

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 $\cos(2\varphi)$ 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 π periodic in the phase difference, φ , of the superconducting order parameter across the junction [12]. Similar to Majorana qubits, π -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 π -periodic JJs it is the parity of the number of

Cooper pairs on an island. Protected π -periodic JJs also allow for protected quantum operations [13], suggesting a fruitful path towards fault-tolerant quantum computing.

Several implementations of π -periodic Josephson devices have appeared [14,15]. A recent version [16] used four JJs in a rhombus configuration to generate a π -periodic $\cos(2\varphi)$ 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 $\cos(2\varphi)$ 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 gatemon [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 *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 π -periodic qubit. We observe that when the interferometer is gate tuned *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

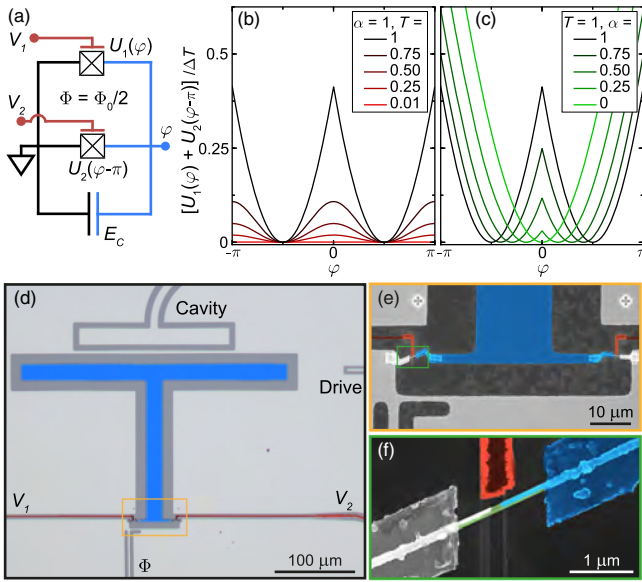


FIG. 1. Qubit circuit and device design. (a) Circuit schematic of the parity-protected qubit formed from high-transparency few-channel semiconductor Josephson junctions in a flux-biased interferometer shunted by a large capacitor (blue). (b),(c) Energy-phase relation of the interferometer for (b) different junction transmission coefficients and (c) junction asymmetries. (d) False-color optical micrograph of the device showing the large island (blue) that forms one side of the shunting capacitor. (e),(f) False-color electron micrographs of the nanowire junctions. (f) A small segment of the Al shell on an InAs nanowire is etched away to form a semiconductor Josephson junction. A nearby electrostatic gate (red) allows for the tuning of the electron density in the junction.

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 ($i = 1, 2, \dots$) 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,

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

where Δ is the superconducting gap and φ_k is the superconducting phase difference across the k th JJ. The total system Hamiltonian is given by

$$H = 4E_C \hat{n}^2 - U_1(\hat{\varphi}) - U_2(\hat{\varphi} - 2\pi\Phi/\Phi_0), \quad (2)$$

where Φ is the applied flux through the SQUID loop with $\Phi_0 = h/2e$ the superconducting flux quantum. For identical, highly transmissive JJs at one-half flux quantum ($\Phi = \Phi_0/2$), odd harmonics in the Hamiltonian potential, $-U_1(\hat{\varphi}) - U_2(\hat{\varphi} - 2\pi\Phi/\Phi_0)$, are suppressed, leaving a

dominant $\cos(2\hat{\varphi})$ term and higher even harmonics. This results in a qubit with a π -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 $\alpha = U_2(\hat{\varphi})/U_1(\hat{\varphi})$. 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, $\alpha \rightarrow 0$, 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 $E_C/h \sim 240$ MHz using electrostatic simulations. The semiconductor JJs are fabricated from molecular beam epitaxy-grown InAs nanowires with a ~ 10 nm thick epitaxial aluminum layer grown on two of the nanowire facets. Each JJ is formed by etching away a ~ 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 shorted 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 ~ 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

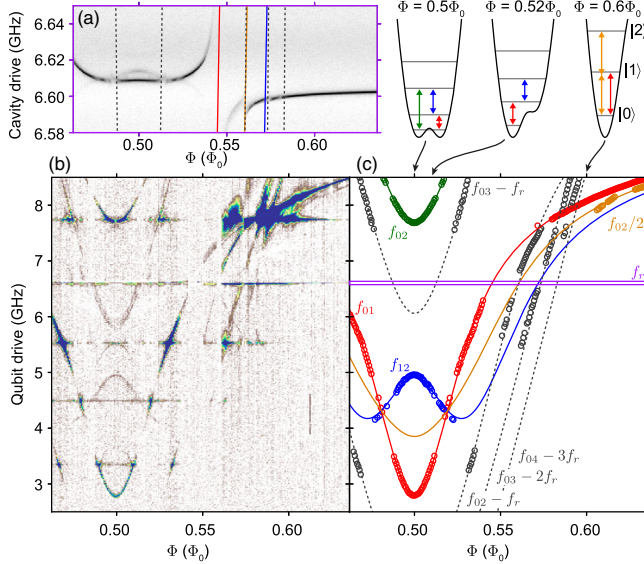


FIG. 2. Qubit spectroscopy as a function of applied flux ($V_1 = 1.4$ V and $V_2 = -0.445$ V). (a) Frequency of the readout cavity as the qubit spectrum is tuned with flux. Solid and dashed lines indicate crossings of qubit transition frequencies as determined from fits to the data in (c). (b) Two-tone 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 Φ . 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 coincident 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 Φ . 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 $\varphi \sim \pi$. 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 on resonance. The spectrum is reminiscent of a heavy fluxonium, which also has a double potential well but with minima separated by 2π instead of π [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 $\varphi \sim \pm\pi/2$ 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(e) 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

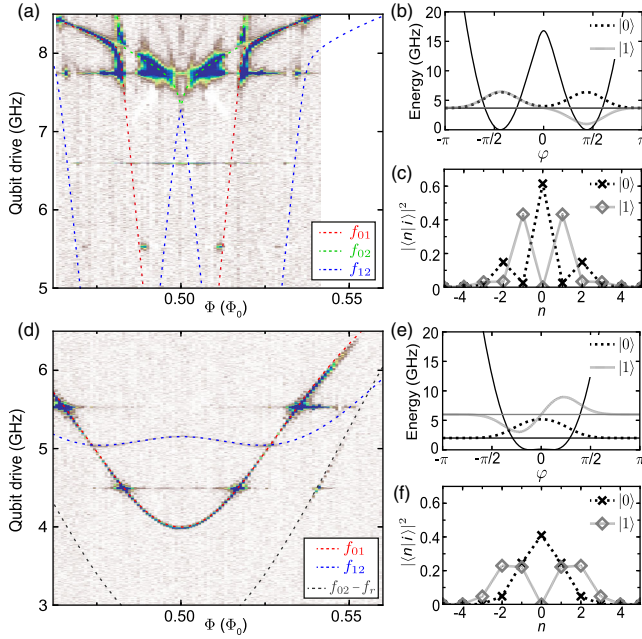


FIG. 3. Voltage control of potential barrier. (a) Gate voltages are tuned to a balanced regime with the two junctions of similar value ($V_1 = 1.2$ V and $V_2 = -0.12$ V). (b) Qubit potential (solid black line) and wave functions for the two lowest energy states extracted from a fit to data in (a) at $\Phi = \Phi_0/2$. (c) The charge distribution of the two lowest energy states. (d) Gate voltages tuned to an unbalanced regime with one junction much smaller than the other ($V_1 = 1.241$ V and $V_2 = -0.386$ V). (e) Qubit potential and wave functions for the two lowest energy states extracted from fits to (d). (f) The charge distribution of the two states.

the protection of the $4e$ -parity states of the qubit, states are indistinguishable through dispersive measurements. Instead, we operated at $\Phi = 0.512\Phi_0$ giving a slightly tilted double well potential while allowing visible readout [Fig. 4(b) diagram]. In the asymmetric (transmon) regime, applying a drive tone at the qubit resonance frequency for a time τ yielded Rabi oscillations, as shown in Fig. 4(a). On the other hand, near the symmetric configuration, the $|0\rangle \leftrightarrow |1\rangle$ transition was strongly forbidden, preventing a direct comparison to the asymmetric regime. Instead, in the near-symmetric case, we applied microwave drive at the unprotected $|0\rangle - |2\rangle$ transition frequency. Figure 4(b) shows the microwave-induced Rabi oscillations between the $|0\rangle$ and $|2\rangle$ states in this configuration. Oscillations occur around an exponentially decaying offset (black line), which we interpret as decay from the $|2\rangle$ state to the $|1\rangle$ state, trapping the population in $|1\rangle$ at long drive times. We estimate $f_{01} \approx 3.1$ GHz, as extracted from our model.

We measured qubit lifetime in the unprotected regime by applying a π pulse followed by readout after a wait time τ (Fig. 5, blue). Fitting the data to an exponential decay, we extract a lifetime $T_1 = 0.6$ μ s. Near the protected regime,

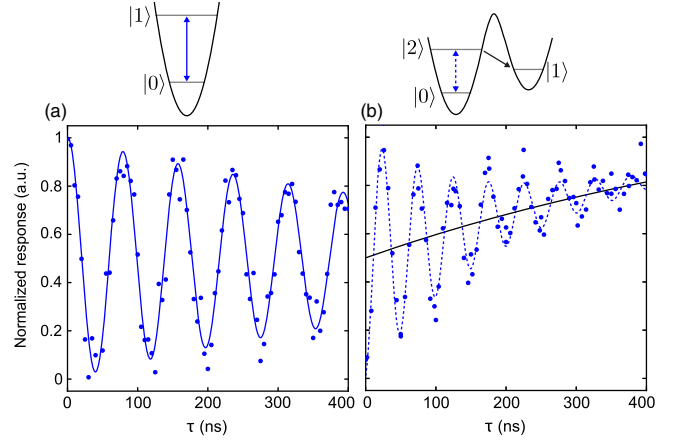


FIG. 4. Coherent control. Rabi oscillations in (a) the transmon regime with $\Phi = 0$ and $f_{\text{Drive}} = 7.911$ GHz and (b) a tilted π qubit regime with $\Phi = 0.512\Phi_0$ and $f_{\text{Drive}} = 5.725$ GHz. Diagrams show the qubit potentials and lowest energy states. Voltages are fixed at $V_1 = -1.25$ V and $V_2 = -0.445$ V for both (a) and (b). The solid line in (a) is a fit to an exponentially decaying sinusoidal function, while in (b) the fit function has an additional exponentially decaying offset (black line).

we drove the $|0\rangle \leftrightarrow |2\rangle$ transition with a long 3 μ s pulse to initialize the $|1\rangle$ state, followed by readout after a wait time τ (Fig. 5, red). We observe two superimposed exponential decays with lifetimes $T_1^{(1)} = 7.2$ μ s and $T_1^{(2)} = 1.2$ μ s that we interpret as relaxation from an incoherent mixture of the $|1\rangle$ and residually populated $|2\rangle$ states, respectively. The factor of ~ 12 enhancement in $|1\rangle$ state lifetimes, corresponding to a factor ~ 5 enhancement in Q factor, near the protected regime is qualitatively consistent with a suppressed charge matrix element, $\langle 0|\hat{n}|1\rangle \rightarrow 0$. Extracted matrix elements indicate much longer lifetimes are achievable [30],

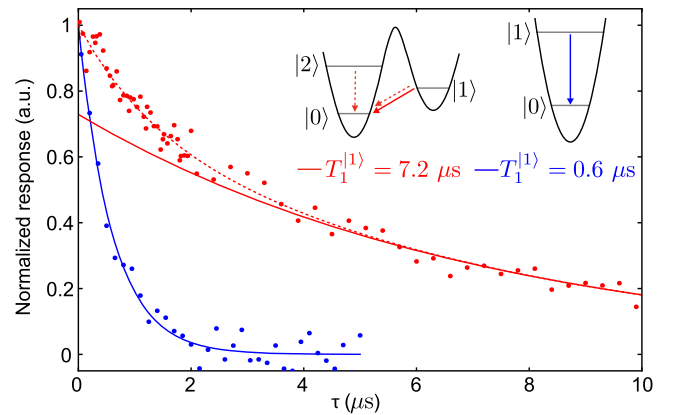


FIG. 5. Lifetime measurements in the transmon regime with $\Phi = 0$ and $f_{\text{Drive}} = 7.911$ GHz (blue) and the tilted potential regime with $\Phi = 0.512\Phi_0$ and $f_{\text{Drive}} = 5.725$ GHz (red). Blue solid line is an exponential fit. Red dashed line is a double exponential fit $A_1 e^{-\tau/T_1^{(1)}} + A_2 e^{-\tau/T_1^{(2)}}$ with the solid line showing $A_1 e^{-\tau/T_1^{(1)}}$ (see main text). Data are normalized to fit parameters.

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 qubit states might be distinguished using parametrically driven readout schemes [42]. Finally, further work might take advantage of recently demonstrated high-impedance resonators ($Z \gg 1 \text{ k}\Omega$) [43–45] and fast superconducting switches such as superconducting FETs [46] to implement a topological qubit with protected qubit operations [13].

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