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https://doi.org/10.5109/6781091

出版情報：Evergreen. 10 (1), pp.340-347, 2023-03. 九州大学グリーンテクノロジー研究教育センター
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Quantum Computing using Superconducting Qubits: A Review

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(Received July 12, 2022; Revised January 24, 2023; accepted January 24, 2023).

Abstract: Quantum computing aims at overcoming the limitations of conventional computers. Over the last few decades quantum computing has seen significant advances, particularly in superconducting quantum processor architecture based on superconducting qubits. In our work, we have provided a review over the superconducting qubits, their types, and the advantages these possess over other forms of qubits. Besides the theoretical aspects, we have also discussed different challenges and recent advancements that have been made till now in dealing with those challenges. With this review we lay out some future opportunities in this field and motivate further research in this field.

Keywords: Quantum Computing, Superconducting Qubits, Quantum error correction, Quantum scalability.

1. Introduction

Although conventional computing has many applications in different field and one of them gaining interest nowadays is Virtual Reality[1-3].virtual reality has tremendous use in various field but now-a-days has special impact on education[4-8]. Of late, tremendous advances in the field of Quantum computing have led to their acknowledgement across the globe, attracting scientists and researchers for intrinsic study on quantum computing, and its realization. Quantum Computing is the intersection of intrinsic properties of computer science, mathematics, and quantum physics. It is most concerned with the quantum physics fundamentals and promises to efficiently solve problems that are out of the reach of the conventional computers[9-18]. A good example is the Shor's Algorithm, which describes potential of quantum computers to find the factors of large numbers efficiently[19-20]. Being based on the concept of reversible computing, quantum computers are expected to eventually enable us to limit the energy to Von Neumann Landauer limit[21-29], in a more efficient way, compared to conventional computers. The quantum computer's properties are also expected to enable improved quantum simulation, and also revolutionize the classical way of computation, transforming machine learning and artificial intelligence. In recent years the development of quantum technologies has paced up, thus laying path for a fully functional, practical quantum computer. As we are advancing each step forward, we are able to achieve a better control over the quantum system. We have reached in the Quantum era which is a strident Intermediate-Scale. Here we can anticipate having achieved a qubit control with over 53 qubits [30-31].

Many techniques have emerged for the implementation of practical quantum computers, like trapped ion computing[32] that offers scalability even at room temperature, semiconductors[33-39] which owns a fabrication advantage, superconducting circuits[40-43] nuclear magnetic resonance[44] that provides less molecular diffusion decoherence, silicon[45-46], heteropolymer quantum computer, and many others. Amongst these, superconducting qubits have emerged to be a potential participant for scalable quantum computing. Quantum supremacy conveys that the most effective stalk to quantum computing was for the first time recognized by a superconducting quantum system[47]. Superconducting quantum computing has increased the rhythm of the global race of quantum computing, encouraging many technical companies to invest. Superconducting qubits-based quantum computers shows the possibilities of a better future of quantum computing.

In our review, we offer an outline of quantum computing using superconducting qubits. We review

Superconducting qubits, their types, and the ascendancies they possess over other forms of qubits. Furthermore we discuss the limitations as well as the advances made in overcoming those limitations, thus providing an overview about the future opportunities.

2. Superconducting Qubits

Superconducting qubit is the implementation of superconducting electrical circuits[48-49]. The basic difference between superconductors and conductors is that the charge carriers in superconductors are pairs of electrons, called Cooper pairs, while in conductors it is just a single electron. These cooper pairs are bosons, and cooled bosons are enabled to attain single quantum energy level, as a consequence of Bose-Einstein condensate. Contrary to the classical counterparts, these show properties of superposition, interference, and entanglement. Superconducting circuits display a proper condensate wave function that describes the flow of charge at each point of circuit, unlike the simple conductor circuit, where the wave functions are averaged, which embroils quantum effects observation.

2.1 Types of Superconducting Qubits

Based on the degree of freedom, superconducting qubits are categorized in three parts- charge qubit[50] , phase qubit[51], and flux qubit[52] shown in fig1.

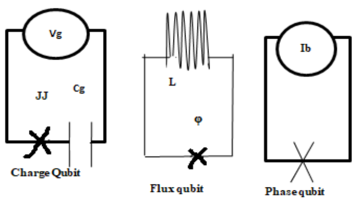

Fig1: Different types of qubit

These can be differentiated based on the ratio of Josephson energy to electrostatic energy. In charge qubits, electrostatic energy is much larger compared to Josephson energy. The ratio ranges between (1, 100) in case of flux qubits. While in phase qubits, we observe Josephson energy to be much larger than charging energy.

Based on these three archetypes, many superconducting qubits have been derived, namely: Transmon-type qubits, hybrid qubit, J-J flux qubit, Fluxonium, 0-∏ qubits, and more. In this section we review these different types of superconducting qubits. Transmon qubits include Transmon, Xmon, Gmon, 3D Transmon, and are presently very popularly used qubits because of their simple and flexible nature. Transmon charge qubits have reduced charge noise sensitivity, due to larger Josephson energy than electrostatic energy, resulting in the ratio ~100[53], achieved with the use of a large shunting capacitor. Xmon[54] qubits unlike Transmon, are composed of a cross capacitor, and are connected to a common transmission line via resonant cavity. A scalable quantum computation is achieved by its faster control, longer coherence, and a proficient connectivity. Gmon qubits [55] avoids frequency crowding which occurs due to fixed coupling. It provides a flexible space for quantum simulation and quantum computation. 3D Transmon on the other hand, is a transformed form of Transmon, which offers control over the electromagnetic environment, minimizing decoherence while maintaining coupling, provided by 3D waveguide cavity. However, scalability remains a concern.

The Josephson junction qubit or 3-JJ flux qubit comprises three loops Josephson junction (semiconductor electrodes decoupled by a non-superconducting material). Reduced loop size results into reduced sensitivity to magnetic flux noise. Fluxonium[56-58] is another type, which overcomes the problem of inductance and offset noise, supported by its serial array-like structure of large capacitor tunnel. 0-∏ qubit is sketched such as, to obtain dual interleaved-potential well, which provides simultaneous protection against bit flip and phase flip errors. Hybrid qubit was proposed to own the advantages of each of the different quantum systems. Coupling Nitrogen Vacancy center in diamonds was proposed to show hybrid qubit behavior, which combines the advantage of flux qubits which offers good control, and Nitrogen Vacancy center which offers long decoherence time, good to serve as a memory for superconducting processor[59]. Lifetime of different qubits is noted in table 1.

Table1. Lifetime of different Qubits

Qubits	Life time(μs)
Transmon[60]	503
Xmon[61]	44
3D Transmon[62]	300
3-JJ flux qubit[63]	12
C-shunt flux qubit[64]	55
Fluxonium[65]	8100
0-πqubit[66]	1560

2.2 Ascendancies of Superconducting Qubits

Ascendancy of superconducting qubits over other qubit forms like trapped ion, semiconductors, nuclear magnetic resonance, and so on are discussed in this section.

i. Scalable: Superconducting qubits are made using the advantage of semiconductor nano-fabrication technology, which provides a high quality manufacturing and scalability advantage.

ii. Easy coupling: The superconducting qubits can be coupled with capacitors and inductors, owing to the well-defined circuit design of the superconducting qubits.
iii. Well-Controlled: Superconducting qubits measurements can be easily integrated with the microwave control and operations, thus providing easy control over the measurement and operations of the qubit.
iv. Well-designed: Superconducting qubits offer a good designability, enabling different qubits like flux qubits, charge qubits, and phase qubits which can even be further divided to derive different types of qubits like Transmon type, f-f flux qubit, and so on.

These different advantages of the superconducting qubits describe probability for describing scalable quantum computing. Large-scale quantum computing based on superconducting qubits, still remains a challenge, concerned with its tunability and big size, offering short decoherence times. Moreover, these superconducting qubits require a dilution refrigerator to maintain lower temperatures, which ensures high performance.

3. Present Challenges

Superconducting qubits have seen an increased interest of researchers, showing significant promises in the future as well. Despite the advances, there lie some challenges that need attention. In this section we introduce some of them, in order to observe future opportunities.

Coherence time is an important parameter which distinguishes between qubits based on their quality performance. Different approaches have come forward for improving coherence times, like hybrid system of coupled Nitrogen Vacancy center, and fabricating tantalum on 2D Transmon qubits[67-68].

A significant improvement has been made in high-fidelity gates, as well. The single qubit operation is most basic operation that operates over a single qubit, which further involves XY operation, and Physical Z operation. XY operation in principle couples the qubit with microwave using capacitance which results into microwave drive $\Omega(t)=\Omega_x\cos(w_d t-\varphi)$, and Hamiltonian $H= -(\hbar/2)\omega\sigma_z+ \Omega_x\cos(w_d t-\varphi)\sigma_x$. While in physical Z operation, a SQUID loop using two Josephson junctions is realized[69]. z line of qubit is connected with a loop such that, as the current flows, it generates extra flux which produces changes in qubit frequency, generating Hamiltonian $H= -(\hbar/2)\omega_q\sigma_z$. Whereas from 2009 to 2014, the improvement in fidelity realized by the two qubit gate using adiabatic tuning is from 80% to 99.4%[70-71], which was achieved by optimizing frequency, and reducing the leakage. iSWAP , and CPHASE gates were reported with average fidelity of about 99.66% [72]. Use of optimized Control-control-Z gate in case of a multi-qubit gate, can be realized with a fidelity of about 93.3% [73].

Although in past years we have seen improvement in coherence time and gate fidelity. But for large scale quantum computation, quantum error correction still remains a necessity. Some prominent quantum error correction schemes are surface code, bosonic codes, and others. Surface code promises universally scalable fault tolerant quantum computing, owing to its coupled qubit design, and high error-rate threshold. Repetition code is a modified scheme of surface code, which offers protection against bit and phase flip, however it is unable to detect both simultaneously. A two qubit gate was proposed to offer fidelity of about 99.4%, which surpassed the threshold for surface code, further laying path for 2D-surface code that could detect both bit and phase flip simultaneously[74] Bosonic codes on the other hand promise quantum error correction based on the hardware implementation, which makes use of the infinite-dimensional Bosonic Hilbert space. Recent experiments show, quantum system and surroundings interaction can bring constancy in quantum state, thus raising potential for sturdy quantum encoding [75]. The oscillator encoded with logical qubit shows high fidelity realization was demonstrated using cat code favored by universal gates set[76]. Bosonic QEC typically offers protection to quantum information against propagation loss and gates error, providing longer storage time, long distance propagation, as well as hardware productivity.

Along with the scalability, small-scale realization of algorithms is also crucial for improving performance of quantum systems. Quantum simulation is a step forward in this path, and is easier to realize owing to less control required in the implementation of quantum simulators. Keeping, Hamiltonian of the quantum simulator similar to quantum system produces a copy of system. Analog and digital quantum simulations are used for such realization. Where the analog simulation uses controllable system, the digital simulation is not limited to the system behavior, rather it uses gate model for simulation, which involves deploying unitary operation in a quantum gate set. Quantum Rabi model[77], fermionic model [78], and spin model[79] are some quantum systems that were explored using digital quantum simulation. Quantum algorithm demonstration is yet another step toward scalable computation. Harrow-Hassidim-Lloyd algorithms, and Shor's factoring algorithm are little algorithms that show potential applications, however these cannot be implemented practically, on noisy intermediate-scale quantum or NISQ tools, owing to their dependence on error correction improvement. Hybrid quantum algorithms promise to overcome this. Variation quantum eigensolver[80] and quantum machine learning[81] are potential participants for practical implementation on noisy intermediate-scale quantum tools. Quantum machine learning is an emerging topic, and recently for the first time, generation of the handwritten digits was made possible using superconducting quantum processor. However, implementing the quantum machine learning concept on the quantum devices remains a concern, which needs to be addressed in order to get solutions for the real-world problems.

4. Conclusion and future outlook

In this review article, we are trying to present superconducting quantum computing with elementary concepts and current advances in this field. Quantum computing is expected to overcome all the disabilities of conventional computation, revolutionizing the computational approaches in the near future. In recent years, we have achieved great progress in this field, and we believe there are even more significant improvements awaiting in the future. The realization of scalable fault-tolerant quantum computers would lay the path for using quantum computers publicly, which would revolutionize quantum simulation as well as the different aspects of computing and research. Although drastic improvement in coherence time, operational fidelity, realization of error correction and quantum algorithms has been observed, still a number of challenges lie in both the theoretical as well as practical implementations. Developing quality superconducting qubit which would result in improved qubit connectivity, higher operational fidelity, and coherence time, still remains a key challenge. We need to address all such challenges in order to develop practical quantum computers. Quantum supremacy is just a single step towards realizing practical quantum computers, urging for other significant steps in future to come forward. Probably the near term breakthrough that needs our attention is, developing an error correcting quantum computer with longer coherence time. Although the study is still underway, the near future applications of these superconducting qubits can bring significant improvements in the science and engineering sectors.

Nomenclature

SQUID	superconducting quantum interference device
σ_z.	Spin polarization
iSWAP	Imaginary swap
φ	Phase

Greek symbols

ђ	h-bar
ω	Angular frequency

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