an important gate in quantum computer to make a qubit reverse if the control bit is true. However, the quantum gate cannot run perfectly. To make the result of computation more incredible, system needs quantum error correction to provide a protection. Some research groups demonstrated a universal set of logic gates in a superconducting multi-qubit processor, achieving an average single-qubit gate with fidelity of 99.92% and a two-qubit gate fidelity up to 99.4%[8]. From this, it can be sure that superconducting qubits can operate with high fidelity.

2.2.5. A qubit-specific measurement capability.

This capability is served for the result of the computation. In order to read out the result of computation, high fidelity measurement capability is required. Like the decoherence, the measurement also needs to pay attention to the impact of the environment. Superconducting system needs high fidelity
measurement to ensure the accuracy of the results. Researchers have used parametric amplification technology to read out 99% of the high-fidelity superconducting qubits[9].

3. Discussion
Through the introduction of superconducting qubits above, it roughly conforms to the DiVincenzo’s five requirements, so the superconducting system is a system with great potential. Next, this advantages and disadvantages on this basis will be further analyzed.

3.1. Advantages
The most essential advantage of the superconducting computer is that it fits well with the current microelectronic processing technology. The core circuits of charge qubits, flux qubits and phase qubits that mentioned above are perfectly compatible with the current microelectronic processing technology. Although the current in the wires and the charge on the capacitors in a quantum circuit is in a superposition state compared with the traditional circuit, these wires and capacitors can still be made from current microelectronic processing technology without the need to invent new capacitors and wires. This means it is convenient to extend superconducting system. The good scalability makes the superconducting quantum computer have a high priority, because the fault-tolerant quantum computing which can reduce the error from the decoherence time and the experimental operation need a large scale of qubits. Thus the quantum error correction is the key to make the result of quantum computer credible.

3.2. Disadvantages
The main problem of quantum computer is that it is hard to improve the coherence time of quantum system. As quantum state is very feasible, it is easy to be influenced by the environment. Coherence makes quantum computer superior to traditional computer, although there are some methods such as cavity quantum electrodynamics theory that are introduced into the superconducting system to solve the decoherence time problem. In addition, as mentioned above, the problem decoherence time has not been completely solved. And other important problems of the superconducting system come from Josephson junction. For instance, it is very difficult to reach the absolute zero, so the Josephson junction can not be a non-dissipative component. And it will influence the stability of quantum computer. Therefore, there are many problems need to be solved to realize superconducting quantum computer.

4. Conclusion
Superconducting quantum computer is an excellent system in quantum computing, which largely conforms to the DiVincenzo’s five requirements. Its scalability, ease of operation and ease of measurement all give it a great advantage in the implementation of quantum computation. But like the other quantum systems, decoherence time problem is a crucial problem of superconducting quantum system that urgently needs to be solved. With this essential problem being solved and advancement of superconducting components, it is believed that superconducting quantum computers can be successfully implemented.

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