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TOPICAL REVIEW — Synergetic Extreme Condition User Facility: Breakthroughs and opportunities for the research of physical science

Solid-state quantum computation station

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Solid-state quantum computation station belongs to the group 2 of manipulation of quantum state in the Synergetic Extreme Condition User Facility. Here we will first outline the research background, aspects, and objectives of the station, followed by a discussion of the recent scientific as well as technological progress in this field based on similar experimental facilities to be constructed in the station. Finally, a brief summary and research perspective will be presented.

Keywords: Quantum computation, superconducting qubit, topological quantum state, Majorana fermion

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1. Introduction

Solid-state quantum devices are among the most promising candidates for the realization of quantum computation, which is expected to perform certain algorithms beyond the ability of the most powerful classical supercomputers. These devices can be well controlled and manipulated; therefore they can also be used for simulations of other quantum systems that are otherwise hard to approach by conventional means. Tremendous progress has been made in these areas in recent years, and there is a growing interest in further experimental studies for future applications. A special station (station 9) in the Synergetic Extreme Condition User Facility (SECUF) will be dedicated to solid-state quantum computation and quantum simulation based on superconducting circuits, topological materials, and electronic spin systems by constructing a state-of-the-art platform with extremely low noise under extreme conditions suitable for various advanced studies.

Superconducting circuits, as the conventional electrical circuits, contain capacitors, inductors, and (effective) resistors, and have Josephson junctions and resonators as their key elements. Over the past years, the quantum coherence times of the superconducting quantum bits (qubits) have been improved steadily, approximately by one order of magnitude every three years, to the present time-scale of 10–100 μs, and beyond. In addition, studies on coupled multi-qubit systems are also progressing. For example, quantum coherence and entanglements have been demonstrated in coupled systems with approximately ten qubits (or more). Systems with a coupled qubit number of up to one (or two) thousand have been developed for implementation of the quantum annealing algorithm.

One of the main constraints in the development of quantum computers is that the quantum state is very vulnerable to perturbations from the surrounding environment, leading to decoherence. Recently, in order to fundamentally solve the problem of decoherence, an alternative approach, using topological protection to develop topological quantum computing (TQC) immune to decoherence, has been actively investigated. The TQC utilizes non-Abelian anyons in $(2+1)$-dimensional space-time. A key feature of non-Abelian anyons is ground-state degeneracy, which is topologically protected by the topological energy gap of the system. Manipulation of the quantum state can be realized by exchange or braiding of these anyons. Such process depends only on the topology of the braiding, immune to weak local perturbations and decoherence.

In the solid-state quantum computation station, an advanced platform for the experimental studies will be developed to expand our present research capability. It mainly involves quantum state manipulation and measurement facilities under some extreme conditions. For the superconducting quantum computation, measurement systems based on cryogen-free dilution refrigerators with $T_{\min} < 30$ mK and residual field smaller than 20 nT will be built, which can be used for studies of multi-qubit chips with a qubit number larger than 100. On the topological side, systems with $T_{\min} < 30$ mK and $B_{\max} > 12$ T will be constructed. Together with auxiliary facilities attached to SECUF, including the microfabrication laboratory for micro- and nano-scale quantum device fabrications, and machine and electronics shops for precision machining, electronic circuit design, and instrument maintenance, it will constitute a world-class research laboratory for the studies of solid-state quantum computation.

2. Research directions and recent progress

A considerable progress in the field of solid-state quantum computation, both scientific and technological, has been achieved in recent years. Below we highlight significant

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achievements in selected aspects, which are important in the further developments and will be the main directions for the future studies on the solid-state quantum computation station.

2.1. Superconducting quantum computation[1–5]

2.1.1. Superconducting qubits and quantum coherence

There are various types of superconducting qubits, including phase qubit, flux qubit, and charge qubit, the latter of which is developed to the transmon and Xmon qubits. The increase of the quantum coherence time is among the key issues in superconducting qubit studies; extensive studies considering various possible mechanisms causing the qubit decoherence have been performed. For example, studies have been performed to reduce the dielectric loss from the qubit surrounding materials, which are always present, such as the substrate, insulation layers, and oxidized tunnel barrier, or metal surface. The dielectric loss at low temperatures, believed to emerge from the two-level states (TLS), can be significantly reduced when the junction size is reduced down to the submicron level. Therefore, smaller junctions combined with shunt capacitors with low-dielectric-loss materials are preferably used. It has been experimentally demonstrated that parallel plate capacitors with a low dielectric loss can provide an improvement of the energy relaxation times by a factor of 20 in the case of phase qubits.

Early experiments of the charge qubits demonstrated only nanosecond-scale coherence times. A significant progress has been achieved with the charge-qubit-derived transmon, which is immune to the $1/f$ charge noise, thus removing the leading source of dephasing, leading to increased microsecond-scale coherence times. A further important improvement can be achieved with the understanding of a resonator modifying the qubit electromagnetic environment, based on the so-called "Purcell effect". The qubit spontaneous emission can be effectively suppressed by coupling it to a resonator, which significantly modifies the modes and density of states of the electromagnetic field in the external circuitry. The reduced spontaneous emission effectively enhances the qubit energy relaxation times.

Transmon (or Xmon) and persistent-current flux qubits only need a modest shunt capacitance. The shunt capacitors can be formed from two electrodes with the substrate as the insulation layer between them. This facilitates the reduction of the dielectric loss if a low-loss substrate is used and if the substrate surface is carefully treated. Dielectric losses of the two-dimensional (2D) resonators, together with the qubits as a whole, have been carefully studied in the past decade. A convenient concept, called "participation ratio", is often used. The participation ratio is defined as the electric field energy stored in the lossy material divided by the total electric field energy stored in the entire device. The participation ratio and dielectric loss decrease with the increase of the device feature size (footprint), which demonstrates that the loss is interface- or surface-limited. Some experiments indicate that the dominant loss originates from the substrate–air and substrate–metal interfaces, while the metal–air interface has a smaller influence. The three-dimensional (3D) transmon is advantageous in this respect as the sizes of the devices are larger, thus reducing the participation ratio and loss from interfaces.

In addition to the advances discussed above, i.e., reduction of the dielectric loss, design of qubits immune to the external noises, and modification of the electromagnetic environment, we mention other studies on the improvement of materials and fabrication techniques, and improvement of filtering and shielding against stray radiation causing quasiparticle dissipation. All of these studies have led to increased qubit coherence times up to the present level of 10–100 μs and beyond.

2.1.2. Logic gates

As discussed above, there are many types of superconducting qubits; in addition, there are also many ways of coupling them together, including capacitive and inductive couplings, and couplings through Josephson junctions and resonators. Single and multi-qubit quantum gate operations, required for the universal gate-based quantum computation, have been experimentally demonstrated with an improving fidelity, starting from the early years after the discovery of the qubit coherence. Single qubit logic operations of different angle rotations about the x, y, and z axes of the Bloch sphere are performed, e.g., in the quantronium, phase, and transmon qubits, which suffice the usual single qubit phase gate, phase-flip gate, NOT gate, and Hadamard gate. Two qubit logic operations, such as controlled-NOT (cNOT) gates, are realized in charge and persistent-current qubits. The square root of the i-SWAP gate is also realized in the phase qubit. The three-qubit Toffoli gate (ccNOT), Toffoli-equivalent controlled controlled phase gate (ccZ), and four-qubit controlled controlled controlled phase gate (cccZ) are successfully demonstrated in transmon qubits. Universal gate sets are proposed, and experimentally implemented and characterized.

2.1.3. Quantum physics and quantum optics

Superconducting circuits and qubits behave quantum mechanically on a macroscopic scale with conveniently controllable system parameters, which provide an excellent platform for studies on quantum physics, atomic physics, and quantum optics. A very large number of studies have been published related to this field; we mention only a few of them: (1) resonant escapes and bifurcation phenomena of nonlinear systems under a strong driving; (2) macroscopic quantum tunneling in cuprate materials and phase diffusion in the quantum regime; (3) quantum stochastic synchronization in

dissipative quantum systems; (4) Landau–Zener–Stückelberg interference and precise control of quantum states in the tripartite system; (5) topological phase diagram and phase transitions in interacting quantum systems; (6) Schrödinger cat living in two boxes; (7) Autler–Townes splitting phenomena; (8) stimulated Raman adiabatic passage and coherent population transfer; (9) electromagnetically induced transparency, a phenomenon similar to the Autler–Townes splitting; however, it is physically distinct; (10) resonance fluorescence and correlated emission lasing.

2.1.4. Quantum simulation

Quantum simulation, i.e., the use of a controllable quantum system to simulate another quantum system, was proposed for the first time by Richard Feynman, envisioned as the main application of a quantum computer. There are two types of quantum simulations: digital and analog quantum simulations. The former simulates a quantum system by dividing the time evolution of a Hamiltonian, expressed as a sum of local terms, into small intervals, which can be realized by a sequence of qubit gate operations. In the analog quantum simulation, the Hamiltonian of the system to be simulated is directly mapped onto the Hamiltonian of the simulator, which can be experimentally controlled. Quantum simulations are promising for applications in various fields including atomic physics, chemistry, condensed-matter physics, cosmology, and high-energy physics.

In particular, in condensed-matter physics, the implementation of digital quantum simulators for the Heisenberg, frustrated Ising, and Fermi–Hubbard models was proposed, which were later experimentally validated. Digital and analog simulations of the Fermi–Hubbard models were discussed. Quantum emulation of creation of anyonic excitations was also achieved experimentally by dynamically generating the ground and excited states of the toric code model. There are many proposals for analog simulators, which need experimental tests: transverse-field Ising or other spin models; Holstein molecular-crystal model exhibiting electron–phonon-induced small-polaron formation; multi-connected Jaynes–Cummings lattice model with Mott-insulator–superfluid–Mott-insulator phase transition; pairing Hamiltonians developed from nearest-neighbor-interacting qubits; quantum emulation of spin systems with topologically protected ground states.

2.1.5. Quantum annealing

Adiabatic quantum computing or quantum annealing was proposed as a heuristic technique for a quantum enhanced optimization approximately two decades ago. This architecture, known to be equivalent to the standard gate-based quantum computation, is simpler and provides a more practical approach for applications in the near term. The first superconducting quantum annealing processors were developed by the D-Wave Systems Inc. based on the rf-SQUID type flux qubits and Nb-junction technology. The D-Wave One, D-Wave Two, D-Wave 2X, and D-Wave 2000Q machines have become available in the years of 2011, 2013, 2015, and 2017 with coupled 128, 512, 1,024, and 2,048 qubits, respectively. Although the superconducting quantum annealing has attracted a significant attention, both academically and industrially, a consensus on the physics and its potential to achieve an optimization algorithm has not been reached; further studies are ongoing.

2.1.6. Quantum computation

Devoret and Schoelkopf discussed key stages in the development of a practical superconducting quantum computer. Briefly, one needs single and multiple physical qubits, which satisfy the first five DiVincenzo criteria: well-defined quantum two-state system, ability to initialize the state, large (relative) coherence times, single- and two-qubit logic gate operations, and state measurement capability. This is followed by logical qubits and memories, which have significantly larger coherence times, by means of quantum error correction. Finally, gate operations on single and multiple logical qubits are realized to reach the ultimate goal of fault-tolerant quantum computation.

Quantum error correction has attracted a significant attention as it is of crucial importance for the realization of quantum computing. In order to perform error correction, the fidelity of gate operation must be above a certain threshold, which can be measured by the double π-pulse, quantum process tomography, and randomized benchmarking methods. It was shown that, using a 5-qubit array, an average single-qubit gate fidelity of 99.92% and two-qubit gate fidelity of up to 99.4% could be achieved. This places the quantum computing at the fault tolerance threshold for surface code error correction. The protection of classical states from environmental bit-flip errors was also reported and the suppression of these errors with an increased system size on a 9-qubit array was demonstrated. In addition, a quantum error detection protocol on a 2×2 planar qubit lattice was reported. The protocol could detect both bit-flip and phase-flip errors, enabling the detection of an arbitrary quantum error. A different approach to implement a full quantum error correction using real-time feedback for encoding, monitoring naturally occurring errors, decoding, and correction was employed. A quantum error correction system was demonstrated, which reached the break-even point (i.e., enhanced lifetime of the encoded information) by suppressing the natural errors due to energy loss, for a qubit logically encoded in superpositions of coherent states of a superconducting resonator.

For a multiple qubit circuit, the demonstration of quantum entanglement and quantum algorithms is an important

step towards quantum computing. Among the various studies, the production and tomography of genuinely entangled Greenberger–Horne–Zeilinger (GHZ) states with up to 10 qubits, which connect to a common bus resonator in a superconducting circuit, were demonstrated. Grover search and Deutsch–Jozsa quantum algorithms as well as solving linear equations were also demonstrated. Multi-qubit devices have been developed for quantum simulations of condensed-matter-physics problems. Furthermore, the quantum advantage in implementation of machine learning algorithms using a 5-qubit superconducting processor was demonstrated.

While most present studies are performed on devices, whose components are arranged on a chip in a planar setting, studies have been performed to fabricate devices with components distributed on different chips stacked vertically in order to accommodate more qubits and reduce interference and cross-talk between different qubits. Similar 3D integration is well-developed for the semiconductor integrated circuits. However, the application of the technology to the superconducting circuits and qubits is not straightforward and requires further investigations. It is particularly concerning that quantum coherence could be seriously suppressed by the requisite processing steps; the progress in the coming years on this issue will be crucial for the development of chips containing approximately 100 qubits (or more).

2.2. Topological quantum computation[6–10]

2.2.1. Topological quantum states

Topology is a branch of mathematics, focused on studies of the overall properties of the spatial geometry. These overall topological properties do not change under a local continuous deformation. For example, if we consider a knotted rope, a local bending of the rope does not affect the number and type of knots. In quantum physics, can we use topologically protected physical states to store quantum information? The answer is yes.

There are indeed topological quantum states in physics, such as integer and fractional quantum Hall states, symmetry protected topological insulators, and topological superconductors. Under local perturbations weaker than the topological energy gap, the overall properties of these states do not change. If these topological quantum states are used to encode quantum information, it is possible to obtain fault-tolerant topological quantum computers. X. G. Wen proposed the concept of topological states in the 1990 s when he studied fractional quantum Hall states. In 1997, Kitaev further proposed a spin grid model. In this model, the quantum information is encoded in the degenerate ground state of the topological states. Quantum computing can be achieved by exchanging (braiding) non-Abelian excitations. The operation of the braiding process is related only to the topological nature of the path, and has no relation to the specific details of the path; therefore, there is no need to consider effects of errors introduced during the operation. Therefore, the TQC has a high fault tolerance. M. Freedman and others further discussed the mathematical architecture of the TQC.

2.2.2. Majorana fermion and Majorana zero mode

In order to perform a TQC, at the current stage, non-Abelian quasiparticles are proposed as a promising approach. Platform candidates include the novel 5/2 fractional quantum Hall state and topological superconductors (such as p-wave superconductor), as they can carry Majorana zero mode (MZM).

What is MZM? In 1928, Dirac proposed a relativistic equation, i.e., the Dirac equation, to describe the motion of spin 1/2 particles (such as electrons), and predicted the existence of an electron antiparticle, positron, which was confirmed by experiments two years later. In 1937, Majorana rewrote the Dirac equation and revealed a real solution, predicting the presence of Majorana fermion. Majorana fermion, as its own antiparticle, is not charged, and follows the Fermi–Dirac statistics. In the field of elementary particles, electrically neutral neutrinos are thought to be Majorana fermions; however, no conclusion has been reached. In the form of an operator, the Majorana operator is a Fermi operator that conforms to $\gamma = \gamma^{\dagger}$. The electrons can be regarded as a pair of Majorana fermions localized at the same point in space. The creation and annihilation operators of an electron j can be expressed as

$$C_j^{\dagger} = (\gamma_{j1} - i\gamma_{j2})/2, \;\; C_j = \left(\gamma_{j1} + i\gamma_{j2}\right)/2.$$

From the anti-commutation relation, we obtained: $\{\gamma_{i\alpha}, \gamma_{j\beta}\} = 2\delta_{ij}\delta_{\alpha\beta}$, $\gamma_{i\alpha}^{\dagger} = \gamma_{i\alpha}$, which is the Majorana operator. The Majorana fermion can be regarded as a "half" electron and always appears in pairs. Certainly, a highly entangled pair of Majorana fermions at the same point in space has no practical significance; the interest of study is focused on spatially separated Majorana fermions.

Although there has been no confirmation of the presence of Majorana fermion in the fields of elementary particles, recently, some traces of it could be observed in condensed matter. In condensed matter, various low-energy quasi-particle excitations can be induced by electromagnetic interactions, possibly producing Majorana fermions. However, collective excitations in condensed matter are mostly collective effects of charged electrons. How can we produce uncharged Majorana fermions? This requires the introduction of superconductivity. The description of quasiparticle excitations in superconductors is provided by the Bogoliubov–de-Gennes equation, corresponding to Bogoliubov quasiparticles as follows:

$$\gamma_k^{\dagger} = \alpha_k C_k^{\dagger} + \beta_k C_{-k}.$$

It is a linear superposition of electrons and holes and satisfies the particle–hole symmetry, $\Gamma_E^{\dagger} = \Gamma_{-E}$, i.e., the creation of an

electron at an energy E is equivalent to the creation of a hole at $-E$. In a conventional s-wave superconductor, spin-opposite electrons pair up, $\gamma_k^\dagger = \alpha_k C_{k,\uparrow}^\dagger + \beta_k C_{-k,\downarrow}$; $\gamma_k^\dagger \neq \gamma_k$, hence, the quasi-particle excitation is not Majorana fermion. In order to satisfy the conditions of the Majorana operator, the spin degree of freedom need to freeze and the momentum and energy need to be zero. P-wave superconductors exactly meet these conditions.

For the one-dimensional case, Kitaev proposed a p-wave superconductivity model with spinless fermions, referred to as the Kitaev model

$$H = -\mu \sum_{j=1}^{N} \left(c_j^\dagger c_j - \frac{1}{2} \right) + \sum_{j=1}^{N-1} \left[-t \left(c_j^\dagger c_{j+1} + c_{j+1}^\dagger c_j \right) + \Delta \left(c_j c_{j+1} + c_{j+1}^\dagger c_j^\dagger \right) \right],$$

where μ is the chemical potential, N is the number of grid points, t is the probability of hopping between neighboring grid points, and Δ is the p-wave pairing order parameter. Fermions on a grid point j can be expressed as superpositions of the two Majorana operators $c_j = \frac{1}{2}(\gamma_j^A + i\gamma_j^B)$, $c_j^\dagger = \frac{1}{2}(\gamma_j^A - i\gamma_j^B)$. We consider two situations. First, when $t = \Delta = 0$, two Majorana fermions on each grid point are coupled to form a Dirac fermion. The entire system is equivalent to a series of fermion chains and is a topologically trivial state. In the other case, $t = \Delta$, $\mu = 0$, and the two Majorana fermions at each grid point are no longer coupled; instead, coupling appears between those at adjacent grid points. At this time, there are zero-energy bound states γ_1^A and γ_N^B at the two ends of the one-dimensional chain, i.e., the Majorana bound state or MZM. Only when the energy is zero, the Bogoliubov quasiparticles can become an equal-amplitude superposition of electrons and holes. The zero energy allows a pair of Majorana bound states to be in an occupied or unoccupied state (degeneracy of the ground state). A fermion parity operator with a pair of Majorana bound states can be defined by

$$P = -i\gamma_{j1}\gamma_{j2} = 1 - 2C_j^\dagger C_j = 1 - 2n = (-1)^n.$$

The parity of the system is related to the ground state occupations. When the ground state is not occupied, $n = 0$, $P = 1$, leading to an even parity; when it is occupied $n = 1$, $P = -1$, leading to an odd parity. Owing to the existence of degenerate ground states, together with the extension of effective dimensions (e.g., experimentally, using one-dimensional nanowires to develop "T" structures), the Majorana bound state no longer obeys the Fermi-Dirac statistics, but the non-Abelian statistics.

In a 2D $p_x + ip_y$ topological superconductor, there is a zero-energy Majorana bound state at a defect (e.g., flux core). When there is an odd number of magnetic fluxes, a one-dimensional Majorana edge mode propagates at the edges. At the core of the magnetic flux, the superconducting energy gap is closed, and the continuous single-particle energy band becomes discrete energy levels owing to the quantum confinement effect. In s-wave superconductors, zero-point motion drives single-particle excitations away from the zero energy. However, for spinless 2D $p_x + ip_y$ topological superconductors, fermions have a Berry phase of π after a circular motion, which causes the discrete energy level to pass through zero, resulting in the appearance of the Majorana bound state in the magnetic flux core.

2.2.3. Topological superconductors

As the Majorana bound state exists in topological superconductors, we need to explain the systems hosting topological superconductivity. There are two types of candidate systems: intrinsic topological superconductors and artificial composite structures that can induce topological superconductivity.

It is theoretically considered that the 5/2 fractional quantum Hall state may be an intrinsic topological superconductor resulting from the p-wave pairing of non-Abelian anyons with an effective charge of e/4. There is already some evidence to support the existence of this topological quantum state; however, further experimental studies are required. In addition, Sr_2RuO_4 is considered as a $p_x + ip_y$ wave superconductor with spin triplet pairing. There is a series of experimental evidences in this respect; however, one of the important evidences, i.e., the edge magnetic moment, has not been observed. The phase A of superfluid ^{3}He is also considered to be p-wave pairing. In general, intrinsic topological superconductors have not yet been fully experimentally confirmed.

Topological superconductivity may also be induced in an artificial composite structure. As mentioned above, in order to construct spinless topological superconductors, it is necessary to "freeze" spin degrees of freedom to form spinless fermions. The studies on topological insulators since 2005 have just solved this problem. At the edges of 2D topological insulators, surfaces of 3D topological insulators, and one-dimensional semiconductor nanowires with strong spin–orbit coupling (SOC), spin-momentum-locked helical electrons exist, satisfying the spinless condition. In 2008, Fu and Kane proposed that conventional s-wave superconductors could be used to introduce superconductivity into the helical surface state of a 3D topological insulator through superconducting proximity effect to form a similar 2D $p_x + ip_y$ superconductor, so that the Majorana zero-energy bound state can be generated at the magnetic flux core or in the Josephson junction. Theoretical approaches have also provided further solutions on the implementation of the one-dimensional p-wave superconductivity (Kitaev chain), suggesting that one-dimensional semiconductor nanowires with strong SOC can be used. A magnetic field perpendicular to the SOC opens a Zeeman gap

of E_Z at $k = 0$. When the chemical potential μ is in the Zeeman energy gap, there is only one spin–orbit-locked Fermi surface, thus forming a helical electron state. A superconducting energy gap Δ is then introduced by s-wave superconductivity. When $E_Z > \sqrt{\Delta^2 + \mu^2}$, the nanowire is in the topological superconductor state, and a Majorana bound state appears at both ends. The replacement of the nanowire with ferromagnetic chains also enables the construction of one-dimensional topological superconductor and Majorana bound state at the end-point.

2.2.4. Experimental detection of Majorana bound state

Two types of experiments are mainly employed to detect Majorana bound state: detection of the zero-bias conductance peak (ZBCP) and probing fractional (4π) Josephson effect. As a Majorana bound state appears at the Fermi energy, a ZBCP can be observed in the tunneling spectrum. In addition, the Majorana bound state in a Josephson junction enables a single-electron transport; the effective charge carrying the supercurrent is changed from the original Cooper pair (2e) to a single electron (e), resulting in a 4π-period current–phase relationship and fractional Josephson effect.

In 2012, Leo Kouwenhoven's group from the Netherlands observed signatures of Majorana bound state in a composite structure containing InSb nanowires with strong SOC and s-wave superconductors. When the parallel magnetic field B increases to ~ 100 mT, the nanowire enters the topological superconductor phase, inducing a ZBCP in the tunneling spectrum. It is just the ZBCP that points to Majorana bound state. Subsequently, similar experiments on nanowires were repeated by many research groups. In 2018, Kouwenhoven's group further observed a ZBCP with a quantized conductance value.

In addition to the above nanowire experiments, many exploratory experiments have been performed based on 2D and 3D topological insulators: (1) ZBCP in a composite structure composed of Bi_2Se_3 and Sn superconductor; (2) complete Andreev reflection in the edge state of a 2D topological insulator InAs/GaSb; (3) ZBCP with spin selectivity in the flux core in epitaxially grown Bi_2Se_3 thin films on $NbSe_2$; (4) disappearance of odd-numbered Shapiro steps in Josephson junctions based on semiconductor InSb/AlInSb, 2D topological insulator HgTe/HgCdTe, and 3D topological insulator HgTe, which was considered to be fractional Josephson effect, i.e., an evidence of Majorana bound state. It is worth noting that when the time-reversal symmetry is conserved, theoretically, the fractional Josephson effect should not occur; therefore, the relevant phenomena need to be further analyzed. When the time-reversal symmetry was broken by magnetic doping, the quantum anomalous Hall effect in Cr-doped $(Bi,Sb)_2Te_3$ was observed. Using the proximity effect to introduce superconductivity into similar materials, the Hall plateau of 1/2 quantum conductance was also detected, which is thought to be derived from a chiral Majorana edge mode. However, there are also other possible explanations for this experimental phenomenon.

2.2.5. Topological quantum computation

Majorana bound state, as an Ising anyon, is expected to be used for TQCs and quantum information storage. There are theoretical proposals on the development of topological quantum computers using one-dimensional nanowires or topological insulators.

The development of a topological qubit requires at least four non-Abelian anyons. Using two nanowires proximitized to superconductors, a magnetic field drives them to a topological superconducting state, thereby producing four Majorana bound states γ_1, γ_2, γ_3, and γ_4. Their degenerate ground states can be divided into four types, according to the different parities of each nanowire: $|ee\rangle$, $|oo\rangle$, $|eo\rangle$, and $|oe\rangle$. When the total parity is conserved, we need to consider only the qubits formed by two degenerate ground states of the same total parity. The state of the qubit, i.e., the specific case of electron occupancy or non-occupancy, can be measured with a single-electron transistor (SET). Using such a qubit, one can also verify Ising anyon fusion rules. First, γ_2 and γ_3 can be fused by the phase change induced by a gate electrode or external magnetic field; γ_1 and γ_4 are then fused, and finally the results are read out through a SET. Currently, studies are ongoing to construct a topological qubit; experiments have successfully produced a Majorana island based on a single nanowire.

However, for the applications of logic gates, the nanowire approach faces natural difficulties, i.e., there is no way to braid Majorana bound state in one-dimensional space. The use of a "T"-shaped nanowire structure or networks has been proposed to achieve this operation. The phase transition of the topological superconductor is related to the chemical potential of the nanowires; therefore, the gate voltage can be locally adjusted to control the boundary of the topological superconductor, thereby moving the Majorana bound state. TQC based on nanowires is one of the main research fields nowadays.

Majorana bound state can also exist in a heterostructure of 3D topological insulators and superconductors. Superconductivity similar to the spinless $p_x + ip_y$ can be induced on the 2D surface of 3D topological insulators through the superconducting proximity effect, hence Majorana bound state can be present in its magnetic flux core or Josephson device. The previously mentioned ZBCP attributed to the Majorana bound state in the magnetic flux core has been observed. In terms of Josephson devices based on 3D topological insulators, some evidence of the existence of Majorana bound state has been observed.

It is obviously easier to braid Majorana bound states in the 2D plane than in the one-dimensional nanowire system. By exchange or braiding Majorana bound states, a series of logic gates can be realized, including the Hadamard and Z gates. However, in order to form a universal gate set, the magic. $\pi/8$ phase gate is lacking. It can be obtained by bringing two Majorana bound states close together to induce finite coupling and then separating them far apart. However, this process is not topologically protected and errors can be induced. In addition, interference was proposed as a clever approach to achieve the phase gate; however, it is also not protected. Furthermore, a geometric multistep protocol with an exponential accuracy in the number of steps has been studied to reduce the phase gate error. It was also pointed out that using the hexagonal or square Josephson junction arrays to encode and braid the Majorana bound state (although only Ising anyons), universal topological quantum computation can be realized. During topological quantum computation, the quantum states are measured through fermion parity. An intuitive approach is to employ a SET adjacent to the Majorana qubit, so that the fermion parity can be read out with a high sensitivity. Another more advanced approach is to combine a superconducting qubit in an optical cavity. All of these ideas, among the others, are currently pursued in physical laboratories.

3. Conclusion and perspective

Recently, significant progress has been made in the studies of superconducting circuits and qubits. In particular, the quantum coherence times have been increased by five orders of magnitude up to the range of 10–100 μs in devices such as the 2D and 3D transmon qubits, Xmon qubits, and persistent-current flux qubits. These devices have improved designs offering better controls over the qubit fabrication, manipulation, measurement, as well as multi-qubit coupling. Studies on various aspects are ongoing, which may finally lead to the physical implementation of quantum computing. At the present stage, it is encouraging that the performed studies have demonstrated most of the basic properties and functionalities required for the development of a quantum computer. On the other hand, we are entering a further stage with more complex quantum systems in which new fundamental physical and technical problems need to be addressed. Before the ultimate goal of quantum computing is reached, valuable results in the studies of quantum physics, atomic physics, quantum optics, quantum annealing, and quantum simulations are expected.

In general, the TQC utilizes the overall topological nature of the system, making it immune to local perturbations, a unique advantage in the implementation of the blueprint of quantum computing. However, the perturbations cannot be infinitely large as they will break the topological protection quantified by the energy gap. At the current stage, most of the above experiments are performed at extremely low temperatures to reduce thermal fluctuations. Moreover, the noise level of the surrounding environment of the device should be sufficiently low, not to overcome the topological energy gap. Therefore, facilities with extreme conditions are required to perform TQCs. By encoding and braiding Majorana bound state, it is expected that universal quantum computing will be eventually realized.

The solid-state quantum computation station, together with the auxiliary facilities attached to the SECUF, is expected to become a world-class research laboratory for experimental studies of solid-state quantum computation based on superconducting circuits, topological materials, and other systems such as the electronic spin device.

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