Gateon Benchmarking and Two-Qubit Operation

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Recent experiments have demonstrated superconducting transmon qubits with semiconductor nanowire Josephson junctions. These hybrid gateon qubits utilize field effect tunability characteristic for semiconductors to allow complete qubit control using gate voltages, potentially a technological advantage over conventional flux-controlled transmons. Here, we present experiments with a two-qubit gateon circuit. We characterize qubit coherence and stability and use randomized benchmarking to demonstrate single-qubit gate errors below 0.7% for all gates, including voltage-controlled Z rotations. We show coherent capacitive coupling between two gateons and coherent swap operations. Finally, we perform a two-qubit controlled-phase gate with an estimated fidelity of 91%, demonstrating the potential of gateon qubits for building scalable quantum processors.

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The scalability and ubiquity of semiconductor technology make it an attractive platform for a quantum processor. Semiconductor qubit devices offer simple and flexible control using voltages on high impedance gate electrodes that readily allow low-power operation at cryogenic temperatures. However, such field effect-based control also makes semiconductor qubits susceptible to electrical charge noise that can strongly degrade the fidelity of gate operations. In both semiconductor charge qubits and spin qubits using exchange coupling, charge noise directly modulates the energy splitting between states, resulting in inhomogeneous dephasing times that are typically only ~10 times longer than gate operation times [1-4]. Recently a new semiconductor-based qubit, the gateon, has been introduced [5]. This hybrid qubit is a superconducting transmon qubit that, crucially, features a semiconductor Josephson junction (JJ). Gateons therefore combine the in situ tunability of a semiconductor with the simple connectivity and operation of transmons [7,8]. Initial experiments measured microsecond dephasing times that far exceeded ~10 ns gate operation times [9], encouraging further investigation and optimization of this qubit.

In this Letter, we explore coherence and gate operations of gateons in a two-qubit circuit. We study the influence of the distinct gateon spectrum on coherence and use Ramsey interferometry to precisely probe the stability of the semiconductor JJ. The excellent stability observed together with improved coherence allow for randomized benchmarking of single-qubit gates [10,11], including Z-rotations implemented with gate pulses [12,13]. We also demonstrate coherent capacitive coupling between two gateons and coherent swap oscillations. Finally, with the implementation of a controlled-phase gate, we demonstrate that semiconductor-based gateons are conceptually similar to transmons, but with the technological advantage of full voltage control, making them ideally suited for large-scale quantum processors.

Figure 1(a) shows the two-qubit device. As with conventional transmons, each gateon operates as an LC oscillator with a nonlinear inductance due to the JJ. This

![Figure 1](https://example.com/figure1.png)

**FIG. 1.** Two-qubit device and single gateon quantum coherence. (a) Optical micrograph of the two-qubit device. Each qubit consists of a T-shaped island and a gated Al-InAs-Al Josephson junction. (b) Scanning electron micrograph of the gated semiconducting weak link Josephson junction of Q1. (c) Lifetime measurement for Q2 (blue) with qubit resonance frequency $f_Q = 5.225$ GHz. In red we perform an echo experiment to determine $T_{2,\text{echo}} \sim 9.5\mu s$. The solid and dashed lines are exponential fits. Inset: pulse sequences for dephasing ($T_{2,\text{echo}}$) [red] and relaxation ($T_1$) [blue] measurements. (d) A Ramsey experiment is performed to determine $T_2$ for Q2 with the pulse sequence shown as an inset. The solid line is a fit to an exponentially damped sinusoid.
allows us to address the qubit states $|0\rangle$ and $|1\rangle$ with a transition frequency $f_Q \approx \sqrt{\frac{E_C E_J}{\hbar}}$, where $E_C$ is the charging energy and $E_J$ is the Josephson coupling energy. In the case of the gatemon, the JJ is a superconductor-semiconductor-superconductor (S-Sm-S) junction with a few-channel Sm region, allowing $E_J$ to be tuned using a gate voltage that controls the carrier density in the Sm region.

The sample is fabricated following the recipe described in Ref. [6], but with the thermal oxide layer removed from the silicon substrate to reduce capacitor loss. The JJ is formed by selectively wet etching a segment of a $\sim 30$ nm thick Al shell epitaxially grown around a $\sim 75$ nm diameter single crystal InAs nanowire [13]. For qubit 1 (Q1) and qubit 2 (Q2) the junction lengths are 220 nm and 200 nm respectively. For each qubit, $E_C/\hbar$ is determined by the capacitance of the T-shaped Al island to the surrounding ground plane and designed to be $\sim 200$ MHz with $f_J/E_C$ tuned to $70 - 130$ using the side gate voltage $V_{g1}(2)$ for Q1(2). The interqubit coupling rate $g_{12}$ is determined by the capacitance $C_{12}$ between the two islands. From electrostatic simulations we estimate $2g_{12}/2\pi \approx 20$ MHz for $f_Q = 6$ GHz.

Qubit manipulation is performed using phase-controlled microwave pulses for rotations around axes in the $X-Y$ plane of the Bloch sphere and voltage pulses on $V_{1,2}$ for $Z$-axis rotations. For readout, the two qubits are coupled to individual $\lambda/4$ superconducting cavities (with resonant frequencies $f_{c1} \sim 7.81$ GHz and $f_{c2} \sim 7.73$ GHz), both coupled to a common feed line [15]. Crossover wiring on control lines is used to tie together interrupted regions of the ground plane to help suppress spurious modes [10]. The sample is placed inside an Al box, surrounded by a cryoperm shield and mounted at the mixing chamber of a cryogen-free dilution refrigerator with base temperature $< 50$ mK [17].

Figure [1(c)] shows a lifetime measurement for Q2. With the qubit excited to the $|1\rangle$ state with a $\pi$ pulse, the delay time $\tau$ before readout is varied and the decay (blue) fitted to an exponential, giving $T_1 = 5.3$ $\mu$s. We attribute the factor of $\sim 10$ improvement in lifetime relative to Ref. [6] to improved sample shielding and reduced interface losses due to the removal of the lossy thermal SiO$_2$ layer [18]. $T_2$ is determined by a Ramsey measurement (Fig. [1(d)]), where two $X/2$ pulses are separated by delay time $\tau$ [19].

A fit to the decay of the Ramsey fringes gives a dephasing time $T_2^\phi = 3.7$ $\mu$s, comparable to dephasing times for flux-controlled transmon devices [20]. We perform an echo experiment by inserting a refocusing $X$ pulse between two $Y/2$ pulses (Fig. [1(c)], red). The extracted $T_{2,echo} = 9.5$ $\mu$s $\approx 2T_1$ indicates that gatemon dephasing is dominated by low frequency noise [21].

In present devices, the gatemon spectrum is a non-monotonic function of gate voltage, reflecting the effect of mesoscopic fluctuations in the transmission through the nanowire [9] [15] [22]. In Fig. [2] we examine how this non-monotonic response impacts the stability of $f_Q$, $T_1$ and $T_2^\phi$. Insets of Figs. [2](a) and (b) plot the qubit transition frequency as a function of gate voltage, as determined by sweeping the XY qubit microwave drive at each gate voltage. Points A and C in Figs. [2](a) and (b) insets are so-called sweet spots where the spectrum is first order insensitive to gate voltage fluctuations. At these operating points, the drift of the resonance frequencies $\Delta f(t) = (f_Q(t) - f_Q(0))/f_Q(0)$ as measured with a Ramsey experiment, is very small over several hours. The frequency drift has a standard deviation of 55 and 15 parts per million for Q1 and Q2 respectively [Fig. [2](a) and (b) main panels, green solid curves]. Away from sweet spots [Figs. [2](a) and (b) main panels, dashed orange curves], we observe two distinct types of behavior. Q1 drifts slowly on a timescale of hours, whereas Q2 exhibits discrete jumps in $f_Q$. The slow timescales of these drifts allow for reproducible $T_1$ (blue) and $T_2^\phi$ (black) measurements for Q2 [Fig. [2](c)]. Coherence times are on the order of $\mu$s but widely fluctuating, similar to observations for flux-controlled transmons [15]. The region of short coherence at $\sim 5.35$ GHz could be due to coupling to a two level system [20]. No correlations between sweet spots and coherence times are observed, when plot-
The microwave pulses are tuned up using both the AllXY interleaved gate and optimized using random sequences with $m \geq 10$ [25]. Benchmarking $Z/2$ and $Z$ rotations, the fidelity decays of both gates are found to be indistinguishable from microwave gates, with extracted errors of $r_{Z/2} = 0.35 \pm 0.19\%$ and $r_{Z/2} = 0.18 \pm 0.15\%$ [Fig. 3]. With $T_1 = 3.5 \mu s$ at point C, all gate errors [Fig. 3 inset] are close to the limit set by relaxation, $r_{\text{limit}} = t_{\text{gate}}/3T_1 = 0.3\%$ [26].

To probe the two-qubit coupling, we measure the spectrum while tuning Q1 and Q2 into resonance, driving both qubits through the same $XY$ control line. On resonance, the two-qubit states hybridize due to the capacitive coupling $C_{12}$ and an anticrossing is observed, see Fig. 4(a). We note the disappearance of the lower branch upon hybridizing, a signature of dark and a bright state formation [27].

Applying the pulse sequence in Fig. 4(b), a single excitation can coherently oscillate between Q1 and Q2. With the two qubits detuned by $\sim 200$ MHz and Q1 idling, Q2 is prepared in $|1\rangle$ away from the resonance and then a gate pulse is applied for time $\tau$, to bring Q2 into resonance with Q1 [28]. Depending on $\tau$ and the pulse amplitude $\Delta V_2$, elementary excitations swap between the two qubits, creating single excitation superpositions of the two qubits. Figure 4(c) shows the typical chevron pattern of swap oscillations [29]. Figure 4(d) shows the swap oscillations for both Q1 and Q2 idling at A and C. From the frequency of sine fits to the oscillations (solid lines), we extract the interaction rate $2g_{12}/2\pi = 17.8$ MHz.

Due to the negative anharmonicity of gateon qubits, the $|20\rangle-|11\rangle$ anticrossing is used to implement a controlled-phase gate following Ref. [30]. Figure 5(a) illustrates the $c_{x}^2$ tune-up procedure. Q1 serves as a control qubit and is either prepared in $|0\rangle$ (blue) or $|1\rangle$ (red). To measure the phase acquired by the target qubit, Q2 is prepared in the $(|0\rangle + |1\rangle)/\sqrt{2}$ state. By applying a gate [Fig. 3 solid black] we find the reference average fidelity $p_{\text{ref}} = 0.98$. Parameters $A = 0.53$ and $B = 0.42$ quantify state preparation and measurement errors. As only microwave pulses are used to generate the whole single-qubit Clifford set, an average Clifford gate consists of 1.875 single pulses [11]. We extract the average single-qubit gate error $r_{\text{ref}} = (1-p_{\text{ref}})/(2 \cdot 1.875) = 0.5 \pm 0.07\%$.

To benchmark individual gates, a specific gate $G$ is interleaved with a random Clifford $m$ times [11], followed by a $C_G$ gate and readout [Fig. 3 lower left inset]. A fit to the decay gives $p_G$. Using the average Clifford gate fidelity as reference, we extract the specific gate error $r_G = (1 - p_G/p_{\text{ref}})/2$. Figure 3 shows all benchmarked microwave gates in grey, including the identity operation $Id$. The inset displays the extracted errors for different gates, which are consistent with the average microwave gate error. Unique to the gateon implementation of the transmon are rotations around the $Z$-axis performed by applying a voltage pulse. The voltage pulses are nominally square pulses with length 28 ns with amplitude optimized using random sequences with $m \geq 10$ [25].
pulse on $V_2$, the system is brought close to the $|20\rangle - |11\rangle$ anticrossing (schematic in the inset of Fig. 5(b)). For $Q_1$ in $|0\rangle$ (grey dashed line) $Q_2$ only acquires a dynamical phase due to the change in frequency, identical to a rotation around the $Z$-axis. For $Q_1$ in the $|1\rangle$ state (black), $Q_2$ acquires an additional two-qubit phase due to the anticrossing. After the gate pulse, $Q_2$ is projected back onto the poles, by a $\pi/2$ pulse with varying phase $\theta$. The used gate pulse is 54 ns long and 0.16 V in amplitude, for which the acquired dynamical phase $\mod 2\pi$ is approximately $0$ [blue in Fig. 5(b)]]. For this gate pulse the controlled phase shift on $Q_2$, if $Q_1$ is in the $|1\rangle$ state (red), is $\sim \pi$ and thus constitutes a $c_{Z}^2$ gate. The probability for $Q_2$ to end up in the $|1\rangle$ state, $P_{Q2(1)}$, oscillates as function of $\theta$ with a period of $2\pi$, as expected.

The fidelity of the two-qubit gate was estimated by interleaving the $c_{Z}^2$ gate with single-qubit random Clifford gates applied to the target qubit, $Q_2$, with the control qubit, $Q_1$, prepared randomly in either the $|0\rangle$ or $|1\rangle$ state, as shown in Fig. 5(c) [31, 32]. $Q_1$ is returned to the $|0\rangle$ state after every $c_{Z}^2$ gate. Because $Q_1$ is only subject to $X$-rotations, the two-qubit phase can essentially be mapped as a single-qubit $Z$ rotation. The sequence is repeated $m$ times, followed by a recovery pulse $C_{R}$ and readout of $Q_2$. The main panel in Fig. 5(d) shows the fidelity decay with $m$, resulting in $c_{Z}^2$ gate error $r = 9 \pm 2\%$. If $Q_1$ is prepared in only $|0\rangle$ or $|1\rangle$ the errors are similar (upper right inset in Fig. 5(d)). Based on measurements using an identity operation instead of a $c_{Z}^2$ gate pulse, we estimate a 4% error due to relaxation. The remaining 5% error is coming from leakage into the $|20\rangle$ state, which can be minimized through improved pulse shaping [29, 33].

In summary, we have presented gate operations for a hybrid superconductor-semiconductor qubit, with inhomogeneous dephasing times comparable to conventional flux-controlled transmon qubits and single-qubit gate fidelities exceeding 99%. Through both optimizing gate operations and further leveraging recent advances in conventional transmon qubit lifetimes, we expect one- and two-qubit gate fidelities comparable with conventional transmons can be achieved. Combined with simple qubit control using gate voltages, gatemon qubits may present an attractive route to large scale quantum computing.

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FIG. 4. Coherent gatemon coupling. (a) Measurement of the avoided level crossing between $Q_1$ and $Q_2$. The sum of the normalized heterodyne readout amplitude $|V_{H1}| + |V_{H2}|$ for both qubits is shown as a function of the qubit drive and $V_1$ ($V_2 = 2.25$ V). On resonance at $V_1 = -3.78$ V the lower branch disappears, suggesting the formation of a dark state. (b) Pulse sequence to probe the coherent coupling between the qubits. With $Q_1$ and $Q_2$ detuned, $Q_1$ is prepared in the ground state and an $X$ pulse prepares $Q_2$ in $|1\rangle$. A gate pulse with amplitude $\Delta V_2$ is turned on for a time $\tau$ and brings $Q_2$ close to or in resonance with $Q_1$. The flanks of the gate pulse are Gaussian with $\sigma = 4$ ns. (c) The $|1\rangle$ state probability, $P_{Q1(1)}$, for $Q_1$ as a function of $\Delta V_2$ and $\tau$. (d) $P_{Q1(1)}$ for both $Q_1$ and $Q_2$ at the voltage pulse amplitude that brings the two qubits into resonance. The flanks of the gate pulse are elongated to $\sigma = 8$ ns, to account for the larger detuning relative to (c).

FIG. 5. Controlled-phase $c_{Z}^2$ gate operation. (a) Pulse sequence to probe the controlled phase shift of $Q_2$ (target). $Q_1$ (control) is either prepared in $|0\rangle$ (blue) or $|1\rangle$ (red). The acquired single-qubit phase of $Q_2$ is measured with a Ramsey experiment (black), where the phase of the second pulse $\theta$ is varied. Between Ramsey pulses $Q_2$ is pulsed towards the $|20\rangle - |11\rangle$ anticrossing. (b) The inset shows that independent of $Q_1$, $Q_2$ acquires a dynamical phase because of the change in resonance frequency (dashed line). Due to the anticrossing the target acquires an additional phase if $Q_1$ is in the $|1\rangle$ state (solid line). In the main panel the probability of $Q_2$ being in $|1\rangle$, $P_{Q2(1)}$, is plotted as a function of $\theta$. (c) Pulse sequence to probe the error of the $c_{Z}^2$ gate. $Q_1$ is prepared either in $|0\rangle$ (blue) or $|1\rangle$ (red). The $c_{Z}^2$ gate is interleaved with a random single-qubit Clifford gate $C$. (d) Lower left inset: The interleaved two-qubit gate sequence is followed by a recovery pulse $C_{R}$ and a measurement. The main panel shows the decay in fidelity with increasing sequence length $m$ for a random preparation of $Q_1$ (green). Two-qubit gate error $r$ extracted from the decay are shown in the upper right inset for different preparations of $Q_1$. The fidelity of $Q_1$, $P_{Q1(1)}$, is varied. Between Ramsey pulses $Q_2$ is pulsed towards the $|20\rangle - |11\rangle$ anticrossing (schematic in the inset of Fig. 5(b)).
See the Supplemental Material at [URL to be inserted by the authors].