Parity-Protected Superconductor-Semiconductor Qubit


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Coherence of superconducting qubits can be improved by implementing designs that protect the parity of Cooper pairs on superconducting islands. Here, we introduce a parity-protected qubit based on voltage-controlled semiconductor nanowire Josephson junctions, taking advantage of the higher harmonic content in the energy-phase relation of few-channel junctions. A symmetric interferometer formed by two such junctions, gate-tuned into balance and frustrated by a half-quantum of applied flux, yields a \(\cos(2\phi)\) Josephson element, reflecting coherent transport of pairs of Cooper pairs. We demonstrate that relaxation of the qubit can be suppressed tenfold by tuning into the protected regime.

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Recent proof-of-concept demonstrations of quantum simulations have highlighted progress in the development of small-scale quantum processors \[1,2\]. While potentially useful for near-term applications \[3,4\], the qubits used in the experiments were still susceptible to errors, limiting the accuracy and complexity of quantum algorithms that these systems can support. Ultimately, qubits with fault-tolerant operations are desired \[5\]. Ideas for fault-tolerant quantum computers rely on redundantly encoding quantum information in a protected subspace of a larger quantum system \[6\]. One approach is through the use of quantum error correction codes such as surface or color codes, which actively perform stabilizer measurements to confine a large Hilbert space to a subspace that is protected from local, random errors \[7\]. Quantum error correction is expected to allow fault-tolerant quantum computing using noisy qubits at the cost of requiring many physical qubits for each logical qubit and increased runtime \[8,9\].

An alternative approach is to engineer fault tolerance at the device level. This can be implemented, for instance, using Majorana zero modes in a network of topological superconductors \[10,11\], forming a highly degenerate ground state in which quantum information can be encoded nonlocally, protecting it from local noise. Another form of device-level protection can be implemented using Josephson junctions (JJs) with potentials that are \(\pi\) periodic in the phase difference, \(\phi\), of the superconducting order parameter across the junction \[12\]. Similar to Majorana qubits, \(\pi\)-periodic JJs protect quantum information using disconnected parity subspaces. For Majoranas, it is the parity of the number of electrons on an island that is relevant; for \(\pi\)-periodic JJs it is the parity of the number of Cooper pairs on an island. Protected \(\pi\)-periodic JJs also allow for protected quantum operations \[13\], suggesting a fruitful path towards fault-tolerant quantum computing.

Several implementations of \(\pi\)-periodic Josephson devices have appeared \[14,15\]. A recent version \[16\] used four JJs in a rhombus configuration to generate a \(\pi\)-periodic \(\cos(2\phi)\) potential, yielding a qubit defined by the parity of Cooper pairs. This qubit is dual to the recently introduced bifluxon qubit, defined by the parity of flux quanta \[17\]. The Josephson rhombus uses four nominally identical JJs in a loop \[18,19\]. Departures from symmetry, for instance due to fabrication variation among the four junctions, lift the degeneracy of the lowest two states and reduce protection.

Here, we implement the \(\cos(2\phi)\) element needed for protection using a pair of gate-tunable semiconductor JJs based on InAs nanowires grown with epitaxial superconducting Al \[20–22\]. Nanowire-based superconducting qubits, or gatemons \[23,24\] and two-junction superconducting quantum interference devices (SQUIDs) \[25\] have been explored recently. A two-gatemon SQUID is particularly useful for creating protected qubits, as gate control of junction transmission allows precise \textit{in situ} balancing of the interferometer at fixed external flux, and, critically, makes use of higher harmonics of the energy-phase relation for a few-channel semiconductor junction \[26–28\] to create a robust and tunable \(\pi\)-periodic qubit. We observe that when the interferometer is gate tuned \textit{in situ} into balance, the resulting protected qubit shows a factor-of-10 enhancement in lifetime compared to unprotected tunings.

The protected qubit circuit is shown in Fig. 1(a). The transmonlike geometry consists of a superconducting
island with charging energy $E_C$ connected to ground through two JJs in a SQUID configuration. Junction transmissions are tuned using gate voltages $V_k$ ($k = 1, 2$). We model the two JJs in the short-junction regime, expressing Josephson coupling as mediated by a number ($i = 1, 2, \ldots$) of Andreev bound states, each characterized by a transmission coefficient, $T_i^{(k)}$ [29]. The energy-phase relation of each JJ is then given by summing over the $i$ energies of the bound states,

$$U_k(q_k) = -\Delta \sum_i \sqrt{1 - T_i^{(k)} \sin^2(q_k/2)},$$  \hspace{1cm} (1)

where $\Delta$ is the superconducting gap and $q_k$ is the superconducting phase difference across the $k$th JJ. The total system Hamiltonian is given by

$$H = 4E_C\hat{n}^2 - U_1(\hat{\phi}) - U_2(\hat{\phi} - 2\pi \Phi/\Phi_0).$$  \hspace{1cm} (2)

dominant $\cos(2\hat{\phi})$ term and higher even harmonics. This results in a qubit with a $\pi$-periodic potential with coherent transport across the SQUID occurring only in units of $4e$ charge, that is, pairs of Cooper pairs. Here, the suppression of single-Cooper-pair transport results in the qubit having doubly degenerate ground states that differ by the parity of Cooper pairs on the island. Figures 1(b) and 1(c) plot the qubit potential term at $\Phi = \Phi_0/2$ as a function of transmission coefficient $T_i^{(k)} = T$ (for all $i, k$) and symmetry parameter $\alpha = U_2(\hat{\phi})/U_1(\hat{\phi})$. Increasing asymmetry between the JJs increases coupling between the potential wells, resulting in a potential that is similar to that of a flux qubit. In the limit of strong asymmetry, $\alpha \to 0$, the single-well potential of a transmon qubit is recovered.

Figures 1(d)–1(f) show micrographs of one of three measured devices. All devices showed similar spectra, with detailed time domain data taken on one of them. A large T-shaped island (blue) embedded in a ground plane was patterned from a 100 nm Al film on a high-resistivity silicon substrate, forming the shunting capacitor of the superconducting circuit. We estimate the charging energy of the island to be $E_C/h \approx 240$ MHz using electrostatic simulations. The semiconductor JJs are fabricated from molecular beam epitaxy-grown InAs nanowires with a $\sim 10$ nm thick epitaxial aluminum layer grown on two of the nanowire facets. Each JJ is formed by etching away a $\sim 200$ nm segment of the Al shell. The JJs are then connected between the island and the ground plane using evaporated Al contacts using in situ argon milling to remove native oxide layers. Proximal electrostatic gates (red) tune the JJ transmission by modulating the electron density predominantly in the junction region (green). The applied magnetic flux is controlled with the current through a nearby shunted transmission line while microwave excitations are driven using an open transmission line. The qubit is read out using a $\lambda/4$ cavity that has a resonance frequency of 6.615 GHz, $Q$ factor of $\sim 6500$, and is coupled with strength $g/2\pi \sim 80$ MHz to the qubit when operated in the transmon regime. The coupling strength and $Q$ factor were chosen to avoid Purcell effects in the dispersive regime. The sample is measured in a dilution refrigerator at $< 50$ mK inside superconducting Al and cryoperm magnetic shielding layers [30].

We first probe the readout cavity as a function of the flux through the SQUID, as shown in Fig. 2(a). Near one-half flux quantum a vacuum Rabi splitting is visible as the first excited cavity and qubit states hybridize (red line). Several other qubit states also weakly couple to the cavity, resulting in additional smaller anticrossings. We utilize two-tone spectroscopy to directly probe the transition frequencies of the qubit system: a readout tone, adjusted at each point in flux to the cavity frequency extracted from Fig. 2(a), was monitored while a second drive tone was swept in frequency to excite energy states. At a point tuned away from one-half flux quantum, we observe two transition
FIG. 2. Qubit spectroscopy as a function of applied flux ($V_1 = 1.4$ V and $V_2 = -0.445$ V). (a) Frequency of the readout cavity as the qubit spectrum is tuned with flux. Solid and dashed lines indicate crossings of qubit transition frequencies as determined from fits to the data in (c). (b) Two-tone spectroscopy of the qubit transition frequencies. An average of each column has been subtracted. (c) Extracted transition frequencies from (b) with solid lines a fit to Eq. (2). Diagrams above illustrate the fitted potential for different values of $\Phi$. Gray dashed lines indicate multiphoton transitions due to the simultaneous drive and readout tones.

frequencies with the spectrum resembling that of a transmon qubit with the higher frequency transition being $f_{01}$ (red) and a lower two-photon excitation $f_{02}/2$ (orange). As the flux is tuned closer to one-half flux quantum, the spectrum diverges from a transmonlike system, with anharmonicity, $h(f_{12} - f_{01})$, changing from negative to positive. Several horizontal lines are observed in the spectrum that we attribute to on-chip resonances, amplifying the readout response when in coincidence with a qubit transition frequency.

To understand the spectrum, we extract the excitation frequencies $f_{01}$, $f_{02}$, $f_{02}/2$, and $f_{12}$, shown as colored circles in Fig. 2(c). The extracted frequencies were fit by numerically calculating energy eigenstates of Eq. (2), taking $\Delta/h = 45$ GHz [30,34] [solid lines in Fig. 2(c)]. From the fit we extract a charging energy $E_C/h = 284 \pm 5$ MHz [30] and sets of transmission coefficients for each junction $\{T_i^{(1)}\} = \{1.0, 0.98, 0.29, 0.28\}$ and $\{T_i^{(2)}\} = \{0.95, 0.09, 0.09, 0.09\}$. Diagrams above Fig. 2(c) show the Josephson potential of the fitted model at different values of $\Phi$. At tuning condition $\Phi = \Phi_0/2$ the NW SQUID forms a symmetric double-well potential due to higher harmonics of the energy-phase relation. The barrier height between the two wells is tuned by the asymmetry of the two arms in the SQUID. Moving away from $\Phi = \Phi_0/2$, the potential is tilted, causing $f_{01}$ to sharply rise in energy, eventually resulting in a single well and the weakly anharmonic spectrum of the transmon. We match other transitions (gray dashed lines) to multiphoton excitations due to simultaneously applied readout and drive tones. These transition frequencies are calculated by subtracting an integer multiple of the cavity resonance frequency, $f_r$, from the fitted spectrum. Minor differences between the model and data may be due to small ac Stark shifts affecting the measured transition frequencies [35].

Next, we study the effect of modifying the gate voltages for each JJ. As highlighted in Fig. 1(c), the relative tuning of the two JJs can strongly modify the qubit potential. First, we tune into the protected qubit regime by adjusting the gate voltages to balance the two junctions such that single-Cooper-pair transport across the SQUID is suppressed, forming a double-well potential with minima separated by $\Phi = \pi$. In this balanced configuration, energy states are strongly localized to each of the wells with microwave-induced interwell transitions suppressed due to the small wave function overlap. The spectrum as a function of flux—controlling the tilt of the double-well potential—features transitions between the ground states and the next energy state of the same well [Fig. 3(a)]. Close to one-half flux quantum with a weakly tilted potential, $f_{01}$ is a forbidden transition between the two wells and is therefore not visible in the spectrum. As the potential is tilted further, two avoided crossings between $f_{01}$ and $f_{02}$ are observed when states $|1\rangle$ and $|2\rangle$, localized in separate wells, are in resonance. The spectrum is reminiscent of a heavy fluxonium, which also has a double potential well but with minima separated by $2\pi$ instead of $\pi$ [36,37]. As for Fig. 2, we extract the transition frequencies and fit them to Eq. (2) with $E_C/h = 284$ MHz and $\Delta/h = 45$ GHz to find the transmission coefficients $\{T_i^{(1)}\} = \{1.0, 1.0, 0.60, 0.0, 0.0\}$ and $\{T_i^{(2)}\} = \{0.99, 0.78, 0.31, 0.30\}$. At $\Phi = \Phi_0/2$ the potential forms a double-well potential with minima at $\phi = \pm \pi/2$ with two nearly degenerate ground states given by the bonding and antibonding eigenstates [Fig. 3(b)]. In Fig. 3(c), the two ground states are plotted in the charge basis, clearly showing the separation in parity with either odd or even numbers of Cooper pairs.

In contrast, Fig. 3(d) shows the qubit spectrum with one junction tuned to have much lower total transmission than the other. Again, fitting the measured spectrum to Eq. (2) yields $\{T_i^{(1)}\} = \{1.0, 0.91, 0.30, 0.20, 0.18\}$ and $\{T_i^{(2)}\} = \{0.90, 0.06, 0.06, 0.06\}$. The potential and two lowest energy states extracted from the fit [Figs. 3(c) and 3(f)] has the form of a harmonic oscillator with a small perturbation giving a positive anharmonicity, similar to a flux qubit [38].

Using in situ gate control, we are able to demonstrate protection of coherence in the symmetric (balanced) regime compared to the asymmetric (transmon) regime. Due to...
we interpret as relaxation from an incoherent mixture of states.

To drive oscillations around an exponentially decaying offset, we operated at $\Phi = 0.512\Phi_0$ giving a slightly tilted double well potential while allowing visible readout. Oscillations occur around an exponentially decaying offset (black line). We estimate $f_{01} \approx 3.1$ GHz, as extracted from our model.

We measured qubit lifetime in the unprotected regime by applying a $\pi$ pulse followed by readout after a wait time $\tau$ (Fig. 5, blue). Fitting the data to an exponential decay, we extract a lifetime $T_1 = 0.6$ $\mu$s. Near the protected regime, we drove the $|0\rangle \leftrightarrow |2\rangle$ transition with a long 3 $\mu$s pulse to initialize the $|1\rangle$ state, followed by readout after a wait time $\tau$ (Fig. 5, red). We observe two superimposed exponential decays with lifetimes $T_1^{(1)} = 7.2$ $\mu$s and $T_1^{(2)} = 1.2$ $\mu$s that we interpret as relaxation from an incoherent mixture of the $|1\rangle$ and residually populated $|2\rangle$ states, respectively. The factor of $\sim 12$ enhancement in $|1\rangle$ state lifetimes, corresponding to a factor $\sim 5$ enhancement in $Q$ factor, near the protected regime is qualitatively consistent with a suppressed charge matrix element, $\langle 0\rangle\langle 1|1\rangle \rightarrow 0$. Extracted matrix elements indicate much longer lifetimes are achievable [30].
and we speculate that lifetimes become limited by decay channels such as a residual resistance of the semiconductor JJs due to subgap states [39,40].

In summary, we have demonstrated a superconducting circuit architecture based on tunable, high-transmission semiconductor JJs configured to realize a parity-protected qubit. The simplicity and in situ tunability of this circuit along with recently reported semiconductor two-dimensional-electron-gas-based JJs [41] pave the way for scalable, parity-protected qubits. Furthermore, we have demonstrated dispersive readout of qubit states with enhanced lifetimes by operating with a small detuning from the protected regime. This points to readout of protected states by dynamically modifying the device tuning to lift the degree of protection. Alternatively, protected states might be distinguished using para-
tuning to lift the degree of protection. Alternatively, protected states by dynamically modifying the device from the protected regime. This points to readout of protected states by dynamically modifying the device tuning to lift the degree of protection. Additionally, protected qubit states might be distinguished using para-
tuning to lift the degree of protection. Alternatively, protected states by dynamically modifying the device from the protected regime. This points to readout of protected qubit states with protected qubit operations [13].

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