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Phase Shift and Control in Superconducting Hybrid Structures

Taro YAMASHITA[†,††a)], ***Member***

SUMMARY The physics and applications of superconducting phase shifts and their control in superconducting systems are reviewed herein. The operation principle of almost all superconducting devices is related to the superconducting phase, and an efficient control of the phase is crucial for improving the performance and scalability. Furthermore, employing new methods to shift or control the phase may lead to the development of novel superconducting device applications, such as cryogenic memory and quantum computing devices. Recently, as a result of the progress in nanofabrication techniques, superconducting phase shifts utilizing π states have been realized. In this review, following a discussion of the basic physics of phase propagation and shifts in hybrid superconducting structures, interesting phenomena and device applications in phase-shifted superconducting systems are presented. In addition, various possibilities for developing electrically and magnetically controllable 0 and π junctions are presented; these possibilities are expected to be useful for future devices.
key words: *superconductivity, superconducting spintronics, π junction, phase shift, Josephson junction*

1. Introduction

A macroscopic phase in superconductors is a key feature of superconductivity. In superconducting structures, various interesting phenomena related to superconducting phases appear, such as Andreev reflections [1] and the Josephson effect [2]. Superconducting phases play essential roles in both fundamental physics and device applications of superconductors and controlling the phase shifts is important for the operation of superconducting devices. Various superconducting devices have been developed over the years, such as superconducting quantum interference devices (SQUIDs) [3], rapid single flux quantum (RSFQ) logic circuits [4], and Josephson voltage standard systems [5]. Almost all superconducting devices operate by utilizing the superconducting phase shift in Josephson junctions.

In recent years, superconductors have once again attracted a lot of attention because superconductor-based quantum bits (qubits) are promising candidates as basic elements of quantum computing systems [6]–[8]. Although there are several types of superconducting qubits, such as charge, flux, phase, and transmon qubits, the basic element in common is the Josephson junctions. Superconducting quantum annealers also comprise arrays of direct-current SQUIDs with Josephson junctions [9]. To realize large-scale quantum computing systems, an efficient control of the superconducting phase in Josephson junctions needs to be achieved. In currently developed superconducting qubits, the phases of the Josephson junctions are primarily controlled by external magnetic fields. This approach is suitable when only a few qubits are used. However, a more efficient approach needs to be developed for large-scale systems because it is difficult to precisely control many qubit phases owing to the variations in physical parameters in the qubits.

In this paper, we review various approaches for controlling the superconducting phases in superconducting hybrid structures. In Sect. 2, the basic principles of Andreev reflection and the Josephson effect are described from the point of view of a superconducting phase; in addition, intrinsic π-phase shifts by ferromagnetic Josephson junctions and d-wave superconductors are introduced. In Sect. 3, interesting phenomena related to phase-shifted superconducting systems are presented, along with their applications to novel devices. In Sect. 4, several methods to control the superconducting phase using the electric current, spin current, and magnetic configuration are described.

2. Physics of Superconducting Phase Shifts

2.1 Phase Propagation via Andreev Reflection

Andreev reflection is a phenomenon that occurs at normal metal/superconductor (NM/SC) interfaces, as shown in Fig. 1 (a) [1]. When a voltage smaller than the superconducting gap is applied to this system, an electron in the NM moves to the interface but cannot enter the SC as an electron because there is no energy state within the gap except a condensed state of Cooper pairs. Therefore, the electron takes another electron with opposite spin from the NM and forms a Cooper pair. As a result, the injected electron is reflected to the NM as a hole, and a Cooper pair propagates to the SC; this is the Andreev reflection. In the Andreev reflection, the reflected hole obtains the superconducting phase (θ in Fig. 1 (a)) in the SC; as a result, the information concerning the superconducting phase propagates into the NM via the hole.

At a ferromagnetic metal/superconductor (FM/SC) interface, the probability of an Andreev reflection is very sensitive to the exchange energy of the FM [10]. Let us consider the limiting case of a half-metallic FM in which only an up-spin state exists at the Fermi level (Fig. 1 (b)). In this case,

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[†]The author is with NICT Advanced ICT Research Institute, Kobe-shi, 651–2492 Japan.
[††]The author is with PRESTO, Japan Science and Technology Agency, Kawaguchi-shi, 332–0012 Japan.
a) E-mail: taro@nict.go.jp
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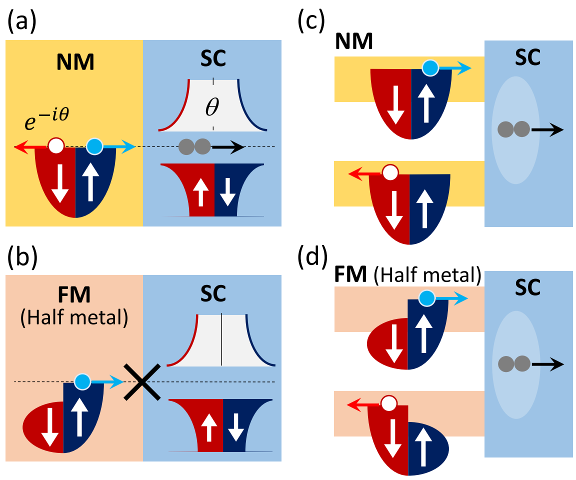

Fig. 1 Schematics of Andreev reflection and crossed Andreev reflection in (a), (b) and (c), (d), respectively. (a) and (c) are for normal metal/superconductor (NM/SC) structures, and (b) and (d) are for ferromagnet/superconductor (FM/SC) structures.

an injected electron with an up spin cannot obtain a down-spin electron from the FM; this means that the formation of a Cooper pair is prohibited. In general, the probability of the Andreev reflection becomes smaller for stronger FMs, and the spin polarization of FMs can be estimated by measuring the conductance via the Andreev reflection [10].

The phase propagation via the Andreev reflection also occurs in *non-local* structures, as shown in Fig. 1 (c) [11]–[13]. In this structure, when the distance between two NM electrodes is small enough [13] and an electron in one electrode is injected into the SC, the hole can be reflected onto the other electrode. This is called a "crossed" Andreev reflection (CAR). In this process, the injected electron and the reflected hole propagate in different NM electrodes, but they are connected via the superconducting phase in the SC. This indicates that the phase is propagated non-locally. When the electrodes are in the FM, the probability of CAR depends on the relative orientation of the magnetizations in the FMs: for example, in the case of half-metallic FMs, a Cooper pair cannot form when the magnetizations are parallel because an up-spin electron in one electrode cannot obtain a down-spin electron in the other electrode. However, when the magnetizations are antiparallel, as shown in Fig. 1 (d), an up-spin electron in one electrode can obtain a down-spin electron in the other electrode; as a result, a Cooper pair can propagate to the SC via the CAR. In general, the conductance and resistance of CAR processes are higher and lower, respectively, for antiparallel alignments than for parallel ones; this means that inverse magneto-resistance effects can occur in such systems [13].

2.2 Phase Shift in Josephson Junctions

It is well known that the Josephson effect appears in systems separated by two SCs, such as SC/insulator/SC or SC/NM/SC junctions, and the Josephson current (J) depends on the phase difference (φ) in the SCs: $J = J_C \sin\varphi$, where J_C is the Josephson critical current [2]. The Josephson effect can be explained by the occurrence of multiple Andreev reflections in a barrier layer [14]. As described above, the superconducting phase propagates by electrons and holes via the Andreev reflection, which means that the superconducting phases in both SCs are coupled. As a result, discrete Andreev bound states that depend on the phase difference between two SCs form in the junction, and the Josephson current flows via the Andreev bound states.

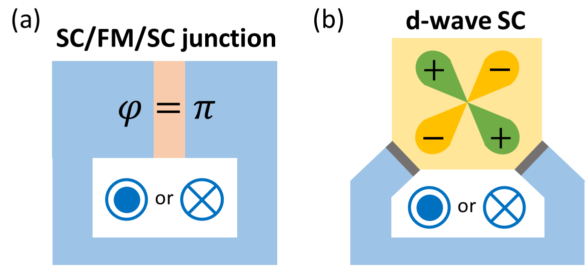

Fig. 2 Schematics of a superconducting loop with (a) a ferromagnetic π junction and (b) d-wave pairing symmetry.

When the barrier between the SCs is ferromagnetic (SC/FM/SC junction), the Andreev bound states are modulated by the exchange energy in the FM and therefore become spin-dependent because the Fermi wavenumbers of the propagating electrons and holes are spin-dependent in a FM [15]. As a result, for specific conditions of the exchange energy and thickness of the FM, the numbers of the Andreev bound states for positive and negative Josephson currents are reversed; thus, the sign of the Josephson critical current changes, and the current–phase relationship for the SC/FM/SC junction is shifted by π; $J = -J_C \sin\varphi = J_C \sin(\varphi + \pi)$. This junction is called a "π junction," and the phase difference is π in the ground state (π state) [16]. The physical mechanism of the π state can be explained by oscillation of the order parameter in the FM [17]. Because of the exchange energy in FMs, the momenta of the up-spin and down-spin electrons in Cooper pairs have finite centers of mass. As a result, a spatial oscillation term appears in the order parameter in the FM, and the phase difference of π becomes stable when the sign of the order parameter is different for the two SCs. After the first experimental demonstration of a π junction, many studies on the π state have been presented [18]–[24]. The ordinary state, in which the phase difference is zero (0 state), and the π state can be set by controlling the temperature and thickness of a FM layer [18], [19].

The simplest geometry, in which the phase shift by the π state appears as a macroscopic phenomenon, is a superconducting loop with a π junction, as shown in Fig. 2 (a). From the condition that the total phase shift in the loop needs to be an integral multiple of 2π, a spontaneous circulating current flows; this results in a magnetic flux corresponding to a half-integer flux quantum being generated in the loop. Another way in which an intrinsic phase shift can be obtained is to use a d-wave pairing symmetry of the order parameter, which often appears in high-transition temperature (high-T_C) superconductors, such as YBCO [25]–[27]. In d-wave symmetry, the positive and negative lobes are separated by a node. As shown in Fig. 2 (b), by connecting the positive and negative lobes via a superconducting loop, a π phase shift is generated in the loop, and a spontaneous magnetic flux is generated in the same manner as it is in a ferromagnetic π junction loop. It is worth noting here that, for both ferromagnetic Josephson junctions and d-wave pairing symmetry, the 0 and π states cannot be controlled externally, *i.e.*, by the current or magnetic field, in simple structures generally. To control the 0 and π states flexibly, therefore, some specific structures need to be prepared; these are presented in Sect. 4.

3. Phase-shifted Superconducting Systems

3.1 Spontaneous Currents in Superconducting Arrays

An interesting experiment regarding phase-shifted superconducting systems with π junctions has been demonstrated by Frolov *et al*. [28]. The authors demonstrated spontaneous current imaging in frustrated superconducting loop array structures. They fabricated an array consisting of superconducting loops with even and odd numbers of ferromagnetic Josephson junctions, as shown in Figs. 3 (a) and (b), respectively. The thickness of the ferromagnetic (CuNi) layer was set to 11 nm, for which the Josephson junction changes to the π state from the 0 state at 2.8 K with decreasing temperature. When the junction was in the π state, no current flowed in the loop containing even numbers of π junctions in the ground state; this occurred because the flux quantization was satisfied for the π phase differences of all the junctions. Conversely, a finite current spontaneously flowed in the loop with odd numbers of π junctions because the phase differences of each junction shifted from π to satisfy the flux quantization of the loop.

The authors measured the spontaneous currents in the various pattern of the arrays with the "frustrated" (odd π junctions) and "unfrustrated" (even π junctions) cells using a scanning SQUID microscope (SSM). Figure 3 (c) shows an SSM image of a 6 × 6 checkerboard-frustrated array at various temperatures. For temperatures above the 0–π transition temperature of 2.8 K, all the ferromagnetic Josephson junctions were in the 0 state, so no spontaneous currents appeared. When the temperature decreased and became lower than 2.8 K, spontaneous currents started to flow in the cells, and a clear magnetic flux pattern appeared in the array because of the spontaneous current at 1.6 K. This is a striking demonstration of the intrinsic phase shift of the π junctions, and the experimental system with the magnetic flux array is attractive for studying the frustrated two-dimensional systems [29].

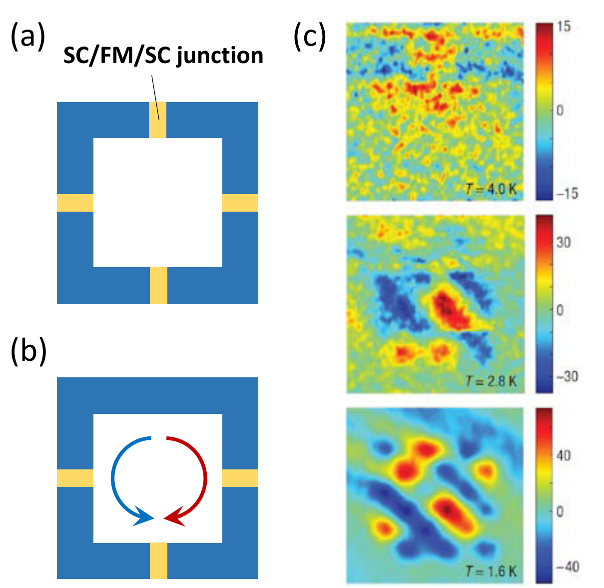

Fig. 3 Schematics of (a) an unfrustrated and (b) a frustrated superconducting cell with π junctions. (c) SSM image of a 6 × 6 checkerboard-frustrated array at temperatures of, from the top, 4.0, 2.8, and 1.6 K. The vertical magnetic field scale is approximately in units of mΦ_0 [28].

3.2 Supercomputing Logic Devices

One important application of superconductors is in cryogenic computing [4], [30]–[33]. Recently, various types of superconducting logic devices have been developed as candidates for post-CMOS computers, such as RSFQ [4], [30], adiabatic quantum flux parametron (AQFP) [31], [32], and reciprocal quantum logic (RQL) [33] devices. The main advantages of these superconducting logic devices are their high-speed operation and ultralow power consumption. For example, RSFQ circuits can operate on the order of 10–100 GHz [30], and an AQFP has been demonstrated to have a power consumption of 10 zJ [32]. Not only do these devices have potential for use in high-performance computing systems, but the RSFQ and AQFP circuits are also expected to find use as cryogenic signal-processing circuits for superconducting nanowire single-photon detectors (SSPDs or SNSPDs) [34], [35].

Efficient phase shift and control are crucial for improving the performance of superconducting logic devices. In a conventional RSFQ circuit, there is a problem associated with a large single-flux storage cell because high geomet-

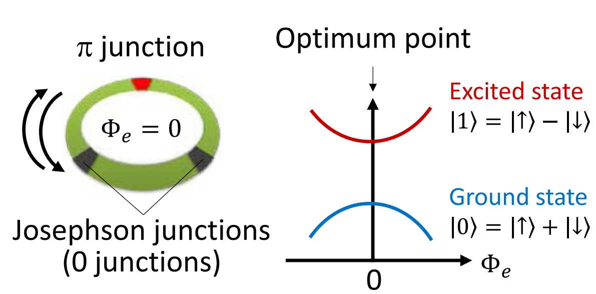

Fig. 4 Schematic of a π-junction flux qubit. The optimum point in the energy diagram of the ground and excited quantum states is located at zero external magnetic field.

rical inductance is required for storing magnetic flux quantum. Such large cells prevent the cell size of RSFQs from being reduced. To overcome this problem, a study has proposed replacing the inductance with a π junction; the authors designed a toggle flip-flop (TFF) circuit that included a π junction [36]. Utilizing a numerical simulation of a π-TFF circuit, they confirmed that their proposed circuits operated correctly and possessed a sufficient margin for operation.

Experimentally, a first phase-shifted RSFQ circuit has been realized by the d-wave pairing symmetry of a high-T_C superconductor, YBCO [37]. The π-TFF was developed by combining the YBCO and Nb, and the authors demonstrated that its operating stability was improved for a variety of parameters in the phase-shifted RSFQ circuit. They also demonstrated that the bias current supply can be reduced because the bias current required to realize the twofold degenerate energy state was replaced by insertion of the π junction. In 2010, the implementation of a SC/FM/SC π junction into a RSFQ logic circuit was reported [38]. The authors fabricated a RSFQ-based frequency divider that included a π-TFF with an Nb/CuNi/Nb junction, and they demonstrated correct operation of the circuit.

3.3 Superconducting Quantum Computers

A quantum computing device is a recent vigorous application of superconductors [6]–[8]. Among the various candidates for a quantum computer, the superconducting qubit has many advantages; the qubit and the peripheral circuit to control and read out the quantum state can be designed, accumulated techniques concerning device fabrication can be adopted, and so on. Actually, in the superconducting qubit, the circuit quantum electrodynamics (circuit QED) has already been demonstrated, and the control and readout of the qubit state can be performed by using the microstrip cavity and line fabricated monolithically. An advantage of the superconducting qubit is that such a quantum system with desired circuit parameters can be designed and fabricated. As a result of many efforts to improve the decoherence time of the qubit, sub-ms decoherence time has now been achieved [39]. One recent trend regarding the superconducting qubit is to realize large-scale systems with many qubits; thus, improvement of the scalability is crucial, as is a longer decoherence time.

Phase shift techniques can be applied to superconducting qubits to improve their performance. The first proposal for superconducting qubits with intrinsic phase shift elements was proposed by Ioffe *et al.* [40]. The basic structure is similar to that shown in Fig. 2 (b). By connecting the positive and negative parts of a d-wave order parameter with an ordinary (s-wave) superconductor, double degenerate states can be intrinsically generated without a constant external magnetic field. This is called a "quiet" qubit because a finite magnetic flux (or circulating current) is not generated in the coherent quantum state; thus, there is no undesired electric or magnetic coupling to the environment. This feature is expected to improve the decoherence time of qubits. However, developing quiet qubits with d-wave superconductors is challenging because fabricating devices with high-T_C superconductors is relatively difficult, and the reproducibility and controllability of the physical parameters are fairly low [41].

As another phase-shifted qubit, a π flux qubit with a SC/FM/SC junction has been proposed [42], [43]. The device structure is similar to conventional flux qubits with Josephson junctions; one π junction and one or two Josephson junctions (0 junctions) are placed in a superconducting loop. In a π flux qubit, the magnetic pre-bias corresponding to the half-integer flux quantum that is necessary in the conventional flux qubit is not required to generate the coherent two energy level and operate at the optimum point with long decoherence time. Thus, similar to the quiet qubit, the decoherence originating from coupling to the environment, such as the magnetic noises of the pre-bias coil, will be suppressed compared with the conventional flux qubit. Furthermore, for the realization of multi qubits, the π flux qubits do not require a uniform magnetic field to pre-bias each qubit precisely, so this feature is an advantage for large-scale integration. From the point of view of device fabrication, the π flux qubit is possible because Nb-based SC/FM/SC π junctions have been developed by many groups [18]–[24]. In the field of superconducting logic devices, Nb is commonly used, and the fabrication of large-scale circuits has already been established; therefore, the π junction is compatible with conventional fabrication processes. Actually, a phase qubit with an Nb/CuNi/Nb π junction has been demonstrated experimentally [38]. In this experiment, the obtained decoherence time was comparable to that of the conventional phase qubit (without a π junction), and further improvement of the decoherence time is desired. Very recently, high-quality NbN-based π junctions have been presented toward a realization of π flux qubits with longer decoherence time [24].

4. Ideas for Control of Phase Difference

4.1 Electron-Distribution Modulation

In the phase-shifted superconducting systems with ferromagnetic π junctions or d-wave paring symmetry discussed in Sect. 3, the degree of the superconducting phase shift is basically fixed. However, if one can control the 0 and π states electrically or magnetically, the possibilities for new device applications will expand.

Baselmans *et al.* presented an electrically controllable 0–π Josephson junction [44]. The device geometry is shown in Fig. 5 (a). They fabricated SC/NM/SC junctions using superconducting Nb electrodes with an Au barrier, and a voltage control line was connected to the Au barrier via reservoirs. In the diffusive Au region, a supercurrent-carrying density of states, which is similar to the Andreev bound states in the ballistic regime, is formed. Positive and negative Josephson currents flow via the positive and negative parts of the supercurrent-carrying density of states, respec-

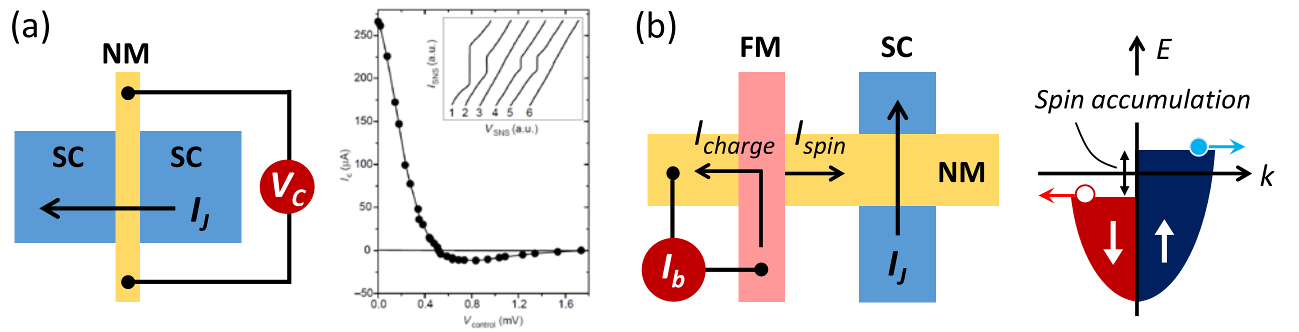

Fig. 5 (a) (left) Geometry of a controllable 0–π junction that utilizes electron-distribution modulation. (right) The control voltage dependence of the Josephson critical current. Inset: current–voltage characteristics for control voltages of 0.38 (curve 1), 0.44 (2), 0.52 (3), 0.64 (4), 0.84 (5), and 1.70 mV (6) [44]. (b) (left) Geometry of a controllable 0–π junction utilizing non-local spin injection. (right) Schematic of spin accumulation caused by the shift of the chemical potentials of the up- and down-spin electrons in the NM region of a SC/NM/SC junction.

tively. Therefore, by modulating the electron distribution in the density of states, the direction of the Josephson current (I_J) can be reversed. In this geometry, the electron distribution can be changed by applying a large control voltage. As shown in the right-hand side of Fig. 5 (a), the current voltage curves were measured as a function of the control voltage, and it was observed that the sign of the Josephson critical current, I_C, reversed with increasing control voltage at approximately 0.5 mV. Although the mechanism of the sign reversal of the Josephson current was different from that for a ferromagnetic π junction, this result indicates a phase shift in the current–phase relation and can be used as a controllable 0–π junction in future applications.

4.2 Non-Local Spin Injection

The 0 and π states are also expected to be controlled by generating a spin imbalance in the NM of an SC/NM/SC junction electrically [45]. Figure 5 (b) shows the geometry of a non-local spin injection. In the left-hand side, the FM electrode contacts the NM bar, and the NM is sandwiched by two SC electrodes (SC/NM/SC junction) in the right-hand side of the geometry. When the current I_b is biased from the FM electrode to the NM bar, spin is injected into the NM because the number of up-spin electrons is greater than that of down-spin ones at the Fermi level in the FM [46], [47]. As a result, the chemical potential in the NM close to the FM/NM interface is spin-split in the range of the spin relaxation length from the interface. Although the charge current flows only to the left-hand side of the NM bar, the spin splitting of the chemical potential relaxes also in the direction of the right-hand side of the NM bar; thus, a spin accumulation is non-locally generated in the NM at the SC/NM/SC junction, as shown in Fig. 5 (b). This non-equilibrium spin accumulation works as the exchange energy in the ferromagnet and will therefore modulate the Andreev bound states formed in the SC/NM/SC junction. Because the degree of spin accumulation can be controlled by the injected current from the FM, the Andreev bound states can also be modulated electrically. As a result, it is possible that the 0–π transition can occur by changing I_b.

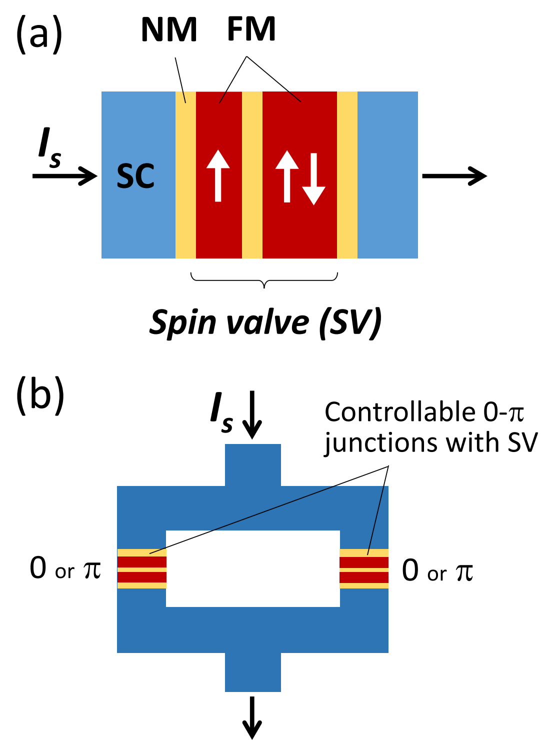

Fig. 6 (a) Schematic of a 0–π controllable Josephson junction with a spin-valve (SV) magnetic layer. The SV layer consists of two ferromagnets with different coercive fields separated by a normal metal layer. Parallel and anti-parallel alignments of the magnetization can be realized by applying a magnetic field. (b) SQUID with two phase-controllable Josephson junctions with a SV layer.

4.3 Josephson Junction with Spin-Valve Structures

Recently, another way to control the 0 and π states has been presented in Josephson junctions with a spin-valve (SV) magnetic layer; SC/SV/SC junctions [48]–[50]. The SV layer consists of two FM layers separated by a non-magnetic metal. The two FM layers have fixed and free magnetizations, and the relative orientation of the magnetization can be set as parallel (P) or antiparallel (AP) by applying an external magnetic field. Because the effective magnetic layer thickness the order parameter experiences depends on the relative orientation of the magnetization, it is expected that the Josephson critical current will change depending on the magnetic state in the SV layer. This indicates that the strength of the Josephson coupling can be controlled by an external magnetic field. Furthermore, by optimally setting the thickness of a SV layer, it is also possible to control the 0 and π states magnetically. In Ref. [48], SC/SV/SC junctions (Nb/Cu/Ni/Cu/NiFeNb/Cu/Nb) were fabricated, and the dependences of the critical current on the magnetic field and on the thickness of the Ni layer were measured systematically. In the measurements of the characteristic voltage of the junction as a function of the Ni thickness, cusp behavior, indicating a 0–π transition, was observed. Here it is striking that the transition point (thickness) between the 0 and π states is different for the P and AP alignments because the effective ferromagnetic layer thickness (*i.e.*, the total phase shift) was larger for the P state than for the AP state. This result indicates that a 0–π magnetically controllable junction can be realized utilizing the SV structure.

More recently, Gingrich *et al*. demonstrated a 0–π controllable SQUID [50]. This SQUID consists of two SC/SV/SC junctions in a superconducting loop, and the coercive fields of the free layers in the two SVs were designed to be different. The ground state of both of the junctions was the 0 state for the AP alignment and the π state for the P alignment of the magnetizations of the layer. Therefore, by controlling the magnetic field, the state of the SQUID could be changed to the 0–0, 0–π, π–0, or π–π states. The authors clearly observed different critical current modulations for the four magnetic states. From an application point of view, 0–π controllable SC/SV/SC junctions and/or SQUIDs with phase-controllable junctions are promising candidates for cryogenic memory devices, which is a missing component in superconductor-based cryogenic computer systems [51].

5. Conclusion

In this review, we introduced the physics and device applications regarding the phase shift and control in superconducting hybrid structures using the π state of ferromagnetic Josephson junctions and the d-wave order parameter. By adopting the intrinsic phase shift in superconducting systems, various interesting phenomena and devices, such as efficient logic circuits, higher-coherence superconducting qubits, and cryogenic memory devices, can be realized. These novel techniques for efficient superconducting phase shift and control will facilitate the improvement of device performances and open up new possibilities for superconducting device applications.

Acknowledgments

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References

[1] A.F. Andreev, "The thermal conductivity of the intermediate state in superconductors," Sov. Phys. JETP, vol.19, no.5, pp.1228–1231, 1964.
[2] B.D. Josephson, "Supercurrents through barriers," Adv. Phys., vol.14, no.56, pp.419–451, 1965.
[3] R.L. Fagaly, "Superconducting quantum interference device instruments and applications," Review of Scientific Instruments, vol.77, no.10, p.101101, 2006.
[4] K.K. Likharev and V.K. Semenov, "RSFQ logic/memory family: a new Josephson-junction technology for sub-terahertz-clock-frequency digital systems," IEEE Trans. Appl. Supercond., vol.1, no.1, pp.3–28, 1991.
[5] C.A. Hamilton, "Josephson voltage standards," Review of Scientific Instruments, vol.71, no.10, p.3611, 2000.
[6] J. Clarke and F.K. Wilhelm, "Superconducting quantum bits," Nature, vol.453, no.7198, pp.1031–1042, 2008.
[7] T.D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J.L. O'Brien, "Quantum computers," Nature, vol.464, no.7285, pp.45–53, 2010.
[8] M.H. Devoret and R.J. Schoelkopf, "Superconducting circuits for quantum information: an outlook," Science, vol.339, no.6124, pp.1169–1174, 2013.
[9] M.W. Johnson, M.H.S. Amin, S. Gildert, T. Lanting, F. Hamze, N. Dickson, R. Harris, A.J. Berkley, J. Johansson, P. Bunyk, E.M. Chapple, C. Enderud, J.P. Hilton, K. Karimi, E. Ladizinsky, N. Ladizinsky, T. Oh, I. Perminov, C. Rich, M.C. Thom, E. Tolkacheva, C.J.S. Truncik, S. Uchaikin, J. Wang, B. Wilson, and G. Rose, "Quantum annealing with manufactured spins," Nature, vol.473, no.7346, pp.194–198, 2011.
[10] R.J. Soulen, Jr., J.M. Byers, M.S. Osofsky, B. Nadgorny, T. Ambrose, S.F. Cheng, P.R. Broussard, C.T. Tanaka, J. Nowak, J.S. Moodera, A. Barry, and J.M.D. Coey, "Measuring the Spin Polarization of a Metal with a Superconducting Point Contact," Science, vol.282, no.5386, pp.85–88, 1998.
[11] G. Deutscher and D. Feinberg, "Coupling superconducting-ferromagnetic point contacts by Andreev reflections," Appl. Phys. Lett., vol.76, no.4, pp.487–489, 2000.
[12] G. Falci, D. Feinberg, and F.W.J. Hekking, "Correlated tunneling into a superconductor in a multiprobe hybrid structure," Europhysics Lett., vol.54, no.2, pp.255–261, 2001.
[13] T. Yamashita, S. Takahashi, and S. Maekawa, "Crossed Andreev reflection in structures consisting of a superconductor with ferromagnetic leads," Phys. Rev. B, vol.68, no.17, p.174504, 2003.
[14] I.O. Kulik, "Macroscopic quantization and proximity effect in S-N-S junctions," Sov. Phys. JETP, vol.30, no.5, pp.944–950, 1970.
[15] H. Sellier, C. Baraduc, F. Lefloch, and R. Calemczuk, "Temperature-induced crossover between 0 and π states in S/F/S junctions," Phys. Rev. B, vol.68, no.5, p.054531, 2003.
[16] A.I. Buzdin, L.N. Bulaevskii, and S.V. Panyukov, "Critical-current oscillations as a function of the exchange field and thickness of the ferromagnetic metal (F) in an S-F-S Josephson junction," JETP Lett., vol.35, p.178, 1982.
[17] E.A. Demler, G.B. Arnold, and M.R. Beasley, "Superconducting proximity effects in magnetic metals," Phys. Rev. B, vol.55, no.22, pp.15174–15182, 1997.
[18] V.V. Ryazanov, V.A. Oboznov, A. Yu. Rusanov, A.V. Veretennikov, A.A. Golubov, and J. Aarts, "Coupling of two superconductors through a ferromagnet: Evidence for a π junction," Phys. Rev. Lett., vol.86, no.11, pp.2427–2430, 2001.
[19] T. Kontos, M. Aprili, J. Lesueur, F. Genêt, B. Stephanidis, and R. Boursier, "Josephson junction through a thin ferromagnetic layer: Negative coupling," Phys. Rev. Lett., vol.89, no.13, p.137007, 2002.
[20] W. Guichard, M. Aprili, O. Bourgeois, T. Kontos, J. Lesueur,

and P. Gandit, "Phase sensitive experiments in ferromagnetic-based Josephson junctions," Phys. Rev. Lett., vol.90, no.16, p.167001, 2003.
[21] S.M. Frolov, D.J. Van Harlingen, V.A. Oboznov, V.V. Bolginov, and V.V. Ryazano, "Measurement of the current-phase relation of superconductor/ferromagnet/superconductor π Josephson junctions," Phys. Rev. B, vol.70, no.14, p.144505, 2004.
[22] V.A. Oboznov, V.V. Bol'ginov, A.K. Feofanov, V.V. Ryazanov, and A.I. Buzdin, "Thickness dependence of the Josephson ground states of superconductor-ferromagnet-superconductor junctions," Phys. Rev. Lett., vol.96, no.19, p.197003, 2006.
[23] M. Weides, M. Kemmler, E. Goldobin, D. Koelle, R. Kleiner, H. Kohlstedt, and A. Buzdin, "High quality ferromagnetic 0 and pi Josephson tunnel junctions," Appl. Phys. Lett., vol.89, no.12, p.122511, 2006.
[24] T. Yamashita, A. Kawakami, and H. Terai, "NbN-based 0 and π ferromagnetic Josephson junctions," Phys. Rev. Appl., vol.8, p.054028, 2017.
[25] D.A. Wollman, D.J. Van Harlingen, W.C. Lee, D.M. Ginsberg, and A.J. Leggett, "Experimental determination of the superconducting pairing state in YBCO from the phase coherence of YBCO-Pb dc SQUIDs," Phys. Rev. Lett., vol.71, no.13, pp.2134–2137, 1993.
[26] J.R. Kirtley, C.C. Tsuei, J.Z. Sun, C.C. Chi, L.S. Yu-Jahnes, A. Gupta, M. Rupp, and M.B. Ketchen, "Symmetry of the order parameter in the high-Tc superconductor $YBa_2Cu_3O_{7-\delta}$," Nature, vol.373, no.6511, pp.225–228, 1995.
[27] E. Il'ichev, V. Zakosarenko, R.P.J. IJsselsteijn, H.E. Hoenig, V. Schultze, H.-G. Meyer, M. Grajcar, and R. Hlubina, "Anomalous periodicity of the current-phase relationship of grain-boundary Josephson junctions in high-Tc superconductors," Phys. Rev. B, vol.60, no.5, pp.3096–3099, 1999.
[28] S.M. Frolov, M.J.A. Stoutimore, T.A. Crane, D.J. Van Harlingen, V.A. Oboznov, V.V. Ryazanov, A. Ruosi, C. Granata, and M. Russo, "Imaging spontaneous currents in superconducting arrays of π-junctions," Nat. Phys., vol.4, no.1, pp.32–36, 2008.
[29] S.E. Korshunov, "Phase transitions in two-dimensional systems with continuous degeneracy," Phys.-Uspekhi, vol.49, no.3, pp.225–262, 2006.
[30] M. Tanaka, K. Takata, R. Sato, A. Fujimaki, T. Kawaguchi, Y. Ando, K. Takagi, N. Takagi, and N. Yoshikawa, "Development of Bit-Serial RSFQ Microprocessors Integrated with Shift-Register-Based Random Access Memories," Ext. Abst. 15th Int. Superconductive Electronics Conf., no.DS-001, pp.157–159, Nagoya, July 2015.
[31] N. Takeuchi, D. Ozawa, Y. Yamanashi, and N. Yoshikawa, "An adiabatic quantum flux parametron as an ultra-low-power logic device," Supercond. Sci. Technol., vol.26, no.3, p.035010, 2013.
[32] N. Takeuchi, Y. Yamanashi, and N. Yoshikwa, "Measurement of 10 zJ energy dissipation of adiabatic quantum-flux-parametron logic using a superconducting resonator," Appl. Phys. Lett., vol.102, no.5, p.052602, 2013.
[33] Q.P. Herr, A.Y. Herr, O.T. Oberg, and A.G. Ioannidis, "Ultra-low-power superconductor logic," J. Appl. Phys., vol.109, no.10, p.103903, 2011.
[34] T. Yamashita, S. Miki, H. Terai, K. Makise, and Z. Wang, "Crosstalk-free operation of multi-element SSPD array integrated with SFQ circuit in a 0.1 W GM cryocooler," Opt. Lett., vol.37, no.14, pp.2982–2984, 2012.
[35] N. Takeuchi, T. Yamashita, S. Miyajima, S. Miki, N. Yoshikawa, and H. Terai, "Low-power and low-current adiabatic interface for superconducting nanowire single-photon detectors," Opt. Exp., vol.25, no.26, pp.32650–32658, 2017.
[36] A.V. Ustinov and V.K. Kaplunenko: "Rapid single-flux quantum logic using π-shifters," J. Appl. Phys., vol.94, no.8, pp.5405–5407, 2003.
[37] T. Ortlepp, Ariando, O. Mielke, C.J.M. Verwijs, K.F.K. Foo, H. Rogalla, F.H. Uhlmann, and H. Hilgenkamp, "Flip-flopping fractional flux quanta," Science, vol.312, no.5779, pp.1495–1497, 2006.
[38] A.K. Feofanov, V.A. Oboznov, V.V. Bol'ginov, J. Lisenfeld, S. Poletto, V.V. Ryazanov, A.N. Rossolenko, M. Khabipov, D. Balashov, A.B. Zorin, P.N. Dmitriev, V.P. Koshelets, and A.V. Ustinov, "Implementation of superconductor/ferromagnet/superconductor π-shifters in superconducting digital and quantum circuits," Nat. Phys., vol.6, no.8, pp.593–597, 2010.
[39] W.D. Oliver and P.B. Welander, "Materials in superconducting quantum bits," MRS BULLETIN, vol.38, no.10, pp.816–825, 2013.
[40] L.B. Ioffe, V.B. Geshkenbein, M.V. Feigel'man, A.L. Fauchère, and G. Blatter, "Environmentally decoupled sds-wave Josephson junctions for quantum computing," Nature, vol.398, no.6729, pp.679–681, 1999.
[41] Y. Makhlin, G. Schon, and A. Shnirman, "Quantum-state engineering with Josephson-junction devices," Rev. Mod. Phys., vol.73, no.2, pp.357–400, 2001.
[42] T. Yamashita, K. Tanikawa, S. Takahashi, and S. Maekawa, "Superconducting π qubit with a ferromagnetic Josephson junction," Phys. Rev. Lett., vol.95, no.9, p.097001, 2005.
[43] T. Yamashita, S. Takahashi, and S. Maekawa, "Superconducting π qubit with three Josephson junctions," Appl. Phys. Lett., vol.88, no.13, p.132501, 2006.
[44] J.J.A. Baselmans, A.F. Morpurgo, B.J. van Wees, and T.M. Klapwijk, Nature, vol.397, no.7, pp.43–45, 1999.
[45] T. Yamashita, S. Takahashi, and S. Maekawa, "Controllable π junction with magnetic nanostructures," Phys. Rev. B, vol.73, no.14, p.144517, 2006.
[46] M. Johnson and R.H. Silsbee, "Interfacial charge-spin coupling: Injection and detection of spin magnetization in metals," Phys. Rev. Lett., vol.55, no.17, pp.1790–1793, 1985.
[47] F.J. Jedema, A.T. Filip, and B.J. van Wees, "Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve," Nature, vol.410, no.6826, pp.345–348, 2001.
[48] B. Baek, W.H. Rippard, S.P. Benz, S.E. Russek, and P.D. Dresselhaus, "Hybrid superconducting-magnetic memory device using competing order parameters," Nat. Commun., vol.5, p.3888 doi: 10.1038/ncomms4888 (2014).
[49] B. Baek, W.H. Rippard, M.R. Pufall, S.P. Benz, S.E. Russek, H. Rogalla, and P.D. Dresselhaus, "Spin-transfer torque switching in nanopillar superconducting-magnetic hybrid Josephson junctions," Phys. Rev. Applied, vol.3, no.1, p.011001, 2015.
[50] E.C. Gingrich, B.M. Niedzielski, J.A. Glick, Y. Wang, D.L. Miller, R. Loloee, W.P. Pratt Jr, and N.O. Birge, "Controllable 0-π Josephson junctions containing a ferromagnetic spin valve," Nat. Phys., vol.12, no.6, pp.564–567, 2016.
[51] T. Yamashita and H. Terai, "Recent Progress in Ferromagnet/Superconductor Hybrid Structure and its Applications to Cryogenic Computing," IEEJ Transactions on Fundamentals and Materials, vol.136, no.12, pp.728–733, 2016.

Taro Yamashita received his Ph.D. degree in physics from Tohoku University, Japan, in 2005. He is currently a Senior Researcher at the National Institute of Information and Communications Technology (NICT), Japan. He is also a PRESTO Researcher, Japan Science and Technology Agency. His research interests include superconducting devices and physics and superconducting spintronics. He is a member of the Japan Society of Applied Physics (JSAP), the Physical Society of Japan (JPS), and the Institute of Electronics, Information, and Communication Engineers of Japan (IEICE).